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Combining Parameters of Fuel and Greenhouse Gas Costs as Single Objective Function for Optimization of Power Flow

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Abstract

The Kyoto Protocol is a protocol that highlights on greenhouse gases that have been adopted by many countries. Based on this protocol, power plants that produce emissions are encouraged to pay compensation. Conventionally, optimization of fuel mix in the electric power system components has not involved emission charges on the electricity system. This paper proposes a single objective function of a mathematical model for the calculation of power flow optimization involving greenhouse gas emissions costs to the fuel cost function. The single objective function derived using the mathematical model approach with linear heat rate function, in order to get the relationship between the fuel cost function with GHG emission. Namely, the function of energy costs as a combination of fuel costs and GHG emission costs can be shown as a quadratic function.

Keywords*: heat rate, fuel cost, a GHG costs*

1. Introduction

The study of energy and emissions management has been a lot written in the studies, but the objective function was discussed separately. Some examples of this can be traced in the books [1, 2] or in the papers [3-7]. Adoption of emissions regulations can be traced within the Kyoto Protocol. These Protocol primarily regulates greenhouse gas (GHG) emissions, i.e., as emissions gases from combustion results indicated to be the cause of global warming. In Indonesia, the Kyoto Protocol has been adopted with the name is the Clean Development Mechanism. In the electricity sector, power systems are expected to manage green energy in accordance with the provision [8]. The technique for managing green energy is to minimize emissions in electrical systems. One of the preconditions for the minimization of electrical systems is the selection of appropriate models to be used as an objective function [9].

According to Zhu [10], that the general problem OPF (Optimal Power Flow) is to obtain the optimal setting of a grid system. Namely, in a way that optimizes the objective function. The objective function can be the cost of power generation, grid losses, and emissions in power plants, load shedding, and also the limitations of the operating device. Furthermore, according to Soleman [9], the use of OPF with the objective function in the form of emission index is one of three strategies to reduce air emissions. The other two is a direct pollutant reduction strategies and strategies for the exchange of fuel with low-pollution fuel.

In this paper, will be merging two objective functions related to electric energy generation that is about the cost of power generation and GHG emissions due to combustion. This paper will conduct a formulation search to incorporate GHG emission as additional of the fuel parameters when used as an overall energy generation. That is to get a single objective function for an optimization of the power system that involves the costs of emissions and fuel.

In the combustion of fuel will be generated energy and exhaust emissions. The model of the fuel combustion system into this energy and flue gas can be reviewed as two objective functions. Namely the objective function of fuel and the objective function of combustion emissions. But in this paper, the two objective functions will be combined into a new purpose function that is the purpose of the combustion function. This new objective function will generate

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new function parameters, which consist of fuel function parameters and GHG emission function parameters.

In the description of this paper will be a search to get the parameters combined above. Namely by using the performance curve as the heat rate curve of the power plant. The search results on the fuel cost function of the heat rate have discussed in the papers, among others about the modeling cost curve [11,12]. But for the relationship of GHG emissions and fuel to heat rate is not writing clearly. In this paper, there will be a deterministic theoretical review of the relationship between heat rate and GHG emissions and fuel. So it will get important parameters related to the emissions, fuel and heat rate of a power generation.

This paper describes the parameters of a fuel cost function and GHG emission cost as a single function with the parameters depending on the component of the heat rate, fuel composition, fuel price, and GHG emission price. This is consistent with the search results of GHG emission paper i.e. by using a cost estimation approaches such as reference at [13]. The joining of parameters so that it becomes a deterministic objective function makes it easy to optimize the electrical system which involves the function of fuel cost and emission cost. Thus a method of deterministic classical optimization such as interior point [14], it can be done. In this paper, the simulation will be performed using the interior point method.

According to the Kyoto Protocol on GHG, the process of burning fossil fuels for electricity generation will bring CO_2 emissions as a result of direct combustion, and the reaction of nitric oxide (NO) to nitrous oxide (N_2O) from the reaction of fuel in the combustion process as well as the reaction of combustion air at high temperatures, see [15-22]. Nitrous oxide is relatively stable at low temperatures so the N_2O gas goes out from the stack also becomes a greenhouse gas, like CO_2 gas. According to the Kyoto Protocol, N_2O has emission factor equivalent to 310 CO_2 emissions. In addition, the combustion of fuel gas often remains unburned CH_4 gas is vented to the atmosphere, according to the Kyoto Protocol also includes material GHG emissions [8]. This gas is usually very small in number, but have the potential GHG or CO_{2e} by 21 times that of CO_2.

And then, in this study will be a mathematical formulation to obtain the objective function model, for the operating costs consist of the fuel cost and the GHG cost, with the condition of stoichiometry. GHG cost is primarily the cost of carbon dioxide equivalent (CO_{2e}) emissions. This objective function model is in the form of merging with the fuel costs and emissions costs in the operation of the electrical system, to obtain the sequence of unit de-commitment and the results of the calculation of the value of the optimization.

From a reference [22], it is known that a decrease heat rate results in reduced greenhouse gas emissions, due to GHG emissions depends on the amount of fuel burned at power plants. In this study, we will use the approach heat rate to as a base model of the electric energy generation cost function.

In this paper will try outlined that the model approach quadratic function to model of the cost function GHG emissions and fuel cost by using basic functions of linear heat rate, it is still good enough to use. Using a model approach quadratic function is presumably very easy to get the parameters of the model function. After getting the objective function can be performed simulation optimization in power system operation.

2. Problem Formulation

Combustion of fossil fuels in power plants, consisting of mainly three different combustion reactions [15,23]. The first is the combustion reaction between the carbon materials (C) to oxygen (O_2) into carbon dioxide (CO_2). The second is the reaction between nitrogen (N) and oxygen (O_2) at temperatures above 800 ^{0}C to produce nitrogen oxides (NOx) are known as Fuel-NOx. In addition, for burning in power plants at high temperatures (above 1200 ^{0}C), it also happens that the reaction of NOx formation known as Thermal-NOx. Most of the NO (part of NOx) reacts with N to become N_2O, and the others will remain as NO_x. And the third is a reaction between sulfur (S) contained in the fuel reacts with oxygen (O_2) to produce sulfur oxides (SOx).

Especially for GHG, based on the three types of combustion reactions over categorization and the results of the Kyoto Protocol [8], the GHG emission from thermal power plants, the main one is carbon dioxide (CO_2), and the other is a nitrous oxide (N_2O). Sulfur oxides (SOx) is not categorized as GHG emission in this protocol. In the gas turbine power plant with a fossil fuel source in the form of a liquid or gas, unburning methane (CH_4) is also included as GHG emissions from power plants [24].

Nitrous Oxide is a part of the reaction NO + N in the combustion process with high temperature. N_2O can react with the chars (C) will be decomposed into N_2 and CO at a pressure (0.2 MPa to 1.0 MPa) [25] or temperature is relatively high (>800 ^{0}C) [26]. It can be said that in an effort to decrease NO_x by burning low temperature (<900 ^{0}C) turned out to increase the levels of N_2O emissions from power plants.

Here is the formulation of the proposed objective function as a function of energy cost model in power plant operations involving GHG emissions from power plants i.e. CO_2 and N_2O, in accordance with the protocol on the environment. The definition of energy cost function here is a combination of fuel costs and emission costs due to the generation of electrical energy from the combustion process of fuel.

2.1. Carbon Dioxide Costs

In a simplified approach, tracing air emissions at power plants can be used as a book Fundamentals of Combustion Processes [27], or book [28]. That is to explore the process of conversion of fuel (C) through the combustion process, it will be obtained carbon dioxide (CO_2) emissions and there will be a release of energy in a certain amount, or in another notation:

Fuel (C) + Oxidizer (O_2) ➔ Results combustion (CO_2) + Energy (kcal/kg)

On a result of combustion, in addition to the energy obtained to be converted into electricity, will also be obtained byproduct emissions (CO_2). These emissions to environmental issues will constitute the environmental costs, thereby generating emission can also be regarded as a direct result of the cost of electric energy generation using combustion process. In addition, thermal energy conversion process of combustion can be known with certainty that a number of greenhouse gases are a direct result of the amount of fuel burned. It can be said that for every 1 mole of carbon (C) if burned perfectly will produce 1 mole of CO_2.

Cost of fuel is usually expressed in units of mass, then the unit mole of fuel (represented by the element carbon or C) and CO_2 gas combustion is then converted into mass units. As a result, it can be said that for every 1 ton of carbon contained in the fuel is burned perfectly will produce carbon dioxide emissions (CO_2) weighing $\frac{44}{12}$ ton. Furthermore, note also that the carbon content of the fuel depends on the type of fuel, the carbon content is usually written as a percentage of the total weight of the fuel. For example, every one ton of fuel then there is a 42% carbon element, it can be said that for every ton of fuel it burned will produce 3,667 tons × 42% or 1.4668 tons of carbon dioxide emissions (CO_2) or GHG emissions.

From the above, it has been shown that CO_2 emissions are directly correlated to the amount of fuel. Because of this direct correlation, it can be calculated fuel costs and GHG emissions costs by using only one variable output of the electrical power.

Then note also that, the amount of fuel used in thermal power plant depends on the heat rate of the power plant and the energy supplied to the electrical system. Furthermore, the approach used in this calculation as a linear heat rate calculation the initial formulation. Verification of the model is done to show that the linear heat rate approach is relevant enough to be used as the basis of the cost function model. The advantage of using this linear approach is the obtainment of a quadratic function on the function of the cost of energy generation. Here are descriptions of the formulation.

2.2. Nitrous Oxide Costs

Pyrolysis and combustion at temperatures between 800 ^{0}C to 900 ^{0}C, it is known that produce less of nitric oxide (NO) when compared to the higher combustion temperatures because of only Fuel-NOx dominant, but it produces nitrous oxide (N_2O) is quite high. At the higher combustion temperatures turned out to be N_2O that will react with the char (C) so that the amount of N_2O will decrease. Combustion under 900 ^{0}C cause Fuel-N converted into two gas emissions of the N_2O and NOx. N_2O is quite high on the burning below 700 ^{0}C and decreases when the temperature has been rising. Instead NOx along with rising higher combustion temperatures. Combustion of Fuel-N at temperatures above 920 ^{0}C relatively stable at a certain value, which is about 8% Fuel-N converted to N_2O and NOx by 80% [29].

The formation of nitrous oxide (N_2O) from nitric oxide (NO) is approximately 1 to 3% of all NO_x resulting from the combustion process in the boiler type's fluidized bed (FBC) and will decline by about 0.1% in the combustion boiler type pulverizer (PC). Nitrous oxide (N_2O) from the combustion process in power generation, in general, is between 20-200 ppm [30]. It relies on the combustion temperature and the type of boiler, for PC boiler about 20 ppm, and a CFB boiler N_2O can reach 200 ppm.

Because the complexity of the formation of N_2O from a combustion at power plants, the empirical approach is used in the formulation of this N_2O emission calculation. This is consistent with the recommendations for the calculation of the Kyoto Protocol on emission factors. To that end, it is proposed that the formulation of empirical GHG on the type of N_2O emissions is thus dependent on the type of boiler. For CFB boiler using a special emission factor CFB and PC using emission factors specific to the PC boiler.

2.3. Formulation Model of GHG Emission and Fuel Costs

At the thermal power plant, the process of conversion of fuel into electricity is measured using a scale conversion performance called heat rate. The amount of this conversion is based on the ability of plants to generate electricity. Heat rate can be simply expressed in a comparison between the amount of fuel calorific value is multiplied by the amount of fuel burned, and then it is divided by electrical energy generated or electrical energy produced $E_{prod}(kWh)$. In the formulation of the gross plant heat rate (GPHR) or $HR\left(\frac{kcal}{kWh}\right)$for fueled thermal power plant can be written as follows.

$$HR = \frac{CV_{fuel} \times Fuel}{E_{prod}} \qquad (1)$$

with $CV_{fuel}\ \left(\frac{kcal}{kg}\right)$ is a calorific value of a fuel.

While this electrical energy according to the terms of the gross power generated $P_T(kW)$ is an electrical power generated multiplied by the time of generation (h). According to this terms, in the mathematical equation can be regarded as,

$$E_{prod} = P_T \times time\ . \qquad (2)$$

Using equations *II-1* and *II-2*, it will further found the equation is

$$Q_{fuel} = \frac{1}{CV_{fuel}} \times P_T \times HR \qquad (3)$$

With P_T (kW) is a gross power generated by each unit of power plant to serve a power system. $Q_{fuel}\left(\frac{kg}{h}\right)$ is the rate of fuel consumption, usually written in units of mass per unit of time or $\frac{Fuel\ (kg)}{time\ (h)}$.

And then by using the equation of the rate of fuel consumption above, it can be stated that the rate of carbon emissions in the perfect combustion is equal to a constant multiplied by the percentage of carbon content in fuels $C_{fuel}(\%)$, multiplied by the rate of fuel consumption. Under conditions of Stoichiometry, or the condition of the perfect combustion, the amount of the rate of carbon dioxide $Q_{CO_2}\left(\frac{kg}{h}\right)$ on the rate of fuel can be written as follows.

$$Q_{CO_2} = \frac{44}{12} \times C_{fuel} \times Q_{fuel} \qquad (4)$$

With the global warming potential of N_2O according to the Kyoto protocol amounted to 310. And, the fraction of nitrogen oxidized to nitrous oxides N_20 or $\varepsilon_{N_2O}(\%)$ are depending on the heat of combustion of the boiler. Then, the amount of the rate of nitrous oxides $Q_{N_2O}\left(\frac{kg}{h}\right)$ can be calculated as follows.

$$Q_{CO_{2e}(N_2O)} = \frac{44}{14} \times \varepsilon_{N_2O} \times N_{fuel} \times 310 \times Q_{fuel} \qquad (5)$$

While the CH_4 emission rate can be written as follows.

$$Q_{CO_{2e}(CH_4)} = \varepsilon_{CH_4} \times CH_{4(fuel)} \times 21 \times Q_{fuel} \quad (6)$$

Thus in this paper, we propose a mathematical model formulation of fuel costs $Cost_E\left(\frac{Rp}{h}\right)$ on carbon-fueled power plants are as follows.

$$Cost_E = \left[\rho_{fuel} + \rho_{em} \times \left(\frac{44}{12} \times C_{fuel} + \frac{44}{14} \times \varepsilon_{N_2O} \times N_{fuel} \times 310 + \varepsilon_{CH_4} \times CH_{4(fuel)} \times 21\right)\right] \times Q_{fuel} \quad (7)$$

In other forms, it can be written as follows.

$$Cost_E = K \times HR \times P_T \quad (8)$$

With

$$K \text{ is } \left[\rho_{fuel} + \rho_{em} \times \left(\frac{44}{12} \times C_{fuel} + \frac{44}{14} \times \varepsilon_{N_2O} \times N_{fuel} \times 310 + \varepsilon_{CH_4} \times CH_{4(fuel)} \times 21\right)\right] \times \frac{1}{CV_{fuel}} \quad (9)$$

With $\rho_{fuel}\left(\frac{Rp}{kg}\right)$ is the price of fuel, and $\rho_{em}\left(\frac{Rp}{kg}\right)$ is the price of GHG (greenhouse gas) emissions equivalent which must be returned to the environment. Simplified without units, then the equation can be rewritten as follows. Heat rate (HR) used above is a gross heat rate, due to be reviewed in the value of the total energy generated.

The total gross power generation (P_T) is the amount of power used for its own purposes or auxiliary power (P_{aux}), and output power (P) to supply power to the grid system. Then the total gross power generated can be written as follows.

$$P_T = P_{aux} + P \quad (10)$$

Auxiliary power (P_{aux}) has a certain minimum value $\left(P_{aux(min)}\right)$ which depends on the capacity and type of power plants. And auxilary power will be increase (K_0) with increasing load demand (P). Then, the auxiliary power can be written as follow.

$$P_{aux} = P_{aux(min)} + K_0 \times P \quad (11)$$

Using the equations *II-9* and *II-10*, then the total power can be written as the following equation.

$$P_T = P_{aux(\min)} + K_1 \times P \quad (12)$$

with

$$K_1 = 1 + K_0 \text{ is a constant.} \quad (13)$$

Heat rate will decrease if the load increases. Model of heat rate function may be a linear function, quadratic and polynomial equation of order three. In this simulation used heat rate equations approximated using a linear equation, that is because of maneuvering system services above 50% nominal power. This linear model is still relevant is used as shown in section III.1 of this article.

To approach a linear function, it is known that the heat rate value depends on the electric power generated. The heat rate will be written as the following linear equation.

$$HR = HR_{nom} + \left(K_2 \times (P - P_{min})\right) \quad (14)$$

With K_2 is a gradient heat rate, as the following equation.

$$K_2 = \frac{HR_{nom} - HR_{min}}{P_{nom} - P_{min}} \quad (15)$$

Heat rate at nominal load can be called as a nominal heat rate (*HR_{nom}*). The minimum power (P_{min}) is defined as the minimum power can still be maintained by each unit to supply power to the grid. Using the equation of the electric power generated and the heat rate mentioned above, the fuel cost equation can then be written as follows.

$$Cost_E = K(K_3 + K_1 \times P) \times [HR'_{nom} + (K_2 \times P)] \quad (16)$$

With

K_3 is minimum of auxiliary power $\left(P_{aux(min)}\right)$, and $HR'_{nom} = HR_{nom} - K_2 \times P_{min}$. (17)

In another writing, the fuel cost equation can be rewritten as the following quadratic equation.

$$Cost_E = K \times HR'_{nom} \times \left[K_3 + \left(\frac{K_3K_2}{HR'_{nom}} + K_1\right) \times P + \left(\frac{K_1K_2}{HR'_{nom}}\right) \times P^2\right] \quad (18)$$

2.4. Creating Power Plant Costs Model

The electric energy generation costs, especially fuel costs and emissions costs in the short-term optimization approach can be approximated by the value of the power generated at each hour. Using these explanations, then the objective function can be determined more easily name the variable cost, which is the fuel costs that depend on plant performance or heat rate (*HR)* consists of the cost of fuel thermal power plant or cost of raw of water for the raw material hydro power plant.

2.4.1. Fuel Cost Model for Fired Thermal Power Plant

Fuel cost function based on heat rate $Cost_{fuel}\left(\frac{Rp}{h}\right)$, equation function is as follows.

$$Cost_{fuel} = \left(\rho_{fuel} \times \frac{HR_{nom}}{CV_{fuel}}\right) \times \left[K_3 + \left(\frac{K_3K_2}{HR_{nom}} + K_1\right) \times P + \left(\frac{K_1K_2}{HR_{nom}}\right) \times P^2\right] \quad (19)$$

2.4.2. Cost model for Hydro Power Plant

The energy cost function of hydro power plant $Cost_{Hyd}$ is a function of variable costs due to levy water $\left({}^{Rp}/_{h}\right)$, namely:

$$Cost_{Hyd} = \rho_{hyd} \times \frac{1}{\tau \times g \times H} \times HR_{hyd} \times P_T \quad (20)$$

with ρ_{hyd} is the price of water levy set by the local government $\left({}^{Rp}/_{m^3}\right)$, HR_{hyd} is a function of the performance of hydro power plant in $\left({}^{tonne.m^2}/_{second^2.kWh}\right)$, τ is the density of water $\left({}^{tonne}/_{m^3}\right)$, *g* is the gravitational constant $\left({}^{m}/_{second^2}\right)$, and H is the net head (m).

2.4.3. Objective Function Costs Model

By manipulating the equations above, then the next generation cost function can be approached and written into the following quadratic equation.

$$f(P) = \alpha + \beta.P_G + \gamma.P_G^2 \quad (21)$$

With α, β, γ are the parameters of the cost with a certain value which depends on the type of power plant, the parameters are as follows Table 1.

Table 1. Fuel and Emission Cost Function Parameters

Notation	Thermal Power Plant	Hydro Power Plant
α	$= \delta \times K_3$	$= \left(\rho_{hyd} \times \frac{HR'_{nom}}{\tau \times g \times H}\right) K_3,$
β	$= \delta \times \left(\frac{K_3 K_2}{HR'_{nom}} + K_1\right)$	$= \rho_{hyd} \times \left(\frac{K_3 HR'_{nom} + K_1}{\tau \times g \times H}\right)$
γ	$= \delta \times (K_1 K_2)$	$= \rho_{hyd} \times \left(\frac{K_1 K_2}{\tau \times g \times H}\right)$
δ	$= \left[\rho_{fuel} + \rho_{em} \times \left(\frac{44}{12} \times C_{fuel} + \frac{44}{14} \times \varepsilon_{N_2O} \times N_{fuel} \times 310 + \varepsilon_{CH_4} \times CH_{4(fuel)} \times 21\right)\right] \times \frac{HR'_{nom}}{CV_{fuel}}$	
K_1	$= 1 + K_0$	
K_2	$= \frac{HR_{nom} - HR_{min}}{P_{nom} - P_{min}}$	
K_3	$= P_{aux(min)}$	
HR'_{nom}	$= HR_{nom} + K\_2 \times P\_min$	

These equations are proposed to be used for a range of heat rate curve was linear.

3. Verifying the Model

Using the model of the objective function and constraint functions that have been outlined in advance, the next will be simulated.

3.1. Verify Function of Heat Rate

Heat generation rate will decrease if the load is increased, namely by following the curvature equation of order 2 [31]. Another view of the heat rate to changes in load can also be traced reference [32]. Using the reference, are shown in Table 2.

Table 2. Variations of Power Plant Heat Rate with Nominal Load 350 MW [32]

Load	MW	350	300	200	100
Heat Consumption	GJ/h	2731.15	2366.70	1637.80	908.90
Heat Rate	kJ/kWh	7803.3	7889.0	8189.0	9089.0
Efficiency	%	46.13	45.63	43.96	39.61

Based on Table 2, the heat rate can be approached by a polynomial function. Using a three-order polynomial function, it has a regression approach with a coefficient of determination factor equal to 1. This function, shown in Figure 1 so which approach is best for heat rate function. Namely, it is the third order polynomial functions.

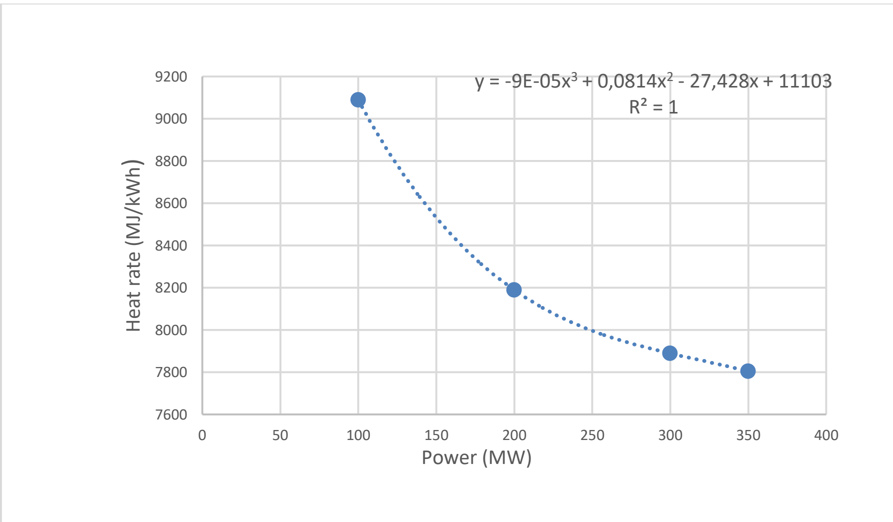

Figure 1. 3rd order function for the heat rate

Interpretation of the data using a quadratic curve fitting it was shown as in Figure 2 below. In the image shown that by using a quadratic curve has a coefficient of determination 0.996. The coefficient of determination for this quadratic approach is included in the very good category.

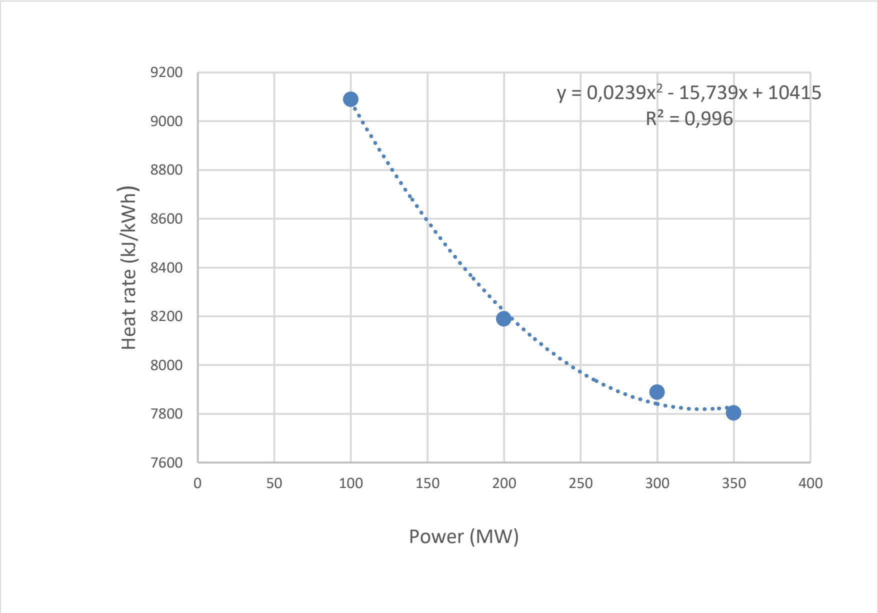

Figure0 2. Quadratic function of heat rate

Similarly, namely by using a linear curve fitting approach, which has a coefficient of a determination 0.9034 as seen in Figure 3. With the determination coefficient value is more than 80%, ie 0.9034 included in the category of a good approach.

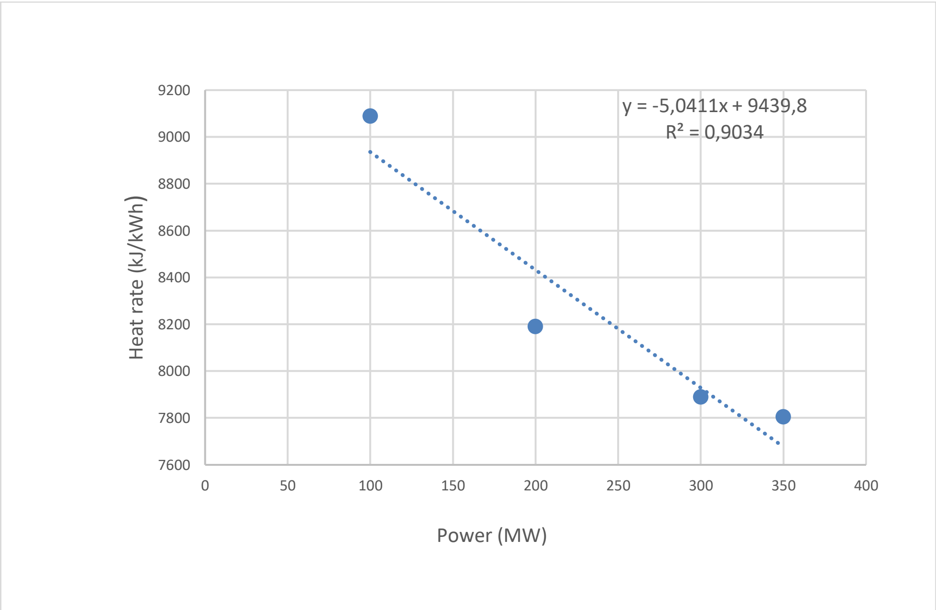

Figure 3. Linear function of heat rate

Thus, the linear approximation of changes in power plant heat rate was still relevant to the determination coefficient of regression is 90%. The verification of the picture above, it can be said that the linear approximation of the function heat rate thermal power station is still relevant enough to be used as the basis for calculation. Other data, namely the use of linear heat rate can be traced to the paper as reference [33].

3.2. Power Plant Data

Based on Table 1 above, power plant data to obtain the cost equation can then be determined to consist of: nominal and minimum heat levels, fuel calorie values, carbon content, and nitrogen in fuel, and fuel prices and levels applicable greenhouse gas emissions in a region. To perform the calculation of cost model of the power plant, sample data to be used are follows. Auxiliary power for thermal power plant has a value between 8.5% and 11% of the electric power generated. For this simulation, the auxiliary power is assumed at 8.5% worth of the power generated by the power changes of 1% of the minimum power.

In this simulation, the Coal Power Plant (CCP) is assumed that all power plants using coal with calories around 5200 kcal/kg, while the use of natural gas fuel gas with a methane content of around 95% Natural gas is used for the combined cycle power plant (CCPP) and gas turbine (GTPP). Coal price of 396 Rp/kg, natural gas if converted to rupiah per kilogram is 2450 Rp/kg. While the price of GHG emissions is assumed around 36 Rp/kg as compensation for environmental costs [13]. Details of the data (dummy) Table 3 as follows.

Table 3. Power Plant Data (Dummy) as for the Determination of the Objective Function Parameters

Bus	Power Plant	Pmin	Pnom	Qmin	Qmax	Fuel price	GHG price	CV_{fuel} (HHV)	HRnom	HRmin	C_{fuel}	N_{fuel}	ε_{N_2O}
	Thermal	kW	kW	kVAr	kVAr	Rp/kg	Rp/kg	kcal/kg	kcal/kWh	Kcal/kWh	%	%	%
1	CPP 1	346125	2769000	-150000	2040000	396	36	5330	2233	2510	0.63	0.3	0.1
8	CPP 2	178750	1430000	-175000	1240000	396	36	5330	2263	2408	0.63	0.3	0.1
15	CPP 3	165000	660000	-60000	500000	396	36	5280	2433	2698	0.61	0.3	0.1
17	CCPP 1	45975	1839000	-152500	1260000	2450	36	12800	2037	2278	0.73	0.2	0.1
22	CPP 4	318000	3180000	-168000	1920000	396	36	5330	2243	2408	0.63	0.3	0.1
23	GTPP 1	22000	440000	-75500	300000	2450	36	12800	2924	3268	0.73	0.2	0.1
	Hydro					G (Rp/m³)		H	1/eff_nom	1/eff_min			
10	HPP 1	26250	700000	-122000	500000	0.5		52	2500	2640			
11	HPP 2	26250	700000	-35000	440000	0.5		40	2556	2643			

3.3. Results of Costs Function Model

By using the dummy data as an example Table 3 then the next will be calculated parameter value of the cost function of the power plant. With estimates for the hydropower plant has a capacity factor of about 0.50 to 0.55. Then, gas turbines have installed capacity factor of approximately 0.70 of annual operations. And then, the steam turbine has a capacity factor of 0.9. Then the calculation results, using dummy data in the example above are shown as Table 4.

Table 4. The Results of Modeling Objective Function with and without GHG Costs

Bus	Power Plant	α	β	γ	Bus	Power Plant	α	β	γ
	Thermal (with GHG cost)					Thermal (without GHG cost)			
1	CPP 1	46.411	0.1974	-0.0000226	1	CPP 1	38.356	0.1631	-0.0000186
8	CPP 2	24.502	0.2018	-0.0000234	8	CPP 2	20.249	0.1668	-0.0000193
15	CPP 3	13.268	0.2118	-0.0001134	15	CPP 3	11.026	0.1760	-0.0000942
17	CCPP 1	68.349	0.3543	-0.0000575	17	CCPP 1	65.771	0.3410	-0.0000553
22	CPP 4	54.059	0.2002	-0.0000115	22	CPP 4	44.676	0.1655	-0.0000095
23	GTPP 1	20.834	0.5576	-0.0005923	23	GTPP 1	20.049	0.5366	-0.0005700
	Hydro					Hydro			
10	HPP 1	0.588	0.0245	-0.0000051	10	HPP 1	0.588	0.0245	-0.0000051
11	HPP 2	0.782	0.0325	-0.0000042	11	HPP 2	0.782	0.0325	-0.0000042

4. Model Simulation
4.1. Equality Constraint in Power System

Constraint equations for active power and reactive power are as follows [14].

a. Equations for active power at bus *i* is,

$$P_{Gi} - P_{Di} - P_{Li} = 0 \quad (22)$$

With the power of the load on the bus itself that is on the bus *i* was (P_{Di}), active power flow through the line from bus i to bus to k is (P_{Li}), active power generated by the power plant is (P_{Gi}). The equation of the active power supplied by the bus *i* to other bus is can be written as follows.

$$P_{Li} = \sum_{k}^{NB} |V_i||V_k|(G_{ik} cos\theta_{ik} + B_{ik} sin\theta_{ik}) \quad (23)$$

With $\theta_{ik} = \theta_i - \theta_k$ is the difference between the phase angle *i* to *k*, G_{ik} is conductance of bus *i* to bus *k*, B_{ik} is suceptance from bus *i* to bus *k.*

b. Equation of reactive power at bus i is,

$$Q_{Li} - Q_{Gi} - Q_{Bi} = 0 \quad (24)$$

Furthermore, reactive power equations of bus *i* to bus *k* can be seen as a function of the following equation.

$$Q_{Li} = \sum_{k}^{NB} |V_i||V_k|(G_{ik} sin\theta_{ik} - B_{ik} cos\theta_{ik}) \quad (25)$$

4.2. Inequality Constraints

Inequality constraints consist of inequality voltage, phase angle, active power and reactive power generation. Here is the inequality that is used [14].

a. inequality voltage and phase angle,

$$V_i^{min} \leq V_i \leq V_i^{max} \quad (26)$$

$$\theta_i^{min} \leq \theta_i \leq \theta_i^{max} \quad (27)$$

b. active and reactive power inequalities,

$$P_{Gi}^{min} \leq P_{Gi} \leq P_{Gi}^{max}, \quad (28)$$

$$Q_{Gi}^{min} \leq Q_{Gi} \leq Q_{Gi}^{max} \quad (29)$$

4.3. Grid Data and Electric Load Data

To run a simulation of power flow optimization with an interior point method [14], the other data that would be required. The other data are a grid data and load data.

4.3.1. Data Grid for the Simulation Model

Data grids which include the data conductive electrical power, namely the from the bus (f_{bus}) and bus ends (t_{bus}) with a resistance, the admittance and the conductor ampacity (ampere capacity). Table 5 show example of a data grid that will be used as a simulation.

4.3.2. Load Data for the Simulation Model

Data for the electrical load is a load change in power at certain hours. Then the data is used to review the effect of the active power, and the amount of electrical power supplied to the grid as shown in Table 6. Active power (P_D) unit is MW, and MVAR is for reactive power (Q_D) unit.

Table 5. Grid Data (Dummy) for Simulation

f_{bus}	t_{bus}	r	x	b	rateA	rateB	rateC	ratio	angle	status	ang min	ang max
1	2	0.000626496	0.00700877	0	2500	2500	2500	0	0	1	-360	360
1	4	0.013133324	0.06257632	0.00599	2500	2500	2500	0	0	1	-360	360
2	5	0.146925792	0.00353057	0	2500	2500	2500	0	0	1	-360	360
3	4	0.001513179	0.01692831	0	2500	2500	2500	0	0	1	-360	360
4	5	0.001246422	0.01197501	0	2500	2500	2500	0	0	1	-360	360
4	18	0.000694176	0.0066693	0	2500	2500	2500	0	0	1	-360	360
5	7	0.00444188	0.0426754	0	2500	2500	2500	0	0	1	-360	360
5	8	0.0062116	0.059678	0	2500	2500	2500	0	0	1	-360	360
5	11	0.00411138	0.04599504	0.00442	2500	2500	2500	0	0	1	-360	360
6	7	0.001973648	0.01896184	0	2500	2500	2500	0	0	1	-360	360
6	8	0.0056256	0.054048	0	2500	2500	2500	0	0	1	-360	360
8	9	0.002822059	0.02711295	0	2500	2500	2500	0	0	1	-360	360
9	10	0.00273996	0.02632419	0	2500	2500	2500	0	0	1	-360	360
10	11	0.001474728	0.01416846	0	2500	2500	2500	0	0	1	-360	360
11	12	0.0019578	0.0219024	0	2500	2500	2500	0	0	1	-360	360
12	13	0.00699098	0.0671659	0.00643	2500	2500	2500	0	0	1	-360	360
13	14	0.013478	0.12949	0.01239	2500	2500	2500	0	0	1	-360	360
14	15	0.01353392	0.15140736	0.00364	2500	2500	2500	0	0	1	-360	360
14	16	0.01579856	0.1517848	0.00363	2500	2500	2500	0	0	1	-360	360
14	20	0.00903612	0.0868146	0	2500	2500	2500	0	0	1	-360	360
15	16	0.037539629	0.3606623	0.00863	2500	2500	2500	0	0	1	-360	360
16	17	0.00139468	0.0133994	0	2500	2500	2500	0	0	1	-360	360
16	23	0.003986382	0.04459666	0	2500	2500	2500	0	0	1	-360	360
18	19	0.014056	0.157248	0.01511	2500	2500	2500	0	0	1	-360	360
19	20	0.015311	0.171288	0.01646	2500	2500	2500	0	0	1	-360	360
20	21	0.010291	0.115128	0.01107	2500	2500	2500	0	0	1	-360	360
21	22	0.010291	0.115128	0.01107	2500	2500	2500	0	0	1	-360	360
22	23	0.004435823	0.04962466	0.00477	2500	2500	2500	0	0	1	-360	360

Table 6. Electric Load Data (Dummy)

Zone		1		Base kV		500								
Hour to		1		2		3		4		5		area	Vmax	Vmin
bus_i	type	P_D	Q_D	P_D	Q_D	P_D	Q_D	P_D	Q_D	P_D	Q_D			
1	3	353	125	553	250	353	45	353	75	553	175	1	1.1	0.9
2	1	245	134	300	227	300	227	3	227	3	227	1	1.1	0.9
3	1	260	31	360	31	660	161	660	161	660	161	1	1.1	0.9
4	1	144	41	344	141	544	181	644	181	644	181	1	1.1	0.9
5	1	397	115	597	45	697	215	697	215	697	215	1	1.1	0.9
6	1	460	181	320	134	760	181	760	181	760	181	2	1.1	0.9
7	1	546	241	346	141	646	170	646	170	646	170	2	1.1	0.9
8	1	0	0	0	0	0	0	0	0	0	0	2	1.1	0.9
9	1	423	217	323	117	823	317	823	317	823	317	2	1.1	0.9
10	1	0	0	0	0	0	0	0	0	0	0	2	1.1	0.9
11	1	0	0	0	0	0	0	0	0	0	0	2	1.1	0.9
12	1	490	151	400	231	590	351	590	351	590	351	2	1.1	0.9
13	1	397	186	247	146	397	136	597	186	597	186	2	1.1	0.9
14	1	129	173	229	173	329	363	529	363	629	363	3	1.1	0.9
15	1	0	0	0	0	0	0	0	0	0	0	3	1.1	0.9
16	1	362	247	422	82	862	317	862	317	862	317	4	1.1	0.9
17	1	310	141	310	91	410	91	410	113	510	113	4	1.1	0.9
18	1	310	110	410	110	150	20	350	50	550	250	3	1.1	0.9
19	1	377	117	220	110	277	17	477	137	477	137	3	1.1	0.9
20	1	224	144	424	144	524	244	524	244	524	244	3	1.1	0.9
21	1	258	196	220	96	358	206	458	206	458	206	4	1.1	0.9
22	1	139	152	439	152	839	272	839	272	839	272	4	1.1	0.9
23	1	313	25	130	0	13	0	13	0	67	0	4	1.1	0.9

4.3.3. Additional Data for the Simulation

It is assumed that the data were taken during the dry season with a limited water supply. Due to the limited supply of water, it is known that the condition of hours to 1 to 3 hours to note that the Hydro Power Plant (HPP) is not enabled. PP-1 and HPP 2, they cannot serve the grid system. At that hour are ready for operation is the thermal power plant. In the hours to 4 to 5, hydro power plants will be ready to serve the load on the grid system.

4.4. Simulation Result

Use the Interior point method for simulation optimization of energy costs, which consist of the cost of fuel and the cost of GHG emissions, the results can be shown in the following

Table 7. As for running the program with no price of greenhouse gas emissions or no GHG cost, the value is zero. Then the results of running the program are as shown in Table 8.

Table 7. Summary Results of Running (with GHG Emissions Cost)

Bus	Hour to Power Plant	MW	1 MW	1 MVAr	2 MW	2 MVAr	3 MW	3 MVAr	4 MW	4 MVAr	5 MW	5 MVAr
1	CPP 1	2769	2769.00	269.42	2769.00	496.54	2769.00	323.79	2769.00	344.51	2769.00	482.95
8	CPP 2	1430	1430.00	814.11	1430.00	599.50	1430.00	1194.83	1430.00	612.78	1430.00	721.15
10	HPP 1	700	0	0	0	0	0	0	700.00	295.95	700.00	373.26
11	HPP 2	700	0	0	0	0	0	0	700.00	455.65	700.00	461.22
15	CPP 3	660	660.00	35.91	660.00	-13.79	660.00	123.31	660.00	97.60	660.00	102.88
17	CCPP 1	1839	0	0	0	0	1223.64	346.04	815.23	348.39	1182.23	310.18
22	CPP 4	3180	851.31	123.94	1305.14	48.28	3180.00	300.98	3180.00	406.12	3180.00	348.24
23	GTPP 1	440	440.00	277.79	440.00	76.65	290.53	99.66	0	0	286.51	116.59
Load			6137.00	2727.00	6594.00	2421.00	9532.0	3514.0	10235.0	3766.0	10889.00	4066.00
Power generated			6150.31	1521.18	6604.14	1207.18	9553.16	2388.62	10254.23	2602.96	10907.74	2917.25
Branch charging (inj)				1239.8		1242.7		1245.2		1241.0		1243.3
Obj. function		M.Rp/h		1156.50		1236.06		1911.48		1712.69		1932.55
Converged		second		18.67		6.91		10.93		14.33		11.96

Using Table 7 and Table 8, it can be created percentage issuance costs against the cost of energy. To find out the effect of GHG emissions price on energy costs that have been optimized, are shown in the following Table 9.

Table 8. Summary Results of Running (without GHG Emissions Cost)

Bus	Hour to Power Plant	MW	1 MW	1 MVAr	2 MW	2 MVAr	3 MW	3 MVAr	4 MW	4 MVAr	5 MW	5 MVAr
1	CPP 1	2769	2769.00	269.43	2769.00	496.54	2769.00	325.52	2769.00	349.04	2769.00	482.96
8	CPP 2	1430	1430.00	814.12	1430.00	599.51	1430.00	1192.77	1430.00	629.55	1430.00	721.02
10	HPP 1	700	0	0	0	0	0	0	700.00	328.53	700.00	373.21
11	HPP 2	700	0	0	0	0	0	0	700.00	454.90	700.00	461.49
15	CPP 3	660	660.00	35.92	660.00	-13.79	660.00	125.19	660.00	100.72	660.00	103.61
17	CCPP 1	1839	0	0	0	0	1223.64	340.22	815.23	327.25	1182.23	310.41
22	CPP 4	3180	851.31	123.97	1305.14	48.28	3180.00	300.43	3180.00	413.33	3180.00	348.18
23	GTPP 1	440	440.00	277.75	440.00	76.64	290.53	104.49	0	0	286.51	116.36
Load			6137	2727	6594	2421	9532	3514	10235	3766	10889	4066
Power Generated			6150.31	1521.18	6604.14	1207.18	9553.16	2388.63	10254.22	2603.33	10907.74	2917.24
Branch charging (inj)				1239.8		1242.7		1245.2		1240.6		1243.3
Obj. function		M Rp/h		976.83		1042.58		1654.72		1464.59		1676.16
Converged		second		10.34		4.81		8.52		11.38		10.27

Table 9. Estimated Percentage of the Cost of Emissions to the Cost of Fuel in the Power System that has been Optimized

	Hour to Unit	1 MW	1 MVAr	2 MW	2 MVAr	3 MW	3 MVAr	4 MW	4 MVAr	5 MW	5 MVAr
Load	MW	6137	2727	6594	2421	9532	3514	10235	3766	10889	4066
Fuel with Emission Cost (Energy Cost)	M Rp/h		1156.5		1236.06		1911.48		1712.69		1932.55
Fuel without Emission Cost	M Rp/h		976.83		1042.58		1654.72		1464.59		1676.16
The results of emission cost optimization	M Rp/h		179.67		193.48		256.76		248.1		256.39
Comparison of emission costs on fuel costs	%		18%		19%		16%		17%		15%

5. Analysis

5.1. Analysis of Modeling

Formulation energy generation costs can be grouped into the costs of fuel and emission costs. Agreed GHG emission as a function of the cost is to use the Kyoto Protocol. By using these protocols, the cost of the main emissions at thermal power plants is the emission of CO_2 and N_2O, as well as for gas-fired power plants are usually coupled with emissions of unburned CH_4 gas. Of the three GHG gases are highly influential in the calculation of costs as a major component is CO_2-emissions combustion. Furthermore, the incorporation of fuel costs and the costs of GHG emissions can be done using the single objective function of costs formulations as in Table 1.

The linear model of heat rate function selected for ease in providing data of power plant. Model function is a linear, it is also still has a good correlation with data from the reference search, i.e. the reference data on heat rate function of the load on the power plant. This is shown in Figure 3 namely, the model function of heat rate as a linear function has a coefficient of determination of regression at 90%. The coefficient of determination above 80%, can be said to have a very good correlation. The model can be used as a model for the calculation of heat rate changes on the power plant. The approach to this linear function will facilitate the calculation of the cost of fuel and emission costs.

By using the linear functions of performance or linear functions of heat rate on the power plant, can be made approach is an energy cost of the power plant. With a heating rate which is a linear function of the above, it was found that the fuel cost and emission cost is a quadratic function. The cost function of a power plant that supports an electricity system in Indonesia, which can be grouped into 3 main namely hydro power plant, thermal power plant, and geothermal power plant. In modeling the above, all the function approach quadratic with parameters such function parameters α, β, and γ as shown in Equation.

The thermal power plant will generate greenhouse gas emissions for each power output, while hydro power plant does not emit greenhouse gas emissions. So that in addition to having function a thermal power plant fuel costs also have the cost of emissions, while the hydro power plant only has water retribution costs.

5.2. Analysis of Simulation Model

By using the quadratic model of a function of fuel costs and the cost of emission using the parameters as illustrated in Table 1, it can be seen that the parameter γ is negative. This can be attributed to the declining value of the power plant heat rate if the load to the nominal load.

Using dummy data from the power plant as shown in Table 3, are used to determine the parameters of the cost function of fuel and emissions costs as shown in Table 4. Differences objective function of fuel cost with emissions cost and fuel cost without the cost of emissions are shown in Table 4. From the Table 4, it is also shown that the parameter values in the objective function of fuel costs which included the cost of emissions will be of higher value than the parameter values without emissions costs included.

5.3. Analysis of simulation results

Having obtained the objective function of the function of fuel cost and the cost of emissions with constraints of its function. It can be done cost calculations namely their fuel cost and emissions cost or without emissions cost. Using data grid and load the data as shown in Table 5 and Table 6, and using interior point methods of calculation are used to determine the fuel cost with GHG emissions price as shown in Table 7. And then, calculated the cost of fuel without involving the cost of GHG emissions is shown in Table 8.

In situations of limited reserves of water, the hydro power plant can only serve the load at peak loads. Furthermore, based on Table 7 and Table 8 can also be seen, that the CPP is more likely to be the base load. Then for the load follower, tends to be done by gas-fired power plants, which is the CCPP and GTPP.

Using Table 9 can be shown that the costs related to the functioning of emissions, it will raise the overall operating variable costs of about 15% to 19%. It is also related to the readiness of renewable energy power plants in servicing load, in this case, the HPP. The readiness of power plants with a low heat rate, it also will reduce emissions cost comparison to the cost of energy, shown in the drop in the percentage ratio of the value of emissions costs against the cost of energy on the hour to 3 to 5 hours.

6. Conclusion

The cost of GHG emissions can be combined with rising fuel costs as operating costs of electric energy generation by determining the parameters of every component of the cost of energy. By using the linear heat rate function model, it will be able to generate a single quadratic objective function both for fuel and emissions with function parameters α, β, γ are dependent on other parameters as shown in Table 1. Based on the simulation result, GHG emissions cost can be reduced with more to generate of renewable energy i.e. hydro power plant as well as power plants with low heat rate.

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Nomenclature

$GPHR$	Gross Plant (Heat Rate)	HR_H	Performance parameter of the hydro power plant
HR_{nom}	Heat rate nominal	τ	Water density
HR_{min}	Heat rate minimal	g	The gravitational constant
P_{nom}	Nominal power of unit power plant	h	Head of hydro power plant
P_{min}	Minimal power of unit power plant	Q_{fuel}	the rate of fuel consumption
P_{aux}	Auxiliary power of unit power plant	N_{fuel}	Percentage of nitrogen content in fuels
$P_{aux(\min)}$	Minimum auxiliary power of unit power plant	ε_{N_2O}	Fraction of nitrogen oxidized to nitrous oxides
CV_{fuel}	Calorific value of fuel	ε_{CH_4}	The fraction of methane gas unburning
P	Electric power generated by the power plants	P_{Di}	Active power of the load on bus i
P_T	Total or gross power generated by each unit of power plant	P_{Li}	Active power flow through the line from bus i to bus k
ρ_{fuel}	The price of fuel	P_{Gi}	Active power generated by the power plant on bus i
ρ_{em} ,	The price of GHG emission	α, β, γ	Parameters unit cost variable there are depends on the type of power plant
C_{fuel}	Percentage of carbon content in fuels		

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