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Article

Sustainable management of energy supplies for Thailand's power generation

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Abstract: We analyze Thailand's projected 2023–2030 energy needs for power generation using a constructed linear programming model and scenario analysis in an attempt to find a formulation for sustainable electricity management. The objective function is modeled to minimize management costs; model constraints include the electricity production capacity of each energy source, imports of electricity and energy sources, storage choices, and customer demand. Future electricity demands are projected based on the trend most closely related to historical data. CO_2 emissions from electricity generation are also investigated. Results show that to keep up with future electricity demands and ensure the country's energy security, energy from all sources, excluding the use of storage systems, will be necessary under all scenario constraints.

Keywords: multi-objective linear programming; optimization problem; electricity generation; CO_2 emissions

1. Introduction

Managing energy supplies for power generation is a crucial issue in the age of environmental challenges. Global electricity demand in 2019 was 22,848 terawatt-hour (TWh), a 1.9% increase from the year before (International Energy Agency: IEA, 2019). A country's electricity consumption growth is generally connected to population and GDP growths (Beretta, 2007). Since 2010, electric energy consumptions by members countries of the Organization for Economic Cooperation and Development (OECD), including the United States, the United Kingdom and Japan, have been decreasing because these countries have begun to shift to a less energy-intensive service economy. In contrast, non-OECD countries such as China, India, Brazil and Egypt have seen power consumption increase about 2% annually due to rapid economic growth and reliance on low-efficiency mass production manufacturing (U.S. Energy Information Administration, 2017). Thailand's power consumption and economic growth are similar to those of the non-OECD countries mentioned above and hence power consumption growth remains high. Literature on the managing electricity generation is summarized in **Table 1**.

Table 1. Summary of literature.

Ref.	**Location**	**Research Approach**	**Model**
Fang et al. (2019)	China	Find optimal solution for electricity generation distribution based on water scarcity and energy resource	Linear programming
Orfanos et al. (2019)	Greece	Investigate the environmental performance of electricity sector by considering various power generation technologies	-
Washburn and Pablo-Romero (2019)	Latin American countries	Analyze measures used to promote renewable energy for electricity generation	-
Afful-Dadzie et al. (2020)	Ghana	Propose a model for policy evaluation to achieve renewable electricity generation target	Mixed-integer linear programming
Muangjai et al. (2020)	Thailand	Estimate the factor cost of electricity generation from renewable energy comprising: 1) natural energy sources (solar, wind and hydro energy), and 2) bioenergy (biomass, biogas, and waste)	Nonlinear model
Wehbe (2020)	Lebanon	Propose economy-and environment-based policies to develop electricity generation scenario by 2030	Linear programming
Gupta et al. (2021)	Canada	Evaluate GHG emissions mitigation, water footprints, and marginal abatement costs of electricity generation decarbonization pathways	Nonlinear model
Kumar et al. (2022)	Thailand	Study effect of a renewable energy policy for electricity generation consisting of three scenarios 1) reduce post-harvest burning 2) follow Alternative Energy Development Policy (AEDP) with a 2036 target and 3) modify AEDP targets by increasing biomass electricity by 50%	Linear system equation
Sahin and Esen (2022)	Turkey	Determine the GHG emission of electricity generation from renewable energy resources	-
Uddin et al. (2023)	Thailand	Explore potential electricity demand drives consisting of 1) industrial production 2) electricity price 3) oil price and 4) energy policies	Statistical model

Over the past several decades, Thailand's electricity demand has been growing at a little over 1200 megawatt (MW) per year (about 4% annually); however, domestic power generation has not fully caught up with demand rises, resulting in power outages in some regions (Zalostiba, 2013). A 2005 blackout incident across southern Thailand caused income losses and economic damage worth an average 28.5 million USD per hour (Sukyod et al., 2012). In 2020, Thailand's highest hourly and total demands were 30,342 MW and 187,047 GWh, respectively, while total domestic energy generation stood at 206,034 GWh (Energy Policy and Planning Office, 2021). From 2010–2017, average domestic generation capacity lagged behind annual demand by 3.45%. The shortfalls were covered by electricity imports from neighboring countries. Economic growth has been a boon to Thailand's energy security (Le and Park, 2021), but as it faces the twin realities of an urgent need for further growth and the looming depletion of conventional energy resources, the country needs to find a prudent formula for managing energy supplies for power generation.

Recent data show Thailand's electricity supplies to be 55% from natural gas, 18% from coal, 10% from renewable energy, 2% from hydro power, 0.4% from crude oil (Energy Policy and Planning Office, 2021) and the remaining 14% imported from neighboring Laos, Myanmar and Malaysia. Natural gas will be running out in 20 years, according to the country's main power producer, the Electricity Generating Authority of Thailand (EGAT) (2022). Electricity generation from natural gas in 2020 was

113859 GWh, down 6.6% from the previous year (Energy Policy and Planning Office, 2021). According to the national Power Development Plan 2018 (PDP 2018), electricity generation from natural gas during 2021-2030 is projected to increase year-on-year by 0.6%, 0.5%, 0.4%, 0.3%, 0.3%, 0.2%, 0.2%, 0.1% and 0.1% (Energy Policy and Planning office, 2018). An immediate shift from natural gas as the main energy source for electricity generation is not feasible and therefore natural gas imports for this purpose are still needed. In 2020, natural gas imports averaged about 1,437 million standard cubic feet per day (MMscfd), up 3.8% from 2019 (Energy Policy and Planning Office, 2021). Given that natural gas is not a "clean" energy source (Moore et al., 2014), other sources of electricity need to be considered.

Coal is Thailand's second-largest energy source for power generation. As coal is the most polluting fossil fuel (Energy Policy and Planning Office, 2021), increasing coal-fired electricity generation would entail heavy environmental costs. Currently, the coal used by Thai power plants is imported because coal from local sources is more polluting (Energy Policy and Planning office, 2018). In 2020, coal-generated electricity amounted to 36,823.17 GWh, up 2.8% from the previous year (Energy Policy and Planning Office, 2021); according to PDP 2018, coal-generated electricity in 2030 will decrease by just 1% compared to 2021 (Energy Policy and Planning office, 2018). Moreover, the International Energy Agency (IEA) predicts that by 2035, the share of coal-fired power generation in Southeast Asia, where Thailand is located, will expand to 50% due to the need for stable and affordable energy sources

Given these issues, the Thai government is trying to shift to more renewable energy. Electricity generation from renewable energy has continuously increased, from 207.12 GWh or 0.24% of domestic demand in 1996 to 20,540.12 GWh or 9.97% of total domestic demand in 2020 (Energy Policy and Planning office, 2021). The number spiked in 2014, rising 9.6% from the previous year to 9025 thousand tons (Department of Renewable Energy Development and Energy Efficiency, 2015). According to the latest available data (2017), the shares of renewable energies in power production are as follows: hydro (28%), solar (28%), wind (14%), bio-mass (21%), biogas (4%), waste (4%), and geothermal energy (< 1%) Under Thailand's Alternative Energy Development Plan 2015 (AEDP2015), electricity generation from renewable sources will account for 15%–20% of domestic energy demand by 2036.

According to the International Energy Agency (2021), carbon from burning biomass will be absorbed by plants as they grow. Burning fossil fuel, on the other hand, increases the total amount of carbon in the biosphere-atmosphere system, exacerbating global warming. However, the unreliability of biomass sources constitutes a big challenge for the promotion and development of biomass-fueled power generation. Thailand is a major agricultural producer and agricultural waste materials can readily be found in every part of the country (Energy Policy and Planning Office, 2008). Biomass supplies are available year-round, but they are scattered around the country making the collection and storage processes inefficient. As a result, biomass power plants are not flexible to peak demands and this energy source has never become a popular option for power generation.

Since 1989, the Thai government has had a policy in place to promote electricity production from renewables (Energy for Environment Foundation, 2011) but in implementing the policy it has faced similar challenges to what China and India have experienced (Iychettira, 2021). From 1998–2003, electricity generation from biomass increased 2%–3% per annum (Energy Policy and Planning Office, 2021). In 2017, biomass accounted for 1908.82 MW of electricity generation. Starting in 2017, Thailand has initiated more projects to establish community biomass electricity generation plants in order to increase both power production and the local populations' income. It is forecasted that by 2036 electricity generation from biomass will reach 5570 MW (Department of Renewable Energy Development and Energy Efficiency, 2015).

Hydropower is the world's most renewable energy source and the least harmful to the environment (Hino and Lejeune, 2012; Mayer et al., 2021). Hydroelectric power plants are known as "peak load plants" because they operate according to demands during peak periods. In 2020, hydropower accounted for 2% of Thailand's total electricity generation (Energy Policy and Planning Office, 2021). According to PDP2015, 4 planned hydro plants are expected to generate 3282.4 MW of electricity by 2036 (Department of Renewable Energy Development and Energy Efficiency, 2015; Energy Policy and Planning office, 2018).

Plants powered by other types of renewable, clean and free energy will generate and distribute electricity whenever that energy source is available. Given the instability of sunlight and wind, however, sometimes these plants are able to operate at full capacity for only 4–5 hours per day (Bangkokbiznews, 2023). Solar and wind energy are currently distributed throughout the country with a generating capacity of 1298.51 MW for solar and 224.47 MW for wind (Energy Policy and Planning office, 2018). Thailand expects that over the next 30 years solar and wind energy will account for 9,002 MW of power production (Energy Policy and Planning office, 2018). Solar and wind offer advantages, but they cannot be harnessed for round-the-clock electricity production. In order to ensure continuous electricity supply, it is necessary to consider energy storage options. Currently, three storage types are in use: Battery Energy Storage, Pumped-Storage and Wind Hydrogen Hybrid (Electricity Generating Authority of Thailand, 2020).

Since domestic electricity generation is inadequate to meet demand, another option is to import electricity from neighboring countries. Electricity imports from Laos, Myanmar and Malaysia cost only 0.06 USD/kW in 2015 compared to 0.09 USD/kW for domestic electricity generation (Energy Policy and Planning Office, 2021). From 2015 to 2017, electricity imports rose by 26.1% annually (Energy Policy and Planning Office, 2021). However, importing electricity or energy sources for electricity generation is not really a self-sustainable option, as illustrated by a 2013 incident where Myanmar halted natural gas supply for 8 days, forcing Thailand to increase domestic generation from diesel and fuel oil and reduce electricity consumption across all sectors (Chokchaichamnankit, 2013). Besides insufficient domestic generation capacity, Thailand has another reason to continue importing electricity: The need to maintain good relations with her neighbors (Energy Policy and Planning office, 2018).

To cover surplus and fluctuating demands, Thailand has proposed a 4-pronged approach consisting of economical and efficient use of electricity, development of primary-fuel power plants, development of renewable-energy power plants, and electricity purchases from neighboring countries (Electricity Generating Authority of

Thailand, 2021). In light of the crucial importance of electricity storage in ensuring effective handling of fluctuating demands and supply efficiency, a number of energy storage projects have been initiated and batteries have been imported to offset the limitations of renewable energy.

This research focuses on electricity management to ensure responsible consumption of energy resources in Thailand. The energy management model shown in the next section seeks to minimize the total cost of energy and fuel consumption over a 1-year planning horizon. This model needs to reflect the country's electricity demand and production capacity. Biomass along with other renewable energy and storage options will be considered as potential fossil-fuel replacements in electricity production. Since the objective function and constraints are linearly related, this problem formulation constitutes linear programming. The details of the model are shown in Section 2.

2. Model formulation

This study aims to propose a formula for minimizing Thailand's total cost of energy and fuel consumption over an 8-year planning horizon from 2023 to 2030. In order to follow the projected electricity demands during the study period, model constraints are set to comprise 4 parts: electricity generation, storage purchase, fuel production, and fuel purchase. Indices, parameters and variables of the constructed model are as follows:

Indices:

Let n_1, n_2, n_3 and m be the number of energy sources, energy storages, energy purchases, and fuel types, respectively.

I is a set of energy sources, $I = \{1,2,3,\dots,n_1\}$.

J is a set of energy storages, $J = \{1,2,3,\dots,n_2\}$.

K is a set of purchased power resources, $K = \{1,2,3,\dots,n_3\}$.

L is a set of fuels for heat generation, transportation, and others, $L = \{1, 2, 3, \dots, m\}$.

Variables:

x_{ij} is the amount of electricity generated from source $i \in I$ at time $j \in t$.

y_{ij} is the amount of electricity stored to storage $i \in J$ at time $j \in t$.

z_{ij} is the amount of electricity purchased from source $i \in K$ at time $j \in t$.

u_{ij} is the amount of produced fuel of type $i \in L$ at time $j \in t$.

v_{ij} is the amount of purchased fuel of type $i \in L$ at time $j \in t$.

q_{ij} is the demand for fuel type $i \in L$ to generate electricity at time $j \in t$.

Parameters:

c_i is the cost of electricity generated from source $i \in I$ (per/unit).

w_i is the cost of electricity stored to storage $i \in J$ (per/unit).

p_i is the cost of electricity purchased from source $i \in K$ (per/unit).

$r1_i$ is the cost of produced fuel of type $i \in L$ (per/unit).

$r2_i$ is the cost of purchased fuel of type $i \in L$ (per/unit).

$s1_i$ is the loss during transportation to customer of electricity generated from source $i \in I$.

$s2_i$ is the loss during transportation to customer of electricity stored to storage $i \in J$.

$s3_i$ is the loss during transportation to customer of electricity purchased from source $i \in K$.

$d1_i$ is the amount of electricity demand at time $i \in t$.

$a1_i$ is the time to transport electricity generated from source $i \in I$ to customer.

$a2_i$ is the time to transport electricity from storage $i \in J$ to customer.

$a3_i$ is the time to transport electricity purchased from source $i \in K$ to customer.

$d2_i$ is the amount of fuel demand for type $i \in L$.

$b1_i$ is the time to transport produced fuel of type $i \in L$ to customer.

$b2_i$, is the time to transport purchased fuel of type $i \in L$ to customer.

$b3_i$ is the time to transport fuel type $i \in L$ for use at electricity generation site.

h_i is the conversion loss of the electricity produced from fuel type $i \in I$.

$Cap\ x_i$ is the electricity generation capacity of source $i \in I$.

Cap_i is the capacity of production from fuel $i \in L$.

2.1. Model

The model described below is constructed as an LP model corresponding to the government's proposed plan to adequately provide electricity for domestic needs.

2.1.1. The objective function

We will consider the objective function to minimize the cost of managing energy and fuel consumption in the stated time horizon, which consists of 5 parts:

1) The total cost of electricity generated from generation sources in I at time $j \in t$ is written as $F_1 = \sum_{i \in I} \sum_{j \in t} c_i x_{ij}$.

2) The total cost of electricity stored in the storages in J at time $j \in t$ is written as $F_2 = \sum_{i \in J} \sum_{j \in t} w_i y_{ij}$.

3) The total cost of electricity imported from the countries in K at time $j \in t$ is written as $F_3 = \sum_{i \in K} \sum_{j \in t} p_i z_{ij}$.

4) The total cost of produced fuel in L at time $j \in t$ is written as $F_4 = \sum_{i \in L} \sum_{j \in t} r1_i u_{ij}$.

5) The total cost of purchased fuel in L at time $j \in t$ is written as $F_5 = \sum_{i \in L} \sum_{j \in t} r2_i v_{ij}$.

Therefore, the objective function of this study is

$$min\,(F_1 + F_2 + F_3 + F_4 + F_5) \tag{1}$$

2.1.2. Constraints

The 8 sets of constraints are as follows:

- Electricity demand constraints

Since $a1_i$ is the lead time to transport the electricity generated from source $i \in I$, and t is the time that the customer requests for the electricity, we have $k1_i = t - a1_i$ as the time to produce the electricity. Since the electricity generated from each source $i \in I$ at time $j \in t$ is denoted as x_{ij} with $s1_i$ being the line loss of electricity generated from source $i \in I$, the electricity obtained from source $i \in I$ at period t will be produced at the time $k1_i$ which can be written as $s1_i x_{i,k1_i}$.

Since $a2_i$ is the lead time to transport the electricity from storage $i \in J$ and t is the time that the customer requests for the electricity, we have $k2_i = t - a2_i$ as the time to release the electricity stored in storage $i \in J$ to the customer. Since the electricity stored in storage $i \in J$ at time $j \in t$ is denoted as y_{ij} and $s2_i$ is the line loss during transportation to customer of electricity stored of storage $i \in J$, electricity obtained from storage $i \in J$ will be released to the customer at time $k2_i$, that is $s2_i y_{i,k2_i}$.

Similarly, electricity imported from source $i \in K$ will be released to the customer at time $k3_i$, that is $s3_i z_{i,k3_i}$.

Since the electricity supply from all sources combined must be enough to meet the demand of that period, the sum of generated, stored and purchased electricity available at the period $j \in t$ must be greater than that period's electricity demand. Therefore,

$$\sum_{i \in I} s1_i x_{ij} + \sum_{i \in J} s2_i y_{ij} + \sum_{i \in K} s3_i z_{ij} \geq d1_j \tag{2}$$

- Generation capacity

To ensure that electricity generated from source $i \in I$ at time $j \in t$ cannot be greater than the source capacity, we write

$$x_{ij} \leq Cap\, x_i,\ i \in I. \tag{3}$$

- Fuel demand as heat generation

We have $l1_i = t - b1_i$ as the time to produce the fuel type $i \in L$. Since the fuel produced from each source $i \in L$ at time $j \in t$ is denoted as u_{ij}, the fuel obtained from source $i \in L$ at period t will be produced at the time $l1_i$ which can be written as $u_{i,l1_i}$. Similarly, the fuel purchased from source $i \in L$ will be released to the customer at the time $l2_i$, that is, the amount of purchased fuel at time t is equal to $v_{i,l2_i}$.

Since the combined amount of fuel must cover the fuel demand in the same period $j \in t$ to be used as heat generation, this constraint can be written as

$$u_{i,l1_i} + v_{i,l2_i} \geq d2_{ij},\ i \in L. \tag{4}$$

- The conversion loss of its generation type

Let $l3_i = t - b3_i$ be the time to generate electricity of fuel type $i \in L$. Since the fuel demand for type $i \in L$ at time $j \in t$ is denoted as q_{ij}, the fuel needed to generate electricity available at period t will be denoted as $q_{i,l3_i}$.

Since the electricity generation from each fuel at time $j \in t$ has the conversion loss of electricity produced from fuel of each source $i \in I$, we can write this constraint as

$$x_{ij} = h_i q_{i,l3_i},\ i \in I. \tag{5}$$

- Production capacity

To ensure that fuel of type $i \in L$ at time $j \in t$ cannot be produced at more than its production capacity at the time, we have

$$u_{ij} \leq Cap_i,\ i \in L. \tag{6}$$

- Fuel demand for electricity generation

Let $l1_i = t - b1_i$ be the time to produce the fuel type $i \in L$. Since the fuel produced from each source $i \in L$ at time $j \in t$ is denoted as u_{ij}, the fuel obtained from source $i \in L$ at period t will be produced at time $l1_i$ which can be written as $u_{i,l1_i}$.

Similarly, the fuel purchased from source $i \in L$ will be released to the customer at the time $l2_i$ that is, the amount of purchased fuel at time t is equal to $v_{i,l2_i}$.

Since the sum of produced and purchased fuel of each type $i \in L$ has to exceed the fuel demand for electricity generation in each period $j \in t$, we write this constraint as

$$u_{i,l1_i} + v_{i,l2_i} \geq d2_{ij} + q_{ij},\ i \in L. \tag{7}$$

- Variable boundary constraints: The amount of electricity produced, stored and purchased, and amount of fuel produced and purchased cannot be negative in each period $j \in t$. Therefore, $x_{ij}, y_{ij}, z_{ij}, u_{ij}, v_{ij}, q_{ij} \geq 0$.

The model representing Thailand's electricity management during the period 2023–2030 can be stated as linear programming with the objective to minimize the total cost of electricity generation, purchase, storage, fuel production and fuel purchase. The constraints in this model comprise 8 parts, which can be summarized as:

$$\min \sum_{i\in I}\sum_{j\in t} c_i x_{ij} + \sum_{i\in J}\sum_{j\in t} w_i y_{ij} + \sum_{i\in K}\sum_{j\in t} p_i z_{ij} + \sum_{i\in L}\sum_{j\in t} r1_i u_{ij} + \sum_{i\in L}\sum_{j\in t} r2_i v_{ij}$$

Subject to

$$\sum_{i\in I} s1_i x_{ij} + \sum_{i\in J} s2_i y_{ij} + \sum_{i\in K} s3_i z_{ij} \geq d1_j$$
$$x_{ij} \leq Cap\, x_i,\ i \in I$$
$$u_{i,l1_i} + v_{i,l2_i} \geq d2_{ij},\ i \in L$$
$$x_{ij} = h_i q_{i,l3_i},\ i \in I$$
$$u_{ij} \leq Cap_i,\ i \in L$$
$$u_{i,l1_i} + v_{i,l2_i} \geq d2_{ij} + q_{ij},\ i \in L$$
$$x_{ij}, y_{ij}, z_{ij}, u_{ij}, v_{ij}, q_{ij} \geq 0$$

3. Data collection and case study

Thailand's electricity management is explored to help increase electricity supply efficiency. We consider hydro power, wind, solar, geothermal power, biomass, solid waste, biogas, natural gas, fuel oil, coal, and diesel, all 11 possible electricity generation sources in the country. We also include electricity storage sources from batteries and electricity imports from Laos, Myanmar and Malaysia in the study. Fuel consumption, most of which is for electricity production, is also illustrated. Domestic and imported generation sources in this study include biomass, biogas, natural gas, fuel oil, coal, diesel, LPG and gasohol.

3.1. Costs

The costs of generating electricity from geothermal resources, waste, natural gas, fuel oil, coal (Sirianuntapiboon et al., 2012) and diesel are summarized in **Table 2**. The cost of hydroelectric, wind and solar generation ranged from 0.03–0.6 USD/kW, 0.14–0.26 USD/kW and 0.18–0.22 USD/kW, respectively (Mulugetta et al., 2007) while that of biomass and biogas electricity generation ranged from 0.18–0.22

USD/kW and from 0.09–0.12 USD/kW, respectively (Kittiyarangsit, 2011). Shown in columns 2 and 3 of **Table 2** are their assigned parameters and the average numbers of these figures, respectively. The line loss of all generated electricity ranged between 5.6950%–6.9446% and averaged out at 6.32%, as shown in column 5 of **Table 2** (International Energy Agency: IEA, 2014). The conversion losses of electricity generation from each source are summarized in the last column of **Table 2** (Energy Policy and Planning Office, 2021).

The cost of biomass, natural gas, fuel oil, diesel, LPG, and gasoline production are 31.88–35.07 USD/ton, 3.57–5.43 USD/million BTU, 0.33–0.39 USD/l, 0.44–0.66 USD/l, 0.39–054 USD/l, and 0.44–0.73 USD/l, respectively (Ministry of Energy, 2022). Shown in columns 2 and 3 of **Table 3** are their assigned parameters and the average values of these figures, respectively. The costs of importing biomass, natural gas, fuel oil, diesel, LPG, and gasoline range from 31.88–35.07 USD/ton, 4.97–5.43 USD/million BTU, 0.38–0.46 USD/l, 0.54–0.56 USD/l, 0.58–0.80 USD/l, and 0.46–1.04 USD/l respectively (Energy Policy and Planning Office, 2022) with the averages shown in **Table 3**. All other costs of fuel production and imports as well as fuel production capacity are also shown in **Table 3**.

Table 2. The costs of generating electricity from different energy sources, the line losses of generated electricity, the conversion losses of electricity generation and their assigned parameters in the model.

	Cost of generating electricity		**Line losses of generated electricity**		**Conversion losses of electricity generation**	
	Parameters	**Value**	**Parameters**	**Value**	**Parameters**	**Value**
		(10^2 USD/kW)		**(%)**		**(%)**
Hydro	c_1	4.27	$s1_1$	6.32	h_1	37.50
Wind	c_2	9.96	$s1_2$	6.32	h_2	15.00
Solar	c_3	20.37	$s1_3$	6.32	h_3	15.00
Biomass	c_4	2.76	$s1_4$	6.32	h_4	75.00
Biogas	c_5	8.80	$s1_5$	6.32	h_5	7.00
Natural gas	c_6	9.85	$s1_6$	6.32	h_6	85.00
Fuel oil	c_7	5.32	$s1_7$	6.32	h_7	85.00
Coal	c_8	19.96	$s1_8$	6.32	h_8	85.00
Diesel	c_9	8.64	$s1_9$	6.32	h_9	85.00
Geothermal	c_{10}	6.31	$s1_{10}$	6.32	h_{10}	15.00
Solid waste	c_{11}	14.76	$s1_{11}$	6.32	h_{11}	7.00

The cost of battery storage is 200 USD/kW (Schmidt et al., 2017). The line losses of all generated electricity ranging from 5.6950%–6.9446% and averaging 6.32%, are used in this study (International Energy Agency: IEA, 2014). The costs of stored electricity and the line loss of stored electricity from batteries are summarized in **Table 4**. Usually, the depreciation costs of batteries are at 20% of the installation cost, but we did not include the depreciation costs in the model. The cost of purchasing electricity from neighboring countries will not exceed 0.09 USD/kW under agreements between Thailand and those countries (Department of Renewable Energy Development and Energy Efficiency, 2015). The cost of electricity imports used in this study, 0.06 USD/kW, is taken from 2015 figures (Energy Policy and Planning Office, 2021).

Note that in further analysis, other related costs can be included. However, it is reasonable to make all units similar.

Table 3. The costs of fuel production and imports, and the fuel production capacity and their corresponding parameters.

	Cost of fuel					**Fuel production capacity**		
	Fuel production		**Fuel imports**		**Units**			
	Parameters	**Value**	**Parameters**	**Value**		**Parameters**	**Value**	**Units**
Biomass	$r1_1$	42.47	$r2_1$	42.47	USD/ton	Cap_1	6.54×10^4	kg
Biogas	$r1_2$	42.47	$r2_2$	42.47	USD/km^3	Cap_2	369.80	m^3
Natural gas	$r1_3$	5.01	$r2_3$	6.07	USD/mBTU	Cap_3	9.73×10^7	BTU
Fuel oil	$r1_4$	0.52	$r2_4$	0.42	USD/l	Cap_4	2.74×10^7	liter
Coal	$r1_5$	56.73	$r2_5$	62.18	USD/ton	Cap_5	1.98×10^7	kg
Diesel	$r1_6$	0.49	$r2_6$	0.49	USD/l	Cap_6	1.21×10^9	liter
LPG	$r1_7$	0.32	$r2_7$	0.32	USD/l	Cap_7	2.21×10^6	liter
Gasohol	$r1_8$	0.56	$r2_8$	0.56	USD/l	Cap_8	4.66×10^8	liter

Table 4. Parameters for energy storage system.

	Battery
Cost of electricity storage	w_1
Value (USD/kW)	200
Line loss of stored electricity	$s2_1$
Value (%)	6.32

3.2. Demands and demand projection

To test the model, data on 15-minute domestic electricity demands in the year 2019 was obtained from the Energy Technology for Environment Research Center (ETE), a specialized research center integrating knowledge on energy and environment. By solving our constructed model, we can see that in order to meet the 15-minute demands, electricity from all sources need to be generated at full capacity and electricity imports from Malaysia need to be at full capacity as well. Not only that, but in order to avoid blackouts, an electricity storage system in the form of batteries will also be needed to meet 15-minute demands. Details of electricity generation to meet 15-minute demands for the year 2019 are shown in **Table 5**. Phusanti et al. (2020) shows that to meet 15-minute and hourly electricity demands of a small but high-consumption study area, the same combination of renewable energy and fossil fuels may be adequate, but to meet daily, weekly and monthly demands, a more varied combination of energy sources will be needed. However, in order to solve the model having 15-minute demands for a 1-year horizon, the problem would involve 1.2 million variables and constraints. Therefore, monthly demand data will be investigated instead.

Electricity demands during the years 1996–2020 are obtained from Energy Statistics of Thailand 2021 (Energy Policy and Planning Office, 2021). To determine future electricity demand, we derive an equation related to said demand. Three equations are of interest to us: linear, exponential and logistic equations. A linear equation, $y = (5.31 \times 10^3)t + (7.15 \times 10^4)$, will be used to project electricity demand because of its minimum error to the real data. Electricity demand data from the years 1996–2020 and their best fitted curve are shown in **Figure 1**. Future monthly demands are estimated from the projected annual demand using the current monthly: annual demand ratio.

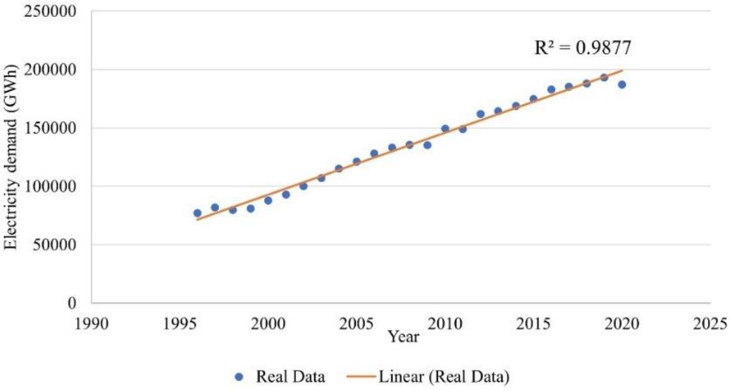


Figure 1. Electricity demand data and their best fitted curve.

Table 5. Monthly electricity generation to meet 15-minute demands in the year 2019.

Month	**Energy source (kW)**												
	Hydro	**Wind**	**Solar**	**Biomass**	**Biogas**	**Natural gas**	**Fuel oil**	**Coal**	**Diesel**	**Geo**	**Waste**	**Imports**	**Storage**
	10^8	**10^8**	**10^8**	**10^8**	**10^7**	**10^{10}**	**10^9**	**10^8**	**10^6**	**10^1**	**10^7**	**10^9**	**10^9**
1	6.43	6.26	3.13	4.70	8.93	0.93	1.87	0.13	7.29	0.30	8.93	1.74	0.00
2	6.25	5.16	2.58	3.87	7.37	0.93	2.57	0.72	7.69	0.30	7.37	1.84	0.00
3	6.86	6.12	3.06	4.59	8.73	1.10	3.20	1.44	4.79	0.30	8.73	2.18	0.32
4	6.20	5.53	2.76	4.14	7.88	1.09	3.17	1.44	4.34	0.30	7.88	2.05	0.14
5	6.35	5.66	2.83	4.25	8.08	1.18	2.60	1.68	5.03	0.30	8.08	2.04	0.00
6	5.43	5.96	2.98	4.47	8.50	1.07	2.46	1.46	4.36	0.30	8.51	2.07	0.00
7	5.51	6.29	3.14	4.71	8.97	1.02	3.28	1.58	85.50	0.30	8.97	1.98	0.00
8	4.01	6.40	3.20	4.80	9.12	0.93	3.05	1.43	4.20	0.30	9.13	2.94	0.99
9	3.49	5.53	2.77	4.15	7.89	0.94	2.92	0.00	3.43	0.30	7.89	2.68	1.18
10	4.23	5.15	2.57	3.86	7.35	1.06	3.10	0.00	2.47	0.30	7.35	2.42	0.95
11	4.38	5.31	2.65	3.98	7.57	1.07	1.81	0.00	3.85	0.30	7.57	1.54	0.00
12	3.96	6.85	3.43	5.14	9.78	0.89	1.69	0.00	4.32	0.30	9.78	2.07	0.00

3.3. Fuel consumption

In determining fuel consumption for electricity generation from various energy sources, we will use a linear equation to estimate the consumption of electricity from fuel oil, and a logistic equation to estimate the consumption of electricity from natural gas, coal, and renewable energy, as they generate the highest R-squared values. **Figure 2a–d** shows data on (a) fuel oil, (b) natural gas, and (c) coal consumptions for electricity consumption and (d) electricity generation from renewable energy during the same period and their best fitted curves. Unlike future monthly demands, future monthly fuel consumptions are estimated based on the scenarios in this study.

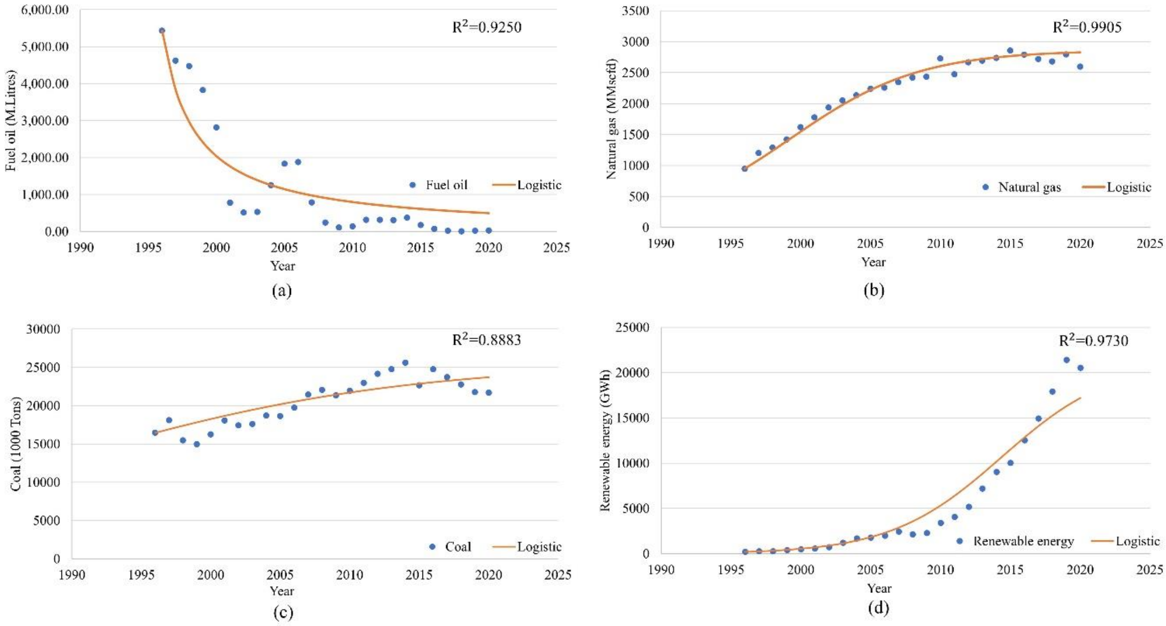


Figure 2. Fuel consumption for electricity generation and their best fitted curves, **(a)** fuel oil; **(b)** natural gas; and **(c)** coal and electricity generation data and their best fitted curves; **(d)** renewable energy.

3.4. Electricity generation capacity

In our analysis, we assume the current electricity capacity of each source. Thailand generates electricity from fossil fuels in the industrialized central and eastern regions. **Figure 3** shows map of Thailand, the study region, and **Figure 4a** shows current electricity generation sites and capacity from various fuel sources in the country. Figures shown are the current capacity while those in parenthesis are projected future capacities. According to the Power Development Plan 2018, 6 more generation sites, also shown in **Figure 4a**, will be built. **Figure 4b** shows electricity generation sites as well as their current and projected future capacities from renewable energy. Hydro energy from dams located around the country accounts for most of the generation capacity from renewable energy. Geothermal energy is currently being produced from a single plant in Fang District of the northern province of Chiang Mai, which has the highest heat source concentration. EGAT expects other potential sites to contribute to domestic electricity generation in the future. The future capacities from each source will be followed in each study scenario.

Figure 3. Thailand's geographical location (adapted and modified from Finwise (2023)).

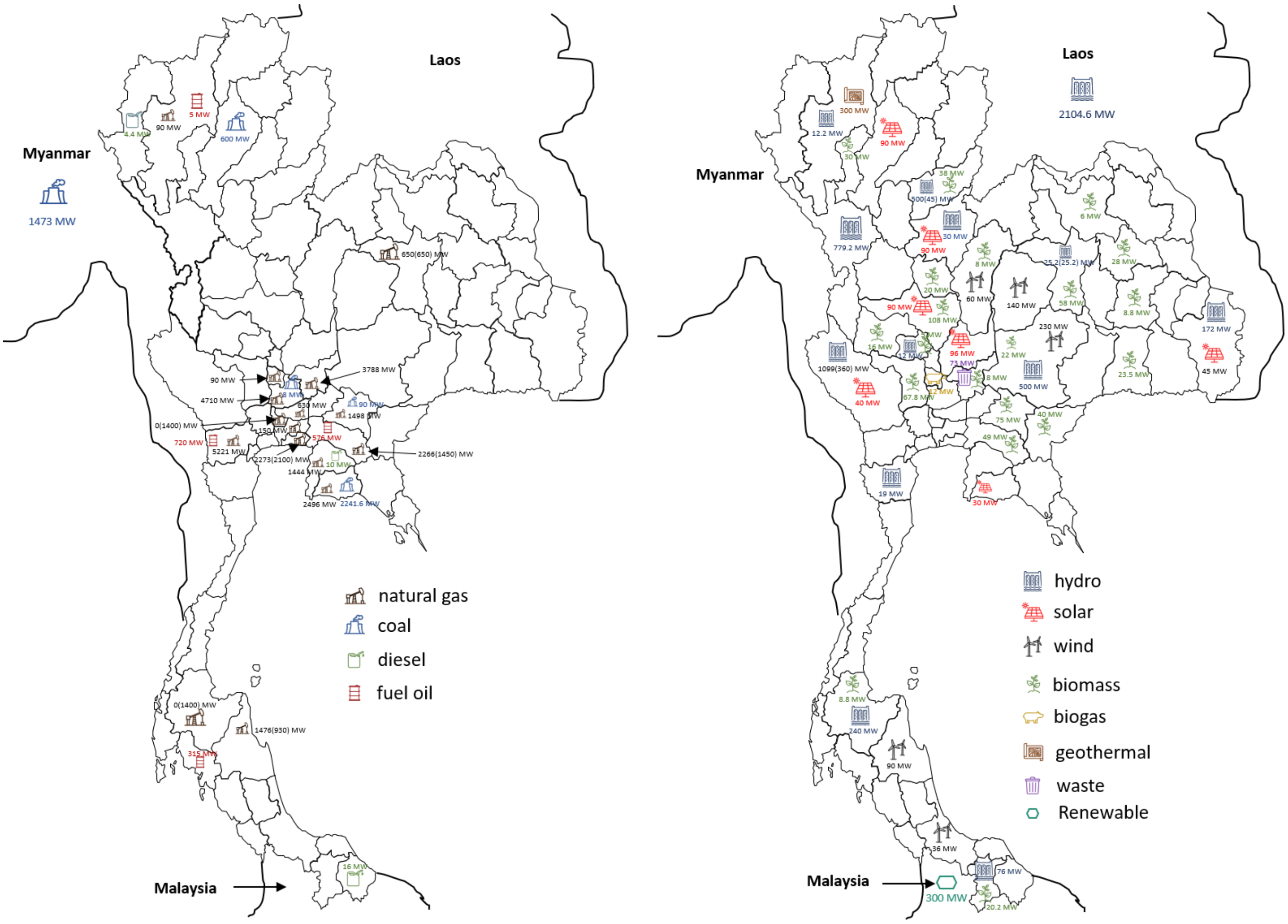


Figure 4. Electricity generation sites and current (future) generation capacity from **(a)** fossil fuels and **(b)** renewable energy.

4. Scenario analysis

To investigate Thailand's energy generation plan, a linear programming model as constructed in Section 2 is solved according to our objective, to minimize the cost of energy and fuel consumption over a 1-year planning horizon using the projected monthly demand data. The optimal plans for energy generation in Thailand during 2023–2030 are solved using IBM ILOG CPLEX Optimization Studio (CPLEX).

Energy sources considered in the model include hydro power, wind, solar, geothermal power, biomass, solid waste, biogas, natural gas, fuel oil, coal and diesel. Since Thailand's current energy storage system is battery, the only energy storage included in this model takes the form of batteries. Electricity imports will come from Malaysia. Fuels for heat generation include biomass, biogas, natural gas, fuel oil, coal, diesel, LPG and gasohol.

As electricity demand in Thailand has been rising steadily at 3.8% per year, we need to consider electricity generation from other sources. According to the Energy Policy and Planning Office (2018), natural gas and crude oil reserves in the Gulf of Thailand will be running out in 20 and 40 years, respectively. Given that these fuels are currently the main energy sources for electricity generation, we are interested in analyzing their consumption for this purpose. Another alternative considered to is renewable energy, a clean and logical supplement to natural gas and crude oil. In this research, we analyze four scenarios: Business as Usual (BaU), Government Proposal (GP), Resource Depletion (RD) and Sustainable Management (SM) scenarios. In each of these, electricity demand follows the current trend. Consumptions of all types of fossil fuels and renewable energy in the BaU scenario follow the current trends while those in the GP scenario follow government policy. In RD scenario, electricity from all sources except natural gas, crude oil and hydro are expected to follow current trends; the three exceptions will be capped according to their limits. Natural gas and crude oil are limited to their future capacity in the Gulf of Thailand while hydroelectric capacity follows the government policy on dam water releases just as in the GP scenario, because hydropower is dependent on the amount of water remaining in dams each year as well as the water needs of the farming sector. However, the hydropower of the BaU scenario follows the same trend as renewable energy. In the SM scenario, we will consider CO_2 emissions of electricity generation from all resources as additional costs to the objective function. The CO_2 emitted will be converted to US dollars, the same unit as other costs in the objective functions. All demands and supplies in this scenario follow the current trends similar to those in BaU scenario.

4.1. Business as usual (BaU) scenario

In the BaU scenario, we let every aspect remain at the same rate throughout the analysis years. With the highest correlation, the linear equation will be used to fit electricity demand data during 1996–2020. We found that Thailand's electricity demand has been increasing at the constant rate of 3.8% per year. We also found from the data for 1996–2020 that electricity generated from natural gas, fuel oil, coal and renewable energy are governed by logistic equations as the variables shown in the model as:

$x_{6t} = (2.71 \times 10^6)/(948 + (1.91 \times 10^3)e^{-0.21t})$,

$x_{7t} = (4.26 \times 10^4)/\left((5.43 \times 10^3) - (5.42 \times 10^3)e^{-(6.04\times10^{-4})t}\right)$,

$x_{8t} = (4.22 \times 10^8)/((1.65 \times 10^4) + (9.14 \times 10^3)e^{-0.08t})$,

and $x_{11t} = (4.43 \times 10^6)/((2.07 \times 10^2) + (2.12 \times 10^4)e^{-0.25t})$,

respectively. We can see that increases in electricity generation from renewable energy are higher than those from fossil fuels. These projections and rates will be used to analyze the electricity generation plan for 2023–2030. Electricity management based on this scenario is shown in **Table 6**. Under this scenario, electricity generation will be from all sources except solar and storage since their cost are relatively high and the demands can be covered by the capacities of other sources. Electricity generation from hydro, wind, biomass, biogas and geothermal will increase at the annual rate of 4.13%, 13.87%, 16.97%, 18.50% and 16.96% respectively, while that from natural gas will increase at 2.39% per year and imported electricity will increase at 4.97% per year. In addition, electricity generation from fuel oil, coal and diesel will decrease at 2.98%, 35.79% and 3.64% per year, respectively. This is a sign that we are naturally converting to renewable energy and trying to be energy self-sustainable.

Table 6. Annual electricity generation under monthly demand—BaU Scenario (kWh).

Year	**Energy sources (kWh)**												
	Hydro	**Wind**	**Solar**	**Biomass**	**Biogas**	**Natural gas**	**Fuel oil**	**Coal**	**Diesel**	**Geo**	**Waste**	**Imported**	**Storage**
	10^9	**10^9**	**10^8**	**10^{10}**	**10^9**	**10^{11}**	**10^8**	**10^{10}**	**10^7**	**10^6**	**10^8**	**10^{10}**	**10^8**
2023	7.33	6.58	0.00	0.98	1.30	1.48	4.46	2.75	4.45	1.46	1.88	2.59	0.00
2024	7.64	7.85	0.00	1.18	1.57	1.52	4.31	2.44	4.27	1.46	2.24	2.71	0.00
2025	7.94	9.32	0.00	1.39	1.88	1.55	4.18	2.07	4.10	1.46	2.66	2.82	0.00
2026	7.94	10.99	0.00	1.65	2.24	1.59	4.05	1.64	3.95	1.46	3.14	2.93	0.00
2027	8.54	12.88	0.00	1.93	2.66	1.62	3.93	1.16	3.80	1.46	3.51	3.04	0.00
2028	8.84	14.66	0.00	2.24	3.14	1.66	3.82	0.68	3.67	1.46	3.65	3.15	0.00
2029	9.15	16.06	0.00	2.59	3.68	1.70	3.71	0.27	3.55	1.46	3.19	3.26	0.00
2030	9.45	16.17	0.00	2.95	4.28	1.73	3.61	0.07	3.43	1.46	1.44	3.37	0.00

4.2. Government proposal (GP) scenario

In the GP scenario, we are interested in analyzing electricity generation from fossil fuel and renewable energy with the capacities projected in the government's plan, PDP2018. Since coal-fueled power generation releases greenhouse gases to the atmosphere, the plan is for this type of power production to decline sharply in 2025 and then increase slowly from 2026–2030 before dropping in 2030 to 11.91% below the current level. Electricity generation from hydro, diesel, and geothermal electricity during 2023–2030 will be at their full capacities of 3105, 60 and 0.3 MW, respectively. Electricity imports during these years will also be at full capacity, from 4762–6162 MW. Electricity generation from biogas and natural gas will increase about 6.86% and 2.26% per year, respectively, while electricity generation from fuel oil fluctuates but generally decreases annually at the average rate of 2.97%, with a constant rate during the last 3 analysis years. Annual electricity generation to meet monthly demands in this scenario are summarized in **Table 7**.

Table 7. Annual electricity generation under monthly demand—GP Scenario (kWh).

Year	**Energy source (kWh)**												
	Hydro	**Wind**	**Solar**	**Biomass**	**Biogas**	**Natural gas**	**Fuel oil**	**Coal**	**Diesel**	**Geo**	**Waste**	**Imports**	**Storage**
	10^{10}	10^{9}	10^{9}	10^{10}	10^{9}	10^{11}	10^{10}	10^{10}	10^{8}	10^{6}	10^{8}	10^{10}	10^{8}
2023	2.72	0.00	0.00	2.29	4.57	1.18	1.42	0.00	5.26	2.63	0.00	4.17	0.00
2024	2.72	0.00	0.00	2.27	4.96	1.24	1.42	0.00	5.26	2.63	0.00	4.17	0.00
2025	2.72	0.00	0.00	2.21	5.35	1.36	0.79	0.00	5.26	2.63	0.00	4.17	0.00
2026	2.72	0.00	0.00	2.19	5.73	1.35	0.79	0.00	5.26	2.63	0.00	4.78	0.00
2027	2.72	0.00	0.00	2.23	6.12	1.43	0.53	0.00	5.26	2.63	0.00	4.78	0.00
2028	2.72	0.00	0.00	2.37	6.50	1.43	0.28	0.00	5.26	2.63	0.00	5.40	0.00
2029	2.72	0.00	0.00	2.55	6.89	1.47	0.28	0.00	5.26	2.63	0.00	5.29	0.00
2030	2.72	0.00	0.00	2.73	7.28	1.51	0.28	0.00	5.26	2.63	0.00	5.29	0.00

4.3. Resource depletion (RD) scenario

In contrast to previous scenarios where natural gas and crude oil in the Gulf of Thailand can be extracted indefinitely, we attempt to reduce electricity generation from natural gas and crude oil to make these resources last as long as possible. As a result, each year's use of natural gas, fuel oil, coal and diesel for electricity generation will be reduced to 90 percent of the current trends. Recall that these trends are governed by logistic equations for natural gas, fuel oil, and diesel, and by linear equation for coal. Electricity generation from all other sources are limited according to the PDP2018 plan. Electricity demands in this scenario are covered by all sources except solar, coal and storage since their electricity generation costs are relatively high.

Electricity generation in this scenario is similar to the GP scenario but different from the BaU scenario. Here, electricity from waste is utilized and diesel is reduced as an energy source. Electricity from wind and biomass will be fluctuating but that from biogas will generally increase at 6.86%. Electricity from biogas will also increase at the same rate as in the GP scenario, 6.86% per year, while electricity from fossil fuels—fuel oil and diesel—will decrease at 2.98% and 3.64%, respectively. Electricity generation from 7 sources, hydro, biomass, biogas, natural gas, fuel oil, diesel and geothermal, will be at the full capacity allowed. Hydroelectric production will be limited to the same level as in the GP scenario. Electricity from waste will come in only during the first half of the analysis years because demand will shift to lower-cost imported electricity. Storage will not be utilized in a similar manner to all other scenarios because of its relatively high cost. See details of electricity generation under RD scenario in **Table 8**.

Table 8. Annual electricity generation under monthly demand—RD Scenario (kWh).

	Energy sources (kWh)												
Year	**Hydro**	**Wind**	**Solar**	**Biomass**	**Biogas**	**Natural gas**	**Fuel oil**	**Coal**	**Diesel**	**Geo**	**Waste**	**Imported**	**Storage**
	10^{10}	**10^{9}**	**10^{9}**	**10^{10}**	**10^{9}**	**10^{11}**	**10^{8}**	**10^{10}**	**10^{7}**	**10^{6}**	**10^{8}**	**10^{10}**	**10^{10}**
2023	2.72	2.20	0.00	2.29	4.57	1.30	4.01	0.00	4.00	2.63	0.00	4.17	0.00
2024	2.72	3.26	0.00	2.27	4.96	1.35	3.88	0.00	3.84	2.63	1.75	4.17	0.00
2025	2.72	4.55	0.00	2.21	5.35	1.39	3.76	0.00	3.69	2.63	4.09	4.17	0.00
2026	2.72	2.59	0.00	2.19	5.73	1.41	3.65	0.00	3.55	2.63	0.04	4.78	0.00
2027	2.72	3.34	0.00	2.23	6.12	1.45	3.54	0.00	3.43	2.63	1.68	4.78	0.00
2028	2.72	1.17	0.00	2.37	6.50	1.45	3.44	0.00	3.30	2.63	0.00	5.40	0.00
2029	2.72	1.60	0.00	2.55	6.89	1.49	3.34	0.00	3.19	2.63	0.00	5.29	0.00
2030	2.72	1.71	0.00	2.73	7.28	1.52	3.25	0.00	3.09	2.63	0.00	5.29	0.00

4.4. Sustainable management (SM) scenario

In the SM scenario, we let every aspect be as projected in the BaU scenario, with the exception that the costs in the objective function will include CO_2 elimination cost. Since electricity generation emits CO_2 and other greenhouse gases into the atmosphere regardless of energy source, the CO_2 emission will be converted to USD using figures in IPCC (2005) and Environment for Development (2014). The CO_2 emissions for each generation are taken from Yasukawa and Anbumozhi (2018). The cost of CO_2 capture is defined as

The cost of CO_2 capture = ($COE_{cap} - COE_{ref}$)/(the total mass CO_2 captured per kWh)

where COE_{cap} is the cost of electricity with CO_2 capture, COE_{ref} is the cost of electricity without CO_2 capture.

These figures are summarized in **Table 9**. We can see that the cost of CO_2 emissions per kWh after conversion to USD, even the highest cost from coal-fired generation, is relatively low. Consequently, even with CO_2 emissions taken into account, electricity generation from various sources are similar to those in BaU scenario. However, some generation shifted from coal to solar energy to reduce the cost of CO_2 emissions. In fact, electricity generation from wind and biomass increases at 16.70% and 2.52% per year, while solar and coal-fired generation decreases at 25.89% and 54.17% per year, respectively. See details of electricity generation in SM scenario in **Table 10**.

Table 9. Cost of CO_2 elimination.

	CO_2 Emission Factor	**Cost of CO_2 Capture**
	kg-CO_2/kWh	**USD/kg-CO_2**
Hydro	0.01	0.00
Wind	0.01	0.00
Solar	0.03	0.00
Biomass	0.03	0.00

Table 9. (*Continued*).

	CO_2 Emission Factor	Cost of CO_2 Capture
	kg-CO_2/kWh	USD/kg-CO_2
Biogas	0.04	0.00
Natural gas	0.44	0.05
Fuel oil	0.78	0.09
Coal	1.00	0.12
Diesel	0.78	0.09
Geothermal	0.01	0.00
Waste	0.03	0.00
Import	0.39	0.05
Storage	0.01	0.00

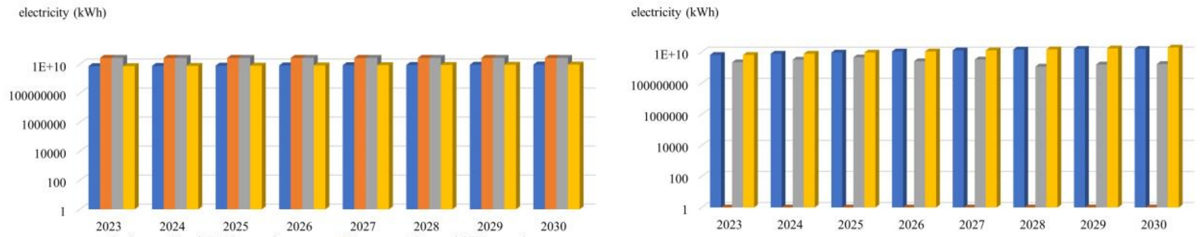
Source: Yasukawa and Anbumozhi (2018).

Table 10. Annual electricity generation under monthly demand—SM Scenario (kWh).

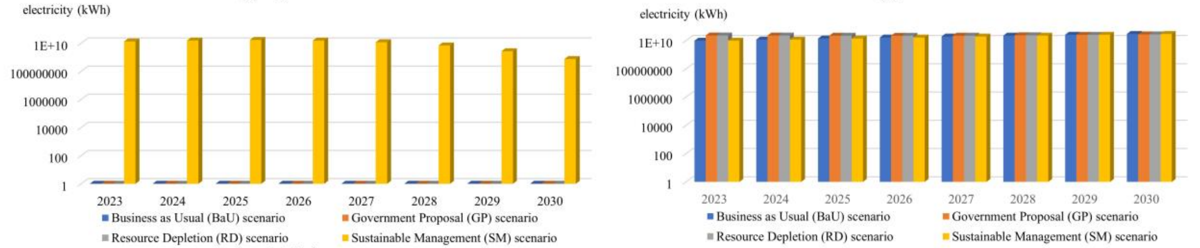
Year	Energy sources (kWh)												
	Hydro	Wind	Solar	Biomass	Biogas	Natural gas	Fuel oil	Coal	Diesel	Geo	Waste	Imported	Storage
	10^{9}	10^{10}	10^{10}	10^{10}	10^{9}	10^{11}	10^{8}	10^{10}	10^{7}	10^{6}	10^{8}	10^{10}	10^{8}
2023	7.33	0.66	1.32	0.99	1.30	1.48	4.46	1.43	4.45	1.46	1.88	2.59	0.00
2024	7.64	0.79	1.54	1.18	1.57	1.52	4.31	0.90	4.27	1.46	2.24	2.71	0.00
2025	7.94	0.93	1.69	1.40	1.88	1.55	4.18	0.39	4.10	1.46	2.66	2.82	0.00
2026	7.94	1.10	1.52	1.65	2.24	1.59	4.05	0.12	3.95	1.46	3.14	2.93	0.00
2027	8.54	1.29	1.16	1.93	2.66	1.63	3.93	0.00	3.71	1.46	3.51	3.04	0.00
2028	8.84	1.50	0.68	2.24	3.14	1.66	3.82	0.00	3.45	1.46	3.65	3.15	0.00
2029	9.15	1.72	0.27	2.59	3.67	1.69	3.71	0.00	2.79	1.46	3.19	3.26	0.00
2030	9.45	1.97	0.07	2.95	4.28	1.70	3.61	0.00	2.26	1.46	1.44	3.37	0.00

The bar chart in **Figures 5–7** was created to compare electricity generation from all sources in each scenario. **Figure 5** is to compare electricity generation from renewable sources. We can see that solar appears only in the SM scenario and no others, while waste appears in all scenarios except GP. **Figure 6** is to compare electricity generation from fossil fuels. We can see that electricity generation from all sources except for coal will be needed in all scenarios, and coal-fired generation will eventually be needed only in the BaU scenario. Comparisons of the total annual cost of electricity generation during the year 2023–2030 in all scenarios are shown in **Table 11**.

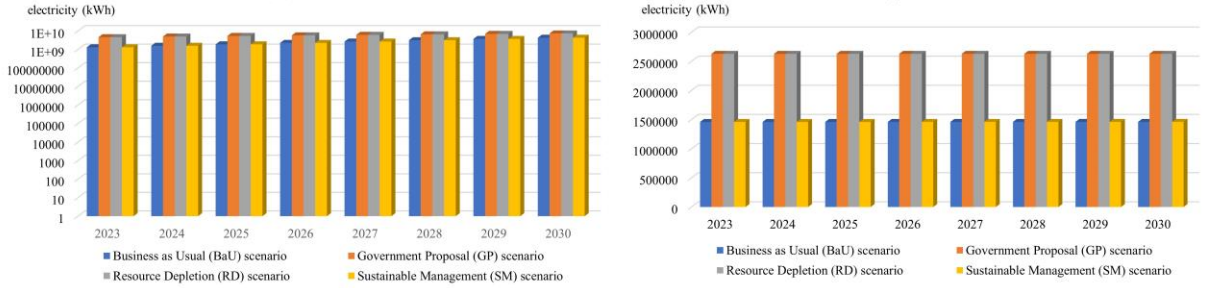
In addition to the fact that domestic power supply plus imports will be enough to cover domestic demand during the years 2023–2030, storage cost is generally high. Electricity storage will therefore not play a part under any scenario. However, development of electricity storage needs to continue in order to allow renewable energy utilization to increase. Moreover, storage systems should definitely be an alternative in the near future because the government makes it a policy to improve their cost and lifetime, as shown in Wongdet et al. (2023). Renewable-energy promotion policy, including tax incentives, is also necessary to reduce electricity imports and allay domestic energy security concerns.



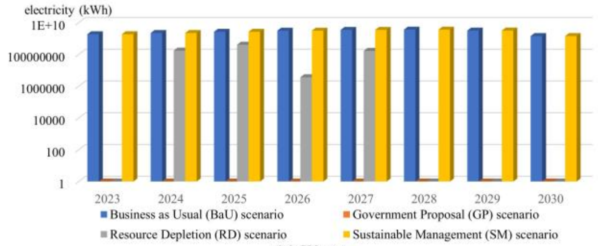
(a) Hydroelectric (b) Wind



(c) Solar (d) Biomass



(e) Biogas (f) Geothermal



(g) Waste

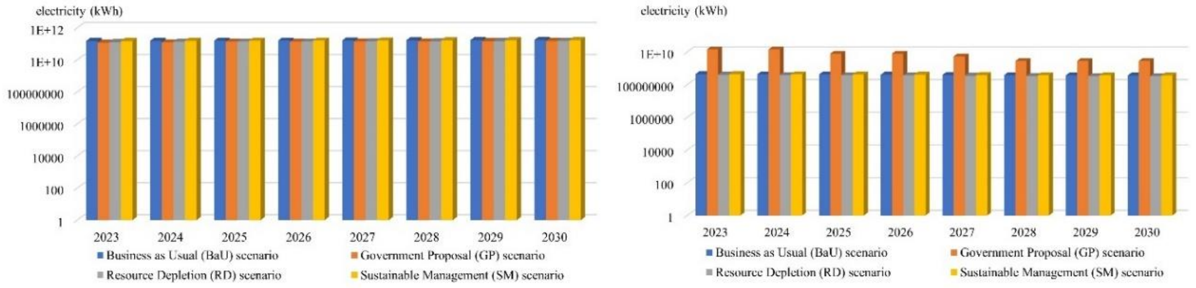
Figure 5. Electricity generation from renewable sources **(a)** hydroelectric (kWh), **(b)** wind (kWh), **(c)** solar (kWh), **(d)** biomass (kWh), **(e)** biogas (kWh), **(f)** waste (kWh), and **(g)** geothermal (kWh) under BaU, GP, RD, and SM scenarios during 2023–2030.

Table 11. Total cost of annual electricity generation under monthly demand in each scenario.

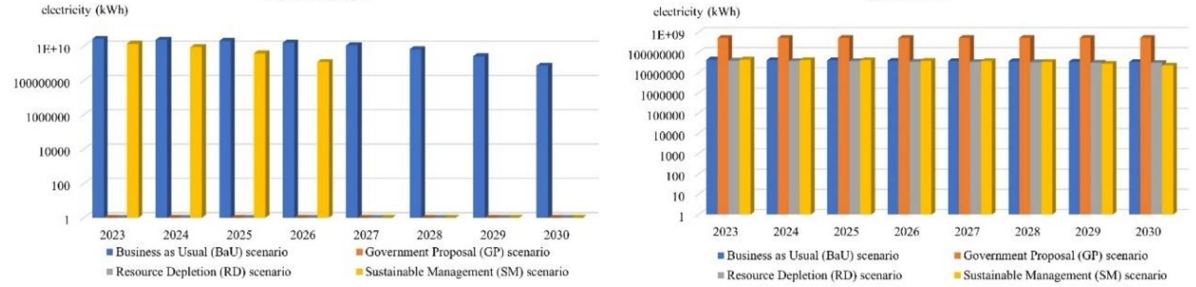
	Total cost (USD)			
Year	**BaU Scenario**	**GP Scenario**	**RD Scenario**	**SM Scenario**
	10^{14}	**10^{14}**	**10^{14}**	**10^{14}**
2023	2.19	1.49	1.55	3.02
2024	2.19	1.55	1.61	2.99
2025	2.18	1.63	1.67	2.95

Table 11. (*Continued*).

	Total cost (USD)			
Year	**BaU Scenario**	**GP Scenario**	**RD Scenario**	**SM Scenario**
	10^{14}	**10^{14}**	**10^{14}**	**10^{14}**
2026	2.17	1.63	1.67	2.92
2027	2.14	1.69	1.72	2.90
2028	2.12	1.69	1.71	2.88
2029	2.09	1.75	1.76	2.87
2030	2.08	1.79	1.80	2.87

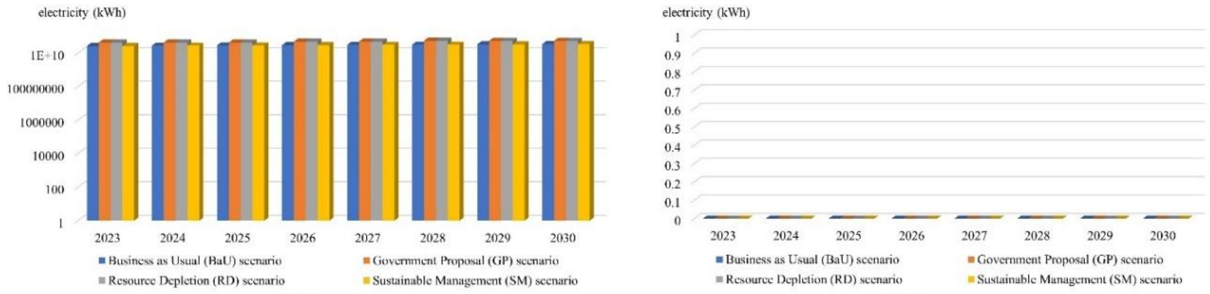


(a) Natural gas (b) Fuel oil



(c) Coal (d) Diesel

Figure 6. Electricity generation from fossil fuel sources **(a)** natural gas (kWh), **(b)** fuel oil (kWh), **(c)** coal (kWh), and **(d)** diesel, (kWh) under BaU, GP, RD, and SM scenarios during 2023–2030.



(a) Imports (b) Storage

Figure 7. Electricity from alternative sources **(a)** imports (kWh) and **(b)** storage (kWh) under BaU, GP, RD, and SM scenarios during 2023–2030.

5. Conclusions and policy implications

Electricity supply in Thailand comes from 4 main sources: renewable energy, fuel energy, imports and energy storage. This research analyzes electricity consumption plans for 2023–2030 under 4 scenarios, Business as Usual, Government Proposal, Resource Depletion and Sustainable Management. In all scenarios, future electricity demand is projected using a linear equation, which is most closely related to existing data. In BaU and SM scenario, the use of natural gas, crude oil, and coal for electricity generation is projected using logistic equations. Also in these two scenarios, renewable energy as well as hydropower follow logistic equations. In the GP scenario, the 2018 Power Development Plan is used to limit all future electricity generation, i.e., natural gas, coal, crude oil and renewable energy will be governed by linear equations as planned. Since natural gas and crude oil in the Gulf of Thailand, the country's main reserves, will be running out in 20 and 40 years, respectively, electricity generation from these sources in the RD scenario will decrease annually to slow down the depletion. The projected use of natural gas and crude oil follows linear equations while hydroelectric capacity follows GP scenario projections.

To meet demands during the year 2023–2030, electricity under BaU, GP, RD and SM scenarios are generated from 11, 8, 10 and 12 sources, respectively. Since the cheapest energy sources for electricity generation are hydropower, biomass, biogas, natural gas, fuel oil, diesel, and geothermal, we make them the main energy sources for electricity generation in all scenarios. Under all 4 scenarios, electricity imports from neighboring countries are used at full capacity because imports are the second-cheapest way to acquire electricity. Storage systems are not explicitly presented in any scenarios because demands will be adequately covered by a combination of domestic generation and imports throughout the analysis period. However, storage systems are utilized in the current renewable energy electricity generation. Cost evaluation shows that renewable energies' potential remains limited, preventing them from being used at full capacity. In terms of future research, energy management for electricity generation should focus on such alternatives as storage systems and renewable energy.

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