Green Hydrogen Modeling in Indonesia: Potential for Production, Consumption, and Greenhouse Gases Emissions

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Abstract. To overcome the climate change crisis, the Indonesian government is developing nature-based solution, one of which is green hydrogen. This is a quantitative research using emissions and energy data in Indonesia for the latest 20 years. We build a dynamic model and perform computer simulations in python. Every 1 million BOE consumption of green hydrogen can reduce greenhouse gasses (GHG) emissions by 0.06 to 0.51 billion tons of CO_2e. The resistivity of water and the power used in the are the main factors during the green hydrogen production. The best type of water is coastal seawater with a resistivity of 0.3 Ωm. Using power surplus of 0.1 GW with rate of 1.1 GW per year in coastal seawater, it is estimated that Indonesia will produces 608 million BOE Green hydrogen and achieve net-zero emissions by 2030. This research can be continued to build a green hydrogen prototype.

Keywords: Nature based solution, Greenhouse Gases (GHG), Emissions, Resistivity, Green Hydrogen.

1 Introduction

Energy consumption continues to increase pertaining to population and economic expansion, Primary energy consumption rises in the home, transportation, and industrial sectors, which has a more negative impact on living standards [3]. Numerous significant challenges pertaining to the environment and the reserves of primary energy supplies are directly tied to the interaction between population increase, energy demand, and ongoing economic advancement. These inquiries are a part of the global knowledge that, absent changes to the existing paradigms of economic and social development, the expansion of the human population, economic prosperity, and accompanying energy demand may not be sustainable for very long [1].

The primary cause for concern regarding the environment is the rise in concentration of carbon dioxide (CO_2) in the atmosphere (with the consequent increase in the greenhouse effect), which is attributed to the burning of carbon-containing fossil fuels and reconsiders responsible for the global climate change observed for many years. According to the Indonesia Energy Outlook 2019 estimate, an increase in population and living standards of the community is followed by an increase in energy demand which has an impact on the high rate of growth of CO_2 emissions if not followed by the selection of fuel types with low carbon content and the use of efficient and environmentally friendly technology. The release of CO_2 emissions resulting from burning

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energy in power plants, transportation or transportation, industry, commercial, households, and other sectors into the atmosphere in certain amounts will have an impact on global warming. To reduce the causes of global warming can be done through increasing the efficiency of energy technology and the use of energy sources with low carbon content.

The achievement of NRE by 23% in 2025 and 31% in 2050 can be done through optimizing the use of NRE for power and non-electricity plants (mandatory application of BBN), the use of electric vehicles and carrying out energy efficiency in all energy user sectors. Most of the NRE is used for power generation and the rest for the transportation, industrial, commercial, and other sectors as raw materials for a mixture of biodiesels and bioethanol. The provision of NRE is sourced from biomass, garbage, sun, wind, water, geothermal, and biodiesel.

At the core of the hydrogen project is an electrolysis installation. Hydrogen is extracted from water inside a giant container. For this reason, it takes a lot of electrical energy sourced from wind power. Hydrogen is separated from cleaned water. These are then transported to hydrogen refueling stations. In the process to obtain hydrogen, a high temperature is formed. The heat is then flowed to the local network to be channeled. That way, people's homes can be warmed in winter, without releasing CO_2 emissions.

Hydrogen fuel is a zero-emission fuel used as fuel for electricity generation along with oxygen using a unit called a hydrogen fuel cell. Like a battery, a fuel cell has an anode and cathode pole where hydrogen (H_2) and oxygen (O_2) are flowed to the two different poles. The reaction between the two poles will produce electricity and water vapor (H_2O).

This study's main objective is to identify and evaluate new renewable energy sources from hydropower, namely *Green Hydrogen*, which will later model the availability and potential possessed by Indonesia in terms of new renewable energy (EBT) production, besides that a study of green hydrogen production as one of the renewable and sustainable energy sources that are environmentally friendly in Indonesia will also be conducted.

2 Methodology

The stages of research methodology are as follows:
1. Identification and definition of the problem
2. Conceptualization of the system
3. Formulation of the model
4. Validation of the model and exploratory investigation
5. Policy simulation, execution, and assessment

2.1 Problem definition

Temperature change and the greenhouse effect. The mechanism by which the atmosphere absorbs some of the solar energy that heats the planet and moderates its temperature is known as the "greenhouse effect". Man-made developments add 'greenhouse gases' to the atmosphere leading to rising global temperatures and climate disruption. Among these greenhouse gases are numerous industrial chemicals, methane emitted from animals, plants, and landfills, and carbon dioxide, which is created by burning fossil fuels and deforestation, as well as have negative impacts on nature and the environment in the decades to come. Thus, we must significantly reduce greenhouse gas emissions.

Energy sector is one of the most important sectors in Indonesia as it is the basis for all other development. There are many challenges related to energy, and one of the things that concerns the Indonesian government is how to expand the electricity network, especially by building electricity supply infrastructure to rural areas. There are still many rural areas that often experience power outages due to inadequate infrastructure. Many places do not have access to electricity infrastructure, so people use expensive and inefficient energy sources, such as kerosene lamps and generators, or wood for cooking.

Renewable energy is an energy source that can run out naturally. Renewable energy comes from natural elements available on earth in large quantities, for example: sun, wind, rivers, plants, water, and so on. Renewable energy is the cleanest energy source available on the planet.

There are many reasons why renewable energy (EBT) became an option, including relatively inexpensive, carbon neutral, mostly non-polluting and increasingly getting support from various parties to replace non-renewable energy solutions based on fuel oil. Furthermore, implementing this technology in the community can provide opportunities for independence to the community to manage and pursue their own energy needs and solutions.

New renewable energy we focused on this research is renewable energy sourced from hydropower, namely *Green Hydrogen* which can be used as alternative energy that can be used to support emission reduction programs [4], greenhouse effects and climate change that can disrupting human ecosystems in the world, especially in this study in Indonesia. The technology used is electrolysis, where there are several different types of electrolysis technologies such as alkaline, *Proton Exchange Membrane* (PEM) and *Solid Oxide Electrolysis Cells* (SOEC). Alkaline electrolysis is the most economical and technically mature, followed by PEM technology which offers greater current density and hydrogen quality. SOEC technology combines the s quality of the other two types of electrolyzers but to this day is still in the development stage. For this reason, in this paper the analysis is focused on modeling with alkaline electrolysis and PEM.

2.2 Conceptual systems

Energy consumption consists of two parts, namely fossil energy consumption and renewable energy consumption (EBT). Increasing energy consumption will reduce the availability of energy. In the causal loop, researchers chose *green hydrogen* as one of the renewable energy sources used as a nature-based energy source.

The use of fossil energy sources as energy sources has increased emissions that continue to increase, resulting in the quality of environmental and human health declining. There is a positive influence when using green hydrogen, so that if *green hydrogen* is used as an energy source, it will increase the mind and availability of energy to meet the needs of the community. This will form an ecosystem that supports the use of new renewable energy to create a healthy environment.

The *green* hydrogen production process is sourced from water, where the hydrogen separation process is carried out by electrolysis with energy sources from solar energy and wind energy, which requires large costs. With the participation of the community to conduct research in finding technology that can support the process of forming green hydrogen, it will accelerate *the* production of *green hydrogen*. The government has an important role in accelerating the implementation of *green hydrogen* production to be used as an energy source.

2.3 Model formulation

The main purpose of water electrolysis is to produce hydrogen gas. Hydrogen gas is a chemical widely used in modern society to produce ammonia, metals, and plastics; for petroleum processing; and can also be used as a fuel. In principle, electrochemical separation of water does not require other chemicals.

There is a close relationship between "electricity" and "chemistry". One such relationship was discovered by Michael Faraday in 1833: Faraday's law of electrolysis is used to directly relate the amount of electric charge Q passed in an electrochemical cell (electrolytic or galvanic) and the amount of chemical m (kg) produced (consumed) at the electrodes of the cell [6]:

$$m = \frac{QV_iM_i}{nF} \tag{1}$$

Where:
V_i = stoichiometric number
M_i = molar mass (kg/mol)
n = number of electrons in half reaction
F = Constant Faraday (96485 C mol^{-1})

However, the electrical resistivity of pure water is very high due to the low concentration of ions. Here is the water resistivity data in Table 1.

Table 1. Water resistivity [8]

Water Kind	R (Ω cm)
Pure Water	20.000.000
Distilled Water	500.000
Rain Water	20.000
Tap Water	1.000– 5.000
River Water (Brackish)	200
Sea Water	30
Sea Water (Open Sea)	20 - 25

$$R = \rho \frac{l}{A} \tag{2}$$

Where:
R = resistance
ρ = resistivity
l = electrode distance
A = cross-sectional area of each electrode, with both electrodes having the same dimensions.

$$P = I^2 \times R \tag{3}$$

$$I = \sqrt{\frac{P}{R}} \tag{4}$$

$$Q = I \times t \tag{5}$$

$$\rho = \frac{m}{V} \tag{6}$$

Where:
ρ = density
m = mass
V = volume

Electrolysis is the most widely used method for producing high-purity hydrogen by water splitting. The electrolysis of water is based on the movement of electrons, powered by external e circuits. Alkaline, Solid Oxide Electrolyser (SOE), and proton exchange membrane (PEM) are commercially available types of electrolysers for practical applications. In the process of water separation, a certain amount of DC electricity must be applied to both electro silicones, which are separated from each other by an aqueous electrolyte that has high ionic conductivity. This applies to all three types of electrolyser systems discussed in this study. The following overall reactions occur in the electrolyser system [5].

$$H_2O\ (l) + \text{electric energy} \rightarrow H_2\ (g) + ½\ O_2\ (g)$$

2.4 Model validation and exploratory analysis

Where the model will be evaluated to find out whether the designed model can provide reasonable predictions and explanations about the system built. A model is valid if its predictions of system performance adequately mimic how the system behaves. Before a model can be used to understand or predict system behavior, it examines it and determines whether it accurately represents the system being built. The level of accuracy required for a model to be valid depends on the overall purpose of the modeling effort. To validate the model, the author uses the RMSE (*Root Mean Square Error*) formula where the validation formulas; The RMSE weighs big mistakes much more heavily than small mistakes. The following is the RMSE formula:

$$SE = \frac{1}{n}\sum\left(X_p - X_a\right)^2 \tag{7}$$

$$RMSE = \sqrt{MSE} \tag{8}$$

Where:
X_p = predicted value
X_a = actual value
MSE = Mean Square Error
$RMSE$ = Root Square Mean Error

It is important to know the source of the error as well as the total size of the error. Large errors may be due to poor models or many random glitches in the data. The total error may be large if the mode of behavior in the real system is deliberately excluded because irrelevant to the purpose of the model. While there is ultimately no substitute for plotting simulated data and actual data together, some statistical methods help decompose errors into systematic and unsystematic components.

Structural validity. A model is said to be structurally valid if its system infrastructure (as represented in system diagrams, units of measurement, and underlying equations) accurately represents the best understanding of ab-effect relationships in real systems. The system diagram should provide an accurate schematic representation of how the system works.

Predictive validity. The model shows predictive validity if the predictions of system behavior adequately mimic the real system. Running mode for some "benchmark" cases where the behavior of real-life systems can be predicted from theory or can be known through direct observation to assess the validity of the best predictions. Some possible "benchmark" cases that can be used to check predictive validity are:

- *Baseline behavior patterns*. We may know something about how systems behave under "normal" circumstances before we even build models. This knowledge may be quite detailed (e.g., "the system rotates every 25 hours with a balance of 60 units") or it may be general (e.g., "the system rotates every 20-30 days around a balance of 50-80 units"). The model should always run under conditions that correspond to this basic behavior. If the output n models match what we know about the system, predictive validity is supported.
- *Steady-state behavior patterns*. If theoretical conditions can be identified where real systems are known to exhibit steady-state behavior, these conditions can be applied to the system model and the model can be run. If the model exhibits steady-state behavior, then the validity of the if predictor is supported.
- *Runaway behavior patterns*. Sometimes it is possible to identify conditions in which the system will exhibit "escape" or "out of control" behavior. This condition can be duplicated in the model and checked.
- Exploratory Analysis, where models are used to explore systems and gain insight into how systems work. This step involves two types of analysis, namely:
- Experiments in which a system is intentionally "disrupted" by simulating a PULSE, RAMP, or STEP in one or more stream or converter systems.
- Sensitivity analysis, which helps identify those elements of the system that apply a high degree of leverage to the behavior of the system.

There are three types of sensitivity: *numerical*, *behavior mode*, and policy sensitivity. Numerical (*numerical*) sensitivity exists when changes in assumptions change the numerical value of the result. Behavioral mode sensitivity (*behavior mode*) exists when changes in assumptions change the behavior patterns produced by the model. Policy sensitivity exists when changes in assumptions reverse the impact or desirability of a proposed policy [9].

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2.5 Policy analysis

The model is applied in various conditions, for example in being implemented into policy simulation and policy evaluation [2].

2.5.1 Scenario

Based on the results of calculation simulations and models, 2 different scenarios were carried out, namely:

1. Green Hydrogen production with new and renewable energy potential:
    a) Using Green Hydrogen as fuel
    b) Without using Green Hydrogen as fuel.
2. Production of Green Hydrogen with surplus power potential of new and Renewable energy:
    a) Using Green Hydrogen as fuel
    b) Without using Green Hydrogen as fuel.

2.5.2 Software

In this study, the initial model was built using Stella software, and the final model was built using Vensim PLE. Once the model is formed in the ".mdl" format, it is translated into Python (format ". py") to be simulated. Model simulation is done inside the online Jupyter Notebook IDE provided free of charge by Google Collaboration. The considerations for doing simulations in Python language are as follows:

1. Stella's simulation is limited to 12 time periods (in this case equivalent to 12 years), because the author does not have a premium Stella license,
2. Vensim PLE are not limited to time periods, but the resulting response graph does not support multiplot, i.e. multiple plots in 1 image.
3. Python modules (libraries) needed in the process of translating and simulating models include: pysd, netCDF4, numpy, pandas, matplotlib, and seaborn.
4. The pysd module is used to read ".mdl" files and translate them into python.
5. The netCDF4 module is used to run the model and generate the model response in the form of a dataframe (table)

The numpy module is used to perform numerical operations i.e. addition, multiplication, integral, derivative and so on. The pandas module is used to manage dataframes, for example in selecting columns, deleting rows, and recognizing empty data (null entry). The matplotib and seaborn modules have almost every use for plotting (data visualization) based on dataframes. But in terms of presentation, seaborn produces more beautiful visualization.

3 Results and discussion

3.1 Casual Loop Diagram (CLD)

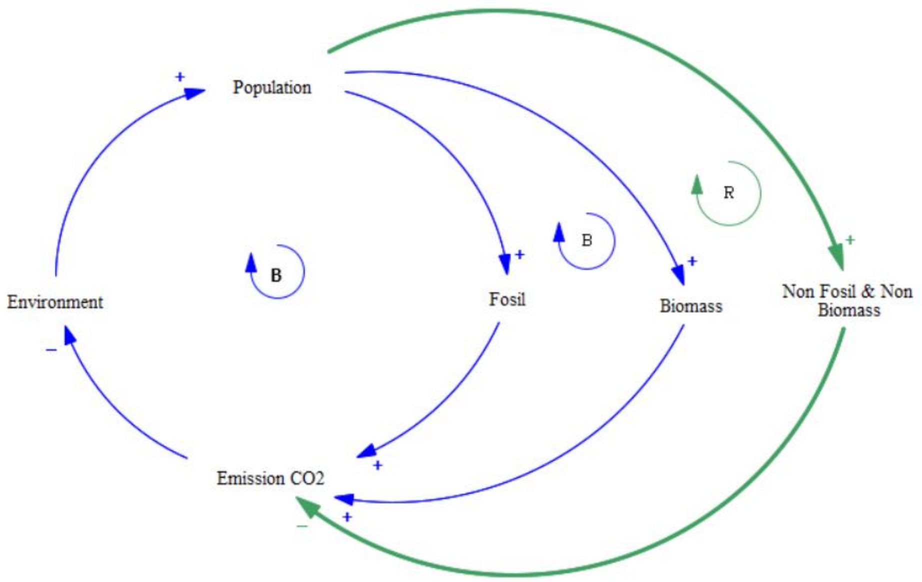

Fig. 1. Causal Loop Diagram

Figure 1 explained that energy consumption consists of two parts, namely fossil energy consumption and renewable energy consumption (EBT). As the population increases, energy consumption will increase, where the energy that is currently widely used is fossil energy that produces GHG emissions. Increasing GHG emissions from the use of fossil energy will result in a decrease in environmental quality which adversely affects living things. And the adverse impact on the environment will have a bad effect on the population rate. Therefore, many new energies have emerged that aim to reduce emissions, namely biomass energy and non-fossil and non-biomass energy. However, biomass still produces GHG emissions. Therefore, with the increase in the number of islands, the increase in the use of non-fossil and non-biomass energy will reduce GHG emissions in this case is energy derived from water, namely green hydrogen, which in the production process uses electricity sources derived from solar power and wind power , thus improving the quality of the environment and population. This will form an ecosystem that supports the use of new renewable energy to create a healthy environment.

3.2 Stock Flow Diagram

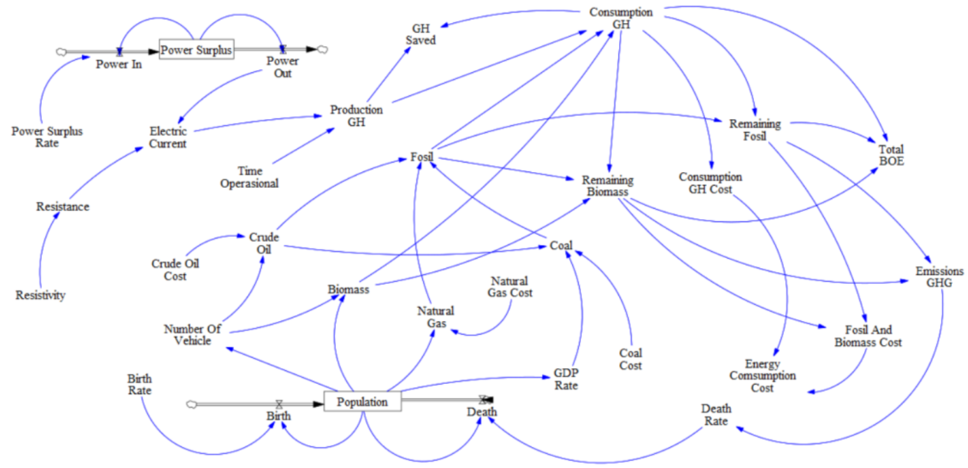

Fig. 2. Stock Flow Diagram

Production process green hydrogen, which is carried out from water sources, where the hydrogen separation process is carried out by electrolysis process with an energy source from the generator of renewable energy electricity. **Figure 2** stock flow diagram shows the formation process of green hydrogen. At stock flow diagram is carried out prediction of the amount of fossil energy and biomass needed by the community based on historical data from 2002-2019. Furthermore, regression was carried out the amount of GHG emissions caused by fossil energy emissions and biomass. Correlated GHG emissions obtained positive for fossil consumption, but negatively correlated with biomass consumption. Therefore, alternative energy is needed as a substitute for fossil energy. In this case it is Green Hydrogen. The environmental aspect observed in this study was mortality. Based on historical data from 2002-2019, a trend is obtained that when GHG emissions rise, the death rate tends to increase in **Figure 2.**

Based on data from the Statistics Indonesia report published by BPS, the calculation of electricity generated, and electricity distributed by the government to the community has an energy surplus of 3.63 GW. This value is determined by subtracting from the electricity generated minus the electricity distributed to the community.

3.3 Model validation

Model validation is done with the RMSE formula where validation is done on several model variables in **Figure 3**. Population validation graph with 0.3% RMSE value. GDP rate validation graph with an RMSE value of 6%. Death rate validation graph with RMSE value of 2%. Validation graph of the number of vehicles with an RMSE value of 5%. GHG emission validation graph with RMSE value of 6%. Graph of validation of petroleum consumption with RMSE value of 7%. Biomass consumption validation graph with RMSE value of 22%. Natural gas validation graph with an RMSE value of 11%. Coal consumption validation with RMSE value of 31%.

The population validation shows that the differences are not very significant between the actual and predicted data. This is influenced by birth, death, and migration factors. Indonesia's population growth rate from period to period has a downward trend, one of the causes is the government's policy to reduce the rate of population growth through the Family Planning program. In the GDP rate validation, there’s a very high fluctuations in GDP rate values. After the Asian Financial Crisis in the 2000-2004 period, Indonesia's economic recovery occurred with average GDP growth of 4.6 percent per year.

The period of recovery and acceleration of economic growth between 2000 and 2011 was mainly caused by the interrelated factors of increasing household consumption as well as increasing consumer purchasing power and the explosion in commodity prices in the 2000s (2000s commodities boom). The impact of the global financial crisis on the national economy in 2008, Indonesia was already affected by the global financial crisis. Sectors that weakened were trade, hotels and restaurants, industry, oil and gas and non-oil and gas exports.

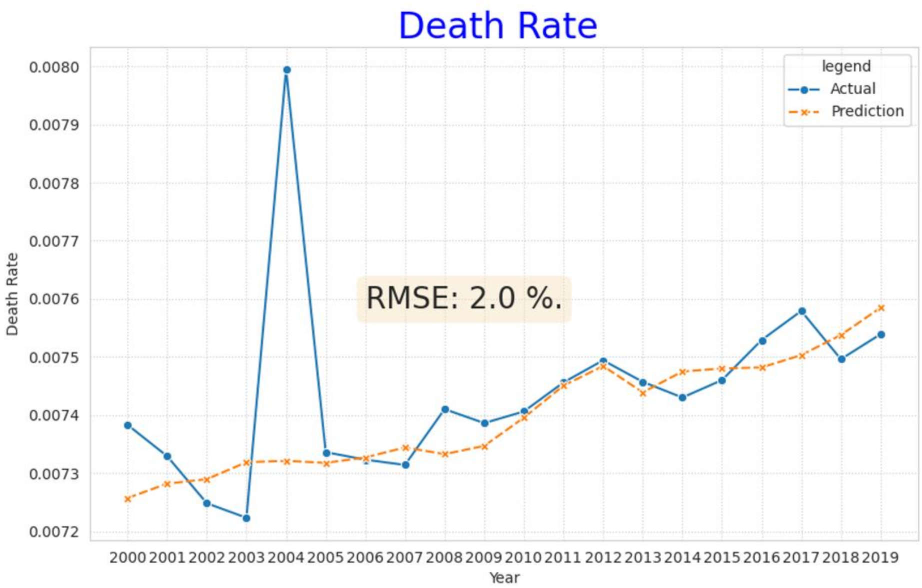

Fig. 3. Validation model death

The death rate validation graph shows that there is a spike in data between 2003-2006. During that year, on December 26, 2004, an earthquake occurred in Banda Aceh, followed by a tsunami in most areas of Banda Aceh with a strength of 9.1 on the Richter scale. The number of vehicles increased around 2010-2014 due to increasing purchasing power and consumerism in society. The existence of new regulations in 2012 regarding motor vehicle credit regulations means that the public knows and anticipates the amount of down payment that must be paid so that they can still make purchases. In general, the increase in motor vehicles before and after the implementation of the new motor vehicle credit policy in 2012 was not much different. This shows that the motor vehicle credit regulations have little effect on reducing the number of motor vehicles.

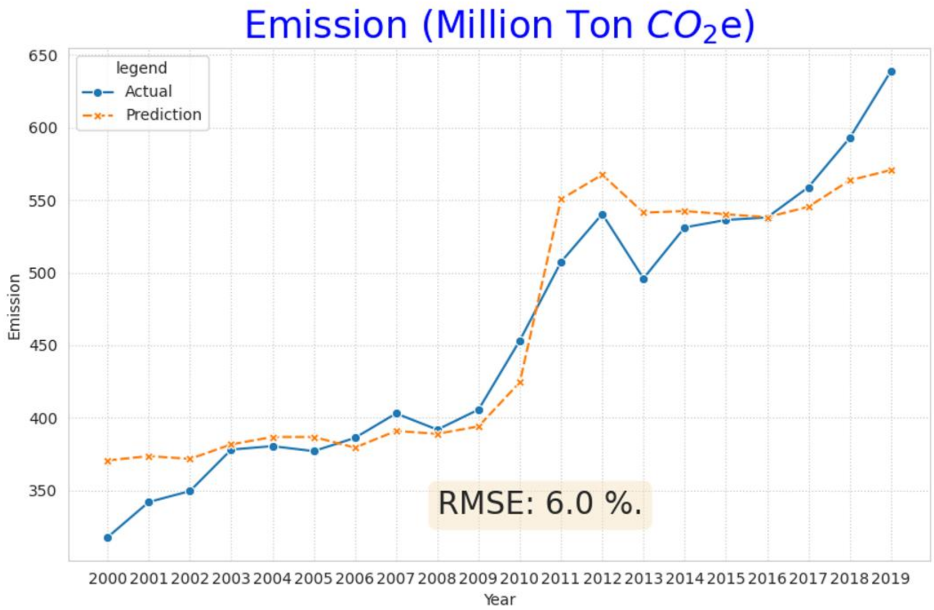

Fig. 4. Validation model GHG emission

In **Figure 4**, the validation graph for GHG emissions shows that the increase in GHG emissions is directly proportional to the increase in the number of vehicles in **Figure 5**. This is also related to the increasing population in as consumers using motorized vehicles.

The validation of biomass consumption shows that around 2010 and thereafter, biomass consumption began to fall drastically. The use of solid biomass energy in households is still widely available and easy to access. Especially in rural areas. Almost half of households still use firewood for cooking, and most of it is used indoors in rural areas, even though a program to change fuel consumption from kerosene to gas was implemented and considered successful. The impact of incomplete combustion is that the residual smoke contains dangerous substances such as dust particles, carbon monoxide (CO) and nitrogen oxides (NOx). The smoke that arises from the use of firewood in cooking activities is a major contributor to the threat to people's health, especially women. Therefore, developing the use of solid biomass in the household sector also needs to be equipped with policies and programs to increase fuel efficiency and ensure that public health is maintained.

Apart from price issues, the use of biomass materials is also closely related to competition to obtain them. In this case, domestic industry or power plants will compete with exporters to obtain biomass energy due to increasing world market demand. Increasing export market demand will encourage the growth of the solid biomass energy processing industry in the form of pellets. The problem of world market demand competition seems to be very strong. This is supported by the increasing world demand for biomass pellets, both for energy needs and the biochemical industry.

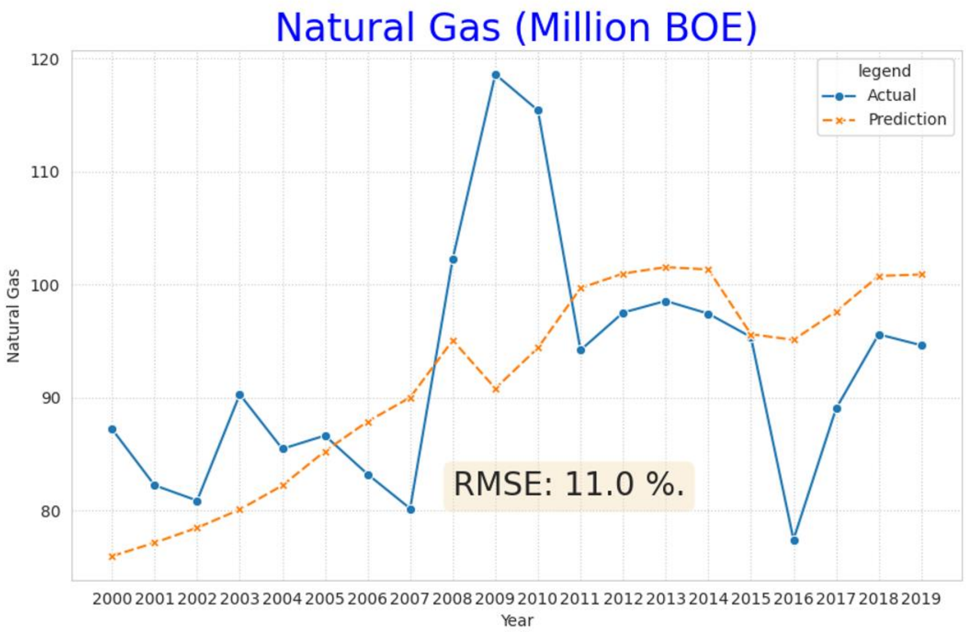

Fig. 5. Validation model natural gas

The coal consumption validation shows a spike in coal consumption after 2016. This increase in coal consumption is due to the operation of Steam Power Plants (PLTU) which has increased to meet domestic electricity needs.

4 Exploratory analysis

Based on the results of the simulations using a water source with resistivity different, water resistivity and power values used in the electrolysis process is the most sensitive variable. When simulating on offshore and coastal seawater, the simulation that produces the most hydrogen is offshore seawater with resistivity 0.2 Ωm. But the difference is not too far with coastal seawater with a resistivity of 0.3 Ωm.

The exploratory analysis was tested on simulations with the best results according to the authors of hydrogen production using surplus power. PULSE, RAMP, STEP disturbances are carried out by resistivity and power used in producing green hydrogen.

Based on PLN's RUPTL in 2021, the estimated electrical energy demand for electric vehicles (EV), assuming that the minimum average mileage range of electric vehicles in one year is 8,500 km and the maximum is 18,800 km / year, then the maximum electricity consumption of electric vehicles with an average battery capacity is 0.189 kWh / km [7]. Hydrogen fuel costs $2.5 – $3.5 per Kg (Dincer, 2012a). About 1 kg of H_2 is used per 100 km of distance traveled by car. The demo car currently has a mileage of about 500-650 km. Fuel cell driving performance and refueling time are similar to conventional cars. Therefore, fuel cell vehicles can offer conventional car mobility with very low emissions, based on H_2 production sources and systems (Dincer & Acar, 2017).

To transport hydrogen in large quantities, it must be pressurized and sent as a compressed, or liquefied, gas. In hydrogen production it is necessary to consider the magnitude of the best delivery method and the price. For instance, because it produces more hydrogen, a large, centrally situated hydrogen production station can create hydrogen at a reduced cost, but it is more expensive to deliver hydrogen because the point of use is further away. In comparison, distributed production facilities produce hydrogen at the locations to relatively low shipping costs, but the cost to produce hydrogen tends to be higher due to less production volume.

A viable hydrogen infrastructure requires that hydrogen can be delivered from its production site to an end-use point, such as an industrial facility, power plant, or refueling station. The gasoline distribution process's infrastructure consists of trucks, storage facilities, pipelines, liquefaction plants, compressors, and dispensers.

Hydrogen infrastructure delivery technology is being offered for sale. The development of new technologies, such as chemical carriers for the conveyance of high-density hydrogen and high-level fueling technologies for fuel cell transportation, will be necessary to meet the growing demand for hydrogen in the region [10].

Hydrogen storage can be done by several methods, namely: gas, chemical and hybrid. Compressed gas storage is a proven technology with most gas available in containers up to 200 bar or 300 bar. Thermodynamically, compression itself is attractive in high-pressure storage, but so is the filling of pressure vessels, which occurs through a corresponding pressure gradient. High demands are placed on pressure vessels in terms of material, design, and safety. The infrastructure includes pipelines for distribution and delivery points to fill vehicle containers or tanks.

5 Sensitivity analysis

Sensitivity analysis assists in determining which system components exert a significant amount of influence over the system's behavior. Sensitivity analysis was performed on exogenous parameters namely resistivity, power surplus, power rate, operating clock, and birth rate. The results of sensitivity analysis are presented in the form to find out in what year GHG emissions are at their maximum point and when zero emissions will be achieved.

Sensitivity analysis was performed by adding +50%, +25%, 0%, -25% and -50% from the initial data of each exogenous parameter. From the results it is known that the parameters that are most sensitive to changes in values are resistivity, power surplus parameters. Operating hours and less sensitive are birth rates.

Conclusion

Based on the results of the research and simulations carried out, the author can provide several conclusions as follows:

1. Green Hydrogen produced from water can reduce greenhouse gas (GHG) emissions
2. Green hydrogen production is greatly influenced by the resistivity of water and the amount of power used during electrolysis.
3. The most economical and efficient green hydrogen production is produced from the electrolysis process using sea water coastal.
4. A good electric vehicle is to use green hydrogen fuel compared to electric vehicles using batteries to reduce greenhouse gas (GHG) emissions.
5. To produce 1 million BOE green hydrogen, 0.42 MW of power is required within 24 hour operational hours and electrolyzed water has a resistivity of 0.3 Ωm.
6. The simulation results of green hydrogen production can answer the research hypothesis by using coastal sea water (sea water-coastal) for the electrolysis process in green hydrogen production in 2030 amounting to 608 million BOE equivalent to 123,063 MW, which is in the PLN RUPTL report for 2021-2030 projected at 443,208 MW, and 10% of the projection is 44,320.8 MW.

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