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Extended Electric System Cascade Analysis (ESCA) for optimal power system targeting considering generation flexibility and heat rate factor

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Abstract

In order to cater for fluctuating energy demand, power plants are designed either as base power plant or peak power plant. The advantage of base power plant is that due to its constant power generation, the power plant has a higher efficiency. To optimize and design a power plant, many previous study has been conducted. Among the studies, Power Pinch tool named Electric System Cascade Analysis (ESCA) was applied to design an optimal power system. ESCA analysis is conducted by assuming that the power plant generates constant power as it is more efficient. However, further analysis using ESCA shows that with a minimal power plant capacity would result in a trade-off that the energy storage system would be larger and leads to higher energy charging and discharging tendency (result in higher energy lost). Considering the time change of heat rate with the corresponding load factor, this study incorporates new algorithm for flexible power generation into the existing ESCA methodology. To validate the new algorithm, an off-grid distributed energy generation system is mathematically modelled and solved. The result from the new algorithm is compared with that of the mathematical model. The comparison of optimal generator capacity shows a difference of 5.71%. The similarity of the result hence validates that the new algorithm is suitable.

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Nomenclature

DEG	Distributed energy generation
ES	Energy storage
ESCA	Electric System Cascade Analysis
GAMS	General Algebraic Modelling System
MINLP	Mixed integer non-linear programming

1. Introduction

Most of the power plants operate using steam turbines. Fuel such as coal, natural gas or biomass are burned to heat water into super-heated steam - a high-pressure steam which then turns the turbine-generator to produce electricity. One of the challenges of the power plants nowadays is to deliver a reliable and quality power supply. In recent years, the increase of non-linear loads (peak loads) causes power disturbances to the power system which was initially designed to serve only base loads [1]. At the generation level, the growing penetration of renewable sources may also affect the system performances. While power generating unit is the most essential component in power plant design, it is also necessary to install power conditioning units such as energy storage (ES) system, back-up generator and inverter to counter these issues.

Previously, a Power Pinch tool named Electric System Cascade Analysis (ESCA) was applied to design an optimal power system, by assuming that the power plant is operating with a constant generation [2]. Constant power generation could maximize the load factor and the operating efficiency of the generator itself; however, when evaluating from the perspective of the overall system efficiency, the efficiency is in fact lower due to larger requirement to charge and discharge energy into and out of the energy storage. Besides, by operating at a fixed generation, the power plant may require a larger ES capacity. By assuming that the power generation is constant, it does not achieve the optimization objective especially when energy efficiency and cost are taken into consideration. In this study, in order to refine the optimization process of ESCA, a new algorithm is included in ESCA to consider flexible power generation that results in trade-off between power plant capacity and operational efficiency.

2. Literature Review

Pinch Analysis has been widely applied in Process Integration for the design of optimal resource utilization and recovery network including power system management. One of the Power Pinch based tools, ESCA, was established to optimize the design and operation of distributed energy generation (DEG) system that utilizes renewables as their power source. ESCA has been explored to size the system with intermittent [3] or non-intermittent sources [2], as well as to perform load-shifting [4] for efficient energy utilization in the DEG system.

Several studies applying Power Pinch concept has shown a more optimal and realistic design of the DEG system when other system losses involving battery charging and discharging [5] and current inversion [6] are considered. Most of the studies discussed load manipulation strategies for DEG system such as load-shifting [7], load reduction via energy efficient appliances [8] and power regulation using energy storage system [9]. In comparison, similar discussions related to the supply-side management in the literature are fairly limited. One of the examples are from Ho et al. [10], who demonstrated that cost and thermal efficiency can be improved when the trade-off between power plant capacity and energy storage capacity is considered.

3. Methodology

Figure 1 presents the extended steps which are incorporated into the existing ESCA methodology as to determine the most optimal power system design with its operational efficiency enhanced. First, the optimal size of generator is determined from the existing ESCA algorithm (with constant generation) [2] and is labelled as “first optimal”. Based on the analysis reported from Ho et al. [10], the operational efficiency of the plant is enhanced when a larger generator capacity is used. Hence for the scenario analysis (Step 2), several generator capacities are scaled up from the “first optimal” and are used in the subsequent cascade analysis (Step 3). The cascade analysis is performed for each generator capacity by adjusting the power generation accordingly until the system is feasible. For every generator capacity analyzed, its operational efficiency is determined. The result is used to plot an efficiency-capacity graph (Step 4) in order to estimate the generator size with the highest efficiency, known as “second optimal”. Lastly in Step 5, the “second optimal” is used to repeat the cascade analysis to determine the corresponding capacities of other operating units such as ES and inverter.

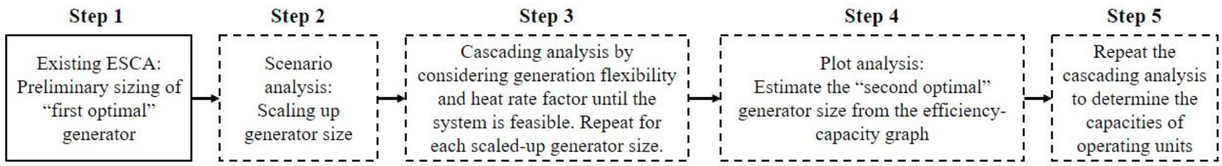

Fig. 1. New extended steps (dotted boxes) that incorporates generation flexibility and heat rate factor in ESCA.

To consider the fluctuation in power generation in Step 3, the changes in heat rate are accounted in the Extended ESCA, based on the corresponding operating load as shown in Figure 2.

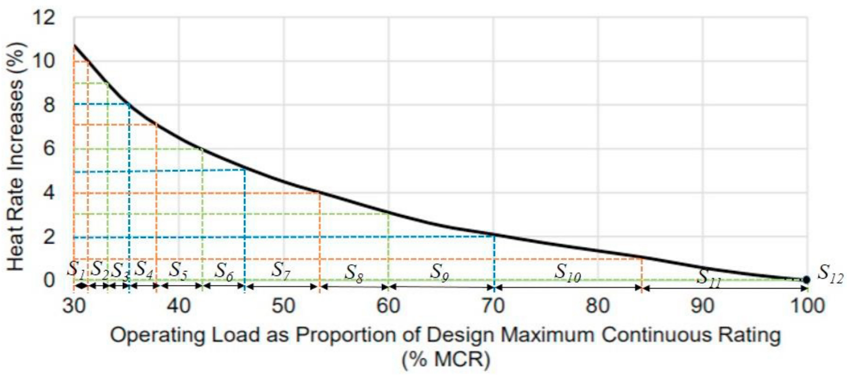

Fig. 2. Heat rate increase vs. operating load of a typical power generator [11].

Apart from Extended ESCA, the development of mathematical model follows the flow chart as shown in Figure 3. From the power system configuration defined and the data collected, mathematical equations that represent the property and operation of the system are formulated. These equations are then coded and solved using a renowned optimization software, General Algebraic Modelling System (GAMS). The optimization results determined by GAMS are then used to compare with the results from the Extended ESCA for validation purpose.

Twelves ranges on operating load in Figure 2 are segmented manually and arranged in Table 1 with their respective lower and higher load factors, as well as the corresponding heat rate increment. At a full load (100% load factor), there is no heat rate increase. When operated between 85.0% and 99.9%, the heat rate of the power generator increases by 1% (see Table 1). The data from Table 1 are input into the model to let the model consider the variation of heat rate and operating load when optimizing the power system. New heat rate for power plant after increment, HR_s is calculated using Eq(1).

$$HR_s = HR_o(1+i) \tag{1}$$

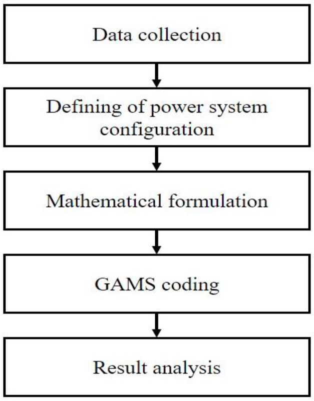

Fig. 3. Flow diagram of mathematical modelling approach in this study.

Table 1. Operating load range and the corresponding heat rate increment extracted from Figure 2 to be input into the power system model.

Range, *s*	Load Factor (%)		Heat rate increase, *i* (fraction)
	Lower Load Factor, *LLF*	Higher Load Factor, *HLF*	
1	30.0	30.9	0.11
2	31.0	32.9	0.10
3	33.0	34.9	0.09
4	35.0	37.9	0.08
5	38.0	42.9	0.07
6	43.0	46.9	0.06
7	47.0	53.9	0.05
8	54.0	59.9	0.04
9	60.0	69.9	0.03
10	70.0	84.9	0.02
11	85.0	99.9	0.01
12	100.0	100.0	0.00

3.1 Data and power system configuration for case analysis

Illustrated in Figure 4, the DEG system designed as case study is an off-grid direct-fired bubbling fluidized bed power plant with biomass fuel as the energy input [10]. It operates continuously for 24 h to supply electricity to a typical residential community with a total demand of 84.5 MWh/d [10]. The residential demand profile is shown in Figure 5. Besides, the system is embedded with energy storage to cater the demand variations by smoothening the energy distribution during power surplus or deficit periods [12]. In addition, inverter helps to convert different types of current flowing in the system (from direct current to alternating current and vice versa). The initial heat rate of the power generator, HR_o at 100% load factor is 14,240 MJ/MWh [10].

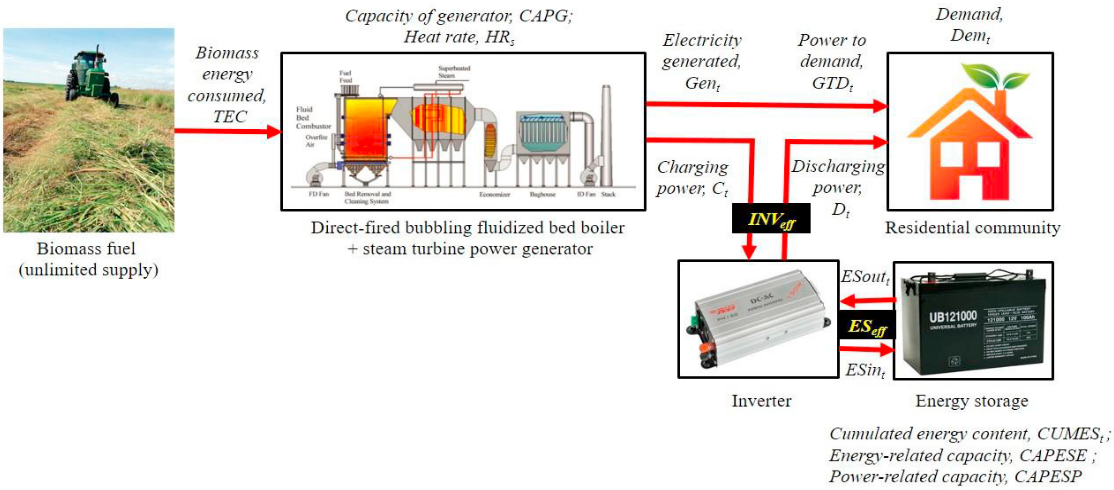

Fig. 4 Off-grid DEG system configuration in this study.

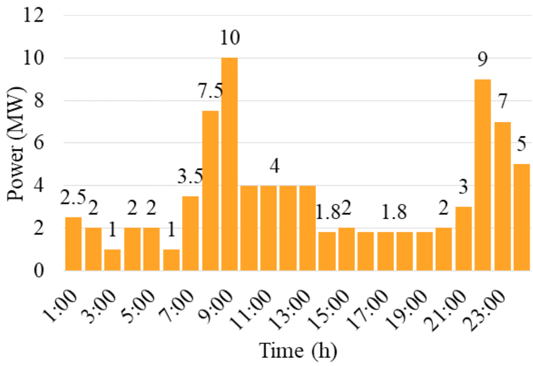

Fig. 5 Typical demand of a residential community for the analysis in this study [10].

3.2 Mathematical formulations of DEG system

3.2.1 Objective function

Eq(2) describes the objective of the model, i.e. to minimize the total energy generated by the power plant, *TEG* (MWh/d). Index *t* represents the instantaneous time of analysis in h while index *s* is the range of operation load of the power plant. Consequently, the overall plant operational efficiency, OP_{eff} (%) can be determined using Eq(3).

$$TEG = \sum_{t,s} Gen_{t,s} \tag{2}$$

$$OP_{eff} = \frac{\sum_t Dem_t}{TEG} \times 100\% \tag{3}$$

3.2.2 Capacity constraint

The output of a system or a content within a system could not exceed its capacity. The hourly generation, $Gen_{t,s}$ (MW) of the power generator can either be equal or less than its maximum capacity, *CAPG* (MW). Eq(4) depicts the generation limits given to the power generator where the upper limit is subjected to the upper load factor, ULF_s (%) and the lower limit is subjected to the lower load factor, LLF_s (%) of the plant. The term $x_{t,s}$ is a binary variable used to let the model choose the optimal load factor that the plant should operate in order to achieve the objective function. The sum of all $x_{t,s}$ has to be equal to 1, as depicted in Eq(5).

$$CAPG \times LLF_s \times x_{t,s} \leq 100\, Gen_{t,s} \leq CAPG \times ULF_s \times x_{t,s} \qquad \forall t,s \tag{4}$$

$$\sum_s x_{t,s} = 1 \qquad \forall t \tag{5}$$

For energy storage system, the cumulated energy content in the storage at every hour, $CUMES_t$ (MW) cannot exceed its maximum energy-related capacity – shown in Eq(6) as the product of depth of discharge of energy storage, *DOD* (taken as 80%) [10] and the actual installed energy-related capacity of storage, *CAPESE* (MWh). The *DOD* factor is considered as to avoid battery degradation due to charging and discharging cycles. The power-related capacity of the storage system, *CAPESP* (MW) is determined where the net energy input into energy storage (after conversion and charging losses), $ESin_t$ (MW) and the energy output from energy storage (before conversion and discharging losses), $ESout_t$ (MW) cannot exceed *CAPESP*, as shown in Eq(7) and Eq(8). To ensure no energy accumulation in the energy storage, Eq(9) depicts that the initial energy content (at $t=1$) should be the same as the final energy content (at $t=24$) before the next cycle begins.

$$CUMES_t \leq CAPESE \times DOD \qquad \forall t \tag{6}$$

$$ESin_t \leq CAPESP \qquad \forall t \tag{7}$$

$$ESout_t \leq CAPESP \qquad \forall t \tag{8}$$

$$CUMES_{t=1} = CUMES_{t=24} \tag{9}$$

3.2.3 Energy Balance

The energy flows from the generator, the demand and the storage are described by energy balance equations. For the generator, the total generated power, $Gen_{t,s}$ (MW) is supplied to the demand, GTD_t (MW) at every time t (Eq(10)). The net surplus energy, C_t (MW) is charged into the storage only when the $Gen_{t,s}$ is more than the total demand for power, Dem_t. Eq(11) is for the total biomass energy consumed by the system, *TEC* (MJ/d), accounted from the summation of $Gen_{t,s}$ and the heat rate HR_s at the particular time t.

$$\sum_s Gen_{t,s} = C_t + GTD_t \qquad \forall t \tag{10}$$

$$TEC = \sum_{t,s} \left(Gen_{t,s} \times HR_s \right) \tag{11}$$

On the demand side, the hourly demand, Dem_t (MW) is met by GTD_t. As presumed, the generation has to first meet the demand before storage. When the generated power at time t is insufficient for the demand, the system would source from the excess energy stored prior to that time period by discharging the required power from the energy storage, D_t (MW) (after conversion and discharging losses). This is described in Eq(12).

$$Dem_t = GTD_t + D_t \qquad \forall t \tag{12}$$

From Eq(13), the new energy content accumulated inside the storage at time $t+1$, $CUMES_{t+1}$, is resulted from the cumulated energy in the storage at the previous time t, $CUMES_t$, plus the energy input ($ESin_t$) and output ($ESout_t$) at time t. The losses of power due to energy conversion at the inverter as well as charging or discharging at the energy storage are depicted in Eq(14) and Eq(15). The inverter efficiency, INV_{eff} is taken as 90% and the energy storage charging/discharging efficiency, ES_{eff} is taken as 88.3% [10].

$$CUMES_{t+1} = CUMES_t + ESin_t - ESout_t \qquad \forall t \tag{13}$$

$$ESin_t = C_t \times INV_{eff} \times ES_{eff} \qquad \forall t \tag{14}$$

$$ESout_t = \frac{D_t}{INV_{eff} \times ES_{eff}} \qquad \forall t \tag{15}$$

4. Results and Discussion

A mixed integer non-linear programming (MINLP) model is defined and solved using BARON solver in GAMS 24.4.1. With the objective to minimize *TEG*, the optimal solution is found after the first iteration with 4.28 s of execution time. The results obtained from GAMS (mathematically) and Extended ESCA are arranged in Table 2. The ESCA result in Table 2 is recalculated based on the suggested "second optimal" generator capacity of 7 MW from the analysis conducted by Ho et al. [10]. Figure 6 shows the energy profiles of the power plant optimized by GAMS and Extended ESCA.

Table 2. Comparison of system variables from mathematical modelling (from this study) and Extended ESCA [10].

Result	Total energy generation, *TEG* (MWh/d)	Plant operational efficiency, OP_{eff} (%)	Generator capacity, *CAPG* (MW)	ES capacity, $CAPESE_a$ (MWh)	ES power capacity, *CAPESP* (MW)	Total energy consumption, *TEC* (MJ/d)
GAMS	87.00	97.12	7.40	5.00	4.00	1.293 x10^6
ESCA	87.71	96.34	7.00	5.87	3.77	1.304 x10^6

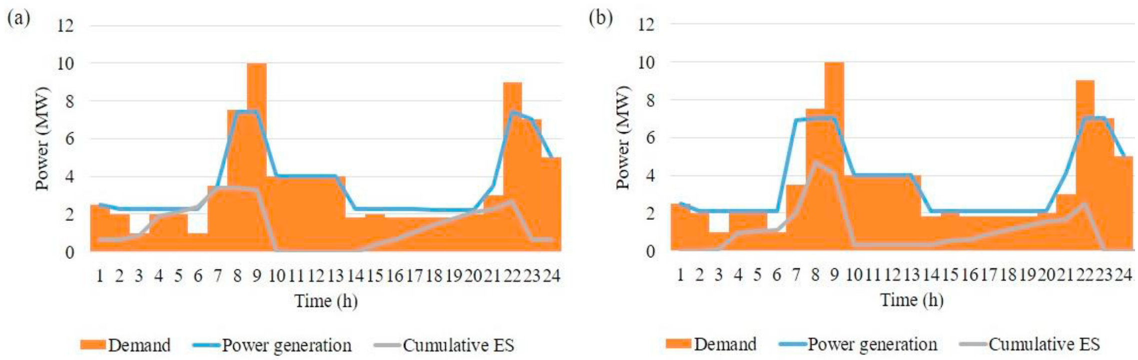

Fig. 6 Plant generation and energy storage profiles from (a) GAMS (from this study) and (b) Extended ESCA [10].

Based on Table 2, the power plant optimized using GAMS has a higher OP_{eff} and a lower *TEG* and *TEC* compared to the Extended ESCA. As for the technical design of the power system, GAMS suggests a larger *CAPG* and *CAPESP* but a smaller *CAPESE* to be installed. This could be due to that costing is not a constraint in the model.

From Figure 6, the interaction between the generator and the energy storage in order to meet the power demand is slightly different in both approaches. For instance, GAMS decides to start its $CUMES_{t=1}$ as 0.634 MW in order to cater the peak demand at 8-9 h; however in Extended ESCA, the $CUMES_{t=1}$ is 0 MW and the plant increases its generation at 7 h prior to the peak demand at 8-9 h. The decision on the starting amount of energy content in ES could be one of the causes for a higher *TEG* and its corresponding *TEC* required in the ESCA case.

Overall, it can be seen that both mathematical and numerical approaches produce very similar results. The optimal generator size solved by GAMS is only 5.71% different from that by Extended ESCA, and that brings only 0.8% improvement in the plant operational efficiency. This verifies that the new algorithm extended in ESCA can improve the optimization procedure to obtain a better optimized result.

5. Conclusion

In this study, a mathematical modelling is used to perform optimization for off-grid power system design, in which the result is compared with that conducted using numerical Power Pinch method known as Extended ESCA. It is found that a significant high overall plant operational efficiency (about 97%) can be achieved when the generation flexibility in power plant is taken into account. Since there is no significant deviation between the results (with only 5.71 % different in the optimal generator capacity), the mathematical model validates the result accuracy obtained from Extended ESCA. The result also concludes the need to include plant generation factor, i.e. heat rate to the general ESCA methodology. A set of heuristics will be determined for the methodology development of ESCA in the next study. The mathematical modelling developed in this study will also be further expanded to include costing (apart from the technical parameters such as plant efficiency and energy consumption) for a multi-objective optimization.

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