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Optimization of Electricity Generation Schemes in the Java-Bali Grid System with CO₂ Reduction Consideration

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Abstract

This research considers the problem of reducing CO₂ emissions from the Java-Bali power grid system that consists of a variety of power-generating plants: coal-fired, natural gas, oil, and renewable energy (PV, geothermal, hydroelectric, wind, and landfill gas). The problem is formulated as linear programming and solved using LINGO 10. The model was developed for a nation to meet a specified CO₂ emission target. Two carbon dioxide mitigation options are considered in this study, i.e. fuel balancing and fuel switching. In order to reduce the CO₂ emissions by 26% in 2021, State Electric Supply Company (PLN) has to generate up to 30% of electricity from renewable energy (RE), and the cost of electricity (COE) is expected to increase to 617.77 IDR per kWh for a fuel balancing option, while for fuel switching option, PLN has to generate 29% of electricity from RE, and the COE is expected to increase to 535.85 IDR per kWh.

Abstrak

Optimasi Skema Pembangkitan Listrik pada Sistem Jaringan Listrik Jawa-Bali dengan Memperhatikan Aspek Pengurangan Emisi CO₂. Penelitian ini membahas tentang masalah pengurangan emisi CO₂ dari jaringan listrik Jawa-Bali yang pembangkitnya terdiri dari kombinasi berbagai jenis pembangkit yaitu: batubara, gas alam, minyak, dan energi terbarukan RE (yang meliputi *solar cell*, panas bumi, tenaga air, angin, dan gas dari sampah). Permasalahan dimodelkan dengan program linier dan dipecahkan dengan menggunakan bantuan perangkat lunak LINGO 10. Dalam penelitian ini digunakan dua opsi pengurangan emisi CO₂, yaitu keseimbangan bahan bakar (*fuel balancing*) dan penggantian bahan bakar (*fuel switching*). Hasil penelitian menyebutkan bahwa untuk mencapai target pemerintah yaitu pengurangan emisi CO₂ hingga 26% di tahun 2021, Perusahaan Listrik Negara (PLN) harus membangkitkan listrik hingga 30% dari sumber energi terbarukan dan dengan biaya listrik (*cost of electricity* COE) akan meningkat menjadi Rp. 617.77 per kWh untuk opsi *fuel balancing*, sedangkan untuk opsi *fuel switching*, PLN harus membangkitkan listriknya sebesar 29% dari RE dan dengan COE diperkirakan meningkat menjadi Rp. 535.85 per kWh.

Keywords: linear programming, electricity generation, CO₂ mitigations, renewable energy.

1. Introduction

Fossil fuels burning contributes 80% of the energy consumption in the world (UNFCCC, 2008). Burning of fossil fuels produces green house gases (GHG) that cause global warming and destroy the earth. GHG emissions which result from fossil fuels burning have increased extensively over the past two decades. Since 2009, many countries have committed to reduce GHG emissions by 2020 with the aim of inhibiting the pace of global warming (UNEP, 2011). Indonesia is among the five emitters of GHG in the world. In 2000, Indonesia was accounted for 12% of the world's GHG emissions, an increase of 27% from 1990 levels (Globe International,

2011). To reduce regional GHG emissions, Indonesian government's was issuing the Presidential Regulation No.61 of 2011 on the reduction of GHG by 2020 by 26% on their own effort or as high as 41% with the international assistance.

Table 1 shows the composition of CO₂ by fossil fuel sources by sector. The data show that the industrial activity remains a major CO₂ emitter. CO₂ emissions of the transport sector grew steadily but were lower than the industrial sector. Emissions from the electricity sector grew most rapidly since the mid-1990s. This shows the same issue: the industry is the fastest CO₂-producing sector, but the electricity sector is experiencing the fastest

growth in emissions. When the total emissions grew about 7.5 percent per year, emissions from electricity grew at about 11 percent per year over the last two decades.

Given the growth in power generation capacity and the increase of CO₂ emissions in Indonesia, it makes sense to require a power generation capacity expansion plan to have to meet the electricity needs while reducing overall CO₂ emissions at the same time. Therefore, this study aims to obtain an optimization model to minimize the cost of power generation and CO₂ emission reduction targets using a mix of fossil fuels and renewable energy. The research question in this study will be: "With the CO₂ reduction target, what are the best mixed power generation plants in Indonesia with the minimum cost but those have to meet future electricity needs?"

Some previous researchers have developed models of energy power generation technologies in the context of emissions reductions. Rubin *et al.* (2005) developed the Integrated Environmental Control Model/Integrated Environmental Control Model (IECM) as a comparative analysis of various environmental controls for fossil-fueled power plants. The model was built in a modular fashion that allows the new technology to be incorporated into the overall framework. Then the user can configure and evaluate a specific environmental control system design. Environmental control options include a variety of conventional and advanced systems to control SO₂, NO_x, CO₂, particulate matter, and mercury emissions. The IECM framework is expanded to include a wider array of options and power generation systems of multi-pollutant carbon management.

Han (2012) planned a power plant based on CO₂ mitigation (Carbon Emission Trading & Carbon Capture and Storage). The goal is maximizing total benefits and minimizing the financial risk while meeting power needs. Trade off between risks and profits is taken into consideration in the model. Bai and Wei (1997) developed a linear programming model to evaluate the effectiveness of CO₂ mitigation options for the electricity sector in Taiwan. Strategies include alternative fuels, reducing the peak load, energy conservation, improved efficiency of power generation, and CO₂ capture technologies. The result shows that the combination of peak production declines and increases efficiency of power plants with CO₂

conservation, without considering the cost-effectiveness, an effective strategy to reduce CO₂ emissions significantly.

Iniyana *et al.* (2006) developed a linear program to determine the optimal allocation of final energy by a variety of environmental constraints. The paper estimates that the demand and supply of energy for 2020 will be using the econometric model. The gap between energy demand and energy supply will be met by renewable energy by using models Optimal Renewable Energy Mathematical (OREM) based on cost, efficiency, social acceptance, reliability, potential of renewable energy, and energy requirements. The scope of the renewable energy that exists in this paper is limited to a few types of renewable energy.

Hashim (2005) developed a model using Mixed Integer Linear Programming (MILP) and implemented in GAMS (General Algebraic Modeling System) to reduce CO₂ emissions from the electricity grid contained in Ontario. The number of different power generation plants, such as coal, natural gas, nuclear, hydroelectric, and alternative energy, is to be variable. The model is applied in three different operating modes: (1) economic mode, (2) environmental mode, and (3) integrated mode. The integration model combines the goals of both economic and environmental modes using an external pollution index as a conversion factor to the cost of pollution. However, the analysis in this paper is that the static what? is constant, while for the demand for the electricity supply in the real situation there is a high variability in the electricity demand. The optimization model for renewable energy generation for the country has also been studied by Cong (2012). Cong proposed a new model, Renewable Energy Optimization Mode (REOM) combined with a model of the learning curve, technology diffusion models and prospects for economic development in the future to analyze the development of the three sources of renewable energy (wind power, solar power, and biomass energy) in China.

The purpose of this paper is to determine the maximum possible capacity of various sources of renewable energy generation in order to plan the construction of the power grid including environmental aspects in the study.

Table 1. Emission per Sector in Indonesia

Category	Fossil source Type (Mt CO ₂ year of 2007)				Emission Portion (%)	Growth 1990-2007 (%)
	Coal	Oil	Gas	Total		
Industry	31.9	35.4	50.7	118	35	48
Electricity	54.9	25.2	9.9	90	27	170
Transportation	-	78	-	78	23	74
Residential	-	41	9	50	15	71
Total	86.8	179.6	69.6	336	100	80

From a variety of existing research, it is clear that GHG emission and economic aspects should be considered in evaluating the power generation mix with a different power supply. The holistic analysis needs to be done in order to meet the ever demand increase for electrical energy supply with respect to environmental and economic aspects. Indonesia should find a sustainable energy mix in order to realize the challenges of the future. Therefore, renewable energy, such as solar, wind, geothermal, and biomass, has been introduced as a mitigation strategy to reduce CO₂ emissions (Hasan *et al.*, 2012).

2. Methods

Superstructure development. The superstructure concept represents all possible configurations of alternative electrical energy. The concept can be very complex if the sources have many varieties. Units of fossil power plant energy sources that were analyzed in this study include: coal, natural gas, petroleum. Petroleum further consists of high speed diesel, HSD & marine fuel oil, and MFO. Moreover, the renewable energy power generation sources include solar, geothermal, hydro, wind power, and biomass. Six types of new generating unit candidates in this study are: geothermal plant, solar farm, biomass plant, hydro, wind plant, and ultrasupercritical (pulverized) coal plant.

For the purpose, two CO₂ mitigation strategies are applied: Fuel Balancing (base model) and Fuel Switching. In the fuel balancing strategy, the operation of the two plant types, i.e. fossil-fueled plant and renewable energy plant, will be adjusted to meet the energy demand. When the CO₂ reduction targets are put in the constraint, power plants that produce low emissions, such as hydroelectric and geothermal power plants, will be prioritized to get into the power system. Fuel switching strategy will change the use of petroleum gas in the power plant, combined cycle and gas engine (PLTMG). Direct fuel switching will also reduce CO₂ emissions because they have lower gas emissions than petroleum emission factors. When the fuel of the power plants is switched, there will be no cost to retrofit or to replace the technologies, but it will be additional investment for installing gas pipelines and gas tank.

Mathematical model. This study has adopted a mathematical model proposed by Muis *et al.* (2010). The model consists of an objective function and twelve constraints. This model was implemented for the Java-Bali interconnection system that takes into consideration the operating cost of the existing generating units and the investment costs of new units while at the same time fulfilling the CO₂ reduction targets. For the purpose, the objective function of the model is to minimize the cost of electricity generation which consists of the operating cost in place units and investment costs and operating

costs of new generating units. The objective function of the model is represented on Equation 1.

The complete mathematical model is as follows:

$$\begin{aligned} \min Z = & \sum_{i \in F} \sum_j V_{ij} E_{ij} + \sum_{i \in NF} \sum_j V_{ij} E_{ij} \text{ (Operation } O \& M \text{ PP)} \\ & + \sum_{p \in New} S_p^{new} E_p^{new} y_p \text{ (Investation cost New PP)} \quad (1) \\ & + \sum_{p \in New} M_p^{new} E_p^{new} \text{ (New } O \& M \text{ PP)} \end{aligned}$$

$$\left[\sum_{i \in NF} E_i^{NF} + \sum_{p \in New} E_p^{New} + \sum_{i \in F} \sum_j E_{ij} \right] \geq Demand \quad (2)$$

$$E_{ij} \leq E_{ij}^{max} X_{ij}, \quad \forall i \in F, \forall j \quad (3)$$

$$E_i^{NF} \leq E_i^{max}, \quad \forall i \in NF \quad (4)$$

$$E_p^{New} \leq E_p^{max} y_i, \quad \forall p \in New \quad (5)$$

$$F_{ij} \geq l_{ij} \times X_{ij}, \quad \forall i \in F, \forall j \quad (6)$$

$$F_i \geq l_i, \quad \forall i \in NF \quad (7)$$

$$F_p \geq l_p \times y_p, \quad \forall p \in New \quad (8)$$

$$E_{ij} = f_{ij} E_i^{max}, \quad \forall i \in F \quad (9)$$

$$E_i = f_i E_i^{max}, \quad \forall i \in NF \quad (10)$$

$$E_p = f_p E_p^{max} y_p, \quad \forall i \in New \quad (11)$$

$$\sum_{i \in F^C} CO_2^F ij_{ij} E_{ij}^F + \sum_{p \in P^{new}} CO_2^{new} E_p^{new} \leq CO_2 \text{ lim} \quad (12)$$

$$V_p^{RE} E_p^{RE} \leq R_p, \quad \forall p \in New \quad (13)$$

Index: i = power plants in the Java-Bali grid system

where $I = 1, 2, \dots, 84$

j = plant fuel type where $j = 1, 2, \dots, 9$

p = a new power plant candidate where $p = 1, 2, \dots, 33$

Sets: F = for a fossil power plant where $F = 1, 2, \dots, 35$.
 NF = non fossil power plant where $NF = 1, 2, \dots, 49$.
 New = for a new power plant where $New = 1, 2, \dots, 33$.

Binary Variables:

$$x_{ij} \begin{cases} 1, & \text{plant } i \text{ is operated with fuel } j \\ 0, & \text{otherwise} \end{cases}$$

$$y_i \begin{cases} 1, & \text{new plant } i \text{ is operated} \\ 0, & \text{otherwise} \end{cases}$$

Decision Variables:

E_{ij} = actual electricity generated from plant i with fuel type j (in MWh)
 E_p^{new} = electricity generated from new plant p (in MWh)

Parameters:

V_{ij} = O&M costs of existing power plants i with fuel type j (IDR/MWh)
 S_i^{new} = Capital cost of new power plants i (IDR/MWh)
 M_i^{new} = O&M cost of new power plants i (IDR/MWh)
 R_{ij} = the fuel switching cost from coal to natural gas (IDR/MWh)
 $l_i(l_{ij})$ = the annual minimum capacity factor of the plants
 $f_i(f_{ij})$ = the annual capacity factor of plant i
 CO_{2ij} = CO_2 emission from the i plant with fuel j over the generated electricity (ton CO_2 /MWh)
 CO_{2p} = CO_2 emission from a new plant (ton CO_2 /MWh)
 V_i^{RE} = the conversion factor from the RE plant to electricity for fuel type j (ton/MWh)
 R_p = RE availability for new plant p

Equations (2)–(13) are the constraints of the model. Equation (2) is electricity demand constraint. This constraint will make sure that the electricity needed in the year 2021 will be fulfilled by both existing and new plants. In this case, the electricity generated is set at least the same as the demand. Equations (3)–(5) are operational constraints that state that the electricity produced by all plants should not exceed the full installed capacity. Equations (6)–(8) are a lower bound operational constraint. The annual capacity factor of each plant must be greater than a certain minimum value; otherwise, the plant will be shut down. Equations (9)–(11) relate between the annual capacity factor and electricity generated. Equation (12) restricts each plant, either the existing or the new ones, should emit CO_2 emissions less than a specified government target. Meanwhile, the last equation, equation (13), is RE availability constraint. Energy from renewable resources cannot exceed the availability of renewable energy resources.

Data collection. Data collected for this study were electricity demand, CO_2 emissions for each existing and new plant, actual electricity production, O&M costs, fuel costs, fuel switching costs and investment costs, plant capacity factors. These data were projected for the year 2021. 2021 is the year when the 26% emission target is set to be reached.

3. Results and Discussion

Electricity mix optimization of a fuel balancing strategy. For a fuel balancing strategy, the cost of electricity (COE) is 451.87 IDR/kWh with the total CO_2 emissions in 2021 of 212,540,143.30 tons. This value is slightly better than the PLN's RUPTL (state owned electricity company's electricity long range plan) which is 214 million tons. When the CO_2 reduction is imposed, the COE is obtained as 617.765 IDR per kWh with CO_2 emissions as 158,360,000.00 tons. Imposing CO_2 reduction is indeed reducing the emissions, but it increases the electricity price.

Electricity fuel mix results and RE fuel mix results are shown in Figures 3 and 4, respectively.

As shown clearly from Figure 3 imposing the CO_2 emission reduction target, the utilization of coal as power plant fuel decreases from 66% to 43% of the total electrical energy utilization. Coal as the fuel plant is not an attractive option when the target of 26% reduction in CO_2 is put into the system constraints since the plants produce more emission. To meet CO_2 reduction targets, PLN should prioritize plants with low emissions, such as natural gas and the RE power plant. This situation is clearly shown in Figure 3. Another impact of the imposing CO_2 emission reduction target is that the RE utilization option increases more than double.

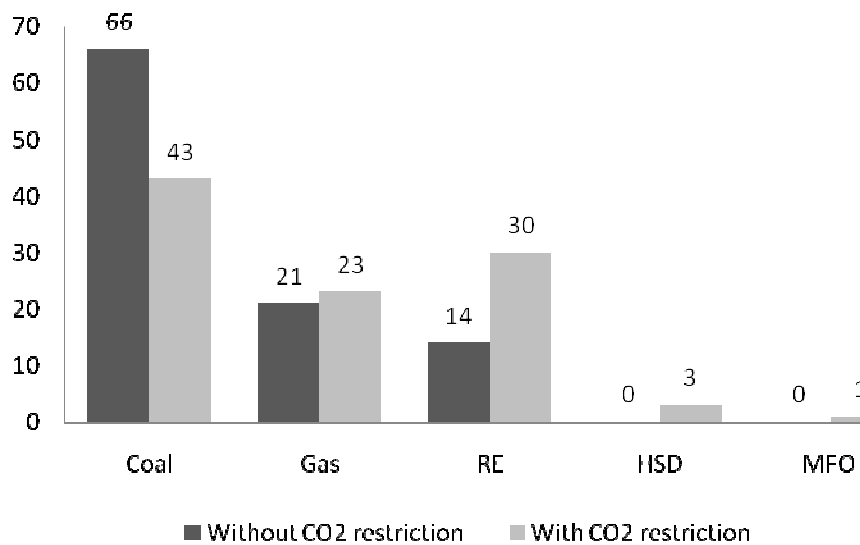


Figure 3. Electricity Fuel Mix in 2021

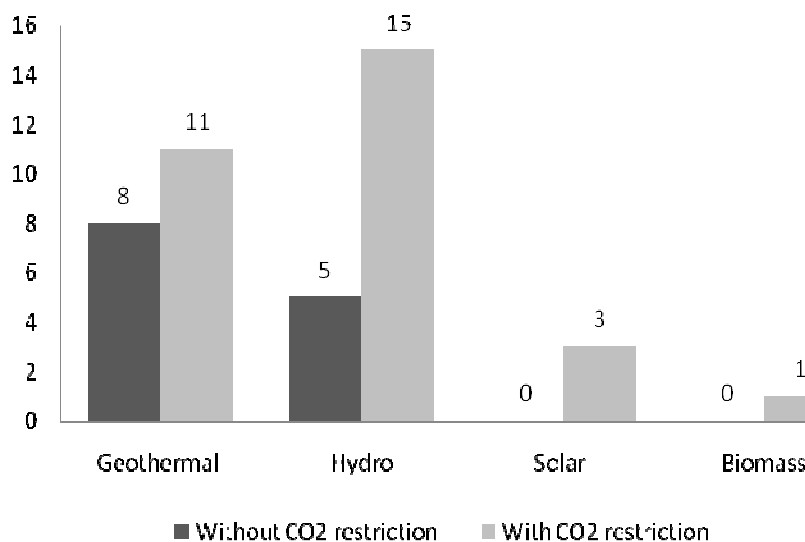


Figure 4. RE Fuel Mix in 2021

Further explanation is depicted from Figure 4. Not only does the portion of RE fuels increase, but the fuel type is also more diverse. When the 26% reduction is imposed, solar and biomass appear as fuel alternatives besides geothermal what? and hydroelectric what? However, suppressing CO₂ emission is not free. The trade off is a higher electricity price. In this scenario, petroleum in a form of HSD and MFO is still used since they release less CO₂ emissions than coal, even though their fuel prices are higher.

For the electrical energy mix, NRE generation technologies contribute up to 30% of the total electrical energy utilization. Utilization of NRE mostly comes from existing plants that have been in operation before,

such as the hydroelectric and geothermal power plants and from the development of new generating units, such as hydropower, geothermal, wind, and Biomass plants. Utilization of solar energy as electrical energy only comes from purchasing electricity from IPP.

The mix plant type in Figure 5 shows that plants which have been in operation are generally dominated by fossil fuel, such as coal, natural gas, and oil that emit CO₂ emissions. These existing plants produce less electricity. To fulfill the demand, some additional plants are needed. Since there is no CO₂ emission restriction, like shown in Figure 5, the new proposed plants are dominated with coal plants (80%).

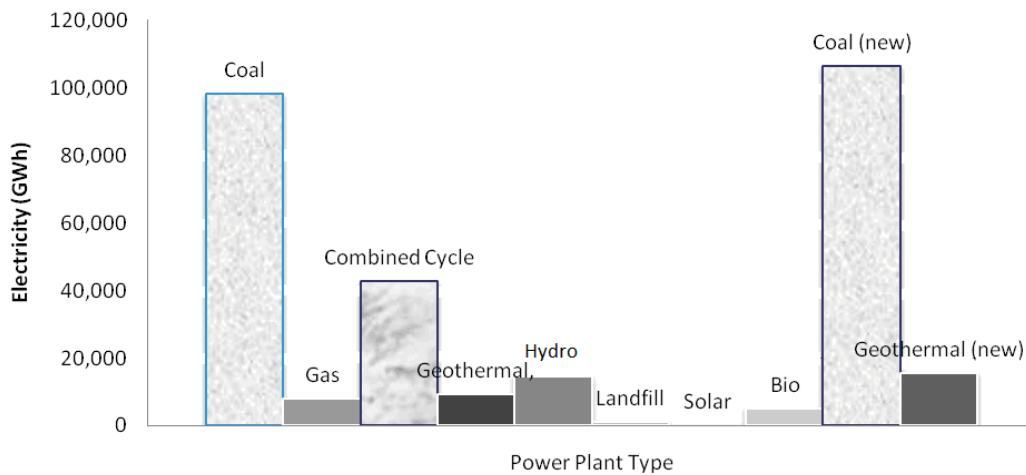


Figure 5. Power Plant Types Mixed without the CO₂ Target

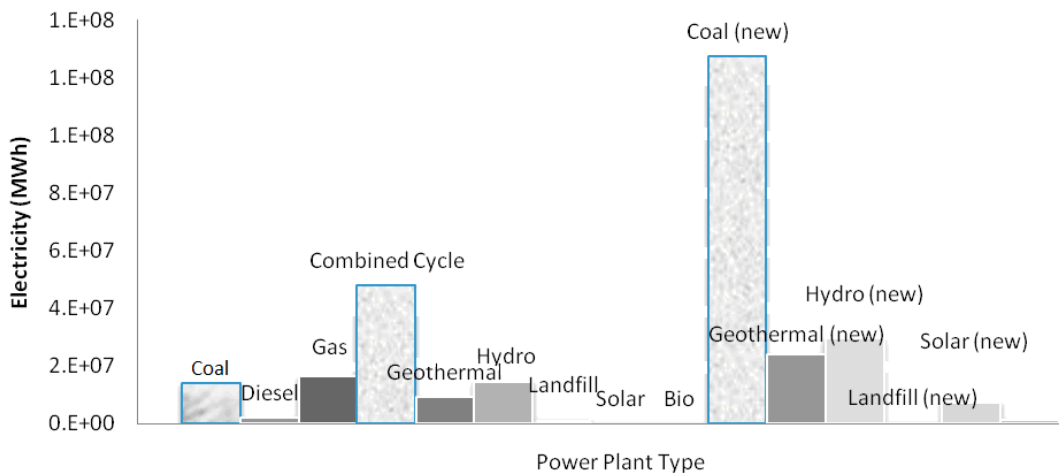


Figure 6. Power Plant Mixed with 26% of the CO₂ Target

When CO₂ emissions are applied, the energy mix is composed with more diverse sources as shown in Figure 6. With this option, a combined cycle plant that produces less GHG emission dominates the energy mix, and even a diesel plant contributes to the energy mix. However, when considering new plant expansion, this emission restriction forces the utility company to utilize more NRE sources, such as geothermal power, hydro power, and solar plants as well. As a result, new coal plants just contribute 67% of the total new plants compared to 80% when the restriction is relaxed.

Electricity mix optimization of the fuel switching strategy. PLN plans to transform an oil based power plant to a gas power plant, combined cycle and gas engine plants. This fuel switching strategy will directly reduce CO₂ emissions because of the lower gas emissions than the petroleum CO₂ emission factor.

The COE when the fuel switching strategy is implemented is 434.62 IDR/kWh. This COE is a bit less than the

COE of the fuel balancing strategy mentioned earlier. For the fuel switching strategy, the investment cost includes gas pipelines installation to transport the gas from transmission pipelines closest to the plant and tanks. The length of gas pipelines to be installed to connect 11 units and a combined cycle power plant is about 584 miles long. For this strategy, the CO₂ emissions produced by 2021 are estimated to become 214,000,000 tons. When this strategy is coupled with implementing the emission reduction target, the COE is 535.85 IDR/kWh and with the CO₂ emissions going down to 158,360,000 tons.

The electricity mix fuel switching strategy is shown in Figure 7 and Figure 8.

Figure 7 shows that, to achieve the CO₂ emission reduction target by using the fuel switching strategy, the portion of coal used as power plants' fuel decreases from 66% to 43%. Large-scale coal plants will increase the level of CO₂ emissions; therefore, these plants are not an attractive option when the target of 26% reduction in

CO₂ is put into the system constraints. Utilization of natural gas also increases from 22% to 28%. The increased use of natural gas as fuel due to substitution of petroleum fuels in a combined cycle power plant and natural gas. The use of petroleum is as fuel electricity generation using only petroleum type High Speed Diesel (HSD) by 1% because there are some steam generating units that are still using HSD as fuel as well as coal. Therefore, some operating power plants using coal instead of the HSD given emission factor of coal generate higher emission? (this sentence is confusing! Power plants are higher than emissions? That does not make sense!) than the emission factor of HSD.

To meet CO₂ reduction targets, PLN prioritizes power plants with low fuel emission plants, such as natural gas

and RE generation technologies, i.e. hydroelectric and geothermal plants, and even the trade-off is a higher electricity price. Figure 8 shows that the geothermal plant percentage is almost twice the CO₂ restriction applied. Even hydro plant utilization becomes triplet with this scenario.

Mix types of power plants are shown in Figures 9 and 10. At the conditions of business as usual, in Figure 9, the dominated plant is the power plant that has been operating to produce electricity. This is because the installed capacity plant is greater than the capacity of other plant types. For the new development, the result is not that different from the fuel balancing strategy.

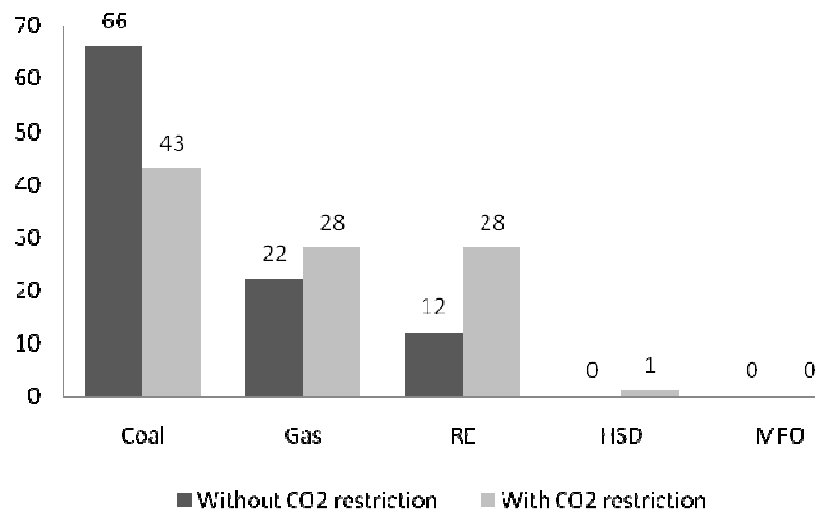


Figure 7. Fuel Switching Electricity Generation Mix

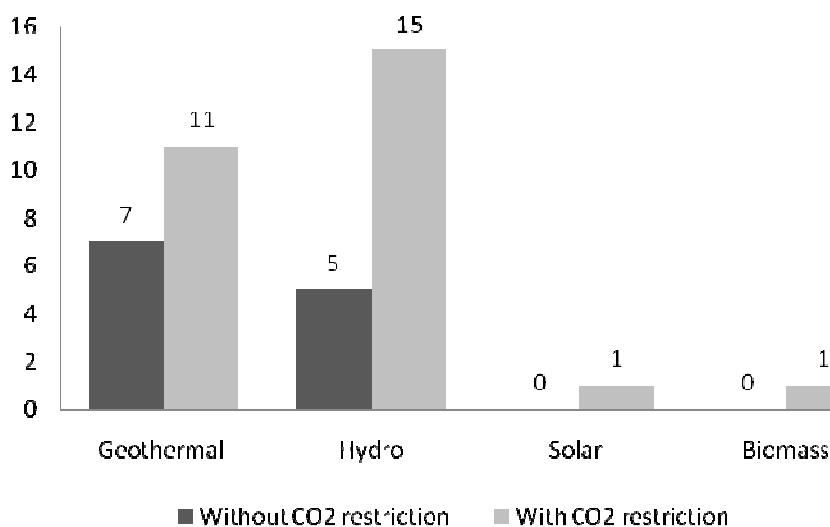


Figure 8. Fuel Switching Mixed Electricity Generation with 26% of the CO₂ Target

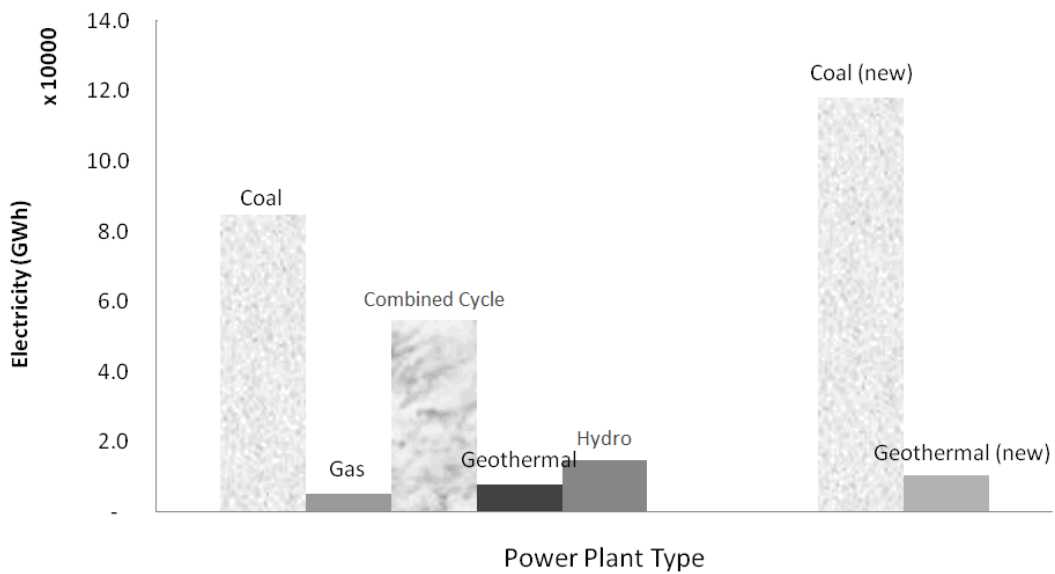


Figure 9. The power Plant Mix with the Fuel Switching Strategy

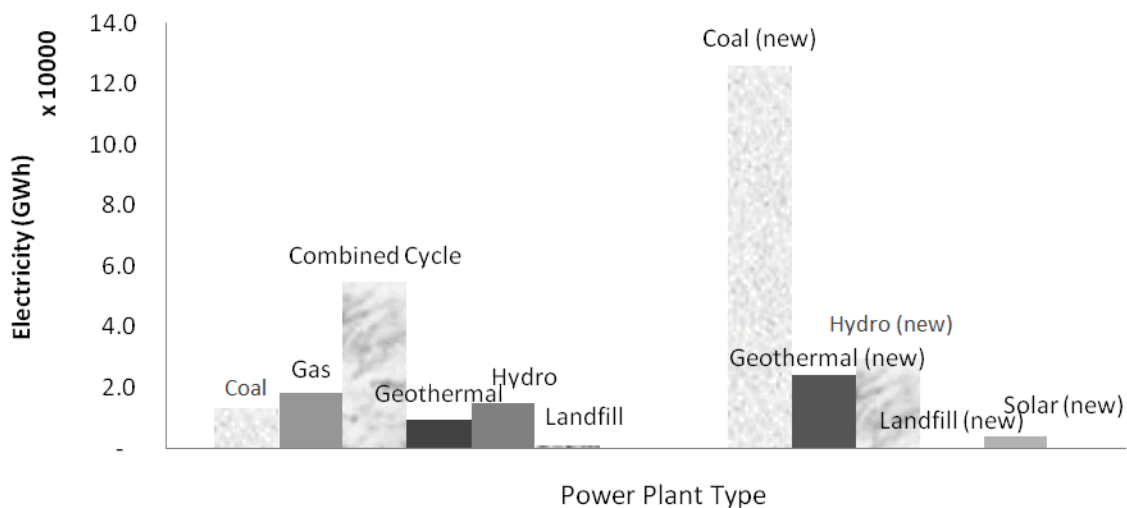


Figure 10. The Fuel Switching Strategy Power Plant Mix with 26% of the CO2 Target

However, to achieve CO₂ emission reduction targets, existing generating units produce less electricity. This is because the units already in operation are generally dominated by fossil fuel, such as coal, natural gas, and oil that emit large CO₂ emissions when operated. The use of a combined cycle plant becomes dominant because the entire combined cycle fuel produces low-emission than natural gas. Comparing Figures 6 and 10, the fuel switching strategy is about 2% on using a coal plant for new plants.

Table 2 shows the summary of each scenario. For both scenarios, imposing the CO₂ restriction drives to use more NRE sources of energy. For both scenarios, the NRE portions become double. These conditions furthermore

generate less CO₂ emissions by slightly more than one fourth. However, conflicting values cause the COE to occur. The COE for the fuel balancing strategy without 26% of the CO₂ emission reduction intervention (a base model) is 451.87 IDR/kWh, while for the fuel switching scenarios, the cost is 434.62 IDR/kWh, but the portion of RE utilization is reduced from 14% in the strategy of balancing fuel to 12% in the fuel switching strategy. When the 26% reduction target of CO₂ emissions is put into the model, the base model produces the COE of 617,765 IDR/kWh, while for the fuel switching scenarios it is 535.85 IDR/kWh. The switching scenarios have less COE compared to a fuel balancing model, but unfortunately its NRE portion also drops from 30% to 29%.

Table 2. Result Summary

Scenario	COE (IDR/kWh)	Portion of NRE (%)	CO ₂ Emission Reduction (k ton)
Basic Model (Fuel Balancing)	451.87	14	212,540.14
Basic Model with 26% CO ₂	617.77	30	158,360
Fuel Switching Model	434.62	12	214,000
Fuel Switching Model with 26% CO ₂	535.85	29	158,360

4. Conclusions

The mathematical model developed for configuring the type of planning power plants and energy sources can be used as a tool to achieve government target to reduce CO₂ emissions by 26% by 2021. Using the model, the lowest electricity cost to meet the electricity demand of the grid and at the same time fulfilling the CO₂ reduction target is 535.85 IDR/kWh. This COE is achieved though utilizing fuel switching strategy.

Lifting up the utilization of NRE as electrical energy source will reduce CO₂ emissions on one hand but it will increase COE. While fuel strategy or fuel switching from oil to natural gas in power generation unit will reduce the COE, but on the other side it will reduce the portion of NRE utilization.

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