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Grid-connected distributed energy generation system planning and scheduling

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ABSTRACT

Conservation of fossil fuel energy, energy management (peak shaving), energy economic and pollution of energy sector has been among the recent topics of discussion. This paper examines possibilities of achieving the said topics through an integrated energy system also known as distributed energy system (DES) consisting of renewable energy and energy storage devices. With aim to minimise system cost while abiding to carbon footprint reduction target and pollutant emissions limit, a mixed integer linear programming model is developed for optimisation and planning of a DES. Universiti Teknologi Malaysia, in planning to become an eco-campus, is taken as a case study for this research work. The model reveals that with a target of 40% carbon footprint reduction and 30 tonne of total nitrogen oxides emissions (in a year), an annual cost of 5,687,000 $/y is required, achieving a reduction of 17.3%.

Keywords: Distributed energy system (DES); Energy storage (ES); Carbon footprint; Nitrogen oxides (NO_x); Renewable energy (RE); Mixed integer linear programming (MILP)

1. Introduction

Fossil fuels are the main element that drives our economy today. Unfortunately, our dependency on the world petroleum and natural gas reserve leads to energy crisis which subsequently causes increasing price of daily groceries, fuels and especially electricity bills, affecting mostly the end users, residential, commercial and industrial users alike. In order to be less affected by the fluctuating price of global fossil fuels, users can consider producing power through renewable energy (RE) resources incorporated with load shifting strategy (through energy storage (ES) devices) for better efficient energy utilisation and management through a distributed energy generation (DEG) system [1–4].

In fact, load shifting can solely be implemented on a grid-connected energy system without local energy production, to reduce the overall cost of electricity although increases in energy consumption may be expected due to compensation of energy losses during current inversion and charging/discharging of energy in and out of ES [5]. As for local RE systems, ES benefits the system by balancing out and distributes energy produced by intermittent resources such as

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solar and wind energy [6] and increases efficiency of non-intermittent RE systems such as biomass thermal system via peak shaving [7]. In all of the above examples, ES operates by storing energy during off-peak/high power generation periods and supplies during peak/low power generation periods. Through these strategies, a possible reduction in electricity cost can be expected. Correspondingly, end users may also decide to select a different tariff rate (for grid electricity) based on improvement done on the load profile or vice versa where an optimal load profile is scheduled based on a specific tariff rate.

Cost, undeniably being the major concern of end users, is, however, not the only factor that requires consideration during designing and planning stages [8,9]. Due to obligation by local governments across the world to achieve energy sustainability economically and environmentally, greenhouse gases emission planning has now become a necessity [10] including other types of polluting emission such as nitrogen oxides (NO_x) and sulphur oxides (SO_x) from thermal power plants [11].

By setting environmental obligation as limits, the economic feasibility of the aforesaid DEG system and its extent for cost reduction is studied in this research work. An optimisation model with the objective function to minimise annual cost of electricity was developed for analysis. The model, a mixed integer linear programming (MILP) model, incorporates several factors such as weather variation, pollutant emission and tariff selection to provide insight on optimal system sizing and scheduling.

2. Literature review

Recently, many deterministic mathematical models had been developed for DEG system. Among the notable works are by Ren et al. [12], who presented a multi-objective linear programming (MOLP) model showcasing power generation technologies such as solar PV, fuel cell and gas engine for an eco-campus in Japan. The study was then extended to incorporate a larger number of factors such as load profiles, local climate and utility tariff structure [13]. Gupta et al. [14–16] on the other hand developed an MILP model for rural and remote area with aim to minimise system cost. Another study was carried out by Yun and Li [17] to optimise a DEG system for a hospital in Tianjin, China. The model was developed as a mixed integer nonlinear programming (MINLP) model. Herran and Nakata [18] introduced a linear programming (LP) model for DEG system applicable for urban, rural and remote areas in Colombia, South America. Ho and Hashim [19] introduced an MILP model for sizing and scheduling of a DEG system under consideration of various weather scenarios. Alternatively, Mehleri et al. (2012) [20] developed an MILP model for designing a community at a neighbourhood level with objective to minimised annualised investment cost and annual operating cost. A study analysing suitability of DEG system for building complexes in different climate zone through LP was then carried out by Ren et al. [21]. Zhou et al. (2012) [22] on the other hand demonstrated the application of an MILP model to design an energy system for a typical hotel in Beijing, China.

Based on the "state-of-art" analysis, it can be concluded that little or no works had considered the polluting limits of thermal power plant in a DEG system on system cost. In this work, this factor will be included and analyse to provide a holistic view on the sizing and scheduling of a DEG system.

3. Methodology

3.1. Superstructure

The superstructure of the model is shown in Fig. 1. Based on the figure, energy demands at each weather, w, and time, t, are met by power generator, i, the power grid (based on type of tariff), f, and ES, e, where energy in ES originating from the power generator, i, and the power grid, f.

3.2. Mathematical formulation

In detail of the optimisation model, the model represents a MILP model with an objective function bounded by equality and inequality constraints.

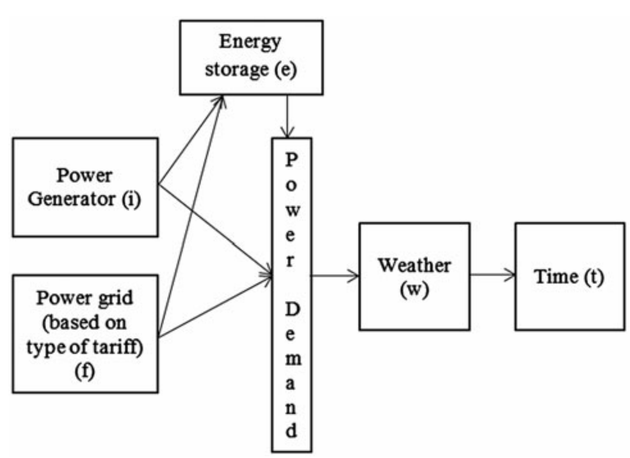

Fig. 1. Superstructure of model.

3.2.1. Objective function

The objective function to minimise total annual cost of electricity consists of three cost components, annualised investment cost, annual operating cost and annual power grid electricity as shown in Eq. (1).

$$\mathrm{CT} = \mathrm{CI} + \mathrm{CO} + \mathrm{CP} \tag{1}$$

(1) Annualised investment cost

The annualised investment cost (Eq. (2)) consists of capital cost of each operating unit of a DEG system. For ES, power related refers to the maximum amount of chargeable/dischargeable energy, EP_e while energy related refers to the maximum amount of storable energy, EE_e. Hence, each with its own cost factor. These costs are factorised by an amortised factor, M.

$$\mathrm{CI} = \underbrace{\sum_i C_i \times T_i \times M \times Mn}_{\text{capital cost of power technology}} + \underbrace{\sum_e EP_e \times TP_e \times M \times Mn}_{\text{power-related cost of ES}} + \underbrace{\sum_e EE_e \times TE_e \times M \times Mn}_{\text{energy-related cost of ES}} + \underbrace{I \times TI \times M \times Mn}_{\text{capital cost of inverter}} \tag{2}$$

(2) Annual operating cost

The annual operating cost (Eq. (3)) mostly consists of fixed and variable operating and maintainance cost of each operating unit, with an additional cost on fuel-based power technologies (fuel cost).

$$\mathrm{CO} = \underbrace{\sum_i C_i \times F_i}_{\text{fixed cost of power technology}} + \underbrace{\sum_e EP_e \times F_e}_{\text{fixed cost of ES}} + \underbrace{\sum_i \sum_w \sum_t G_{iwt} \times V_i \times N_w}_{\text{variable cost of power technology}} + \underbrace{\sum_i \sum_w \sum_t G_{iwt} \times Pr_i \times H_i \times N_w}_{\text{fuel cost of power technology}} \tag{3}$$

(3) Annual power grid electricity cost

The annual power grid electricity cost (Eq. (4)) consists of charges for maximum power usage and total energy consumption. Both charges depend on a selected tariff plan. Eq. (5) was derived to avoid non-linear terms in Eq. (4) [23].

$$\mathrm{CP} = \underbrace{\sum_f MD_f \times \mathrm{MDC}_f \times Mn}_{\text{charge of maximum power usage}} + \underbrace{\sum_f \sum_w \sum_t G_{fwt \times TF_{ft} \times N_w}}_{\text{charge of energy consumption}} \tag{4}$$

$$MD_f \leq Q \times x_f \tag{5}$$

3.2.2. Constraint

Equality constraints in this model were defined for the system scheduling while other inequality constraint is logical constraint forming boundaries of the model.

(1) Equality constraint (energy balance)

The model consists of four energy balance equality constraints. Eq. (6) defines that energy demands are met by energy produced from power generators, ES, or energy drawn from the grid. Eq. (7) on the other hand defines that the total energy produced by each power generator is supplied to meet load demands or sent for storage, similarly for Eq. (8), the total energy drawn from the power grid is supplied to meet load demands or sent for storage. Eq. (9) refers to the cumulative energy in the ES, where the cumulative energy is equal to its cumulative energy at the previous time interval plus incoming energy from power generator or the power grid minus outgoing energy to the load with no net energy changes in a day [24,25]. Several energy losses taken into account in this model include distribution losses, losses during current inversion, charging losses and discharging losses.

(a) Load demand

$$D_t = \sum_i GL_{iwt} \times L \times If_i + \sum_f GL_{fwt} + \sum_e ES_{ewt} \times L \times If_e \times df_e \quad \forall w, t \tag{6}$$

(b) Power generator

$$G_{iwt} = GL_{iwt} + \sum_e GE_{iewt} \quad \forall i, w, t \tag{7}$$

(c) Power grid

$$G_{fwt} = GL_{fwt} + \sum_e GE_{fewt} \quad \forall f, w, t \tag{8}$$

(d) ES devices

$$S_{ewt} = S_{ewt-1} + \sum_i GE_{iewt} \times L \times If_{ie} \times cf_e + \sum_f GE_{fewt} \times L \times If_e \times cf_e - ES_{ewt} \quad \forall e, w, t \tag{9}$$

(2) Inequality constraints

The inequality constraint of the model includes thermal power generator capacity and resource constraint, solar PV capacity constraint, ES power and capacity constraint, inverter capacity constraint, charging/discharging binary constraint, power grid constraint, tariff selection binary constraint and emission constraint. These constraints are explained in detail below.

(a) Thermal power generator capacity and resource constraint

The thermal power generator is restricted to generate power above is turn down ratio, $TR_{(\text{thermal})}$ and below its maximum capacity, $C_{(\text{thermal})}$ both constraints are shown in Eqs. (10)–(12), on the other hand, is formulated for biomass power generators restricting their total consumption of biomass in all biomass power generators to not exceed the available amount of biomass resources, R. $Al_{(\text{solar})}$

$$G_{(\text{thermal})wt} \leqslant C_{(\text{thermal})} \quad \forall w, t \tag{10}$$

$$G_{(\text{thermal})wt} \geqslant C_{(\text{thermal})} \times TR_{(\text{thermal})} \quad \forall w, t \tag{11}$$

$$\sum_{\text{biomass}} \sum_w \sum_t G_{(\text{biomass})wt} \times H_{(\text{biomass})} \times N_w \leqslant R \tag{12}$$

(b) Solar PV capacity constraint

In cases of a solar PV system, energy generation is based on daily solar radiation, SR_{wt} and the solar PV module area and efficiency as shown in Eqs. (13) and (14) indicates that the total installation area, $A_{(\text{solar})}$ of solar PV panel must be equal or less than the available space for solar PV installation, $Al_{(\text{solar})}$ with Eq. (15) as a correlation between the total installed area of solar PV and its equivalent capacity in kilowatt-peak (kWp).

$$G_{(\text{solar})wt} = SR_{wt} \times sf_{(\text{solar})} \times A_{(\text{solar})} \quad \forall w, t \tag{13}$$

$$A_{(\text{solar})} \leqslant Al_{(\text{solar})} \tag{14}$$

$$C_{(\text{solar})} = \frac{A_{(\text{solar})}}{W_{(\text{solar})}} \tag{15}$$

(c) ES power and capacity constraint

Eqs. (16)–(18) are defined generally for all types of ES. Eq. (16) shows that the cumulative energy, S_{ewt} has to be equal or less than its energy-related capacity, EE_e (with consideration over its depth of discharge, DOD_e). Eqs. (17) and (18) both indicate that the chargeable and dischargeable power is limited by the power-related capacity of an ES.

For certain ES systems such as hydro-pump ES (HPES) and compressed air ES (CAES), as the construction of such a system may require an extremely huge amount of land space, an additional geographical constraint shown in Eq. (19) was formulated to limit its storage size in kWh equivalent (instead of volume). Users are required to pre-evaluate their availability in kWh equivalent before application of this model.

Battery:

$$S_{ewt} \leqslant EE_e \times \text{DOD}_e \quad \forall e, w, t \tag{16}$$

$$ES_{ewt} \leqslant EP_e \quad \forall e, w, t \tag{17}$$

$$\sum_i GE_{iewt} \times L \times If_{ie} + \sum_f GE_{fewt} \times L \times If_e \leqslant EP_e \quad \forall e, w, t \tag{18}$$

HPES and CAES:

$$EE_e \leqslant U_e \tag{19}$$

(d) Inverter capacity constraint

Total current which requires inversion at any specific time interval has to be less or equal to the capacity of the inverter. In addition, as different technology operates at a different current type, inversion may or may not be required. A binary parameter, Cu is thus introduced for each designated flow, where 1 for technology which requires inversion and 0 otherwise.

$$\sum_i GL_{iwt} \times Cu_i + \sum_i \sum_e GE_{iewt} \times Cu_{ie} + \sum_f \sum_e \times GE_{fewt} \times Cu_e \quad \forall w, t + \sum_e ES_{ewt} \times Cu_e \leqslant I \tag{20}$$

(e) Charging/discharging binary constraint

In this model, ES is designed to operate in either a charging state or a discharging state. Eq. (21) shows the model for ES charging and Eq. (22) for discharging. Eq. (23), on the other hand, constrains the model to choose either charging or discharging or not in operation.

$$\sum_i GE_{iewt} + \sum_f GE_{fewt} \leqslant Q \times y_{ewt} \quad \forall e, w, t \tag{21}$$

$$ES_{ewt} \leqslant Q \times z_{ewt} \quad \forall e, w, t \tag{22}$$

$$y_{ewt} + z_{ewt} \leqslant 1 \quad \forall e, w, t \tag{23}$$

(f) Power grid constraint

In most cases, electricity is charged based on total energy consumption and the maximum power demand in an instance. With maximum power demand being analogous to capacity of power generator, Eq. (24) was derived to ensure that withdrawment of energy from the power grid must not exceed the maximum power demand.

$$G_{fwt} \leqslant MD_f \quad \forall f, w, t \tag{24}$$

(g) Tariff selection binary constraint

Since only one tariff plan is eligible, Eq. (25) was derived to prevent selection of multiple tariffs.

$$\sum_f x_f \leqslant 1 \tag{25}$$

(h) Emission constraint

RE is considered as carbon neutral technologies, the only factor contributing to carbon footprint in this model is through the consumption of energy from the power grid. As the power grid operates on mixed energy resources (fossil, clean and RE), a certain amount of carbon footprint per kWh of consumption is accounted. In this model, carbon reduction target is more accurately referred as reduction in carbon footprints instead of emissions. Eq. (26) represents the formulation for carbon footprints reduction target.

Among other emissions of major concern are the NO_x and SO_x, however, as RE does not emit SO_x and only thermal-based RE generator such as biomass generates NO_x, only NO_x emissions are considered in the formulation. The model for limiting NO_x emissions is shown in Eq. (27).

Carbon footprint reduction target:

$$\sum_f \sum_w \sum_t G_{fwt} \times CO_2 \times N_w \leqslant ECO_2 \times (1 - Red) \tag{26}$$

NO_x emission limit:

$$\sum_i \sum_w \sum_t G_{iwt} \times NO_{xi} \times H_i \times N_w \leqslant EN \tag{27}$$

Apart from the objective function and constraints, in order to analysis the amount of saving after retrofication, Eq. (28) was thus derived.

$$\mathrm{Sav} = \left(\frac{\mathrm{EBB} - \mathrm{CT}}{\mathrm{EBB}}\right) \times 100\% \tag{28}$$

4. Case study

Universiti Teknologi Malaysia, UTM had been paying millions of dollar for electricity. Despite the fact that UTM is located on a hillside beside a palm oil plantation in a tropical climate giving it tremendous access to biomass and solar resources, no initiative had been presented for implementation of a sustainable energy system to reduce its annual cost of electricity. Moreover, as the main research university in the region of Iskandar Malaysia (emerging low carbon society in Malaysia), UTM would be a good platform for the development of RE within the region. The proposed DEG system for UTM is shown in Fig. 2.

Based on the figure, the proposed energy system is separated into two buses, alternating current (AC) and direct current (DC) bus. Three power generators are recommended for the system, two biomass generators (utilising empty fruit bunches (EFB) from a nearby palm oil mill as fuel), biomass bubbling fluidised bed (BBFB) and biomass combined cycle (BCC) connected to the AC bus, and a solar PV system connected to the DC bus.

Two ES devices are recommended for the system, a HPES (located at hillside) connected to the AC bus

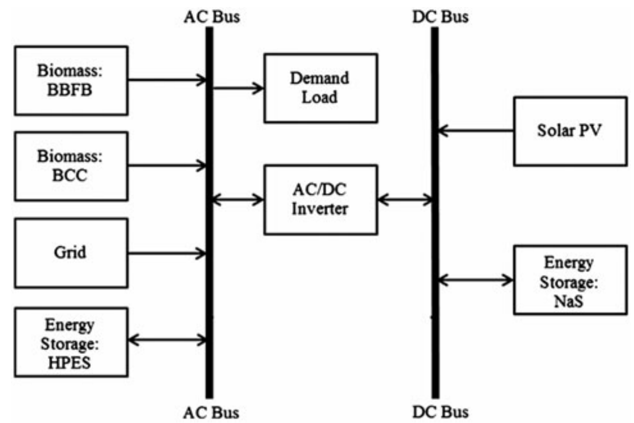

Fig. 2. Configuration of DEG system of UTM.

and sodium sulphur (NaS) battery connected to the DC bus. The system is connected to a power grid through the AC bus with demand loads required energy of AC. At any instance if energy is required to flow from the AC bus to DC bus or vice versa, it will have to go pass the inverter where it will be inverted to its designated current type.

4.1. Data collection

Based on a survey with the Office of Asset and Development of UTM, several targets and available area for green energy developments had been identified. Data collected from the survey includes, carbon footprint reduction target, NO_x emissions limit, available rooftop area for solar PV system, available land area for HPES system and the current annual electricity bill. These data are tabulated in Table 1 with other miscellaneous data. Typical load profile, D_t of UTM is shown in Fig. 3 while solar radiation, SR_{wt} for typical weather patterns of clear, cloudy and rainy day in Malaysia is shown in Fig. 4 [26]. Estimated days of occurrence for each weather pattern, N_w, in a year are 70 days for clear weather, 245 days for cloudy weather and remaining 50 days for rainy weather [26]. Lastly,

Table 1
Miscellaneous data of DEG system

System information		
Distribution network efficiency, L	95	%
Economic information		
Current annual electricity bill[a], EBB	6,880,000	\$/y
Amortised factor for a year[b], M	0.00665	–
Solar PV [27]		
Available area, $Al_{(solar)}$	10,000	m^2
Surface area required for 1 kWp installation, $W_{(solar)}$	8	m^2/kWp
Module efficiency, $sf_{(solar)}$	15	%
Biomass [28]		
Empty Fruit Bunch (EFB) availability, R	3,726	TJ/y
Turn down ratio, TR_i	50	%
Energy storage		
Available capacity for HPES[c], $U_{(HPES)}$	15,000	kWh
Emission constraints		
Grid carbon factor, CO_2 [29]	0.635	Tonne/MWh
Present annual carbon footprint, ECO_2	36,000	Tonne/y
Reduction target, Red	40	%
BBFB NO_x emission, NO_{xBBFB} [30]	0.0344	Tonne/TJ
BCC NO_x emission, NO_{xBCC} [30]	0.0232	Tonne/TJ
NO_x emission limit, EN	30	Tonne/y

[a]TNB commercial tariff rate, currently utilising Tariff C1 [31]. [b]Interest rate of 7% paid monthly over 30 years period. [c]Estimated at net head of 80 m, efficiency of 70%, flow of 27.5 m^3/s (total of 100,000 m^3/h).

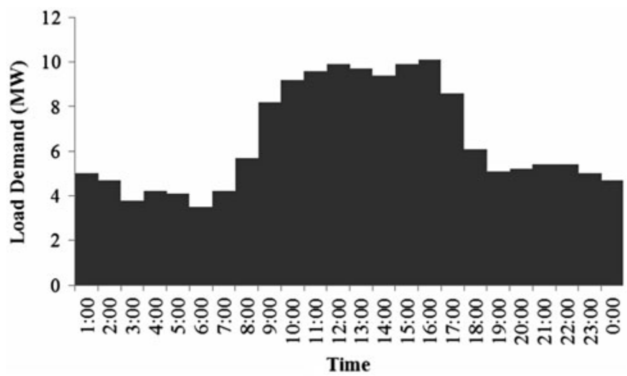

Fig. 3. Load profile of UTM.

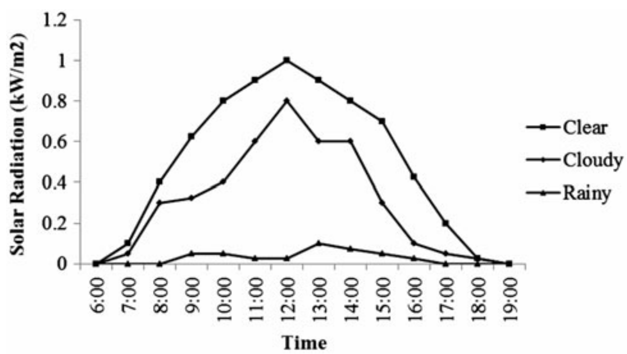

Fig. 4. Solar radiations for clear, cloudy and rainy day in Malaysia [26].

the cost of power generators, ES, inverter and tariff rates of the local power provider, Tenaga National Berhad (TNB) is tabulated in Table 2.

5. Results and discussion

The MILP model was programmed into the General Algebraic Modelling System (GAMS) software and via CPLEX 12 solver, the model reveals that in order to comply with 40% carbon footprint reduction and limitation of 30 tonne of NO_x emissions a year, a grid-connected DEG system consisting of at least a BBFB generator of 5,982 kW, solar PV of 1,250 kW, HPES with energy-related capacity of 15,000 kWh and power-related capacity of 1,679 kW, NaS ES with energy-related capacity of 1,069 kWh and power-related capacity of 575 kW, and inverter of 1,125 kW is required. Based on the results, the system will operate with a maximum power demand of 2,512 kW from the power grid via TNB commercial C1 tariff.

Among the RE technologies considered for UTM, solar PV is selected as it does not emit any form of pollutants. However, due to limited rooftop areas, BBFB generator is selected in addition to solar PV to provide sufficient RE to meet carbon footprint reduction of 40%. BCC generator is not selected as it is relatively more expensive than the other two choices. As for ES, both technologies are selected. C1 tariff is selected over C2 tariff solely due to the fact that the maximum power demand rate for C1 tariff is lower than that of C2 tariff. Based on Fig. 5 (energy from generator, the power grid or ES to load) and Fig. 6 (energy from generator or the power grid to ES), it can be clearly seen that electricity from the power grid is needed during peak periods. With both tariff having the same rate during peak periods, there is absolutely no advantage in selecting C2 which have lower rate during off-peak periods. The summary of results is shown in Table 3.

Fig. 5 shows the energy of various generators, the power grid and various ES supplied to meet load demands at clear, cloudy and rainy day. Fig. 6 on the other hand shows the energy of various generators generated for storage in various ES.

From the results, generally, energy is supplied by BBFB generator with contribution from the power grid, solar PV and ES during peak periods. Energy generated from BBFB generator is also stored during off-peak periods as shown in Fig. 6. The results indicate that BBFB is the main power producer in the DEG system. BBFB power generator operates similarly across all three weather patterns.

Comparing between three weather patterns, solar PV supplies a larger portion of energy during clear day when solar radiation is found abundant. Some excess solar energy is also being stored (Fig. 6). On the contrary, the power grid contributes a larger portion of required energy at rainy days rather than at clear or cloudy days.

ES on the other hand, a peak shaving/load shifting device operates by storing energy during off-peak periods to supply during peak periods. A clear illustration of a shaved load profile can be seen in Fig. 5 (rainy day) where the top portion (shaved portion) of load demands is supplied by the ES. In support of the argument, Fig. 7 shows the total energy content in both ES on different weather patterns which generally support the statement that energy is stored during off-peak periods. The charging/discharging trend of the ES is similar for each weather conditions.

Economically, with the grid-connected DEG system working as a platform for integration, synergy between the operating units resulted in total reduction of 17.3% on the annual cost of electricity. The total annual cost of the proposed system is 5,687,000 $/y (annualised investment cost of 2,171,000 $/y, annual O&M cost of 2,585,000 $/y, and annual electricity bill of 931,000 $/y), a reduction of 1,193,000 $/y. The

Table 2
Cost and parameter of operating units

Power generator [30]					
	Capital cost, T_i (\$/kW)	Fixed O&M cost, F_i (\$/kW.y)	Variable O&M cost, V_i (\$/kWh.y)	Heat rate, H_i (GJ/kWh)	Fuel price, Pr_i [32](\$/GJ)
BBFB	3860	100.50	0.005	0.01424	2.26
BCC	7894	338.79	0.01664	0.01303	2.26
PV [27]	800	16.7	–	–	–
Energy storage [33]					
	Energy-related cost, TE_e (\$/kWh)	Power-related cost, TP_e (\$/kW)	Fixed O&M cost, F_e (\$/kW.y)	Charging, cf_e / discharging, df_e efficiency (%)	Depth of discharge, DOD_e (%)
NaS	288	173	23	92.2/92.2	80
HPES	10	1000	2.5	92/89	80
Inverter					
	Capital cost, TI (\$/kW)		Inverter efficiency, If (%)		
Inverter	775		90		
Tariff [31]					
	Max demand rate[a], MDC_f (\$/kW. month)		Electricity rate[a], TF_{ft} (\$/kWh)		
			Off-peak rate 10 pm – 8 am	Peak rate 8 am – 10 pm	
C1	7.77		0.104	0.104	
C2	12.87		0.064	0.104	

[a]10% discounted rate.

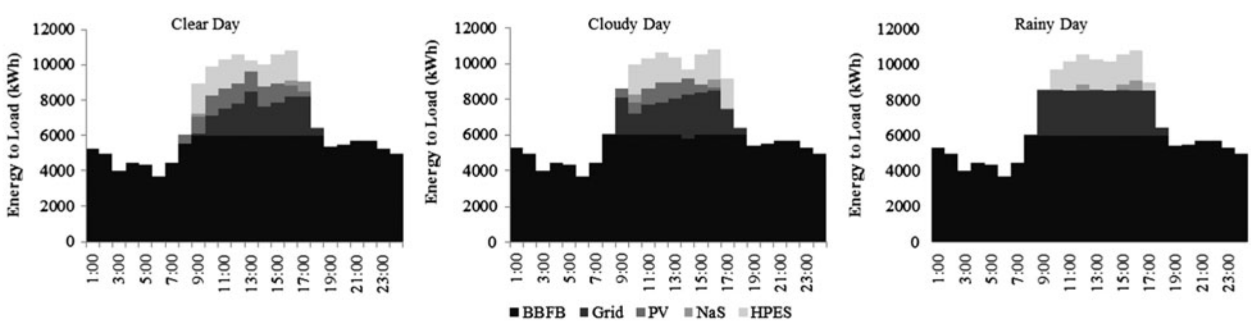

Fig. 5. Energy of various operating units supplied to meet load demands at different weather patterns.

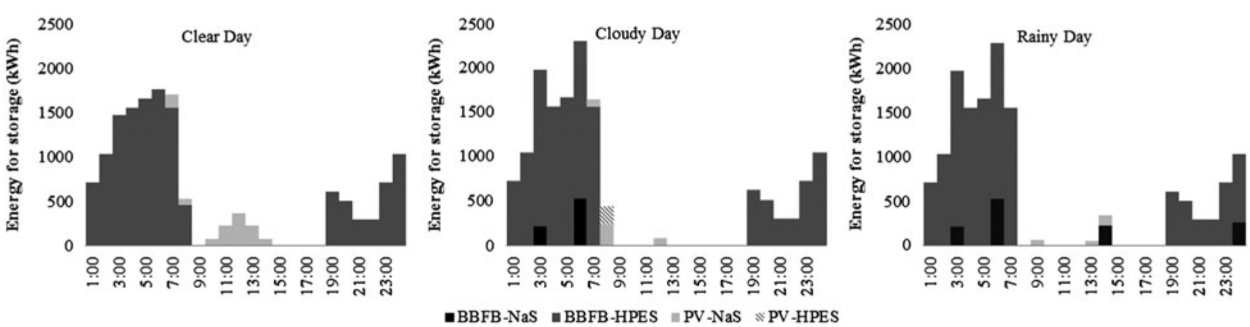

Fig. 6. Energy of various power generators generated for storage in various ES devices.

recommended DEG system is therefore significant to UTM as it does not only reduce the cost of energy but also able to achieve a substantial reduction in carbon footprint while limiting pollutant (NO_x) emission, making the system economically and environmentally sound.

Table 3
Optimised results based on 40% carbon footprint reduction and 30 tonne of annual NO_x emission limit

DEG system	
BBFB capacity	5,982 kW
Solar PV capacity	1,250 kW
NaS energy-related capacity	1,069 kWh
NaS power-related capacity	575 kW
HPES energy-related capacity	15,000 kWh
HPES power-related capacity	1,679 kW
Inverter capacity	1,125 kW
Power grid maximum demand	2,512 kW
Tariff	C1

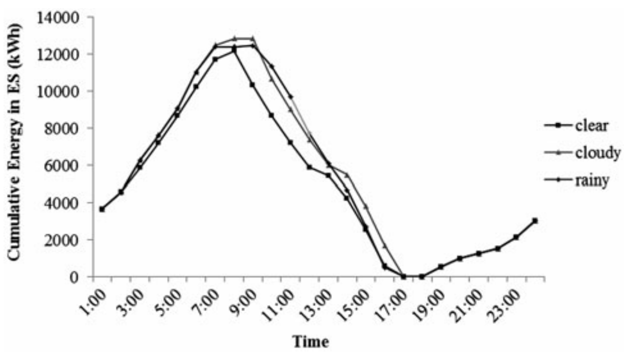

Fig. 7. Cumulative energy in ES at different weather.

5.1. Sensitivity analysis

In order to study the impacts of the decision variables (carbon footprint reduction target and NO_x emissions limit) on the objective function, two sensitivity analyses were performed. The first sensitivity analysis involves the study of NO_x emissions limit reduction on the annual cost of electricity, while the second analysis is conducted to study the effects of reducing NO_x emissions limit on the optimal carbon footprint reduction.

5.1.1. Total cost

The result of decreasing NO_x emissions limit on the annual cost of electricity at 40% carbon footprint reduction is shown in Figs. 8 and 9.

Based on Fig. 8, BBFB generator as the sole emitter of NO_x reduces in capacity, solar PV generator maintained at a constant capacity (fully utilised its available rooftop surface area), maximum power demand of the power grid increases, with decreasing NO_x emissions limit. The annual cost of electricity on the other hand increases with decreasing NO_x emissions limit, mainly due to reduction in BBFB capacity where its operation is more economical than withdrawing energy from the power grid. Referring to Fig. 8, at 10 tonne of NO_x emissions limit, in addition to BBFB power generator, BCC power generator is also selected. BCC is selected to maintain the portion of RE mix within the system while producing less NO_x, as BCC generator is relatively cleaner compared to BBFB generator.

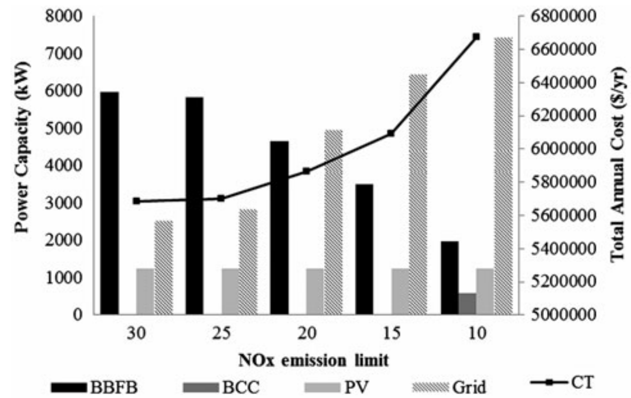

Fig. 8. Impact of reducing NO_x emission limit on power capacity and total annual cost.

ES capacities on the other hand decreases with decreasing NO_x emission limits. The main reason behind the reason of ES capacity reduction is due to increasing power requirement of the power grid. With increasing maximum power demand of the power grid (C1 tariff), higher flexibility in energy demand is made possible reducing the needs of ES for major peak shaving and load balancing. From Fig. 9, it can be seen that at NO_x emissions limit of 15 tonne/y onward, HPES is no more required; however, Nas ES

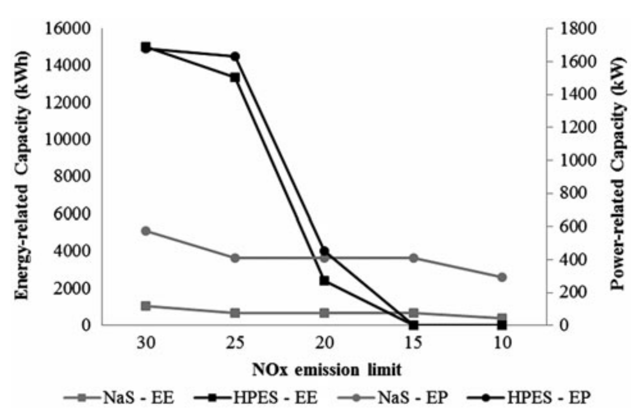

Fig. 9. Impact of reducing NO_x emission limit on ES capacities (cases of total cost).

is maintained in the system. Beyond the limit of 15 tonne/y of NO_x emissions, solar PV became the main contributor of energy for storage and as solar PV operates in the DC bus, NaS ES which also operates in the DC bus became more favourable compare to HPES which operates in the AC bus.

5.1.2. Carbon footprint reduction

In this analysis, total cost, which is originally the objective function, is set as a constraint such that the annual cost of electricity must be equal or less than the present cost of electricity (the amount UTM is currently paying). Carbon footprint reduction on the other hand is modified as the new objective function, with objective to maximise carbon footprint reduction. The analysis is performed for NO_x emissions limit of 5, 10, 15, 20, 25 and 30 tonne/y. The result of this analysis is shown in Figs. 10 and 11.

Referring to Fig. 10, carbon footprint reduction percentage decreases with decreasing NO_x emissions limit, consequence of decreasing capacity of BBFB generator. In additional to BBFB generator, BCC is selected in all cases except for the case of 30 tonne/y of NO_x emissions limit. BCC is selected to maintain a maximal mix of RE in the system while minimising the amount of NO_x produced.

Similar to the earlier sensitivity analysis, ES capacities decrease with decreasing NO_x emissions limit and at 15 tonne/y of NO_x emission and beyond, HPES is no more required.

6. Conclusion and recommendation

In this research, it shows that it is definitely feasible for UTM to take up energy management strategies to reduce its annual electricity bill in addition to

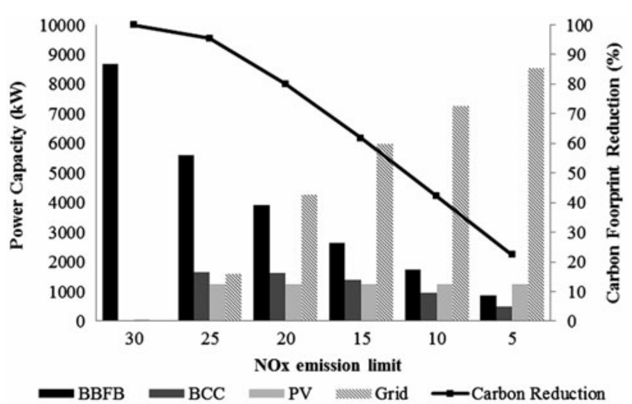

Fig. 10. Impact of reducing NO_x emission limit on power capacity and carbon footprint reduction.

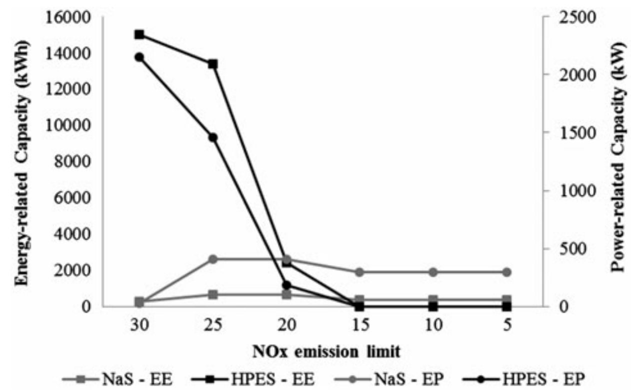

Fig. 11. Impact of reducing NO_x emission limit on ES capacities (cases of carbon footprint reduction).

reduction in carbon footprint. With low carbon initiative being profoundly endorsed by the local government, this project will definitely be a good start for RE developments in Iskandar Malaysia region.

The model on the other hand, which is capable of determining the optimal capacity and configuration of a system as well as providing optimal schedules for power utilisation during different weather patterns, is an important tool for energy engineers and policymakers to design and relatively set targets for an energy system in planning.

Good as it is, the model can yet be further developed such as to include rain water collection for HPES system which then can function as a mini hydropower generator as well as a HPES. Strategy of collecting rain water is in fact a great option to counter the intermittency of solar PV in location with frequent rain. Application of this strategy will lead to a greater cost reduction. When there is no sun, there is rain and vice versa. Inclusion of this factor into the model thus represents the future extension of the model.

Symbols

$Al_{(solar)}$	—	maximum area for solar PV installation, m^2
cf_e	—	ES charging efficiency, %
CO_2	—	grid CO_2 factor, tonne/kWh
D_t	—	energy demand, kWh
df_e	—	ES discharging efficiency, %
DOD_e	—	ES depth of discharge (battery only); 100% for other ES technology, %
EBB	—	present electricity bill, \$/y
ECO_2	—	present carbon footprint, tonne/y
EN	—	NO_x emission limit, tonne/y
F_e	—	fixed O&M cost of ES, \$/kW y
F_i	—	fixed O&M cost of generator, \$/kW y
H_i	—	heat rate of generator (thermal power generator only); 1 for other generation technology, GJ/kWh

If_e — inversion efficiency, from ES to load; 100% if no inversion is required, %
If_i — inversion efficiency, from generator to load; 100% if no inversion is required, %
If_{ie} — inversion efficiency, from generator to ES; 100% if no inversion is required, %
L — distribution network efficient, %
M — amortised factor
MDC_f — rate of maximum power usage (grid), $/kW
Mn — number of months in a year
N_w — number of occurring weather in a year, day
NO_{xi} — NO_x emission, tonne/kWh
Pr_i — fuel price (power generator with external fuel only), $/GJ
Q — a large positive value
R — biomass availability, GJ/y
Red — reduction target
$sf_{(\mathrm{solar})}$ — solar PV module efficiency, %
SR_{wt} — solar radiation, kW/m^2
T_i — capital cost of generator, $/kW
TE_e — energy-related cost of ES, $/kWh
TF_{ft} — tariff rate (grid), $/kWh
TI — capital cost of inverter, $/kW
TP_e — power-related cost of ES, $/kW
TR_i — turn down ratio (thermal power generator only)
U_e — maximum storage for HPES/CAES system, kWh
V_i — variable O&M cost of generator, $/kWh
$W_{(\mathrm{solar})}$ — area required for 1 kWp installation, m^2/kWp
Cu_e — 1 if requires current inversion from ES to load; 0 otherwise
Cu_i — 1 if requires current inversion from generator to load; 0 otherwise
Cu_{ie} — 1 if requires current inversion from generator to ES; 0 otherwise
CT — total annual cost, $/y
$A_{(\mathrm{solar})}$ — solar PV installation area, m^2
C_i — capacity of generator, kW
CI — annualised investment cost, $/y
CO — annual O&M cost, $/y
CP — annual power grid electricity cost, $/y
EE_e — ES energy-related capacity, kWh
EP_e — ES power-related capacity, kW
ES_{ewt} — energy discharge from ES to load, kWh
G_{fwt} — total energy from grid, kWh
G_{iwt} — total energy generation from generator, kWh
GE_{fewt} — energy from grid to ES, kWh
GE_{iewt} — energy from generator to ES, kWh
GL_{fwt} — energy from grid to load, kWh
GL_{iwt} — energy from generator to load
I — inverter capacity, kWh
MD_f — maximum demand required of power grid, kW
Sav — annual cost saving percentage, %
S_{ewt} — cumulative energy in ES, kWh
x_f — tariff selection; 1 if selected, 0 otherwise
y_{ewt} — charging of ES; 1 if charge, 0 otherwise
z_{ewt} — discharging of ES; 1 if discharge, 0 otherwise

Subscripts

e — energy storage
f — tariff
i — power generator
t — time
w — weather

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