Sustainable Energy Storage Management for a Power Plant-Transmission Station System with Hybrid Power Generation and Stochastic Electricity Demand

W A Jauhari¹,², I N Pujawan¹ and M Suef¹

¹Department of Industrial Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
²Department of Industrial Engineering, Universitas Sebelas Maret, Surakarta, Indonesia.
wachid_aj@yahoo.com, pujawan@ie.its.ac.id, mokhsuef@gmail.com

Abstract. This paper proposes an energy storage management for electrical energy supply chain system (EESCS) involving a power plant and a transmission station under carbon emission investigation. The transmission station faces stochastic electricity demand from household and uses a continuous review policy to control electrical energy storage. The power plant has two power generations, namely green power generation and regular power generation. The green power generation is cleaner than the regular one, thus it generates less emissions. Although the green power generation is more environmentally, however, its electricity production cost is more expensive than the regular one. A carbon tax is implemented in the investigated system to lessen the amount of emissions coming from electricity production. An efficient algorithm is developed to solve the problem and a numerical example is presented to show the applicability of the model and to explore the behaviour of the model.

1. Introduction

In recent years, the research dealing with electrical energy storage has received a great deal of attention from scholars and practitioners. Musolini et al. [1] was the first who introduced an electrical energy lot-sizing model considering energy recovery. Fossati et al. [2] developed a method to determine the optimal energy and power storage capacities in an electrical energy storage system (EESS) using genetic algorithm. The objective of the model was to minimize total operational cost of microgrid chain. Wichman et al. [3] studied the influence of EESS utility on total cost and energy saving by considering some aspects, such as energy quantity, energy price and characteristic of EESS. Later, some scholars developed EESS using an inventory approach. Schneider et al. [4] used newsvendor model to formulate EESS on apartment equipped with photovoltaic system. Biel and Glock [5] proposed a multi-stage production model considering the integration between heat recovery system and EESS.

Recently, EESS has been extended by some scholars to an electrical supply chain problem. They proposed new model, known as electrical energy supply chain system (EESCS), which is developed using joint economic lot-sizing problem (JELP) approach. They argued that the process of determining the optimal energy storage is similar with the process of specifying optimal lot size in a JELP. Wangsa and Wee [6] proposed an EESCS consisted of a power plant, transmission station, distribution station
and customers with stochastic electricity demand. Wangsa et al. [7] investigated the influence of price dependent demand on energy lot-sizing decision. Various types of demand are investigated to show how it can influence the behaviour of EESCS. Mishra et al. [8] considered carbon emission reduction and price dependent demand. Later, Jauhari et al. [10] proposed an EESCS considering fuel procurement and the electricity demand from utility system.

Our review to energy lot-sizing literature showed that both EESS and EESCS have been discussed widely by scholars and practitioners. Nevertheless, the problem concerning with emission reduction and the employment of cleaner power generation (PG) were rarely discussed in the literature. Accordingly, we propose a mathematical model for EESCS taking into consideration carbon emission released from electricity production, green power generation and stochastic electricity demand. A simple procedure is also suggested to obtain the optimal values of electricity power consumption, electricity power distribution factor, emergency backup factor and allocation factor for electricity generation.

2. Notations and assumptions

2.1. Notations
Here are the notations employed to formulate the proposed EESCS

Input parameters:

\( D \) average of electrical demand (MWh/year)
\( \sigma \) standard deviation of electrical demand (kWh/year)
\( A \) transmission station’s ordering cost ($/transmission)
\( F_T \) transmission cost for transmission station ($/transmission)
\( h_T \) transmission station’s holding cost rate per unit time (%/year)
\( \pi_x \) blackout cost per electricity consumption ($/kWh)
\( \pi_0 \) marginal profit loss per electricity consumption ($/kWh)
\( t \) consumption period (h)
\( \beta \) blackout ratio, \( 0 < \beta \leq 1 \)
\( K_1 \) GPG’s setup cost ($/setup)
\( K_2 \) RPG’s setup cost ($/setup)
\( P_1 \) GPG’s power supply (kWh/year)
\( P_2 \) RPG’s power supply (kWh/year)
\( h_p \) power plant’s holding cost per unit time ($/kWh/year)
\( F_p \) power plant’s transmission cost ($/transmission)
\( c_{\text{tax}} \) carbon tax ($/kgCO_2$)
\( a_1 \) emission parameter for GPG’s electricity production (kg year$^2$/unit$^3$)
\( b_1 \) emission parameter for GPG’s electricity production (kg year/unit$^2$)
\( c_1 \) emission parameter for GPG’s electricity production (kg /unit)
\( a_2 \) emission parameter for RPG’s electricity production (kg year$^2$/unit$^3$)
\( b_2 \) emission parameter for RPG’s electricity production (kg year/unit$^2$)
\( c_2 \) emission parameter for GPG’s electricity production (kg /unit)
\( g_{11} \) GPG’s per unit time cost for running the system independent of power supply rate ($)
\( g_{21} \) the increase in GPG’s unit system cost due to one unit increase power supply rate ($/unit)
\( g_{12} \) RPG’s per unit time cost for running the system independent of power supply rate ($)
\( g_{22} \) the increase in RPG’s unit system cost due to one unit increase power supply rate ($/unit)
\( n \) electricity power distribution factor
\( Q \) emergency backup factor
\( k \) electricity power consumption
\( \alpha \) allocation factor for electricity generation, \( \alpha_{\text{min}} < \alpha < \alpha_{\text{max}} \)
2.2. Assumptions
Here are the assumptions used to develop the proposed EESCS

1. The electricity demand from end customers is assumed to be normally distributed with mean $D$ and standard deviation $\sigma$.
2. The transmission station adopts a continuous review policy to manage the electrical energy storage level.
3. The green power generation is cleaner than the regular one, hence it emits lower emission. The electricity production cost of regular power generation is relatively cheaper than that of green power generation.
4. The power plant generates electricity of $nQt$ kWh, which is $n(1 - \alpha)Q$ kWh is generated from green power plant and $n\alpha Q$ kWh units is generated from regular power generation.
5. Both power generations work in parallel to generate electricity. The power supply rate of green power generation and regular power generation are given by $P_1 = (1 - \alpha)P$ and $P_2 = \alpha P$, respectively.
6. The supply rate of both power generations is restricted by $P_1 < P_1^{max}$ and $P_2 < P_2^{max}$.

3. Model formulation
The total cost for transmission cost consists of ordering cost, transmission cost, storage cost and blackout cost. Equation (1) presents the ordering and transmission costs incurred by the transmission cost.

$$ TCT_1 = \frac{D}{Qt} (F_r + A) $$

The average of electrical energy stored per year can be formulated by referring to the formulation of average inventory with lost sale. Thus, the storage cost charged by the transmission cost per year is given by the following expression

$$ TCT_2 = h_T \left( \frac{Q_t}{2} + k\sigma \sqrt{\frac{Q_t}{P} + T_s + (1 - \beta)\sigma \sqrt{\frac{Q_t}{P} + T_s \psi(k)}} \right) $$

The blackout cost per year for the transmission station is expressed by equation below

$$ TCT_3 = \frac{D[\pi_3 \beta + \pi_0(1 - \beta)]\sigma}{Qt} \sqrt{\frac{Q_t}{P} + T_s \psi(k)} $$

The total cost for transmission station can be formulated by considering the above costs, which is

$$ TCT = \frac{D}{(1 - \gamma)Qt} (F_r + A) + h_T \left( \frac{(1 - \gamma)Q_t}{2} + k\sigma \sqrt{\frac{Q_t}{P} + T_s + (1 - \beta)\sigma \sqrt{\frac{Q_t}{P} + T_s \psi(k)}} \right) $$

$$ + \frac{D[\pi_3 \beta + \pi_0(1 - \beta)]\sigma}{(1 - \gamma)Qt} \sqrt{\frac{Q_t}{P} + T_s \psi(k)} $$

The total cost for power plant consists of total cost incurred by the green power generation, total cost incurred by the regular power generation and the transmission cost. The power generation incurs setup cost, storage cost, emission cost and electricity production cost. The setup cost and storage cost of green power generation are given by equation (5) and (6), respectively

$$ TCP_{G_1} = \frac{DK_1}{Qt_n} $$

3
\[ T_{CPG_2} = h_p \frac{(1 - \alpha)Q t}{2} \left( n \left[ 1 - \frac{(1 - \alpha)D}{P_1} \right] - 1 + \frac{2(1 - \alpha)D}{P_1} \right) \]  

(6)

Here, we follow the formulation developed by Bogaschewsky [11] to develop the equation of carbon emission cost. The carbon emission generated from electricity production depends upon the power supply rate of power generation. Thus, the carbon cost for green power generation is expressed as follows

\[ T_{CPG_3} = c_{tax}(a_1 P_1^2 - b_1 P_1 + c_1)(1 - \alpha) \frac{D}{(1 - \gamma)} \]  

(7)

The electricity production cost which depends on the power supply is formulated as follows

\[ T_{CPG_1} = \left( \frac{g_{11}}{P_1} + g_{21} P_1 \right)(1 - \alpha) \frac{D}{(1 - \gamma)} \]  

(8)

Therefore, the total cost for green power generation can be calculated by summing up the above costs, which is

\[ T_{CPG} = \frac{DK_1}{(1 - \gamma)Q t n} + h_p \frac{(1 - \alpha)Q t}{2} \left( n \left[ 1 - \frac{(1 - \alpha)D}{P_1} \right] - 1 + \frac{2(1 - \alpha)D}{P_1} \right) + c_{tax}(a_1 P_1^2 - b_1 P_1 + c_1)(1 - \alpha) + \left( \frac{g_{11}}{P_1} + g_{21} P_1 \right)(1 - \alpha)D \]  

(9)

By using similar way as above, the total cost incurred by the regular power generation can be obtained, which is

\[ T_{CPR} = \frac{DK_2}{(1 - \gamma)Q t n} + h_p \frac{a Q t}{2} \left( n \left[ 1 - \frac{a D}{P_2} \right] - 1 + \frac{2a D}{P_2} \right) + c_{tax}(a_2 P_2^2 - b_2 P_2 + c_1)\alpha D + \left( \frac{g_{12}}{P_2} + g_{22} P_2 \right)\alpha D \]  

(10)

Thus, the power plant total cost and the joint total cost for EESCS are given by the equations (11) and (12), respectively

\[ TCP = T_{CPG} + T_{CPR} \]  

(11)

\[ JTC = T_{CT} + TCP \]  

(12)

4. Solution method

For fixed values of \( n \) and \( \alpha \), the optimal solutions of the proposed EESCS can be found by taking the partial derivatives of joint total cost with respect to \( k \) and \( Q \) and setting the results to zero, which are

\[ F_s(k) = 1 - \frac{h_p Q t}{D[\pi_\alpha \beta + \pi_\alpha (1 - \beta)] + h_p(1 - \beta)Q t} \]  

(13)
The total costs charged by the green power generation chain are $113,620.38 and 84,785.25 kWh is generated from regular power generation. Thus, we observe that 144,364.08 kWh generated from green power generation and 140,307.08 kWh from regular power generation.

The optimal solutions for the proposed problem are listed below:

1. Set $\alpha = 0.01$
2. Set $n=1$ and $JTC(Q_{n-1}, k_{n-1}, n - 1, \alpha) = \infty$
3. Set the values of $Q$ and $k$ to equal zero. Compute $Q$ using equation (14).
4. Compute $k$ by inserting the previous value of $Q$ into equation (13).
5. Update the value of $Q$ by substituting the previous values of $Q$ and $k$ into equation (14).
6. Repeat steps 3-5 until no change occurs in the values of $Q$ and $k$.
7. Set $Q_n = Q$ and $k_n = k$. Compute $JTC(Q_n, k_n, n, \alpha)$ using equation (12).
8. If $JTC(Q_n, k_n, n, \alpha) \leq JTC(Q_{n-1}, k_{n-1}, n - 1, \alpha)$ repeat steps 2-7 with $n=n+1$, otherwise go to step 9.
9. Set $JTC(Q, k, n, \alpha)=JTC(Q_{n-1}, k_{n-1}, n - 1, \alpha)$.
10. Repeat steps 2-10 for the set value of $\alpha$, ($0 < \alpha < 1$) with the change of $\alpha = \alpha + 0.01$.
11. Find the minimum values of $JTC(Q, k, n, \alpha)$ and set the values of $Q, k, n$ and $\alpha$ as the optimal solutions of the proposed problem.

5. Numerical example

Here, we present a numerical experiment and sensitivity analysis of the proposed model. Let us consider the following data set: $D=1500$, $\sigma=500$, $A=50$, $F_1=150$, $F_2=120$, $h_1=0.02$, $h_2=0.02$, $\pi_x=50$, $\pi_0=100$, $P=200$, $P_{\max}^1=140$, $P_{\max}^2=90$, $T_r=0.005$, $W_r=8$, $c_{\text{loss}}=0.0618$, $K_1=400$, $K_2=400$, $\beta=0.2$, $r=24$, $g_{11}=3500$, $g_{12}=2500$, $g_{21}=0.0000027$, $g_{22}=0.0000016$, $a_1=0.000000007$, $b_1=0.0000012$, $c_1=0.014$, $a_2=0.0000000021$, $b_2=0.00000036$, $c_2=0.042$.

The optimal solutions for the proposed problem are provided in Table 1. It shows that the electricity production is more allocated to cleaner power generation. We observe that 144,364.08 kWh generated from green power generation and 84,785.25 kWh is generated from regular power generation. Thus, the total cost incurred by the green power generation is much higher than that of the regular power generation.

| Table 1. Optimization results for proposed EESCS |
|------------------------------------------------|
| Decision variables and costs | Optimum values | Unit |
| Electricity allocation factor | 0.37 | kWh |
| Power distribution factor | 5 | times |
| Power supplied by transmission station | 1909.58 | kW |
| Emergency backup factor | 3.701 | times |
| Electrical energy generated by green PG | 144,364.08 | kWh |
| Electrical energy generated by regular PG | 84,785.25 | kWh |
| Total cost for transmission station | 1,148.92 | $ |
| Description                      | Cost       | Unit |
|----------------------------------|------------|------|
| Total cost for green PG          | 70,707.94  | $    |
| Total cost for regular PG        | 41,763.51  | $    |
| Joint total cost                 | 113,620.38 | $    |

**Figure 1.** The impact of the changes in $X_{g2}$ on power supply rate and demand satisfied from PG

**Figure 2.** The impact of the changes in $X_{g2}$ on carbon emissions and total cost
It is interesting to explore how the production cost can influence the decision variables and the performance of the model. We may see from Figure 1 that when the green PG’s electricity production cost gets higher, the system tends to allocate more production to the regular one. It seems that the electricity demand satisfied by the regular PG significantly increases while the electricity demand satisfied by the green PG decreases. This is intuitively correct, since moving from expensive production cost to the cheaper production cost will consequently reduce the total cost. Although this policy may raise the emissions, the saving on production cost is always higher than the increase in emission cost. Later, in order to maintain the electricity demand with the production the system will adjust the power supply rate of both PG. Figure 2 shows the influence of the changes in green PG’s electricity production cost on total cost and emissions. We observe that if PG’s electricity production cost increases by 400%, the emission released by the regular PG and green PG change by 8.37% and -4.7%, respectively. In addition, the total cost incurred by the regular PG and green PG increase by 13.19% and 7.86%, respectively. We note that by giving an opportunity to the decision maker to allocate the electricity production flexibly, the system can maintain the power supply rate which leads to reducing the total cost.
Figure 3 describes how the proposed model behaves towards emission parameter’s changes. The results show that if regular’s emission parameter increase by 40%, the electricity demand satisfied by green PG and regular PG change by 6.35% and -10.81%, respectively. Further, the regular’s emission parameter changes also give similar impact on power supply rate of both PGs. Figure 4 presents the behaviour of the model influenced by changes of regular’s emission parameter. We observe that the amount of emissions generated from green PG and total cost incurred by green PG drastically increase due to the increase of emission level of regular PG. It is understood, since moving the production from regular PG to green PG will consequently increase the power supply rate and electricity generated by green PG. Here, we also note that by adjusting the production allocation, the system can control the emissions which leads to reducing the total cost. Thus, the decision makers need to pay more attention in controlling production allocation carefully to ensure the power generation system can work efficiently and environmentally.

6. Conclusions

In this study, we introduced EESCS involving of single power plant and single transmission station under carbon emission reduction. The power plant can access both green PG and regular PG to produce electricity. Thus, to comply with a carbon tax regulation implemented by regulator, the power plant can manage the emissions by controlling the allocation of electricity production. However, the action to control the emissions is not easy because it confronts with the electricity production cost. The model gives a guidance for decision maker to manage electricity storage in EESCS. The results show that by allocating the electricity production wisely and controlling the power supply rate, the emissions released from power plant and joint total cost can be minimized simultaneously. The model can be developed further by considering the inclusions of electrical energy loss and setup cost reduction.

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