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Optimising Thermal Power Plant with Generation Flexibility and Heat Rate Factor

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Operational flexibility appears to be a significant paradigm shift for conventional thermal power plants when power demand keeps fluctuating and due to the integration of renewable energy sources with the existing power systems. This study considers heat rate variation with load factor in the design and targeting of an optimal off-grid power plant with generation flexibility. The effect of heat rate in power system is investigated in this study via the comparison between two case scenarios: (1) plant with constant heat rate regardless of plant load factor and (2) plant with varying heat rate depending on load factor. The models formulated for each case scenario are solved mathematically using optimisation software, General Algebraic Modelling System (GAMS). The models will decide which load factor to be operated at each hour (the flexible generation profile) and the corresponding heat rate value that will result in optimal plant configuration and operation. The result evaluating the plant performance in term of energy and operational efficiencies are slightly different between both case scenarios.

1. Introduction

The structural change in electrical power systems as a result of increased renewable energy penetration poses the need for flexible operation in power plants. Conventional thermal power plants fired by coal and natural gas are designed to operate at base load; however, they are now expected to shift into dynamic operation to balance the intermittent supply from the renewables as well as to cater the variability of electricity demand.

Numerous research works have been conducted to study on plant's operational flexibility. For example, Abadie (2015) demonstrated the importance of operational flexibility in power plants to cater price volatility. Decommissioning of the conventional unit into smaller and flexible units in combined heat and power plants was discussed by Streckiene et al. (2009). To improve the reliability of flexible low-carbon power systems, Pavic et al. (2016) introduced electric vehicle on the demand side while Haas et al. (2017) reviewed on Storage Expansion Planning (SEP). In the recent study by Mechleri et al. (2017), flexible operation is deployed in post-combustion carbon capture plants via process control strategies. Flexibility in plant operation is generally envisaged to enhance energy efficiency in power plants with minimised cost and reduced carbon emissions from the fuel combustion.

The optimal configuration planning and targeting for power plants that have flexible characteristic is not an easy task. In this study, a mathematical model is developed for an off-grid thermal power plant (biomass is chosen as the fuel source) with generation flexibility in hourly basis. This study focuses on the effect of heat rate in accordance with the hourly load factor. The relationship of heat rate (which determines the energy consumption) and the load factor (resulting from the generation profile) has not been considered in power plant's operational studies before. With the objective to increase overall plant operational efficiency, two case scenarios (with and without heat rate change) are modelled using General Algebraic Modelling System (GAMS). The analysis reveals the optimal capacities of power generator and energy storage whereas the performance in term of energy consumption and operational efficiency are evaluated.

2. Heat rate and load factor

The heat rate of a thermal power plant is influenced by the plant load factor. Heat rate is a measure of energy conversion efficiency, defined as how much fuel energy (in kJ) must be expended to obtain a unit of useful work (in kWh) (usually in the form of electricity and/or steam delivered to the end consumers) (Nowling, 2015). In the context of the power plant, load factor is a measure of average capacity utilisation. It is the actual amount of kWh produced on a system in a designated period of time, as opposed to the maximum kWh that could be produced (Dakota Electric, 2018).

Figure 1a indicates how a power plant's heat rate changes with respect to its operating load (load factor in percentage). Within the allowable operational range of a typical thermal power plant (30 – 100 %), a fully loaded operation results in high operational efficiency (no heat rate increase at 100 % operating load) compared to a partially loaded operation.

3. Methodology and case study

Figure 1b shows the power plant configuration of an off-grid direct-fired combustion system embedded with energy storage in this analysis. The power generator consists of a Biomass-fired Bubbling Fluidised Bed Boiler. Biomass is burnt directly in the boiler to produce high pressure steam which drives the turbine generator to generate electricity. Energy storage system is installed in order to reduce the requirement of large generator capacity (IEA, 2012) while smoothening the energy flows from supply to demand during the power peak or low-peak periods (Lee et al., 2015). The inverter is incorporated as to convert the different types of electric current from the source to storage (AC to DC) or from storage to demand (DC to AC).

A few assumptions on the power plant operation are:

(a) All the biomass fuel energy is converted in the form of electricity.

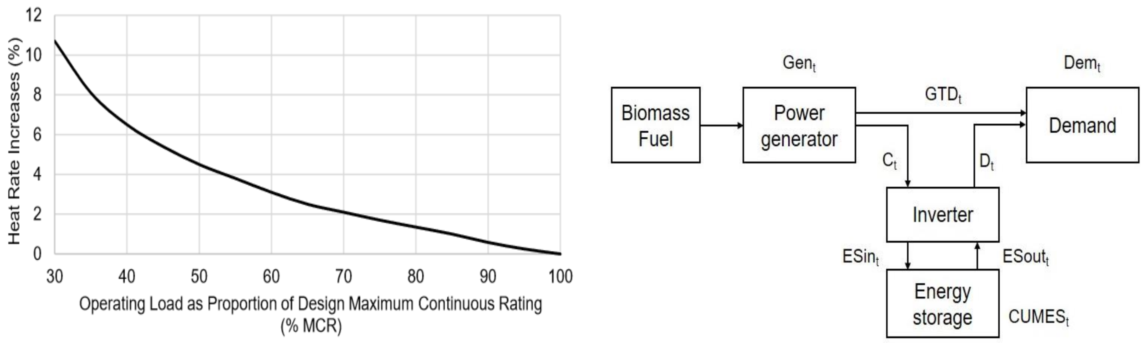
(b) Generated power (indicated as Gen_t) from the power generator is first delivered to meet the demand (indicated as GTD_t) before considered for storage.

(c) When the generated power is more than the demand, net surplus energy, C_t is charged into the energy storage for later use. When the generated power is less than the demand, the system has a net energy deficit, D_t which this amount of energy is discharged from the energy storage.

(d) The plant operates in a continuous pattern with 24 h as the period of analysis.

(e) Initial cumulated energy content in the storage, $CUMES_{t=1}$ has to be the same as the final cumulated content, $CUMES_{t=24}$ to prevent energy accumulation in the storage system.

(f) No supply limit for the biomass fuel used.



(a) (b)

Figure 1: (a) Changes in power generator's heat rate with its operating load (IEA, 2010). (b) Off-grid power plant configuration used in this analysis

General Algebraic Modelling System (GAMS 24.4.1) is used to formulate and perform optimisation on the power system explained above. The index t represents the instantaneous time of analysis used in the model.

3.1 Data of analysis

In this study, the biomass power plant is designed to supply energy to a residential community in tropical region. Taking the demand profile as shown in Figure 2, the total daily energy required is 84.5 MWh. Other data inputs in the model are tabulated in Table 1.

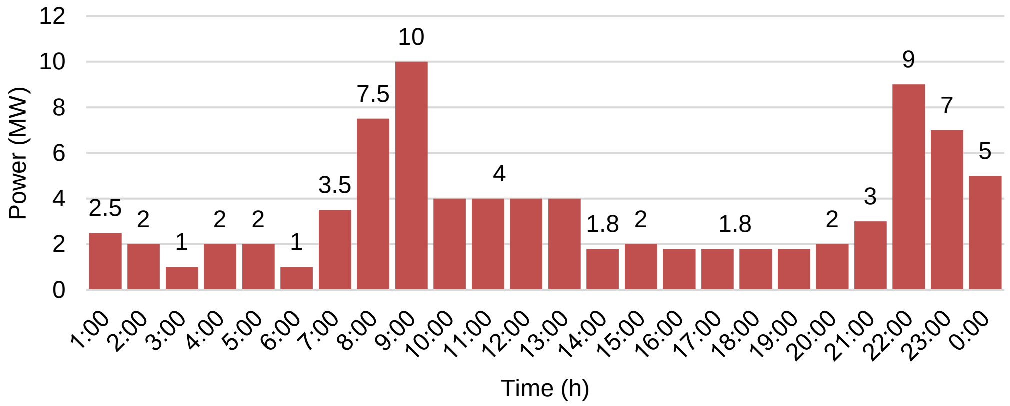


Figure 2: Power demand profile (Dem_t) in this analysis (Ho et al, 2015)

Table 1: Data input for power system model in this analysis (Ho et al., 2015)

Parameter	Value (unit)
Energy storage charging/discharging efficiency, ES_{eff}	0.883
Inverter efficiency, INV_{eff}	0.90
Heat rate of power generator at full-load, HR_o	14,240 MJ /MWh

3.2 Case scenario

Two case scenarios are designated to study and compare the effect of heat rate change factor to the power plant performance and the capacity targeting of generator and energy storage system. The scenarios to be optimised by the model are described as follow.
Scenario 1: Flexible plant generation with constant heat rate regardless of load factor
Scenario 2: Flexible plant generation with varying heat rates in correspond to load factor
Heat rate increment in relation to plant's load factor from Figure 1a is transformed into discrete segments shown in Table 2. These data are input into the model for scenario 2 and the index s is used in addition to the t index. New heat rate after increment, HR_s is calculated using Eq(1).

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

Table 2: Segmental data extracted from Figure 1a to be input into the power system model for scenario 2

Range, s	Load Factor (%)		Heat rate increase, i (fraction)
	Lower Load Factor, LLF_s	Higher Load Factor, HLF_s	
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

3.3 Mathematical formulations

3.3.1 Objective function

The objective of the model is to maximise the overall plant operational efficiency, OP_{eff}, as described in Eq(2).

$$OP_{eff} = \frac{\sum_t Dem_t}{\sum_t Gen_t} \times 100\ \% \tag{2}$$

3.3.2 Capacity constraint

Generally, the output of a system or a content within a system must not exceed its installed capacity. In this study, this rule is applied to the power generator and the energy storage system. The hourly generation, Gen_t of the power generator must be greater than or equal to the minimum generation limit and less than or equal to the maximum capacity, CAPG. In Eq(3), the factor of 0.3 is multiplied to the CAPG to set the plant's turndown at 30 % (IEA, 2012).

Eq(3) applies only for scenario 1 but more complex equations, Eq(4) and (5), are used for scenario 2 with another index, index s, included. Eq(4) and (5) are the generation limits given to the power generator. Eq(4) gives the upper generation limit subject to the upper load factor, ULF_s of the plant while Eq(5) gives the lower generation limit subjected to the lower load factor, LLF_s. The term $x_{t,s}$ is a binary variable used in the model to choose only one range or optimal load factor that the plant should operate in order to achieve the objective function. The sum of all $x_{t,s}$ must be equal to 1, as depicted in Eq(6).

$$0.3 \times CAPG \leq Gen_t \leq CAPG \qquad \forall\, t \tag{3}$$

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

$$100 \times Gen_{t,s} \geq CAPG \times LLF_s \times x_{t,s} \qquad \forall\, t,s \tag{5}$$

$$\sum_s x_{t,s} = 1 \qquad \forall\, t \tag{6}$$

Eq(7) to (10) are constraints applied to the energy storage system. First, the cumulated energy content in the storage at every hour, $CUMES_t$ must not exceed its maximum energy-related capacity, CAPESE as described in Eq(7). While for Eq(8) and (9), the power-related capacity of the storage system, CAPESP is determined where the net energy input into energy storage (after conversion and charging losses), $ESin_t$ and the energy output from energy storage (before conversion and discharging losses), $ESout_t$ has to also not exceed CAPESP. To ensure no energy accumulation in the energy storage, Eq(10) 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.

$$CUMES_t \leq CAPESE \qquad \forall\, t \tag{7}$$

$$ESin_t \leq CAPESP \qquad \forall\, t \tag{8}$$

$$ESout_t \leq CAPESP \qquad \forall\, t \tag{9}$$

$$CUMES_{t=1} = CUMES_{t=24} \tag{10}$$

3.3.3 Energy balance

In this section, the energy balance occurring at the generator, the demand and the storage are described. For the generator, the total generated power, Gen_t supplies to the demand, GTD_t at every time t. Charging power, C_t only exists when the generated power is more than the demand power. The total biomass energy consumed by the system, TEC, is accounted for the summation of the product of Gen_t and heat rate. Eq(11) and Eq(12) are dedicated for scenario 1 with constant HR_o (100 % load factor) while Eq(13) and Eq(14) are for scenario 2 which incorporates varying heat rates, HR_s.

$$Gen_t = C_t + GTD_t \qquad \forall\, t \tag{11}$$

$$TEC = \sum_t (Gen_t \times HR_o) \tag{12}$$

$$\sum_s Gen_{t,s} = C_t + GTD_t \qquad \forall\, t \tag{13}$$

$$TEC = \sum_{t,s}(Gen_{t,s} \times HR_s) \quad (14)$$

On the demand side, the hourly demand, Dem_t is met by GTD_t. As assumed, 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. (after conversion and discharging losses). This is described in Eq(15).

$$Dem_t = GTD_t + D_t \qquad \forall\, t \quad (15)$$

From Eq(16), the energy storage operates such that the new energy content accumulated inside the storage at time t+1, $CUMES_{t+1}$, is resulted from the cumulated energy in the storage, $CUMES_t$, 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(17) and Eq(18).

$$CUMES_{t+1} = CUMES_t + ESin_t - ESout_t \qquad \forall\, t \quad (16)$$

$$ESin_t = C_t \times INV_{eff} \times ES_{eff} \qquad \forall\, t \quad (17)$$

$$ESout_t = D_t \,/ \left(INV_{eff} \times ES_{eff}\right) \qquad \forall\, t \quad (18)$$

4. Results and discussion

With the objective to maximise overall plant operational efficiency, the optimal solutions for two mathematical models (each for one case scenario) coded in GAMS are found. The detail of the models is shown in Table 3 whereas the optimisation results are displayed in Table 4 and Figure 3.

Table 3: Details of mathematical models solved using GAMS

Detail	Scenario 1	Scenario 2
Type of model	Linear programming (LP)	Mixed integer non-linear programming (MINLP)
Type of solver	CPLEX 12.6.1.0	DICOPT
Iteration count	61	1275
Execution time	0.031 s	0.016 s

Table 4: Comparison of optimised variables for scenario 1 and 2 from GAMS

Scenario	Generator capacity, CAPG (MW)	Energy storage capacity, CAPESE (MWh)	Energy storage power capacity, CAPESP (MW)	Total biomass energy consumption, TEC (MJ/d)	Plant operational efficiency, OP_{eff} (%)
1	7.55	3.08	3.08	1.2357 x10^6	97.37
2	7.27	5.37	3.43	1.3174 x10^6	95.69

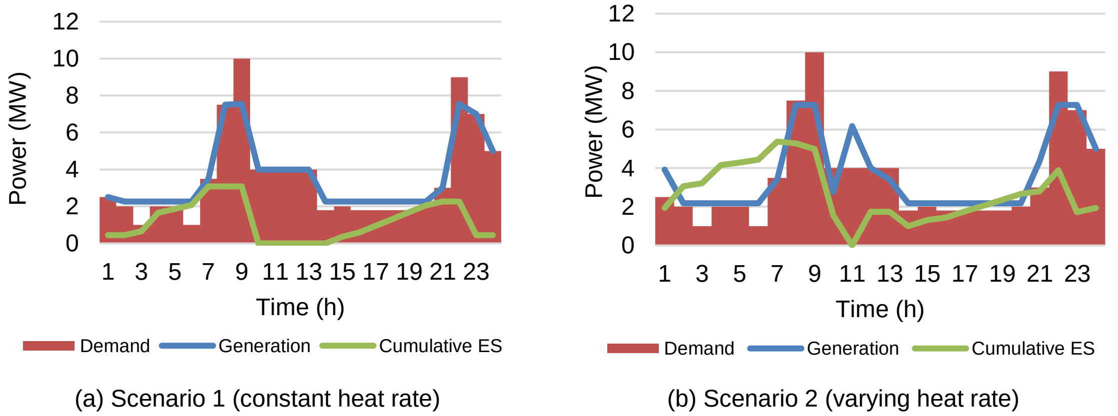


Figure 3: Comparison of generation and energy storage profiles from GAMS result for (a) scenario 1 and (b) scenario 2

Two different models are formulated to solve each case scenario. The relationship between two variables, heat rate and load factor as well as the use of a binary variable, x for the model, cause non-linearity as depicted in Eq(4), Eq(5) and Eq(14) and a MINLP model is used to solve scenario 2.
Table 4 shows the result of optimal plant configurations and their performance in term of energy consumption and operational efficiency. If the plant considers varying heat rate factor (scenario 2), it requires 7.27 MW power generator which offers 95.69 % operational efficiency and consumes about 1.32 x10^6 MJ biomass energy per day. If the plant operates with a constant heat rate (scenario 1), a larger plant generator and smaller energy storage capacities are required. Operational efficiency as high as 97.37 % and 6.2 % less biomass energy utilisation can be achieved. From Figure 3, the optimal generation profiles determined by GAMS in both cases scenarios are slightly different. For instance, in Figure 3b, more power is generated at the beginning of the day (at t=1) resultingg in a higher energy content accumulated in the energy storage. Throughout the analysis period, there is only one Pinch point (at t=11) at the cumulative energy storage curve as shown in Figure 3b. The frequency which the power plant is in the state of high load factor is higher in scenario 2.
Distinctive results between the two case scenarios indicate that heat rate factor imposes a significant constraint on the flexible operation of power plants especially in the design and targeting of an optimal power plant. The modelling for scenario 2 is more realistic and practical. In reality, power plant operations depend on many other external factors such as ramp rate, cycling capability, etc. (IEA, 2012).

5. Conclusions

The effect of heat rate factor in power system design and operation is investigated. Two illustrative case scenarios are designated and solved mathematically in GAMS models. Their optimum result on plant performance are slightly different from each other. When heat rate is considered, the model portrays a more realistic scenario, representing the actual dynamic operation in typical combustion power plants. Parameters like system economics and environmental impact should be assessed in future studies to ensure power system's feasibility and profitability.

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