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An Integrated Renewable Energy System for the Supply of Electricity and Hydrogen Energy for Road Transportation Which Minimizes Greenhouse Gas Emissions

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ABSTRACT

Greenhouse gas emissions produced by the energy sector, including the transportation sector, are a problem that must be resolved. One way to solve this problem is to provide energy in the transportation sector in a sustainable way, by using renewable energy. An integrated renewable energy system has been implemented through an optimization model for the supply of electricity and hydrogen energy for road transportation. The proposed model is in the form of mixed-integer linear programming with two objective functions: planning costs and greenhouse gas emissions. The multi-objective model was solved using the linear weighted-sum method. In this article, three scenarios are developed, namely the business-as-usual scenario, the renewable energy scenario, and the renewable energy with energy storage system scenario. The business-as-usual scenario is used to analyze the supply of electricity and hydrogen by prioritizing the objective function of planning costs. The renewable energy scenario prioritizes the objective function of greenhouse gas emissions in the optimization calculation, but without an energy storage system. The optimization calculation with the renewable energy with energy storage system scenario prioritizes the objective function of greenhouse gas emissions by including the energy storage system. The proposed model in a multi-objective form is implemented in a case study of road transportation in the Province of Yogyakarta, Indonesia. The results obtained indicate that the renewable energy with energy storage system scenario produces the lowest emission level of 56.55 Mt CO_2 Equivalent, but with the highest planning cost of 192.13 Billion USD.

Keywords

Renewable energy;
Optimization model;
GHG emission;
Transportation sector;
Electricity;
Hydrogen

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1. Introduction

Demand for energy is increasing along with the growth in economic activity. This growth in energy demand causes a negative impact on the environment and has now become a global problem. One sector with a large energy demand is the transportation sector. Globally, the transportation sector has 23.3% of the total energy demand [1]. In particular, the energy demand for the transportation sector in Indonesia reached 41.1% of overall energy demand [2] and in Yogyakarta Province it reached 57.9% of overall energy demand [3]. Energy demand in the transportation sector in Indonesia is met by using two main types of fuel: gasoline and diesel.

In terms of supplying energy for the transportation sector, meeting energy demand at a minimum cost is a very challenging goal to achieve. It is increasingly facing greater challenges when taking into account the impact of energy use on the environment. The negative impact in the form of exhaust emissions from the combustion of fossil fuels will increase along with the increase in demand for fossil energy. Thus, minimizing the cost of

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providing energy and minimizing the impact on the environment from the use of fossil fuels are two goals that must be achieved simultaneously by energy providers.

Strategies that combine aspects of energy planning costs and total emissions must be developed in an integrated manner. Several energy supply strategies that can be applied in the transportation sector while taking into account the impact on the environment are changes in transportation modes, application of fuel switches, and use of more efficient technology. The combination of these three strategies can reduce energy demand and greenhouse gas emissions in the transportation sector by 20.5% and 24.8%, respectively [4]. In particular, the fuel switch strategy in the transportation sector has been comprehensively described to reduce emissions [5].

From the point of view of technological developments in the transportation sector, alternative technology is expected to produce a transportation system that is environmentally friendly as a result of the use of different energies, namely hydrogen and electricity. There are two types of hydrogen-fueled vehicles: Hydrogen Fuel Cell (H2FC) and hydrogen Internal Combustion Engine (H2ICE). H2FC has a higher average performance compared with H2ICE [6] based on the parameters of emissions, social costs, and energy efficiency. The battery electric vehicle produces 35%–50% fewer emissions with current technology compared with the internal combustion engine vehicle [7]

To obtain maximum benefits from an environmental perspective, the supply of electrical and hydrogen energy must be carried out in a sustainable way, namely with a renewable energy system (RES). Many studies have been conducted to analyze the supply of electricity based on RES. Despite higher costs, the provision of electricity with RES can significantly reduce greenhouse gas (GHG) emissions [8]. The implementation of wind turbines and photovoltaics can provide 77% of energy demand per year, according to a case study of a village in Switzerland [9]. In the provision of electricity, RES shows a good sustainability index, especially for environmental and social indicators [10].

Hydrogen can be produced using several methods, including electrochemical water splitting, thermochemical water splitting, and biomass gasification. For electrochemical water splitting, hydrogen is produced by using electricity to separate the hydrogen components from water. Electrochemical water splitting with high-temperature electrolysis technology has good efficiency, but there are structural and environmental challenges [11]. Hydrogen production can be carried out more sustainably with catalysts made from chemical waste from the pulping industry [12]. For hydrogen produced from biomass, efficiency can be increased using the solar thermal electrochemical process [13].

Although many studies have been conducted on the design and analysis of RES in the supply of energy, there are still some shortcomings in previous research, namely how to provide support to decision makers to develop an integrated RES, especially for the transportation sector. Most research focuses on processes that consist of one direction, i.e., RES to produce electricity and hydrogen production to meet hydrogen demand (including H2FC). Several optimization models have been developed to produce sustainable energy in the transportation sector based on RES [14]. Another study has produced a model of energy supply for the transportation sector by integrating carbon capture and sequestration technology [15]. The two studies did not provide information on how much capacity must be built to meet the demand per year.

Planning for energy supply to meet energy demand in the transportation sector must be able to determine optimally the capacity of the facilities that must be built. In addition, the optimal value of the planning costs and the resulting emissions must be calculated simultaneously. To achieve both these goals simultaneously, one approach is to develop an optimization model that is solved by a multi-objective method. In energy planning, the optimization model calculated by the multi-objective method has been shown to be effective in planning power generation capacity while taking into account the potential of renewable energy [16], [17]. In addition, a combination of multi-objective methods and the calculation of the sustainability index is applied in power generation capacity planning [18] and expansion of the electricity distribution network [19] taking into account the load in the form of electric vehicles.

This article aims to produce an integrated optimization model in the supply of electricity and hydrogen for the transportation sector by maximizing profits from an environmental point of view. The resulting optimization model is mixed-integer linear programming (MILP) with two objective functions. Furthermore, the two objective functions are solved by using the linear weighted-sum method. The innovative methods proposed in this article are: (i) representation of RES using a network-based, and (ii) an integrated model to optimize renewable energy sources in the supply of electricity and hydrogen in the transportation sector while taking into account planning costs and emissions.

The optimization model design is based on RES with various energy conversion technologies. The optimization model is designed based on the general constraint functions (i.e., energy demand fulfillment, energy balance, and available capacity), which also include RES-related constraint functions. Finally, the model is applied using energy demand data in the transportation sector for the Province of Yogyakarta, Indonesia to illustrate the effectiveness of the model design

2. An integrated energy supply system

Figure 1 shows the integrated renewable energy system (RES) developed in this article. In this figure, renewable energy sources consist of wind energy, solar radiation, and biomass. Wind energy and solar radiation are classified as variable renewable energy, whereas conversion technology, namely wind turbine and photovoltaics, is a non-dispatchable power plant. Biomass energy sources are converted into electricity with power generation technology using biomass fuel, which is categorized as a dispatchable power plant.

The electricity produced by the technology of converting renewable energy into electricity is then used to meet the demand for electricity in the transportation sector, in this case electric vehicles. In addition, electricity is also used as input for the electrochemical water-splitting process to produce hydrogen. The electrochemical process used in this model is water electrolysis technology. Electricity needs for the transportation sector and water electrolysis are supplied through RES.

If the potential for renewable energy is insufficient, the need for electricity will be supplied by electricity imported from the grid. In the same way, electricity from the grid is used to meet the demand for electricity in the transportation sector, and electricity is also used for hydrogen production. In the model, electricity obtained by importing from the grid is modeled using a dispatch rule in the form of process share. This approach has been taken because the development of the existing power generation capacity has been determined by the electricity grid planning.

3. Model description

This section consists of two parts. The first part describes the RES model, and the second part describes the

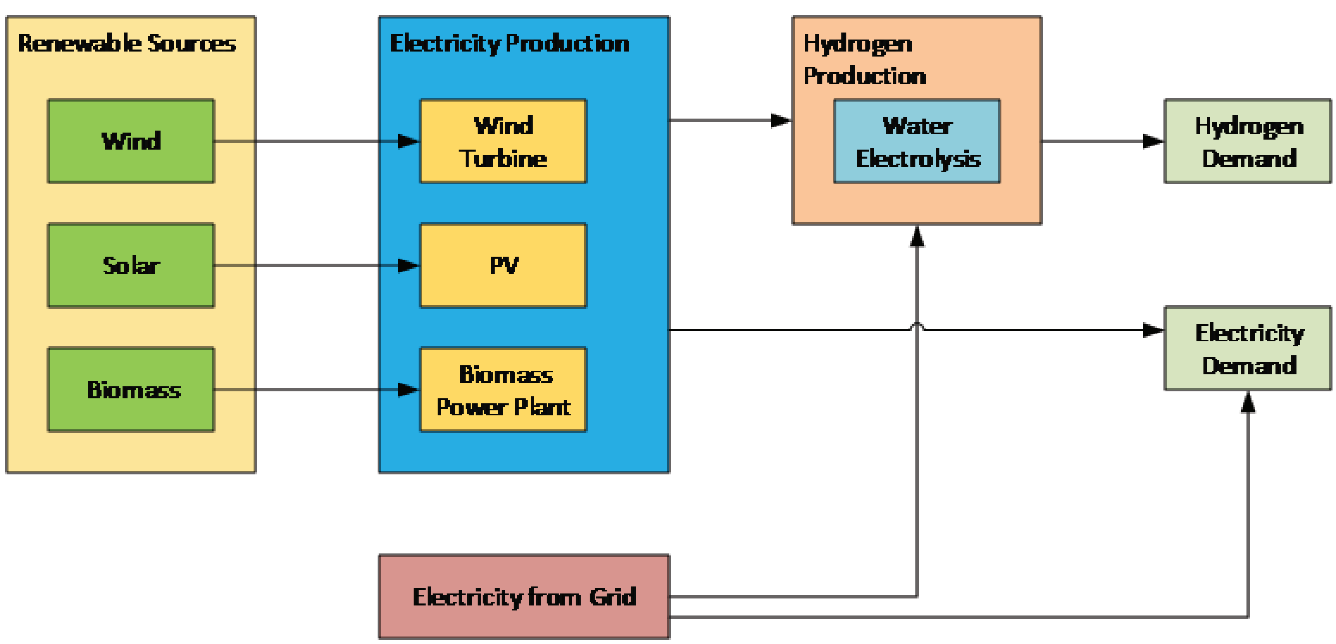

Figure 1: Integrated energy supply system.

optimization model used in this study. The RES model, consisting of wind turbines, photovoltaics, and biomass generators, is described in detail in the first section. The second section describes in detail the objective functions and constraint functions used in the optimization model.

3.1 Renewable energy system

There are three renewable energy technologies that are included in the integrated RES to produce electricity, namely wind turbines (WT), photovoltaics (PV), and biomass power plants (BP). The production of electricity for these three technologies is expressed as

$$W^{E}_{t,o,g} = 8760 \times \alpha_{o,g} \times P^{N}_{t,g} \tag{1}$$

where $W^{E}_{t,o,g}$ is the electricity (MWh) produced by generating technology *g*, at operating time *o*, and in year *t*. $\alpha_{o,g}$ is the availability factor (percent) for each generation technology *g* at operating time *o*. $P^{N}_{t,g}$ is the generation technology *g* installed in year *t* in MW. The constant 8760 is the number of hours in a year.

Energy from hydrogen fuel is obtained from the electrochemical water-splitting process using water electrolysis technology. Energy production from hydrogen fuel is determined by

$$W^{H}_{t,h} = HHV^{H} \times \eta_{h} \times W^{E,WE}_{t,h} \tag{2}$$

where $W^{H}_{t,h}$ is the energy produced (MWh) by technology *h* (in this case, water electrolysis) in year *t*. Parameters HHV^{H} and η_h are the higher heating value of hydrogen in MWh/t and the efficiency of the water electrolysis process in producing hydrogen as a percent, respectively. $W^{E,WE}_{t,h}$ is the electricity required by technology *h* in year *t* in MWh.

WT and PV are variable renewable energies, so the energy storage system (ESS) needs to be included in the integrated RES model. The ESS used is a battery. The battery operation in the integrated RES is expressed by

$$SOC_{t,o} = SOC_{init} + \left(\eta^{c} \times P^{C} - \frac{P^{d}}{\eta^{d}} \right) \times \Delta T_{o} \tag{3}$$

where $SOC_{t,o}$ is the state of charge of the battery (percent) at operating time *o* in year *t*. The SOC_{init} parameter is the state of charge in the initial state. η^{c} and η^{d} are efficiency parameters when the battery is charging and discharging, respectively. P^{C} and P^{d} are battery charging power and discharging power, respectively. ΔT_o is a time step (1 hour).

In the designed integrated RES, when the potential for renewable energy has reached its maximum limit, the electricity demand for both road transportation and water electrolysis is provided through the import of electricity from the grid. The electricity imported from the grid is modeled using the process share dispatch rule stated by

$$W^{E,Imp}_{t} = \sum\nolimits_{i \in I} \beta_{i} \times \eta_{i} \times W^{C}_{t,i} \tag{4}$$

where $W^{E,Imp}_{t}$ is the electricity imported from the grid in year *t* in MWh, β_i is the process share of power generation technology *i* in the grid system as a percent, η_i is the efficiency of power generation technology *i*, and W^{C}_{i} is the amount of energy consumed by generating technology *i* in year *t* in MWh. W^{C}_{i} is generated from

$$W^{C}_{t,i} = HHV_{i} \times FUEL_{t,i} \tag{5}$$

where HHV_i is the higher heating value of the fuel used by power generation technology *i* in MWh/fuel units. $FUEL_{t,i}$ is the amount of fuel required by generating technology *i* in year *t* in fuel units. The fuel unit is tonne for coal, liter for diesel, and MMBTU for natural gas.

3.2 Optimization model

In this section, the optimization model is formulated based on the integrated RES described in sections 2 and 3.1. The optimization model is a mixed-integer linear programming (MILP) model with a single node approach. With the single node approach, the transmission system of electricity and hydrogen is not included in the model. This model consists of two objective functions and the constraint functions, which will be explained later. The purpose of the optimization model is to determine the RES capacity that must be built in year *t* to meet the demand for electricity and hydrogen energy while minimizing the impact on the environment. In this model, the planning interval runs from 2020 to 2050.

3.2.1 Constraint functions

The first constraint function is energy balance, which states that energy production, both generated by integrated RES and imported from the grid, must be able to meet energy needs in the transportation sector. For electricity, the energy balance is expressed by

$$\begin{aligned} &\sum\nolimits_{g \in G} W^{E}_{t,o,g} + W^{E,Imp}_{t} - W^{E,WE}_{t,h} + \left(P^{d} \times \Delta T_{o} \right) \\ &\geq \sum\nolimits_{m \in M} W^{ED}_{t,o,m} + \left(P^{C} \times \Delta T_{o} \right), \forall \left(t \in T \right), \forall \left(o \in O \right) \end{aligned} \tag{6}$$

where $W_{t,o,m}^{ED}$ is the demand for electricity in the transportation sector (MWh) in each operating hour *o*, for each mode of transportation *m*, and in year *t*. This constraint function states that the amount of electricity produced by RES, imported electricity, and electricity produced by the ESS must be more than or equal to the total electricity needs of the transportation sector, electricity used for the water electrolysis process, and electricity stored in the ESS. For energy derived from hydrogen, the energy balance constraint function is expressed as

$$\sum\nolimits_{h\in H} W_{t,h}^{H2} \geq \sum\nolimits_{m\in M} W_{t,m}^{H2D}, \forall (t \in T) \tag{7}$$

where $W_{t,m}^{H2D}$ is the demand for hydrogen energy (MWh) for transportation mode *m* in year *t*.

The electricity used for the water electrolysis process cannot exceed the total production of integrated RES electricity and electricity imported from the grid. This is expressed by the function constraint

$$W_{t,h}^{E,WE} \leq \sum\nolimits_{g\in G} W_{t,o,g}^{E} + W_{t}^{E,Imp}, \forall (t \in T), \forall (o \in O) \tag{8}$$

where this constraint function applies to every hour of operation *o* in year *t*. The purpose of the constraint function in equation (8) is to relate the electricity requirements of the water electrolysis process to the production and import of electricity, as shown in Figure 1.

The power generation capacity added in a given year is determined by

$$P_{t,g}^{Added} = P_{g}^{E,Avail} \times N_{t,g}^{E}, \forall (t \in T), \forall (g \in G) \tag{9}$$

where $P_{t,g}^{Added}$ is the capacity of generating technology *g* added in year *t* in MW and $N_{t,g}^{E}$ is an integer variable representing the number of generating technology *g* in year *t*. Parameter $P_{g}^{E,Avail}$ is a parameter that indicates the addition size (MW) that can be added for each type of technology *g*.

The total generating capacity for each type of technology installed is the total generating capacity in year *t* and previous years. This is stated by

$$P_{t,g}^{N} = \sum\nolimits_{t'\in T|t'\leq t, t-t'\leq L_g} P_{t',g}^{Added}, \forall (t \in T) \tag{10}$$

where $P_{t,g}^{N}$ is the installed generating capacity (MW) for each type of technology *g* in year *t*. The same applies to the total capacity of hydrogen facilities where hydrogen energy production cannot exceed the capacity established in year *t*. This is stated by

$$W_{t,h}^{H2} \leq \sum\nolimits_{t'\in T|t'\leq t, t-t'\leq L_h} P_{h}^{H2,Avail} \times N_{t,h}^{H2}, \forall (t \in T) \tag{11}$$

where $P_{h}^{H2,Avail}$ is the capacity of the hydrogen facility that can be added and $N_{t,h}^{H2}$ is an integer variable that represents the number of hydrogen facility. The capacity of the hydrogen production facility is expressed in MW, which is the conversion result of t/day.

The constraint function for ESS, which states that the electricity that can be stored in the battery does not exceed the amount of available capacity, is expressed as

$$\sum\nolimits_{t'\in T|t'\leq t} OC_{min} \times N_{t'}^{ESS} S \leq SOC_{t,o} \leq \sum\nolimits_{t'\in T|t'\leq t} SOC_{max} \times N_{t'}^{ESS}, \forall (t \in T), \forall (o \in O) \tag{12}$$

where N_{t}^{ESS} is the number of batteries installed in year *t*.

Furthermore, the installed power generation technology capacity cannot exceed the available renewable energy potential. This constraint function is represented by

$$P_{t,g}^{N} \leq P_{g}^{RE}, \forall (t \in T) \tag{13}$$

where P_{g}^{RE} is the technical potential for any renewable energy (MW) used as primary energy in the generation of electricity.

3.2.2 Objective functions

The proposed optimization model has two objective functions: planning costs and impact on the environment. The objective function of planning costs consists of investment costs and operating costs of electricity and hydrogen energy production facilities. The objective function of the impact on the environment expresses the amount of greenhouse gas (GHG) emissions produced by electricity imported from the grid. GHG emissions consist of non-biogenic carbon dioxide (CO_2), methane (NH_4), and nitrogen oxide (NO_x) gases. Both objective functions must be minimized in the optimization calculation.

The objective function of planning costs is expressed as

$$\min_{\Delta} F^{1} = F^{IC} + F^{VOC} + F^{FOC} + F^{imp} \tag{14}$$

where F^{IC}, F^{VOC}, and F^{FOC} are total investment costs, total variable operating costs, and total fixed operating costs for electricity and hydrogen energy production facilities, respectively. F^{imp} is the total cost of electricity imported from the grid. Variables in set

$\Delta = \left\{ P_{t,g}^{Added}, P_{t,g}^{N}, N_{t,g}^{E}, N^{ESS}, N_{t,h}^{H2}, W_{t,o,g}^{E}, W_{t,h}^{H2}, P_{t,g}^{N}, W_{t}^{E,Imp} \right\}$ are the optimization decision variables of the cost-related objective function.

The investment cost of energy production facilities is expressed as

$$F^{IC} = \Gamma\left(\begin{array}{l} \sum_{t\in T}\sum_{g\in G} I_g^C \times N_{t,g}^E + \sum_{t\in T} I^{ESS} \times N^{ESS} \\ +\sum_{t\in T}\sum_{h\in H} I_h^C \times N_{t,h}^{H2} \end{array} \right) \quad (15)$$

where parameters I_g^C, I^{ESS}, and I_h^C are investment costs for electricity production facilities, investment costs for ESS units, and hydrogen, respectively, in USD/MW. Γ is the capital recovery factor expressed as

$$\Gamma = r\left(1+r\right)^n / \{\left(1+r\right)^n - 1\} \quad (16)$$

where r is the interest rate and n is the technology lifetime.

The variable operating costs of energy production facilities are expressed as

$$F^{VOC} = \sum_{t\in T}\sum_{o\in O}\sum_{g\in G} C_g^V \times W_{t,o,g}^E + \sum_{t\in T}\sum_{h\in H} C_h^V \times W_{t,h}^{H2} \quad (17)$$

where parameters C_g^V and C_h^V represent the operating costs of electricity and hydrogen energy production facilities, respectively, expressed in USD/MWh. Fixed operating costs, F^{FOC}, applied only to power generation technology and ESS, are expressed as

$$F^{FOC} = \sum_{t\in T}\sum_{g\in G} C_g^F \times P_{t,g}^N + \sum_{t\in T} C^{ESS} \times N^{ESS} \quad (18)$$

where C_g^F and C^{ESS} are fixed operating cost parameters for each type of power generation technology g and ESS units, respectively, in USD/MW.

The last part of the objective function of planning costs is the cost of electricity imported from the grid, F^{imp}, which is expressed as

$$F^{imp} = \sum_{t\in T} C^{imp} \times W_t^{E,Imp} \quad (19)$$

where C^{imp} is the cost of electricity imported from the grid in USD/MWh.

The objective function of the impact on the environment is expressed as

$$\min_{\Omega} F^2 = \sum_{t\in T}\sum_{i\in I}\sum_{e\in E} \gamma_e \times \varepsilon_{i,e} \times W_{t,i}^C \quad (20)$$

where γ_e is the externality cost of pollutant e in USD/t, $\varepsilon_{i,e}$ is the emission factor for each type of pollutant e (t/MWh) generated from fuel combustion of the grid system power generation technology i. The variable in set $\Omega = \left\{ W_{t,i}^C \right\}$ is the optimization variable related to the emission objective function.

3.2.3 Proposed scenarios of the multi-objective model

The multi-objective model that has been developed is solved by using the linear weighted-sum method. Using this method, the two objective functions can be expressed as

$$\min F = \sum_{k\in K} \omega_k F^k \quad (21)$$

where ω_k is the weight for each objective function k that satisfies

$$\sum_{k\in K} \omega_k = 1, \omega_k \geq 0 \quad (22)$$

and F^k is the kth objective function. In this model, there are two objective functions and both objective functions have the same unit, namely USD. Thus, the objective function can be written as

$$\min F = \omega_1 \times F^1 + \omega_2 \times F^2 \quad (23)$$

Based on the formulation of the multi-objective optimization model in equation (23), three scenarios are used to analyze the role of renewable energy sources in the supply of electricity and hydrogen in the transportation sector. The first scenario is the business-as-usual (BAU) scenario, which focuses on the objective function of planning costs. The second scenario is a renewable energy (RE) scenario, which focuses on providing electricity and hydrogen energy by minimizing the impact on the environment. The second scenario is divided into two, namely the RE scenario without ESS and the RE scenario with ESS. The scenarios are summarized in Table 1.

Table 1: Proposed scenario for optimization.

Scenario Code	Scenario	Remarks
BAU	Business as Usual	$\omega_1 = 1, \omega_2 = 0$
RE	Renewable Energy without ESS	$\omega_1 = 0, \omega_2 = 1, N^{ESS} = 0$
RE-ESS	Renewable Energy with ESS	$\omega_1 = 0, \omega_2 = 1, N^{ESS} \neq 0$

4. Application to the future road transportation sector in Yogyakarta Province

The proposed optimization model is applied to anticipate changes in the energy structure of the transportation sector in Yogyakarta Province, Indonesia. This province does not have fossil energy resources. All energy demands, including those for the transportation sector, are met by importing energy from outside the province. However, there are several potential renewable energy sources in Yogyakarta Province. The proposed model is used to analyze the role of available renewable energy sources in providing electricity and hydrogen in the transportation sector while minimizing the impact on the environment.

4.1 Energy demand projections

Road transportation in Yogyakarta Province consists of passenger transportation and freight transportation. Passenger transportation consists of passenger cars, buses, and motorcycles, while the mode of freight transportation is trucks. Table 2 shows road transportation activities in Yogyakarta Province in 2020, based on Indonesia's national energy roadmap [20]. The fuel used for the transportation sector in 2020 consists of gasoline and diesel, with an energy consumption of 19.81 x 10^6 GJ and 4.48 x 10^6 GJ, respectively. Table 3 shows the energy intensity of each mode of road transportation.

The energy demand projection in the transportation sector is calculated using

$$ED_{i,t} = EI_{i,t} \times A_{i,t} \tag{24}$$

where $ED_{i,t}$ is the energy demand for mode i in year t (in GJ or GWh), $EI_{i,t}$ is the energy intensity for transportation mode i in year t, and $A_{i,t}$ is the activity for transportation mode i in year t. Energy demand projections carried out in national energy roadmap [20], energy intensity is assumed to be constant during the projection period. Meanwhile, activity for each mode of transportation is determined using

$$A_{i,t} = A_{i,t-1} \times \left(1 + \Delta G_t\right) \tag{25}$$

where $A_{i,t-1}$ is the activity of the transportation sector for mode i in the previous year and ΔG_t is GDP growth in year i (as %). In the same document, gasoline and diesel are no longer used as fuel in the transportation sector at the end of the projection year. Both fuels are replaced with electricity and hydrogen. In 2050, the target of using electricity and hydrogen in the transportation sector is 85% and 15% of total energy consumption, respectively.

Table 2: Activity level of road transportation in 2020.

Mode	Activity in 2020	Unit
Passenger Car	4,612.40	Million Passenger-km
Bus	5,897.15	Million Passenger-km
Motorcycle	16,599.00	Million Passenger-km
Truck	3,836.74	Million Tonne-km

Table 3: Energy intensity of road transportation in 2020.

Mode	Energy Intensity in 2020	Unit
Passenger Car	1,711.38	GJ/Passenger-km
Bus	149.67	GJ/Passenger-km
Motorcycle	744.75	GJ/Passenger-km
Truck	914.42	GJ/Tonne-km

Figure 3 shows the results of the projected energy demand for road transportation for Yogyakarta Province based on the type of energy (a) and the type of road transportation mode (b). This figure shows an optimistic projection of energy demand in the transportation sector. The results of this projection show that fossil energy will no longer be used to support road transportation activities in 2050. Fossil fuels, namely gasoline and diesel, will be replaced with energy derived from electricity and hydrogen.

Figure 3 shows the demand for electricity and hydrogen through 2050. The energy demand for road transportation will reach 11.99 TWh in 2050. This energy demand consists of 9.95 TWh of electricity and 2.04 TWh of energy from hydrogen fuel. In general, energy demand for road transportation has increased by an average of 2.0 % per year. The proposed optimization model is used to analyze the potential role of available renewable energy in the energy supply as shown in Figure 3. For electric vehicle loads, the load pattern used is shown in Figure 4 [21]. This load pattern is used to determine the operating hours of renewable energy generation technology, which is 24 hours.

4.2 Energy sources

As previously explained, Yogyakarta Province does not have fossil energy sources to meet energy demand. However, it has several renewable energy sources that can be used to partially meet this demand. Three renewable energy sources are used in the optimization calculations with the proposed model, namely solar radiation, wind power, and biomass. Power plants with

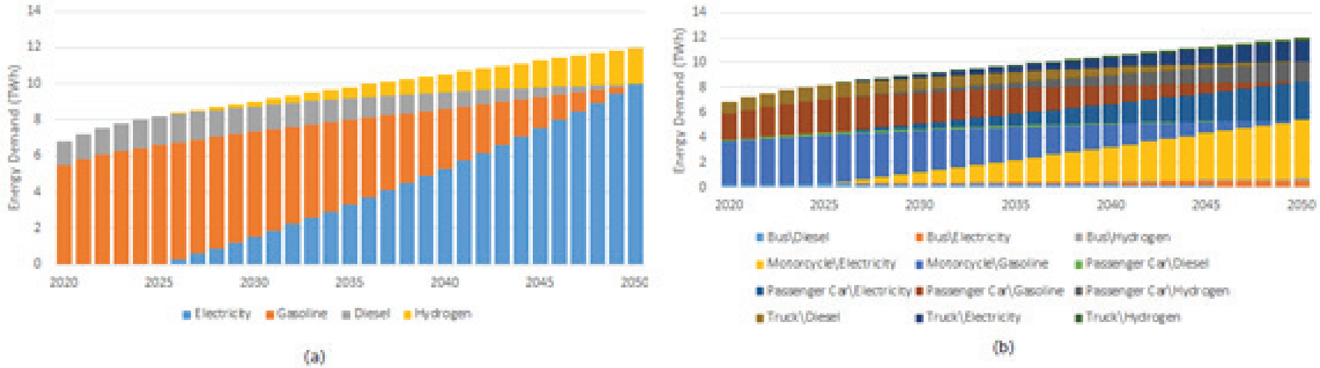

Figure 2. Energy demand for road transportation based on (a) fuel and (b) transportation mode.

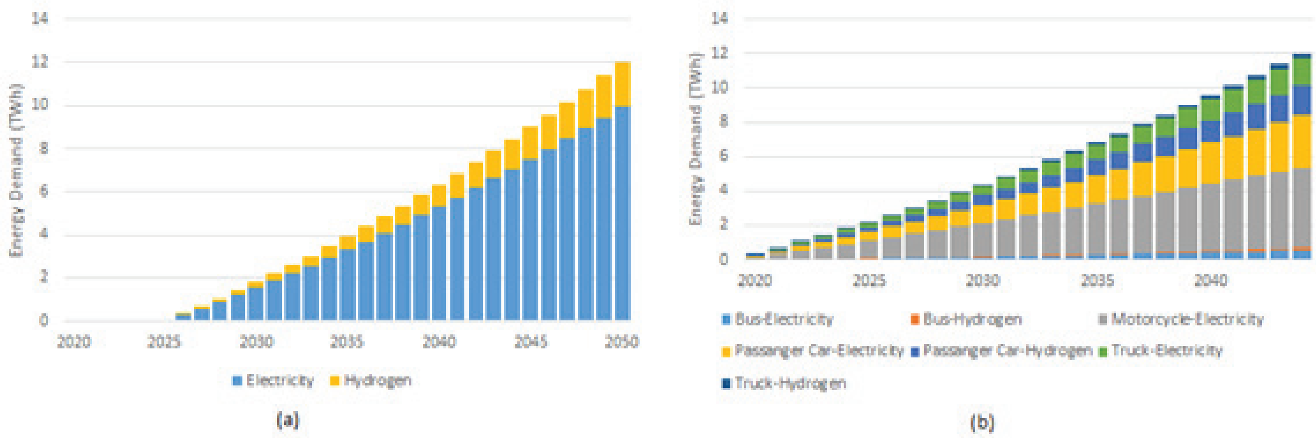

Figure 3: Projections of electricity and hydrogen energy demand.

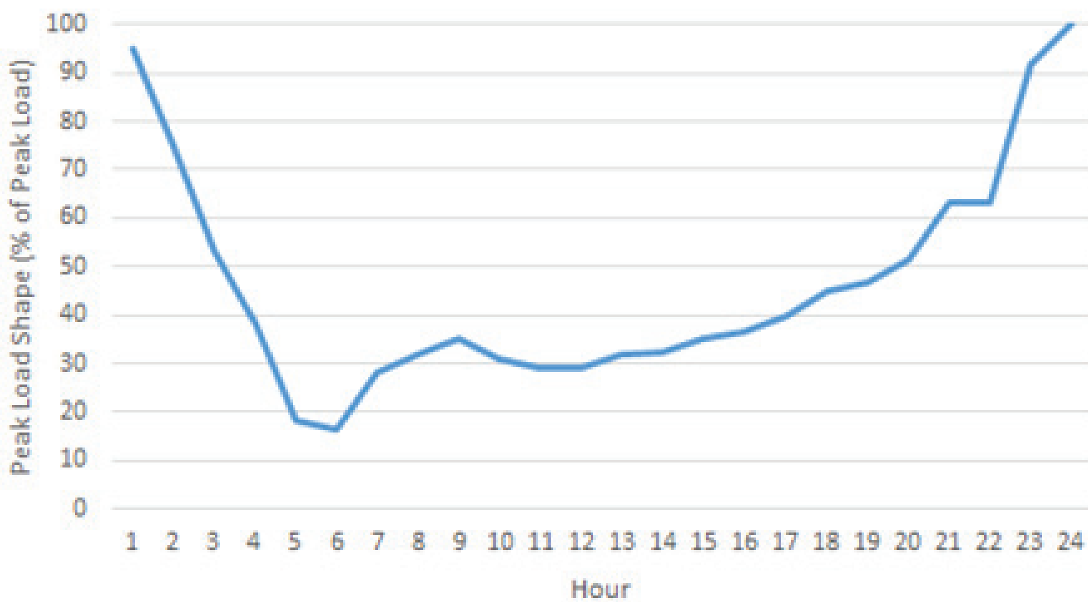

Figure 4: Electric vehicle load shape.

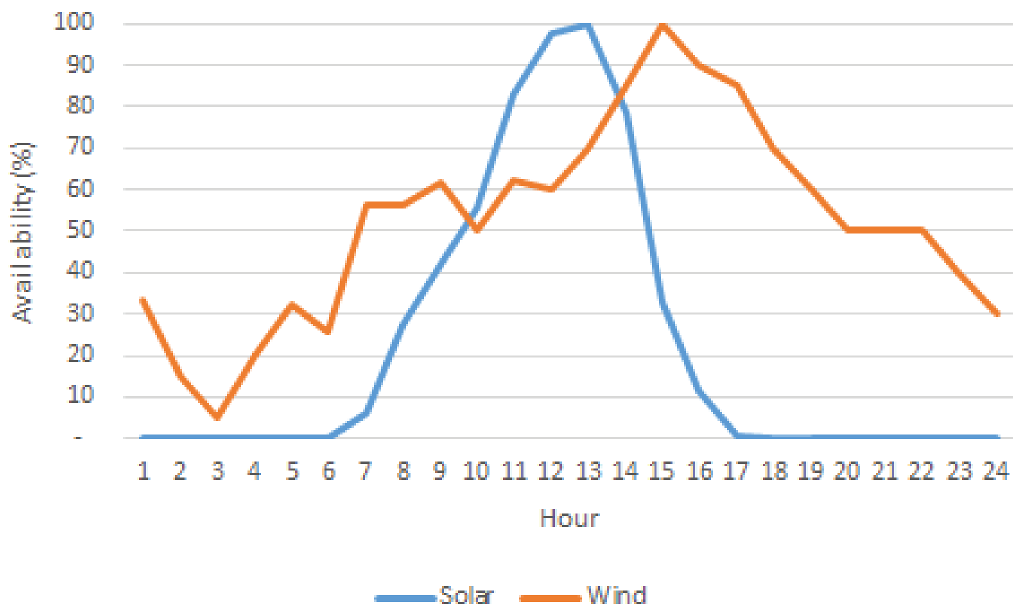

Figure 5: Availability factor of solar and wind energy.

Table 4: Technical renewable energy potential.

Renewable Energy	Technical Potential (MW)
Solar Radiation	996
Wind Power	1,079
Biomass	224

primary energy from solar radiation and wind power are non-dispatchable variable renewable energy power plants. Figure 6 shows the daily availability factor for these two types of power generation technologies in Yogyakarta Province. Power plants with biomass as their primary energy source are categorized as dispatchable power plants. Table 4 shows the potential for the three renewable energy sources [20].

4.3 System component characteristics

The integrated RES component consists of components for generating electricity and hydrogen production facilities. These two components have economic and technical characteristics. Economic characteristics include investment costs and operating costs. Technical characteristics include production capacity, efficiency, and lifetime. Table 5 summarizes the technical characteristics for the components of electricity generation with renewable energy [22] and hydrogen production facilities [23]. For the hydrogen production facilities, the production capacity expressed in t/day is then converted into MW using the higher heating value (HHV) of hydrogen value of 33.27 MWh/t. In calculating the capital recovery factor, the interest rate used is 5%.

The environmental characteristics of electricity generation are applied to the grid system. The grid system is an interconnected system in Java, Madura, and Bali which is known as the Java-Madura-Bali (JAMALI) system. Figure 7 shows the composition of the power plant in the JAMALI system [2]. It is estimated that coal-fired power plants will still dominate in generating electricity in the JAMALI system. Renewable energy potentials, such as hydro, PV, wind, and geothermal, are developed in the generation of electricity to replace part of the need for natural gas. Based on the composition of power plants in the JAMALI system, GHG emissions are generated by coal, natural gas, and diesel power. Table 6 summarizes the GHG emissions for these three power plants [24]. The GHG emissions shown in Table 6 are then converted into units of global warming potential (t CO_2 Equivalent) using coefficients for CO_2, CH_4, NO_x of 1, 30, and 265, respectively.

5. Results and discussion

The data described in Section 4 are used as parameters in the proposed optimization model for electricity and hydrogen energy production, capacity of facility

Table 5: Economic and technical parameters of the electricity and hydrogen production facilities.

Type	Additional Capacity	Investment Cost (M USD)	Fixed OM Cost (USD/MW)	Variable OM Cost (USD/MWh)	Efficiency (%)
Electricity Production					
Photovoltaics (PV)	150 MW	1.31	\$15.25/MW	-	-
Wind Turbine (WT)	50 MW	1.67	\$35.14/MW	-	-
Biomass Power Plant (BP)	50 MW	4.09	\$125.72/MW	\$4.83/MWh	-
Battery	50 MW	1.39	\$24.8/MW		85
Hydrogen Production					
Water Electrolysis	3 t/day	70.4	-	\$270/t-H_2	59

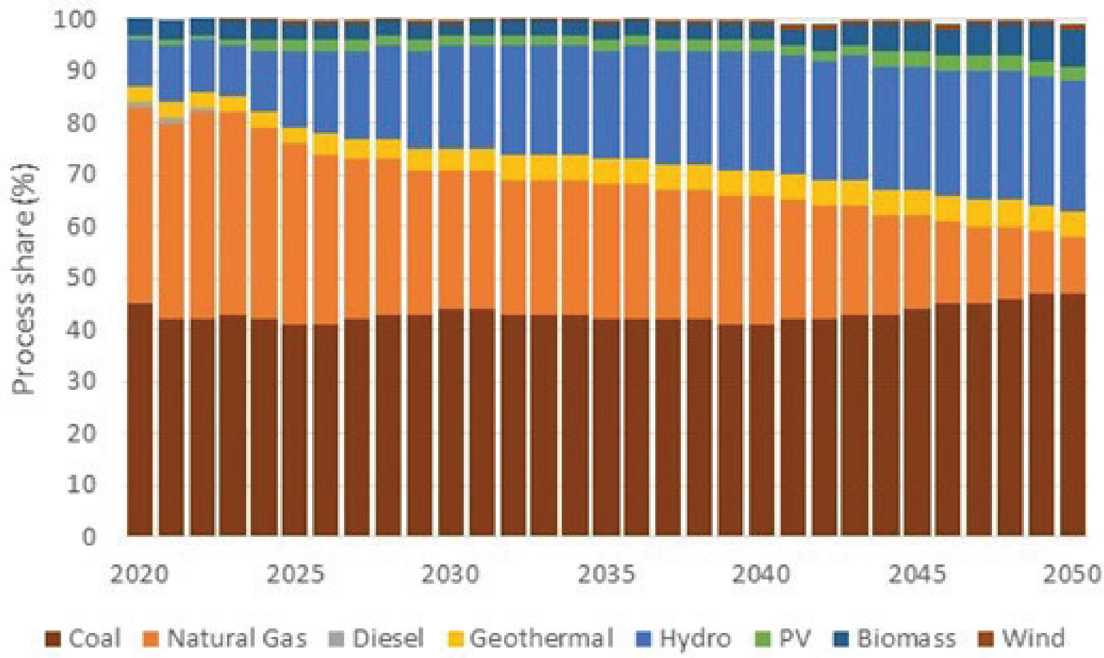

Figure 6: Process share of the JAMALI power system.

Table 6. Environmental characteristics of power generation technology.

Type	CO_2 (t/MWh)	CH_4 (g/MWh)	NO_x (g/MWh)
Diesel	0.26	10.79	719.99
Coal	0.33	9.88	13.8
Natural Gas	0.18	7.07	9.9

expansion analysis, and cost and emission analysis. The analysis is carried out for three predetermined scenarios, namely the BAU scenario, the RE scenario without ESS, and the RE scenario with ESS.

5.1 Energy production

Figure 7 and Figure 8 show the production of electricity and hydrogen for the three scenarios. The three scenarios produce the same amount of electricity and hydrogen to meet the demand for both electricity and production of hydrogen energy for road transportation. Based on the BAU scenario shown in Figure 7, imports of electricity and production of hydrogen energy in 2050 will reach 12.50 TWh and 2.04 TWh, respectively. The results from the BAU scenario show that importing electricity is more cost-effective compared with producing electricity from renewable energy sources. Figure 8 (b) shows the electricity generated by each generation technology in the JAMALI system if the electricity imported from the grid is aggregated.

The RE scenario, which focuses on minimizing the impact on the environment, results in the production of electricity and hydrogen as shown in Figure 8. The RE scenario consists of two scenarios: without ESS and with ESS. The RE scenario without ESS is shown in Figure 8 (a). When compared with the BAU scenario, the RE scenario prioritizes the production of electricity using renewable energy technology. It is also seen that the renewable energy potential in Yogyakarta Province cannot meet demand during the simulation period. In 2050, imported electricity is 5.79 TWh and energy produced from renewable energy technology is 6.53 TWh. Of this total electricity, 2.55 TWh is used as input for water electrolysis to produce hydrogen. In 2050, the amount of energy obtained from hydrogen will be 2.28 TWh. In the RE scenario, imports of electricity constitute only 47.8% of the total electricity demand.

The impact of ESS implementation in integrated RES is shown in Figure 8 (b). With the implementation of ESS, RES can generate more electricity compared with the scenario without ESS. In 2050, the electricity produced from the integrated RES is 7.61 TWh and the electricity that must be imported is 4.97 TWh. The electricity used by water electrolysis to produce hydrogen is the same as that produced in the scenario without ESS, which is 2.55 TWh. Thus, the implementation of ESS in the integrated RES resulted in imports of electricity which constitute only 39.5% of the total electricity demand. In particular, in Figure 8 (b) in 2044 and 2045, the production of electricity by PV increases compared with the scenario without ESS. This is due to the use of batteries, which have an impact on the addition of higher PV capacity for the scenario with ESS compared with the scenario without ESS.

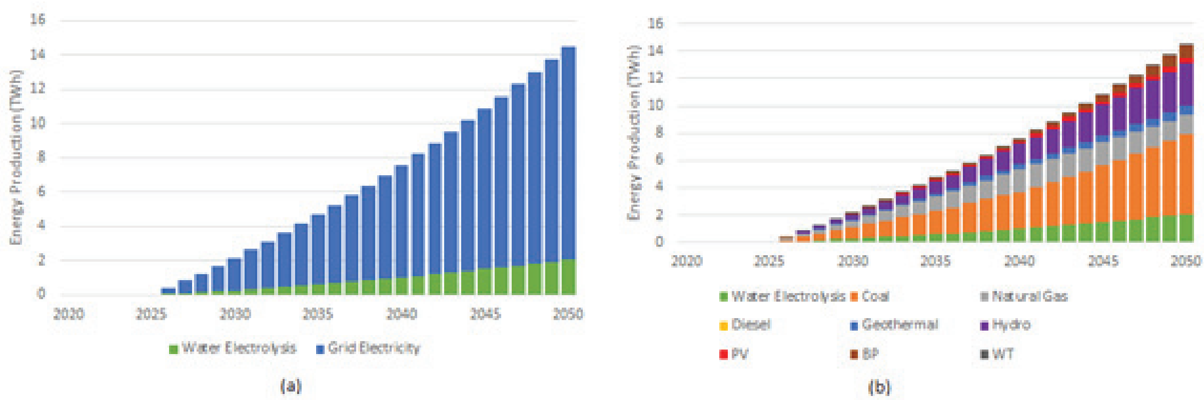

Figure 7: Energy production based on the BAU scenario: (a) total grid electricity and (b) aggregated based on process share of grid electricity.

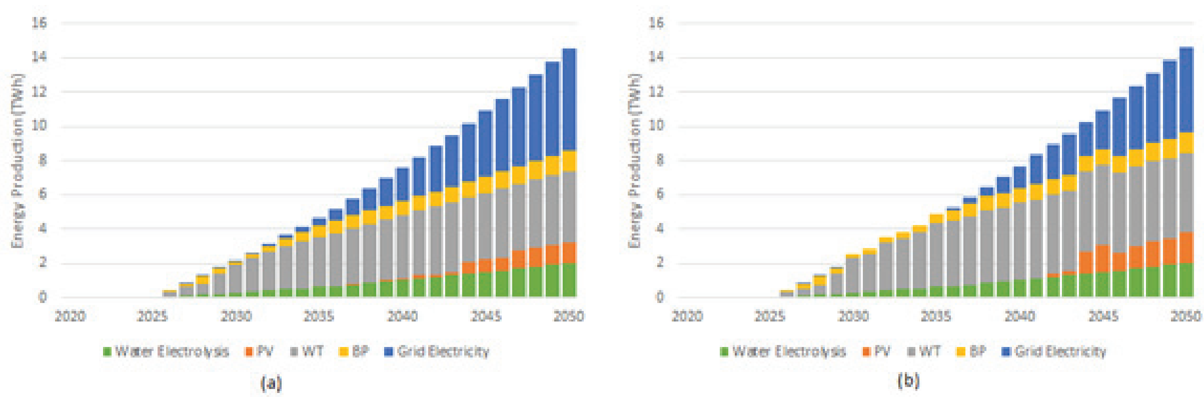

Figure 8: Energy production based on (a) the RE scenario and (b) the RE-ESS scenario.

Figure 9: Daily electricity generation based on (a) the RE scenario and (b) the RE-ESS scenario.

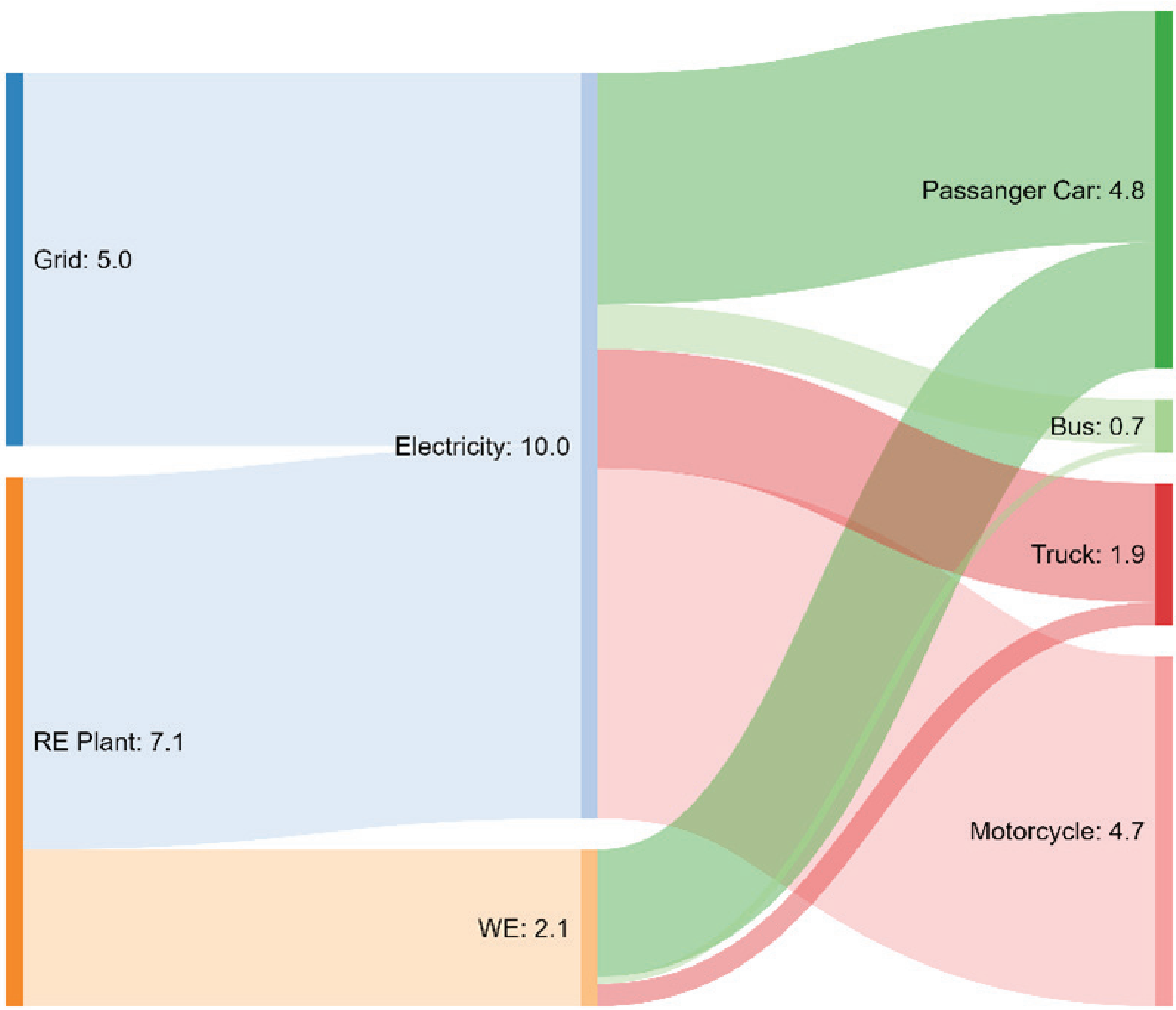

Figure 10: Sankey diagram of electricity and hydrogen in 2050 based on the RE-ESS scenario (in TWh).

The difference between the RE scenario and the RE-ESS scenario in electricity generation based on operating hours is shown in Figure 9 (a) and (b). It can be seen that the implementation of ESS produces a different pattern of electricity generation compared with the RE scenario. Electricity generated in the RE-ESS scenario is greater than in the RE scenario. ESS stores electricity during the day and will be used at night. The difference in electricity production with ESS is due to the addition of battery capacity in the integrated RES.

Figure 10 is a Sankey diagram showing the flow of electricity from the grid and the integrated RES. This diagram was produced based on the flow of electricity in 2050 using the RE-ESS scenario. It can be seen that the amount of electricity imported from the grid and electricity produced from the integrated RES meet the demand for electricity for road transportation and for water electrolysis in 2050. Furthermore, the hydrogen produced by water electrolysis meets the energy demand in 2050 for road transportation.

5.2 Capacity of facility expansion

The energy production described in the previous section results from the construction of energy production facilities. For electricity, the capacity that must be built during the optimization interval is shown in Figure 11. The addition of power generation capacity will reach its maximum value in 2044 with the total capacity for PV, WT, and BP of 900 MW, 1,050 MW, and 200 MW, respectively. The RE-ESS scenario results in additional battery capacity of 50 MW from 2031, reaching the highest capacity of 150 MW in 2035. The RE-ESS scenario results in additional PV capacity starting in 2042, reaching the highest value in 2044.

Figure 12 shows the required additional capacity for water electrolysis. It can be seen that the addition of water electrolysis capacity occurs gradually with an average capacity increase of 9 t/day. Overall, the total water electrolysis capacity required until 2050 is 235 t/day.

5.3 Emission and cost analysis

Figure 13 shows the impact on the environment represented by GHG emissions for each scenario. It can be seen that the BAU scenario produces the largest emissions compared with the other scenarios. This is due to the overall demand for electricity being met by importing from the grid, where the composition of power generation in the grid system is dominated by coal and natural gas. In 2050, the cumulative value of GHG emissions based on the BAU scenario will reach 394.95 Mt CO_2 Equivalent.

Compared with the BAU scenario, the other two scenarios, the RE and RE-ESS scenarios, produce lower GHG emissions. The GHG emissions produced by the RE and RE-ESS scenarios in 2050 are 91.55 Mt CO_2 Equivalent and 56.55 Mt CO_2 Equivalent, respectively. The percentage reduction in GHG emissions from the RE and RE-ESS scenarios compared with the BAU scenario is 76.8% and 85.7%, respectively.

In terms of planning costs, the opposite phenomenon occurs, where the BAU scenario results in lower planning costs compared with the RE and RE-ESS scenarios (Figure 14). In the BAU scenario, the cumulative planning costs in 2050 only reach 125.30 Billion USD. For the RE and RE-ESS scenarios, the planning costs only have a slight difference as the two lines in Figure 14 almost overlap. The minor differences between the RE and RE-ESS scenarios lie in externality costs, operation and maintenance costs, and investment costs. The externality costs in the RE scenario are 1.11 Million USD higher than in the RE-ESS scenario. Operation and maintenance costs for the RE-ESS scenario are lower by

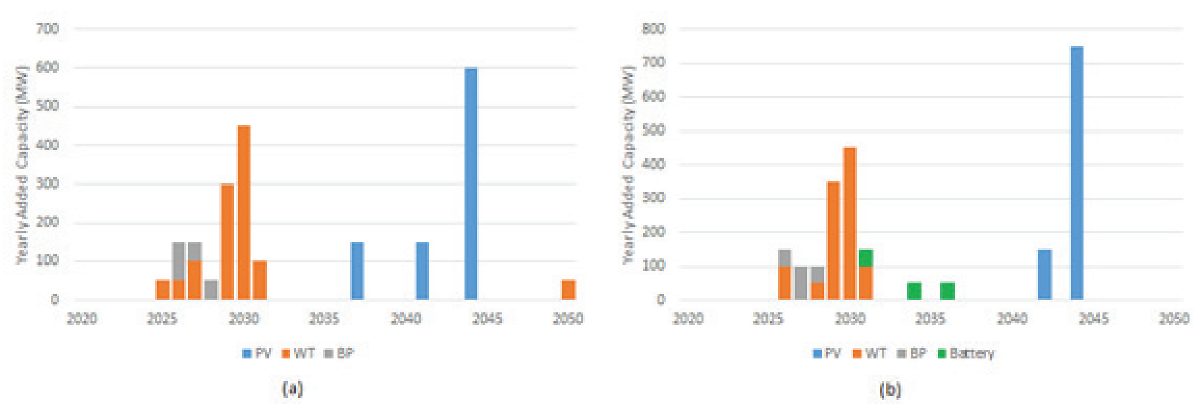

Figure 11: Capacity addition of renewable energy power plants based on (a) the RE scenario and (b) the RE-ESS scenario.

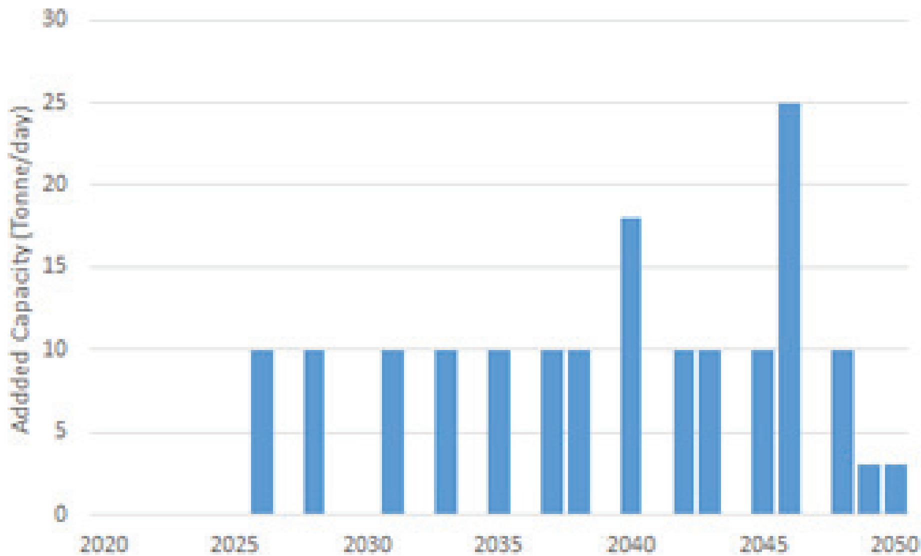

Figure 12: Additional capacity for water electrolysis.

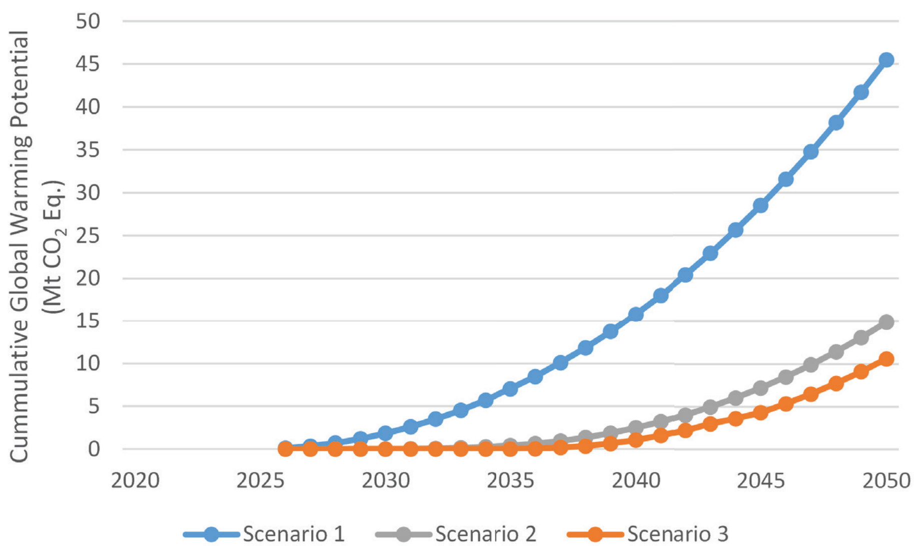

Figure 13: Cumulative global warming potential based on the scenarios.

3.72 Million USD compared with the RE scenario. The investment costs generated by the RE-ESS scenario are 14.78 Million USD lower than the RE scenario. In 2050, the cumulative planning costs for the RE and RE-ESS scenarios are 191.74 Billion USD and 192.13 Billion USD, respectively. Compared with the BAU scenario, the planning costs for the RE and RE-ESS scenarios are higher by 53.0% and 53.3%, respectively.

The BAU scenario simulates the state of road transportation based on the results of energy planning carried out by the Indonesian Ministry of Energy and Mineral Resources for the Province of Yogyakarta [20]. Without the intervention of renewable energy-based power generation technology, the environmental impact that occurs is far greater than the optimization of renewable energy sources in the provision of electricity for road transportation. Although there are shortcomings in terms of planning costs, utilizing local energy sources will increase the independence of the energy supply in Yogyakarta Province.

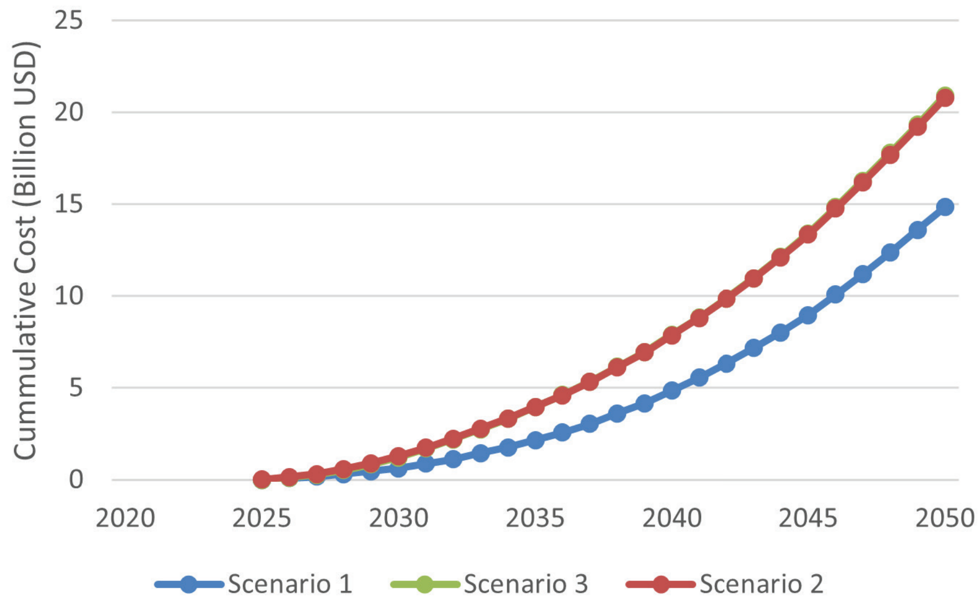

Figure 14: Cumulative planning costs based on the scenarios.

6. Conclusion

The mixed-integer linear programming optimization model was developed to analyze the potential of locally available energy in supplying electricity and hydrogen for road transport. The model was applied to a case study in Yogyakarta Province, which is one of the smallest provinces in Indonesia and which does not have fossil energy sources. The optimization model is used to analyze the role of available renewable energy sources in providing electricity and hydrogen in this province.

The results obtained show that renewable energy sources can reduce dependence on imported electricity for road transportation. In the RE scenario without ESS, less electricity is generated for road transportation and there is a higher percentage of electricity imports. In the integrated RES scenario with implementation of ESS, more electricity is generated but with a lower percentage of electricity imports. From the perspective of the impact on the environment, the integrated RES with ESS scenario produces lower GHG emissions than the BAU scenario. However, the cost of planning an integrated RES with ESS is higher than that of the BAU scenario.

The analysis can be developed to include sustainability indices, from an economic, environmental, and social point of view. By including sustainability indices, the implementation of integrated RES in the provision of electricity for the transportation sector or other sectors can be carried out more comprehensively. In addition, the proposed model can be further developed with a larger implementation scale and consist of several areas with diverse energy potentials. Thus, energy exports and imports can be analyzed more thoroughly. Furthermore, the impact of the penetration of electric vehicles needs to be analyzed in terms of power system planning and operation.

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