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Article

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Energy Sustainability through Generation Scheduling

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ABSTRACT

In a modest electrical energy sector, an economical unit cost of electricity generation is inevitable. For tropical countries like Malaysia, apart from attractive energy cost, the environmental issues due to electricity sector also play a significant role because of its tropical nature. The energy cost and its related environmental concerns are of the momentous issues of the Malaysian Government. So as to resolve the concerned issues, this research presents a direct generation scheduling strategy to match demand against power generation, to augment opportunity for energy sustainability, and to offer an attractive unit electric energy cost. Besides, the same strategy aims at minimizing emissions due to thermal power plants through generation scheduling and incorporation of renewable energy systems.

Keywords: Generation Scheduling, Energy Cost, Environmental Concerns, Thermal and Renewable Energy Systems
JEL Classifications: Q21, Q41, Q43, Q55

1. INTRODUCTION

In a modest electrical energy sector, an economical unit cost of electricity generation is inevitable. For tropical countries like Malaysia, apart from attractive energy cost, the environmental issues due to electricity sector also play a significant role because it's tropical nature. The energy cost and its related environmental concerns are of momentous issues of the Malaysian Government. To meet the Government's vision, a method of utilizing energy effectively and economically through energy conservation has been addressed in the previous chapter. Besides, proper generation–demand matching results in the attractive unit cost of electricity and the efficient usage of the generating plants and the auxiliaries.

Hence, to achieve the research objective (a) besides energy conservation, this research presents a direct generation scheduling strategy to match demand against power generation, to augment opportunity for energy sustainability, and to offer an attractive unit electric energy cost. The same strategy aims at the research objective (b) of minimizing emissions due to thermal power plants through generation scheduling and incorporation of renewable energy systems.

2. GENERATION – DEMAND MATCHING

The unit cost of electricity generation is a significant index in regional and global development. In the case of fossil-fuelled power systems which is the dominant energy source, the energy tariff depends on the fuel cost that carries the maximum share of the total operation cost (Jayakumar et al., 2016; Rameshkumar et al., 2016; Saravanan et al., 2016). So as to keep electricity tariff as low as doable, fuel cost which is the highest portion of the total operating cost needs to be minimized. This is achieved through the economic operation of the power plants through generation scheduling and unit commitment (Wang et al., 2013; Sivakumar and Devaraj, 2014).

To perform economic power dispatch to attain the least cost of electricity generation, the fuel cost function of the generators becomes essential (Hong et al., 2016). This cost function is generally nonlinear and the quadratic cost representation is precise and the most common one in practice where the fuel is oil, coal and gas, but also diesel generators, gas micro turbines, biomass power plants, fuel cells, etc. (Palanichamy and Babu, 2008).

The fuel cost of an individual generating unit is represented as

$$F_i = (a_i P_{Gi}^2 + b_i P_{Gi} + c_i)\$/h \quad (1)$$

and the total fuel cost of several generating units taking part together is

$$F_T = \sum_{i=1}^{n}(a_i P_{Gi}^2 + b_i P_{Gi} + c_i)\$/h \quad (2)$$

where
F_i: Fuel cost of generating unit, i ($/$h$),
F_T: Total fuel cost, ($/$h$),
P_{Gi}: Generation of unit, i (MW)
a_i, b_i, and c_i: Fuel cost coefficients of unit, i, in ($/MW^{2}h), ($/MWh), and ($/h) respectively, and
n: Number of generating units.

2.1. Objective Function

The objective function for economic dispatch to attain minimum energy cost is optimised subject to the power balance, transmission power loss and the plant's capacity constraints as given in 4, 5 and 6 (Rezaie et al., 2018; Jevtic et al., 2017).

$$\phi = Min\sum_{i=1}^{n} F_i \$/hr \quad (3)$$

i. Power balance constraints

$$\sum_{i=1}^{n} P_{Gi} = P_D + \sum_{i=1}^{n} P_{Li} \quad (4)$$

where
P_D = System demand, and
P_{Li} = Transmission power loss due to generator, i.

ii. Transmission loss constraints
and

$$P_{Li} \leq P_{Limax} \quad (5)$$

iii. Plants capacity constraints

$$P_{imin} \leq P_{Gi} \leq P_{imax} \quad (6)$$

Apart from these constraints, environmental restrictions also take part in the optimisation process due to large consumer receptiveness for clean electrical energy (Radosavljević, 2016). Hence, power suppliers must now control their emissions so as to meet the specified ecological requirements.

iv. Plants emission constraints

$$\sum_{i=1}^{n} E_i \leq E_{Target} \quad (7)$$

where
E_i: Emission from generator, i, and
E_{Target}: Hourly emission target (kg/h)

The economic dispatch is very intricate to resolve because of the frequent varying system demand, huge amount of data and constraints, and the non-linear objective function. Many optimisation approaches such as integer and dynamic programming (Nemati et al., 2018; Wang et al., 2014), Genetic Algorithm (Singh et al., 2014), Simulated Annealing (He et al., 2018), hopfield neural network (Reddy and Momoh, 2015), Particle Swarm Optimization (Chen et al., 2018), Tabu Search Algorithm (Naama et al., 2013), and Grasshopper Optimization Algorithm (Suriya et al., 2018; Karthikeyan et al., 2018) are available in the market; however, each one has its own convenience and constraints.

3. AUXILIARY POWER CONSUMPTION (APC)

While performing generation-demand matching through economic power dispatch, the APC of the associated components of the power systems other than the generators is not usually considered (Palanichamy et al., 2015). Auxiliary systems are a significant part of a power system, regardless of whether it is of sustainable power source, fossil-fuel or nuclear energy type (ABB, 2013). Their primary purpose is to power and controls the power systems utilizing a minimum of input energy to attain most output and accessibility. They embrace all the drive control applications (pumps, fans, motors, drives), electrical stability of plant and instrumentation, management and improvement frameworks. The APC in thermal power stations is in the range of 9-10% of the power at the generator end due to the high inductive loads of motors and boiler fans (Sinha, 2015; Bhatia, 2010). For a PV plant, these auxiliaries are inverter control circuitry, transformer magnetizing circuitry, cooling fan, air conditioner, lights, computers and night time auxiliaries like street light, server, etc. The average APC is in the range of 1.5-2% of the power generated by the PV system (CERC - New Delhi, 2017). For the wind turbines, electrical energy is needed for the yaw mechanism, blade-pitch control, magnetizing the stator, heating the blade, lights, controllers, communication, sensors, metering, and data collection, etc. The auxiliary consumption for these functions exceeds even 20% of the rated capacity of the wind turbine (AWEO, 2012; Joshi, 2017; Jiang et al., 2015). Hence, due to the higher magnitude of APC, the generation scheduling to meet an attractive unit energy cost, has to accommodate the share of it in the optimization process. The proposed generation scheduling considers the transmission power losses and the APC as well.

4. ECONOMIC DISPATCH WITH APC

P_{Gi} is the net power available from the generating unit, i after the unit's APC to meet the load. So as to meet the system demand considering the APC of the unit, i its generation has to be increased depending upon the magnitude of its power consumption. Hence, the power generation of generating unit, i becomes $P_{Gi}/(1-\eta_{ai})$. Due to this consideration, the generation of unit, i represented by (1) becomes

$$F_i = a_i\left(\frac{P_{Gi}}{1-\eta_{ai}}\right)^2 + b_i\left(\frac{P_{Gi}}{1-\eta_{ai}}\right) + c_i \$/h \quad (8)$$

Equation (4.8) is conveniently rewritten as

$$F_i = a_i^{'} P_{Gi}^2 + b_i^{'} P_{Gi} + c_i \ \$ / h \tag{9}$$

where
$a_i^{'} = \{1/(1-\eta_{ai})\}^2$, and
$b_i^{'} = \{1/(1-\eta_{ai})\}$.

4.1. The Coordination Equation

By making use of the Lagrange formulation, the coordination equation for economic power dispatch becomes

$$(dF_i/dP_{Gi})/(1-\partial P_L/\partial P_{Gi})=\lambda \tag{10}$$

where $\partial P_L/\partial P_{Gi}$: Incremental transmission loss of i^{th} generating unit (expressed in terms of transmission loss B_{mn} coefficients), and λ: The incremental cost of received power, \$/MWh.

The transmission power loss is a function of the transmission loss coefficients and all the coordinating generators. Representation of the transmission losses in terms of an equivalent parameter in every coordination equation in terms of the i^{th} generator would be advantageous to avoid iterations and large amount of time taken for the solution. To do so, the other generating units are expressed in terms of the i^{th} generator in every coordination equation; as the result of this tactics, the transmission power loss of generator, i results in the form as

$$P_{Li} = P_{Gi}{}^2 \left(B_{ii} + \sum_{i \neq j} B_{ij} \alpha_{ij} \right) + P_{Gi} \left(\sum_{i \neq j} B_{ij} \beta_{ij} \right) \$ / hr \tag{11}$$

where
$\alpha_{ij} = a_i^{'}/a_j^{'}$, and $\beta_{ij} = (b_i - b_j)/2a_j$
B_{ii} = Self-transmission loss coefficients of generator, i, and
B_{ij} = Mutual transmission loss coefficients of generators i and j.

Taking partial derivatives of (9) and (11) with respect to i, then substituting them in (10) and applying binomial expression and simplification results in:

$$A_i P_{Gi}^2 + B_i P_{Gi} + C_i = \lambda \tag{12}$$

where

$$A_i = 4\left\{ a_i^{'} \left(B_{ii} + \sum_{i \neq j} B_{ij}\alpha_{ij} \right)\left(1 + 2\sum_{i \neq j} B_{ij}\beta_{ij} \right) + b_i^{'} \left(B_{ii} + \sum_{i \neq j} B_{ij}\alpha_{ij} \right)^2 \right\}$$

$$B_i = 2\left\{ \begin{array}{l} a_i^{'} \left(1 + \sum_{i \neq j} B_{ij}\, \beta_{ij} (1 + \sum_{i \neq j} B_{ij}\, \beta_{ij}) \right) \\ + b_i^{'} \left(B_{ii} + \sum_{i \neq j} B_{ij}\alpha_{ij} \right)\left(1 + 2\sum_{i \neq j} B_{ij}\beta_{ij} \right) \end{array} \right\}$$

and

$$C_i = b_i^{'} \left(1 + \sum_{i \neq j} B_{ij}\, \beta_{ij} (1 + \sum_{i \neq j} B_{ij}\, \beta_{ij}) \right).$$

4.2. Generations in Terms of λ

The coordination equation represented by equation (13) is rewritten as:

$$A_i P_{Gi}^2 + B_i P_{Gi} + \left(C_i - \lambda \right) = 0 \tag{13}$$

Equation (13) is of quadratic in nature yielding two values for the unit generations. As the unit generations can't be negative, the individual unit generations, P_{Gi} are given by:

$$P_{Gi} = \frac{-B_i + \sqrt{B_i{}^2 - 4A_i \left(C_i - \lambda \right)}}{2A_i} \tag{14}$$

Simplifying and rearranging of the above equation, the individual unit generations are concisely given in terms of λ as:

$$P_{Gi} = (\lambda - C_i)/B_i - Ai\, (\lambda - Ci)^2/B_i^3 \tag{15}$$

Once the value of λ is known, the individual unit generations are readily available from (15).

4.3. The Power Balance Equation

In terms of the generations of all the participating generating units, the transmission power losses and the system demand at an instant is given by the power balance equation as:

$$\sum_{i=1}^{n} P_{Gi} - \sum_{i=1}^{n} P_{Li} - P_D = 0 \tag{16}$$

where
P_D = System demand, MW

Substituting P_{Gi} from (15) and P_{Li} from (11) in (16) and simplifying, a quadratic equation in terms of λ and the system demand, P_D results in as:

$$\alpha\, \lambda^2 + \beta\, \lambda + \gamma - P_D = 0 \tag{17}$$

where

$$\alpha = \sum_{i=1}^{n} \left\{ -(A_i / B_i^3)\left(1 + \sum_{i \neq j}^{n} B_{ij}\beta_{ij} \right) - \left(1 / B_i{}^2 \right)\left(B_{ii} + \sum_{i \neq j}^{n} B_{ij}\alpha_{ij} \right) \right\}$$

$$\beta = \sum_{i=1}^{n} \left\{ \begin{array}{l} \left(1/B_i + 2A_i C_i / B_i^3 \right)\left(1 - \sum_{i \neq j}^{n} B_{ij}\beta_{ij} \right) \\ +(2C_i / B_i^2)\left(B_{ii} + \sum_{i \neq j}^{n} B_{ij}\alpha_{ij} \right) \end{array} \right\}$$

and

$$\gamma = \sum_{i=1}^{n} \left\{ \begin{array}{l} -\left(C_i / B_i + A_i C_i^2 / B_i^3 \right)\left(1 - \sum_{i \neq j}^{n} B_{ij}\alpha_{ij} \right) \\ -(C_i^2 / B_i^2)\left(B_{ii} + \sum_{i \neq j}^{n} B_{ij}\alpha_{ij} \right) \end{array} \right\}$$

Equation (17) provides two values for λ; only the positive value is considered for evaluating the individual unit generations. Once the plant generations are known, the total fuel cost is readily available. The computational strategy is shown in Figure 1.

5. ENVIRONMENTAL FRIENDLY ECONOMIC DISPATCH (EFED)

The dispatch outcome of economic dispatch provides the generation of individual generating plants such that the system

Figure 1: Generation scheduling flow diagram

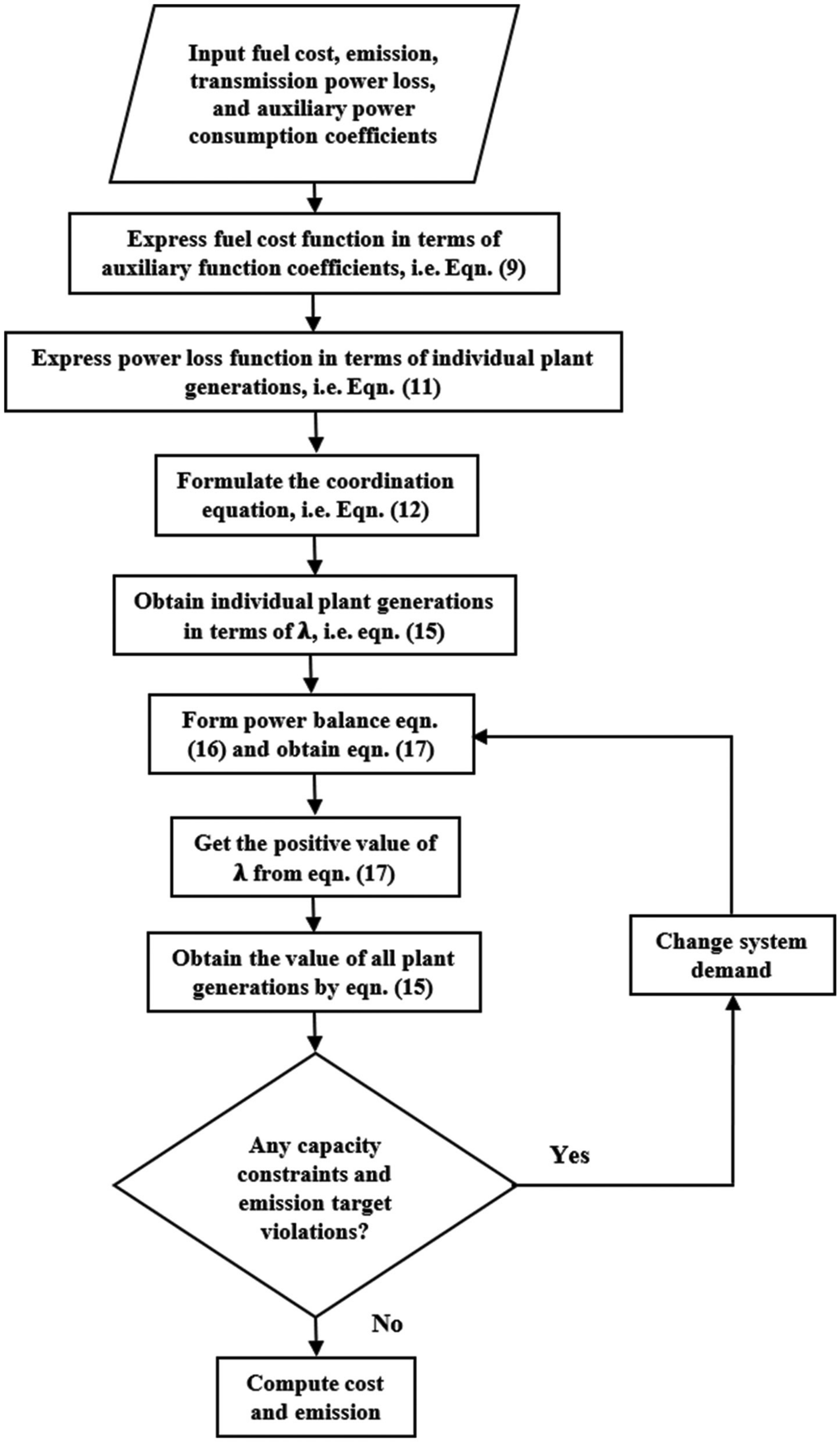

Figure 2: Energy statistics

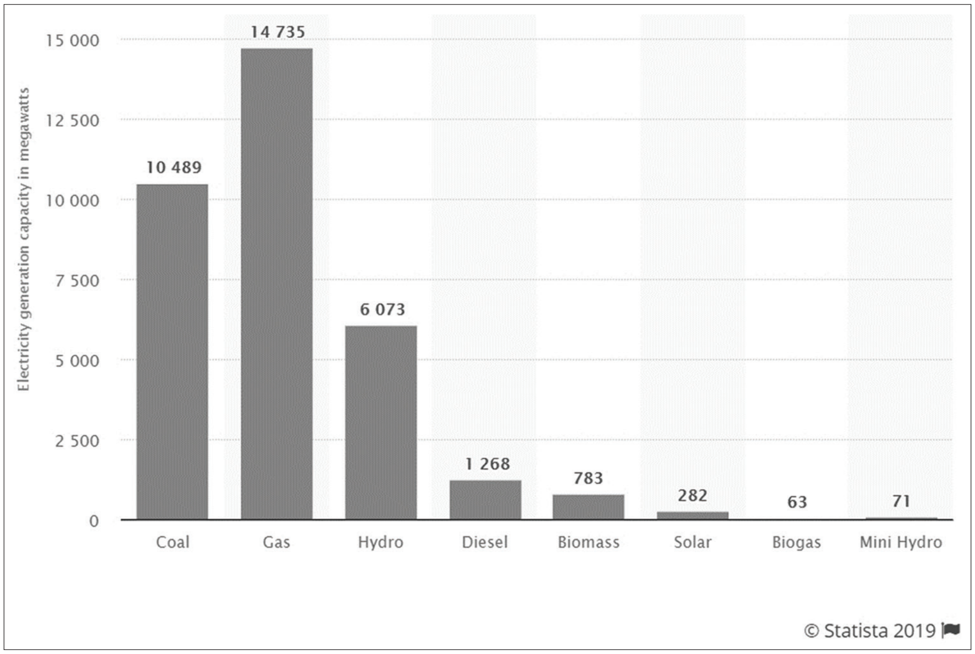

Table 1: Fuel cost and emission coefficients

Plant	Fuel cost coefficients			Emission coefficients			P_{imin}	P_{imax}	APC_i (%)
	a_i	b_i	c_i	d_i	e_i	f_i			
1	0.03546	38.30553	1243.5311	0.00683	−0.54551	40.26690	35	210	10.24
2	0.02111	36.32782	1658.5696	0.00461	−0.5116	42.89553	130	325	8.78
3	0.01799	38.27041	1356.6592	0.00461	−0.5116	42.89553	125	315	8.95

demand is at minimum energy cost without violating the several said constraints. Due to the recent environmental restrictions on regional and global level, the emission from fossil-fuelled power stations has to meet the stipulated specifications. For instance, if the emission level by the economic dispatch exceeds the stipulated constraints, then the generation has to be rescheduled either by reducing the plant generations or by making use of less polluting plants to generate more compared to highly polluting older power plants. In tropical countries like Malaysia, the higher percentage of humidity does not support the emissions to move up to the safe altitude; besides the haze due to the man-made forest fire also offers burden for thermal emission dispersion. Further, the day and night weather have its own influence in emission dispersal. So in energy sector the production of electricity has to be economical and environmentally friendly.

In this research, while generation scheduling to match the generation against demand, the power plant emission characteristics are amalgamated with the fuel cost equations through a price penalty factor. There are various ways of determining the price penalty factor (Palanichamy and Babu, 2008; Rao et al., 2017; Ramachandaran and Avirajamanjula, 2018). These price penalty factors result increasingly reasonable qualities just when the generating plants are working at their planned maximum capacity; for other generation levels (i.e., at less-than-full load conditions), the resulting values differ extensively from the more practical values. During partial load conditions, the heat rate requirements are higher, which makes the power plant less efficient and more

Table 2: Transmission loss coefficients

B_{i1}	B_{i2}	B_{i3}
0.000071	0.000030	0.000025
0.000030	0.000069	0.000032
0.000025	0.000032	0.000080

polluting. Thus, in this research, a new price penalty factor appropriate for all operating load conditions is presented in the following paragraphs.

Before proceeding with the determination of the proposed price penalty factor, *h,* the total cost and emission equations are obtained following the coordination equation tactics with the respective cost and emission coefficients as:

$$A_i P_{GS}^2 + B_i P_{GS} + C_i \left(\$ / \mathrm{h}\right) \text{and } D_i P_{GS}^2 + E_i P_{GS} + F_i \left(\mathrm{kg} / \mathrm{h}\right)$$

where P_{GS} is the sum of the maximum generating capacity limit of all the coordinating plants.

Then the proposed price penalty factor is of the form:

$$h = h_{opt} + \frac{\left(h_{max} - h_{min}\right)\left(P_{Dmax} - P_D\right)}{P_{Dmax}} \tag{18}$$

where

$$h_{opt} = \frac{A_i P_{GS}^2 + B_i P_{GS} + C_i}{D_i P_{GS}^2 + E_i P_{GS} + F_i} \$ / kg \tag{19}$$

$$h_{max} = \frac{a_i P_{Gi}^2 + b_i P_{Gi} + c_i}{d_i P_{Gi}^2 + e_i P_{Gi} + f_i} \$ / kg \tag{20}$$

In (20), P_{Gi} is the maximum generating capacity limit of the plant with lowest generating capacity among the coordinating plants.

$$h_{min} = \frac{a_i P_{Gi}^2 + b_i P_{Gi} + c_i}{d_i P_{Gi}^2 + e_i P_{Gi} + f_i} \$ / kg \tag{21}$$

In (21), P_{Gi} is the maximum generating capacity limit of the plant with the largest generating capacity among the coordinating plants.

Figure 3: Sarawak state grid

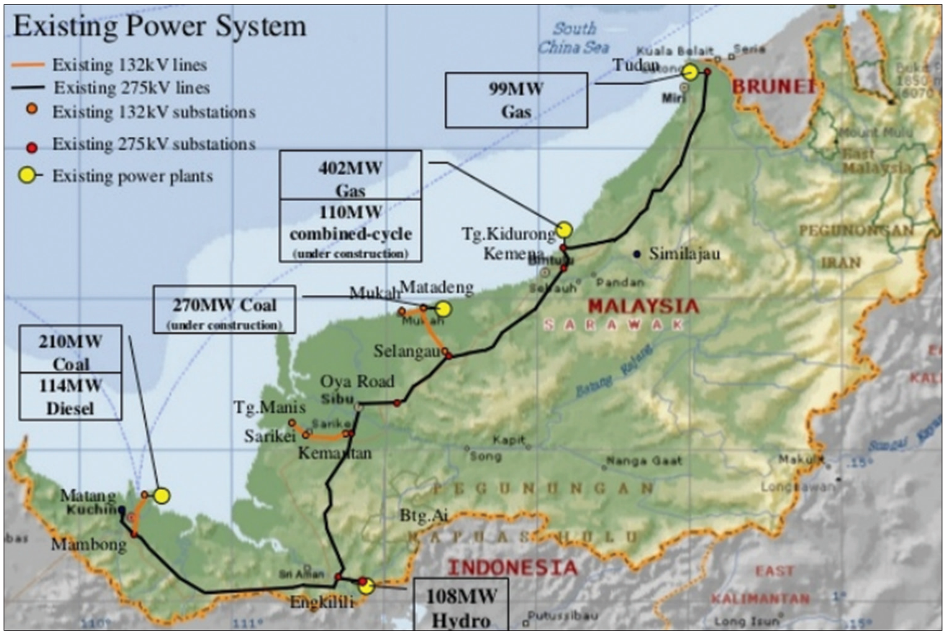

Table 3: Economic dispatch with 300 MW

System demand: 300 MW							
REG							
Solar, PV_S: 0 MW; Wind, P_W: 2 MW							
Thermal plant generations, (MW)				Total generation ($P_{GT}+PV_S+P_W$) MW	Excess quantities		
P_{G1}	P_{G2}	P_{G3}	Total P_{GT}	P_G	APC, MW	Fuel cost, \$/h	Emission, kg/h
58.57	149.91	123.72	332.19	334.19	30.23	1281.99	18.34

Parameters	Proposed method	GWO method (Jayabarathi et al., 2016)
Total cost (\$/h)	17554.12	17554.22
Total emission (kg/h)	151.71	151.79
Total transmission loss (MW)	3.96	3.97
Reduced emission due to REG (kg/h)	1.44	1.43
Number of iterations	Nil	270
Average execution time (s)	0.03	0.695

REG: Renewable energy generation

Table 4: Economic dispatch with 400 MW

System demand: 400 MW							
REG							
Solar, PV_S: 10 MW; Wind, P_W: 2 MW							
Thermal plant generations, (MW)				Total generation, ($P_{GT}+PV_S+P_W$) MW	Excess quantities		
P_{G1}	P_{G2}	P_{G3}	Total P_{GT}	P_G	APC, MW	Fuel cost, \$/h	Emission, kg/h
81.52	187.03	166.34	434.89	446.89	39.66	1740.93	37.13

Parameters	Proposed method	GWO method (Jayabarathi et al., 2016)
Total cost (\$/h)	22013.50	22013.69
Total emission (kg/h)	235.01	235.11
Total transmission loss (MW)	7.23	7.25
Reduced emission due to REG (kg/h)	13.96	13.94
Number of iterations	Nil	270
Average execution time (s)	0.03	0.695

REG: Renewable energy generation

With this price penalty factor, the objective function for the EFED is presented in terms of the blended fuel cost and emission equations.

$$\phi = Min\sum_{i=1}^{n}(F_i + hE_i)\$/h \quad (22)$$

6. ILLUSTRATION AND DISCUSSION

The energy statistic (Statistica-2019, 2018; Malaysia Energy Information Hub, 2018), portrays the total electricity generation capacity in Malaysia as of January 2018, as by source type shown in Figure 2. In 2018, the total electricity generation capacity worked out to be 33,764 MW, and 26,492 MW came from coal, gas, and oil, which means that around 78.50% of electricity generation come from fossil-fuels.

Because of the dominance of fossil-fuels in electricity generation, the unit cost of electricity and the environment generally lie on the thermal power plants. To analyze the energy sustainability, the performance of these power plants plays a vital role apart from the

Table 5: Economic dispatch with 500 MW

System demand: 500 MW							
REG							
Solar, PV_S: 15 MW; Wind, P_W: 2 MW							
Thermal plant generations, (MW)				Total generation, (P_{GT}+PV_S+P_W) MW	Excess quantities		
P_{G1}	P_{G2}	P_{G3}	Total P_{GT}	P_G	APC, MW	Fuel cost, \$/h	Emission, kg/h
106.12	226.67	211.76	544.56	561.56	49.72	2262.22	64.26

Parameters	Proposed method	GWO method (Jayabarathi et al., 2016)
Total cost (\$/h)	26953.23	26953.89
Total emission (kg/h)	364.37	364.51
Total transmission loss (MW)	11.83	11.86
Reduced emission due to REG (kg/h)	27.76	27.72
Number of iterations	Nil	270
Average execution time (s)	0.03	0.695

REG: Renewable energy generation

Table 6: Economic dispatch with 600 MW

System demand: 600 MW							
REG							
Solar, PV_S: 15 MW; Wind, P_W: 2 MW							
Thermal plant generations, (MW)				Total generation, (P_{GT}+PV_S+P_W) MW	Excess quantities		
P_{G1}	P_{G2}	P_{G3}	Total P_{GT}	P_G	APC, MW	Fuel cost, \$/h	Emission, kg/h
132.49	268.94	260.12	661.55	678.55	60.46	2853.90	101.22

Parameters	Proposed method	GWO method (Jayabarathi et al., 2016)
Total cost (\$/h)	32425.37	32426.02
Total emission (kg/h)	548.37	548.88
Total transmission loss (MW)	18.09	18.11
Reduced emission due to REG (kg/h)	36.31	36.24
Number of iterations	Nil	270
Average execution time (s)	0.03	0.695

REG: Renewable energy generation

Table 7: Economic dispatch with 700 MW

System demand: 700 MW							
REG							
Solar, PV_S: 19 MW; Wind, P_W: 3 MW							
Thermal plant generations, (MW)				Total generation, (P_{GT}+PV_S+P_W) MW	Excess quantities		
P_{G1}	P_{G2}	P_{G3}	Total P_{GT}	P_G	APC, MW	Fuel cost, \$/h	Emission, kg/h
158.04	309.69	306.63	774.35	796.35	70.82	3459.14	144.71

Parameters	Proposed method	GWO method (Jayabarathi et al., 2016)
Total cost (\$/h)	37899.05	37899.95
Total emission (kg/h)	770.68	771.33
Total transmission loss (MW)	25.53	25.58
Reduced emission due to REG (kg/h)	58.34	58.25
Number of iterations	Nil	270
Average execution time (s)	0.03	0.695

REG: Renewable energy generation

quantum of their installed capacities. For this research, the eastern part of Malaysia's – Sarawak State Grid is considered (Figure 3). The actual system data is not available; however, a standard IEEE-14 bus system which resembles the number of major thermal power stations with almost closer generating capacities of the Sarawak grid has been used for exploration.

6.1. Test Data

Table 1 shows the fuel cost and emission coefficients of the modified IEEE-14 bus system with three fossil-fuelled power plants along with their respective APC. These values of APCs are considered from existing power plants of similar capacities and aging (Palanichamy et al., 2015; ABB, 2013; Sinha, 2015; Bhatia, 2010). To account for the transmission losses, the loss coefficients of the test system are presented in Table 2. The loss coefficients are updateable periodically depending on the system configuration changes; however, they remain constant while performing the economic active power dispatch.

To account for the transmission power losses, the transmission loss coefficients of the test system are offered in Table 2. These coefficients are updateable every so often subject to the system configuration changes; however, they persist constant while executing the economic power dispatch.

Apart from the thermal power plants, renewable energy generations like solar PV and small wind turbine generators are also considered following the Governments Renewable Energy Integration policy. As per the renewable energy statistics (Statistica-2019, 2018; Malaysia Energy Information Hub, 2018), solar PV is in existence and wind energy is in the exploration stage. Anticipating the future of small wind turbine in Malaysia, a small capacity of 2-3 MW generation has been considered in this work.

6.2. Economic Dispatch

The economic power dispatch has been performed for various hourly load conditions ranging from 300 MW to 700 MW without exceeding the total generating capacity of all the thermal plants. PV and wind generations are accommodated to reduce the hourly load demand to be met by thermal generators so that excess generations due to APC and pollution liberation are controllable. Following

Table 8: Excess quantities due to APC

System demand, P_D, MW	Excess quantities APC		
	Generated power, MW	Fuel cost, $	Emission, kg
300	30.23	1281.99	18.34
400	39.66	1740.93	37.13
500	49.72	2262.22	64.26
600	60.46	2853.90	101.22
700	70.82	3459.14	144.71
Total	250.89	11598.18	365.66

APC: Auxiliary power consumption

Table 9: Environmental friendly economic dispatch with 300 MW

System demand: 300 MW; Price penalty factor, h=47.88269 $/kg							
REG							
Solar, PV_S: 0 MW; Wind, P_W: 2 MW							
Thermal plant generations, (MW)				Total generation (P_{GT}+PV_S+P_W) MW	Excess quantities		
P_{G1}	P_{G2}	P_{G3}	Total P_{GT}	P_G	APC, MW	Fuel cost, $/h	Emission, kg/h
84.96	125.42	122.64	333.02	335.02	30.69	1305.11	17.62

Parameters	Proposed method	GWO method (Jayabarathi et al., 2016)
Total cost ($/h)	17621.50	17621.62
Total emission (kg/h)	143.96	144.02
Total transmission loss (MW)	4.33	4.34
Reduced emission due to REG (kg/h)	1.43	1.42
Number of iterations	Nil	289
Average execution time (s)	0.039	0.811

REG: Renewable energy generation

Table 10: Environmental friendly economic dispatch with 400 MW

System demand: 400 MW; Price penalty factor, h=47.39013 $/kg							
REG							
Solar, PV_S: 10 MW; Wind, P_W: 2 MW							
Thermal plant generations, (MW)				Total generation (P_{GT}+PV_S+P_W) MW	Excess quantities		
P_{G1}	P_{G2}	P_{G3}	Total P_{GT}	P_G	APC, MW	Fuel cost, $/h	Emission, kg/h
111.06	163.52	161.12	435.70	447.70	40.15	1768.67	36.60

Parameters	Proposed method	GWO method (Jayabarathi et al., 2016)
Total cost ($/h)	22088.25	22088.41
Total emission (kg/h)	226.57	226.68
Total transmission loss (MW)	7.55	7.57
Reduced emission due to REG (kg/h)	13.85	13.81
Number of iterations	Nil	289
Average execution time (s)	0.039	0.811

REG: Renewable energy generation

Table 11: Environmental friendly economic dispatch with 500 MW

System demand: 500 MW; Price penalty factor, h=46.87022 \$/kg							
REG							
Solar, PV_S: 15 MW; Wind, P_W: 2 MW							
Thermal plant generations, (MW)				Total generation, $(P_{GT}+PV_S+P_W)$ MW	Excess quantities		
P_{G1}	P_{G2}	P_{G3}	Total P_{GT}	P_G	APC, MW	Fuel cost, \$/h	Emission, kg/h
139.03	204.15	202.14	545.32	562.32	50.25	2295.45	63.93

Parameters	Proposed method	GWO method (Jayabarathi et al., 2016)
Total cost (\$/h)	27036.91	27037.05
Total emission (kg/h)	354.87	235.01
Total transmission loss (MW)	12.07	12.10
Reduced emission due to REG (kg/h)	27.54	27.52
Number of iterations	Nil	289
Average execution time (s)	0.039	0.811

REG: Renewable energy generation

Table 12: Environmental friendly economic dispatch with 600 MW

System demand: 600 MW; Price penalty factor, h= 46.32293 \$/kg							
REG							
Solar, PV_S: 15 MW; Wind, P_W: 2 MW							
Thermal plant generations, (MW)				Total generation $(P_{GT}+PV_S+P_W)$ MW	Excess quantities		
P_{G1}	P_{G2}	P_{G3}	Total P_{GT}	P_G	APC, MW	Fuel cost, \$/h	Emission, kg/h
168.97	247.47	245.79	662.22	679.22	61.03	2893.55	101.10

Parameters	Proposed method	GWO method (Jayabarathi et al., 2016)
Total cost (\$/h)	32519.33	32519.48
Total emission (kg/h)	537.34	537.47
Total transmission loss (MW)	18.19	18.23
Reduced emission due to REG (kg/h)	36.01	35.99
Number of iterations	Nil	289
Average execution time (s)	0.039	0.811

REG: Renewable energy generation

Table 13: Environmental friendly economic dispatch with 700 MW

System demand: 700 MW; Price penalty factor, h = 45.80302 \$/kg							
REG							
Solar, PV_S: 19 MW; Wind, P_W: 3 MW							
Thermal plant generations, (MW)				Total generation $(P_{GT}+PV_S+P_W)$ MW	Excess quantities		
P_{G1}	P_{G2}	P_{G3}	Total P_{GT}	P_G	APC, MW	Fuel cost, \$/h	Emission, kg/h
197.92	289.20	287.76	774.88	796.88	71.41	3505.46	144.77

Parameters	Proposed method	GWO method (Jayabarathi et al., 2016)
Total cost (\$/h)	38003.20	38003.37
Total emission (kg/h)	757.77	757.93
Total transmission loss (MW)	25.47	25.51
Reduced emission due to REG (kg/h)	57.83	57.80
Number of iterations	Nil	289
Average execution time (s)	0.039	0.811

REG: Renewable energy generation

the generation scheduling flow diagram (Figure 1), economic power dispatch has been performed and the results are presented in Tables 3-7. At every dispatch, the plant capacity constraints are duly considered and the stipulated pollution concentration has not been exceeded. The outcome of the proposed direct optimisation has been compared against a Grey Wolf Optimisation approach (Jayabarathia et al., 2016).

Among the three fossil-fuelled generating plants, Plant 1 has the uppermost APC and Plants 2 and 3 are having lesser APCs.

Table 14: Excess quantities due to APC

System demand, P_D, MW	Excess due to APC		
	Generated power, MW	Fuel cost, \$	Emission, kg
300	30.69	1305.11	17.62
400	40.15	1768.67	36.60
500	50.25	2295.45	63.93
600	61.03	2893.55	101.10
700	71.41	3505.46	144.77
Total	253.53	11768.24	364.02

APC: Auxiliary power consumption

Table 15: Comparison between ED and EFED outcomes

System demand, P_D, MW	ED		EFED		Increase in cost due to EFED, $	Decrease in emission due to EFED, kg
	Total fuel cost, $	Total emission, kg	Total fuel cost, $	Total emission, kg		
300	17554.12	151.71	17621.50	143.96	67.38	7.75
400	22013.50	235.01	22088.25	226.57	74.75	8.44
500	26953.23	364.37	27036.91	354.87	83.68	9.50
600	32425.37	548.37	32519.33	537.34	93.96	11.03
700	37899.05	770.68	38003.20	757.77	104.15	12.91
Total	136845.27	2070.14	137269.19	2020.51	423.92	49.63

ED: Economic dispatch, EFED: Environmental friendly economic dispatch

From the dispatch outcome, it is noticeable that for every demand varying from 300 MW to 700 MW, the excess generation needed to overcome the APC is in the range of 30.23-70.82 MW. Due to this, excess fuel cost has been incurred from a minimum of $1281.99 to a maximum of $3459.14 apart from the excess emission varying from 18.34 kg to 144.71 kg. Normally, the APC is not considered while dispatching and only the transmission power losses are considered; hence, the excess power generated, fuel cost and emission are not transparent to the utility operators and the consumers. This excess generation of power, cost and emission levels are indications for the efficient operation of power systems, and minimization of this is significant for energy sustainability. The consolidated excess quantities are provided in Table 8. From the summary, it is evident that the total auxiliary consumption is around 10% of the hourly demand in spite of the renewable energy contribution. The excess generation and power plant emissions would have been higher if there are no renewable energy generation incorporated. An emission reduction of 137.81 kg has been resulted due to the minor renewable energy integration. The dispatch outcomes are compared with a GWO (Jayabarathia et al., 2016) and the results show the accuracy, the speed of dispatching, and the convenience of the direct method of dispatching.

6.3. EFED

The economic power dispatch offers an attractive energy cost through generation scheduling in such a way that the efficient plant (consuming less fuel) generates more than others. However, depending upon their emission characteristics and aging of the plants, the same fuel-efficient plants need not liberate less emission. The globally accepted fact that the electricity cost has to be economically and environmentally friendly to have a healthy life.

The EFED minimizes the emission level from fossil-fuelled power plants by scarifying the energy cost. Normally, both the fuel cost and emission cost coefficients are blended together with the introduction of a price penalty factor. The reduction in emission and the rise in energy cost of this approach depends on the choice of the price penalty factor. In this work, a unique penalty factor has been proposed as elaborated in Section 5. Following the proposed strategy, the price penalty factors at every load condition are determined as shown in Tables 9-13. It is worth pointing out that the price penalty factor decreases with increase in system demand. Alike the economic dispatch, the EFED has been carried out with the same varying demand conditions using the blended cost coefficients instead of the fuel cost coefficients, and the results are presented in Tables 9-13. The dispatch outcome shows the changes in individual plant generations, transmission losses, and emission levels, which are different from the economic dispatch outcome. The consolidated excess power generated, additional cost involved and extra emission due to APC has been shown in Table 14. The performance of economic and environmental friendly dispatches has been compared as shown in Table 15.

From Table 15, an increase of $423.92 has been noticed due to EFED, but at an advantage of 49.63 kg of emission reduction with respect to economic dispatch. So the EFED gives a comparatively clean energy at a moderate additional energy cost.

7. CONCLUSION

This research has offered the apprehensions of the economics and emissions controls of power systems. Two kinds of generation scheduling options are suggested - economic, and environmental friendly dispatching to improve the performance of power systems. A single direct dispatching algorithm has been proposed for both dispatch options with due consideration for APC. These two dispatching options achieve the demand matching against power generation, to augment opportunity for energy sustainability, and the minimizing emissions due to thermal power plants through generation scheduling and incorporation of renewable energy systems.

An IEEE modified 14-bus test system is used to evaluate the feasibility of the suggested algorithm. The total fuel cost, plant emissions, and transmission power loss, and the excess quantities such as generation, fuel cost and emission are the benchmarks used while performing the scheduling. Being a direct optimisation algorithm, the solution time was noticeably less than the alternative approach.

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