Master's Thesis in Engineering

Effects of Renewable Energy Utilization on the Security of Cambodia Electricity Supply

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Abstract

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Due to the fast-rising energy demand in Cambodia in the last two decades, conventional electricity power plants have been deployed together with additional electricity imported. Among domestic resources, coal power plants and large hydro are dominant in the generation mix, while green energy sources are relatively low. Energy security and environmental emissions reduction have become higher priorities to ensure sustainable energy supply at affordable costs for continued economic growth and development in Cambodia. In addressing these issues, renewable energy plays a vital role in the long-term electricity supply security and sustainable development.

This study applied the ARIMA (1,2,2) model for electricity demand forecasting, then applied the Low Emission Analysis Platform (LEAP) model to estimate and analyze the renewable energy potential in Cambodia's electricity generation mix. It determines the best mix of electricity generation technologies based on availability of domestic renewable energy sources, renewable energy share target, and emissions reduction target. Six scenarios, excluding the baseline scenario, have been formulated: two scenarios focus on the availability of renewable energy potential; on the other hand, two scenarios consider only the specified shares of renewable energy in the generation mix in 2050, and the last two scenarios combine the availability of renewable potential and targeted shares of renewable energy in generation mix. Results from the LEAP model, such as capacity expansion, energy generation, costs, and emissions, were used to investigate the effects of their changes on Cambodia's future electricity supply.

The results showed that electricity demand in Cambodia would rise from 12.12 TWh in 2020 to 87.74 TWh in 2050. For domestic electricity generation, in optimal utilization of renewable energy with maximum net present value, renewable energy electricity generation would reach 6.16TWh (22.27%), 13.11TWh (25%), and 33.14TWh (40%) in 2030, 2040, and 2050, respectively. The remaining supply comes from mostly natural gas-based generation and electricity import from neighboring countries. Based on the most implemental scenario, the total installed capacity would be 25.05 GW in 2050. Large hydro will be the dominant source, followed by a tremendous solar photovoltaic and natural gas share. In the meantime, Cambodia would need 126.25 billion U.S. dollars (BUSD) until 2050 for such a development. Such an implementation would emit greenhouse gas (GHG) emissions in the amount of just 118.85 million metric tonnes of CO_2 equivalent (Mt CO_2e), and in this case, Cambodia could meet its 2030 INDC reduction target. However, to successfully achieve both renewable energy targets and emission reduction targets, the Royal Government of Cambodia (RGC) will play an essential role in various actions. Such interventions could be seen from raising awareness to the public, establishing legal framework and policy measures, and looking for support from both local and international investors in renewable energy technology.

Keywords: Optimal utilization, renewable energy, supply security, INDC, carbon emission

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Chapter 1. Introduction

During the past sixteen years, Cambodia’s energy demand has increased 13 times, and energy delivery has increased 12 times. These resulted from sustained growth of economic activities, industrialization, population growth, and rapid urbanization. Both primary and final energy demand in the Kingdom would reach more than double in the next thirty years, comparing to those in 2015. Under the absolute terms, Cambodia's primary energy supply has been forecast to increase from 7.02 Mtoe in 2015 to 15.24 Mtoe in 2040; meanwhile, final energy demand would also increase from 5.93 Mtoe to 11.77 Mtoe in the same period (Kimura & Han, 2019). Kimura and Han (2019) also added that aggressive growth in final energy consumption is expected to occur in the transport and industry sector, with average growth rates of 3.9% and 3.5%, respectively.

There is a significant increase in electricity demand in Cambodia, with an estimated annual growth rate of 9% between 2015 and 2040. The fastest growth in electricity generation would be in hydropower (9.1% per year), followed by coal (7.5% per year). On the other hand, owing to high fuel prices, generation from oil-fired power plants would decline dramatically. In 2019, the share of hydropower and coal power generations in the generation mix accounted for 33.53% and 32.62%, respectively. Meanwhile, even though Cambodia has abundant renewable energy resources, its share, excluding large hydro[1], was less than 2%. Such a low number indicated that Cambodia depends mostly on fossil fuel

[1] Hydropower plant with capacity more than 50 megawatts (assumption)

and large-hydro electricity generation. Such dependency could be a burden to both energy security, socio-economic development, and the environment. For clear evidence, during the dry season in 2019, Cambodia had experienced a power shortage, losing approximately 400 MW of electricity due to insufficient water for running the plants. To handle this issue, in September 2019, the Royal Government of Cambodia (RGC) has signed a power purchasing agreement (PPA) to import electricity from Laos PDR, one of her neighboring countries, with the capacity of 2400 MW (Ministry of Mines and Energy [MME], 2020). Following these changes in the energy landscape, import electricity in 2020 is expected to increase to almost 30% of combined power sources. Among the total import electricity in 2020, the primary source is from Laos PDR, followed by Vietnam and Thailand with a maximum capacity of 421 MW, 323.45 MW, and 277.3 MW, respectively. Such dependency would not be a big issue for meeting energy demand in a short period; however, in long-term supply security, alternative sources of domestic energy need to be considered (Norvaisa & Arvydas, 2016).

On the other hand, as it depends on imported coal, oil, and natural gas, Cambodia has a very high reliance on fossil fuel imports. Cambodia continues to increase importing these fossil fuels to sustain economic growth, which will pressure energy security whenever there is import disruption. Statistically, in three consecutive years, from 2013 to 2016, Cambodia's import dependence increased from 50% to almost 60%. In this regard, increasing fossil fuel prices could bring vulnerability to energy supply in the country.

Finally, while some countries in the region have already targeted the specific shares of renewable energy in either electricity generation or primary energy as a whole, Cambodia remains unclear on such a target. Based on these statements and evidence, the study proposed research problems as follows:

- As the country relies heavily on imported gas, oil, and electricity, Cambodia has a very high reliance on fuel imports.
- Steadily increasing energy demand in Cambodia will also increase carbon dioxide (CO2) emissions from fossil fuel combustion, with the main sources of CO2 emissions are coal and oil consumption.
- About one-third of domestically produced electricity is from large hydropower plants, so that drought would threaten energy supply from such a type of generation in the future.
- A considerable gap between development to potential ratios of each renewable energy resource; for instance, large hydropower has been so far more developed, followed by the recent development of utility-scale solar photovoltaic. However, domestic bioenergy development is relatively low; likewise, wind power plant does not have significant development.
- Cambodia does not have a clear target of renewable energy shares, which aggregated all domestic renewables, in the generation mix neither in medium- or long-term planning.

Based on the issues mentioned above, this study proposed three research questions:

1. What is the status of the security of electricity supply in the context of Cambodia?
2. How much would domestic renewable energy sources be introduced into Cambodia's electricity generation mix?
3. What are the benefits of optimal utilization of renewable energy sources on Cambodia's electricity supply security and CO2 emissions mitigation?

These research questions have been designed to estimate and analyze the renewable energy potential in the electricity generation mix in Cambodia, determine the best mix, and determine renewable energy targets and the share from each renewable source of future power generation.

1.1 Thesis Structure

There is a total of six chapters in this thesis. Chapter I points out current issues of Cambodia's energy sector, then it comes up with research problem statements. Chapter I also proposes research questions according to stated problems; finally, it shows the whole study's primary objectives. In Chapter II, three prominent figures about Cambodia's energy sector are given, such as the overview of Cambodia's energy sector, a brief description of energy security, and Cambodia INDC's emission reduction target, particularly in the energy industry. Considering the inexistence of the future target of renewable energy in Cambodia, this chapter also compares Cambodia's past target with countries in the ASEAN region.

Chapter III focuses on reviewing previous studies on the relationship between energy security and renewable energy development, some models for energy demand forecasting, and the applications of LEAP energy modeling tool, which will be used for this study. Chapter IV explains this study's flow of methodologies, key assumptions, data inputs, and how all scenarios were formulated. Chapter V interprets this study's results; specifically, it focuses on annual capacity expansion, energy generation mix, costs, and emissions in each proposed scenario. It also compares and finds the best scenario option so that such a scenario can be used for proposing policy implications after the overall conclusion in Chapter VI. In addition, at the end of Chapter V, eight indicators of electricity supply security are individually and aggregately interpreted and compared for all scenarios. Finally, besides giving the conclusion and policy implications, Chapter VI states the limitation and future works of this study.

Chapter 2. Research Background

2.1 Overview of Cambodia's Energy Sector

2.1.1 Electricity Generation and Consumption in Cambodia

To achieve enough electricity supply of decent quality and meet the demand sustainably and stably at a reasonable price throughout the Kingdom of Cambodia, the RGC has set two main targets: (i) by 2020, 100% of Cambodian villages will have access to some forms of electricity service, and (ii) by 2030, at least 90% of households would have access to grid-quality electricity (MME, 2019a). By the end of 2018, as a result, 86.8% of villages and 72.16% of households accessed to grid-quality electricity (MME, 2019b). Along with Cambodia's remarkable economic development, energy demand has been rapidly increasing in the past two decades. During the past 16 years, power sources' capacity has increased more than 13 times; in the meantime, energy delivery has also increased 12 times (MME, 2019b). Last year, energy consumption reached 12,015GWh, showing 23.37% increases over the previous year's consumption. Such a vast increase in demand has already broken down demand forecasting in the past. Among this consumption, the total domestic generation accounted for 74.80% in 2019, and its share is expected to decrease by roughly 4% as more electricity will be imported from neighboring countries.

Regarding electricity import, it is also important to mention that Cambodia's electricity supply system has been categorized into three primary sources, namely (i) electric power supply through the national grid, (ii) the electric power supply in areas that have not yet been reached by the national grid, by importing electricity from neighboring countries through medium voltage (MV) lines, and (iii) a small amount of energy supply provided by diesel generators or stand-alone technologies through mini-grids.

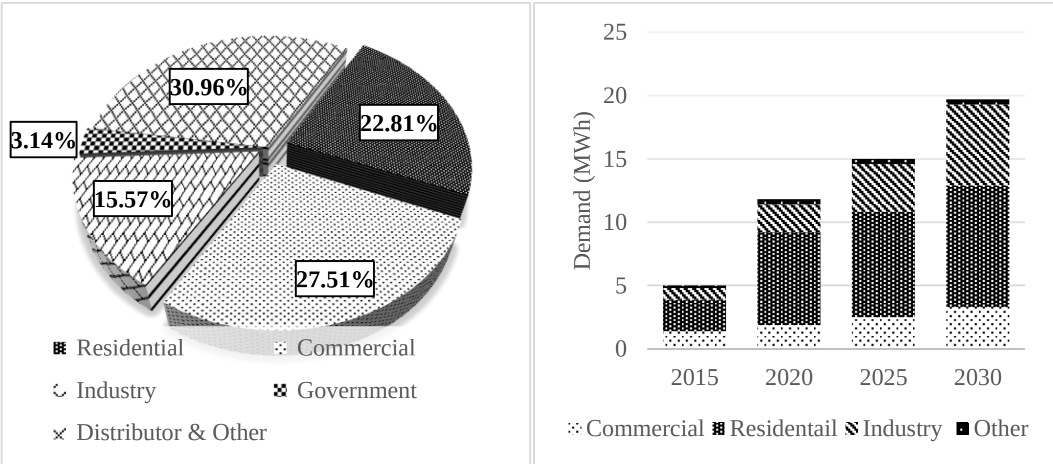

Figure 1. Cambodia Sectoral Energy Consumption in 2018 and Future Demand

In the perspective of sectoral energy demand, the distributor and others together accounted for 30.96%, and then closely followed by consumption for commercial purposes. Energy uses in the residential and industrial sectors were 22.81% and 15.57%, respectively, in the same year. MME (2019) predicted that the total energy demand would reach approximately 20 TWh in 2030. The residential sector would take almost half of the total energy demand (see Figure 1).

2.1.2 Renewable Energy Potential and Development

2.1.2.1 Hydropower

Hydropower has proven technical potential of 10,000 MW, 50% on the mainstream Mekong River, 40% in its tributaries, and 10% outside the Mekong Basin in the southwest.

There are 63 possible sites for large-hydro and small-hydro power dam development; however, hydroelectricity's current installed capacity is only 1.33% (MME, 2019a). By the end of 2019, seven hydropower plants have been operated, with an installed capacity of 1330 MW (33.53% share in generation mix) (MME, 2019a). Most of these are large-hydro power plants, and each capacity is up to 400 MW. The electricity supply of hydropower plants is greatly vulnerable to seasonal changes in hydrology, weather patterns, and climate phenomena (Poch, 2016). Due to various environmental impacts of large hydropower plants, energy fluctuation caused by intermittency of water levels (Poch & Phoumin, 2013), and devastation of river's fragile biodiversity, the RGC has planned to no longer build new hydropower projects on the mainstream Mekong for ten years, starting from 2020 (Ratcliffe, R., 2020). Table 1 summarizes the proven technical potential of renewable energy sources in Cambodia (Intelligent Energy System [IES], 2016).

Table 1. Summary of Renewable Potential and Existing Installed Capacity

Process	Technical Potential (MW)	2019 Installed Capacity (MW)	Remark
Large hydro	10000	1329.69	
Small hydro	700	37	Capacity ≤ 50
Solar PV	8074	24.80	Concentrated Solar Power (CSP) is not considered
Biomass	2392	64.80	
Onshore Wind	500	0.13	

Municipal Solid Waste (MSW)	not applicable	not applicable	Feasibility study
Other Renewables	not applicable	not applicable	No feasibility study

2.1.2.2 Solar Power

In Cambodia, the average sunshine period is 6-9 hours a day, with solar radiation measured at 5 kWh/m2 per day. Global Horizontal Irradiation (GHI) is technically high, ranging from 1450 to 1950 kWh/m2/year. Also, since approximately 65% of the Kingdom's land area is estimated to have GHI levels around 1,800 kWh/m2/year, there is no doubt that Cambodia has a vast potential for solar energy resources. According to the Asian Development Bank (ADB, 2010), solar photovoltaics' technical potential is 8.1 GW, equivalent to 12 TWh annually for electricity generation.

In terms of solar photovoltaic (PV) development, the government has already approved ten projects. These projects are expected to inject 424.8 MW to the national total installed capacity in 2022 (MME, 2019). Specifically, four solar farms have already been connected to the grid, one among which is a 9.8-megawatt-peak plant[2], using to supply a cement factory (Cleantech Solar, 2019). The development of solar PV is the second-largest energy source among its kind, followed hydropower; however, solar thermal applications are relatively small in Cambodia, while there is no plan for concentrated solar power (CSP) development.

[2]Solar floating (2.8MW) + Solar rooftops (7MW)

2.1.2.3 Bioenergy

Bioenergy, here in general, refers to biomass, biogas, and biofuel. Around 76% of the Cambodian population resides in the countryside (World Bank [WB], 2018), and they work mostly in the agricultural sector. Besides, such a sector accounted for one-third of Cambodia's total GDP (ADB, 2015); hence, there is no doubt that agricultural residues are abundant as energy sources. Rice husk, rice straw, and maize are giant in the potential for biomass feedstock for energy generations. The theoretical energy potential of biomass from agricultural residues is 15 TWh. Since 2006, Cambodia has used biomass power plants with an installed capacity of 4.50 MW for generating electricity, and the number had steadily risen to about 64.8 MW in 2019 (MME, 2019). However, this utilization is relatively small compared to its technical potential.

Moreover, Cambodia has considerable theoretical potential for bioethanol and biodiesel production. This fuel would significantly supplement the use of diesel and gasoline in road transportation up to 10% and 30%, respectively, in the next ten years (Economic Research Institute for ASEAN and East Asia [ERIA], 2013). Furthermore, Cambodia's biogas potential from animal manure is also high; however, given the small land and livestock holdings of most farmers, its availability is significantly limited to production at the household level. Until 2016, about 25383 biogas digesters with capacities ranging from $2m^3$ to $15m^3$ were installed in rural areas (MME, 2019a). After rapid expansion of the electricity grid to almost all the villages across the country[3], even remote areas, biogas

[3] By the end of 2019, 95.7% of villages have already been electrified (MME, 2019b)

digesters are no longer the alternatives and convenient energy sources for cooking. For these reasons, only some of them are still in operation nowadays.

2.1.2.4 Wind Power

Wind power has been widely overlooked in Cambodia; however, Cambodia can generate electricity up to 500 MW per year from wind power plants, according to the recent feasibility study. This kind's potential is not that high since only 3% of total land areas could meet electricity-generate-able requirements—average speed ranges from 6m/s to 9m/s. The development of wind energy is relatively low, and only two kilowatt-scale turbines are being in operation. However, according to the latest updates, if the government approves the projects within this year, ten wind turbines with 80 MW of capacity will be built before 2023 on a mountainous area in the country's southwest region (MME, 2020).

2.1.2.5 Other Renewables

There is no available data or previous literature regarding geothermal resource potential, waste-to-energy (W2E), or other new and renewable energy sources. However, recently, the government seeks investors to develop waste-to-energy projects to diversify domestic energy resources and solve increased waste disposals. The RGC, through the Ministry of Mines and Energy Cambodia, also emphasized that waste-to-energy development is a must in future energy generation even though this technology's price is relatively higher than that of other renewable sources.

2.1.3 Cambodia’s Renewable Energy Target vs. ASEAN’s

Association of Southeast Asian Nations (ASEAN) planned to realize the regional target of 23% share of renewable sources in the energy mix by 2025. Following this target, most ASEAN member states (AMSs) have shown ambition in increasing the shares of renewable energy by setting up national renewable energy development targets for short-, medium- and long-term planning. For instance, Laos PDR planned to increase renewable energy share to 30% of the total energy consumption by 2025. In the meantime, Indonesia set two different renewable energy targets: 23% and 31% of renewable energy in the energy mix in 2025 and 2050, respectively. In terms of installed capacity targets, Vietnam and the Philippines ambitiously planned to have 27 GW and 15 GW of capacity developed from renewable sources in 2030 (Mamat et al., 2019; Phoumin et al., 2018). As seen in Table 2, while most of the AMSs are on the way to utilize domestic renewable resources, Cambodia tends to develop only in hydropower plants.

Table 2. The Target of Renewable Energy in AMSs

Member States	Renewable Energy Target
Brunei	10% of RE share in power generation in 2035*
Cambodia	Increase share of hydropower to 2,241MW by 2020
Indonesia	23% and 31% of RE in the energy mix in 2025 and 2050, respectively
Laos PDR	30% RE share of total energy consumptions by 2025*
Malaysia	Increase RE to 2,080 MW by 2020 and 4,000 MW by 2030*
Myanmar	15%–20% RE share in the energy mix by 2030*

Philippines	15 GW of RE will be installed by 2030
Singapore	Install 350 MW of Solar PV by 2020
Thailand	30%** share of RE by 2036*
Viet Nam	27 GW RE installation in 2030*
ASEAN	23% share of RE by 2025

* large hydropower is not included in renewable energy type due to its environmental burdens (Rosa et al., 2004)

** share of renewables-based power generation capacity to 20.11% and share of renewables in transport fuel consumption to 25.04%

2.2 Cambodia's Energy Security

Being one of the developing countries and having relatively high economic growth, energy demand in Cambodia is expected to increase rapidly until the next few decades. In particular, electricity demand has shown a relatively high annual growth rate; according to MME (2019a), such a rate is almost 9% between 2015 to 2040. The increase in demand could threaten Cambodia's energy security and impact future socio-economic development if energy planning was not well-established. The major threat in securing supply is the high dependency on energy imports, petroleum products, and electricity imports. For instance, in 2019, Cambodia imported electricity from neighboring countries such as Vietnam, Thailand, and Laos PDR, approximately 3 TWh. This amount of electricity accounted for more than a quarter of the total energy delivered across the nation in 2019. According to the plan (MME, 2019), this share will reach 29.47% to meet energy demand in 2020. From an economic perspective, such a high dependency on low-cost electricity imports is also an attractive alternative for long-term planning; however, this negatively affects electricity supply security if unexpectedly interrupted or costly (Norvaisa & Galinis, 2016). There existed a controversial topic in the region in Singapore about the consequences of electricity imports' overcapacity (Lim, 2011).

On the other hand, even though there were no critical cross-border disputes, a geopolitical conflict is unpredictable, and the consequences of it will not be pleasant. The latest border demarcation disagreements between Cambodia and Laos PDR happened in 2017 and had recently been resolved with both parties' significant efforts. Although it had been entirely ended, it is also important to point out the dispute between Cambodia and Thailand, which lasted for almost three and a half years, from June 2008 to December 2011. Regarding geopolitical concerns in energy supply security, electricity grids have deepened international cooperation, yet it is a stick against enamoring states. There happened reconsideration of power purchase agreements (PPAs) or being used as a hostage when relations between parties deteriorate (Fischhendler et al., 2016).

In addition to high import dependency, the lack of fuel diversification in the generation mix also poses a threat to Cambodia’s electricity supply security. The primary sources of domestic power generation are hydropower and coal-fired power plants. Last year, the installed capacity from hydro and coal-fired generations was 33.53% and 32.62%, respectively, while the share of renewable sources was less than 2% (MME, 2019b). As already mentioned in the introduction, during the dry season in 2019, Cambodia experienced a power shortage, dropping approximately 400 MW of energy output from hydropower generations due to insufficient water to run the plants. Furthermore, due to seasonal variations of power generated from hydropower plants, the output drops in the dry season; such a shortage requires the back-up power from coal-fired generations. Besides, in addition to the impacts of hydropower dam constructions in countries along the mainstream of Mekong River on fisheries, agriculture, and some other habitats in Lower Mekong Basin (LMB) as shown in Yoshida et al., (2020), there have also been concerns regarding environmental and social impacts from Cambodia's hydroelectric projects itself.

2.3 Cambodia's Intended Nationally Determined Contribution

A transformative international climate agreement was ratified by about 197 nations worldwide at the United Nation Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP21) in Paris in December 2015. The aim is to limit the global temperature from 1.5 to 2 degrees Celsius below that in pre-industrialization. The nationally determined contributions (NDCs) mechanism is the core instrument for achieving such an ambitious target. By publicly drawing on what post-2020 climate interventions they intended to take under the new international agreement, known as Intended Nationally Determined Contributions (INDCs), all member countries demonstrated their initiatives and commitment to this contribution obligation. Priority actions for emission reduction in various sectors have been set up and being implemented. Those major sectors are energy generation, industrial and manufacturing, transportation, and agriculture. There is no question that reducing GHG emissions in the power sector is a must for all nations since this sector produces relatively high fossil fuel emissions. For example, according to International Energy Agency's recent report, in 2018, among 33.1 Gt CO2e, power sector accounts for two-thirds of emission growth[4]. For this reason, the investigations on either NDCs or INDCs are necessary for energy-environment planning, such that can be seen in many of existing studies (Ferrão, 2017; Handayani et al., 2019; Ho et al., 2019; Hussain et al., 2018; Prasad & Raturi, 2019; Simsek et al., 2020).

More specifically, according to Cambodia's Intended Nationally Determined Contribution (INDC), in order to address challenges regarding carbon dioxide emission and climate change issue, Cambodia has planned a 27% reduction of its GHG emissions by 2030 (3,100 Gg CO2e compared to baseline emissions of 11,600 Gg CO2e), relative to its 2010 level, contingent upon international support (Ministry of Environment [MOE], 2015). To this point, Cambodia has placed policy mechanisms in various sectors such as the power sector, transportation, manufacturing, and many more. Particularly, in order to reduce emission in energy industries, three main priority actions are being implemented such as (i) connecting renewable energy resource and decentralized renewable generation to the grid, (ii) developing off-grid electricity such as solar home system (SHS), and developing small

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[4] IEA. (2019). *Emissions – Global Energy & CO2 Status Report 2019 – Analysis*. https://www.iea.org/reports/global-energy-co2-status-report-2019/emissions, (last accessed on December 18, 2020)

hydro (pico-, mini-, and micro-scale), and (iii) introducing energy efficiency in the demand side. If these actions to be successfully implemented, it will contribute around 16% or 1,800 Gg CO2e of the total intended emission reduction target. The remaining actions in manufacturing industries, transport, and others can be achieved with energy-related actions such as promoting energy efficiency in specific industries, shifting to eco-friendly vehicles, and applying renewable energy technologies in the agricultural sector (RGC, 2015).

As addressed in the previous section about the dominance of large hydropower in Cambodia's electricity generation, there is no doubt that more demand in conventional energy resources is needed to cope with demand fluctuation; consequently, vast amounts of greenhouse gases will be generated. It is also essential to bring some of Cambodia's emissions facts here, especially ones resulting from the electricity generation or energy-related sectors. Sarasy (2017) predicted that the increase in Cambodia's energy demand would also increase carbon dioxide emissions from fossil fuel combustion. Carbon emissions are expected to rise by 5.6% per year from 1.96 Mt CO2e in 2015 to 8.62 Mt CO2e in 2040 under the business-as-usual scenario. Two main emerging sources for such emissions are transportation and energy production. In particular, oil is the largest carbon emissions source; it has been expected to increase from 1.39 Mt CO2e in 2015 to 3.55 Mt CO2e in 2040. Meanwhile, coal consumption emissions would grow the fastest at 6.8% per year, from 0.63 Mt CO2e in 2015 to 3.24 Mt CO2e in 2040.

Even though these numbers seem to be small compared to the world's cumulative emissions, it would also contribute to the increase in global temperature. Hence, following the existing emission reduction target, Cambodia would need to effectively implement her INDC's prioritized measures, especially in electricity generation.

Chapter 3. Literature Review

3.1 Renewable Energy and Energy Security

Energy security, described as the equitable provision to end-users of accessible, affordable, effective, productive, environmentally sustainable, proactively regulated, and socially acceptable energy services, has emerged as a key factor in energy and political policy (Sovacool & Brown, 2010). Advancing in energy security becomes the priority of many countries, especially in mandating sustainable energy policies. Several dimensions are considered for defining energy security, starting from the availability of energy resources until the latest development of cloud-based technology emerging in end-use energy supply (Azzuni & Breyer, 2018). Specifically, Paravantis and Kontoulis (2020) defined energy security by including 4A definition: physical availability, economic affordability, socio-political accessibility, and environmental acceptability.

Coping with the rise in energy demand, resource depletion, and cost of environmental externality in the power sector, many countries have been trying to shift to a cleaner source of energy supply as much as possible. Renewable energy utilization has been seen as an answer to addressing such issues. Gouveia et al., (2014) investigated the impact of high utilization of onshore wind technologies on Portuguese electricity by looking into various components of electricity, using a supply chain approach. Five main categories of electricity supply security indicators have been proposed: resource, infrastructure, electricity production technologies, transmission and distribution, and demand.

Interestingly, renewable energy indicators can be found as the share of it on electricity generation's primary energy and capacity. This study showed that a huge development of onshore wind from 2005 onward had a vital role in Portuguese electricity supply security by 2011. Such a utilization could reduce energy dependency and increase the share of renewable electricity, as stated in the Portuguese power development plan. Besides, due to the increase of wind energy development, the country would decouple hydroelectric variability from fossil consumption.

Moreover, according to a study done by Abu and Bressler (2019), renewable energy's rapid development would bring socio-economic benefits to Israel and Jordan. It plays an important role in enhancing energy security in these countries. The study has been conducted because both countries have been affected by the events of Arab Spring, political instability and climate-change vulnerabilities, and their low and lagging-behind target of renewable energy utilization. It is obvious that environmental sustainability is the main reason for any development of renewable sources; however, the contribution of renewable electricity in these two countries is necessary for addressing the most political, social, and environmental challenges.

Furthermore, there are arguments on whether renewable energy integration could lead to a sustainable electricity system or economic transition. For example, Galyan et al., (2020) offered an overview of the history of renewable energy production for the production of electricity and the strategies implemented in 17 transition economies to encourage its use.

It concluded that recent progress made to encourage the use of renewable sources for electricity generation seems to affect non-conventional REs in these countries positively; however, the increase in levels remains poor.

On the contrary, fossil fuel technologies no longer strongly contribute to the modern energy security paradigm, while renewable energy technologies now play crucial roles in achieving secured supply planning (Valentine, 2011). According to Kanchana and Unesaki (2014) and the statement in section 2.1.3, ASEAN included renewable energy development in her action plans to promote regional cooperation and enhance energy security and sustainability in the region. More specifically, Brahim (2014) asserted how renewable energy deployment positively affects the Philippines' sustainability agenda and how the government's role and commitment could determine such energy diversifying. Later, in Kumar (2016), a considerable proportion of the generation mix would be generated from domestic renewable energy resources for securing energy supply in Indonesia and Thailand. Furthermore, this study has also projected that more than 80% of carbon emissions will be reduced in each country by 2050.

By focusing on the supply insecurity of hydropower dominance, which is quite similar to Cambodia's case, Gyam et al., (2015) and Corrêa et al., (2016) provided insightful results and discussion on the benefits of shifting to renewable electricity. For example, Corrêa et al., (2016) argued that only hydroelectricity alone could not guarantee electricity supply security in Brazil; thus, a proper balance of renewable sources' future development must be considered. Similarly, since Ghana’s power generation has been dominant by inexpensive hydropower; therefore, in order to prevent the hydrological shocks in hydroelectricity, reliance on fossil-based power plants, and supply security as a whole, Ghana is suggested to consider domestic renewable energy sources such as solar PV, biomass, medium- and small-hydropower and wind energy (Gyam et al., 2015).

We may not reject that the cost of renewable energy is a significant hindrance to its development, especially in developing countries. Nevertheless, Valentine (2011) indicated that the renewable energy sector's fragmented structure is also a significant barrier to compete with conventional energy in terms of costs. Only after a more effective and healthier structure is obtained will the price be getting lower from time to time. For instance, the cost of renewable energy sources worldwide is getting more and more competitive than conventional fossil fuels, even ones without subsidies (Groissböck & Gusmão, 2020).

3.2 Energy Demand Forecasting

To minimize electricity waste, accurate forecasting of future electricity consumption is crucial, especially for new emerging-economy countries having budget and resource constraints. An accurate energy prediction helps policymakers efficiently determine the investment costs and costs of production in the power sector, and optimally utilize energy resources that are limited or costly. There have been various methodologies were applied for energy, or specifically electricity demand forecasting. As seen in Suganthi and Samuel (2012), energy models for demand forecasting are categorized and summarized as follows:

time series models, regression models, econometric models, decomposition models, co-integration models, ARIMA models, artificial systems, grey prediction models, input-output models, fuzzy logic or genetic algorithm models, and integrated models. Also, this study made a review on a bottom-up model such as MARKet Allocation (MARKAL), The Integrated MARKAL-EFOM1 System (TIMES), and last but not least, Low Emissions Analysis Platform (LEAP).

In Cambodia's case, energy demand forecasting has been undertaken using various approaches for specific periods. Recently, in The Chukogu Electric Power Co. Inc. (CEP, 2020), Simple-E was applied to predict Cambodia’s energy demand between 2018 and 2030. Moreover, ASEAN Center for Energy (ACE, 2019) forecast electricity consumption in Cambodia until 2040. Demand forecasting in industrial and commercial sectors were based on the GDP variable in each sector and the relative price of electricity in the respective sectors. On the other hand, energy intensity, percentage of grid-connected households, and household growth rate were used to estimate electricity demand in the household sector. In another study done by Chhay and Limmeechokchai (2020), electricity demand's GDP and GDP elasticity were employed to predict future electricity demand within 2015-2050 in Cambodia.

In particular, Autoregressive Integrated Moving Average (ARIMA) model is a popular technique for energy and electricity demand forecasting and prediction, considered historical and present data. ARIMA can be used to predict future electricity demand based either on its time-series data (Cabral et al., 2017; Mahia et al., 2019; Wu & Cao, 2012), and as well as with major energy-dependent variables such as gross domestic product (GDP), population growth, or rate of urbanization (Rahman et al., 2016; Sarkodie, 2017). While considering the seasonal ARIMA (SARIMA), such a model was used by Ediger and Akar (2007) to forecast the demand of primary energy by fuel type from 2005 to 2020 in Turkey; as a result, the separate forecasting of individual fuel is more reliable than that of fuel aggregation. Similarly, Jamil (2020) deployed the ARIMA model to predict hydroelectricity consumption until 2030 in Pakistan. In addition, for effectiveness, the authors compared the result with hydroelectricity generation existing in the government plan; last but not least, they also conducted a sensitivity analysis to investigate the relation between hydroelectricity consumption and the annual population and GDP growth rate of the country.

However, determining the fittest ARIMA model is crucial for highly accurate and stable prediction. For instance, Sarkodie (2017) applied ARIMA (0,1,0) for estimating Ghana's electricity consumption until 2030, while ARIMA (2,2,2) was used to predict Jiangsu province's electricity consumption by Wu and Cao (2012). Also, among all tentative ARIMA models in Mahia et al., (2019), the ARIMA (1,1,1) has been seen as the most appropriate model in estimating electricity consumption in Guangdong province in China. In this study, ARIMA (1,2,2) is the best model for forecasting Cambodia's electricity consumption from 2020 until the next three decades.

3.3 Energy Modeling Software

3.3.1 MARKAL

MARKet Allocation (MARKAL) is a bottom-up, dynamic linear programming model of a country's energy system whose basic components are specific energy or emission control technology types. Considering the performance and cost characteristics of energy technologies, MARKAL can automatically choose the best technology combination that minimizes the total energy system cost. Since the model integrates both supply-side and demand-side energy systems, it automatically responds to any side changes.

It has been used to identify the least-cost energy system alone and include changes or restrictions in carbon emissions (Krzemie, 2013). Besides, it has the capability in evaluating the effects of new energy technology, government regulations, taxes, and subsidies (Endo, 2007; Ferrão & Fournier, 2017a; Timothy L. Johnson, Joseph F. DeCarolis Carol L. Shay, Daniel H. Loughlin, Cynthia L. Gage, 2006; Victor et al., 2014). Even though MARKAL has more advantages in energy system planning, it required intensive data compilation, proper training, and experiences (Mirjat et al., 2017).

3.3.2 TIMES

TIMES is the successor to the MARKAL framework and was established by the International Energy Agency (IEA) under the Energy Technology Systems Analysis Program (ETSAP) in 2008. The characteristics of TIMES are almost the same as its predecessor. Having to use linear programming, it can optimize an energy system based on inputs of constraints. It is applicable for both medium- and long-term future energy systems for a single or a group of countries. TIMES encompasses all energy system components such as resource extraction, transformation of energy, and devices in each sector or unit (Energy PLAN, 2015).

According to Tash et al. (2019), as TIMES is a technology-rich bottom-up model generator, it can generate and select the least-cost combination of renewable and non-renewable energy technologies (Amorim et al., 2014; Tambari et al., 2020; Yong et al., 2016), subject to specified physical, technological, environmental and political constraints (Ferrão & Fournier, 2017b). Due to its environmental component analysis, some of many studies have used TIMES to investigate INDC policies (Postic et al., 2017). Nevertheless, its predecessor's same disadvantages, TIMES required matured knowledge and experiences; additionally, it does not include the database of technologies and environment (Mirjat et al., 2017).

3.3.3 MESSAGE

The International Institute for Applied Systems Analysis (IIASA) in Austria has been developing MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) since 1980. It is a dynamic linear programming (DLP) model that minimizes cumulative discounted energy supply costs over a given period. The limits on the speed of the implementation of technology, the presence of indigenous and imported resources, and technical relationships are mirrored by the most relevant model constraints in MESSAGE (Schrattenholzer, 1981).

As far as this, researchers have created many different MESSAGE versions, depending on the studies' specified scopes. Similar to MARKAL/TIMES, energy experts use MESSAGE to optimize medium- and long-term energy systems, considering changes in climate policies and technical and economic characteristics of each energy technology. It does include not only conventional energy and renewable energy technology but also energy storage and conversion. It can be used for estimating the global, regional, and national energy planning subject to sectoral mitigation constraints rather than climate targets. In addition to the covering of GHGs analysis, it has been extended to investigate radioactive substances. The applications of MESSAGE can be found in some studies. For example, in the study of formulating an optimal long-term energy supply strategy for Syria (Hainoun et al., 2010), linking the model of energy supply with a macroeconomic module (Messner & Schrattenholzer, 2000), and optimizing of renewable energy utilization in Iran's electricity generation and emission planning (Aryanpur & Sha, 2015).

MESSAGE was recently extended to resolve endogenous learning by using Mixed Integer Programming (MIP) algorithms and various technologies. Another important model development includes extending the model to cover all six Kyoto GHGs, their drivers, and their mitigation technologies (Rofat, 2014). However, Mirjat et al. (2017) have argued that the MESSAGE has major difficulties in troubleshooting, running the model, and inputting the data due to a lack of clarity in the user manual.

3.3.4 REMIX—OPTIMO

REMix-OptiMo is a deterministic linear optimization program realized in forming a general algebraic modeling framework (GAMS). This method was built to provide a powerful tool for the layout and evaluation of future energy supply scenarios based on high temporal and spatial resolution system representation. The model is set up in a specific design with a wide variety of technically independent technology modules. Each module specifies the parameters, variables, formulas, and inconsistencies needed to describe the respective technological and economic characteristics. All technology modules allow the analysis of technology dispatch and capacity expansion.

According to the available resources and system characteristics, the model will optimize power plants' expansion, transmission lines, or storage capacity. Investments in new capacity expansion consider technology costs, depreciation times, and interest rates, enabling the estimation of appropriate capital expenditure for the preferred optimization interval.

Demand and supply are integrated into model clusters across predefined areas, connected via electricity grids. All generation units of each technology are grouped and regarded as single power manufacturers within the nodes. The model relies on a perfect modeling technique for foresight and optimizes the overall time horizon, normally one year. Within the designated optimization period, this means the expectation of a near future and the negligence of predicting ambiguity.

The objective function, boundary conditions, and constraints of REMix-OptiMo are characterized. The model variables encompass technology-specific electricity generation, electrical transmission, and storage in each time step and model region. Additional factors affect the model-endogenous installation of assets in each area if an expansion of capacity is considered. In addition to power balancing, drawbacks arise from technology-specific model equations and inequalities. The sum of the device costs in the overall investigation area is the optimal solution that is minimized. The proportional expenditure and fixed operating costs of all endogenously installed device components for one year of their amortization time and the variable operating costs of all technologies are composed (Gils et al., 2017).

Fattahi et al. (2020) introduced REMix to optimize the capacity expansion of conventional and renewable energy generation technologies starting from the current portfolio of power plants by modeling each existing and candidate unit's hourly output. Similarly, capacity expansion and hourly dispatch at different photovoltaic and wind power penetration stages in Europe's power supply were also assessed using this model (Gils et al., 2017). However, REMix seems to be more popular in the studies of energy generation mix with high-share of renewable energy or selected renewable energy generation technologies (Fichter et al., 2017; Gils & Simon, 2017; Scholz et al., 2017), rather than ones in the common approach of the energy mix.

3.3.5 **WEM**

The World Energy Model (WEM) is a very data-intensive model developed by the International Energy Agency (IEA) since 1993. It covers the whole energy system, consisting of three main components: energy supply, energy transformation, and final energy consumption module. Such a model provides different results, including energy flow by fuel type, costs for the investment, carbon dioxide emission, and even energy price at the end uses.

The current version of the WEM model has been more developed to investigate regional and global energy prospects, the impact of energy consumption on the environment, costs for investment in specific sectors, modern energy prospects, and even the effects of changes in energy policy energy technologies. Such a version also considers how the recent pandemic, COVID-19, could shape the world energy landscape. We can assess the effect of specific policies and initiatives, particularly in the current energy paradigm, such as renewable energy, energy efficiency, and climate change, by formulating different scenarios in WEM (IEA, 2018).

3.3.6 **LEAP**

The Low Emission Analysis Platform (LEAP) model is a widely used energy policy analysis and climate change mitigation measurement software tool. It was built at the Stockholm Environment Institute (SEI). Hundreds of organizations in almost 200 countries worldwide have implemented it. Government agencies, researchers, non-governmental organizations, professional organizations, and energy companies are among its consumers. Its scope of application varies from cities and states to nations, continents, and the world as a whole. By comparing to the most used energy models with a high share of renewable energy, the LEAP model has been widely used in developing countries, especially in Southeast Asian countries (see Appendix 2).

This study applied LEAP model because it can be used for both medium-term and long-term energy planning, considering any variables in the energy sector and non-energy-sector GHG emissions, the marginal abatement costs (MAC), and as well as recently developed energy technologies. Moreover, since various time slices of a year can be split, LEAP would determine the variation of loads and how electric power plants are dispatched as hourly, daily, or seasonally. Additionally, the LEAP model provides Technology and Environmental Database (TED); hence, quantitative information on technical characteristics, environmental factors of each GHG, and other useful information are crucial for energy-economic-environment analysis. Last but not least, LEAP is a user-friendly modeling tool having more straightforward accounting principles; moreover, the required data is less compared to other sophisticated energy models.

3.3.6.1 LEAP in Renewable-Energy-Related Studies

Kumar (2016) applied the LEAP model to assess renewables for energy security and carbon mitigation in two countries in Indonesia and Thailand. The study found that if the full capacity of renewables is tapped, renewables would have to generate a significant proportion of electricity by 2050. In this situation, in Indonesia and Thailand, respectively, 81% and 88% of CO_2 emissions will be decreased. However, the large-scale deployment of renewables has seen a significant increase in both countries' energy production costs. According to Meilandari (2020), for the optimal analysis for long-term electricity planning in the Java-Bali power system from 2018 to 2050, the LEAP model was carried out in Indonesia's similar case. This study shows that the high renewable energy deployment goal will reduce the dominance of fossil fuel-based power generation by 2050 to reduce CO_2 emissions through such use substantially.

Similarly, Handayani et al. (2017) also used the LEAP model to investigate the trade-offs between electrification and climate change mitigation in Indonesia's case of the Java-Bali power system. There is no doubt that this study's result also showed the role of renewable energy development in electrification on the Java-Bali islands. As a result, the utilization of renewable energy sources is expected to cut the projected CO_2 emissions by 38.9 million tons and, thus, assure meeting the target.

As renewable energy is one of the key sources of environmental planning, Ferrão (2017) investigated the potential and role of renewable energy in achieving Thailand's INDC target in emission reduction. An interesting result of this study is that Thailand can reach its INDC target even if Thailand meets only half of the renewable energy share target (as stated in Table 2). Likewise, Kusumadewi et al. (2017) applied LEAP model for analyzing the potential of CO_2 emission mitigation in power sector in Thailand. Four mitigation scenarios were formulated regarding the target of Thailand's 2015 power development plan (PDP), implementation of new and clean generation technologies, deployment of clean fossil fuel technologies, and the peak of CO2. Additionally, LEAP model has also been used to evaluate the impact of national energy efficiency and alternative energy planning on long-term energy development and greenhouse gas. The study found that Thailand would reduce greenhouse gas emissions up to 55% in 2036 and decrease the grid's emission factor (Kusumadewi et al., 2017).

Besides, LEAP has been widely used for developing long-term planning of electricity demand and supply (Hussain et al., 2018; Mcpherson & Karney, 2014; Ouedraogo, 2017), considering the transition to sustainable energy system (Ho et al., 2019), and high integration of low-carbon energy technologies (Tambari et al., 2020). In the meantime, there have been many studies investigated the role of renewable energy utilization in CO2 reduction potential (Kumar & Madlener, 2016), effects of CO2 emission abatement (Cai & Guo, 2018), and the future of free pollutant from power industry (Bhuvanesh et al., 2018).

3.4 Energy Security Indicator (ESI)

In both developed countries and developing countries (Johansson & Nilsson, 2014), energy security becomes the matter of national security even though the definition of it varies due to the differences in each country's major energy resources, political system, economic welfare, ideologies, geographical locations or international relation (Luft & Korin, 2009). Energy security principles can be divided into three key components, as reviewed in Gasser

(2020) by the International Energy Agency (IEA), the Asia Pacific Energy Research Center (APERC), and the European Commission, namely: (i) the physical availability and accessibility of supply sources, (ii) economic affordability, and (iii) environmental sustainability. The term availability refers to the existence of any types of energy resources, which are geologically available, while the affordability term encompasses economic elements (Kruyt et al., 2009). Environmental and social acceptability is another useful indicator for investigating the supply security of modern energy systems. For this reason, to have an in-depth understanding of energy security, it is necessary to investigate energy security indicators in these mentioned components.

Indicator-based approaches are popularly applied for studying the energy system of a single or a group of countries. Song and Sun (2019) selected 18 indicators from the energy supply dimension, environmental dimension, and economic-technical dimension, based on the banding approach, for China's energy security index (CEIS). In the final part of this study, the author applied SWOT analysis for conducting policy implications. In another study done by Bin et al. (2020) formulated 22 indicators in five dimensions: availability, affordability, technology, governance, and environment, from 1991 to 2018 to evaluate energy security performance in Pakistan. This study applied a z-score method for indicator normalization and conducted the weighting based on principal component analysis (PCA). This study's interesting results showed that Pakistan's energy security went down from 1991 to 1999, then increased until the last study year. Portugal-Pereira and Esteban (2014) also conducted an indicator-based assessment for Japan's electricity supply security in a similar dimension: availability, reliability, technological development, and environmental sustainability. By assuming different shares of renewables, fossil fuels and nuclear, it found that electricity supply security can be enhanced through the reduction of fossil fuels and nuclear energy while deploying more endogenous renewable energy sources for power generation.

By considering the environmental impact in the energy industry, Shah et al. (2019) developed new Energy Security and Environmental Sustainability Index (ESESI) for South Asian countries by evaluating 11 indicators. Six indicators from the energy security component and five indicators from the environmental sustainability component. For a closer look, Sharifuddin (2014) conducted a qualitative assessment of energy security in some Southeast Asian countries such as Malaysia, Indonesia, Thailand, and Vietnam by focusing on 35 indicators in aspects of affordability, affordability, and environmental impact, stability, and efficiency. As reviewed in most previous studies on energy security index (Bin et al., 2020; Gasser, 2020; Neelawela, Selvanathan, & Wagner, 2019; Paravantis & Kontoulis, 2020; Ragulina, Bogoviz, Lobova, & Alekseev, 2019; Shah et al., 2019; Song & Sun, 2019), all selected indicators were normalized, aggregated or weighted to form the indexes, and mainly based on historical data raging from energy resource extraction to specific final energy use in various units and sector.

More specific view on Cambodia's electricity supply security, Gasser et al. (2020) ranked Cambodia in the 122nd among 140 countries worldwide, based on normalized resilience score. Such a study included 12 major indicators from technical, economic, socio-political, and governmental aspects; all these main dimensions here can also be seen in a composite index study by Neelawela et al. (2019). However, this study focuses only on few indicators regarding electricity generation on the supply side; hence, it has no intention to develop a full index for Cambodia’s energy security performance. Instead of the whole energy system's historical data, all indicators are formulated based on some of the LEAP model results and electricity demand forecasted in this study's ARIMA model. In another word, rather than building a sophisticated index, this study investigated the future trend of most important and available indicators to understand the future electricity supply security in Cambodia. All selected indicators for understanding Cambodia’s electricity supply security are formulated based on previous and most relevant studies (see Appendix 3).

Chapter 4. Methodology

4.1 Flow Chart of Methodology

In this study, the methodology is classified into three main parts: pre-LEAP model, LEAP Model, and post-LEAP model, as shown in Figure 2. In the pre-LEAP model, future electricity demand has been forecast using the ARIMA regression model. Moreover, the study has considered the current government power development plan (PDP), the committed capacity of power generation mix in Cambodia’s Basic Energy Plan (MME, 2019), the government ambition in emission reduction target, and proposed renewable energy plans for Baseline Scenario (BAS or FRE) development. Since this study's period exceeds government master plans and committed capacity in future power generation is limited, the study has compiled more data from existing, and most relevant studies in addition to government proposed capacity from 2030 to 2050.

In the LEAP model, three main scenarios are created to reflect future energy development trends in Cambodia. Each main scenario technically consists of two sub-scenarios, except the third main scenario. All scenarios are optimized so that each one will illustrate a proper future energy mix with the least net present value. After all, scenarios are optimized with and without constraints based on specified targets of investigation on each scenario. Some of the results, such as production costs, investment costs, capacity expansion, energy mix options, and GHG emissions, will be chosen for comparison and used as inputs in the energy security indicator (ESI) for a more in-depth evaluation of Cambodia’s electricity supply security. Following these steps, we will find the most implementable scenarios for Cambodia's power development in the future. Finally, this study proposes the policy implications and measures needed to obtain such measures implemented by selecting preferable scenarios. Last but not least, limitations and future work can be found at the end of this study.

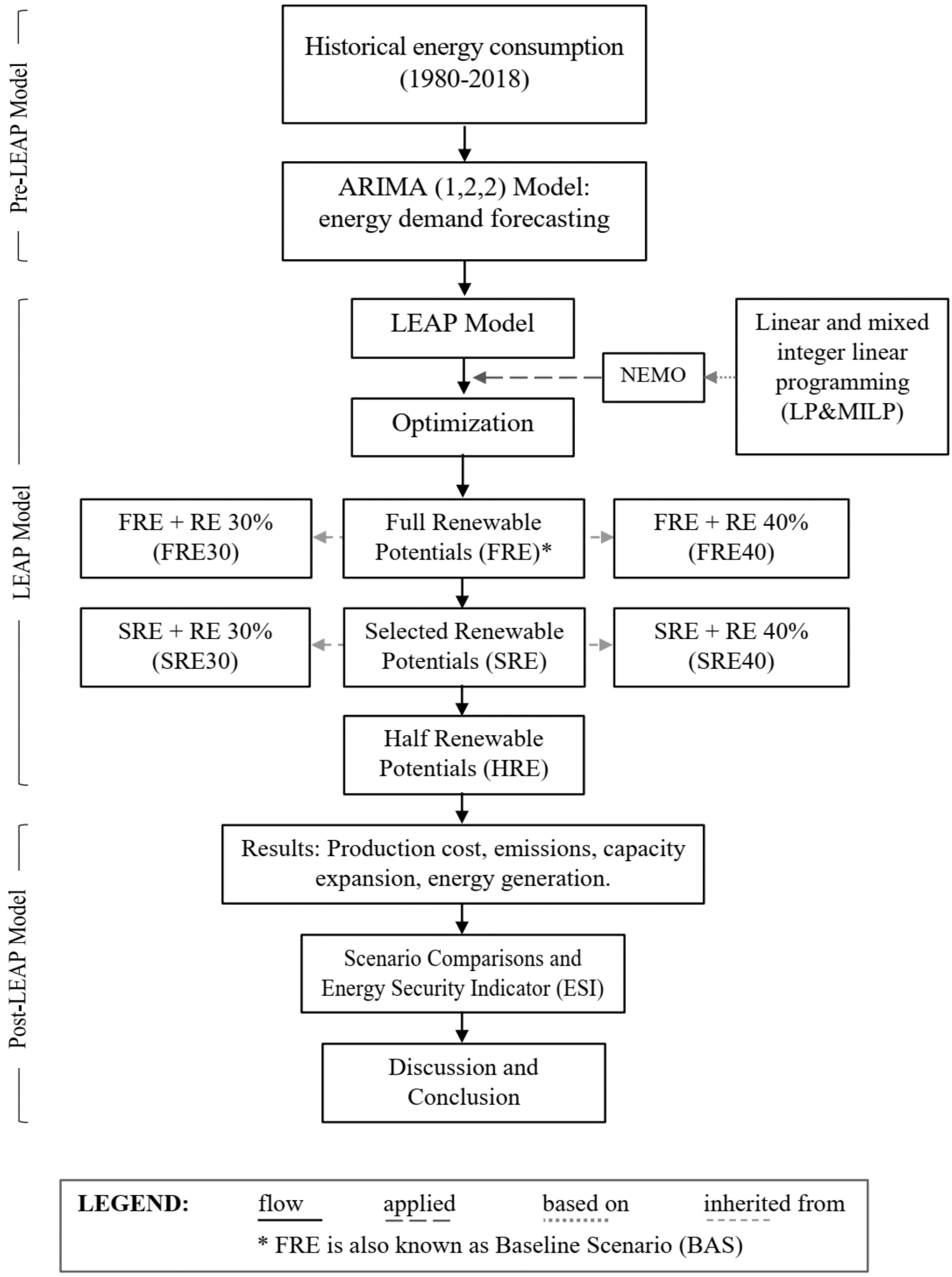

Figure 2. Flow Chart of Methodologies

4.1.1 **ARIMA Model**

ARIMA models derived from autoregressive moving average have been widely used in energy demand forecasting in aggregated terms or separated sectors, and even different fuels. Typically, the ARIMA model has different sets of parameters, namely: number of autoregressive terms (*p*), the number of non-seasonal differences (*d*), and the number of lagged error values (*q*). To select the most appropriate value of each parameter, it is essential to visualize historical data of electricity consumption (1980-2018 in this study) and then stationaries such time-series data. Detailed steps in such a process can be found in Mahia et al. (2019); however, this study only focused on the main process, which could quickly lead to the final electricity demand forecasting—the main input for the LEAP model analysis. Figure 3 shows the selection process of the ARIMA model.

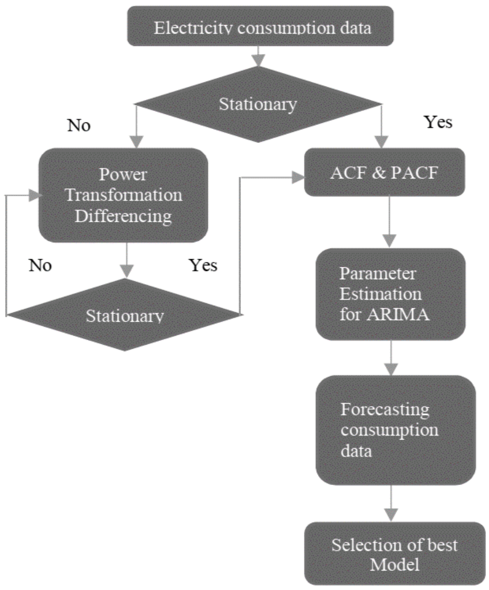

Figure 3. ARIMA Model Selection Process

Source: (Mahia et al., 2019)

A specific form of ARIMA model can be expressed as ARIMA (*p,d,q*). The first parameter to be considered is the number of non-seasonal differences (*d*) chosen from what d-difference makes the series stationary. According to Wu and Cao (2012), we can express a general model of the ARIMA model as in Eq. (1) below:

$$Y_t = \theta + \alpha_1 Y_{t-1} + \alpha_2 Y_{t-2} + ... + \alpha_k Y_{t-k} + \beta_0 \mu_{t-1} + \beta_1 \mu_{t-2} + ... + \beta_q \mu_{t-q} \text{ .... Eq. (1)}$$

4.1.1.1 Model Identification

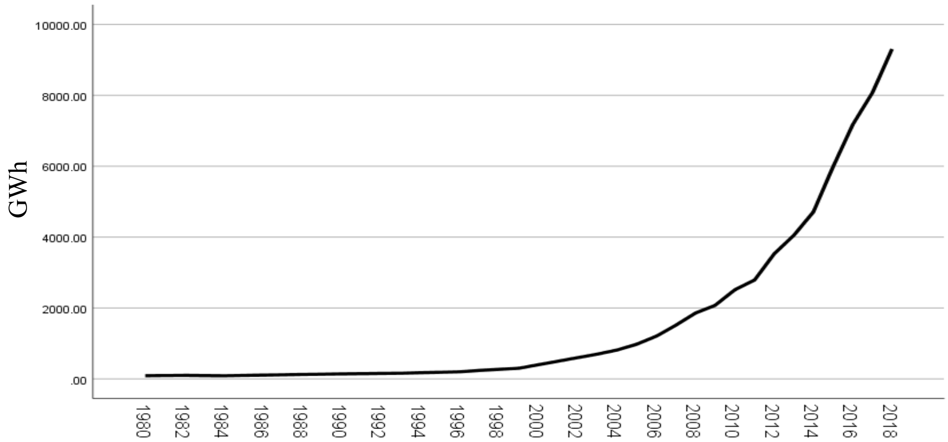

Figure 4. The Trend of Electricity Consumption

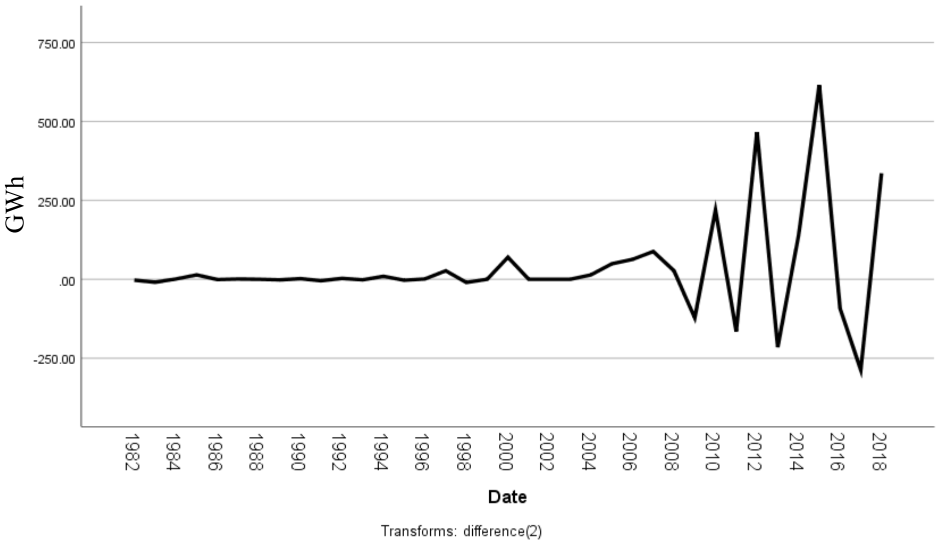

Figure 5. Stationary Transformation of the Series

As seen in Figure 4, the trend of electricity consumption shows that the series is not stationary. Also, the unit root test result showed that this series is non-stationary. It becomes stationary at second-order differencing; hence, we may solely assume that the *d* (non-seasonal difference) value is 2. We will then identify the value of *p* and *q* by visualizing partial autocorrelation function (PACF) and autocorrelation function (ACF), respectively. Such figures could be obtained from various econometric software; however, this study's whole econometric work was analyzed using SPSS. Figure 6 and Figure 7 obtained from the Statistical Package for the Social Sciences (SPSS) showed partial autocorrelation function (PACF) and autocorrelation function (ACF) of this series.

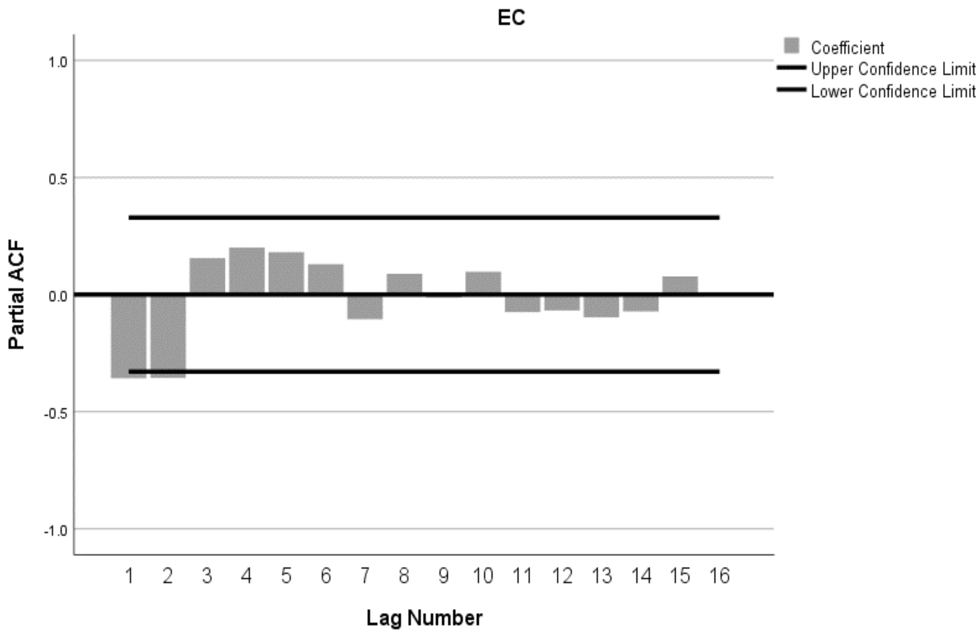

Figure 6. Partial Autocorrelation Function (PACF)

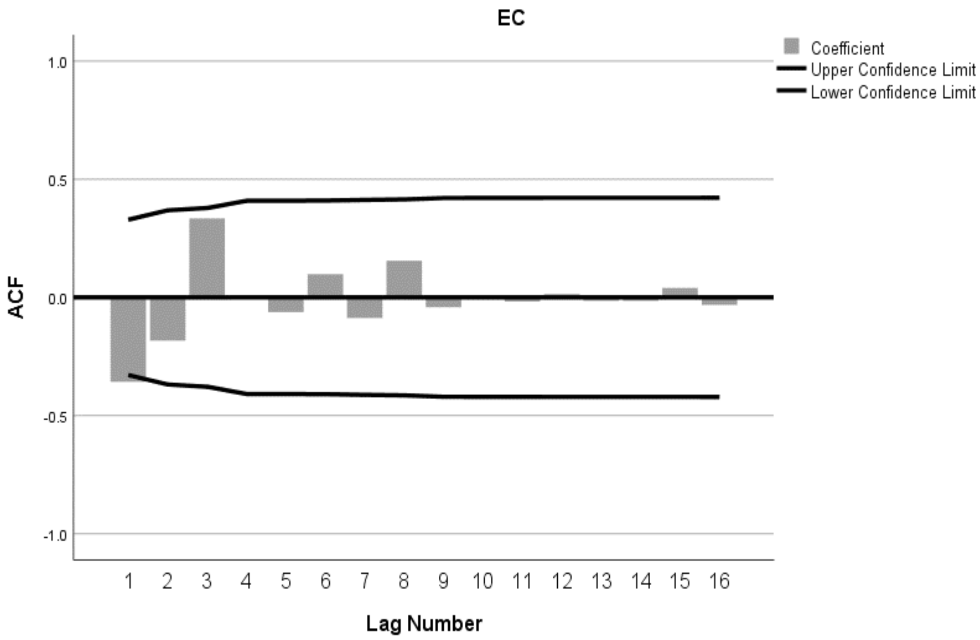

Figure 7. Autocorrelation Function (ACF)

According to the value of selected order of non-seasonal differencing, and values of coefficients in PACF and ACF chart; we may select tentative models as follows: ARIMA (1,2,1), ARIMA (1,2,2), ARIMA (1,2,3), ARIMA (2,2,1), ARIMA (2,2,2), and ARIMA (2,2,3). The results of significances, estimates, and normalized BIC of each model are summarized and shown in Table 3. The most appropriate model will be chosen based on the number of significance and the value of the normalized Bayesian Information Criterion (BIC). ARIMA (1,2,2) model has three significant numbers at AR1, MA1, and MA2; besides, it has a relatively lower BIC value. For these reasons, ARIMA (1,2,2) is the most suitable model for accurate prediction of Cambodia's future electricity consumption.

Table 3. Essential Parameters of Tentative ARIMA Models

Models	Significance		Normalized BIC	Estimate(s)
ARIMA (1,2,1)	Con.	.039	10.310	31.433
ARIMA (1,2,2)	AR1	.016	10.303	.906
	MA1	.001		1.544
	MA2	.012		-.711
ARIMA (1,2,3)			10.400	
ARIMA (2,2,1)	Con.	.030	10.329	31.268
	AR2	.026		-.463
ARIMA (2,2,2)	AR2	.012	10.205	-.643

ARIMA (2,2,3)	10.299

Let Z be the second-order difference, then substituting the values of estimates of selected model in Table 3 into Eq. (1), Cambodia's electricity consumption can be expressed in a model as follows:

$$Z_t = 0.906Z_{t-1} + 1.544\mu_{t-1} - 0.711\mu_{t-2} \quad \text{Eq. (2)}$$

4.1.1.2 Forecasting Result

Figure 8 illustrated the forecast electricity consumption in Cambodia, both past and future consumption, based on ARIMA (1,2,2) model. It also provided the upper confidence limit (UCL) and lower confidence limit (LCL) of such a prediction to compare it to real demand in the future, if necessary. However, only the forecast data is used as an input in LEAP model in the next section.

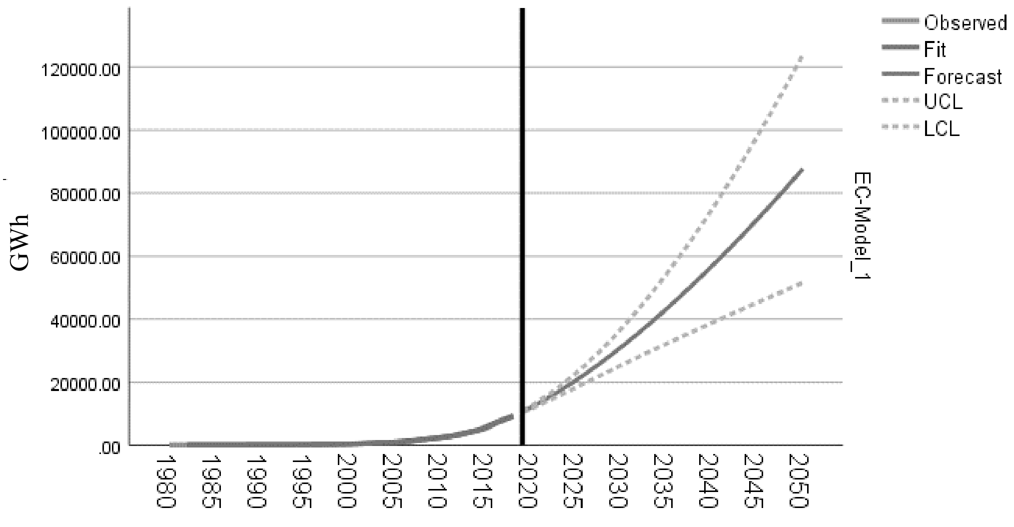

Figure 8. Result of Electricity Demand Forecasting

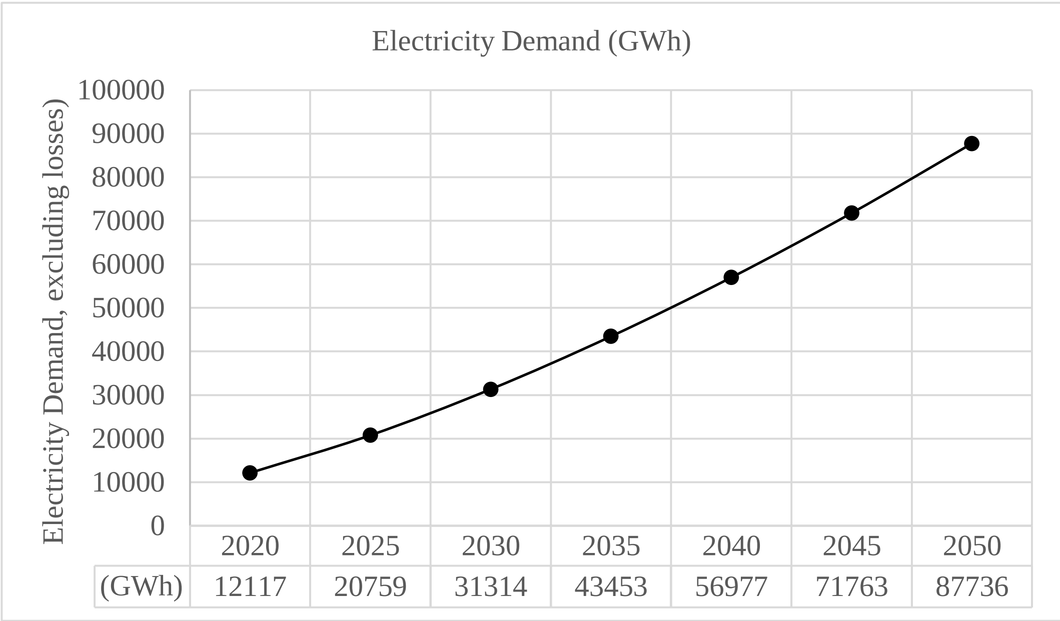

Figure 9. Electricity Demand Forecasting (2020-2050)

According to the projected results, electricity consumption in Cambodia will rise from 12.12 TWh in 2010 to 87.74 TWh in 2050, with an average growth rate of 7.3% over the entire study horizon. Some previous studies showed a similar projection of future electricity consumption in Cambodia. For example, Chhay and Limmeechokchai (2020) projected that the total electricity demand would reach roughly 85 TWh in 2050, which is 16.32 times compared to demand in the study's base year (2015). Likewise, according to the "Power Sector Vision" report, on-grid electricity demand in Cambodia (which include losses in transmission and distribution) is expected to grow at a rate of 8.7% pa over the 35 years to 2050, which is equivalent to approximately 88 TWh in 2050 (Intelligent Energy System [IES], 2016). Even though the methods applied for such projections are different, ARIMA (1,2,2) shows consistent results compared to existing pieces of literature.

4.1.2 Low Emissions Analysis Platform (LEAP) Model

Stockholm Environment Institute has developed LEAP to assist policy-making concerning energy, economy, and environment. It has been currently used by almost 200 hundred countries worldwide, not only by those working in the government sector but also by many more energy companies and non-governmental organizations. It can calculate the least-cost energy generation mix based on the use of linear programming-based optimization frameworks. The Open Source Energy Modeling System (OSeMOSYS), based on the GNU Linear Programming Kit (GLPK), has been widely used for optimization purposes in many energy-environment studies. Nevertheless, this study applied NEMO (the Next Energy Modeling system for Optimization) to calculate the optimal generation mix considering security electricity supply and carbon dioxide mitigation target, due to its flexibility and fastness compared to classical OSeMOSYS. LEAP and NEMO combination provides powerful optimization features for energy planners to predict future energy planning, capacity expansion, and de-carbonization purposes. Such optimization is obtained subject to various variables such as capital cost of building new power plants, fixed and variable costs of plants' operation and maintenance, maximum availability of each generation candidate, and cost of environmental externalities (SEI, 2020).

4.1.2.1 the Next Energy Modeling system for Optimization (NEMO)

NEMO, an open-source energy system optimization tool, has recently been developed by the Stockholm Environment Institute (SEI), aiming to provide the modelers substantial optimization capabilities compared to standard open-source alternative tools. It is designed to answer critical questions in current energy policies, from utilizing renewable energy into the national or regional grid, deployment of energy storage, and many more climate change topics or resource depletion issues. Since NEMO is developed using Julia program, the users may extend it whenever necessary using Julia, or directly use it through the LEAP interface. Also, NEMO supports several solvers such as Cbc, CPLEX, GLPK, Gurobi, Mosek, and Xpress.

NEMO has strong leads over OSeMOSYS, and it is well-positioned to meet the future developmental needs of the LEAP user community. Like OSeMOSYS, NEMO is also an open-source, but unlike OSeMOSYS, it is built in a new programming language called Julia, originally developed at the Massachusetts Institute of Technology (MIT). Julia is fast, flexible, and well suited for scientific and numerical computing. It also has a vibrant and growing community of users. This makes NEMO particularly good at the types of optimization problems encountered in LEAP: linear (LP) and mixed-integer linear programming (MILP), especially for large problem sets. Table 4 briefly explains the advantages and disadvantages of OSeMOSYS and NEMO. However, the OSeMOSYS framework was used as a fundamental in creating NEMO; hence, most of the NEMO's mathematical expression can be described by the review of OSeMOSYS done by Howells et al. (2011).

Table 4. Comparison of the OSeMOSYS and NEMO frameworks

Feature	OSeMOSYS	NEMO
Developer:	KTH	SEI
Installation:	Integrated into LEAP	Via separate download
Platform:	GLPK (last updated 2018)	Julia (actively developed at MIT)
Open source:	Yes	Yes
Licensing:	Free & Included with LEAP	Requires add-on license to use with LEAP, but free for low and lower middle income countries
Small data set:	Faster	Fast
Larger data sets:	Slow	Fast
Time slicing:	Limited flexibility	Very flexible
Energy storage:	No	Yes
Solvers:	GLPK, CPLEX	GLPK, Cbc, CPLEX, MOSEK, etc.
Parallel processing:	Only when using CPLEX	Yes
Actively developed:	Unknown	Yes, by SEI, new capabilities planned
Network & power flow simulations:	No	Yes
Support	Community-supported forum	Professional and community support

As of my knowledge, none of the previous studies have used NEMO yet. It is because NEMO has just been created. However, this study's application will be a turning point to a more flexible and free optimization tool, which will help extend this work with the most recent contemporary energy or environment policy issues. For instance, whenever energy storage technology is introduced into Cambodia’s energy system, this study can be extended with a small change in a flexible manner.

4.1.2.2 The Algebraic Formulation in LEAP

a) Objective Function

Optimization calculations in LEAP work with the integration with the optimizer, whose purpose is to minimize the total discounted cost of the whole study horizon's energy system. It estimates the lowest net present value (NPV) cost while meeting energy demands or energy services. The objective function of such an optimization is expressed as:

$$\text{Minimize} \sum_{y,t,r} \text{TotalDiscountedCost}_{y,t,r} \quad \text{Eq. (3)}$$

where *y* represents each year of the modeled period, *t* represents each generation technology, and *r* is the rate of activity[5].

b) Cost Equation

According to (Howells et al., 2011), In order to determine a net present value (NPV), costs should be measured in constant monetary terms and then discounted.

[5] Rate of activity for each generation technology for each year and time slice defined.

The most general equation regarding costs in this study is shown in Eq. (4) below.

$$\forall y,t,r \ TotalDiscountedCost_{y,t,r} = DiscountedOperatingCost_{y,t,r} + DiscountedCapitalInvestment_{y,t,r} + DiscountedTechnologyEmissionsPenalty_{y,t,r} - DiscountedSalvageValue_{y,t,r} \ \ldots\ldots\ldots \ Eq. (4)$$

Total discounted cost of technology *t* in a single year *y* is the summation of discounted values of operating cost, capital investment, and penalty cost of emission from each generation technology. In case the cost of salvage[6] is considered, the total discounted cost can be lessened by the deduction of salvage value. Since this study lacks reliable data on salvage value, it is ignored for the whole model. Besides, because Cambodia does not impose taxes or penalties on the emission from the power sector, this study neither includes these cost variables' effects. Thus the remaining and important cost variables are only operating cost and capital cost for the investment; then Eq. (4) can be written in Eq. (5), as shown below.

$$\forall_{y,t,r} \ TotalDiscountedCost_{y,t,r} = DiscountedOperatingCost_{y,t,r} + DiscountedCapitalInvestment_{y,t,r} \ \ldots\ldots\ldots \ Eq. (5)$$

We may obtain the value of discounted operating cost and capital investment cost by using Eq. (6) and Eq. (9) below.

$$\forall_{y,t,r} \ DiscountedOperatingCost_{y,t} = OperatingCost_{y,t,r} / ((1+DiscountRate_{t,r})\text{^}(y - StartYear + 0.5)) \ \ldots\ldots\ldots \ Eq. (6)$$

[6] The salvage value represents the net value of a process at the end of its lifetime.

In which

$$\forall_{y,t,r}\ OperatingCost_{y,t,r}$$

$$= AnnualFixedOperatingCost_{y,t,r} + AnnualVariableOperatingCost_{y,t,r} \ldots\ldots\ldots\ldots \text{ Eq. (7)}$$

Or

$$\forall_{y,t,r}\ OperatingCost_{y,t,r} = TotalCapacityAnnual_{y,t,r} \times Fixed\ Cost_{y,t,r}$$

$$+ \sum_{m,l} RateOfActivity_{y,l,t,m,r} \times VariableCost_{y,t,m,r} \ldots\ldots\ldots\ldots \text{ Eq. (8)}$$

l is the intra-annual time step within a year, and *m* represents a certain generation technology operation mode.

And

$$\forall_{y,t,r}\quad DiscountedCapitalInvestment_{y,t,r}$$

$$= CapitalInvestment_{y,t,r} / ((1+DiscountRate_{t,r})\char`^(y - StartYear)) \ldots\ldots\ldots\ldots \text{ Eq. (9)}$$

In which

$$\forall_{y,t,r}\ CapitalInvestment_{y,t,r} = CapitalCost_{y,t,r} \times NewCapacity_{y,t,r} \ldots\ldots\ldots\ldots \text{ Eq. (10)}$$

c) Capacity Expansion

It is important to ensure a certain technology or power generation's adequate capacity to meet all requirements. The total annual capacity is defined by sum up the accumulated new capacity and residual capacity in each year during the planning horizon period, and it can be expressed as:

$$\forall_{y,t,r}\ TotalCapacityAnnual_{y,t,r}$$

$$= AccumlatedNewCapacity_{y,t,r} + ResidualCapacity_{y,t,r} \ldots\ldots\ldots\ldots \text{ Eq. (11)}$$

In which

$$\forall_{y,t,r}\ \text{AccumlatedNewCapacity}_{y,t,r} = \sum_{yy: y-yy < \text{OperationalLife}[t,r] yy \geq 0} \text{NewCapacity}_{yy,t,r} \quad \text{......... Eq. (12)}$$

where NewCapacity variable represents the investment of new capacity of each generation technology, rather than installed capacity of each generation technology. It needs to follow both the lower and upper boundary of annual investment on new capacity expansion. Eq. (13) shows the constraints of the NewCapacity variable.

$$\text{TotalAnnualMaxCapacityInvestment}_{y,t,r} \leq \text{NewCapacity}_{y,t,r} \leq \text{TotalAnnualMaxCapacityInvestment}_{y,t,r} \quad \text{...... Eq. (13)}$$

d) Emission

$$\forall_{e,,r}\ \text{ModelPeriodEmission}_{e,r} = \sum_{y,t} \text{AnnualTechnologyEmission}_{y,t,e,r} \quad \text{...... Eq. (14)}$$

Eq. (14) shows that the total emission of the whole study period is the summation of annual emission *e* from each of its modes of operation. This study also clarifies that emission occurred only in conventional technologies such as coal, natural gas, oil-based, and biomass generations.

4.1.3 Energy Security Indicator (ESI) Selection

Specifically and similarly with work done by Gasser (2020), this study also investigated energy security indexing and major indicator selection process in many different studies to support its selected indicators. As a result, this study proposed three main dimensions: physical availability, economic affordability, and environmental acceptability. Previous studies included electricity import (Gasser et al., 2020) and electrification rate (Jamasb et al., 2005) as energy security indicators. However, this study does not consider the electrification rate while assuming electricity import to be the same in all proposed scenarios (see Appendix 4 [3]). Hence, there are finally eight selected indicators, such as share of renewable capacity (AV1), the share of renewable electricity generation (AV2), electricity feedstock imports dependency (AV3), costs for electricity generation (AF1), Levelized cost of energy (AF2), annual GHG emission from electricity generation (EN1), GHG emission intensity (EN2), and share of hydroelectric generation (EN3). After obtaining the LEAP model results, indicators, and dimensions of each scenario will be used to compare and discuss. Table 5 shows the dimensions, selected energy security indicators, and mathematical expressions of such classifications. In some of the equations in the table below, *i* represents each generation technology, and *t* represents modeled periods.

Table 5. Selected Dimensions and Indicators

Dimension	Indicator	Code	Expressions
Physical availability (AV)	Share of renewable capacity	AV1	$\frac{\text{Installed capacity from RE}}{\text{Total installed capacity}} \times 100$
	Share of renewable energy in generation mix	AV2	$\frac{\text{Energy generation from RE}}{\text{Total energy generation}} \times 100$
	Power-generation-fuel imports dependency	AV3	$\sum \text{Fuel}_{i,t}$
Economic affordability	Energy generation cost	AF1	$\sum \text{Cost}_{i,t}$
	Levelized cost of energy	AF2	$\frac{\text{Energy generation cost}}{\text{Total energy generation}}$

(AF)	(LCOE)		
Environmental acceptability (EN)	Total GHG emission	EN1	$\sum \text{Emission}_{i,t}$
	GHG emission intensity (/GDP)	EN2	$\frac{\sum \text{Emission}_{i,t}}{\sum \text{GDP}_t}$
	Share of large hydropower (LH) in total power generation mix	EN3	$\frac{\text{Energy generation from LH}}{\text{Total energy generation}} \times 100$

In the physical availability dimension, AV1 indicates the installed capacity by renewable energy (Shah et al., 2019b; Song & Sun, 2019; Yao & Chang, 2014), and it represents the availability and diversification of domestic indigenous resources such as small hydro, solar photovoltaics, biomass, and wind. Similarly, AV2 determines future electricity generation from local sources (Sharifuddin, 2014; Yao & Chang, 2014). Positive growth in these two indicators showed more development of controllable energy sources, and it would increase flexibility and energy dependency for power generation in Cambodia. In the meantime, AV3 is closely related to AV1 and AV2 because whenever there is an increase in renewable energy utilization, the burden from the imports of electricity feedstock fuels would decrease. Such a decrease in fuel imports would lessen the burden on electricity generation's security, so would on electricity supply (Shah et al., 2019b).

Similar to comparing the cumulative cost of production in section 5.2.3, AF1 investigated the annual production cost change required for future capacity expansion. At the same time, AF2 is useful for the comparison of the cost of output electricity. Cumulative cost does not provide a clear understanding of when the system requires less or more investment; hence, it is important to carefully investigate AF1 and AF2 in the view of economic affordability (Awerbuch & Yang, 2007; Gasser, 2020).

The final dimension is the environmental acceptability. Normally, besides the absolute value of emissions emitted from the power sector (EN1), emission intensity (EN2) has also been seen as an important indicator for evaluating power generation's impact on both the environment and the economy (ERIA, 2012; Gasser, 2020; Ragulina et al., 2019; Shah et al., 2019b). This last dimension is useful for investigating Cambodia's INDC target status and committed future emission intensity in any environmental policy. Finally, due to the extensive environmental impact of large-hydro power development, the decline in EN3's in values from time to time would also positively affect energy generation security.

4.2 Data Inputs and Key Assumptions

The most important data for optimization in LEAP model is shown in Table 6. All most data of candidate technology characteristics have been acquired from (International Renewable Energy Agency [IRENA], 2016), while fuel cost and the average of electricity import price are locally available. Even though few previous studies used the changes of capital cost and fuel cost (IES, 2016), and even included a variety of carbon tax (Chhay & Limmeechokchai, 2020; IES, 2016) for the case of Cambodia, this study assumed such data to be fixed for the whole study period.

Table 6. Characteristics of Generation Technology

Generation Technology	Efficiency	Capacity Credit	Capacity Factor	Capital Cost ($1000/MW)	Fixed O&M ($1000/MW/yr)	Variable O&M[7] ($/MWh)	Lifetime (yrs)	Maximum Availability (%)
Large Hydro	100	51.00	35	2100.00	50.00	1.00	40	41
Small Hydro	100	58.00	35	2300.00	50.00	1.00	40	46
Solar PV	100	22.00	15	1400.00	20.00	0.40	30	18
Biomass	38	100.00	40	2750.00	69.00	1.10	25	90
Wind	100	35.00	20	1500.00	60.00	0.80	30	28
Coal	30	100.00	85	1300.00	52.00	2.00	60	80
Natural Gas	55	100.00	85	1000.00	40.00	1.00	30	58
Oil	40	100.00	85	1200.00	18.00	1.00	50	57

Table 7. Assumption of Fuel Cost and Electricity Cost

Fuel Type	US$/million BTU	US$/toe	US$/kWh
Coal		152.00	
Natural Gas	11.00		
Fuel Oil	16.40		
Biomass		40.00	
Import Electricity			10.36

Source: (MME, 2013)

[7] Source: (Meilandari, 2020)

Table 8. Key Assumptions

Scenarios	Electricity[8] Import (2050)	GDP Growth (Real, pa)[9]			Reserve Margin	Interest[10] Rate	T&D[11] Losses
		2020-2030	2030-2040	2040-2050			
All scenarios	3026.75 MW (14.62TWh)	7.00%	6.50%	3.50%	20.00%	4.91%	10.00%

4.3 Scenario Development

This study investigates and compares three main scenarios, namely full renewable potential (FRE), selected renewable potential (SRE), and half renewable potential (HRE), in order to demonstrate the optimal benefits for electricity supply security and emission mitigation, regarding the proper share of renewable sources in the future electricity generation mix. In each main scenario, there are two sub-scenarios inherited from the main scenario. In the FRE scenario, two sub-scenarios are FRE30 (FRE + 30% share of renewable source in electricity generation mix in 2050) and FRE40 (FRE + 40% share of renewable source in electricity generation mix in 2050). Meanwhile, another two sub-scenarios under selected renewable potential (SRE) are SRE30 and SRE40. SRE30 and SRE 40 are differentiated from their parent scenario (SRE) by including the share of renewable energy 30% and 40%, respectively, in 2050. Since the last main scenarios (HRE) limit 50% of each renewable source to be deployed, it is unfortunately not feasible to increase renewable energy shares

[8] (MME, 2020)
[9] (IES, 2016)
[10] https://www.theglobaleconomy.com/Cambodia/deposit_interest_rate/ (accessed on November 17, 2020)
[11] (MME, 2019)

the same as what has been done in FRE scenario and SRE scenario. Hence, there are no reports regarding the results of HRE's sub-scenarios.

Most of the data have been acquired from the Ministry of Mines and Energy Cambodia (MME), World Bank (WB) database webpage, International Energy Agency (IEA), the U.S. Energy Information Administration (EIA), World Energy Council (WEC), ASEAN Center for Energy (ACE), and some of the previous works of literature (MME, 2019; IES, 2016; IRENA, 2016; Meilandari, 2020; MME, 2013).

Energy demand is the same across all scenarios because the study does not consider the effect of end-use consumption behaviors, change of transmission and distribution losses, and any factors embodied in the demand side. Such a demand has been forecast using the ARIMA regression model considering the trend of historical data of energy consumption from 1980-2018 obtained from (EIA, 2020) in addition to recently published data from the Ministry of Mines and Energy (MME). According to IES (2016), Cambodia's real GDP growth continues to rise approximately 7% between 2015-2030, and then decreases 0.5% during the period 2030-2040, and sharply decreases to just 3.5% from 2040 to 2050. On the other hand, the current and projected database of the population from 1960 to 2050 was collected from WB (2020).

Additionally, and most importantly, variations in electric load during baseload or peak load were carefully managed and imported to LEAP model using the available data in annual energy supply and annual & supply plan 2018. It is crucial to see what mix of baseload and peak-load plants to be built and operated (SEI, 2020). Cambodia shape load is illustrated in Figure 10 and Figure 11 below.

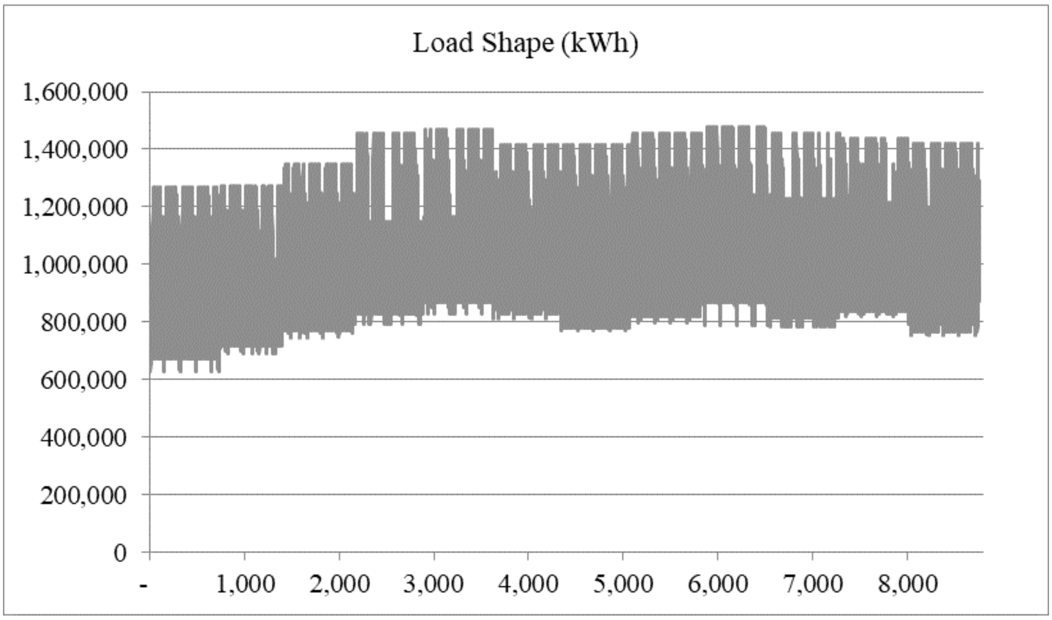

Figure 10. Cambodia Hourly Load Shape (2018)

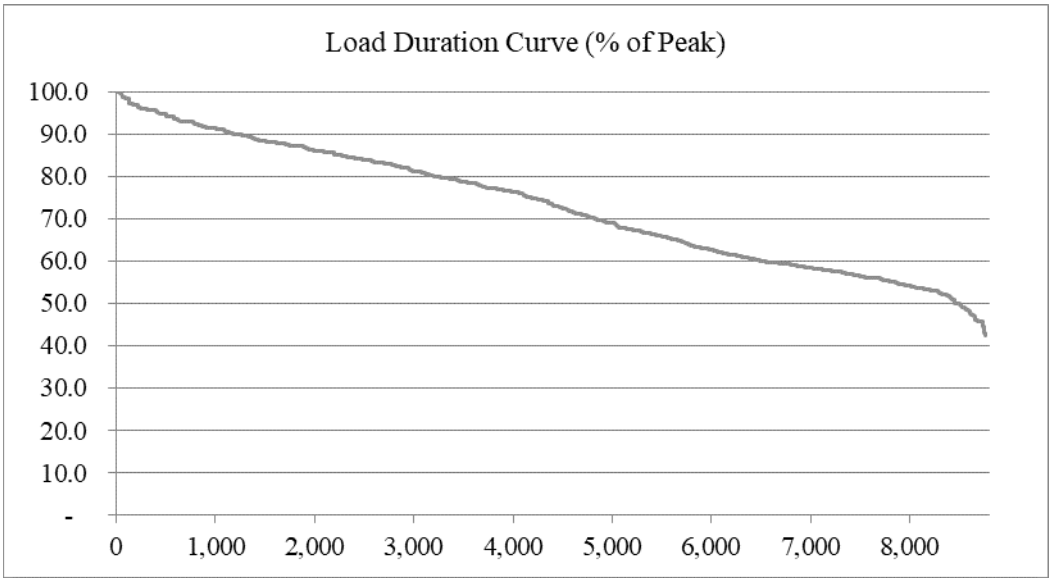

Figure 11. Cambodia Load Duration Curve (2018)

4.3.1 **Full Renewable Potential (FRE)**

With proven technical potential, all renewable sources will be optimally mixed and fully utilized without emissions constraints, limitation on potential, or specified renewable energy targets. Two sub-scenarios are created and inherited from the FRE scenario based on two different renewable energy shares assumptions in generation mix in 2050. Two sub-scenarios, such as FRE30 and FRE40, have been created to target renewable energy shares in total electricity generation in 2050 to 30% and 40%, respectively. It is also important to point out that both in FRE30 and FRE40, only renewable energy targets are set, but there is no constraint on each technology's renewable potential. Again, the FRE scenario is regarded as the baseline scenario (BAS) for accessing the scenario comparison.

4.3.2 **Selected Renewable Potential (SRE)**

All renewable energy technologies are allowed to be fully and freely optimized, except large hydropower. Since the development of large hydropower dams in mainstream poses impacts on the environment, fisheries, and agriculture, this scenario investigates the cost and benefits of limiting large hydro with 5000MW (half of its proved technical potential). There are two sub-scenarios in the SRE scenario: SRE30 and SRE40. Both the SRE30 scenario and SRE40 scenario are inherited from the SRE scenario. The distinguishable differences between SRE and SRE30 and SRE40 are that 50% of large hydropower is limited in SRE without the target of renewable generation. In comparison, SRE30 and SRE40 have specified shares of renewable energy targets in addition to 50% limitation of large hydropower potential.

4.3.3 **Half Renewable Potential (HRE)**

HRE scenario is almost identical to its parent scenario (FRE); however, only 50% of each renewable source's potential is allowed for optimization by 2050—the end year of the study. Initially, two sub-scenarios have also been formulated based on the share of renewable sources 30% and 40% in 2050, which are the same in the FRE scenario and the SRE scenario. Unfortunately, only the main scenario (HRE) is feasible during the optimization process. Both sub-scenarios do not work due to the limitation of allowed renewable energy sources to be optimized. It is because, with such a limit, the maximum share of renewable energy could not reach even 30% by 2050. For this reason, the study only reports seven possible scenarios, namely and orderly: FRE, FRE30, FRE40, SRE, SRE30, SRE40, and HRE.

Chapter 5. Result Comparison and Energy Security Indicator (ESI)

5.1 Results

5.1.1 Full Renewable Potential (FRE)

The total capacity expansion of power generation increases from 4.1 GW in 2020 to 27.1 GW in 2050, with an annual average of 9%. In 2050, large hydro accounts for 36.9%, followed by solar photovoltaic, approximately 30%. Since a vast amount of renewable-source-based power plants to be installed, natural gas shows a significant share compared to its kind. Natural gas accounts for 23.9% of fossil fuels, while coal and oil shares are roughly 5%. In this scenario, domestic renewable energy resources are expected to inject one-third of the total installed capacity at the end year of the study horizon. Solar photovoltaic dominant other sources in its kind, while wind, small hydro and biomass together are less than 5%.

On the other hand, the total electricity generation would increase from 10.1 TWh in 2020 to 82.9 TWh in 2050. In this scenario, the share of large hydro is 56.2% in 2020. Its share in the energy generation mix would decrease to 43.3% in 2050 due to its limited availability; however, it would still be the dominant source in the total electricity generation. After large hydro, natural gas, solar photovoltaic, small hydro, and wind would account for 35.8%, 15.4%, 3.4%, and 1.5%, respectively. 16.8 TWh of electricity, with a percentage share of 20.3%, would be generated from renewable energy resources in 2050.

Table 9. The Installed Capacity in First and Last Scenario Year (GW) in FRE

Generation Technology	Installed Capacity (GW) (2020)	Installed Capacity (GW) (2050)
Large Hydro	1.57	10.00
Small Hydro	0.06	0.70
Solar PV	0.36	8.07
Biomass	0.03	0.03
Wind	0.02	0.50
Coal	0.71	0.71
Natural Gas	0.74	6.47
Oil	0.63	0.63
Total	4.11	27.11

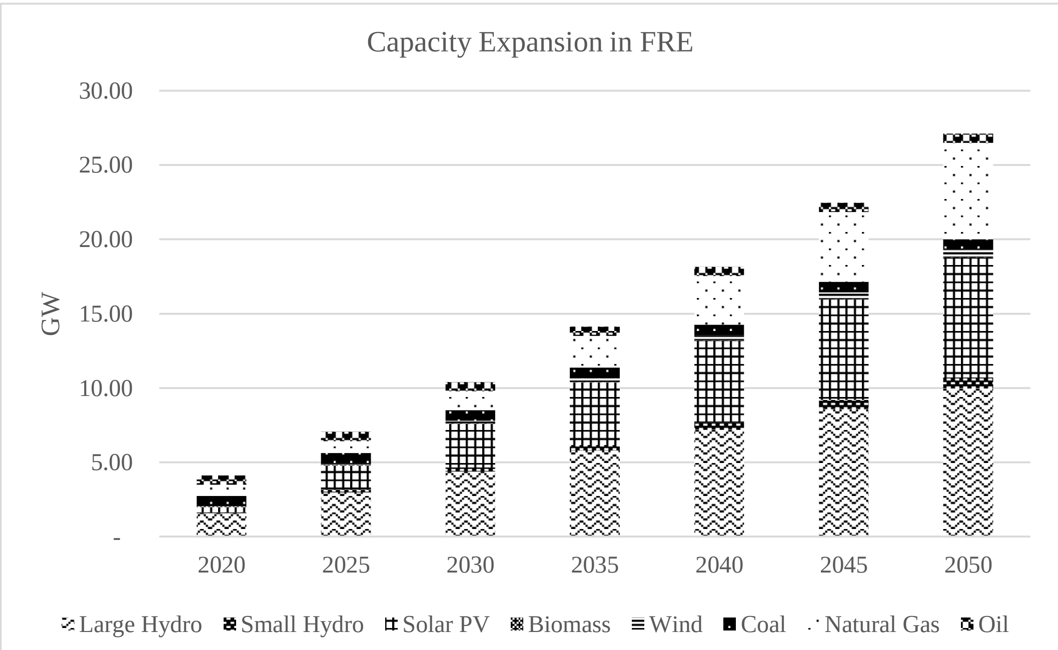

Figure 12. Capacity Expansion in FRE Scenario (GW)

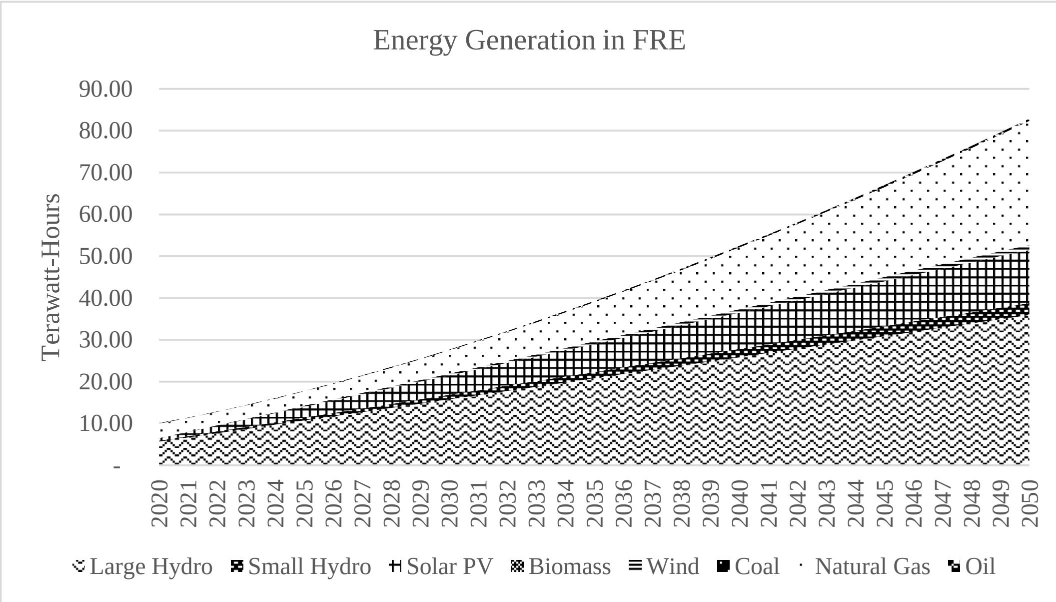

Figure 13. Electricity Generation in FRE Scenario (TWh)

In the whole study period, 97.66 billion US dollars would be necessary for electricity generation, among which natural gas would take 37.53 billion U.S. dollars, while large hydro would need only 31.25 BUSD. The remaining 22.64 BUSD would be given mainly to solar photovoltaic generation and coal, while production costs for oil, small hydro, and wind are relatively small.

Also, GHG emissions would increase from 9.7 Mt CO2e in 2019 to 150.4 Mt CO2e in 2050. In 2050, almost 90% of GHG emission comes from natural gas, while the emission from coal bituminous and oil would be just 8.8% and 4.6%, respectively. In contrast, if we looked back at emissions in 2019, emissions come from coal bituminous alone accounted for 90.5%, and oil contributed 9.5%, while natural gas had not yet been introduced.

5.1.1.1 Full Renewable Potential + RE 30% Scenario (FRE30)

The total capacity expansion of power generation increases from 4.1 GW in 2020 to 26.5 GW in 2050, with an average annual growth rate of 6.44%. Large hydro remains the dominant source in total installed capacity until the end year of the study horizon. The second and third largest shares are solar photovoltaic and natural gas. Coal and oil remain the same as their shares in installed capacity in 2020. Small hydro and wind will gradually increase and then reach their maximum capacity in 2050; however, biomass would be reconsidered only after 2042. In 2050, large hydro, solar photovoltaic, and natural gas would contribute 37.7%, 30.5%, and 18.4%, respectively, into the total capacity. The remaining shares are relatively small, and they are 3.9%, 2.7%, 2.6%, 2.4%, 1.7% for biomass, coal, small hydro, oil, and wind, respectively. In this scenario, renewable generation would increase from 0.5 GW in 2020 to 10.3 GW in 2050.

The share of renewable energy in the electricity generation mix would rapidly increase with an average annual growth rate of 18% from 0.8 TWh in 2020 to 24.9 TWh in 2050. Among 82.9 TWh of the total electricity generation in 2050, 43.3%, 26%, 15.4%, 9.8%, 3.4%, 1.5%, and 0.6% come from the large hydro, natural gas, solar photovoltaic, biomass, small hydro, wind, and oil, respectively. In this scenario, 30% of total electricity in 2050 would be generated from renewable energy sources, while the total share of such sources was roughly 22% from 2030-2040.

Table 10. The Installed Capacity in First and Last Scenario Year (GW) in FRE30

Generation Technology	Installed Capacity (GW) (2020)	Installed Capacity (GW) (2050)
Large Hydro	1.57	10.00
Small Hydro	0.06	0.70
Solar PV	0.36	8.07
Biomass	0.03	1.02
Wind	0.02	0.50
Coal	0.71	0.71
Natural Gas	0.74	4.88
Oil	0.63	0.63
Total	4.11	26.52

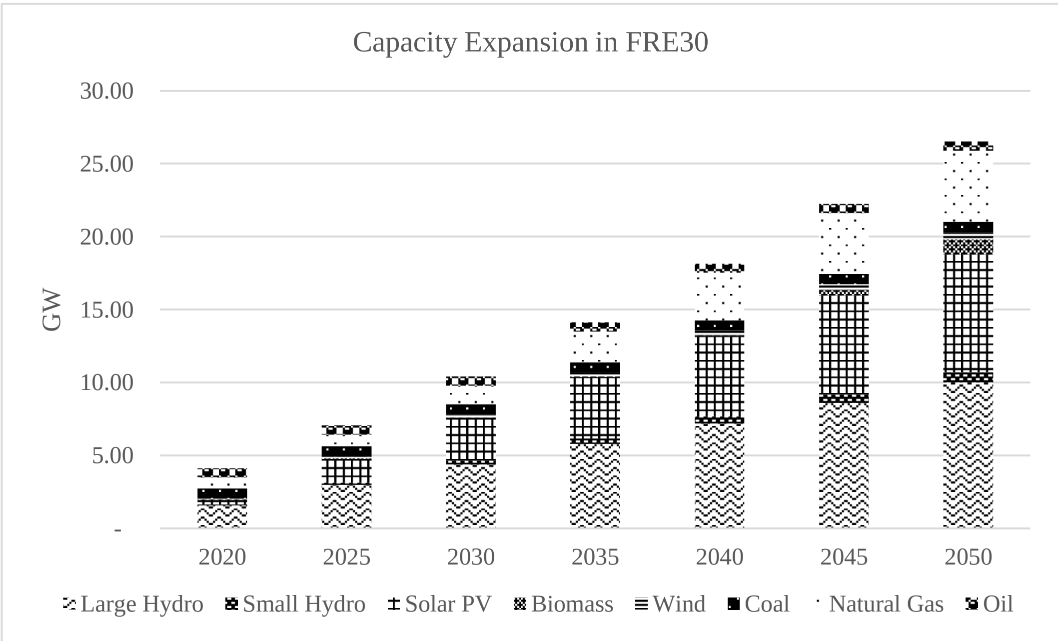

Figure 14. Capacity Expansion in FRE30 Scenario (GW)

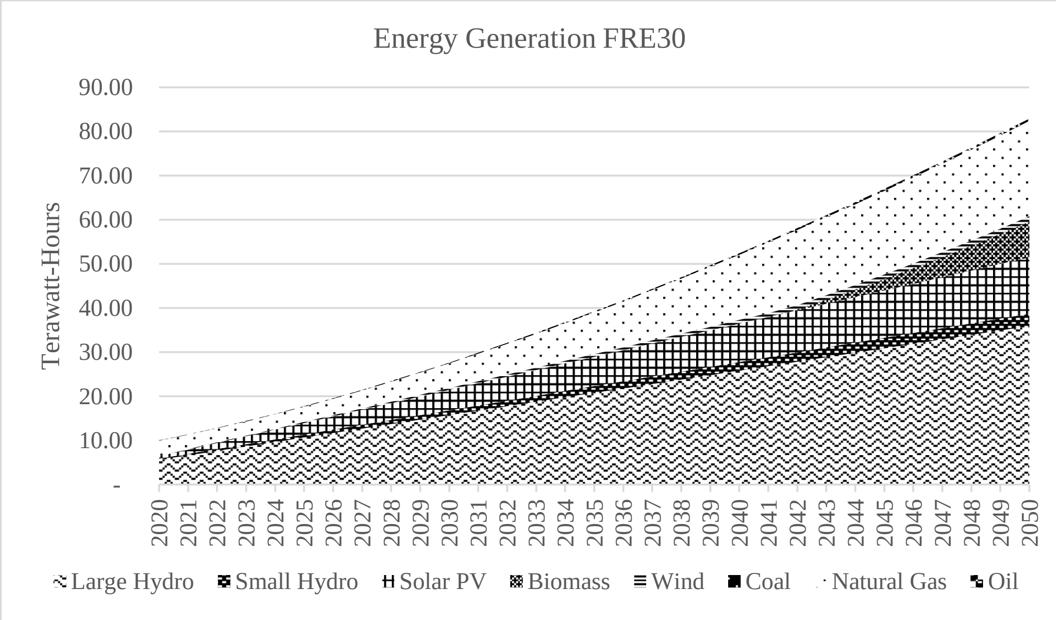

Figure 15. Electricity Generation in FRE30 Scenario (TWh)

The cumulative production cost of electricity generation would increase from 0.63 BUSD in 2020 to 108.42 BUSD in 2050. The total cost of large hydropower development would reach 31.24 BUSD; meanwhile, fossil fuels such as natural gas, coal, and oil would together require 45.19 BUSD, and renewable energy development needs 32 BUSD by 2050.

In the whole study horizon, emissions emitted by electricity generation would reach 138.50 Mt CO2e by 2050. Natural gas would show the highest number, emitting 122.20 Mt CO2e to the atmosphere. The remaining emitted amount of emission would be 8.76 Mt CO2e, 6.93 Mt CO2e, and 0.61 Mt CO2e from coal bituminous, oil, and biomass.

5.1.1.2 Full Renewable Potential + RE 40% Scenario (FRE40)

The total capacity expansion of power generation increases from 4.11 GW in 2020 to 25.94 GW in 2050, with an average annual growth rate of 6.60%. Large hydro remains the dominant source in total installed capacity, and it would reach its maximum potential in 2050. The second-largest share is solar photovoltaic, and it would be fully utilized by 2050 as well. Natural gas, biomass, coal, small hydro, oil, and wind would contribute with the amount of 3.25 GW, 2.08 GW, 0.71GW, 0.7GW, 0.63GW, and 0.5GW, respectively in the end year of the study.

Among 82.9 TWh of the total electricity generation in 2050, 43.3%, 19.8%, 16%, 15.4%, 3.4%, 1.5%, and 0.6% come from the large hydro, biomass, natural gas, solar photovoltaic, small hydro, wind and oil, respectively. In this scenario, renewable energy electricity generation would be 6.16TWh (22.27%), 13.11TWh (25%), and 33.14TWh (40%) in 2030, 2040, and 2050, respectively.

Table 11. The Installed Capacity in First and Last Scenario Year (GW) in FRE40

Generation Technology	Installed Capacity (GW) (2020)	Installed Capacity (GW) (2050)
Large Hydro	1.57	10.00
Small Hydro	0.06	0.70
Solar PV	0.36	8.07
Biomass	0.03	2.08
Wind	0.02	0.50
Coal	0.71	0.71
Natural Gas	0.74	3.25
Oil	0.63	0.63
Total	4.11	25.94

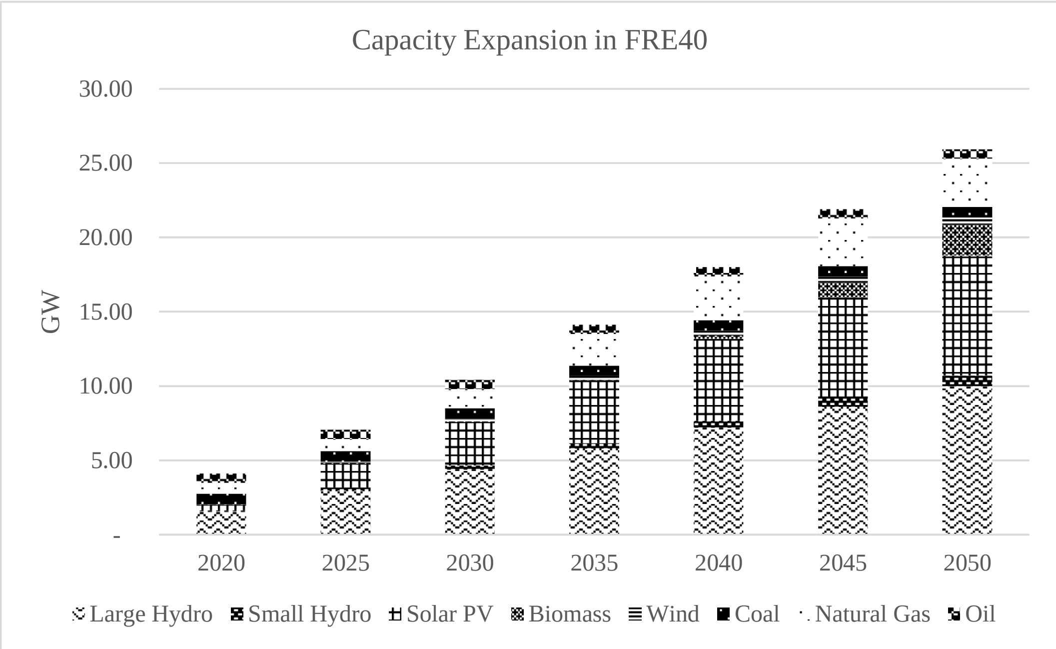

Figure 16. Capacity Expansion in FRE40 Scenario (GW)

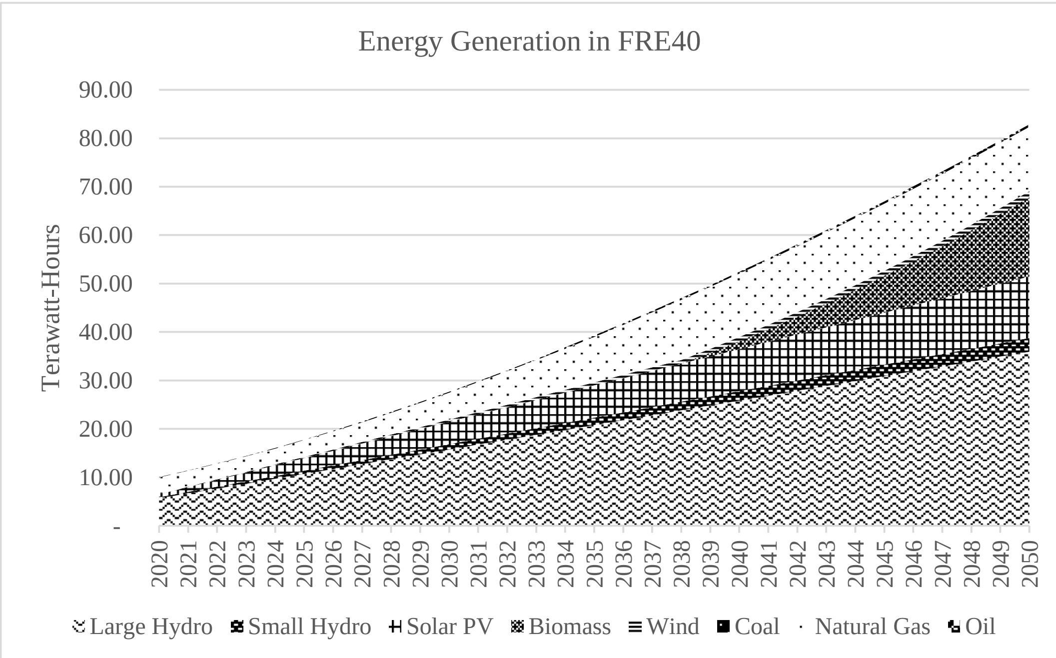

Figure 17. Electricity Generation in FRE40 Scenario (TWh)

Production cost of electricity would increase from 0.63 BUSD in 2020 to 126.25 BUSD in 2050. The cost of large hydropower development would reach 31.25 BUSD, fossil fuel such as natural gas, coal, and oil would require 39.58 BUSD, and renewable energy development needs 55.43 BUSD – more than that of fossil fuel or large hydro.

In the whole study horizon, emission emitted by electricity generation would reach 118.85 Mt CO2e by 2050. Natural gas would show the highest number, emitting 101.55 Mt CO2e to the atmosphere. The remaining emitted amount of emission would be 8.76 Mt CO2e, 6.93 Mt CO2e, and 1.61 Mt CO2e from coal bituminous, oil, and biomass.

5.1.2 Selected Renewable Potential (SRE)

The total capacity expansion of power generation increases from 4.09 GW in 2020 to 25.64 GW in 2050, with an average annual growth rate of 6.34%. Since the development of hydropower dams in the mainstream are avoided, the share of large hydro would reach only 5GW by 2050. For this reason, the absence of large hydro, natural gas will play an important role in sustaining the growth to meet the demand. In 2050, natural gas reaches 10.01GW and is closely followed by solar photovoltaic with a full capacity of 8.07GW. Natural gas, solar photovoltaic, large hydro, coal, small hydro, oil, wind and biomass would account for 39%, 31.5%, 19.5%, 2.8%, 2.7%, 2.4%, 1.9%, and 0.1%, respectively.

Similarly, natural gas shows an even more significant share in the total electricity generation mix in 2050. It would reach 57.5%, followed by a 21.7% share of large hydro and a 15.4% solar photovoltaic share. The remaining comes from small hydro, wind, and oil; once again, biomass would be negligible. Regarding the share of renewable energy resources, it would reach 6.16TWh (22.27%), 11.47TWh (21.88%), and 16.78TWh (20.25%), respectively.

Table 12. The Installed Capacity in First and Last Scenario Year (GW) in SRE

Generation Technology	Installed Capacity (GW) (2020)	Installed Capacity (GW) (2050)
Large Hydro	1.41	5.00
Small Hydro	0.06	0.70
Solar PV	0.36	8.07
Biomass	0.03	0.03
Wind	0.02	0.50
Coal	0.71	0.71
Natural Gas	0.87	10.01
Oil	0.63	0.63
Total	4.09	25.64

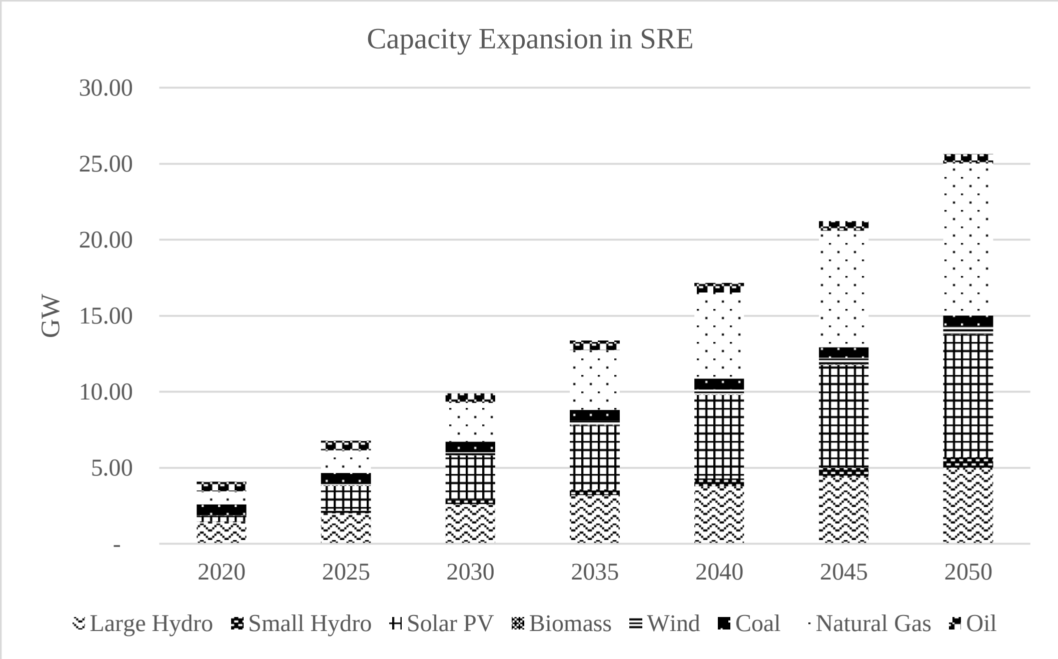

Figure 18. Capacity Expansion in SRE Scenario (GW)

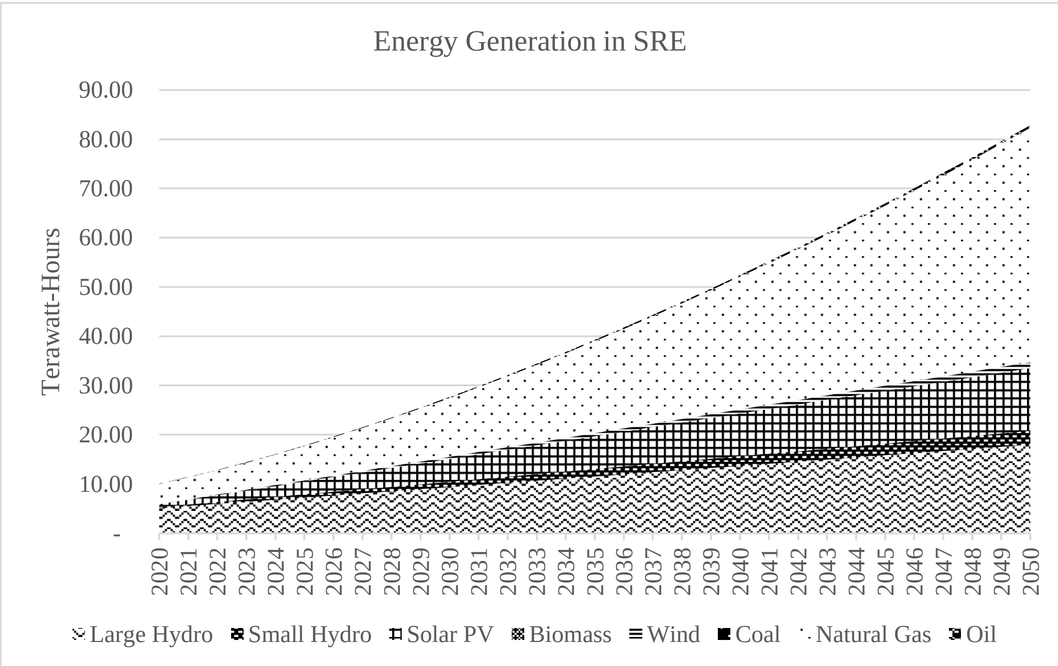

Figure 19. Electricity Generation in SRE Scenario (TWh)

Cambodia would need 109.92 BUSD to generate electricity 82.9TWh between the period 2019 and 2050. Natural gas alone would cost 66.04 BUSD in the whole study horizon, while large hydro and solar photovoltaic similarly require the total cost of production 15 BUSD and 14.20 BUSD, respectively. The remaining 14.87 BUSD would be needed for electricity generation from coal power plants, oil-based power plants, small hydro, and wind turbines.

Natural gas would emit almost 94% of the total emissions in the SRE scenario, followed by coal bituminous and oil, with the proportion of 3.4% and 2.7%, respectively. The amount of coal-based emission remains the same from the base year to the end year of the study, with 8.8 Mt CO2e. Meanwhile, oil-based emission would increase from 0.9 Mt CO2e in 2019 to 6.9 Mt CO2e in 2050. Since natural gas would be introduced from 2020, emissions from this fuel type would increase with an average annual growth rate of approximately 17% until 2050.

5.1.2.1 Selected Renewable Potential + RE 30% Scenario (SRE30)

The total capacity expansion of power generation increases from 4.09 GW in 2020 to 25.05 GW in 2050, with an average annual growth rate of 6.26%. The share of large hydro, small hydro, solar photovoltaic, wind, and oil is the same as in its parent's (SRE) scenario. The difference is that in SRE30, natural gas in 2050 decrease from 10.01GW to 8.41GW, while biomass increase from 0.03GW to 1.02GW in 2050. Due to the changes in the capacity of natural gas and biomass, the share of each technology in 2050 would be 33.6%, 32.2%, 20%, 4.1%, 2.8%, 2.8%, 2.5%, and 2% from natural gas, solar photovoltaic, large hydro, biomass, coal, small hydro, oil, and wind, respectively.

Natural gas would show the fastest growth regarding energy generation, followed by large hydro and solar photovoltaic. Coal is not a preference in this scenario; moreover, biomass would be introduced only after 2040. For this reason, the share of renewable energy increase from 11.47 TWh (21.88%) in 2040 to 24.86 TWh (30%) in 2050.

Table 13. The Installed Capacity in First and Last Scenario Year (GW) in SRE30

Generation Technology	Installed Capacity (GW) (2020)	Installed Capacity (GW) (2050)
Large Hydro	1.41	5.00
Small Hydro	0.06	0.70
Solar PV	0.36	8.07
Biomass	0.03	1.02
Wind	0.02	0.50
Coal	0.71	0.71
Natural Gas	0.87	8.41
Oil	0.63	0.63
Total	4.09	25.05

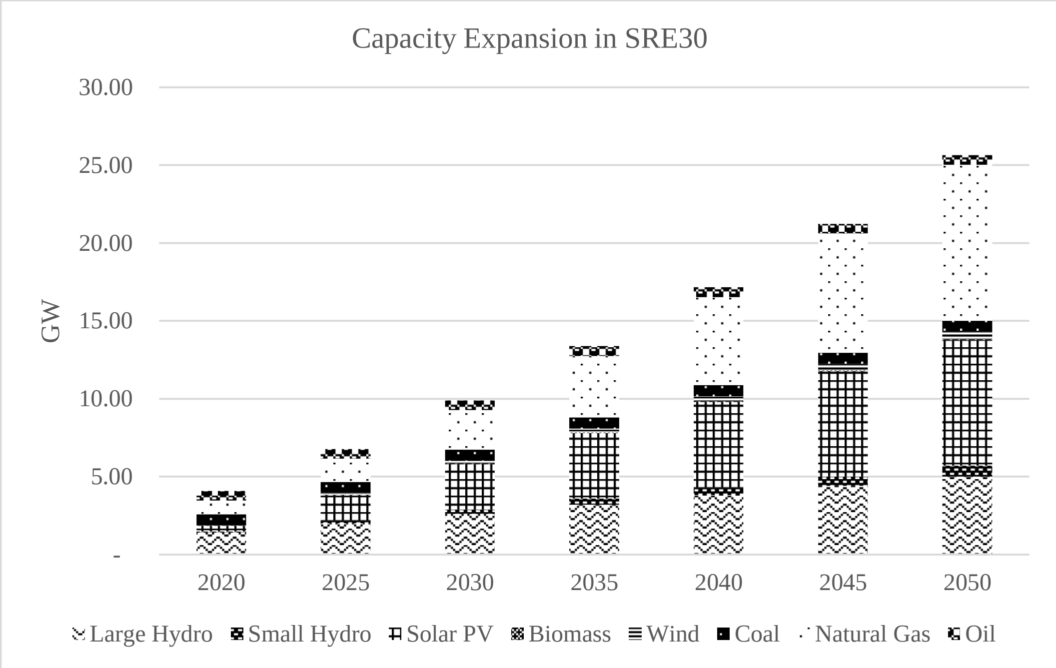

Figure 20. Capacity Expansion in SRE30 Scenario (GW)

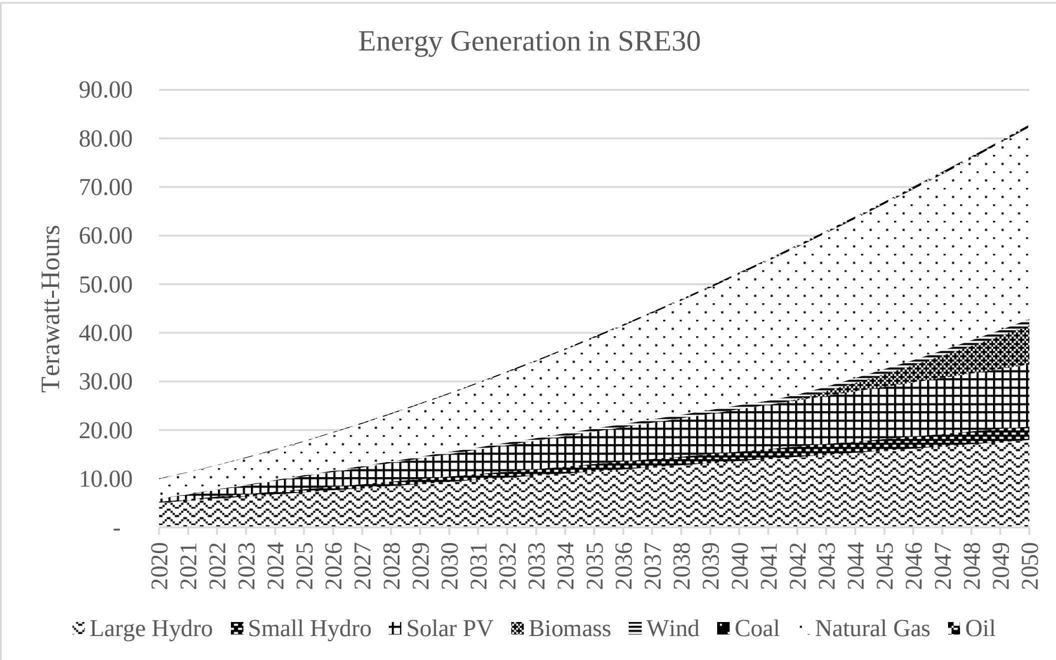

Figure 21. Electricity Generation in SRE30 Scenario (TWh)

The total production cost increase from 0.65BUSD in 2020 to 120.69BUSD in 2050, with an average annual growth rate of 9.48%. The highest rate is 2027 (10.88%), then gradually decreases, and reaches its lowest value in 2050 (8.41%). Among all cumulative production costs until 2050, natural gas would cost 62.63BUSD, which is more than half of the total cost. Interestingly, large hydro, biomass, and solar photovoltaic development require similar production costs, between 14-15 BUSD.

The cumulative amount of emission in this scenario is 243.50 Mt CO2e. The emission of natural gas consumption accounts for more than 90%, while the share of emissions from coal bituminous, oil, and biomass together are less than 7%.

5.1.2.2 Selected Renewable Potential + RE 40% Scenario (SRE40)

The total capacity expansion of power generation increases from 4.09 GW in 2020 to 25.05 GW in 2050, with an average annual growth rate of 6.17%. The share of large hydro, small hydro, solar photovoltaic, wind, and oil is the same as in its parent's scenario (SRE). The difference is that in SRE40, natural gas in 2050 decrease from 10.01GW to 6.78GW, while biomass increase from 0.03GW to 2.08GW in 2050. Due to the changes in the capacity of natural gas and biomass, the share of each technology in 2050 would be 33%, 27.7%, 20.4%, 8.5%, 2.9%, 2.9%, 2.6%, and 2% from solar photovoltaic, natural gas, large hydro, biomass, coal, small hydro, oil, and wind, respectively.

Natural gas would show the fastest growth regarding energy generation, followed by large hydro and solar photovoltaic growth. The same thing here, coal is not preferred for optimization in this scenario; meanwhile, biomass would be introduced only after 2038. For this reason, the share of renewable energy increase from 13.11 TWh (25%) in 2040 to 33.14 TWh (40%) in 2050.

Table 14. The Installed Capacity in First and Last Scenario Year (GW) in SRE40

Generation Technology	Installed Capacity (GW) (2020)	Installed Capacity (GW) (2050)
Large Hydro	1.41	5.00
Small Hydro	0.06	0.70
Solar PV	0.36	8.07
Biomass	0.03	2.08
Wind	0.02	0.50
Coal	0.71	0.71
Natural Gas	0.87	6.78
Oil	0.63	0.63
Total	4.09	24.47

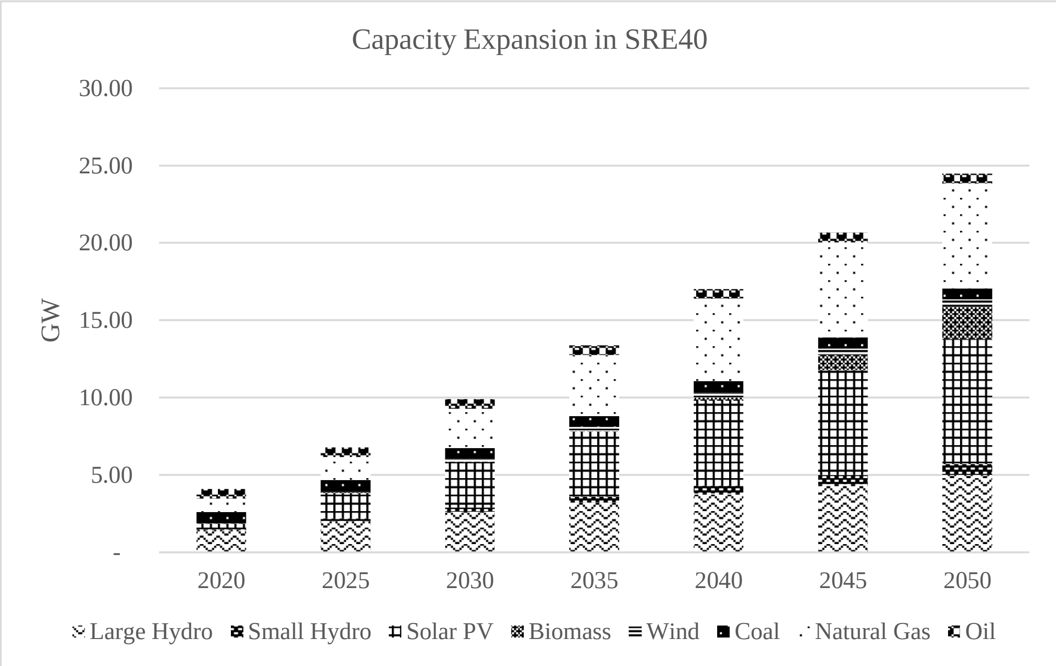

Figure 22. Capacity Expansion in SRE40 Scenario (GW)

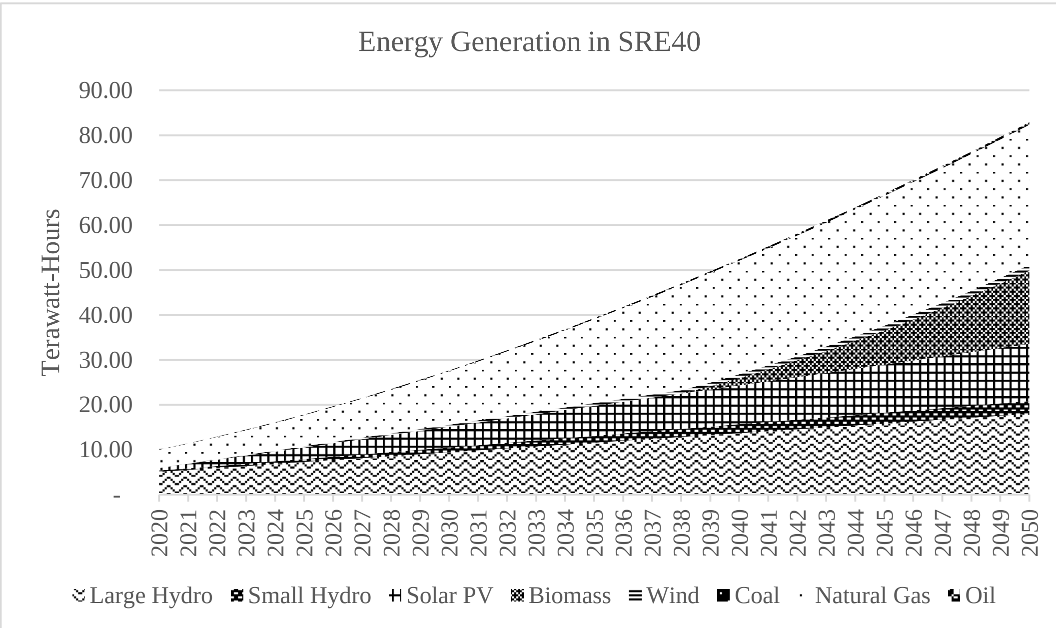

Figure 23. Electricity Generation in SRE40 Scenario (TWh)

Cambodia would need to spend 138.51 BUSD for producing total electricity generation in this scenario for the whole period of the study. Like the previous scenario (SRE30), natural gas would take more than half of the total production cost, while requirements for large hydro, biomass, solar photovoltaic, and coal would be 12%, 11.4%, 11.3%, and 6.8%, respectively.

The cumulative amount of emission in this scenario is 223.86 Mt CO2e; similar to the SRE30 scenario, the emission of natural gas consumption accounts for more than 90%, yet it is slightly lower than that in SRE30 scenario. The share of emissions from coal consumption, bituminous, oil, and biomass for power generation is also low—less than 7%.

5.1.3 Half Renewable Potential (HRE)

The total capacity expansion of power generation increases from 4.0 GW in 2020 to 22.7 GW in 2050, with an average annual growth rate of 6%. Large hydro keep dominating in the total installed capacity until 2026. Natural gas would then surpass the large hydro in 2027 and show the largest share until the end year of the study horizon. In the meantime, wind generation would be introduced in 2027 and keep growing slowly until 2050. In this scenario, biomass is the only generation that technology would not be seen in the whole planning period.

At the end year of the HRE scenario, half of the total installed capacity comes from natural gas; in the meantime, large hydro and solar photovoltaic would also share a relatively large proportion of the total installed capacity. In absolute terms, large hydro and solar photovoltaic would account for 5GW and 4.037GW, respectively. In this scenario, renewable energy sources 4.7GW would inject into 2050's total capacity. Among all renewable energy generation technologies, small hydro, wind, and biomass contribution would only be 10% in 2050.

In terms of electricity generation, natural gas would play an important role, starting in 2023 and rapidly increase until the end of the study horizon. It would reach approximately 56TWh or 67.6% in 2050. The second-largest share is large hydro, which would account for 21.7%, followed by a 7.7% share coming from solar photovoltaic. The reaming share of 3% is composed of small hydro, wind generation, and oil. In this scenario, 8.4 TWh would be generated from renewable-resource-based power plants in 2050.

Table 15. The Installed Capacity in First and Last Scenario Year (GW) in HRE

Generation Technology	Installed Capacity (GW) (2020)	Installed Capacity (GW) (2050)
Large Hydro	1.41	5.00
Small Hydro	0.05	0.35
Solar PV	0.23	4.04
Biomass	0.03	0.03
Wind	0.01	0.25
Coal	0.71	0.71
Natural Gas	0.92	11.66
Oil	0.63	0.63
Total	3.99	22.66

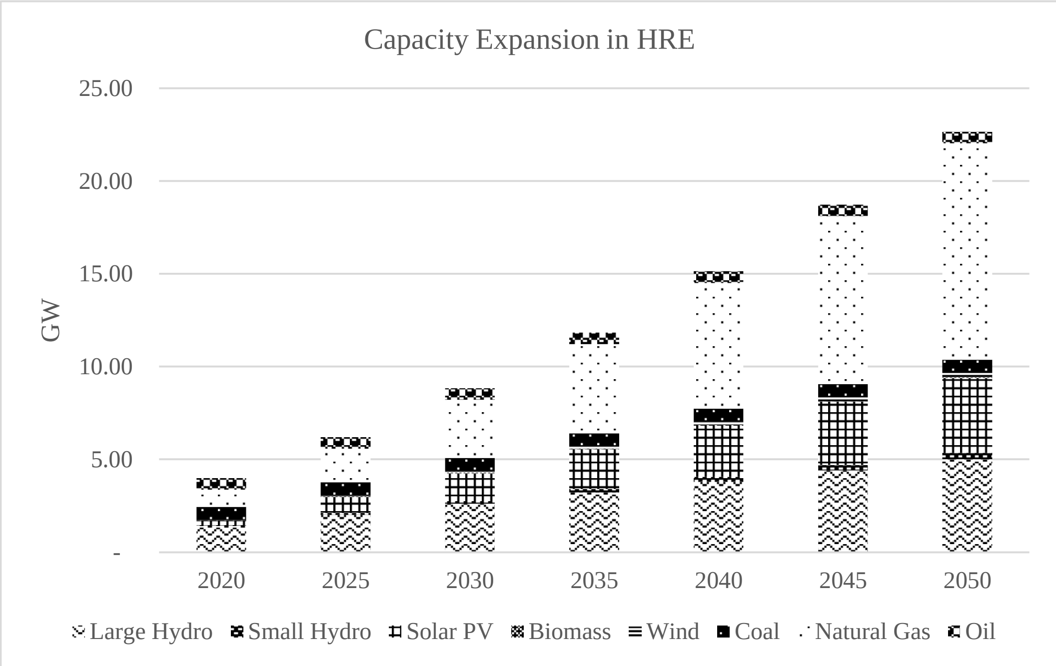

Figure 24. Capacity Expansion in HRE Scenario (GW)

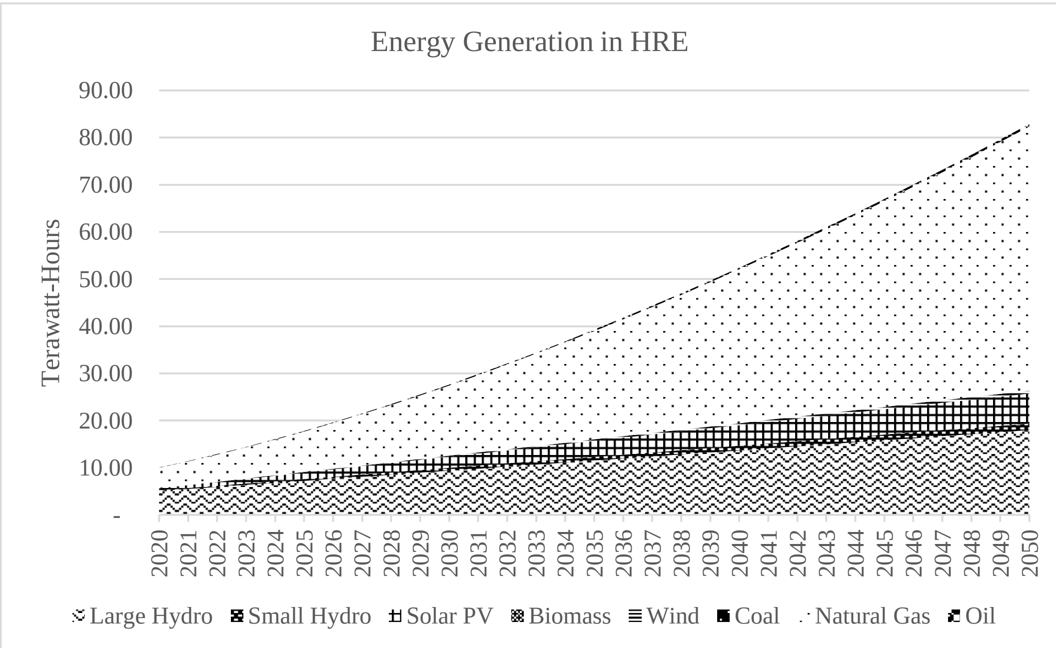

Figure 25. Electricity Generation in HRE Scenario (TWh)

Besides spending on electricity imports from neighboring countries, Cambodia would spend 114.29 BUSD for domestic electricity generation from 2019 to 2050. For the next three decades, natural gas development would cost 79.36 BUSD, while large hydro, coal and solar photovoltaic would cost 15 BUSD, 8.45 BUSD, and 7.04 BUSD, respectively. Another 4.36 BUSD would be distributed to oil-based power plants, small hydropower plants, and wind turbine development.

In this scenario, 288.79 Mt CO_2e of the total emission from 2019 to 2050 would come from the consumption of natural gas in power generation; in the meantime, coal bituminous and oil would emit only 8.75 Mt CO_2e and 6.93 Mt CO_2e, respectively. On the other hand, since the share of biomass is relatively small, total emission from this type shows an insignificant amount.

5.2 Comparison

5.2.1 Capacity Expansion

FRE, SRE, and HRE

FRE scenario shows the highest capacity expansion, which would reach 27.11GW in 2050. Of course, since there is no limitation on renewable energy potential, large hydro is fully optimized, and it would reach its maximum technical potential of 10GW in 2050. The total installed capacity in the SRE scenario is less than that in FRE since only 50% of large hydro potential (5GW) is allowed for the optimization. Due to the sharp decrease of large hydro capacity, natural gas would increase significantly, ensuring this scenario meets the demand. However, while large hydro decrease 5GW, only 3.53GW of natural gas would increase to fill the gap; meanwhile, other remaining technologies remain the same.

On the other hand, only half of all renewable potential is allowed for optimizing the HRE scenario; hence, natural gas would increase to 5.19 GW to sustain the huge absence of renewable energy resources and large hydro. Interestingly, the HRE scenario's total installed capacity is 22.66GW, 16.41% less than the FRE scenario's total installed capacity in 2050. Figure 26 illustrated the installed capacity by type of generation technologies in 2050 of all scenarios.

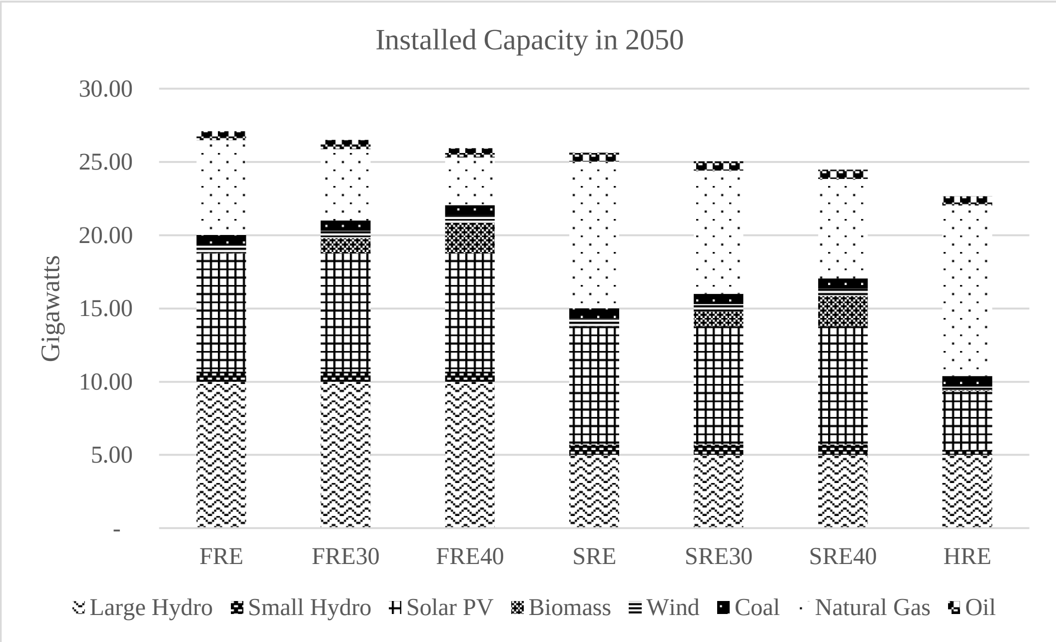

Figure 26. Total Installed Capacity in All Scenarios (GW) in 2050

FRE, FRE30, and FRE40

The total installed capacity in the FRE scenario reaches 27.11GW in 2050. For the intra-comparison, large hydro, small hydro, solar photovoltaic, and wind would be fully utilized in 2050; it is the same in FRE, FRE30, and FRE40 scenarios. Also, the capacity for coal and oil are the same in this family.

The major difference is the capacity expansion of natural gas and biomass. By increasing the share of renewable energy to 30% and 40% in FRE30 and FRE40, biomass is the only renewable generation showing changes, from 0.03GW in FRE to 1.02GW in FRE30 2.08GW in FRE40. In contrast, natural gas drops from 6.47GW in FRE to 4.88GW in FRE30 and finally 3.25GW in FRE40.

SRE, SRE30, and SRE40

On the other hand, the second intra-scenario comparison is within the SRE family. The pattern of change in the capacity expansion is almost the same as one in the FRE family. With increasing the share of renewable energy to 30% and 40% in SRE, capacity expansion of large hydro, small hydro, solar photovoltaic, wind, coal, and oil are the same across SRE, SRE30, and SRE40; in the meantime, installed capacity of biomass would also increase from 0.03GW in SRE to 1.02GW in SRE30, and 2.08GW in SRE40. On the contrary, natural gas would drop from 10.01GW in SRE to 8.41GW in SRE30 and 6.78GW in SRE40.

Therefore, we may conclude as follows: (i) natural gas is the most preferred generation technology whenever renewable energy sources are limited or after renewable energy sources are fully utilized, and (ii) an increase in biomass capacity, with more decrease in natural gas, are the main supporters when increasing the share of renewable energy; this would happen after 2042 for FRE30 and after 2039 for FRE40.

5.2.2 Electricity Generation

Whenever there is no clear target for renewable energy and that renewable energy development is pessimistic (only 50% of each renewable energy potential can be utilized), natural gas accounts for two-thirds of total electricity generation in 2050. On the other hand, for optimistic scenarios (100% of renewable energy potential can be fully utilized), the increase of renewable energy share in the generation mix can be seen as either biomass increase or natural gas decrease. It means that biomass would be introduced only if the renewable energy target is not met, and other sources of its kind are limited—biomass is the most expensive one. Similarly, in the most optimistic scenarios, renewable energy could reach 40% by 2050 (as seen in FRE40 and SRE40).

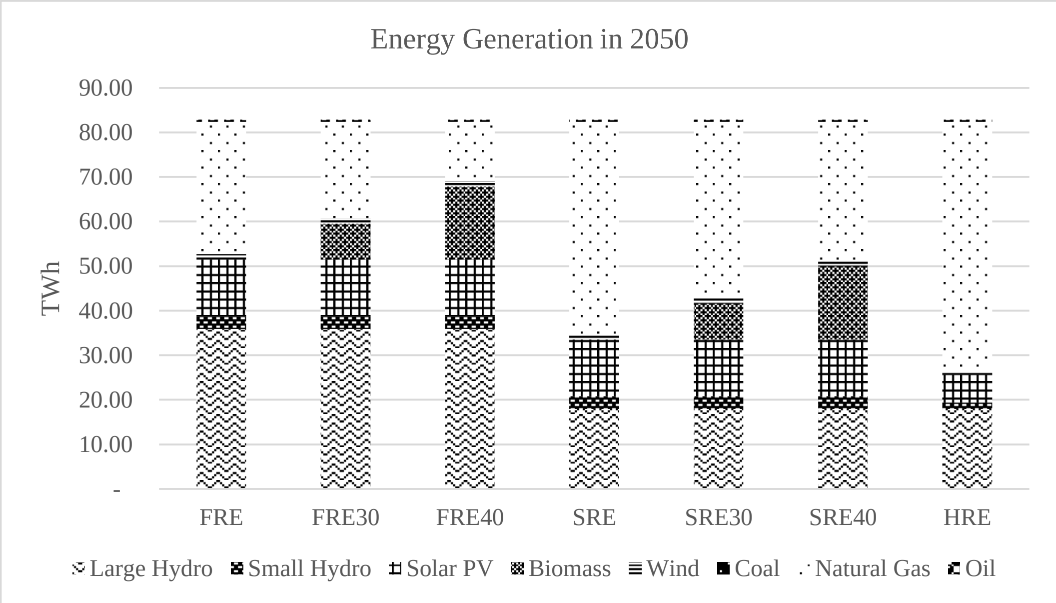

Figure 27. Total Electricity Generation in All Scenarios (TWh) in 2050

We may observe that coal is the less preferred alternative, followed by oil. It means natural gas is far cheaper than oil and coal. However, the future of domestic renewable energy resources or the re-introduction of coal or oil depends on the price and amount of future electricity import from neighboring countries. Finally, the presence of new energy (W2E, tidal, and distributed energy systems) in the Kingdom would also determine the future renewable energy mix.

5.2.3 Cost of Production

Among the seven scenarios, the SRE40 scenario requires more production cost (138.51 BUSD) because only half of large hydro (the cheapest technology) is expected to go online from now until the next three decades. Besides, 40% of renewable energy targets in 2050 would also cost a lot because biomass (the most expensive renewable energy source) would be introduced to reach the target. On the other hand, by keeping the largest share of renewable energy yet allow large hydro to be fully developed, FRE40 becomes the second-most expensive scenario (126.25 BUSD), closely followed by SRE30 (120.69 BUSD) and HRE (114.29 BUSD).

The most least-cost scenario would be FRE, which requires only 97.66 BUSD for the whole study period to meet every single year's demand. It is the most optimistic scenario because it assumes all renewable energy resources could reach their maximum individual capacity for utilization. In this case, biomass, oil, and coal show relatively small contribution; hence, the cost is lesser among all scenarios. The second least-cost scenario is FRE30 (108.42 BUSD) because the share target of renewable energy is only 30%, and there is no limitation on large-hydro power development.

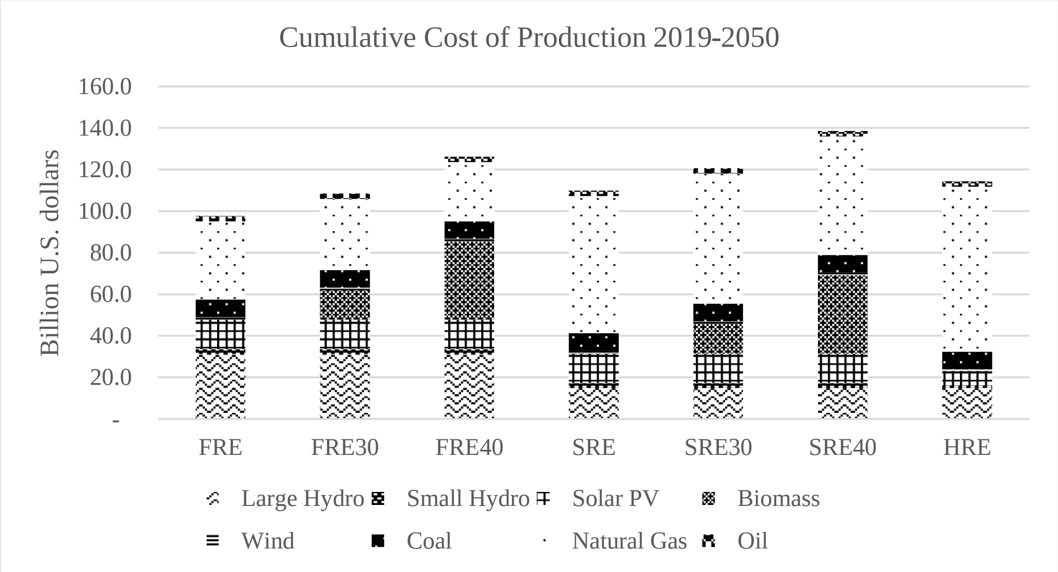

Figure 28. Cumulative Cost of Production in All Scenarios (Billions U.S. Dollars)

5.2.4 **Investment Cost**

In terms of cumulative investment cost, HRE is the least-cost scenario. In absolute terms, the cost for investment in the HRE scenario would be 28.29 BUSD by 2050. The second- and third-lowest costs are the SRE scenario and SRE30 scenario, respectively. On the other hand, the FRE40 scenario would be the costliest in 2050; the total investment cost would reach 43.77BUSD. Similarly, the FRE30 scenario and FRE scenario would require 42.51BUSD and 41.37BUSD, respectively.

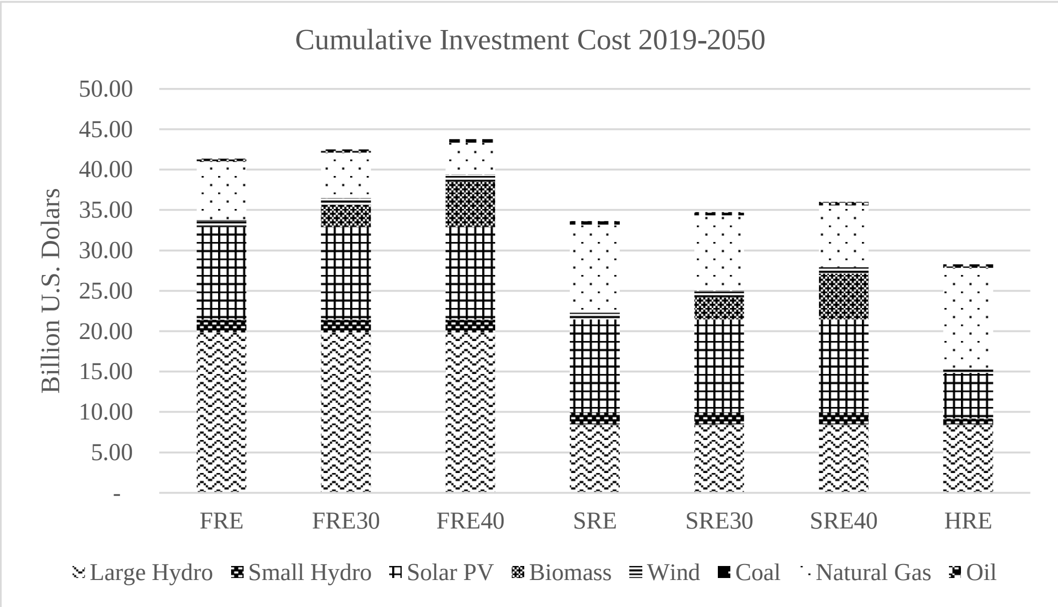

Figure 29. Cumulative Investment Cost in All Scenarios (Billions U.S. Dollars)

5.2.5 Emissions

Cumulative emissions from coal, bituminous, oil, and biomass together would be similar and small in all scenarios compared to the natural gas-consumption-based emissions. HRE scenario would emit more GHG emission, with an amount of 304.45 Mt CO2e, followed by the SRE scenario (239.74 Mt CO2e). Total emission in the SRE30 scenario and SRE40 scenario would be less than that in SRE due to the increase of the share of renewable generation in each technology. By observing the FRE40 scenario, we may see that the lowest emission would be emitted due to less natural gas sharing in the generation mix.

In addition, since FRE, FRE30, and FRE40 allow a maximum amount of large hydro to be installed, this would logically reduce natural-gas-based power plants; hence, it is obvious that emissions in these three scenarios are lower (less than 150 Mt CO2e).

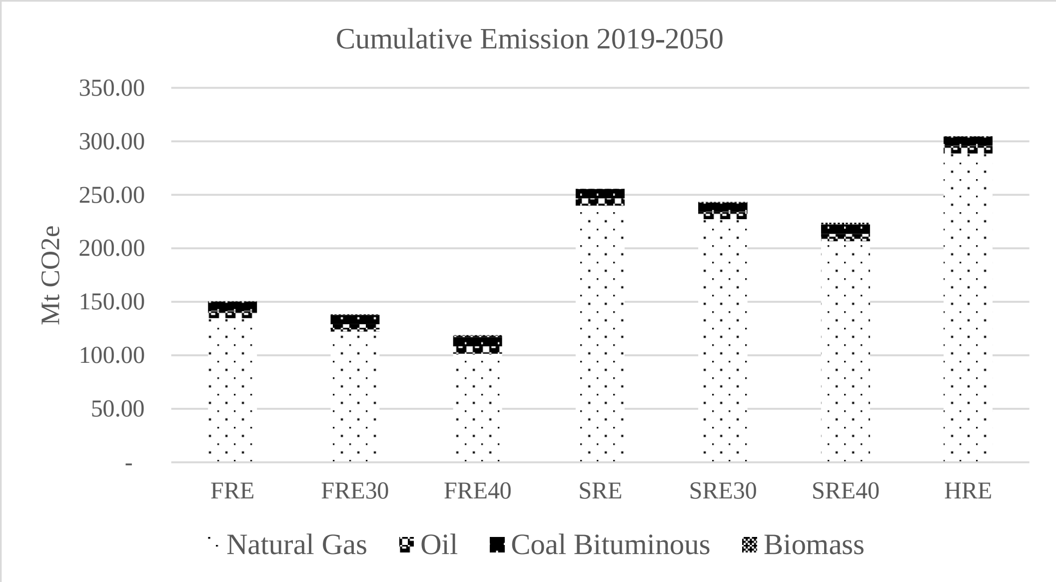

Figure 30. Cumulative Emissions by Fuel Type in All Scenarios (Mt CO2e)

5.2.5.1 Is it higher than INDC's target?

Cambodia plans to reduce emissions in the energy industry by 16% compared to the baseline level of emissions in 2030. At baseline, total emission from the power industry is forecast to reach 11.25 Mt CO2e in 2030. According to the plan of reduction, the remaining emissions would be just 9.45 Mt CO2e. Among which, emission form energy generation is assumed to be 3.81 Mt CO2e in 2030, according to the data of emission share by fuel from IEA, energy production by fuel sources, and RGC's commitment to emission reduction in electricity generation (MME, 2019b; RGC, 2015; Sarasy, 2017).

Among the seven proposed scenarios, only three scenarios without large hydro limitation would reach Cambodia's INDC target in 2030. FRE, FRE30, and FRE40 would emit only half of the emission limits, while emissions in SRE, SRE30, and SRE40 are the same and higher than the upper boundary stated in Cambodia’s INDC emission target. In the last scenario (HRE), which is the most pessimistic scenario, more fossil fuel emissions would hinder the INDC target's achievement.

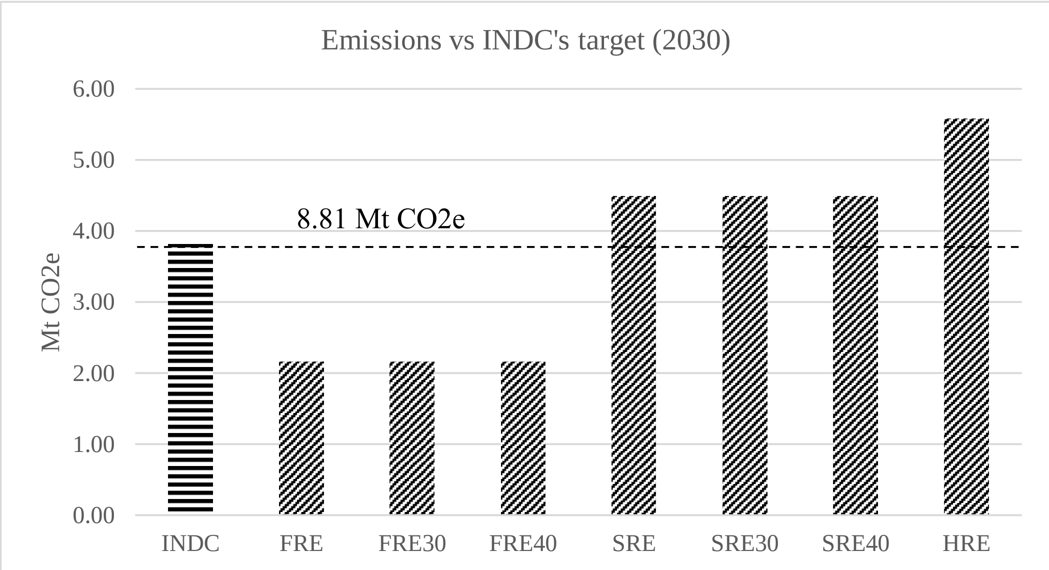

Figure 31. Emissions in 2030 from All Scenarios vs. Emissions in INDC’s target

5.2.5.2 Electricity Generated from Renewable Energy

The amount of renewable energy generation in each scenario is shown in Figure 32. Future electricity from renewable sources is expected to increase from 0.85 TWh in the first scenario year to 33.14 TWh in 2050; remarkably, such a huge increase would only be seen in the FRE40 scenario and SRE40 scenario. In contrast, the utilization of renewable energy in the HRE scenario is the smallest one than that in all scenarios; it would reach only 8.39TWh in absolute terms. Renewable share in the HRE scenario is small because it limits half of each renewable energy resource's potential, and there is no committed renewable energy target. Since there is no specified target of renewable energy in FRE and SRE, these two scenarios showed the same growth rate and value of energy generation in the whole period of the study. Renewable energy generation in these two scenarios would increase with an average annual rate of 11% from 2020 to 2050, and the maximum energy is 16.78TWh at the end of the scenario year.

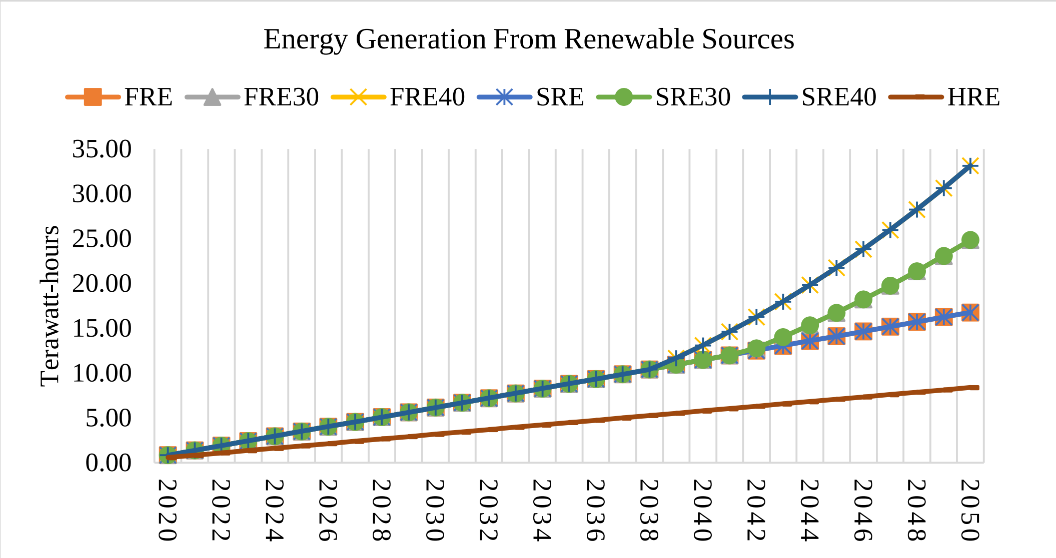

Figure 32. Electricity Generated from Renewable Energy in All Scenarios

Furthermore, since the FRE30 scenario and SRE30 scenario have the same renewable energy target (30% in 2050), their trends overlap. They show the injection of 24.86 TWh of renewable energy generation in 2050. In conclusion, scenarios with a high RE target (40%), a medium target of RE (30%), and no specified target of RE would produce electricity from renewable energy resources with the amount of 33.14 TWh, 24.86 TWh, and 16.78 TWh, respectively. Meanwhile, with 50% of each renewable energy limited, the most pessimistic scenario would produce only 8.39TWh.

5.3 Energy Security Indicator (ESI) Result

Each indicator is individually illustrated in Figure 33-40 for an in-depth understanding of the future trend of significantly impacting Cambodia's electricity supply security. In addition to the individual interpretation, this study also demonstrated a quick view of all indicators together by investigating the averaged values (see Table 16) and non-normalized scores of all proposed scenarios (see Table 17).

AV1: Utilization of renewable energy

All scenarios show the increase of renewable energy share in total installed capacity, even though such shares seem to slow down after 2030. It is obvious that the share of renewable energy-based mainly on the targets set for each scenario.

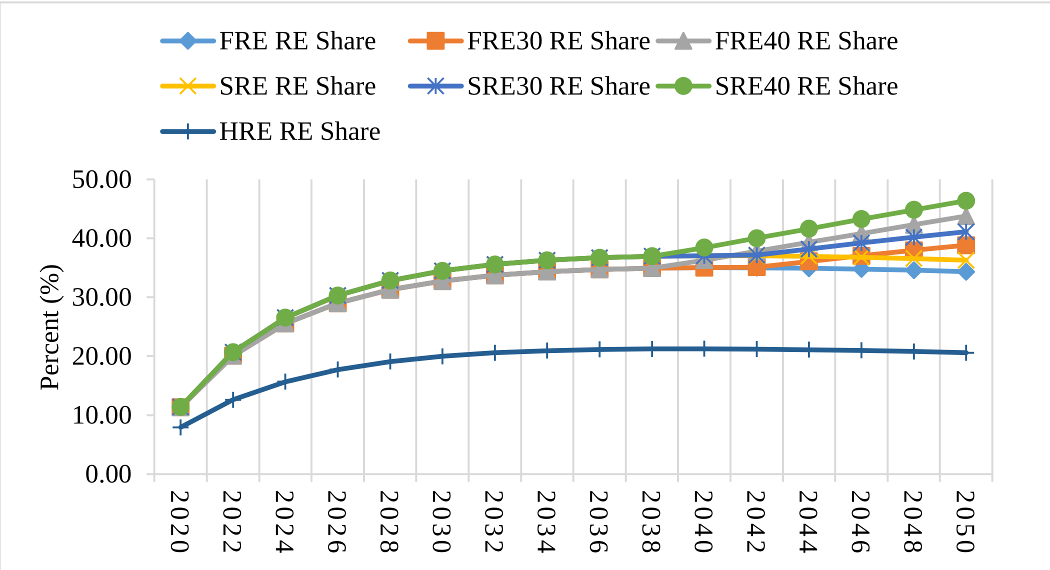

Figure 33. Share of Renewable Capacity of Each Scenario

The interesting result is that even though the target shares of renewable energy are the same, for example, FRE40 and SRE40, SRE40 requires more renewable sources (from biomass) to respond to the absence of 50% of large hydro. In FRE40, it fully developed large hydro, so that the share from biomass is lower than that in SRE40. Since large hydro is not considered a renewable source, renewable sources in FRE40 and SRE40 must differ. Similarity happened between FRE30 and SRE30. As shown in Figure 33, renewable capacity in 2050 would reach 46.38%, 43.76%, 41.11%, 38.84% and 36.28% in SRE40, FRE40, SRE30, FRE30, SRE and FRE, respectively. Since HRE is the most optimistic renewable energy development scenario, the share from renewable sources is roughly 23%.

This indicator shows more shares from domestic renewable sources development, the less reliance on electricity generation fuel import and electricity imports. Hence, SRE40 could secure a supply of electricity based on the availability of domestic resources.

AV2: Share of renewable energy in generation mix

Trends of renewable energy share in the generation mix are not completely the same as ones in total installed capacity. Scenarios with a higher target of renewable generation keep showing higher shares; however, shares of renewable energy in SRE40 and FRE40 are the same for the whole period. Similar trends, but lower, SRE30 and FRE40 also showed the same share from the first to the end scenario year. Even though we have not set the FRE and SRE targets, the contribution of renewable energy in generation mix in these two scenarios is also identical but for lower than those in the previous four scenarios. Once again, the maximum shares of renewable energy in HRE are just around 10% for the whole study period.

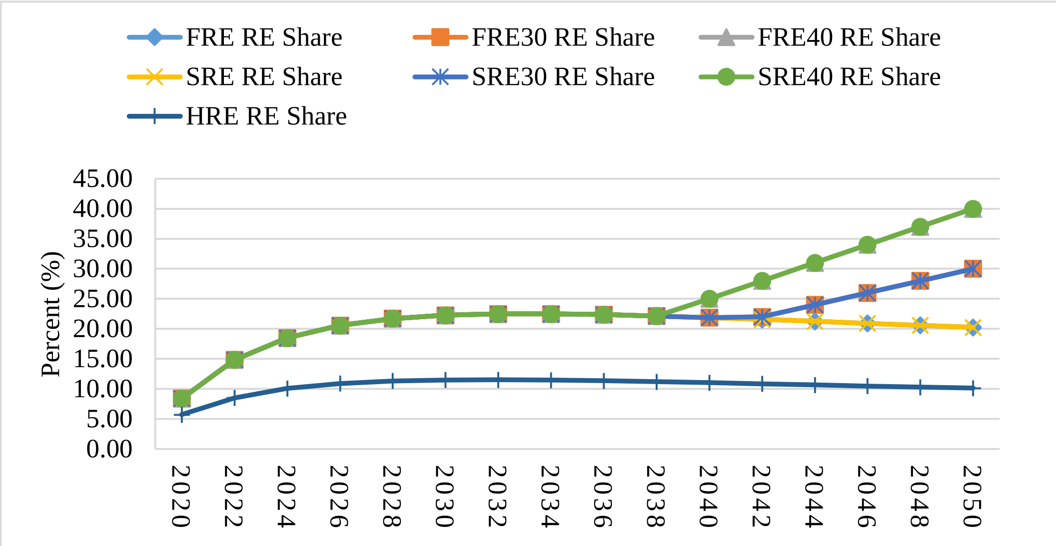

Figure 34. Share of Renewable Energy Generation of Each Scenario

AV3: Electricity feedstock fuel dependency

Cambodia would need to import more fossil fuels for electricity generation to meet the demand, especially natural gas. In the HRE scenario, fuel import for electricity generation would increase to 64.16 Mtoe in 2050, with an average annual growth rate of 8.52%. The annual growth rate of SRE closely follows that of HRE, and the total fuel import in 2050 in this scenario would be 53.33 Mtoe. After that, SRE40, SRE30, FRE, FRE40, and FRE30 would show average annual growth rate of 7.97%, 7.68%, 7.16%, 6.80% and 6.30%, respectively. In this case, the more electricity feedstock imports, the less electricity dependency. Such a case would threaten electricity supply security whenever there is a disruption in the import process or increase in fuel price. In this indicator, the FRE scenario would strongly address the issue.

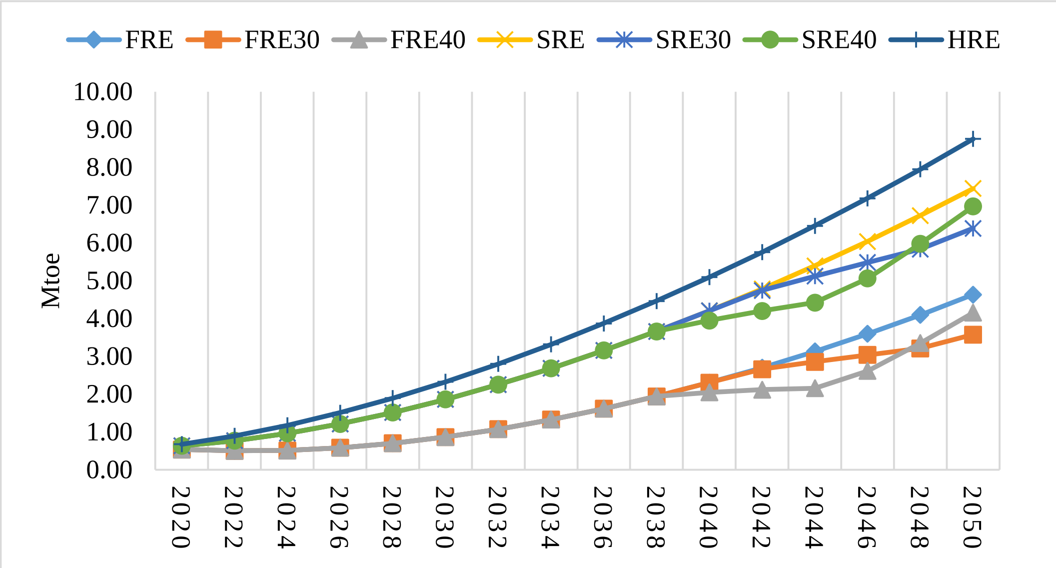

Figure 35. Electricity Feedstock Fuel Imports by Scenarios

<u>AF1: Energy generation costs</u>

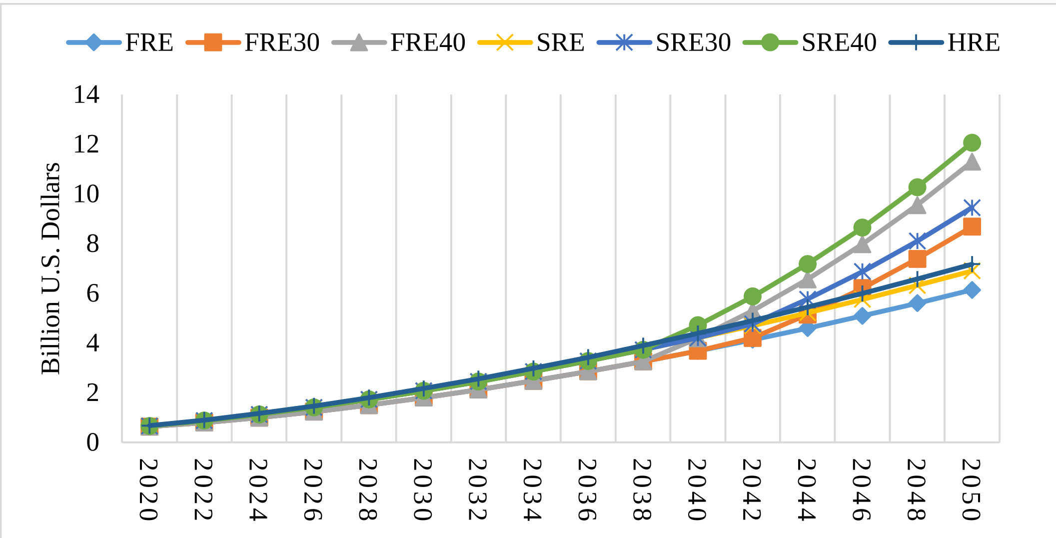

Figure 36. Cost of Generation of Each Scenario

A similarity between this indicator (AF1) and the previous indicators (AV1 and AV2) is that any scenarios with targeted renewable energy shares are higher than those without the targets. It implies that the cost of electricity generation and share of renewable generation are closely related. It is because renewable sources are still relatively expensive for development. In this indicator, the annual growth rate of production costs of SRE40 and FRE40 are similarly almost 10%. In 2050, the total production cost of SRE40 and FRE40 would reach 12.05 BUSD and 11.28 BUSD, respectively. Cambodia would spend 9.43 BUSD, 8.67 BUSD, 6.89 BUSD, and 6.12 BUSD in SRE30, FRE30, SRE, and FRE, in the same year respectively for expansion of new generation capacity. Regarding the cost, none of the scenarios would compete with the FRE scenario because the FRE scenario is freely and fully optimized without any targets or constraints.

AF2: Levelized cost of energy (LCOE)

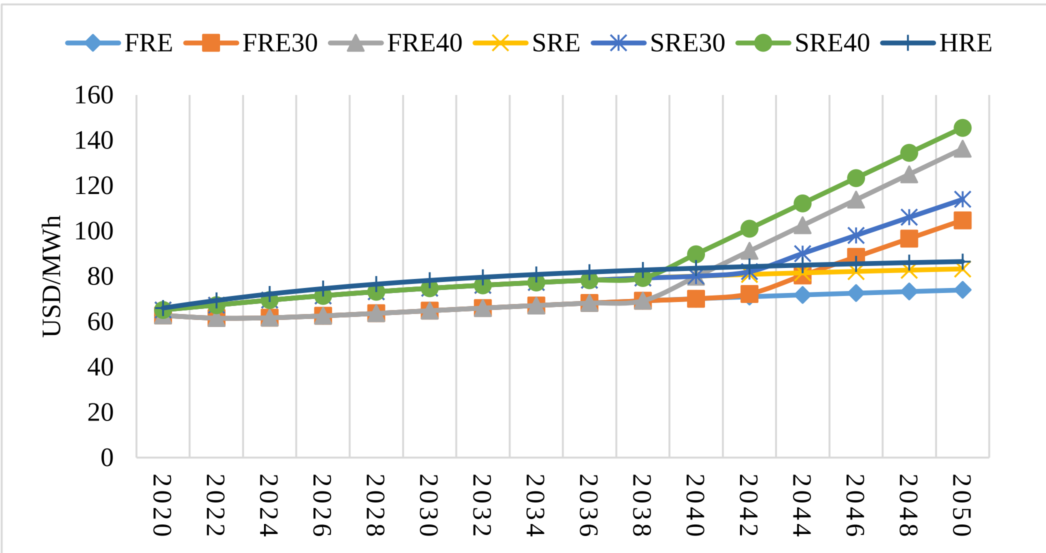

Figure 37. Levelized Cost of Energy (LCOE) in Each Scenario

The study also found that the averaged LCOEs range from 74.88USD/MWh in FRE to 106.20USD/MWh in SRE40. The second most expensive LCOE is FRE40, followed closely by SRE30 with approximately 92-97 USD/MWh. These resulted from the same causes of production cost—more cost occurred from more renewable energy development. On the other hand, for example, FRE30 has a lower target of renewable energy share, so that the LCOE of this scenario is only 83.13USD/MWh. Finally, SRE also has LCOE lower than 85USD/MWh sincere there is no commitment to increasing renewable energy share, except limiting large-hydro power development. As seen in Figure 37, LCOE in FRE, SRE, and HRE scenarios are almost constant during the study period. In contrast, the remaining four scenarios with high renewable energy targets show the increase of LCOE rapidly after the year 3038.

Hence, we may conclude that in both indicators (AF1 and AF2) in the affordability dimension, the more renewable energy sources be utilized, the more threat to electricity supply security (see Figure 36 and Figure 37). As a result, the electricity tariff would also increase, or the government would spend more on subsidies to deploy this type of generation.

EN1: Total GHG emission

Figure 38 shows that the HRE scenario would emit more GHG emissions into the atmosphere, reaching 20.80 Mt CO2e in 2050, with an average growth rate of 8.9% per year. For the remaining six scenarios, SRE, SRE30, SRE40, FRE, FRE30, and FRE40 would emit 17.74 Mt CO2e, 14.93 Mt CO2e, 12.05 Mt CO2e, 11.17 Mt CO2e, 8.36 Mt CO2e, and 5.48Mt CO2e, respectively. In addition to section 5.2.5.1, the FRE family's emissions are approximately 40% lower than the maximum allowance of emissions stated in Cambodia's 2030 IND. Such trends would remain the same for almost ten years after achieving the first INDC target. Interestingly, especially in FRE30, FRE40, SRE30, and SRE40, the rates of emissions from energy generation are expected to decline gradually. For instance, the emission in SRE40 and FRE30 almost intersect in 2050 due to the rapid development of biomass-based power generation from 2030 to meet the renewable energy share target in SRE40.

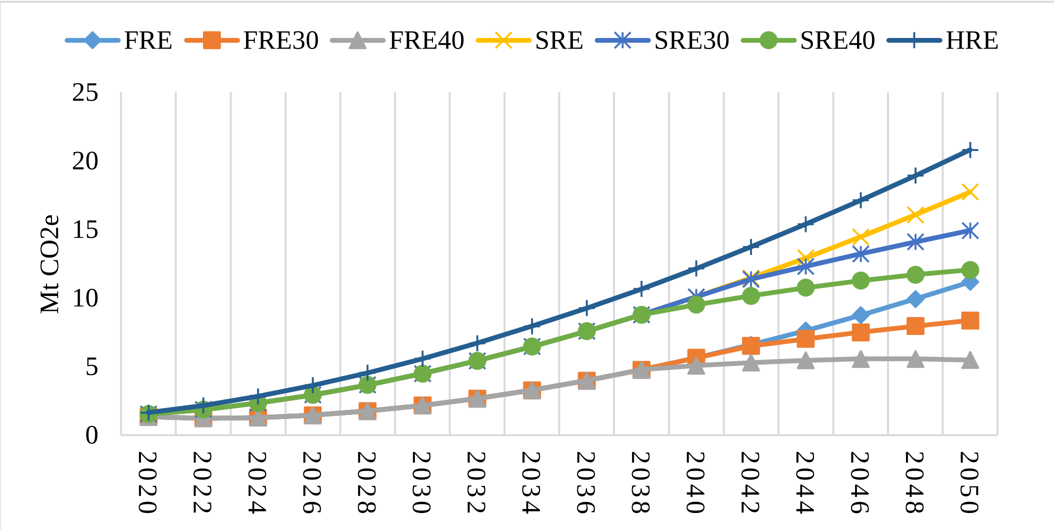

Figure 38. Total Annual GHG Emission of Each Scenario

The average growth rate of GHG emissions in these scenarios is ranging from 7.1-8.5% annually. We may observe that these scenarios' order is the inversion of renewable energy share (AV1 and AV2) and the affordability dimension (AF1 and AF2). Obviously, the emission trend is fully controlled by limiting large hydropower development and renewable energy share targets in electricity generation.

EN2: GHG emission intensity

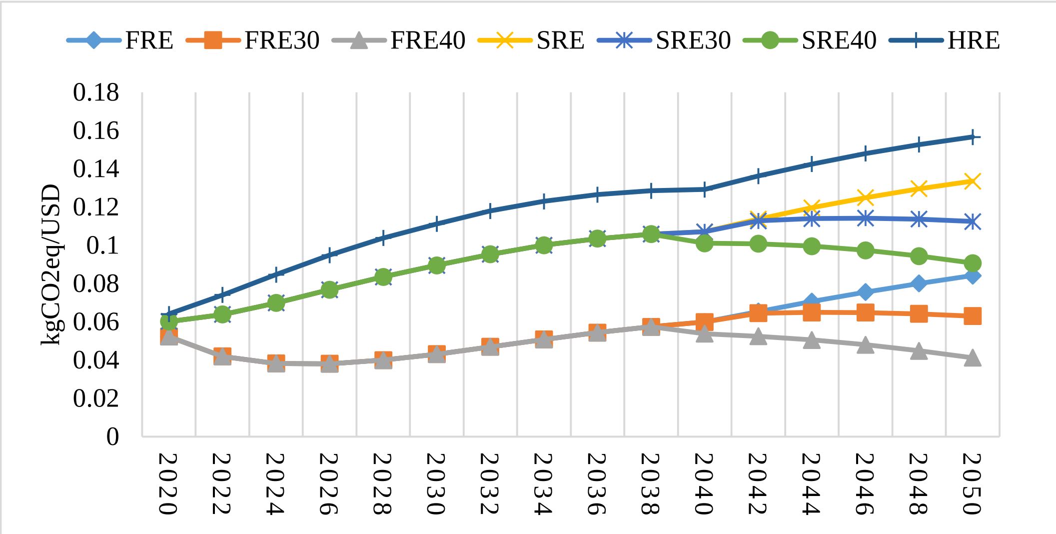

Figure 39. GHG Emission Intensity of Each Scenario

The lowest-emission intensity is SRE40, while the HRE scenario shows the highest intensity. Emission intensity in SRE40 significantly grows at an average of 3% annually, and it would reach 0.14 kgCO2eq in 2050. The second highest intensity is found in the SRE and SRE30 scenario, having an annual growth rate of 2.65% and 2.08%. Within this indicator, FRE and SRE40 show similar growth of 1.4%, and they would reach 0.07 and 0.08 kgCO2/USD, respectively. Interestingly, the growth rate of FRE40's emission intensity is negative. With an average annual growth rate of -0.7%, the intensity in 2050 would be just one-fifth of that in the highest emission scenario. It implies that FRE40 would be feasible for the implementation because it poses less threat to the environment than emission per GDP.

EN3: Share of large hydro in generation mix

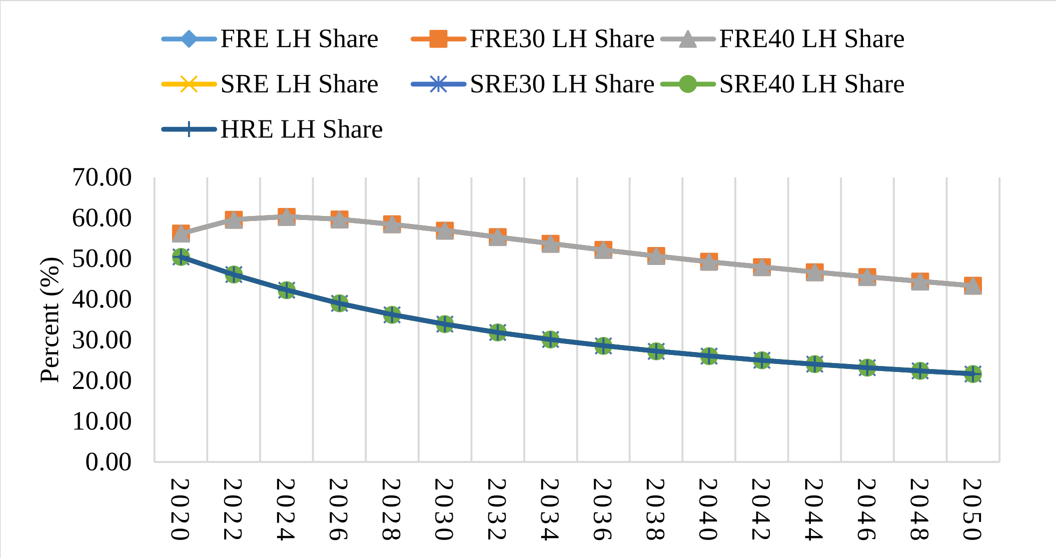

Figure 40. Share of Large-Hydroelectric Generation of Each Scenario

Due to large-hydro power development limitation, especially in the mainstream Mekong River, the share of large hydro in the generation mix of SRE, SRE30, SRE40, and HRE scenarios would gradually decrease 50.42% in 2020 to roughly 32% in 2050. This study also found that the share of this type of generation would increase in the first five years from 56% to around 60%, then gradually decrease and reach its lowest share in 2050. Such a finding was found only in the FRE family, having no limitation on large-hydro development. This indicator showed that FRE, FRE30, and FRE40 scenarios negatively affect electricity supply security due to its huge share of large hydropower, compared to the remaining scenarios. Nevertheless, based on the negative trend of large hydroelectric shares in these scenarios, this type of generation's burdens would not heavily impact supply security in the future.

Table 16. Averaged Values of Each Energy Security Indicator (ESI)

Dimension	Indicator	Scenarios						
		FRE	FRE30	FRE40	SRE	SRE30	SRE40	HRE
AV	AV1	31.03	31.74	33.00	32.65	33.42	34.77	18.93
	AV2	20.14	21.73	24.42	20.14	21.73	24.42	10.44
	AV3	30.15	27.34	26.14	53.34	50.53	49.32	64.17
AF	AF1	100.57	111.08	128.50	114.92	125.44	142.86	120.28
	AF2	77.11	85.18	98.53	88.12	96.19	109.54	92.23
EN	EN1	150.43	138.50	118.85	255.43	243.50	223.86	304.49
	EN2	0.12	0.11	0.09	0.20	0.19	0.17	0.24
	EN3	52.51	52.51	52.51	8.81	31.76	31.76	31.76

Table 16 showed the averaged values from all scenarios to better understand each indicator, and different colors mark all the values. These can be marked in light grey, grey, and dark grey colors from the best to the worse averaged values. Values in light grey, grey, and dark grey have less, medium, and heavy burden, respectively, on Cambodia's electricity supply security. Each indicator's unit is different since none of the indicators were normalized and weighted for cross-indicator comparison. For this reason, Table 16 just summaries all averaged values from each indicator separately by keeping the existing units. The scoring version of these indicators can be found in Table 17 of the conclusion part.

Chapter 6. Conclusion

6.1 Overall Conclusion

In addressing the rising energy demand in Cambodia in the last two decades, conventional electricity power plants have been deployed together with additional electricity imported from neighboring countries. Coal and hydropower have been the dominants in the generation mix, while green energy sources are relatively low. Conventional coal-fired power plants, without proper carbon capture and storage, damage the environment and human health in various forms. The fluctuation of large hydropower has been seen as a threat to energy security and forestry, wildlife habitat, agricultural land, and scenic lands. Meanwhile, energy security and emissions reduction have become higher priorities, with socio-political accessibility and environmental acceptability, ensuring energy supply at reasonable prices. Domestic renewable energy resources development can be a long-term solution for Cambodia's electricity supply security and emission reduction targets.

This study applied ARIMA (1,2,2) to forecast future electricity demand, then it applied the LEAP model to estimate and analyze the renewable energy potential in future generation mix based on proven technical potential, the proposed target of renewable energy shares, and Cambodia's INDC emission reduction target. Three main scenarios, such as full renewable potential (FRE), selected renewable energy potential (SRE), and half renewable potential (HRE), have been formulated; also, each parent scenario has two sub-scenarios inherited. Two sub-scenarios in the FRE scenario are FRE + RE 30% (FRE30) and FRE +

RE 40% (FRE40). Similarly, another two sub-scenarios under selected renewable potential (SRE) are SRE + RE 30% (SRE30) and SRE + RE 40% (SRE40). All seven scenarios are differentiated by setting technical potential and/or targeting the share of renewable energy sources in future electricity generation mix.

ARIMA (1,2,2) regression model forecast that electricity consumption in Cambodia would increase from 12.12 TWh in 2020 to 87.74 TWh in 2050, with an average growth rate of 7.3% the whole study horizons. However, since the future import of electricity from neighboring countries is assumed to be linearly increased and reached 14.62 TWh by 2050, only the remaining annual demand was used for LEAP model's domestic power generation optimization. For the optimization purpose, NEMO and LEAP model are integrated for predicting future energy capacity expansion, the share of renewable energy sources in the generation mix, cost of production, investment cost, and emissions of GHG. This study investigated a feasible scenario or a combination of scenarios that could positively impact Cambodia's electricity supply security and help the country reach its INDC's emission reduction target.

The results showed that the FRE scenario requires a huge amount of new capacity expansion, yet it would cost less than other proposed scenarios. In the FRE scenario, Cambodia would need only 97.66 BUSD for expanding the capacity of 27.1 GW to meet the demand of electricity 82.9TWh in 2050. In this scenario, large hydro, natural gas, solar photovoltaic, small hydro, and wind would take the shares of 43.3%, 35.8%, 15.4%, 3.4%, and 1.5%, respectively, in 2050. Specifically, 20.3% of total electricity generation would be generated from renewable energy. It is projected to have a cumulative amount of emission of 150.43 Mt CO2e emitted to the atmosphere.

The SRE scenario would cost 109.92 billion U.S. Dollars for capacity expansion of total installed capacity 25.64 GW in 2050. Since half of the large hydro was limited from future development, natural gas would play an important role in balancing electricity demand and supply. In total energy generation in the end year, natural gas, large hydro, solar photovoltaic, small hydro, wind, and oil would account for 57.45%, 21.67%, 15.36%, 3.40%, 1.48%, and 0.62%, respectively. The same as the FRE scenario, biomass and coal still would not have further development besides the existing installed capacity. The share of renewable sources in the generation mix is 16.8 TWh or 20.3% in 2050. Finally, in SRE, the cumulative emissions, mainly from natural gas, would be 255.43 Mt CO2e.

In the HRE scenario, the new installed capacity is expected to increase to only 22.7 GW in 2050, and the total production cost of such a development is 114.29 billion U.S. Dollars. Natural gas development alone would take 79.36 billion U.S. dollars because natural gas would increase significantly due to renewable energy resource limitations. The share of natural gas, large hydro, and oil together account for almost 90% of the total generation mix; hence, only about 10% of electricity would be generated from renewable energy. For this reason, HRE shows the highest emission among all scenarios—cumulative emission is 288.79 Mt CO2e.

With a 30% renewable energy share in 2050, the FRE30 scenario would require 108.42 billion U.S. dollars of production cost to expand new capacity with a total installed capacity of 26.5GW. Among 82.9 TWh of the total electricity generation in 2050, 43.3%, 26%, 15.4%, 9.8%, 3.4%, 1.5%, and 0.6% would come from the large hydro, natural gas, solar photovoltaic, biomass, small hydro, wind, and oil, respectively. Regarding the emissions, it is expected to emit 138.50 Mt CO2 by 2050.

FRE's second sub-scenario is the FRE40 scenario—with 40% of renewable energy share in 2050. As seen in previous scenarios, biomass does not have a significant share in the generation mix; however, it plays an important role in pushing more renewable energy share in the generation mix. Large hydro, biomass, natural gas, solar photovoltaic, small hydro, wind, and oil would account for 43.3%, 19.8%, 16%, 15.4%, 3.4%, 1.5%, and 0.6% in 2050's total energy generation. It shows the lowest emission amount, which would be just 126.25 Mt CO2e in the whole study period.

In SRE30, the production cost requirement is 120.69 billion U.S. dollars would be needed to expand approximately 25 GW of new capacity. In terms of capacity, the share of each power plants would be 33.6%, 32.2%, 20%, 4.1%, 2.8%, 2.8%, 2.5%, and 2% from natural gas, solar photovoltaic, large hydro, biomass, coal, small hydro, oil, and wind, respectively, in 2050. Due to the limit of the large hydro and relatively high share of renewable energy, biomass has shown a more significant share in this scenario. However, emission from biomass power plants is still small compared to the total emission of 243.50 Mt CO2e.

With the limit of large hydro potential, while aiming to increase another 10% share of renewable energy in the SRE40 scenario, biomass, an expensive energy source, would increase more than 2G W by 2050. Meanwhile, natural gas could not stay but drop its share from 10.01 GW to 6.78 GW in such a suppressed scenario. In this scenario, 138.51 billion U.S. dollars would be needed to have 25.05 GW of capacity expansion installed; as a result, it would emit 223.86 Mt CO2e into the atmosphere.

In conclusion, future new capacity expansion in the FRE scenario is the highest one. It means that Cambodia would reach optimal utilization of domestic renewable energy resources if this scenario is applied, and none of the new energy resources to be introduced within this period. FRE scenario is the most optimistic scenario, in which all technical potential of renewable energy can be freely optimized. Even though such technologies' production costs will not hinder its development, it is highly unlikely that other hindrances are negligible. On the other hand, as the HRE scenario assumed that only half of the maximum renewable potential can be developed, its projected capacity is the lowest among the seven scenarios. It is likely implementable in terms of generate-able potential, yet the impact of overexpansion of natural gas on the environment or human health should be considered.

On the other hand, by evaluating and comparing the results of eight energy security indicators (ESI) in each scenario, we may score each indicator separately from 1 score (worse) to 7 scores (best), then investigate the most implementable scenarios. The total scores of each scenario, which are shown in Table 17, are directly obtained from the averaged values in Table 16.

Table 17. The Score of Energy Security Indicator in Each Scenario

Dimension	Indicator	Scenario						
		FRE	FRE30	FRE40	SRE	SRE30	SRE40	HRE
AV	AV1	2	3	5	4	6	7	1
	AV2	2	4	6	3	5	7	1
	AV3	5	6	7	2	3	4	1
AF	AF1	7	6	2	5	3	1	4
	AF2	7	6	2	5	3	1	4
EN	EN1	5	6	7	2	3	4	1
	EN2	5	6	7	2	3	4	1
	EN3	1	1	1	3	2	2	2
Total Score		34	38	37	26	28	30	15

Based on the scores in Table 17, we may see that FRE30 is likely implementable; similarly, FRE40 also shows almost the same total scores. In the availability dimension (AV), FRE40 shows more advantages because it would generate more domestic energy sources. The maximum score for the renewable energy share indicators (AV1 and AV2) and fuel import dependency indicator (AV3) all belong to FRE40. On the contrary, FRE30 strongly relies on importing generation feedstock fuel, so the electricity supply security would be threatened by fuel price fluctuation, disruption in fuel transportation, or socio-political hindrance in assessing such fuel sources.

Considering the affordability dimension (AF), FRE is the least-cost scenario and is closely followed by the FRE30 scenario. On the contrary, either in production cost indicator (AF1) or LCOE indicator (AF2), FRE40 can compete with neither FRE30 nor FRE. It is because FRE40 requires more production cost for a massive share of renewable electricity generation. As illustrated in Figure 28, Cambodia would spend just 97.66 billion U.S. dollars domestically producing energy to meet the demand for the next three decades. In terms of the average Levelized cost of energy (LCOE), from the cheapest to the highest LCOE, energy production would cost 74.88U.S. dollars, 83.13 U.S. dollars, 84.28 U.S. dollars, 87.63 U.S. dollars, 92.54 U.S. dollars, 96.80 U.S. dollars, and 106.20 U.S. dollars, per megawatt-hours in FRE, FRE30, SRE, HRE, SRE30, FRE40, and SRE40, respectively.

From an environmental point of view (as seen in EN1 and EN2), the FRE40 scenario shows the smallest amount of greenhouse gases (GHG) emitted from the power generation process, which is 21% lower than that in the FRE scenario. It indicates that, even though FRE requires less energy production cost, it has more environmental externality cost. Based on the amount of emissions emitted by scenarios, we can rank such scenarios as follows: cumulative emissions (in Mt CO_2e) from FRE40, FRE30, FRE, SRE40, SRE30, SRE, and HRE would reach 118.85, 138.85, 150.43, 223.86, 243.50, 255.43, and 304.49, respectively.

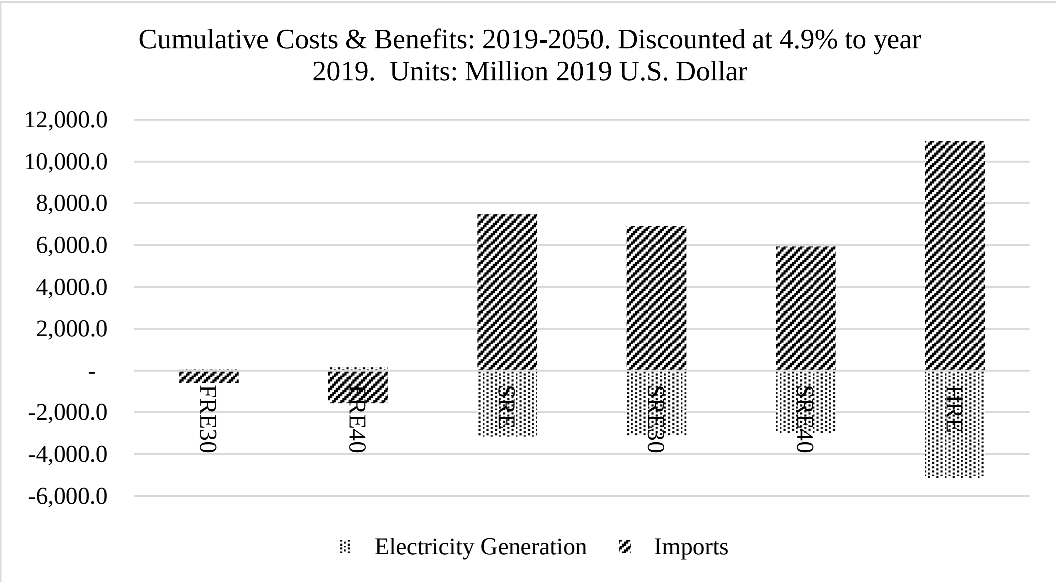

Figure 41. Cumulative Costs and Benefits, Relative to FRE (BAS) Scenario

However, to choose a reliable scenario for future development, observing each scenario's characteristics is not enough. It involves many different attributes and factors such as the demand cost, transformation cost, resource production, import-import, externality cost, and avoided GHGs. Figure 41 demonstrates cumulative costs and benefits relative to the baseline scenario (FRE scenario), considering only on the cost of electricity generation and import costs (primary energy and secondary energy).

The cost of import in the HRE scenario is the highest one, followed by the SRE scenario, SRE30 scenario, and SRE40 scenario. Compared to the baseline scenario, these four scenarios have lower electricity generation costs; however, these scenarios' net present value is negative. Only FRE30 scenarios and FRE40 scenarios show a positive net present value. The FRE30 scenario's total net present value is 523.36 million U.S. dollars, while that of the FRE40 scenario is 1378.90 million U.S. dollars for the whole study period. For this reason, future energy development in the FRE40 scenario is likely more affordable for Cambodia. Nevertheless, if the externality cost of large hydropower development is huge and the government prefers more environmentally-friendly renewable sources, SRE30 and SRE30 would be implementable in the future. This approach is not impossible in the future based on current intention in reconsidering the development of large-hydropower dams in the Mekong River mainstreams in Cambodia.

6.2 Policy Implication and Recommendation

The results of this study would provide alternative solutions and recommendations for Cambodian policymakers in developing long-term electricity planning, considering optimal economic benefits and environmental acceptability. As it is seen that the FRE40 scenario is the best option in terms of its total net present value, it is important to see the necessary measures to be undertaken in detail.

The full technical potential of almost all domestic renewable energy resources is expected to be utilized. A huge amount of renewable energy sources would take a 40% share in the total electricity generation in the next three decades. There is no doubt why this option requires more investment cost compared to other scenarios. The cost of renewable energy, especially biomass, is still relatively high compared to fossil fuel-based generation technologies, yet it reduces emissions of fossil fuel dependency and relevant environmental burdens.

Given the lowest emission, this alternative would be a foreseeable pathway for Cambodia's energy transition. Following this scenario, Cambodia would also reach its INDC's emission reduction target, specifically in the energy industry. Since the development of more renewable energy resources is one of the key measures to achieve INDC's target, this scenario is expected to be the optimal implementation of such a priority. For this reason, the RGC should aggressively promote and support domestic renewable energy development while keeping the same amount of electricity import until 2050. Furthermore, decentralized renewable energy systems such as small hydro (pico- or micro-hydro), kilowatt-scale solar rooftop, or utility-scale biomass plants would be good for Cambodia's 100% rural electrification and emission reduction target.

To have this scenario be successfully implemented, the RGC should (i) strives to provide safe and efficient electrical services, resulting in minimal negative impacts on the environment at an acceptable cost, (ii) offer legal frameworks, effective guidance, a range of incentives, and promoting private sector engagement in the provision of electricity services through the use of renewable energy, based on the optimum share of renewable energy in the generation mix (23% in 2030, 25% in 2040, and 40% in 2050), (iii) promote electricity generation, transmission, and distribution with renewable energy technologies by setting electricity prices in compliance with electricity law in Cambodia, and (iv) promoting the electricity system that uses the cheapest renewable energy system.

It is important to initially provide financial and fiscal incentives in renewable energy investment, especially to local companies. Likewise, since the energy business requires a more transparent and competitive market, the government needs to consider if the existing monopoly is enough to deploy renewable energy. Some mechanisms, such as Renewable Portfolio Standard (RPS), Feed-in-Tariff (FIT), and Renewable Energy Certificate (REC), or net metering, are also crucial to have more participation from investors, both locals, and foreign investors. On the contrary, fossil fuel incentives should be reduced and transferred to clean energy instead while acquiring adequate financial support for renewable energy development from international institutions. It has also been seen that a sufficient share of natural gas for power generation is important to address the fluctuation of renewable energy generation. Hence, the government should pay more attention to oil or natural gas stockpiling, making sure there is sufficient oil or natural gas for backing up renewable energy systems if there is a sudden supply disruption or unexpected power shortage. In the meantime, the government should also consider improving electricity infrastructure to trigger domestic renewable sources' utilization. It is because grid flexibility is significant to overcome fluctuation arising from integrating various renewable energy sources into the national grid.

Moreover, following the establishment of all required legal frameworks, the government needs more effort to raise awareness to the public and efficiently inject more budgets into research and development activities to create suitable human capital in the field. Due to the lack of local experts and professionals, the government should facilitate capacity building by working with local and international partners such as universities, research facilities, investment bodies, development banks, and international energy organizations.

As mentioned in the previous section, if the government continued to ban large hydro in the Mekong River mainstreams until the next three decades and keep a high share of renewable energy in generation mix, the SRE40 scenario would be more implementable. However, in this case, Cambodia would emit more emissions from electricity generation, so that its INDC's emission reduction target could not be fully met without adequate international support.

6.3 Limitation and Future Work

The real cost data from Cambodia could not be obtained; thus, the study assumes such data is the same as previous studies for the whole ASEAN region. Hence, the study would not 100% reflect the real cost applied in Cambodia's energy development.

Previous studies considered the change of fossil fuel cost for power generation and decrease of the capital cost of renewable energy generation technology; however, this study assumed that all candidate technology's fuel cost and capital cost remain the same for the whole study period. In addition, since there is no data of the proven potential of waste-to-energy technology, geothermal and other new and renewable energy, only small hydro, solar photovoltaic, biomass and wind are considered renewable energy sources in this study.

In conclusion, the future extension of this study is to include, as much as possible, the real cost data for candidate technology so that the result would be even more realistic.

Furthermore, parameter changes in the capital cost of renewable energy, fuel cost, and newly introduced technology would be well-considered. In the future, the study will investigate the application of clean coal technology, carbon capture and storage technology, and will also include domestic fossil resources into this energy model. The future work will also focus on the whole energy system, not just on electricity generation, so it is possible to build an energy security index from various energy-related sectors as a sophisticated energy policy document for Cambodia.

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Appendix 1: Mitigation Actions in Key Sectors in Cambodia's INDC 2030

Sector	**Priority Actions**	**Reduction as Gg CO2eq and % in the year 2030 compared to the baseline**
Energy Industries	- National grid-connected renewable energy generation (solar energy, hydropower, biomass, and biogas) and connecting decentralized renewable generation to the grid. - Off-grid electricity such as solar home systems, hydro (pico, mini and micro). - Promoting energy efficiency by end-users.	1,800 (16%)
Manufacturing Industries	- Promoting renewable energy use and adopting energy efficiency for garment factories, rice mills, and brick kilns.	727 (7%)
Transport	- Promoting mass public transport. - Improving the operation and maintenance of vehicles through motor vehicle inspection and eco-driving, and the increased use of hybrid cars, electric vehicles, and bicycles.	390 (3%)
Other	- Promoting energy efficiency for buildings and more efficient cookstoves. - Reducing emissions from waste through the use of biodigesters and water filters. - Use of renewable energy for irrigation and solar lamps.	155 (1%)
Total Saving		3,100 (27%)

Appendix 2: Energy Models in Relevant Literatures

Energy Model	Focused Areas	Country	Literatures
MARKAL	Optimization of heating supply system at a provincial level	Poland	(Krzemie, 2013)
	Analysis of market penetration and effects of a carbon tax of fuel cell vehicles	Japan	(Endo, 2007)
	Impact of the carbon tax	Nepal and Thailand	(Ferrão & Fournier, 2017a)
	Impact of technological option on air quality	United State	(Timothy L. Johnson, Joseph F. DeCarolis Carol L. Shay, Daniel H. Loughlin, Cynthia L. Gage, 2006)
TIMES	Decarbonization of the electricity generation sector	Portugal	(Amorim et al., 2014)
	Renewable energy utilization, emission reduction	South Korea	(Yong et al., 2016)
	INDCs, climate change	Latin America	(Postic et al., 2017)
	Optimal energy system, renewable energy source utilization, and decision on the investment	Germany	(Tash et al., 2019)
	Energy transition, renewable energy, CO2 emission reduction	Nigeria	(Tambari et al., 2020)
MESSAGE	Optimal energy mix, macroeconomic model	Austria	(Messner & Schrattenholzer, 2000)
	Optimal energy mix	Syria	(Hainoun et al., 2010)
	Optimal energy mix, renewable energy utilization, emission reduction	Iran	(Aryanpur & Sha, 2015)
REMix-OptiMo	Optimal energy mix, renewable energy utilization	Netherlands	(Fattahi et al., 2020)
	Capacity expansion, hourly dispatch, renewable energy	Spain	(Gils & Simon, 2017)
WEM	Generation mix, CO2 emission, energy price	World	(International Energy Agency, 2018)
LEAP	Optimal energy mix, renewable energy utilization, CO2 emission mitigation, energy security	ASEAN Indonesia Thailand	(Kumar, 2016)
	Optimal energy mix, renewable energy utilization, CO2 emission, long-term electricity planning, electrification	Indonesia	(Handayani et al., 2017; Meilandari, 2020)
	Renewable energy utilization, CO2 emission mitigation, carbon tax, INDC, long-term energy development plan	Thailand	(Ferrão & Fournier, 2017a; Kusumadewi et al., 2017)

	Long-term energy planning, electricity demand, electricity supply	Pakistan	(Hussain et al., 2018)
	Long-term electricity planning	Panama	(Mcpherson & Karney, 2014)
	Electricity system, optimal energy mix, renewable energy utilization	Africa	(Ouedraogo, 2017)
	Renewable energy utilization, CO2 emission mitigation, renewable energy target	India	(Bhuvanesh et al., 2018; Kumar & Madlener, 2016)
	Renewable energy utilization, CO2 emission mitigation, renewable energy target, optimal energy mix, climate change	Cambodia	(Chhay & Limmeechokchai, 2020; Intelligent Energy System, 2016)

Appendix 3: Sources for Energy Security Indicator Selection and Formulation

Dimension	Indicator	Code	Sources
Physical availability (AV)	Share of renewable capacity	AV1	(Bin et al., 2020; Gouveia et al., 2014a; Jamasb, 2013; Shah et al., 2019b; Song & Sun, 2019; Yao & Chang, 2014)
	Share of renewable energy in generation mix	AV2	(Jamasb, 2013; Shah et al., 2019b; Sharifuddin, 2014; Yao & Chang, 2014)
	Power-generation-fuel imports dependency	AV3	(Gouveia et al., 2014b; Ragulina et al., 2019)
Economic affordability (AF)	Energy generation cost	AF1	(Awerbuch & Yang, 2007; Gasser, 2020)
	Levelized cost of energy (LCOE)	AF2	(Azzuni & Breyer, 2020; Breyer et al., 2017; Sung & Jung, 2019)
Environmental acceptability (EN)	Total GHG emission	EN1	(Bin et al., 2020; Shah et al., 2019b)
	GHG emission intensity (/GDP)	EN2	(ERIA, 2012; Gasser, 2020; Ragulina et al., 2019; Shah et al., 2019b)
	Share of large hydropower (LH) in total power generation mix	EN3	(Bin et al., 2020)

Appendix 4: Total Energy Demand, Domestic Generation and Electricity Import

[1] Total electricity demand 2020-2050 (GWh)

2019	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**
10661	12117	13670	15316	17048	18864	20759	22729	24773	26887	29068	31314	33623	35993	38422	40909
2035	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**	**2043**	**2044**	**2045**	**2046**	**2047**	**2048**	**2049**	**2050**
43453	46052	48705	51410	54168	56977	59836	62745	65702	68709	71763	74864	78012	81208	84449	87736

[2] Domestic electricity generation 2020-2050 (GWh)

2019	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**
8804	10061	11413	12867	14418	16061	17793	19608	21505	23479	25528	27650	29841	32101	34426	36816
2035	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**	**2043**	**2044**	**2045**	**2046**	**2047**	**2048**	**2049**	**2050**
39268	41781	44355	46987	49677	52424	55227	58085	60997	63963	66982	70054	73178	76354	79582	82860

[3] Assumption of electricity import 2020-2050 (GWh)

2019	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**
3028	3402	3776	4150	4525	4899	5273	5647	6021	6395	6769	7143	7517	7891	8265	8639
2035	**2036**	**2037**	**2038**	**2039**	**2040**	**2041**	**2042**	**2043**	**2044**	**2045**	**2046**	**2047**	**2048**	**2049**	**2050**
9013	9387	9761	10136	10510	10884	11258	11632	12006	12380	12754	13128	13502	13876	14250	14624

Appendix 5: Annual Capacity Expansion

[1] Annual Capacity Expansion by Technology in FRE scenario (GW)

Year	Large Hydro	Small Hydro	Solar PV	Biomass	Wind	Coal	Natural Gas	Oil	Total
2020	1.6	0.1	0.4	0.0	0.0	0.7	0.7	0.6	4.1
2021	1.9	0.1	0.6	0.0	0.0	0.7	0.7	0.6	4.7
2022	2.1	0.1	0.9	0.0	0.0	0.7	0.7	0.6	5.3
2023	2.4	0.1	1.1	0.0	0.1	0.7	0.7	0.6	5.8
2024	2.7	0.1	1.4	0.0	0.1	0.7	0.8	0.6	6.4
2025	3.0	0.2	1.6	0.0	0.1	0.7	0.8	0.6	7.1
2026	3.3	0.2	1.9	0.0	0.1	0.7	0.9	0.6	7.7
2027	3.5	0.2	2.2	0.0	0.1	0.7	1.0	0.6	8.4
2028	3.8	0.2	2.4	0.0	0.1	0.7	1.0	0.6	9.0
2029	4.1	0.3	2.7	0.0	0.2	0.7	1.2	0.6	9.7
2030	4.4	0.3	2.9	0.0	0.2	0.7	1.3	0.6	10.4
2031	4.7	0.3	3.2	0.0	0.2	0.7	1.4	0.6	11.1
2032	4.9	0.3	3.4	0.0	0.2	0.7	1.6	0.6	11.9
2033	5.2	0.3	3.7	0.0	0.2	0.7	1.7	0.6	12.6
2034	5.5	0.4	4.0	0.0	0.2	0.7	1.9	0.6	13.4
2035	5.8	0.4	4.2	0.0	0.3	0.7	2.1	0.6	14.1
2036	6.1	0.4	4.5	0.0	0.3	0.7	2.3	0.6	14.9
2037	6.3	0.4	4.7	0.0	0.3	0.7	2.5	0.6	15.7
2038	6.6	0.4	5.0	0.0	0.3	0.7	2.8	0.6	16.5
2039	6.9	0.5	5.2	0.0	0.3	0.7	3.0	0.6	17.3
2040	7.2	0.5	5.5	0.0	0.3	0.7	3.3	0.6	18.2
2041	7.5	0.5	5.8	0.0	0.4	0.7	3.5	0.6	19.0
2042	7.8	0.5	6.0	0.0	0.4	0.7	3.8	0.6	19.8
2043	8.0	0.6	6.3	0.0	0.4	0.7	4.1	0.6	20.7
2044	8.3	0.6	6.5	0.0	0.4	0.7	4.4	0.6	21.6
2045	8.6	0.6	6.8	0.0	0.4	0.7	4.7	0.6	22.5
2046	8.9	0.6	7.0	0.0	0.4	0.7	5.0	0.6	23.4

2047	9.2	0.6	7.3	0.0	0.5	0.7	5.3	0.6	24.3
2048	9.4	0.7	7.6	0.0	0.5	0.7	5.7	0.6	25.2
2049	9.7	0.7	7.8	0.0	0.5	0.7	6.1	0.6	26.1
2050	10.0	0.7	8.1	0.0	0.5	0.7	6.5	0.6	27.1

[2] Annual Capacity Expansion by Technology in FRE30 scenario (GW)

Year	**Large Hydro**	**Small Hydro**	**Solar PV**	**Biomass**	**Wind**	**Coal**	**Natural Gas**	**Oil**	**Total**
2020	1.6	0.1	0.4	0.0	0.0	0.7	0.7	0.6	4.1
2021	1.9	0.1	0.6	0.0	0.0	0.7	0.7	0.6	4.7
2022	2.1	0.1	0.9	0.0	0.0	0.7	0.7	0.6	5.3
2023	2.4	0.1	1.1	0.0	0.1	0.7	0.7	0.6	5.8
2024	2.7	0.1	1.4	0.0	0.1	0.7	0.8	0.6	6.4
2025	3.0	0.2	1.6	0.0	0.1	0.7	0.8	0.6	7.1
2026	3.3	0.2	1.9	0.0	0.1	0.7	0.9	0.6	7.7
2027	3.5	0.2	2.2	0.0	0.1	0.7	1.0	0.6	8.4
2028	3.8	0.2	2.4	0.0	0.1	0.7	1.0	0.6	9.0
2029	4.1	0.3	2.7	0.0	0.2	0.7	1.2	0.6	9.7
2030	4.4	0.3	2.9	0.0	0.2	0.7	1.3	0.6	10.4
2031	4.7	0.3	3.2	0.0	0.2	0.7	1.4	0.6	11.1
2032	4.9	0.3	3.4	0.0	0.2	0.7	1.6	0.6	11.9
2033	5.2	0.3	3.7	0.0	0.2	0.7	1.7	0.6	12.6
2034	5.5	0.4	4.0	0.0	0.2	0.7	1.9	0.6	13.4
2035	5.8	0.4	4.2	0.0	0.3	0.7	2.1	0.6	14.1
2036	6.1	0.4	4.5	0.0	0.3	0.7	2.3	0.6	14.9
2037	6.3	0.4	4.7	0.0	0.3	0.7	2.5	0.6	15.7
2038	6.6	0.4	5.0	0.0	0.3	0.7	2.8	0.6	16.5
2039	6.9	0.5	5.2	0.0	0.3	0.7	3.0	0.6	17.3
2040	7.2	0.5	5.5	0.0	0.3	0.7	3.3	0.6	18.2
2041	7.5	0.5	5.8	0.0	0.4	0.7	3.5	0.6	19.0
2042	7.8	0.5	6.0	0.0	0.4	0.7	3.8	0.6	19.8
2043	8.0	0.6	6.3	0.1	0.4	0.7	3.9	0.6	20.6
2044	8.3	0.6	6.5	0.2	0.4	0.7	4.0	0.6	21.4

2045	8.6	0.6	6.8	0.3	0.4	0.7	4.2	0.6	22.2
2046	8.9	0.6	7.0	0.5	0.4	0.7	4.3	0.6	23.1
2047	9.2	0.6	7.3	0.6	0.5	0.7	4.4	0.6	23.9
2048	9.4	0.7	7.6	0.7	0.5	0.7	4.6	0.6	24.8
2049	9.7	0.7	7.8	0.9	0.5	0.7	4.7	0.6	25.6
2050	10.0	0.7	8.1	1.0	0.5	0.7	4.9	0.6	26.5

[3] Annual Capacity Expansion by Technology in FRE40 scenario (GW)

Year	**Large Hydro**	**Small Hydro**	**Solar PV**	**Biomass**	**Wind**	**Coal**	**Natural Gas**	**Oil**	**Total**
2020	1.6	0.1	0.4	0.0	0.0	0.7	0.7	0.6	4.1
2021	1.9	0.1	0.6	0.0	0.0	0.7	0.7	0.6	4.7
2022	2.1	0.1	0.9	0.0	0.0	0.7	0.7	0.6	5.3
2023	2.4	0.1	1.1	0.0	0.1	0.7	0.7	0.6	5.8
2024	2.7	0.1	1.4	0.0	0.1	0.7	0.8	0.6	6.4
2025	3.0	0.2	1.6	0.0	0.1	0.7	0.8	0.6	7.1
2026	3.3	0.2	1.9	0.0	0.1	0.7	0.9	0.6	7.7
2027	3.5	0.2	2.2	0.0	0.1	0.7	1.0	0.6	8.4
2028	3.8	0.2	2.4	0.0	0.1	0.7	1.0	0.6	9.0
2029	4.1	0.3	2.7	0.0	0.2	0.7	1.2	0.6	9.7
2030	4.4	0.3	2.9	0.0	0.2	0.7	1.3	0.6	10.4
2031	4.7	0.3	3.2	0.0	0.2	0.7	1.4	0.6	11.1
2032	4.9	0.3	3.4	0.0	0.2	0.7	1.6	0.6	11.9
2033	5.2	0.3	3.7	0.0	0.2	0.7	1.7	0.6	12.6
2034	5.5	0.4	4.0	0.0	0.2	0.7	1.9	0.6	13.4
2035	5.8	0.4	4.2	0.0	0.3	0.7	2.1	0.6	14.1
2036	6.1	0.4	4.5	0.0	0.3	0.7	2.3	0.6	14.9
2037	6.3	0.4	4.7	0.0	0.3	0.7	2.5	0.6	15.7
2038	6.6	0.4	5.0	0.0	0.3	0.7	2.8	0.6	16.5
2039	6.9	0.5	5.2	0.1	0.3	0.7	2.9	0.6	17.2
2040	7.2	0.5	5.5	0.2	0.3	0.7	2.9	0.6	18.0
2041	7.5	0.5	5.8	0.3	0.4	0.7	3.0	0.6	18.8
2042	7.8	0.5	6.0	0.5	0.4	0.7	3.1	0.6	19.6

2043	8.0	0.6	6.3	0.6	0.4	0.7	3.1	0.6	20.3
2044	8.3	0.6	6.5	0.8	0.4	0.7	3.2	0.6	21.1
2045	8.6	0.6	6.8	1.0	0.4	0.7	3.2	0.6	21.9
2046	8.9	0.6	7.0	1.2	0.4	0.7	3.2	0.6	22.7
2047	9.2	0.6	7.3	1.4	0.5	0.7	3.2	0.6	23.5
2048	9.4	0.7	7.6	1.6	0.5	0.7	3.2	0.6	24.3
2049	9.7	0.7	7.8	1.8	0.5	0.7	3.3	0.6	25.1
2050	10.0	0.7	8.1	2.1	0.5	0.7	3.2	0.6	25.9

[4] Annual Capacity Expansion by Technology in SRE scenario (GW)

Year	**Large Hydro**	**Small Hydro**	**Solar PV**	**Biomass**	**Wind**	**Coal**	**Natural Gas**	**Oil**	**Total**
2020	1.4	0.1	0.4	0.0	0.0	0.7	0.9	0.6	4.1
2021	1.5	0.1	0.6	0.0	0.0	0.7	1.0	0.6	4.6
2022	1.7	0.1	0.9	0.0	0.0	0.7	1.1	0.6	5.1
2023	1.8	0.1	1.1	0.0	0.1	0.7	1.2	0.6	5.6
2024	1.9	0.1	1.4	0.0	0.1	0.7	1.3	0.6	6.2
2025	2.0	0.2	1.6	0.0	0.1	0.7	1.5	0.6	6.8
2026	2.1	0.2	1.9	0.0	0.1	0.7	1.7	0.6	7.4
2027	2.2	0.2	2.2	0.0	0.1	0.7	1.9	0.6	8.0
2028	2.4	0.2	2.4	0.0	0.1	0.7	2.1	0.6	8.6
2029	2.5	0.3	2.7	0.0	0.2	0.7	2.3	0.6	9.2
2030	2.6	0.3	2.9	0.0	0.2	0.7	2.5	0.6	9.9
2031	2.7	0.3	3.2	0.0	0.2	0.7	2.8	0.6	10.6
2032	2.8	0.3	3.4	0.0	0.2	0.7	3.1	0.6	11.2
2033	3.0	0.3	3.7	0.0	0.2	0.7	3.3	0.6	11.9
2034	3.1	0.4	4.0	0.0	0.2	0.7	3.6	0.6	12.7
2035	3.2	0.4	4.2	0.0	0.3	0.7	3.9	0.6	13.4
2036	3.3	0.4	4.5	0.0	0.3	0.7	4.3	0.6	14.1
2037	3.4	0.4	4.7	0.0	0.3	0.7	4.6	0.6	14.9
2038	3.6	0.4	5.0	0.0	0.3	0.7	4.9	0.6	15.6
2039	3.7	0.5	5.2	0.0	0.3	0.7	5.3	0.6	16.4
2040	3.8	0.5	5.5	0.0	0.3	0.7	5.7	0.6	17.2

2041	3.9	0.5	5.8	0.0	0.4	0.7	6.0	0.6	18.0
2042	4.0	0.5	6.0	0.0	0.4	0.7	6.4	0.6	18.8
2043	4.2	0.6	6.3	0.0	0.4	0.7	6.8	0.6	19.6
2044	4.3	0.6	6.5	0.0	0.4	0.7	7.2	0.6	20.4
2045	4.4	0.6	6.8	0.0	0.4	0.7	7.7	0.6	21.2
2046	4.5	0.6	7.0	0.0	0.4	0.7	8.1	0.6	22.1
2047	4.6	0.6	7.3	0.0	0.5	0.7	8.5	0.6	22.9
2048	4.8	0.7	7.6	0.0	0.5	0.7	9.0	0.6	23.8
2049	4.9	0.7	7.8	0.0	0.5	0.7	9.5	0.6	24.7
2050	5.0	0.7	8.1	0.0	0.5	0.7	10.0	0.6	25.6

[5] Annual Capacity Expansion by Technology in SRE30 scenario (GW)

Year	Large Hydro	Small Hydro	Solar PV	Biomass	Wind	Coal	Natural Gas	Oil	Total
2020	1.4	0.1	0.4	0.0	0.0	0.7	0.9	0.6	4.1
2021	1.5	0.1	0.6	0.0	0.0	0.7	1.0	0.6	4.6
2022	1.7	0.1	0.9	0.0	0.0	0.7	1.1	0.6	5.1
2023	1.8	0.1	1.1	0.0	0.1	0.7	1.2	0.6	5.6
2024	1.9	0.1	1.4	0.0	0.1	0.7	1.3	0.6	6.2
2025	2.0	0.2	1.6	0.0	0.1	0.7	1.5	0.6	6.8
2026	2.1	0.2	1.9	0.0	0.1	0.7	1.7	0.6	7.4
2027	2.2	0.2	2.2	0.0	0.1	0.7	1.9	0.6	8.0
2028	2.4	0.2	2.4	0.0	0.1	0.7	2.1	0.6	8.6
2029	2.5	0.3	2.7	0.0	0.2	0.7	2.3	0.6	9.2
2030	2.6	0.3	2.9	0.0	0.2	0.7	2.5	0.6	9.9
2031	2.7	0.3	3.2	0.0	0.2	0.7	2.8	0.6	10.6
2032	2.8	0.3	3.4	0.0	0.2	0.7	3.1	0.6	11.2
2033	3.0	0.3	3.7	0.0	0.2	0.7	3.3	0.6	11.9
2034	3.1	0.4	4.0	0.0	0.2	0.7	3.6	0.6	12.7
2035	3.2	0.4	4.2	0.0	0.3	0.7	3.9	0.6	13.4
2036	3.3	0.4	4.5	0.0	0.3	0.7	4.3	0.6	14.1
2037	3.4	0.4	4.7	0.0	0.3	0.7	4.6	0.6	14.9
2038	3.6	0.4	5.0	0.0	0.3	0.7	4.9	0.6	15.6

2039	3.7	0.5	5.2	0.0	0.3	0.7	5.3	0.6	16.4
2040	3.8	0.5	5.5	0.0	0.3	0.7	5.7	0.6	17.2
2041	3.9	0.5	5.8	0.0	0.4	0.7	6.0	0.6	18.0
2042	4.0	0.5	6.0	0.0	0.4	0.7	6.4	0.6	18.7
2043	4.2	0.6	6.3	0.1	0.4	0.7	6.6	0.6	19.5
2044	4.3	0.6	6.5	0.2	0.4	0.7	6.9	0.6	20.2
2045	4.4	0.6	6.8	0.3	0.4	0.7	7.1	0.6	21.0
2046	4.5	0.6	7.0	0.5	0.4	0.7	7.4	0.6	21.8
2047	4.6	0.6	7.3	0.6	0.5	0.7	7.6	0.6	22.6
2048	4.8	0.7	7.6	0.7	0.5	0.7	7.9	0.6	23.4
2049	4.9	0.7	7.8	0.9	0.5	0.7	8.2	0.6	24.2
2050	5.0	0.7	8.1	1.0	0.5	0.7	8.4	0.6	25.0

[6] Annual Capacity Expansion by Technology in SRE40 scenario (GW)

Year	**Large Hydro**	**Small Hydro**	**Solar PV**	**Biomass**	**Wind**	**Coal**	**Natural Gas**	**Oil**	**Total**
2020	1.4	0.1	0.4	0.0	0.0	0.7	0.9	0.6	4.1
2021	1.5	0.1	0.6	0.0	0.0	0.7	1.0	0.6	4.6
2022	1.7	0.1	0.9	0.0	0.0	0.7	1.1	0.6	5.1
2023	1.8	0.1	1.1	0.0	0.1	0.7	1.2	0.6	5.6
2024	1.9	0.1	1.4	0.0	0.1	0.7	1.3	0.6	6.2
2025	2.0	0.2	1.6	0.0	0.1	0.7	1.5	0.6	6.8
2026	2.1	0.2	1.9	0.0	0.1	0.7	1.7	0.6	7.4
2027	2.2	0.2	2.2	0.0	0.1	0.7	1.9	0.6	8.0
2028	2.4	0.2	2.4	0.0	0.1	0.7	2.1	0.6	8.6
2029	2.5	0.3	2.7	0.0	0.2	0.7	2.3	0.6	9.2
2030	2.6	0.3	2.9	0.0	0.2	0.7	2.5	0.6	9.9
2031	2.7	0.3	3.2	0.0	0.2	0.7	2.8	0.6	10.6
2032	2.8	0.3	3.4	0.0	0.2	0.7	3.1	0.6	11.2
2033	3.0	0.3	3.7	0.0	0.2	0.7	3.3	0.6	11.9
2034	3.1	0.4	4.0	0.0	0.2	0.7	3.6	0.6	12.7
2035	3.2	0.4	4.2	0.0	0.3	0.7	3.9	0.6	13.4
2036	3.3	0.4	4.5	0.0	0.3	0.7	4.3	0.6	14.1

2037	3.4	0.4	4.7	0.0	0.3	0.7	4.6	0.6	14.9
2038	3.6	0.4	5.0	0.0	0.3	0.7	4.9	0.6	15.6
2039	3.7	0.5	5.2	0.1	0.3	0.7	5.1	0.6	16.3
2040	3.8	0.5	5.5	0.2	0.3	0.7	5.3	0.6	17.0
2041	3.9	0.5	5.8	0.3	0.4	0.7	5.5	0.6	17.7
2042	4.0	0.5	6.0	0.5	0.4	0.7	5.7	0.6	18.5
2043	4.2	0.6	6.3	0.6	0.4	0.7	5.9	0.6	19.2
2044	4.3	0.6	6.5	0.8	0.4	0.7	6.0	0.6	19.9
2045	4.4	0.6	6.8	1.0	0.4	0.7	6.2	0.6	20.7
2046	4.5	0.6	7.0	1.2	0.4	0.7	6.3	0.6	21.4
2047	4.6	0.6	7.3	1.4	0.5	0.7	6.4	0.6	22.1
2048	4.8	0.7	7.6	1.6	0.5	0.7	6.5	0.6	22.9
2049	4.9	0.7	7.8	1.8	0.5	0.7	6.7	0.6	23.7
2050	5.0	0.7	8.1	2.1	0.5	0.7	6.8	0.6	24.5

[7] Annual Capacity Expansion by Technology in HRE scenario (GW)

Year	Large Hydro	Small Hydro	Solar PV	Biomass	Wind	Coal	Natural Gas	Oil	Total
2020	1.4	0.0	0.2	0.0	0.0	0.7	0.9	0.6	4.0
2021	1.5	0.1	0.4	0.0	0.0	0.7	1.1	0.6	4.4
2022	1.7	0.1	0.5	0.0	0.0	0.7	1.2	0.6	4.8
2023	1.8	0.1	0.6	0.0	0.0	0.7	1.4	0.6	5.3
2024	1.9	0.1	0.7	0.0	0.0	0.7	1.6	0.6	5.7
2025	2.0	0.1	0.9	0.0	0.0	0.7	1.8	0.6	6.2
2026	2.1	0.1	1.0	0.0	0.1	0.7	2.0	0.6	6.7
2027	2.2	0.1	1.1	0.0	0.1	0.7	2.3	0.6	7.2
2028	2.4	0.1	1.2	0.0	0.1	0.7	2.6	0.6	7.7
2029	2.5	0.1	1.4	0.0	0.1	0.7	2.8	0.6	8.3
2030	2.6	0.1	1.5	0.0	0.1	0.7	3.1	0.6	8.8
2031	2.7	0.2	1.6	0.0	0.1	0.7	3.4	0.6	9.4
2032	2.8	0.2	1.8	0.0	0.1	0.7	3.8	0.6	10.0
2033	3.0	0.2	1.9	0.0	0.1	0.7	4.1	0.6	10.6
2034	3.1	0.2	2.0	0.0	0.1	0.7	4.4	0.6	11.2

2035	3.2	0.2	2.1	0.0	0.1	0.7	4.8	0.6	11.8
2036	3.3	0.2	2.3	0.0	0.1	0.7	5.2	0.6	12.5
2037	3.4	0.2	2.4	0.0	0.1	0.7	5.6	0.6	13.1
2038	3.6	0.2	2.5	0.0	0.2	0.7	6.0	0.6	13.8
2039	3.7	0.2	2.6	0.0	0.2	0.7	6.4	0.6	14.5
2040	3.8	0.2	2.8	0.0	0.2	0.7	6.8	0.6	15.1
2041	3.9	0.3	2.9	0.0	0.2	0.7	7.2	0.6	15.8
2042	4.0	0.3	3.0	0.0	0.2	0.7	7.7	0.6	16.5
2043	4.2	0.3	3.1	0.0	0.2	0.7	8.1	0.6	17.3
2044	4.3	0.3	3.3	0.0	0.2	0.7	8.6	0.6	18.0
2045	4.4	0.3	3.4	0.0	0.2	0.7	9.0	0.6	18.7
2046	4.5	0.3	3.5	0.0	0.2	0.7	9.5	0.6	19.5
2047	4.6	0.3	3.7	0.0	0.2	0.7	10.0	0.6	20.2
2048	4.8	0.3	3.8	0.0	0.2	0.7	10.6	0.6	21.0
2049	4.9	0.3	3.9	0.0	0.2	0.7	11.1	0.6	21.8
2050	5.0	0.3	4.0	0.0	0.2	0.7	11.7	0.6	22.7

Appendix 6: Annual Energy Generation

[1] Annual Energy Generation by Technology in FRE scenario (TWh)

Year	Large Hydro	Small Hydro	Solar PV	Biomass	Wind	Coal	Natural Gas	Oil	Total
2020	5.7	0.2	0.6	-	0.0	-	3.5	0.1	10.1
2021	6.7	0.3	1.0	-	0.1	-	3.3	0.1	11.4
2022	7.7	0.4	1.4	-	0.1	-	3.2	0.1	12.9
2023	8.7	0.5	1.8	-	0.2	-	3.2	0.1	14.4
2024	9.7	0.6	2.2	-	0.2	-	3.3	0.1	16.1
2025	10.7	0.7	2.6	-	0.2	-	3.5	0.1	17.8
2026	11.7	0.8	3.0	-	0.3	-	3.7	0.1	19.6
2027	12.7	0.8	3.4	-	0.3	-	4.1	0.2	21.5
2028	13.7	0.9	3.8	-	0.4	-	4.5	0.2	23.5
2029	14.7	1.0	4.2	-	0.4	-	5.0	0.2	25.5
2030	15.7	1.1	4.6	-	0.4	-	5.6	0.2	27.6
2031	16.7	1.2	5.0	-	0.5	-	6.2	0.2	29.8
2032	17.8	1.3	5.4	-	0.5	-	6.9	0.2	32.1
2033	18.8	1.4	5.8	-	0.6	-	7.7	0.2	34.4
2034	19.8	1.4	6.2	-	0.6	-	8.5	0.3	36.8
2035	20.8	1.5	6.7	-	0.6	-	9.4	0.3	39.3
2036	21.8	1.6	7.1	-	0.7	-	10.3	0.3	41.8
2037	22.8	1.7	7.5	-	0.7	-	11.4	0.3	44.4
2038	23.8	1.8	7.9	-	0.8	-	12.4	0.3	47.0
2039	24.8	1.9	8.3	-	0.8	-	13.6	0.4	49.7
2040	25.8	2.0	8.7	-	0.8	-	14.8	0.4	52.4
2041	26.8	2.0	9.1	-	0.9	-	16.0	0.4	55.2
2042	27.8	2.1	9.5	-	0.9	-	17.3	0.4	58.1
2043	28.9	2.2	9.9	-	0.9	-	18.6	0.4	61.0
2044	29.9	2.3	10.3	-	1.0	-	20.0	0.5	64.0
2045	30.9	2.4	10.7	-	1.0	-	21.5	0.5	67.0
2046	31.9	2.5	11.1	-	1.1	-	23.0	0.5	70.1

2047	32.9	2.6	11.5	-	1.1	-	24.6	0.5	73.2
2048	33.9	2.6	11.9	-	1.1	-	26.2	0.5	76.4
2049	34.9	2.7	12.3	-	1.2	-	27.9	0.5	79.6
2050	35.9	2.8	12.7	-	1.2	-	29.6	0.5	82.9

[2] Annual Energy Generation by Technology in FRE30 scenario (TWh)

Year	**Large Hydro**	**Small Hydro**	**Solar PV**	**Biomass**	**Wind**	**Coal**	**Natural Gas**	**Oil**	**Total**
2020	5.7	0.2	0.6	-	0.0	-	3.5	0.1	10.1
2021	6.7	0.3	1.0	-	0.1	-	3.3	0.1	11.4
2022	7.7	0.4	1.4	-	0.1	-	3.2	0.1	12.9
2023	8.7	0.5	1.8	-	0.2	-	3.2	0.1	14.4
2024	9.7	0.6	2.2	-	0.2	-	3.3	0.1	16.1
2025	10.7	0.7	2.6	-	0.2	-	3.5	0.1	17.8
2026	11.7	0.8	3.0	-	0.3	-	3.7	0.1	19.6
2027	12.7	0.8	3.4	-	0.3	-	4.1	0.2	21.5
2028	13.7	0.9	3.8	-	0.4	-	4.5	0.2	23.5
2029	14.7	1.0	4.2	-	0.4	-	5.0	0.2	25.5
2030	15.7	1.1	4.6	-	0.4	-	5.6	0.2	27.6
2031	16.7	1.2	5.0	-	0.5	-	6.2	0.2	29.8
2032	17.8	1.3	5.4	-	0.5	-	6.9	0.2	32.1
2033	18.8	1.4	5.8	-	0.6	-	7.7	0.2	34.4
2034	19.8	1.4	6.2	-	0.6	-	8.5	0.3	36.8
2035	20.8	1.5	6.7	-	0.6	-	9.4	0.3	39.3
2036	21.8	1.6	7.1	-	0.7	-	10.3	0.3	41.8
2037	22.8	1.7	7.5	-	0.7	-	11.4	0.3	44.4
2038	23.8	1.8	7.9	-	0.8	-	12.4	0.3	47.0
2039	24.8	1.9	8.3	-	0.8	-	13.6	0.4	49.7
2040	25.8	2.0	8.7	-	0.8	-	14.8	0.4	52.4
2041	26.8	2.0	9.1	-	0.9	-	16.0	0.4	55.2
2042	27.8	2.1	9.5	0.2	0.9	-	17.0	0.4	58.1
2043	28.9	2.2	9.9	1.0	0.9	-	17.7	0.4	61.0
2044	29.9	2.3	10.3	1.8	1.0	-	18.3	0.5	64.0

2045	30.9	2.4	10.7	2.6	1.0	-	18.9	0.5	67.0
2046	31.9	2.5	11.1	3.6	1.1	-	19.5	0.5	70.1
2047	32.9	2.6	11.5	4.6	1.1	-	20.0	0.5	73.2
2048	33.9	2.6	11.9	5.7	1.1	-	20.6	0.5	76.4
2049	34.9	2.7	12.3	6.8	1.2	-	21.1	0.5	79.6
2050	35.9	2.8	12.7	8.1	1.2	-	21.6	0.5	82.9

[3] Annual Energy Generation by Technology in FRE40 scenario (TWh)

Year	Large Hydro	Small Hydro	Solar PV	Biomass	Wind	Coal	Natural Gas	Oil	Total
2020	5.7	0.2	0.6	-	0.0	-	3.5	0.1	10.1
2021	6.7	0.3	1.0	-	0.1	-	3.3	0.1	11.4
2022	7.7	0.4	1.4	-	0.1	-	3.2	0.1	12.9
2023	8.7	0.5	1.8	-	0.2	-	3.2	0.1	14.4
2024	9.7	0.6	2.2	-	0.2	-	3.3	0.1	16.1
2025	10.7	0.7	2.6	-	0.2	-	3.5	0.1	17.8
2026	11.7	0.8	3.0	-	0.3	-	3.7	0.1	19.6
2027	12.7	0.8	3.4	-	0.3	-	4.1	0.2	21.5
2028	13.7	0.9	3.8	-	0.4	-	4.5	0.2	23.5
2029	14.7	1.0	4.2	-	0.4	-	5.0	0.2	25.5
2030	15.7	1.1	4.6	-	0.4	-	5.6	0.2	27.6
2031	16.7	1.2	5.0	-	0.5	-	6.2	0.2	29.8
2032	17.8	1.3	5.4	-	0.5	-	6.9	0.2	32.1
2033	18.8	1.4	5.8	-	0.6	-	7.7	0.2	34.4
2034	19.8	1.4	6.2	-	0.6	-	8.5	0.3	36.8
2035	20.8	1.5	6.7	-	0.6	-	9.4	0.3	39.3
2036	21.8	1.6	7.1	-	0.7	-	10.3	0.3	41.8
2037	22.8	1.7	7.5	-	0.7	-	11.4	0.3	44.4
2038	23.8	1.8	7.9	-	0.8	-	12.4	0.3	47.0
2039	24.8	1.9	8.3	0.7	0.8	-	12.8	0.4	49.7
2040	25.8	2.0	8.7	1.6	0.8	-	13.1	0.4	52.4
2041	26.8	2.0	9.1	2.6	0.9	-	13.4	0.4	55.2
2042	27.8	2.1	9.5	3.7	0.9	-	13.6	0.4	58.1

2043	28.9	2.2	9.9	4.9	0.9	-	13.7	0.4	61.0
2044	29.9	2.3	10.3	6.2	1.0	-	13.8	0.5	64.0
2045	30.9	2.4	10.7	7.6	1.0	-	13.9	0.5	67.0
2046	31.9	2.5	11.1	9.2	1.1	-	13.8	0.5	70.1
2047	32.9	2.6	11.5	10.8	1.1	-	13.8	0.5	73.2
2048	33.9	2.6	11.9	12.5	1.1	-	13.7	0.5	76.4
2049	34.9	2.7	12.3	14.4	1.2	-	13.5	0.5	79.6
2050	35.9	2.8	12.7	16.4	1.2	-	13.3	0.5	82.9

[4] Annual Energy Generation by Technology in SRE scenario (TWh)

Year	**Large Hydro**	**Small Hydro**	**Solar PV**	**Biomass**	**Wind**	**Coal**	**Natural Gas**	**Oil**	**Total**
2020	5.1	0.2	0.6	-	0.0	-	4.1	0.1	10.1
2021	5.5	0.3	1.0	-	0.1	-	4.5	0.1	11.4
2022	5.9	0.4	1.4	-	0.1	-	4.9	0.1	12.9
2023	6.4	0.5	1.8	-	0.2	-	5.5	0.1	14.4
2024	6.8	0.6	2.2	-	0.2	-	6.2	0.1	16.1
2025	7.2	0.7	2.6	-	0.2	-	6.9	0.1	17.8
2026	7.6	0.8	3.0	-	0.3	-	7.8	0.1	19.6
2027	8.1	0.8	3.4	-	0.3	-	8.7	0.2	21.5
2028	8.5	0.9	3.8	-	0.4	-	9.7	0.2	23.5
2029	8.9	1.0	4.2	-	0.4	-	10.8	0.2	25.5
2030	9.4	1.1	4.6	-	0.4	-	11.9	0.2	27.6
2031	9.8	1.2	5.0	-	0.5	-	13.1	0.2	29.8
2032	10.2	1.3	5.4	-	0.5	-	14.4	0.2	32.1
2033	10.7	1.4	5.8	-	0.6	-	15.8	0.2	34.4
2034	11.1	1.4	6.2	-	0.6	-	17.2	0.3	36.8
2035	11.5	1.5	6.7	-	0.6	-	18.7	0.3	39.3
2036	11.9	1.6	7.1	-	0.7	-	20.2	0.3	41.8
2037	12.4	1.7	7.5	-	0.7	-	21.8	0.3	44.4
2038	12.8	1.8	7.9	-	0.8	-	23.4	0.3	47.0
2039	13.2	1.9	8.3	-	0.8	-	25.1	0.4	49.7
2040	13.7	2.0	8.7	-	0.8	-	26.9	0.4	52.4

2041	14.1	2.0	9.1	-	0.9	-	28.7	0.4	55.2
2042	14.5	2.1	9.5	-	0.9	-	30.6	0.4	58.1
2043	15.0	2.2	9.9	-	0.9	-	32.5	0.4	61.0
2044	15.4	2.3	10.3	-	1.0	-	34.5	0.5	64.0
2045	15.8	2.4	10.7	-	1.0	-	36.6	0.5	67.0
2046	16.2	2.5	11.1	-	1.1	-	38.7	0.5	70.1
2047	16.7	2.6	11.5	-	1.1	-	40.8	0.5	73.2
2048	17.1	2.6	11.9	-	1.1	-	43.0	0.5	76.4
2049	17.5	2.7	12.3	-	1.2	-	45.3	0.5	79.6
2050	18.0	2.8	12.7	-	1.2	-	47.6	0.5	82.9

[5] Annual Energy Generation by Technology in SRE30 scenario (TWh)

Year	Large Hydro	Small Hydro	Solar PV	Biomass	Wind	Coal	Natural Gas	Oil	Total
2020	5.1	0.2	0.6	-	0.0	-	4.1	0.1	10.1
2021	5.5	0.3	1.0	-	0.1	-	4.5	0.1	11.4
2022	5.9	0.4	1.4	-	0.1	-	4.9	0.1	12.9
2023	6.4	0.5	1.8	-	0.2	-	5.5	0.1	14.4
2024	6.8	0.6	2.2	-	0.2	-	6.2	0.1	16.1
2025	7.2	0.7	2.6	-	0.2	-	6.9	0.1	17.8
2026	7.6	0.8	3.0	-	0.3	-	7.8	0.1	19.6
2027	8.1	0.8	3.4	-	0.3	-	8.7	0.2	21.5
2028	8.5	0.9	3.8	-	0.4	-	9.7	0.2	23.5
2029	8.9	1.0	4.2	-	0.4	-	10.8	0.2	25.5
2030	9.4	1.1	4.6	-	0.4	-	11.9	0.2	27.6
2031	9.8	1.2	5.0	-	0.5	-	13.1	0.2	29.8
2032	10.2	1.3	5.4	-	0.5	-	14.4	0.2	32.1
2033	10.7	1.4	5.8	-	0.6	-	15.8	0.2	34.4
2034	11.1	1.4	6.2	-	0.6	-	17.2	0.3	36.8
2035	11.5	1.5	6.7	-	0.6	-	18.7	0.3	39.3
2036	11.9	1.6	7.1	-	0.7	-	20.2	0.3	41.8
2037	12.4	1.7	7.5	-	0.7	-	21.8	0.3	44.4
2038	12.8	1.8	7.9	-	0.8	-	23.4	0.3	47.0

2039	13.2	1.9	8.3	-	0.8	-	25.1	0.4	49.7
2040	13.7	2.0	8.7	-	0.8	-	26.9	0.4	52.4
2041	14.1	2.0	9.1	-	0.9	-	28.7	0.4	55.2
2042	14.5	2.1	9.5	0.2	0.9	-	30.4	0.4	58.1
2043	15.0	2.2	9.9	1.0	0.9	-	31.6	0.4	61.0
2044	15.4	2.3	10.3	1.8	1.0	-	32.8	0.5	64.0
2045	15.8	2.4	10.7	2.6	1.0	-	33.9	0.5	67.0
2046	16.2	2.5	11.1	3.6	1.1	-	35.1	0.5	70.1
2047	16.7	2.6	11.5	4.6	1.1	-	36.2	0.5	73.2
2048	17.1	2.6	11.9	5.7	1.1	-	37.4	0.5	76.4
2049	17.5	2.7	12.3	6.8	1.2	-	38.5	0.5	79.6
2050	18.0	2.8	12.7	8.1	1.2	-	39.5	0.5	82.9

[6] Annual Energy Generation by Technology in SRE40 scenario (TWh)

Year	Large Hydro	Small Hydro	Solar PV	Biomass	Wind	Coal	Natural Gas	Oil	Total
2020	5.1	0.2	0.6	-	0.0	-	4.1	0.1	10.1
2021	5.5	0.3	1.0	-	0.1	-	4.5	0.1	11.4
2022	5.9	0.4	1.4	-	0.1	-	4.9	0.1	12.9
2023	6.4	0.5	1.8	-	0.2	-	5.5	0.1	14.4
2024	6.8	0.6	2.2	-	0.2	-	6.2	0.1	16.1
2025	7.2	0.7	2.6	-	0.2	-	6.9	0.1	17.8
2026	7.6	0.8	3.0	-	0.3	-	7.8	0.1	19.6
2027	8.1	0.8	3.4	-	0.3	-	8.7	0.2	21.5
2028	8.5	0.9	3.8	-	0.4	-	9.7	0.2	23.5
2029	8.9	1.0	4.2	-	0.4	-	10.8	0.2	25.5
2030	9.4	1.1	4.6	-	0.4	-	11.9	0.2	27.6
2031	9.8	1.2	5.0	-	0.5	-	13.1	0.2	29.8
2032	10.2	1.3	5.4	-	0.5	-	14.4	0.2	32.1
2033	10.7	1.4	5.8	-	0.6	-	15.8	0.2	34.4
2034	11.1	1.4	6.2	-	0.6	-	17.2	0.3	36.8
2035	11.5	1.5	6.7	-	0.6	-	18.7	0.3	39.3
2036	11.9	1.6	7.1	-	0.7	-	20.2	0.3	41.8

2037	12.4	1.7	7.5	-	0.7	-	21.8	0.3	44.4
2038	12.8	1.8	7.9	-	0.8	-	23.4	0.3	47.0
2039	13.2	1.9	8.3	0.7	0.8	-	24.4	0.4	49.7
2040	13.7	2.0	8.7	1.6	0.8	-	25.3	0.4	52.4
2041	14.1	2.0	9.1	2.6	0.9	-	26.1	0.4	55.2
2042	14.5	2.1	9.5	3.7	0.9	-	26.9	0.4	58.1
2043	15.0	2.2	9.9	4.9	0.9	-	27.6	0.4	61.0
2044	15.4	2.3	10.3	6.2	1.0	-	28.3	0.5	64.0
2045	15.8	2.4	10.7	7.6	1.0	-	28.9	0.5	67.0
2046	16.2	2.5	11.1	9.2	1.1	-	29.5	0.5	70.1
2047	16.7	2.6	11.5	10.8	1.1	-	30.0	0.5	73.2
2048	17.1	2.6	11.9	12.5	1.1	-	30.5	0.5	76.4
2049	17.5	2.7	12.3	14.4	1.2	-	30.9	0.5	79.6
2050	18.0	2.8	12.7	16.4	1.2	-	31.2	0.5	82.9

[7] Annual Energy Generation by Technology in HRE scenario (TWh)

Year	Large Hydro	Small Hydro	Solar PV	Biomass	Wind	Coal	Natural Gas	Oil	Total
2020	5.1	0.2	0.4	-	0.0	-	4.3	0.1	10.1
2021	5.5	0.2	0.6	-	0.0	-	5.0	0.1	11.4
2022	5.9	0.3	0.8	-	0.1	-	5.7	0.1	12.9
2023	6.4	0.3	1.0	-	0.1	-	6.6	0.1	14.4
2024	6.8	0.4	1.2	-	0.1	-	7.5	0.1	16.1
2025	7.2	0.4	1.4	-	0.1	-	8.6	0.1	17.8
2026	7.6	0.4	1.6	-	0.1	-	9.7	0.1	19.6
2027	8.1	0.5	1.8	-	0.2	-	10.9	0.2	21.5
2028	8.5	0.5	2.0	-	0.2	-	12.1	0.2	23.5
2029	8.9	0.6	2.2	-	0.2	-	13.5	0.2	25.5
2030	9.4	0.6	2.4	-	0.2	-	14.9	0.2	27.6
2031	9.8	0.6	2.6	-	0.2	-	16.4	0.2	29.8
2032	10.2	0.7	2.8	-	0.3	-	17.9	0.2	32.1
2033	10.7	0.7	3.0	-	0.3	-	19.6	0.2	34.4
2034	11.1	0.8	3.2	-	0.3	-	21.2	0.3	36.8

2035	11.5	0.8	3.4	-	0.3	-	23.0	0.3	39.3
2036	11.9	0.8	3.6	-	0.3	-	24.8	0.3	41.8
2037	12.4	0.9	3.8	-	0.4	-	26.7	0.3	44.4
2038	12.8	0.9	4.0	-	0.4	-	28.6	0.3	47.0
2039	13.2	1.0	4.2	-	0.4	-	30.6	0.4	49.7
2040	13.7	1.0	4.4	-	0.4	-	32.6	0.4	52.4
2041	14.1	1.0	4.6	-	0.4	-	34.7	0.4	55.2
2042	14.5	1.1	4.8	-	0.5	-	36.8	0.4	58.1
2043	15.0	1.1	5.0	-	0.5	-	39.0	0.4	61.0
2044	15.4	1.2	5.2	-	0.5	-	41.3	0.5	64.0
2045	15.8	1.2	5.4	-	0.5	-	43.6	0.5	67.0
2046	16.2	1.2	5.6	-	0.5	-	46.0	0.5	70.1
2047	16.7	1.3	5.8	-	0.6	-	48.4	0.5	73.2
2048	17.1	1.3	6.0	-	0.6	-	50.9	0.5	76.4
2049	17.5	1.4	6.2	-	0.6	-	53.4	0.5	79.6
2050	18.0	1.4	6.4	-	0.6	-	56.0	0.5	82.9

Appendix 7: Cumulative Cost of Production Composition (Billion U.S. Dollars)

Category/Scenario	FRE	FRE30	FRE40	SRE	SRE30	SRE40	HRE
Auxiliary Fuel Costs	-	-	-	-	-	-	-
Capital Costs	38.0	38.4	39.0	31.2	31.5	32.2	25.9
Externality Costs	-	-	-	-	-	-	-
Feedstock Fuel Costs	35.2	45.7	63.0	55.9	66.4	83.7	65.5
Fixed O&M Costs	17.6	17.6	17.6	15.8	15.9	15.9	15.1
Stranded Costs	-	-	-	-	-	-	-
Variable O&M Costs	6.9	6.7	6.5	7.0	6.9	6.7	7.8
Total	97.7	108.4	126.3	109.9	120.7	138.5	114.3

Appendix 8: Cumulative Emissions by Fuel Type (Mt CO2e)

Fuel Type/Scenario	FRE	FRE30	FRE40	SRE	SRE30	SRE40	HRE
Biomass	0.00	0.61	1.61	0.00	0.61	1.61	0.00
Coal	4.38	4.38	4.38	4.38	4.38	4.38	4.38
Natural Gas	134.73	122.20	101.55	239.74	227.20	206.55	288.79
Oil	6.48	6.48	6.48	6.48	6.48	6.48	6.48
Total	145.59	133.66	114.01	250.60	238.67	219.02	299.65

Abstract (Korean)

지난 20년 동안 캄보디아의 에너지 수요 급증으로 인해 재래식 전기 발전소에 더해 추가 수입 전기와 함께 배치되었다. 국내 자원 중 석탄 발전소와 대형 수력 발전소가 우세하는 반면 녹색 에너지원은 상대적으로 낮다. 캄보디아의 지속적인 경제 성장과 발전을 위해 저렴한 비용으로 에너지 공급을 보장할 수 있도록 에너지 안보와 환경 배출 감소가 더 높은 우선순위가 되었다. 이러한 문제를 해결함에 있어, 재생 가능 에너지는 지속 가능한 개발과 전기 공급 안보를 위한 장기적인 미래에서 중요한 역할을 한다.

본 연구는 전력 수요 예측에 ARIMA (1,2,2) 모델을 적용한 다음 저배출 분석 플랫폼 (LEAP) 모델을 적용하여 캄보디아의 에너지 혼합에서 재생 가능 에너지 잠재력을 추정하고 분석한다. 국내 재생 가능 자원의 가용성, 재생 가능 에너지 공유 목표 및 배출 감소 목표를 기반으로 재생 가능 자원의 최적 혼합을 결정한다. 기본 시나리오를 제외한 6 개의 시나리오가 만들어진다. 두 가지 시나리오는 재생 가능 에너지 기술 잠재력의 가용성에 중점을 둔다. 다른 두 시나리오는 2050 년의 발전 혼합에서 재생 가능 에너지의 지정된 공유만을 고려하고, 마지막 두 시나리오는 재생 가능 잠재력의 가용성과 발전 혼합에서 재생 가능 에너지의 목표 공유를 결합한다. 용량 확장, 에너지 발전, 비용 및 배출과 같은 LEAP 모델의 결과는 캄보디아의 미래 전력 공급에 대한 변화의 영향을 조사하는 데에 사용된다.

그 결과, 캄보디아의 전력 수요는 2020년 12.12 TWh에서 2050년 87.74 TWh로 증가할 것으로 나타났다. 국내 전력 발전의 경우, 최대 순현재가치를 가진 재생 가능 에너지의 최적 활용에서 재생 가능 에너지 발전은 2030년 6.16 TWh (22.27%), 2040년 13.11 TWh (25%), 2050년 33.14 TWh (40%)에 이를 것으로 예상된다. 나머지 공급은 대부분 천연가스 기반 발전 및 주변 국가로부터의 수입에서 나온다. 가장 시행한 시나리오에 따르면 2050 년 총 설치 용량은 25.05 GW가 될 것이다. 대형 수력 발전소가 우세한 자원이 될 것이고, 그 뒤를 엄청난 태양광발전과 천연 가스가 차지할 것이다. 그러한 발전을 위해 캄보디아는 2050 년까지 1,260 억 달러가 필요하다. 위와 같은 시행은 CO2 등가물 (Mt CO2e)의 1억1885만 메트릭톤의 양으로 온실 가스 배출을 방출하 것이다. 이 경우, 캄보디아는 2030 INDC 배출 감소 목표를 달성 할 수 있다. 재생 가능 에너지 목표와 배출 감소 목표를 모두 성공적으로 달성하기 위해 다양한 조치에서 캄보디아 정부의 역할이 필수적이다. 그러한 개입은 대중의 인식을 높이고, 법적 프레임워크 및 정책 조치를 수립하며, 재생 가능 에너지 기술에 대한 국내외 투자자들의 지원을 구하는 것에서 볼 수 있다.

주요어 : 최적 활용, 재생 가능 에너지, 공급 보안, INDC, 탄소 배출

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