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Sustainable Electrical Energy Supply Chain System With Hybrid Power Generation: An Inventory Approach

WAKHID A. JAUHARI[1,2], I. NYOMAN PUJAWAN[1], MOKH SUEF[1], AND IVAN D. WANGSA[3]

[1]Department of Industrial Engineering, Institut Teknologi Sepuluh Nopember, Surabaya 60111, Indonesia
[2]Department of Industrial Engineering, Universitas Sebelas Maret, Surakarta 57126, Indonesia
[3]HSE Department, PT Pratama Abadi Jaya, Balikpapan 76125, Indonesia

Corresponding author: Wakhid A. Jauhari (wachid_aj@yahoo.com)

ABSTRACT In this paper, we present a sustainable electrical energy supply chain system (SEESCS) where two supply chain parties are involved, namely a power plant and a transmission station. The power plant has two different types of power generation systems. The first power generation system (PG1) is more costly but it generates lower emissions than the second system (PG2). The model is developed based on a lot-sizing inventory problem to decide the load allocation between PG1 and PG2. The objective function is to minimize total costs that consist of energy generation cost and emission cost. The transmission station faces a stochastic demand and employs a continuous review policy to manage the electrical energy storage. An efficient procedure is developed to solve the model and a sensitivity analysis is carried out to explore the impact of changes in some key parameters on the model's behavior. The results show that the allocation of electricity generation is mostly influenced by the change in PG1's production cost parameter and PG2's emissions parameters. The amount of emissions generated from the system is significantly affected by the variation in PG1's production cost parameter, PG2's emissions parameters, and electricity demand. Furthermore, by adjusting the power supply rate of power generation, the supply chain can control the overall emissions produced and maintain the total cost.

INDEX TERMS Electrical energy, emission, energy storage, inventory, lot-sizing, power generation.

NOMENCLATURE

Parameters for transmission stations:

D	average of electrical demand (MWh/year)
σ	standard deviation of electrical demand (kWh/year)
A	ordering cost for transmission station ($/transmission)
F_T	transmission cost for transmission station ($/transmission)
h_T	holding cost rate per unit time of transmission station (%/year)
π_x	blackout cost per electricity consumption ($/kWh)
π_0	marginal profit loss per electricity consumption ($/kWh)
t	consumption period (h)
β	blackout ratio, $0 < \beta \leq 1$

Parameters for power plant:

P_1	power supply of PG1 (kWh/year)
P_2	power supply of PG2 (kWh/year)
h_P	holding cost per unit time of power plant ($/kWh/year)
F_P	transmission cost for power plant ($/transmission)
γ	electricity energy loss
c_{tax}	carbon tax ($/kg$CO_2$)
a_1	emission parameter for PG1 (kg year^2/unit^3)
b_1	emission parameter for PG1 (kg year/unit^2)
c_1	emission parameter for PG1 (kg /unit)
a_2	emission parameter for PG2 (kg year^2/unit^3)
b_2	emission parameter for PG2 (kg year/unit^2)
c_2	emission parameter for PG2 (kg /unit)

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g_{11} PG1's per unit time cost for running the system independent of power supply rate ($)
g_{21} the increase in PG1's unit system cost due to one unit increase power supply rate ($/unit)
g_{12} PG2's per unit time cost for running the system independent of power supply rate ($)
g_{22} the increase in PG2's unit system cost due to one unit increase power supply rate ($/unit)
η_1 fractional opportunity cost for PG1
η_2 fractional opportunity cost for PG2
δ_1 percentage decrease in setup cost per dollar increase in PG1's investment
δ_2 percentage decrease in setup cost per dollar increase in PG2's investment
K_{10} original setup cost for PG1 ($/setup)
K_{20} original setup cost for PG2 ($/setup)

Decision variables:

n electricity power distribution factor
Q electricity power consumption (kW)
k emergency backup factor
α allocation factor for electricity generation, $\alpha_{min} < \alpha < \alpha_{max}$
K_1 setup cost of PG1 ($/setup)
K_2 setup cost of PG2 ($/setup)

I. INTRODUCTION

The increasing amount of Green House Gas (GHG) has caused global warming and environmental damages. The primary sources of greenhouse gas are transportation, electricity production, manufacturing industry, commercial and residential, land use, and forestry. In the USA, the three sectors that have the largest contribution of GHG emissions in 2017 are transportation 28.9%, electricity 27.5% and industry 22.2% [1]. In an electrical energy supply chain, electricity is generated by the power plant and then transmitted via transmission station to the end customers. GHG emissions are mainly produced from activities related to electricity production as they are released during the combustion of fossil fuels, such as oil, natural gas, and coal. Thus, due to the global raising awareness on environmental protection, various actions on lessening the emissions must be taken to minimize the emissions from the system. One of the actions would be to utilize a cleaner electrical technology that generates less emissions.

The first work dealing with electricity distribution was proposed by Banbury [2]. He suggested a model which shows the distribution of electricity from the power generation system to the end customers. In a more recent development, we have seen quite a lot of works addressing the optimization problems applied to the context of the electricity supply chain. Vahidinasab [3] proposed a mathematical model to optimize the distributed energy resources in electricity distribution networks using nonlinear programming. He considered electricity price uncertainties and a trade-off between minimizing monetary cost and minimizing pollutants. Amrutha *et al.* [4] developed an electricity production model using linear programming and investigated the influence of emissions on production decisions. Jeddi *et al.* [5] employed a robust optimization model to solve the problem of distributed energy resources planning. They considered load uncertainty and set total profit as the objective function. Ordoudis *et al.* [6] used a two-stage stochastic programming model to coordinate the supply mix from electricity and natural gas systems. Saghaei *et al.* [7] proposed a four-level electricity supply chain that consists of the supplier, storage, power plant, and consumers. A two-stage stochastic mixed-integer non-linear programming was developed by considering a procurement decision of biomass materials. Saghaei *et al.* [8] developed a stochastic mathematical programming model for the bioelectricity generation supply chain considering disruption effects. Wang *et al.* [9] developed an operation planning model for energy system comprising gas and electricity systems. They used a carbon trading mechanism to lessen the emissions generated by the system. Yan *et al.* [10] suggested a methodology for finding sites of energy stations and distribution stations in a regionally integrated energy system. They used kernel density estimation and shortest path method to optimize the transmission network.

The research on energy storage systems has received a great deal of attention in recent years. Musolino *et al.* [11] developed an energy lot-sizing model by taking into account the recovery of braking energy. Fossati *et al.* [12] suggested the strategy to minimize the micro grid's total cost by specifying the optimal capacity of energies and power. Zucker and Hinchliffe [13] conducted a study to find the optimal size of power storage attached to PV generation taking into account the market signal. Wichmann *et al.* [14] investigated the impact of the utilization of energy storage systems on total cost and energy saving in an energy-oriented lot-sizing and scheduling problem. They considered energy quantities, time-dependent energy prices, and characteristics of energy storage when evaluating the employment of energy storage. Oh and Son [15] determined the optimal size of energy storage system and formulated an operation strategy for improving wind-power generation reliability using discrete Fourier transform. They showed that the proposed strategy can reduce the root-mean-squared error by up to 26% compared to the conventional strategy. Das *et al.* [16] formulated a strategy for obtaining the optimal location of energy storage systems in distribution networks to minimize power losses, line loading and voltage deviation. The artificial bee colony algorithm is used to solve the problem in two different scenarios, (1) with a uniform energy storage size and (2) with non-uniform energy storage size. Karimi *et al.* [17] formulated a stochastic mathematical model for determining the optimal allocation of energy storage units in wind integrated distribution networks. Ademulegun *et al.* [18] proposed a mathematical model of the electricity distribution networks consisting of two wind turbines and energy storage device.

They showed that the use of energy storage in the distribution networks can increase the local consumption of wind energy and provide certain ancillary services that lead to an increase in total profit. Li *et al.* [19] proposed bi-level optimization model to determine the optimal capacity and location of the energy storage system in a virtual power plant. They used a solution framework based on decomposition algorithm to solve the problem and to improve the solution efficiency.

Later, some scholars focused on developing energy storage systems by using an inventory approach. Saran *et al.* [20] was the first author who employed inventory management to formulate network design decision and daily operating policies for wind plant equipped with the battery storage system. Schneider *et al.* [21] and Schneider *et al.* [22] formulated an electrical energy storage system (EESS) by employing the newsvendor model. They tried to determine the optimal size of energy in an apartment equipped with a PV system. Biel and Glock [23] proposed a multistage production system considering the integration between EESS and heat recovery systems. They focused their study on formulating a strategy to reduce energy usage and increase system flexibility. Furthermore, Marchi *et al.* [24] formulated a mathematical model based on a multi-period newsvendor model for obtaining the optimal size of the energy storage system. Loads shifting was allowed in the model and a battery was installed to increase the self-consumption rate.

Recently, some scholars have put their attention on developing an electricity supply chain model based on inventory theory. Wangsa and Wee [25] was the first to introduce a joint economic lot-sizing problem (JELP) of a power plant-transmission station-distribution substation system under stochastic demand. A mathematical model was developed to portray the investigated system and an efficient procedure was derived to determine the decision variables. Wangsa *et al.* [26] showed how the price-dependent demand could give a pronounced impact on energy lot-sizing decisions. They examined the influence of four types of demand function on the model's behavior and proposed an algorithm to solve the problem. Similar to the work of Wangsa *et al.* [26], Mishra *et al.* [27] also proposed a sustainable electrical energy supply chain system (SEESCS) problem considering price-dependent demand, setup cost reduction, and the effort to reduce carbon emissions. The emissions were assumed to release from storage and transmission activities. A carbon tax regulation was applied to lessen the amount of emissions coming from SESCS. Jauhari *et al.* [28] proposed a two-echelon energy storage system comprising of a power generation and a transmission station. They considered an electricity demand from utility system and included the procurement of raw material used to produce electricity.

Our review to the electrical energy supply chain literature shows that some scholars have developed various models by considering some aspects, but none has investigated the impact of using two types of power generation system on energy lot-sizing decisions. While electricity production is one of the sectors that produced the highest emissions, earlier works on electricity supply chain models rarely incorporated the issue of emission reduction. In this paper, we address this issue by finding the best mix of two power generation systems. The first is cleaner than the second power generation system, thus generating less emissions. However, the cost to produce electricity in the first power generation system is higher than that of the second power generation system. A typical example of the first type of power generation system is a power plant system that uses natural gases as fuels to produces electricity. The second one can be exemplified as a power plant that uses coal as a fuel for electricity production. Although power plant that uses natural gas will produce smaller emissions, the high price of gas will make production costs much more expensive. In addition, the regulator implements a carbon tax regulation to limit emissions. Facing this problem, however, the process of determining energy lot-sizing in the SEESCS becomes more complicated. Considering the setting of the above problem, we aim to answer the following questions:

1) How would the allocation of electricity generation among the two power generation systems be determined to deal with the trade-off between emissions and production cost?
2) How much money should be invested by the power plant to reduce the setup cost?

Here, we attempt to answer the above questions by proposing a SEESCS with a hybrid electricity production system consisting of two different power generation systems under stochastic demand. A trade-off between emissions and electricity production cost is involved in the model and a carbon tax is applied to restrict the emissions released from the electricity production. The emissions coming from electricity production are influenced by the power supply rate. Later, the electricity production cost is formulated as a function of the power supply rate. In addition, the power plant has a chance to invest a certain amount of money to reduce the setup cost. This type of investment was widely proposed by other scholars [27], [29], [30] to make sure that the setup cost can be reduced at a reasonable level. Table 1 provides a comparison between our model in this paper and the related works published earlier. Compared with the existing studies, the novel contributions of the proposed model are:

1) We propose a new mathematical model for a hybrid power generation system developed with the inventory modelling approach. To make a hybrid system works, we propose a new decision variable, namely the allocation of the electricity production, that can be used to manage the electricity production in both power generation systems.
2) We consider a situation in which the hybrid power generation system owned by the power plant faces a trade-off between electricity production cost and emissions. The first power generation system (PG1) produces less emissions than the second power generation system (PG2), but it results in a higher electricity

TABLE 1. Comparison of proposed works with previous published works.

Papers	System structure	Demand	Hybrid power generation	Energy loss	Investment	Emissions
Saran et al. [13]	Wind plant and Battery storage	Discrete	No	No	No	No
Schneider et al. [14]	Photovoltaic system and customer	Discrete	No	No	No	No
Schneider et al. [15]	Photovoltaic system and customer	Discrete	No	No	No	No
Biel and Glock [16]	Multi-stage production	Deterministic	No	No	No	No
Wangsa and Wee [18]	Power generation, Transmission substation, Distribution station	Stochastic	No	No	No	No
Wangsa et al. [19]	Power generation, Transmission substation, Distribution substation and customer	Price dependent demand	No	No	No	No
Marchi et al. [23]	Photovoltaic system and Battery storage system	Uncertain	No	Yes	No	No
Mishra et al. [20]	Power generation, Transmission substation, Distribution substation and customer	Linier price dependent demand	No	No	Yes	Yes
Jauhari et al. [21]	Power generation and Transmission station	Stochastic	No	Yes	No	No
Proposed model	Power generation and Transmission station	Stochastic	Yes	Yes	Yes	Yes

production cost. Since the previous studies only used one type of power generation system, this kind of trade offs has not been considered in the previous models.

3) We propose a new mechanism to lessen the emissions from the electricity generation. The emission generated from electricity generation is linked to the rate of electricity power supply, so it's level can be adjusted by controlling the allocation of electricity production.
4) The emissions from the power plants and the power grids are calculated more comprehensively. We assume that the carbon emissions are also released from the electricity production activity. This makes sense since the electricity production generates most emissions due to the fuel combustion process. However, most of the previous studies, i.e Mishra *et al.* [27], neglected this phenomenon and assumed that the emissions are only produced from storage and transmission activities. We use carbon tax regulation to curb the emissions generated by the power generation systems. The earlier studies on electricity supply chain models mostly neglected the issue of emission reduction policy

II. SYSTEM DESCRIPTION

In this paper, we address an electrical energy supply chain system that consists of a power plant and transmission system. The power plant owns two types of power generation systems, where the first one (PG1) is more environmentally friendly but more expensive than the second one (PG2). The two power generation systems produce electricity which will then be transmitted to the end customers through the transmission system. The demand at the end customers follows a normal distribution with a mean value of D and a standard deviation of σ. There is a setup cost when the power generation system initiated the production activity and there is a holding cost for any electricity put in the storage system. In addition, the production and storage activities also generate emissions. The transmission cost is incurred in the transmission process. The transmission system may have to keep the electricity in the storage. If the amount of electricity available is less than the demand, there will be a shortage and as a result, a blackout is occurred and there is a cost associated with this blackout.

The questions to be answered here are, how much electricity will be produced in PG1 and PG2, how much the economical size of energy consumption and emergency backup storage, and how much money should be invested to reduce the setup cost. Production activity produces emissions which should also be a concern. Thus, the objective is to minimize the total cost that includes production setup cost, electricity holding cost at both production and transmission stages, emission costs, the fixed costs associated with any transmission batch, as well as the blackout costs due to shortage in the electricity supply. We call this system as a sustainable electrical energy supply chain system (SEESCS). The structure is very much similar to the classical supply chain inventory system (CSCIS), where there are two manufacturing plants with different characteristics producing the same product which then will be distributed by a distributor to the end customers. Figure 1 presents the analogies between SEESCS and CSCIS. The production of electric power in the power plant resembles the product manufacturing in the manufacturer. Moreover, the process of transmitting the electricity from the power plant to the transmission station looks like the process of transporting the products from the manufacturer to the retailer. The size of energy storage in both manufacturer and transmission station is very much similar to the lot size in inventory management. Thus, it is concluded the that process of determining energy storage in SEESCS is also similar to the process of specifying the order quantity in CSCIS [15], [19], [20].

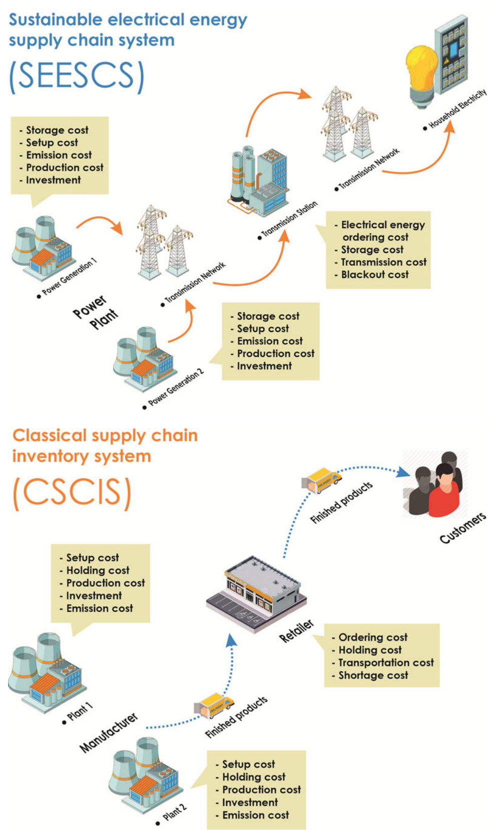

FIGURE 1. **Graphical representation for the analogies between SEESCS and CSCIS.**

In the proposed SEESCS, the power plant produces a batch of electricity Qtn kWh, which is $(1-\alpha)\,Qtn$ kWh generated from PG1 and αQtn kWh generated from PG2. The power plant then transmits a size of Qt kWh to the transmission station over n times. The two power generation systems run in parallel to produce electricity. The power supply rate of PG1 and PG2 is formulated by $P_1 = (1-\alpha)P$ kWh and $P_2 = \alpha P$ kWh, respectively. In this study, we employ the concepts of the joint economic lot-size (JELS) approach where the optimum production and transmission lots are derived to minimize the total cost of the whole supply chain system.

III. ASSUMPTIONS

The following assumptions are used in this paper to develop the mathematical model of the power plant-transmission station electrical energy supply chain system.

1. We consider an electrical energy supply chain system that consists of a single power plant and a single transmission station.
2. The power plant produces electricity and then transmits it to the transmission station. Transmission station faces demand from end customers which follows a normal distribution with mean D and standard deviation σ.
3. The transmission station uses a continuous review policy to manage electricity energy storage.
4. The power plant has a finite rate of power supply, which is $P(1-\gamma) > D$.
5. The power plant has two different power generation systems which produce electrical energy. The electricity production cost of PG1 is higher than the cost of PG2. However, the amount of carbons emitted by PG1 is lower than emissions from PG2.
6. The power plant produces a batch of electricity Qtn (kWh), which is $(1-\alpha)\,Qtn$ (kWh) generated from PG1 and αQtn (kWh) generated from PG2. The power plant then transmits a size of Qt (kWh) to the transmission station over m times.
7. The two power generation systems run in parallel to produce electricity. The power supply rate of PG1 and PG2 are formulated by $P_1 = (1-\alpha)P$ and $P_2 = \alpha P$, respectively.

IV. MATHEMATICAL MODEL DEVELOPMENT

In this section, a brief description of the mathematical model for the electrical energy supply chain system is presented. The investigated system consists of two parties, namely a power plant and a transmission station. The joint total cost of the electrical energy supply chain consists of the expected total cost for the power plant and the expected total cost for the transmission station. In this paper, we model the problem with total cost as a single objective function. An alternative way of formulating this problem is by using multiple objective where the carbon emission is not converted into cost, but measured individually as a separate objective function.

A. TOTAL COST OF TRANSMISSION STATION

As discussed in the above section, the electricity demand from the end customers follows a normal distribution (D, σ). To cope with such a stochastic demand, the transmission station uses a continuous review policy to manage the electrical energy storage level. Thus, whenever the electrical energy storage level reaches the reorder point, the energy replenishment needs to be done immediately. Figure 2 presents the electrical energy storage level for the transmission station. As can be seen in the figure, the blackout will occur if the electrical energy storage level is less than the electricity demand. Thus, emergency backup storage is needed by the

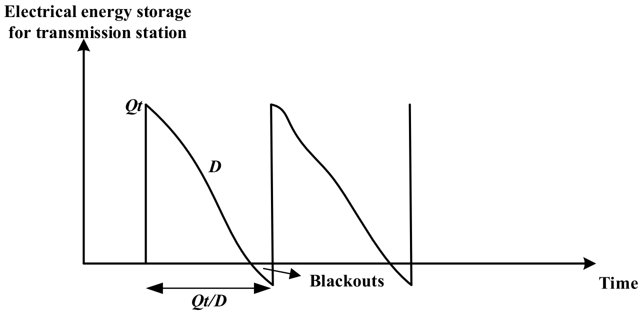

FIGURE 2. Transmission station's energy storage level.

transmission station to overcome blackouts. The emergency backup storage formulation is similar to the safety stock formulation, which is

$$EBS = k\sigma\sqrt{\frac{Qt}{P}+T_s} \tag{1}$$

The expected blackout is expressed by

$$EBL = \sigma\sqrt{\frac{Qt}{P}+T_s}\psi(k) \tag{2}$$

where,

$$\psi(k) = f_s(k) - k[1 - F_s(k)] \tag{3}$$

$f_s(k)$ and $F_s(k)$ are the pdf and cdf of standard normal distribution, respectively. The derivation of equation (2) is given in Appendix.

By following the analogy of average inventory with lost sale case, the annual energy storage cost per year incurred by the transmission station is given by equation (4)

$$h_T\left(\frac{(1-\gamma)Qt}{2}+k\sigma\sqrt{\frac{Qt}{P}+T_s} + (1-\beta)\sigma\sqrt{\frac{Qt}{P}+T_s}\psi(k)\right) \tag{4}$$

The expected blackout and marginal profit loss per order is formulated by $\beta\sigma\sqrt{\frac{Qt}{P}+T_s}\psi(k)$ and $(1-\beta)\sigma\sqrt{\frac{Qt}{P}+T_s}\psi(k)$. The blackout cost per year incurred by the transmission station is presented by equation (5).

$$\frac{D[\pi_x\beta+\pi_0(1-\beta)]\sigma}{(1-\gamma)Qt}\sqrt{\frac{Qt}{P}+T_s}\psi(k) \tag{5}$$

Thus, the total cost of the transmission station can be developed by summing up equations (4), (5) and ordering and transmission costs, which is

$$\begin{aligned} TCT = {} & \frac{D}{(1-\gamma)Qt}(F_T+A)+h_T \\ & \times\left(\frac{(1-\gamma)Qt}{2}+k\sigma\sqrt{\frac{Qt}{P}+T_s} + (1-\beta)\sigma\sqrt{\frac{Qt}{P}+T_s}\psi(k)\right) \\ & + \frac{D[\pi_x\beta+\pi_0(1-\beta)]\sigma}{(1-\gamma)Qt}\sqrt{\frac{Qt}{P}+T_s}\psi(k) \end{aligned} \tag{6}$$

B. TOTAL COST OF POWER PLANT

The total cost of the power plant consists of the total cost of PG1 and the total cost of PG2. As stated in the above assumptions, PG1 is greener than PG2. However, the production cost of PG1 is higher than that of PG2. By having the different characteristics of the two power generation systems, the power plant intends to determine the optimal production allocation, so that the minimum total cost is achieved. The total cost per year incurred by the PG1 consists of setup cost, energy storage cost, emission cost, and production cost. The setup cost incurred by the PG1 is given by

$$STC_1 = \frac{DK_1}{(1-\gamma)Qtn} \tag{7}$$

Figure 3 shows the electrical energy storage level for PG1 and PG2. The average energy storage for the PG1 can be evaluated by subtracting the accumulated transmission station's energy consumption from the accumulated power generation system's energy production, which is

$$INV_1 = \frac{(1-\alpha)Qt}{2}\left(n\left[1-\frac{(1-\alpha)D}{(1-\gamma)P_1}\right]-1+\frac{2(1-\alpha)D}{(1-\gamma)P_1}\right) \tag{8}$$

Thus, the expected storage cost per year for PG1 can be formulated by

$$STR_1 = h_P\frac{(1-\alpha)Qt}{2}\left(n\left[1-\frac{(1-\alpha)D}{(1-\gamma)P_1}\right]-1+\frac{2(1-\alpha)D}{(1-\gamma)P_1}\right) \tag{9}$$

The amount of carbon emissions generated from the electrical energy production depends on the power supply rate [31], [32]. The emission cost charged by the PG1 is expressed as follows

$$EMC_1 = c_{tax}\left(a_1P_1^2 - b_1P_1 + c_1\right)(1-\alpha)\frac{D}{(1-\gamma)} \tag{10}$$

The formulation of production cost is influenced by the power supply rate. Here, we adopt the formula developed by Khouja and Mehrez [33] to express the production cost of the PG1, that is

$$PC_1 = \left(\frac{g_{11}}{P_1}+g_{21}P_1\right)(1-\alpha)\frac{D}{(1-\gamma)} \tag{11}$$

An amount of money is invested by the power plant to reduce the setup cost. The investment on setup cost reduction follows a logarithmic function, which is

$$ISC_1 = \frac{\eta_1}{\delta_1}ln\left(\frac{K_{10}}{K_1}\right) \tag{12}$$

Similar to the total cost of the PG1, the expected total cost of the PG2 can be determined by considering setup cost, storage cost, emission cost, and production cost. Equations (13) and (14) express the setup cost and the storage cost, respectively.

$$STC_2 = \frac{DK_2}{(1-\gamma)Qtn} \tag{13}$$

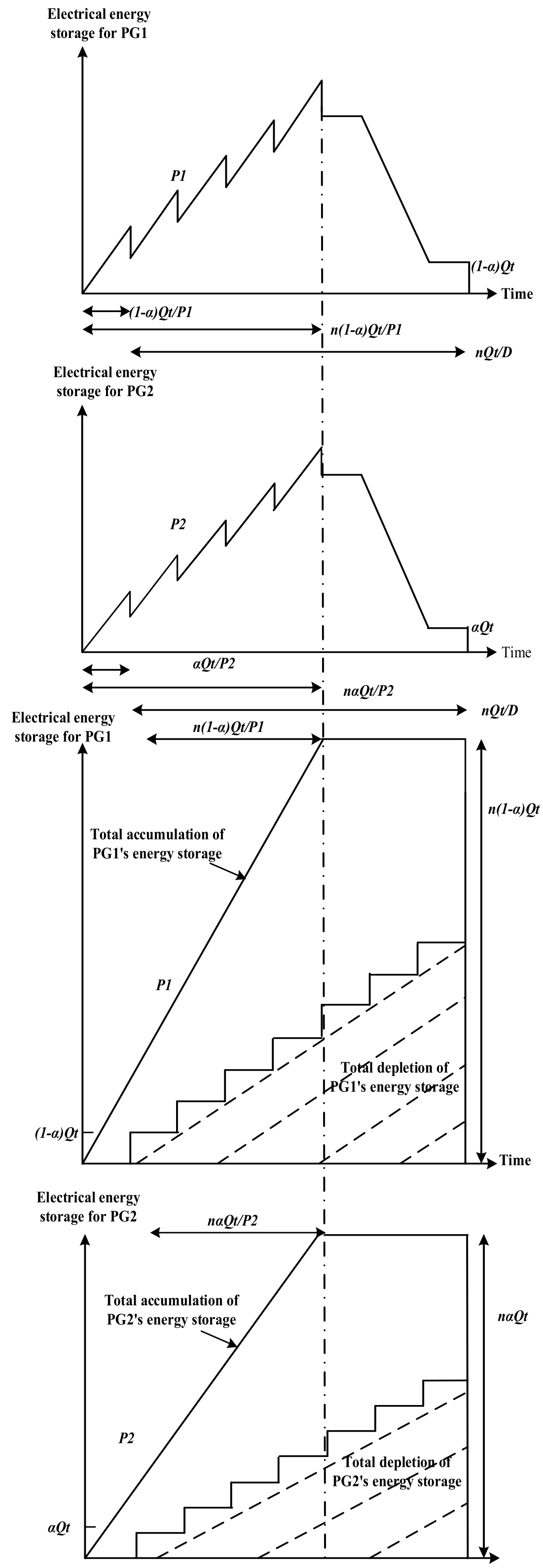

FIGURE 3. Power plant's energy storage level.

$$STR_2 = h_P \frac{\alpha Qt}{2}\left(n\left[1-\frac{\alpha D}{(1-\gamma)P_2}\right]-1+\frac{2\alpha D}{(1-\gamma)P_2}\right) \tag{14}$$

The emission cost, production cost, and investment cost for the PG2 is given by equations (15), (16) and (17), respectively.

$$EMC_2 = c_{tax}\left(a_1 P_2^2 - b_1 P_2 + c_1\right)\frac{\alpha D}{(1-\gamma)} \tag{15}$$

$$PC_2 = \left(\frac{g_{12}}{P_2} + g_{22} P_2\right)\frac{\alpha D}{(1-\gamma)} \tag{16}$$

$$ISC_2 = \frac{\eta_2}{\delta_2} ln\left(\frac{K_{20}}{K_2}\right) \tag{17}$$

The total cost charged by the power plant is derived by the equation (18). The first term represents the power plant's transmission cost. The costs incurred by the PG1 which consists of setup cost, storage cost, carbon cost, production cost, and investment cost are presented in the second term until the sixth term of equation (18). The seventh term until the eleventh term of equation (18) show setup cost, storage cost, carbon cost, production cost and investment cost of the PG2.

$$\begin{aligned} TCP =& \frac{D}{(1-\gamma)Qtn}F_p + \frac{DK_1}{(1-\gamma)\,Qtn} \\ &+ h_T \frac{(1-\alpha)\,Qt}{2}\left(n\left[1-\frac{(1-\alpha)\,D}{(1-\gamma)\,P_1}\right]-1\right. \\ &\left.+\frac{2\,(1-\alpha)\,D}{(1-\gamma)\,P_1}\right) + c_{tax}\left(a_1 P_1^2 - b_1 P_1 + c_1\right) \\ &\times (1-\alpha)\frac{D}{(1-\gamma)} + \left(\frac{g_{11}}{P_1} + g_{21} P_1\right)(1-\alpha) \\ &\times \frac{D}{(1-\gamma)} + \frac{\eta_1}{\delta_1} ln\left(\frac{K_{10}}{K_1}\right) + \frac{DK_2}{(1-\gamma)Qtn} \\ &+ h_P \frac{\alpha Qt}{2}\left(n\left[1-\frac{\alpha D}{(1-\gamma)P_2}\right]-1+\frac{2\alpha D}{(1-\gamma)P_2}\right) \\ &+ c_{tax}\left(a_1 P_2^2 - b_1 P_2 + c_1\right)\frac{\alpha D}{(1-\gamma)} \\ &+ \left(\frac{g_{12}}{P_2} + g_{22} P_2\right)\frac{\alpha D}{(1-\gamma)} + \frac{\eta_2}{\delta_2} ln\left(\frac{K_{20}}{K_2}\right) \end{aligned} \tag{18}$$

C. JOINT TOTAL COST

The joint total cost for an electrical energy supply chain consisting of a power plant and transmission station can be determined by summing up the transmission station total cost (equation 6) and the power plant total cost (equation 18), which is

$$\begin{aligned} JTC =& \frac{D}{(1-\gamma)Qt}(F_T + A) + \frac{D\left[\pi_x \beta + \pi_0 (1-\beta)\right]\sigma}{(1-\gamma)Qt} Y_2 \psi(k) \\ &+ h_T\left(\frac{(1-\gamma)Qt}{2} + k\sigma Y_2 + (1-\beta)\sigma Y_2 \psi(k)\right) \\ &+ \frac{DK_1}{(1-\gamma)\,Qtn} + \frac{D}{(1-\gamma)Qtn}F_p + h_P \frac{(1-\alpha)\,Qt}{2} Y_1 \\ &+ c_{tax}\left(a_1 P_1^2 - b_1 P_1 + c_1\right)(1-\alpha)\frac{D}{(1-\gamma)} \\ &+ \left(\frac{g_{11}}{P_1} + g_{21} P_1\right)(1-\alpha)\frac{D}{(1-\gamma)} + \frac{\eta_1}{\delta_1} ln\left(\frac{K_{10}}{K_1}\right) \end{aligned}$$

$$+\frac{DK_2}{(1-\gamma)Qtn}+h_P\frac{\alpha Qt}{2}Y_1+c_{tax}\left(a_1P_2^2-b_1P_2+c_1\right)\times\frac{\alpha D}{(1-\gamma)}+\left(\frac{g_{12}}{P_2}+g_{22}P_2\right)\frac{\alpha D}{(1-\gamma)}+\frac{\eta_2}{\delta_2}ln\left(\frac{K_{20}}{K_2}\right) \tag{19}$$

where,

$$Y_1=\left(n\left[1-\frac{D}{(1-\gamma)P}\right]-1+\frac{2D}{(1-\gamma)P}\right) \tag{20}$$

$$Y_2=\sqrt{\frac{Qt}{P}+T_s} \tag{21}$$

It is clear that by looking at equations (10), (11), (15) and (16), there is a relationship between production cost and emission cost. Both costs are strongly influenced by the power supply rate. As stated in the system description section, the determination of power supply rate of PG1 and PG1 is related to allocation factor (α), which means that both costs are also influenced by the allocation factor. By looking at the relationship between allocation factor, power supply rate and the costs, we can conclude that by controlling the allocation factor, the system can control the production cost and emission cost simultaneously to minimize the joint total cost. Thus, the process of determining the optimal allocation factor in the model must simultaneously consider these two costs.

V. SOLUTION PROCEDURE

In this section, a procedure to derive the solutions of the proposed system is developed. The objective of the proposed mathematical model is to minimize the joint total cost by simultaneously determining k, Q, n, α, K_1 and K_2. For fixed n and α, the minimum joint total cost occurs at point (Q, k, K_1, K_2) which satisfies $\frac{\partial JTC}{\partial k}=0$, $\frac{\partial JTC}{\partial Q}=0$, $\frac{\partial JTC}{\partial K_1}=0$, $\frac{\partial JTC}{\partial K_2}$, simultaneously. Thus, we take the first derivatives of the joint total cost function with respect to Q, k, K_1, and K_2, respectively.

$$\frac{\partial JTC}{\partial k}=-[1-F_s(k)]\frac{D[\pi_x\beta+\pi_0(1-\beta)]\sigma}{(1-\gamma)Qt}Y_2+h_T\sigma Y_2-[1-F_s(k)]h_T(1-\beta)\sigma Y_2 \tag{22}$$

$$\frac{\partial JTC}{\partial Q}=-\frac{D}{(1-\gamma)Q^2t}(F_T+A)+\frac{D[\pi_x\beta+\pi_0(1-\beta)]\sigma t\psi(k)}{2P(1-\gamma)QtY_2}-\frac{D[\pi_x\beta+\pi_0(1-\beta)]\sigma Y_2\psi(k)}{(1-\gamma)Q^2t}+\frac{h_T(1-\gamma)t}{2}+\frac{h_Tk\sigma t}{2PY_2}+\frac{h_T(1-\beta)\sigma t\psi(k)}{2PY_2}-\frac{D(K_1+K_2+F_P)}{(1-\gamma)Q^2tn}+h_P\frac{t}{2}Y_1 \tag{23}$$

$$\frac{\partial JTC}{\partial K_1}=\frac{D}{(1-\gamma)Qtn}-\frac{\eta_1}{\delta_1K_1} \tag{24}$$

$$\frac{\partial JTC}{\partial K_2}=\frac{D}{(1-\gamma)Qtn}-\frac{\eta_2}{\delta_2K_2} \tag{25}$$

The second partial derivatives of the joint total cost function with respect to k, Q, K_1, and K_2 are given by the following equations

$$\frac{\partial^2 JTC}{\partial k^2}=f_s(k)\frac{D[\pi_x\beta+\pi_0(1-\beta)]\sigma}{(1-\gamma)Qt}Y_2+f_s(k)h_T(1-\beta)\sigma Y_2 \tag{26}$$

$$\frac{\partial^2 JTC}{\partial Q^2}=\frac{D}{(1-\gamma)Q^3t}(F_T+A)+\frac{D(K_1+K_2+F_P)}{(1-\gamma)Q^3tn}+\frac{2D[\pi_x\beta+\pi_0(1-\beta)]\sigma\psi(k)\sqrt{\frac{Qt}{P}+T_s}}{(1-\gamma)Q^2t}-\frac{D[\pi_x\beta+\pi_0(1-\beta)]\sigma t\psi(k)}{4P^2(1-\gamma)Q\left(\frac{Qt}{P}+T_s\right)Y_2}-\frac{D[\pi_x\beta+\pi_0(1-\beta)]\sigma\psi(k)}{2P(1-\gamma)Q^2Y_2}-\frac{D[\pi_x\beta+\pi_0(1-\beta)]\sigma\psi(k)}{2(1-\gamma)PQ^2Y_2}-\frac{h_Tk\sigma t^2}{2P\left(\frac{Qt}{P}+T_s\right)Y_2}-\frac{h_T(1-\beta)\sigma t^2\psi(k)}{4P^2\left(\frac{Qt}{P}+T_s\right)Y_2} \tag{27}$$

$$\frac{\partial^2 JTC}{\partial K_1^2}=\frac{\eta_1}{\delta_1K_1^2} \tag{28}$$

$$\frac{\partial^2 JTC}{\partial K_2^2}=\frac{\eta_2}{\delta_2K_2^2} \tag{29}$$

From equations (26)-(29), we observe that the joint total cost function is convex in k, K_1, and K_2. However, the joint total cost function may not be convex in Q. This property was commonly found by some scholars, i.e Ben-Daya and Hariga [34], Glock [35], Jauhari and Saga [36], when solving a stochastic inventory problem. By setting equations (22)-(25) equal to zero, rearranging and simplifying the terms, we obtain (30)–(33), as shown at the bottom of the next page.

Furthermore, in order to investigate the effect of n and α on the joint total cost function, we take the first and second partial derivatives of the joint total cost with respect to n and α, respectively. We obtain the following expressions

$$\frac{\partial JTC}{\partial n}=-\frac{DK_1}{(1-\gamma)Qtn^2}-\frac{DK_2}{(1-\gamma)Qtn^2}-\frac{DF_p}{(1-\gamma)Qtn^2}+h_P\frac{Qt}{2}\left[1-\frac{D}{(1-\gamma)P}\right] \tag{34}$$

$$\frac{\partial^2 JTC}{\partial n^2}=\frac{DK_1}{(1-\gamma)Qtn^3}+\frac{DK_2}{(1-\gamma)Qtn^3}+\frac{DF_p}{(1-\gamma)Qtn^3}>0 \tag{35}$$

$$\frac{\partial JTC}{\partial \alpha} = -c_{tax}\left(a_1P_1^2 - b_1P_1 + c_1\right)\frac{D}{(1-\gamma)} - \frac{2Dg_{21}P\,(1-\alpha)}{(1-\gamma)} + \frac{2Dg_{22}\alpha P}{(1-\gamma)} + c_{tax}\left(a_1P_2^2 - b_1P_2 + c_1\right)\frac{D}{(1-\gamma)} \tag{36}$$

$$\frac{\partial^2 JTC}{\partial \alpha^2} = \frac{2Dg_{21}P}{(1-\gamma)} + \frac{2Dg_{22}P}{(1-\gamma)} > 0 \tag{37}$$

As can be seen, equations (30)-(33) have interdependencies between each other. For example, the determination of k requires Q and conversely, the determination of Q will require k. Thus, to derive the solution, we develop an iterative procedure based on the idea of Ben-Daya and Hariga [34]. The procedure has three loops i.e, the loop for searching the optimal α, the loop for searching the optimal n and the loop for searching the convergence values of k, Q, K_1, and K_2. The procedure is described as follows. First, set the initial values of α and n. Second, the initial value of Q is then computed by setting the stochastic parameters to zero. Third, the values of k, K_1, and K_2, are computed, which are then used to update the value of Q. This procedure is repeated until a convergent point is reached. Fourth, the solution is found by comparing the values of joint total cost generated by each loop. The procedure is listed below

1. Set $\alpha = 0.01$
2. Set $n = 1$ and $JTC(Q_{n-1}, k_{n-1}, K_{1,n-1}, K_{2,n-1}, n-1, \alpha) = \infty$
3. Set the values of Q and k equal to zero. Compute Q using equation (31).
4. Compute k by inserting the previous value of Q into equation (30).
5. Compute K_1 and K_2 using equations (32) and (33), respectively. If $K_1 > K_{10}$ then set $K_1 = K_{10}$ and if $K_2 > K_{20}$ then set $K_2 = K_{20}$.
6. Update the value of Q by substituting the previous values of Q, k, K_1 and K_2 into equation (31).
7. Repeat steps 4-6 until no change occurs in the values of Q, k, K_1 and K_2.
8. Set $Q_n = Q$, $k_n = k$, $K_{1n} = K_1$ and $K_{2n} = K_2$. Compute $JTC(Q_n, k_n, K_{1,n}, K_{2,n}, n, \alpha)$ using equation (19).
9. If $JTC(Q_n, k_n, K_{1,n}, K_{2,n}, n, \alpha) \leq JTC(Q_{n-1}, k_{n-1}, K_{1,n-1}, K_{2,n-1}, n-1, \alpha)$ repeat steps 2-7 with $n = n+1$, otherwise go to step 9.
10. Set $JTC(Q, k, K_1, K_2, n, \alpha) = JTC(Q_{n-1}, k_{n-1}, K_{1,n-1}, K_{2,n-1}, n-1, \alpha)$
11. Repeat steps 2-10 for the set value of α, $(0 < \alpha < 1)$ with the change of $\alpha = \alpha + 0.01$.
12. Find the minimum values of $JTC\ (Q, k, K_1, K_2, n, \alpha)$. Set $Q, k, K_1, K_2, n, \alpha$ as the optimal solutions of the proposed problem.

VI. NUMERICAL EXAMPLE

To illustrate the proposed SEESCS problem, which consists of a power plant and a transmission station under stochastic demand and emissions, we provide a numerical example where the corresponding parameter values are obtained from Wangsa and Wee [18], Jauhari *et al.* [21] and some values are taken from one major power generating company in Indonesia. The parameter values of our numerical example are presented as follows: $D = 150$, $\sigma = 500$, $A = 50$, $F_t = 150$, $F_p = 120$, $h_T = 0.02$, $h_P = 0.02$, $\pi_x = 150$, $\pi_0 = 200$, $P = 200$, $T_s = 0.005$, $c_{tax} = 0.0618$, $K_{10} = 5{,}400$, $K_{20} = 5{,}400$, $\beta = 0.25$, $\gamma = 0.1$, $t = 24$, $g_{11} = 7{,}500$, $g_{12} = 2{,}500$, $\eta_1 = 0.2$, $\eta_2 = 0.2$, $\delta_1 = 0.0004$, $\delta_2 = 0.0005$, $g_{21} = 0.00000027$, $g_{22} = 0.00000016$, $a_1 = 0.000000000018$, $b_1 = 0.000000012$, $c_1 = 0.0014$, $a_2 = 0.0000000001$, $b_2 = 0.000000216$, $c_2 = 0.00252$.

From the parameter values provided above, we intend to investigate a SEESCS problem in a situation in which the electricity demand is relatively stable. The above values associated with emission and production cost clearly show the trade-off between PG1 and PG2, that is the system in PG1 is cleaner than PG2. However, the production cost of PG 1 is relatively higher than the cost of PG2. To reflect this condition, we assume that $a_1 < a_2$, $g_{11} > g_{12}$ and $g_{21} > g_{22}$. We also face a situation in which the effort to reduce setup cost in PG1 is relatively more difficult than that in PG2.

By utilizing the above iterative procedure, we can obtain the optimal solutions of the proposed problem. Table 2 shows the optimal solutions that minimizes the joint total cost. The amount of carbon emissions per year resulted from PG1 and

$$F_s(k) = 1 - \frac{h_T(1-\gamma)Qt}{D\left[\pi_x\beta + \pi_0(1-\beta)\right] + h_T(1-\beta)(1-\gamma)Qt} \tag{30}$$

$$Q = \sqrt{\frac{\frac{2D}{(1-\gamma)t}\left\{(F_T + A + \left[\pi_x\beta + \pi_0(1-\beta)\right]\sigma Y_2\psi(k) + \frac{K_1}{n} + \frac{K_2}{n} + \frac{F_P}{n}\right\}}{\left\{\begin{array}{l}\frac{D[\pi_x\beta+\pi_0(1-\beta)]\sigma\psi(k)}{P(1-\gamma)QY_2} + h_T(1-\gamma)t + \frac{h_Tk\sigma t}{PY_2}\\ + \frac{h_T(1-\beta)\sigma t\psi(k)}{PY_2} + h_PtY_1\end{array}\right\}}} \tag{31}$$

$$K_1 = \frac{\eta_1(1-\gamma)Qtn}{D\delta_1} \tag{32}$$

$$K_2 = \frac{\eta_2(1-\gamma)Qtn}{D\delta_2} \tag{33}$$

TABLE 2. Results of numerical example.

Decision variables and costs	Values	Unit
Electricity generation's allocation factor (α)	37	%
Power consumption (Q)	2,144.96	kW
Emergency backup factor of transmission station (k)	3.081	times
Emergency backup supply of transmission station	789.01	kW
Electrical power distribution factor (n)	7	times
Electrical energy generated by PG1	227,023.05	kWh
Electrical energy generated by PG2	133,331	kWh
Total cost for PG1	13,709.67	\$/year
Total cost for PG2	6,409.06	\$/year
Total cost for transmission station	1,171.17	\$/year
Joint total cost	21,289.9	\$/year

PG2 are 29,993.88 $kgCO_2$ and 32,938.39 $kgCO_2$, respectively. We can observe from the table that the electrical energy generated from PG1 and PG2 are 227,023.05 kWh and 133,331 kWh, respectively, which clearly shows that the electricity generation is allocated more to the green facility. As the blackout may occur in the electrical energy supply chain system, the transmission station needs emergency backup supply of 789.01 kW to satisfy the demand during blackout period.

VII. SENSITIVITY ANALYSIS

In this section, a sensitivity analysis is carried out to understand how the proposed system operates on varying value of key parameters. We focus on studying the effect of some parameters, which are production cost of PG1, emission of PG2, carbon tax, storage cost, energy lost, investment parameter of PG1, and demand. The discussions of the mentioned parameters are presented below

A. ANALYSIS OF PG1'S PRODUCTION COST PARAMETER (g_{21})

In this subsection, we examine how the proposed model behaves against the PG1's production cost's change. As presented in Table 3, the change in PG1's production cost parameter gives a pronounced impact on the electricity generation's allocation factor. Facing an increased PG1' production cost, the manager should shift the production to the cheaper power generation system to maintain the total cost incurred by the system. As consequence of this decision, the amount of electricity demand satisfied by PG2 rises. This is, however, leads to the increasing of PG2's power supply (see Figure 4). This makes sense since increasing the electricity power supply will increase the electricity capacity, thus balancing the supply and the demand. We note that the total costs of PG1 and PG2 are significantly influenced by the change in PG1's production cost parameter. It is seen that varying PG'1 production cost parameter up to 80%, the PG1's total cost, PG2's total cost and joint total cost increase by 10.63%, 19.02% and 12.57%, respectively, while the transmission's total cost remains unchanged.

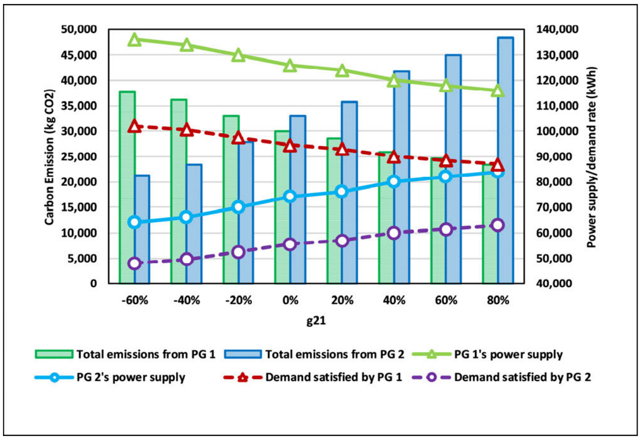

FIGURE 4. The impact of the change in g_{21} on emissions, demand and power supply.

The amount of emissions generated by the power plant is significantly influenced by the change in PG1's production cost parameter. We observe that when PG1's production cost parameter increases by 80%, the emissions generated from PG1 decreases by 21.94% while the emissions resulted from PG2 increases by 46.63% (see Figure 4). The increasing of the demand satisfied by PG2 and the increasing value of the PG2's power supply is the main cause of the increase in emissions resulted from PG2. Higher power supply and larger demand will generally push the emissions generation in the power plant. Later, Figure 5 describes the trade-off between production cost and emissions in the proposed system. It attractively shows that the change in the PG1's production cost parameter affects the production cost per kWh and emissions per kWh. We obtain that increasing the value of PG1's production cost parameter by 80% will lead to the increasing of the production cost per kWh (29.38 %) and the decreasing of emission per kWh (15.2 %) in PG1. The result obtained in PG2 is an opposite of PG1's trend. It is found that the PG2's production cost per kWh decreases by 5.3% and the PG2's emissions per kWh increases by 29.18.

B. ANALYSIS OF PG2'S EMISSION PARAMETER (a_2, b_2, c_2)

The second parameter that we analyse is the influence of the change in the PG2's emission parameters on the model's behavior. As the emission level of PG2 is getting higher, it is wise for the manager to allocate more production to the cleaner power generation system (PG1). Table 4 shows how the model behaves against the change in PG2's emission parameters. Facing an increase in PG2's emission parameters, we observe that the electricity generation's allocation factor (α) drastically decreases indicating a significant shift in production activity to PG1. The change in the α value leads to the changes in both electricity demand satisfied by the power

TABLE 3. The impact of change in PG1's production cost on proposed model.

% change in g_{21}	-60%	-40%	-20%	0%	20%	40%	60%	80%
Production allocation factor (α)	0.32	0.33	0.35	0.37	0.38	0.4	0.41	0.42
Power distribution factor (n)	7	7	7	7	7	7	7	7
Power consumption (Q)	2,144.96	2,144.96	2,144.96	2,144.96	2,144.96	2,144.96	2,144.96	2,144.96
Emergency backup factor (k)	3.08	3.08	3.08	3.08	3.08	3.08	3.08	3.08
Setup cost of PG1 (K_1)	1,081.06	1,081.06	1,081.06	1,081.06	1,081.06	1,081.06	1,081.06	1,081.06
Setup cost of PG 2 (K_2)	864.85	864.85	864.85	864.85	864.85	864.85	864.85	864.85
Power supply of PG 1 (P_1)	136,000	134,000	130,000	126,000	124,000	120,000	118,000	116,000
Power supply of PG 2 (P_2)	64,000	66,000	70,000	74,000	76,000	80,000	82,000	84,000
Emissions from PG 1	37,705.55	36,068.33	32,937.67	29,993.88	28,590.27	25,916.00	24,643.91	23,414.21
Emissions from PG 2	21,242.45	23,312.52	27,848.33	32,938.39	35,701.25	41,682.67	44,909.21	48,298.32
Total Emissions	58,948.00	59,380.85	60,786.00	62,932.27	64,291.52	67,598.67	69,553.12	71,712.53
Transmission total cost	1,171.17	1,171.17	1,171.17	1,171.17	1,171.17	1,171.17	1,171.17	1,171.17
PG1 total cost	12,367.53	12,953.43	13,440.99	13,709.67	14,139.51	14,410.80	14,750.04	15,167.56
PG2 total cost	5,445.54	5,619.72	5,995.73	6,409.06	6,632.59	7,108.61	7,362.79	7,628.09
Power plant total cost	17,813.07	18,573.15	19,436.72	20,118.72	20,772.10	21,519.41	22,112.83	22,795.65
Joint total cost	18,984.24	19,744.32	20,607.89	21,289.90	21,943.27	22,690.58	23,284.00	23,966.82

TABLE 4. The impact of change in PG2's emission parameters on proposed model.

% change in PG2's emission parameters	-60%	-40%	-20%	0%	20%	40%	60%	80%
Production allocation factor (α)	0.47	0.42	0.39	0.37	0.35	0.33	0.32	0.29
Power distribution factor (n)	7	7	7	7	7	7	7	7
Power consumption (Q)	2,144.96	2,144.96	2,144.96	2,144.96	2,144.96	2,144.96	2,144.96	2,144.96
Emergency backup factor (k)	3.08	3.08	3.08	3.08	3.08	3.08	3.08	3.08
Setup cost of PG1 (K_1)	1,081.06	1,081.06	1,081.06	1,081.06	1,081.06	1,081.06	1,081.06	1,081.06
Setup cost of PG 2 (K_2)	864.85	864.85	864.85	864.85	864.85	864.85	864.85	864.85
Power supply of PG 1 (P_1)	105,999	116,000	122,000	126,000	130,000	134,000	136,000	142,000
Power supply of PG 2 (P_2)	93,999.53	84,000.00	78,000.00	74,000.00	70,000.00	66,000.00	64,000.00	58,000.00
Emissions from PG 1	17,876.37	23,414.21	27,231.21	29,993.88	32,937.67	36,068.33	37,705.55	42,913.35
Emissions from PG 2	27,128.63	28,978.99	30,891.74	32,938.39	33,418.00	32,637.53	33,987.93	28,396.10
Total Emissions	45,005.00	52,393.21	58,122.96	62,932.27	66,355.67	68,705.86	71,693.47	71,309.45
Transmission total cost	1,171.17	1,171.17	1,171.17	1,171.17	1,171.17	1,171.17	1,171.17	1,171.17
PG1 total cost	11,800.99	12,700.63	13,292.57	13,709.67	14,145.16	14,599.40	14,833.66	15,565.55
PG2 total cost	6,615.06	6,434.15	6,388.01	6,409.06	6,339.94	6,196.01	6,233.20	5,956.26
Power plant total cost	18,416.05	19,134.78	19,680.58	20,118.72	20,485.09	20,795.41	21,066.86	21,521.82
Joint total cost	19,587.22	20,305.95	20,851.75	21,289.90	21,656.27	21,966.58	22,238.04	22,692.99

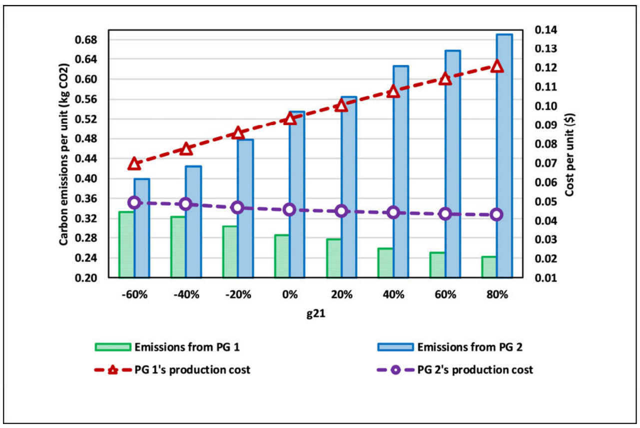

FIGURE 5. The impact of the change in g_{21} on production cost per kWh and emissions per kWh.

generation systems and the power supply. It is found that if the PG2's emission parameter increases by 60%, the electricity demand satisfied by PG1 increases by 7.94% and the electricity demand satisfied by PG2 decreases by 13.51%. Therefore, the manager should adjust the PG1's power supply to a higher level to increase the electricity generation in PG1. Further, the total costs incurred by the power plant and supply chain are significantly influenced by the change in PG2's emission parameters while the total cost charged by the transmission stations remains unchanged.

The impact of the change in the PG2's emission parameters on the emissions is also provided in Figure 6. From the figure, we obtain that changing the value of PG2's emission parameters from −60% to +40%, the emissions generated by PG1 and PG2 go up by 101.77% and 20.31%, respectively. It seems that the emissions are significantly affected by the power supply. This phenomenon indicates that the power supply is the most important parameters in controlling the emission generations in the power plant. Thus, the manager needs to pay more attentions in deciding the optimal value of power supply rate to ensure that the emissions generated from the power plant can be minimized.

C. ANALYSIS OF CARBON TAX

Carbon tax is one of the important policies that are often used by regulators to control the carbon emissions. As regulations on the carbon reduction become more stringent, the regulators can impose higher carbon taxes on emitters to control the overall emissions. Table 5 shows how the electrical energy supply chain reacts to an increase in the carbon tax. We observe that if the carbon tax increases, α decreases, which indicates that the manager must give more electricity generation to PG1. This makes sense since allocating more electricity generation to the greener power generation system reduces the total emissions, which in turns decreases the cost associated with the carbon emissions. Figure 7 presents the

TABLE 5. The impact of change in carbon tax on proposed model.

% change in storage cost	-60%	-40%	-20%	0%	20%	40%	60%	80%
Production allocation factor (α)	0.42	0.4	0.38	0.37	0.36	0.35	0.35	0.34
Power distribution factor (n)	7	7	7	7	7	7	7	7
Power consumption (Q)	2,144.96	2,144.96	2,144.96	2,144.96	2,144.96	2,144.96	2,144.96	2,144.96
Emergency backup factor (k)	3.08	3.08	3.08	3.08	3.08	3.08	3.08	3.08
Setup cost of PG1 (K_1)	1,081	1,081	1,081	1,081	1,081	1,081	1,081	1,081
Setup cost of PG 2 (K_2)	865	865	865	865	865	865	865	865
Power supply of PG 1 (P_1)	116,000	120,000	124,000	126,000	128,000	130,000	130,000	132,000
Power supply of PG 2 (P_2)	84,000	80,000	76,000	74,000	72,000	70,000	70,000	68,000
Emissions from PG 1	23,414.21	25,916.00	28,590.27	29,993.88	31,442.77	32,937.67	32937.67	34479.28
Emissions from PG 2	48,298.32	41,682.67	35,701.25	32,938.39	30,322.08	27,848.33	27,848.33	25,513.15
Total Emissions	71,712.53	67,598.67	64,291.52	62,932.27	61,764.85	60,786.00	60,786.00	59,992.43
Transmission total cost	1,171.17	1,171.17	1,171.17	1,171.17	1,171.17	1,171.17	1,171.17	1,171.17
PG1 total cost	11,832.43	12,450.16	13,145.46	13,709.67	14,313.72	14,959.38	15,366.49	16,074.57
PG2 total cost	5,837.19	6,078.21	6,191.32	6,409.06	6,572.84	6,682.63	7,028.35	7,064.40
Power plant total cost	17,669.61	18,528.37	19,336.79	20,118.72	20,886.56	21,642.01	22,394.83	23,138.97
Joint total cost	18,840.79	19,699.55	20,507.96	21,289.90	22,057.73	22,813.18	23,566.01	24,310.14

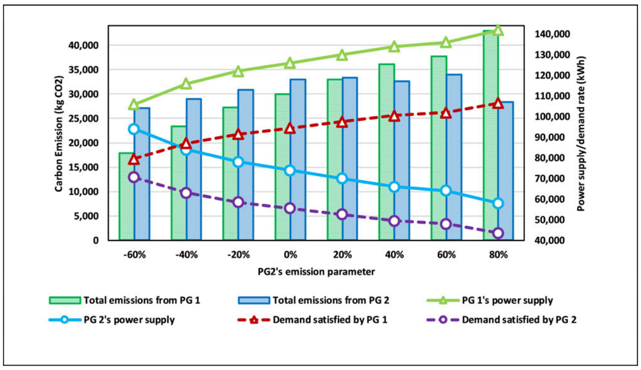

FIGURE 6. The impact of the change in PG2's emission parameters (a_2, b_2, c_2) on emissions, demand and power supply.

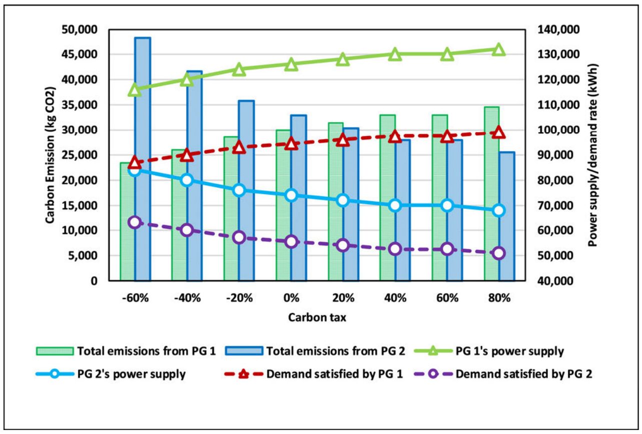

FIGURE 7. The impact of the change in carbon tax on emissions, demand and power supply.

impact of the carbon tax on the emissions, power supply rate and demand satisfied by power generation system. When the carbon tax increases, the PG1's power supply rate increases and the PG'2 power supply rate decreases. This also makes sense since adjusting the power supply rate will balance the electricity production capacity and the production allocation. By examining the results in Figure 7, we also observe that if the carbon tax is increased gradually, the system must minimize its impact by reducing the emissions from electricity generation. When the carbon tax increases by 80%, the emissions from PG1 increases by 14.95% and the emissions from PG2 decreases by 22.54%, which finally leads to 4.67% decrease in total emissions generated by the supply chain. As a result, the total cost incurred by the supply chain and the power plant increase while the total cost incurred by the transmission station remains unchanged.

D. ANALYSIS OF STORAGE COST

In Table 6, we perform sensitivity analysis of decision variables and costs with respect to storage cost. We find that the power consumption, power distribution factor, emergency backup factor and setup cost are negatively related to the storage cost. Increasing the value of storage cost by 80% leads to substantial decrease in the power consumption (28.71%) and the setup cost (38.89%). In addition, we obtain that the power plant is more likely to invest more money to reduce setup cost when the storage cost is more expensive. This is understood since a decreased power consumption results in more frequent setup which generally increases the setup cost charged by the power plant. Facing this condition, it is wise for the manager to invest more money to prevent the system from having higher setup cost. Figure 8 shows that the investment made by the power plant increases due to the increase in the storage cost. We observe that investment made by PG1 is higher than PG2's investment. Furthermore, as storage cost increases, the average cost associated with storing electricity in power plant and transmission station increases drastically. Consequently, costs of all supply chain's members as well as whole system increase.

To further investigate the impact of the storage cost on the model's behavior, we plot the varying electrical energy when the cost changes from −60% to 800% with an increment of 20% in Figure 9. The figure shows that the electrical energy generated by power plant, electrical energy supplied by transmission station and electrical power distribution factor are substantially decrease due to the increase in the storage cost. It is seen that changing the storage cost from 0% to 60%, the electrical energy generated by PG1 and PG2 reduces by

TABLE 6. The impact of change in storage cost on proposed model.

% change in storage cost	-60%	-40%	-20%	0%	20%	40%	60%	80%
Production allocation factor (α)	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Power distribution factor (n)	12	9	8	7	7	6	6	6
Power consumption (Q)	3,245.44	2,765.54	2,371.42	2,144.96	1,891.56	1,809.22	1654.18	1529.08
Emergency backup factor (k)	3.08	3.08	3.08	3.08	3.08	3.08	3.0784	3.078
Setup cost of PG1 (K_1)	2,804.06	1,792.07	1,365.94	1,081.06	953.35	781.58	714.61	660.56
Setup cost of PG 2 (K_2)	2,243.25	1,433.66	1,092.75	864.85	762.68	625.27	571.68	528.45
Power supply of PG 1 (P_1)	126,000	126,000	126,000	126,000	126,000	126,000	126,000	126,000
Power supply of PG 2 (P_2)	74,000	74,000	74,000	74,000	74,000	74,000	74,000	74,000
Emissions from PG 1	29,993.88	29,993.88	29,993.88	29,993.88	29,993.88	29,993.88	29,993.88	29,993.88
Emissions from PG 2	32,938.39	32,938.39	32,938.39	32,938.39	32,938.39	32,938.39	32,938.39	32,938.39
Total Emissions	62,932.27	62,932.27	62,932.27	62,932.27	62,932.27	62,932.27	62,932.27	62,932.27
Transmission total cost	751.73	910.22	1,050.91	1,171.17	1,289.96	1,384.01	1,484.83	1,580.36
PG1 total cost	13,190.38	13,417.18	13,580.12	13,709.67	13,815.02	13,908.09	13,987.29	14,058.56
PG2 total cost	6,003.92	6,184.73	6,309.30	6,409.06	6,485.51	6,561.29	6,617.34	6,667.56
Power plant total cost	19,194.30	19,601.92	19,889.42	20,118.72	20,300.53	20,469.38	20,604.63	20,726.12
Joint total cost	19,946.03	20,512.14	20,940.33	21,289.90	21,590.48	21,853.39	22,089.46	22,306.48

TABLE 7. The impact of change in energy loss on proposed model.

% change in γ	-60%	-40%	-20%	0%	20%	40%	60%	80%
Production allocation factor (α)	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Power distribution factor (n)	8	8	7	7	7	7	7	7
Power consumption (Q)	1,962.01	1,982.87	2,121.13	2,144.96	2,169.51	2,192.46	2,218.54	2,245.45
Emergency backup factor (k)	3.08	3.08	3.08	3.08	3.08	3.08	3.08	3.08
Setup cost of PG1 (K_1)	1,205.46	1,192.90	1,092.81	1,081.06	1,069.13	1,055.89	1,043.60	1,031.11
Setup cost of PG 2 (K_2)	964.37	954.32	874.25	864.85	855.31	844.71	834.88	824.89
Power supply of PG 1 (P_1)	126,000	126,000	126,000	126,000	126,000	126,000	126,000	126,000
Power supply of PG 2 (P_2)	74,000	74,000	74,000	74,000	74,000	74,000	74,000	74,000
Emissions from PG 1	28,119.26	28,717.54	29,341.84	29,993.88	30,675.56	31,388.94	32,136.30	32,920.11
Emissions from PG 2	30,879.74	31,536.75	32,222.33	32,938.39	33,686.99	34,470.40	35,291.13	36,151.89
Total Emissions	58,999.00	60,254.30	61,564.17	62,932.27	64,362.55	65,859.35	67,427.43	69,072.00
Transmission total cost	1,174.48	1,177.51	1,168.46	1,171.17	1,174.11	1,177.50	1,180.93	1,184.63
PG1 total cost	12,937.40	13,183.42	13,442.34	13,709.67	13,988.92	14,280.66	14,586.31	14,906.60
PG2 total cost	6,070.63	6,176.18	6,295.76	6,409.06	6,529.81	6,654.71	6,785.43	6,922.34
Power plant total cost	19,008.03	19,359.59	19,738.10	20,118.72	20,518.73	20,935.38	21,371.74	21,828.94
Joint total cost	20,182.51	20,537.10	20,906.56	21,289.90	21,692.84	22,112.87	22,552.67	23,013.57

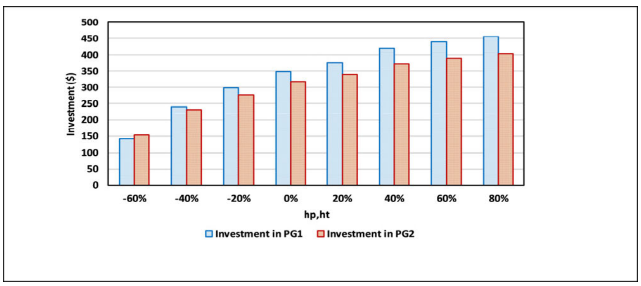

FIGURE 8. The impact of the change in in storage cost on investment.

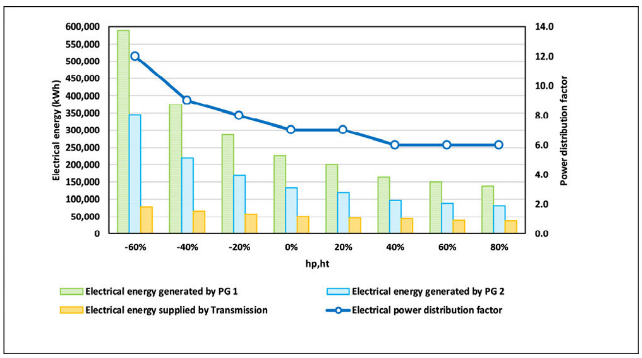

FIGURE 9. The impact of the change in storage cost on electrical energy and power distribution factor.

33.9% while the electrical energy consumed by transmission station reduces by 22.88%. The power plant is more likely to generate smaller electrical energy whereas the transmission station seems to reduce electrical consumption to prevent the system from having a higher total cost. Figure 10 depicts the intuitive effect of varying storage cost on the average electrical energy storage in power plant and the emergency backup storage in transmission station. We obtain that average electrical energy storage in PG1 and PG2 and in transmission station decrease by 31.33% and 22.55%, respectively, due to the 60% increase in storage cost. In addition, the emergency backup storage in transmission station decreases by 4.18%. We note that the impact of varying storage cost in power plant is much higher than that of in transmission station.

E. ANALYSIS OF ENERGY LOSS

We also examine the sensitivity of the solutions by varying the values of the percentage of energy losses. We perform a sensitivity analysis by varying the percentage of energy loss from −60% to 80% and the results are shown in Table 7. We can see that the power consumption considerably decreases by increasing the percentage of energy loss. Facing an increased

TABLE 8. The impact of change in δ_1 on proposed model.

% change in δ_1	-60%	-40%	-20%	0%	20%	40%	60%	80%
Production allocation factor (α)	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Power distribution factor (n)	13	10	8	7	7	6	6	6
Power consumption (Q)	2,111.80	2,090.87	2,133.66	2,144.96	2,066.90	2,137.50	2,094.62	2,063.21
Emergency backup factor (k)	3.08	3.08	3.08	3.08	3.08	3.08	3.0809	3.0809
Setup cost of PG1 (K_1)	4,941.60	2,509.04	1,536.23	1,081.06	868.10	659.57	565.55	495.17
Setup cost of PG 2 (K_2)	1,581.31	1,204.34	983.19	864.85	833.37	738.72	723.90	713.05
Power supply of PG 1 (P_1)	126,000	126,000	126,000	126,000	126,000	126,000	126,000	126,000
Power supply of PG 2 (P_2)	74,000	74,000	74,000	74,000	74,000	74,000	74,000	74,000
Emissions from PG 1	29,993.88	29,993.88	29,993.88	29,993.88	29,993.88	29,993.88	29,993.88	29,993.88
Emissions from PG 2	32,938.39	32,938.39	32,938.39	32,938.39	32,938.39	32,938.39	32,938.39	32,938.39
Total Emissions	62,932.27	62,932.27	62,932.27	62,932.27	62,932.27	62,932.27	62,932.27	62,932.27
Transmission total cost	1,174.38	1,176.58	1,172.23	1,171.17	1,179.27	1,171.86	1,176.17	1,179.70
PG1 total cost	14,234.00	14,096.22	13,892.91	13,709.67	13,557.15	13,430.16	13,326.75	13,241.10
PG2 total cost	6,443.54	6,406.25	6,404.07	6,409.06	6,409.49	6,424.37	6,424.86	6,425.33
Power plant total cost	20,677.54	20,502.47	20,296.98	20,118.72	19,966.65	19,854.53	19,751.61	19,666.42
Joint total cost	21,851.92	21,679.05	21,469.21	21,289.90	21,145.91	21,026.39	20,927.78	20,846.13

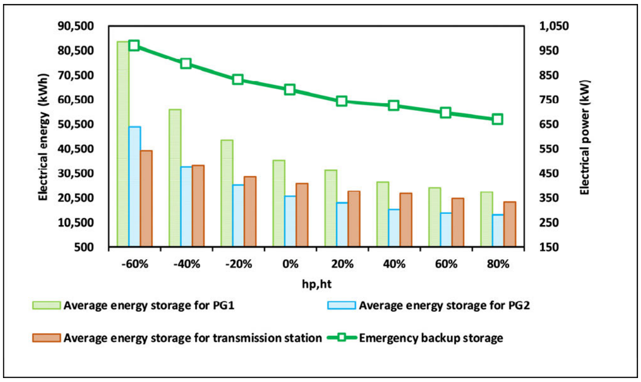

FIGURE 10. The impact of the change in storage cost on average electrical energy storage and emergency backup storage.

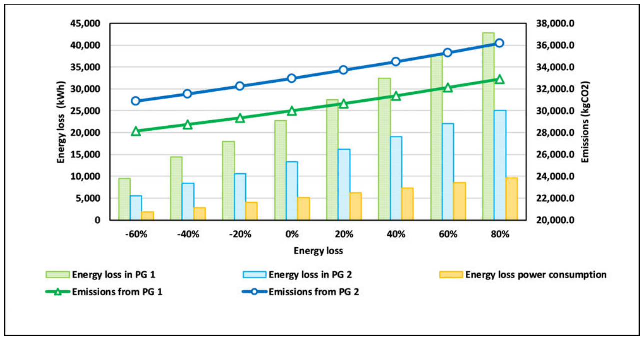

FIGURE 11. The impact of the change in energy loss on amount of electrical energy losses and emissions.

percentage of energy loss, the system is more likely to reduce the electricity generation in the power plant and the electricity consumption in the transmission station. Figure 11 demonstrates the change in the amount of electrical energy loss and emissions by increasing the percentage of energy loss. As can be seen, changing the value of the percentage of energy loss from 0% to 80% leads to 88.43% increase in the electrical energy loss in the power plant and power consumption. According to Figure 11, varying the value of the percentage of energy loss also give a pronounced impact on the emissions. Increasing the value of the percentage of energy loss by 80%, the amount of emissions resulted from power plant increases 9.76%. In reality, the electrical energy loss will greatly depend on the storage equipment. Accordingly, the manager needs to pay more attention in selecting the quality of the equipment to ensure that the electrical energy loss occurred in the system can be minimized.

F. ANALYSIS OF δ_1

It is also interesting to explore the effect of δ_1 on model's solution. The results of the exploration on δ_1 are briefly presented in Table 8. As described in the previous section that higher value of δ_1 reflects the investment on PG1's setup cost carried out by the power plant is getting more efficient. We may see from the Table 8 that the variation of δ_1 gives a pronounced impact on some decision variables, which are power distribution factor, power consumption and setup cost. If the value of δ_1 is increased from -2% to 40%, the PG1's setup cost and PG2's setup cost decrease by 57.06% and 24.86%, respectively (see Figure 12). In addition, the amount of money invested by the PG2 is significantly increasing while the amount of money invested by PG1 is changing based on the value of n (see Figure 13).

Facing the higher value of δ_1, the manager needs to adjust the value of power consumption to higher value and update the power distribution factor to lower value to maintain the total cost. As the electrical power produced per production run gets larger, the system should do production setup more frequent which leads to the increasing the number of setups per year (see Figure 12). This decision, however, will lead to a small decrease in total cost. We observe that increasing the δ_1 from -40% to 80% will give a percentage decrease in a range of 0.03%-2.18% in member's total cost. This suggests that allowing the power plant to invest the money, all supply chain's members can reduce the total cost.

G. ANALYSIS OF DEMAND

In this sub section, we focus on analysing the impact of demand on the optimal solutions. As shown in Table 9,

TABLE 9. The impact of change in demand on proposed model.

% change in demand	-40%	-30%	-20%	-10%	0%	10%	20%	30%
Production allocation factor (α)	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
Power distribution factor (n)	3	4	5	6	7	10	18	55
Power consumption (Q)	2,288.24	2,107.16	2,044.84	2,060.00	2,144.96	2,124.09	2,081.59	2,164.68
Emergency backup factor (k)	3.07	3.08	3.08	3.08	3.08	3.08	3.08	3.08
Setup cost of PG1 (K_1)	823.77	866.94	920.18	988.80	1,081.06	1,390.31	2,248.11	5,400.00
Setup cost of PG 2 (K_2)	659.01	693.56	736.14	791.04	864.85	1,112.25	1,798.49	5,275.16
Power supply of PG 1 (P_1)	126,000	126,000	126,000	126,000	126,000	126,000	126,000	126,000
Power supply of PG 2 (P_2)	74,000	74,000	74,000	74,000	74,000	74,000	74,000	74,000
Emissions from PG 1	17,996.33	20,995.72	23,995.10	26,994.49	29,993.88	32,993.27	35,992.66	38,992.04
Emissions from PG 2	19,763.03	23,056.87	26,350.71	29,644.55	32,938.39	36,232.23	39,526.06	42,819.90
Total Emissions	37,759.36	44,052.59	50,345.81	56,639.04	62,932.27	69,225.49	75,518.72	81,811.95
Transmission total cost	901.26	964.08	1,037.24	1,108.26	1,171.17	1,242.87	1,319.79	1,374.74
PG1 total cost	8,981.84	10,208.87	11,405.57	12,573.37	13,709.67	14,792.52	15,767.33	16,348.88
PG2 total cost	4,465.75	4,980.15	5,475.82	5,953.21	6,409.06	6,818.66	7,139.25	7,160.05
Power plant total cost	13,447.59	15,189.01	16,881.39	18,526.58	20,118.72	21,611.17	22,906.58	23,508.93
Joint total cost	14,348.85	16,153.09	17,918.62	19,634.83	21,289.90	22,854.04	24,226.37	24,883.67

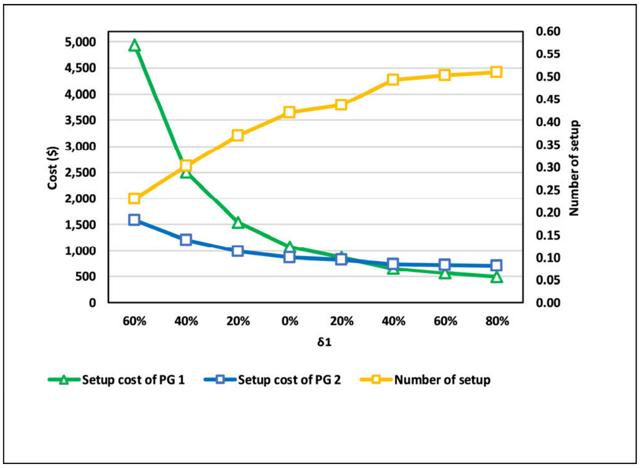

FIGURE 12. The impact of the change in δ_1 on setup cost and setup frequency.

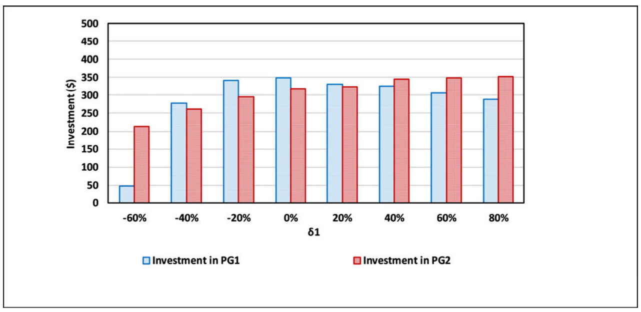

FIGURE 13. The impact of the change in δ_1 on investment.

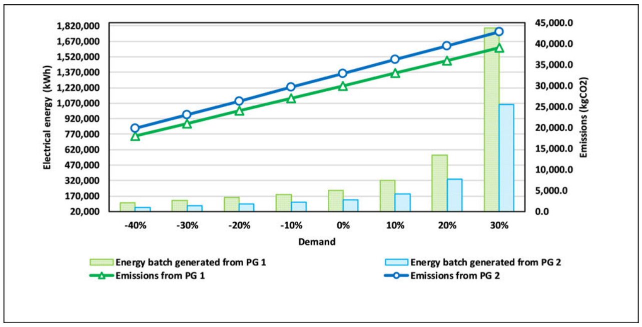

FIGURE 14. The impact of the change in demand on electrical energy generated from power generation system and emissions.

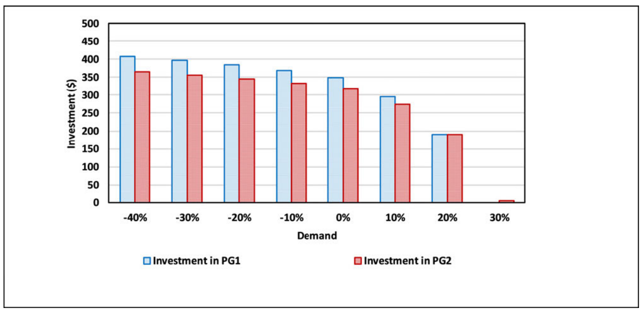

FIGURE 15. The impact of the change in demand on investment.

the power distribution factor, setup cost, emissions and total costs are greatly influenced by the demand variability. One can see that as the demand increases, the electrical energy generated from power plant is increasing simultaneously (see Figure 14). It is logical since increasing the generation of electrical energy results in increasing the energy capacity which in turns balancing the production with the demand. Later, by allowing the value of demand to be varied between −20% and 30%, one can observe that the emissions emitted from power plant increases by 71.43% which leads to the increasing of total cost. We further observe that the total costs incurred by power plant and transmission rise by 43.63% and 35.01%, respectively (see Table 9). It is noted that the percentage increase in power plant's total cost is much higher than that of in transmission station. Furthermore, the change in demand also gives impact on investment on setup cost reduction. Figure 15 presents its impact on the amount of money invested. Clearly, as setup frequencies get lower, it is beneficial for the power plant to reduce the amount of money invested in the efforts to reduce the setup cost.

VIII. CONCLUSION

This paper studied a two-echelon electrical energy supply chain model for a situation where the power plant has two types of power generation systems to generate electricity. The first power generation system is less economical than the second one, but it is more environmentally friendly in the sense that it generates less emissions. The model gives a guidance to the managers to control the energy storage and maintain the trade-off between electricity production cost and emissions. The model allows the managers to share the electricity production between two power generations and adjust the power supply rate to minimize the emissions and total cost. The decisions related to the amount of energy stored and the amount of energy produced by the generator can be used to determine the battery capacity and the number of generators needed, respectively. Furthermore, we note that the load growth is not a factor considered in the proposed problem-solving process.

There are some insights derived from this study. First, the changes in the parameters related to production cost and emissions significantly affect the allocation of electricity generation. By controlling the power supply rate of both power generation systems wisely and referring the action to the production allocation factor, the manager can maintain the joint total cost at a lower level. Second, the energy loss factor was proven to have a large impact on total emissions and joint total cost. As the energy loss factor is closely related to the choice of storage equipment, thus the manager needs to pay more attention in specifying the right storage equipment to be installed in the system. In this paper, we assume that the production capacity of PG1 and PG2 can be adjusted flexibly, for example by altering the number of activated generators. When the allocation to PG1 increases, more generators in PG1 must be activated to increase the electricity production.

An immediate extension of this study would be to consider more parties involved in the electrical energy supply chain system. A supply chain structure can be changed by allowing the participation of other parties, such as raw material supplier and distribution station. A future study can look into the limitation in the electricity storage capacity. In real system, there are many types of storage equipment which have capacity limitations. Such capacity limitation may significantly affect the decision regarding electricity production and transmission management. Furthermore, the model can also be extended by considering the emission limitation allowed by the regulator and the investment to reduce the emission parameters.

APPENDIX

Let x denote continue random variable with normal distribution with mean μ and standard deviation $\sigma > 0$. Hence, the probability density function of x is formulated as

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{\left[-\frac{(x-\mu)^2}{2\sigma^2}\right]} \tag{A.1}$$

If the demand in period L is formulated by DL with standard deviation $\sigma\sqrt{L}$ then, the energy storage level in that period is

$$P = DL + k\sigma\sqrt{L} \tag{A.2}$$

Blackout occurs in period L when $x > P$. The expected blackout in period L can be formulated as

$$EBL = \int_{x=P}^{\infty} (x - P) f(x)\, dx \tag{A.3}$$

By substituting equations (A.1) and (A.2) into Equation (A.3), we have

$$EBL = \int_{x=DL+k\sigma\sqrt{L}}^{\infty} \left(x - DL - k\sigma\sqrt{L}\right) \times \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(x-DL)^2}{2(\sigma\sqrt{L})^2}} dx \tag{A.4}$$

By substituting $z = \frac{x-DL}{\sigma\sqrt{L}}$ and $dx = \sigma\sqrt{L}dz$ into equation (A.4), we have

$$EBL = \int_{x=k\sigma\sqrt{L}/\sigma\sqrt{L}}^{\infty} \left(z\sigma\sqrt{L} - k\sigma\sqrt{L}\right) \frac{1}{\sqrt{2\pi}} e^{-z^2/2} dz$$

$$EBL = -k\sigma\sqrt{L} \int_{z=k\sigma\sqrt{L}/\sigma\sqrt{L}}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-z^2/2} dz + \sigma\sqrt{L} \int_{z=k\sigma\sqrt{L}/\sigma\sqrt{L}}^{\infty} z \frac{1}{\sqrt{2\pi}} e^{-z^2/2} dz \tag{A.5}$$

Consider $F_s(\cdot)$ as the cumulative distribution function and $f_s(\cdot)$ as the probability density function with mean 0 and standard deviation 1. By using $f_s(\cdot)$ formula and the definition of standard normal distribution, we have

$$1 - F_s(y) = \int_{z=y}^{\infty} f_s(z)\, dz = \int_{z=y}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-z^2/2} dz$$

By substituting $w = z^2/2$ into Equation (A.5), we have

$$EBL = -k\sigma\sqrt{L}\left[1 - F_s\left(k\sigma\sqrt{L}/\sigma\sqrt{L}\right)\right] + \sigma\sqrt{L} \int_{w=(k\sigma\sqrt{L})^2/2(\sigma\sqrt{L})^2}^{\infty} \frac{1}{2\pi} e^{-w} dw$$

$$EBL = -k\sigma\sqrt{L}\left[1 - F_s\left(k\sigma\sqrt{L}/\sigma\sqrt{L}\right)\right] + \sigma\sqrt{L} f_s\left(k\sigma\sqrt{L}/\sigma\sqrt{L}\right)$$

$$EBL = \sigma\sqrt{L}\{f_s(k) - k[1 - F_s(k)]\}$$

$$EBL = \sigma\sqrt{L}\psi(k) \tag{A.6}$$

Thus, by considering $L = \frac{Qt}{P} + T_s$, equation (A.6) can be rewritten as

$$EBL = \sigma\sqrt{\frac{Qt}{P} + T_s}\psi(k)$$

REFERENCES

[1] IPPC, "Climate change 2017 mitigation," *Contribution of Working Group III to the Fourth Assessment Report*, New York, NY, USA: Cambridge Univ. Press, 2017.

[2] J. G. Banbury, "Distribution-the final link in the electricity-supply chain. Electron," *Power*, vol. 21, no. 13, pp. 773–775, 1975.

[3] V. Vahidinasab, "Optimal distributed energy resources planning in a competitive electricity market: Multiobjective optimization and probabilistic design," *Renew. Energy*, vol. 66, pp. 354–363, Jun. 2014.

[4] A. A. Amrutha, M. Mathirajan, and P. Balachandra, "A mathematical formulation for low carbon electricity planning in the presence of technology and policy interventions," in *Proc. IEEE Int. Conf. Ind. Eng. Eng. Manage.*, Dec. 2014, pp. 612–616.

[5] B. Jeddi, V. Vahidinasab, P. Ramezanpour, J. Aghaei, and M. Shafi-khah, "Robust optimization framework for dynamic distributed energy resources planning in distribution networks," *Int. J. Elect. Power Energy Syst.*, vol. 110, pp. 419–433, Sep. 2019.

[6] C. Ordoudis, P. Pinson, and J. M. Morales, "An integrated market for electricity and natural gas systems with stochastic power producers," *Eur. J. Oper. Res.*, vol. 272, no. 2, pp. 642–654, Jan. 2019.

[7] M. Saghaei, H. Ghaderi, and H. Soleimani, "Design and optimization of biomass electricity supply chain with uncertainty in material quality, availability and market demand," *Energy*, 197, pp. 117–165, Apr. 2020.

[8] M. Saghaei, M. Dehghanimadvar, H. Soleimani, and M. H. Ahmadi, "Optimization and analysis of a bioelectricity generation supply chain under routine and disruptive uncertainty and carbon mitigation policies," *Energy Sci. Eng.*, vol. 8, no. 8, pp. 2976–2999, Aug. 2020.

[9] Y. Wang, J. Qiu, Y. Tao, X. Zhang, and G. Wang, "Low-carbon oriented optimal energy dispatch in coupled natural gas and electricity systems," *Appl. Energy*, vol. 280, Dec. 2020, Art. no. 115948.

[10] R. Yan, J. Wang, S. Zhu, Y. Liu, Y. Cheng, and Z. Ma, "Novel planning methodology for energy stations and networks in regional integrated energy systems," *Energy Convers. Manage.*, vol. 205, Feb. 2020, Art. no. 112441.

[11] V. Musolino, A. Pievatolo, and E. Tironi, "A statistical approach to electrical storage sizing with application to the recovery of braking energy," *Energy*, vol. 36, no. 11, pp. 6697–6704, Nov. 2011.

[12] J. P. Fossati, A. Galarza, A. Martín-Villate, and L. Fontán, "A method for optimal sizing energy storage systems for microgrids," *Renew. Energy*, vol. 77, pp. 539–549, May 2015.

[13] A. Zucker and T. Hinchliffe, "Optimum sizing of PV-attached electricity storage according to power market signals—A case study for Germany and Italy," *Appl. Energy*, vol. 127, pp. 141–155, Aug. 2014.

[14] M. G. Wichmann, C. Johannes, and T. S. Spengler, "Energy-oriented lot-sizing and scheduling considering energy storages," *Int. J. Prod. Econ.*, vol. 216, pp. 204–214, Oct. 2019.

[15] E. Oh and S.-Y. Son, "Energy-storage system sizing and operation strategies based on discrete Fourier transform for reliable wind-power generation," *Renew. Energy*, vol. 116, pp. 786–794, Feb. 2018.

[16] C. K. Das, O. Bass, G. Kothapalli, T. S. Mahmoud, and D. Habibi, "Optimal placement of distributed energy storage systems in distribution networks using artificial bee colony algorithm," *Appl. Energy*, vol. 232, pp. 212–228, Dec. 2018.

[17] A. Karimi, F. Aminifar, A. Fereidunian, and H. Lesani, "Energy storage allocation in wind integrated distribution networks: An MILP-based approach," *Renew. Energy*, vol. 134, pp. 1042–1055, Apr. 2019.

[18] O. O. Ademulegun, P. Keatley, M. B. Mustafa, and N. J. Hewitt, "Energy storage on a distribution network for self-consumption of wind energy and market value," *Energies*, vol. 13, no. 11, p. 2688, 2020.

[19] J. Li, B. Lu, Z. Wang, and M. Zhu, "Bi-level optimal planning model for energy storage systems in a virtual power plant," *Renew. Energy*, vol. 165, pp. 77–95, Mar. 2021.

[20] P. Saran, J. Goentzel, and C. W. Siegert, "Economic analysis of wind plant and battery storage operation using supply chain management techniques," in *Proc. IEEE PES Gen. Meeting*, Jul. 2010, pp. 1–8.

[21] M. Schneider, K. Biel, S. Pfaller, H. Schaede, S. Rinderknecht, and C. H. Glock, "Optimal sizing of electrical energy storage systems using inventory models," *Energy Procedia*, vol. 73, pp. 48–58, Jun. 2015.

[22] M. Schneider, K. Biel, S. Pfaller, H. Schaede, S. Rinderknecht, and C. H. Glock, "Using inventory models for sizing energy storage systems: An interdisciplinary approach," *J. Energy Storage*, vol. 8, pp. 339–348, Nov. 2016.

[23] K. Biel and C. H. Glock, "Prerequisites of efficient decentralized waste heat recovery and energy storage in production planning," *J. Bus. Econ.*, vol. 87, no. 1, pp. 41–72, Jan. 2017.

[24] B. Marchi, S. Zanoni, and M. Pasetti, "Multi-period newsvendor problem for the management of battery energy storage systems in support of distributed generation," *Energies*, vol. 12, no. 23, p. 4598, Dec. 2019.

[25] I. D. Wangsa and H. M. Wee, "The economical modelling of a distribution system for electricity supply chain," *Energy Syst.*, vol. 10, no. 2, pp. 415–435, May 2019, doi: 10.1007/s12667-018-0274-z.

[26] I. Wangsa, T. Yang, and H. Wee, "The effect of price-dependent demand on the sustainable electrical energy supply chain," *Energies*, vol. 11, no. 7, p. 1645, Jun. 2018, doi: 10.3390/en11071645.

[27] U. Mishra, J.-Z. Wu, and A. S. F. Chiu, "Effects of carbon-emission and setup cost reduction in a sustainable electrical energy supply chain inventory system," *Energies*, vol. 12, no. 7, p. 1226, Mar. 2019, doi: 10.3390/en12071226.

[28] W. A. Jauhari, I. D. Melinda, and C. N. Rosyidi, "Inventory-based optimization of a two-echelon fossil-fuelled energy storage system," *Int. Trans. Electr. Energy Syst.*, vol. 30, no. 3, Mar. 2020, Art. no. e12256.

[29] B. Sarkar and I. Moon, "Improved quality, setup cost reduction, and variable backorder costs in an imperfect production process," *Int. J. Prod. Econ.*, vol. 155, pp. 204–213, Sep. 2014.

[30] B. Sarkar, K. Chaudhuri, and I. Moon, "Manufacturing setup cost reduction and quality improvement for the distribution free continuous-review inventory model with a service level constraint," *J. Manuf. Syst.*, vol. 34, pp. 74–82, Jan. 2015.

[31] R. Bogaschewsky, *Natürliche Umwelt und Produktion*. Wiesbaden, Germany: Gabler-Verlag, 1995.

[32] B. Marchi, S. Zanoni, L. E. Zavanella, and M. Y. Jaber, "Supply chain models with greenhouse gases emissions, energy usage, imperfect process under different coordination decisions," *Int. J. Prod. Econ.*, vol. 211, pp. 145–153, May 2019.

[33] M. Khouja and A. Mehrez, "Economic production lot size model with variable production rate and imperfect quality," *J. Oper. Res. Soc.*, vol. 45, no. 12, pp. 1405–1417, Dec. 1994.

[34] M. Ben-Daya and M. Hariga, "Integrated single vendor single buyer model with stochastic demand and variable lead time," *Int. J. Prod. Econ.*, vol. 92, no. 1, pp. 75–80, Nov. 2004.

[35] C. H. Glock, "Lead time reduction strategies in a single-vendor–single-buyer integrated inventory model with lot size-dependent lead times and stochastic demand," *Int. J. Prod. Econ.*, vol. 136, no. 1, pp. 37–44, Mar. 2012.

[36] W. A. Jauhari and R. S. Saga, "A stochastic periodic review inventory model for vendor–buyer system with setup cost reduction and service–level constraint," *Prod. Manuf. Res.*, vol. 5, no. 1, pp. 371–389, Jan. 2017.

WAKHID A. JAUHARI is currently pursuing the Ph.D. degree with the Industrial Engineering Department, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia. He is also a Senior Researcher with the Production System Laboratory, Universitas Sebelas Maret, Surakarta, Indonesia. He has published more than 80 articles in international journals and proceedings, including *Operations Research Perspectives*, *Journal of Industrial Engineering International*, *Energy Systems*, *Production and Manufacturing Research*, *Journal of Industrial Engineering and Management*, *International Transactions on Electrical Energy Systems*, *Advances in Operation Research*, *Cogent Engineering*, *International Journal of Logistics and Systems Management*, *International Journal of Operational Research*, and *International Journal of Procurement Management*. His research interests include modeling inventory, supply chain management, energy management, and manufacturing design.

I. NYOMAN PUJAWAN received the bachelor's degree in industrial engineering from the Sepuluh Nopember Institute of Technology (ITS), Surabaya, Indonesia, the Master of Engineering degree in industrial engineering from the Asian Institute of Technology (AIT), Bangkok, Thailand, and the Ph.D. degree in management science from Lancaster University, U.K.. From 2003 to 2004, he was a Lecturer in operations management with the Manchester Business School, The University of Manchester, U.K. He is currently a Professor of supply chain engineering with the Department of Industrial Engineering, ITS. He is also the President of the Indonesian Supply Chain and Logistics Institute (ISLI). He also holds Certified Supply Chain Professional (CSCP) from APICS, USA His articles have appeared in many international journals, including the *European Journal of Operational Research*, *International Journal of Production Economics*, *International Journal of Production Research*, *Production Planning and Control*, *International Journal of Physical Distribution and Logistics Management*, *Supply Chain Management: An International Journal*, *International Journal of Logistics Research and Applications*, *Business Process Management Journal*, among others. He worked in industry before moving to the academia. While his academic background is very strong, he is equally well experienced in handling industry problems. He is an active consultant for various supply chain and logistics related industry problems (has involved in over 40 consulting projects).

MOKH SUEF received the bachelor's degree in mechanical engineering from the Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia, in 1989, the Master of Science degree in engineering with specialization in integrated quality management from Birmingham University, in 1997, and the Ph.D. degree in industrial engineering from the Institut Teknologi Sepuluh Nopember, in 2016. He has published articles in international journals and proceedings, including *TQM Journal*, *International Journal of Technology*, and *International Journal of Mechanical Engineering and Technology*. His research interests include quality management, manufacturing process, and maintenance management.

IVAN D. WANGSA received the B.Eng. degree in industrial engineering from the Universitas Islam Indonesia (UII), Indonesia, and the M.Sc. degree in industrial engineering and management from the Institut Teknologi Bandung (ITB), Indonesia. He is currently pursuing the Ph.D. degree with the Department of Industrial and Systems Engineering, Institut Teknologi Sepuluh Nopember (ITS), Surabaya, Indonesia. He has ten years of work experience and consulting with the HSSE Department at the State-owned Enterprise of Indonesia. His Ph.D. is focused on investigates the inventory models on the last-mile logistic systems. He also holds Certified Professional in Logistics Management (CPLM) from ISCEA (USA). His research interests include inventory modeling, logistics and supply chain management, sustainable management, and safety engineering.