P-ISSN 2586-9000
E-ISSN 2586-9027
Homepage : https://tci-thaijo.org/index.php/SciTechAsia
Science & Technology Asia
Vol. 24 No.3 July - September 2019
Page: [39-46]
Original research article

Optimal Feeding Trajectory for an Industrial Sugar Mill Cogeneration Plant

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Received 25 October 2018; Received in revised form 18 May 2019
Accepted 6 June 2019; Available online 9 August 2019

ABSTRACT

Using an optimum dynamic scheduling plan, the formulated problem aimed to maximise daily profitability from an existing 12.5 MW bagasse-based cogeneration plant with a steam capacity of 125 tonne/h used for sugar refining. The optimal bagasse feed rate yielded a maximum daily profit of 838.49 USD (base case), about 5.14% higher than the conservative constant feeding bagasse into the existing plant. A sensitivity analysis of daily profit was constructed by perturbating the fuel low heating value (LHV), electricity selling rate of electric utility (p) and cost of electricity generation (c) . The maximum daily profit was insensitive to increases in LHV until this LHV was 11% lower than its base case value, which resulted in a decrease in maximum daily profit by 11%. Excessive moisture in the bagasse and the cost of generating electricity (c) caused lower profits, whereas the price of electricity (p) increased profits.

Keywords: Cogeneration plant; Linear programming; Optimum scheduling; Sugar refining process; Sugar mill plant

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1. Introduction

Thailand is one of the largest sugar producers in Southeast Asia; there are 52 existing sugar manufacturing plants and 12 more new plants in the approval process. Worldwide, sugar output is expected to decline by 4.3% in the 2015/2016 season due to rainfall variation [1]. Farmers' ability to adapt to climate change is essential to reduce its potential impacts on food security. For instance, because it is more resistant to droughts and floods, switching plantations to sugarcane from rice and cassava has been encouraged by the Thai government. A major cause of rapid climate change is the increased use of fossil fuels, which in turn has stimulated the development of renewable resources. Hence, global energy policies have moved towards sharable, renewable and green energy use to reduce consumption of fossil fuel that causes greenhouse gas emissions. Eight percent of Thailand's 2014 energy matrix consisted of renewable sources, i.e. hydroelectricity, municipal solid waste, biomass, biogas, wind and solar power [2]. Over the next 10 years, renewable energy, as a substitute for fossil fuels, is expected to comprise 25% of total energy consumption in Thailand. To achieve this target, renewable energy generation must increase from 8% to 20% of total power requirements and by at least 50% in crop planting areas. With anticipated waste-based power capacity rising ten-fold, from 500 to 5000 MW [2], increased crop output will provide feedstock supply. Therefore, expected domestic cane output of 180 million tonnes in 2026 will yield 20 million tonnes of sugar, a 60% increase in cane-cultivating areas [1]. This, in turn, will increase agricultural crop residues that contain suitable heating value for energy conversion.

Although sugar historically was the sugar industry's single product, recently its by-products have been used as feedstocks for energy conversion, i.e. stillage used as biogas substrate and bagasse used as fuel for power generation [3]. Sugar mills produce their own energy from bagasse, a fibrous by-product of the juice extraction process that contains about 25-30% of weight of the cane [4, 5]. Cogeneration or combined generation of power and steam in the sugar industry simultaneously generates electricity and superheated steam by burning 40-50% moisture content of wet basis bagasse used as fuel [6, 7]. Steam generation by the sugar industry provides surplus power to the national grid [8, 9] which has motivated private power producers in terms of feed-in tariff policy by the Thai government [10]. To supply steam and electrical energy, boilers are equipped with either backpressure or condensing-extraction turbines [11, 12]. Backpressure steam turbine cogeneration plants (BPST) have been widely implemented in cogeneration plants of the sugar industry [13]. BPST has the lowest initial investment cost and produces high enthalpy steam by boiler expansion until the required pressure is reached. This saves surplus bagasse. However, fluctuation of surplus electrical energy is a drawback of BPST. The surplus is caused by the cane supply and steam requirement of the process [6], which requires saturated steam at 2.5 bar and 120°C and release superheated exhaust steam at 210°C to avoid heat losses. Condensing and extraction steam turbines, the most recent type of cogeneration plant in the sugar industry, combust all possible bagasse for steam generation. After the generated steam satisfies the minimum process steam demand of the plant, the remaining is expanded and condensed to generate surplus electrical energy [13]. Boilers and turbines in cogeneration systems are operated in pressures ranging from 21 to 110 bar, corresponding to a temperature range of 300°C–540°C [14].

In 2015, the total capacity of bagasse- and sugarcane leave-based cogeneration systems in domestic sugar plants was about 1400 MW [15]. Obviously, bagasse can replace fossil fuels for power generation.

Regarding its environmental benefits, release of greenhouse gases can be reduced to 0.166 million tonnes of CO_2, for an annual cogeneration capacity of more than 150 million kWh [16]. The rapidly changing markets for sugar and energy require more efficient use of bagasse for power generation, which then can be sold to the national grid.

In optimising schedules of the industrial cogeneration plants, a linear programming (LP) based model is developed to maximise the total revenue with regard to the constraints of mass conservation, heat storage limitation, and shiftable load requirements. The model does not explicitly consider thermodynamics of the process while utility energy spot prices are assumed for facilitating the calculation of the power rate [17]. The research group of Moslehi [18] considers the thermodynamic of the process explicitly and divides the cogeneration system into two parts: electric and steam. The two parts of the system are solved individually with an LP algorithm to obtain the optimal result of the combined problem. Venkatesh and Chankong [19] developed a mixed integer model including enthalpy calculations and the time-of-use (TOU) rate structure to achieve optimal savings of a cogeneration plant due to various operating conditions of steam or flue gas regeneration. Hence, the objective of this study is to maximise the profit of production of cogenerated power from an optimal hourly feeding profile of excess bagasse. TOU price period (off-peak and on-peak) is included in the utility charge calculation to extend the system complexity. The effects of total heating and electricity demand and the cost of electricity generation on profitability will be discussed.

2. Problem Formulation

We studied an existing 12.5 MW domestic cogeneration plant with a constant bagasse supply rate of 60 tonne/h (as shown in Fig. 1). This plant, which operates 30 days per month, maximises daily profit by scheduling bagasse feedings hourly. Feedstock is available all year because of higher cane yields.

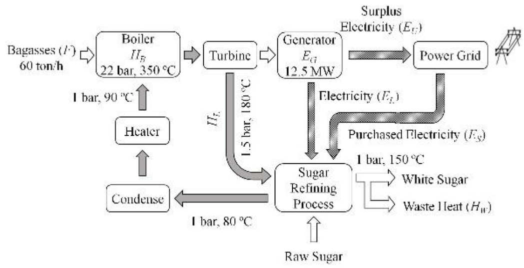

Fig. 1. Operating Conditions at an Existing 12.5 MW Cogeneration Plant.

The objective of this study is to maximise the daily profit of bagasse-based cogeneration plant, calculated as the difference between revenue from selling electricity and the cost of its generation.

There are three decision variables: electricity delivered from a cogeneration plant to an electric utility (E_U^t), electricity delivered from an electric utility to load (E_S^t) and electricity delivered from a cogeneration plant to load (E_L^t), as shown in Fig. 1.

Assumptions:

(i) Thermal properties of bagasse containing 50% moisture did not change significantly throughout the year.

(ii) The quantity of bagasse was sufficient to supply the cogeneration plant all year.

(iii) Waste heat accounted for 20% of heat demand of load.

(iv) Maximum daily profit was achieved by selling excess electricity to the national grid (excluding refined sugar sales).

The profit maximisation problem was defined using the above assumptions and a description of the cogeneration plant.

Objective function:

Maximisation of daily profits

$$\max_{E_U^t, E_S^t, E_L^t} \sum_t p^t E_U^t - r^t E_S^t - c^t (E_L^t + E_U^t) \quad (1)$$

Set of constraints:

Electricity generation for electric load (kWh):

$$E_L^t \le E_D^t \quad (2)$$

Electricity bought from an electric utility (kWh):

$$E_S^t \le E_D^t \quad (3)$$

Electric demand balance (kWh):

$$E_L^t + E_S^t = E_D^t \quad (4)$$

Adjustable electric load (kWh):

$$E_D^t \le E_D^{\max} \quad (5)$$

$$E_D^t \ge E_D^{\min} \quad (6)$$

$$\sum_t E_D^t = T_E \quad (7)$$

Thermal demand balance (MJ):

$$H_L^t = H_D^t \quad (8)$$

Adjustable thermal load (MJ):

$$H_D^t \le H_D^{\max} \quad (9)$$

$$H_D^t \ge H_D^{\min} \quad (10)$$

$$\sum_t H_D^t = T_H \quad (11)$$

Electric and heat generation limit (MJ):

$$3.6\left(E_L^t + E_U^t\right) + H_L^t + H_W^t \le H_B^{\max} \quad (12)$$

$$3.6\left(E_L^t + E_U^t\right) + H_L^t + H_W^t \ge H_B^{\min} \quad (13)$$

Energy balance (MJ):

$$3.6\left(\frac{E_L^t + E_U^t}{\alpha}\right) + \left(\frac{H_L^t + H_W^t}{\beta}\right) \le F^t \cdot \mathrm{LHV} \quad (14)$$

Electric generation limits (kWh):

$$E_L^t + E_U^t \le E_G^{\max} \quad (15)$$

$$E_L^t + E_U^t \ge E_G^{\min} \quad (16)$$

Waste heat model (MJ):

$$H_W^t = 0.2 \cdot H_D^t \quad (17)$$

Fuel supply rate availability (tonne/h):

$$F^t \le F^{\max} \quad (18)$$

2.1 Constraint detail

Each constraint comment is provided as follows:

Eq.(2) represents that electric generation for electric load cannot exceed the electric demand during any time interval. Eq.(3) expresses the purchase of electricity to the load for meeting electric demand. The total demand must be equal to the sum of electric generation and purchase during each time interval as shown in Eq.(4). Eqs. (5)-(7) represent that the levels of shiftable load must be within its minimum and maximum over a time interval and the entire electric demand matches the given value for the overall optimization period. Eq.(8) represents that the thermal demand matches the given thermal load levels during each time interval. Eqs.(9)-(11) represent that the shiftable thermal load levels must be constrained by its minimum and maximum over a time interval and the total heat demand matches the given value for the entire optimization period. Eqs. (12)-(13) represent that the thermal cogeneration produced must be between the corresponding minimum and maximum. Eq.(14) expresses that the output of generated energy cannot exceed energy derived from fuel input. Eqs.(15)-(16) represent that the electric cogeneration output must be within the minimum and maximum over a time interval. Eq.(17) represents that the waste heat is fixed at 20% of heat demand of load. Eq.(18) represents that the bagasse supply rate is limited to its availability.

2.2 Data Collection

Input values used in this study were comprised of average, monthly data collected from an existing 12.5 MW bagasse-based cogeneration plant in May. The parametric values for a base case scenario can be seen in the nomenclature.

3. Optimisation Results and Discussion

After the computing assumptions were defined and the optimisation model was formulated, all parameter values were collected from an existing BPST in Northeast Thailand. The formulated cogeneration plant scheduling model was solved using CPLEX solver in GAMS which was a continuous LP optimisation problem involving a linear objective function subject to a set of linear constraints. The total CPU time required for the solution process was less than 5 seconds.

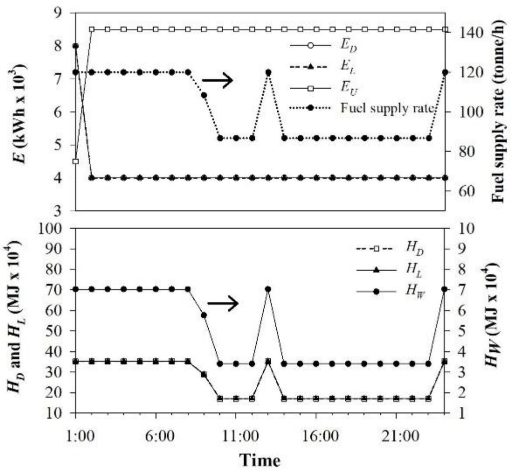

Fig. 2. Optimal Result of the Base Case Scenario.

The optimal base case result in Fig. 2 reduced the bagasse hourly supply rate by about 28%, from 120 tonne/h to 86.75 tonne/h, during peak hours. The later peak of bagasse feed rate occurred at 13:00 to keep up its demand during the start-up period after the lunch break. The 8500 kWh of electricity delivered to the electric utility from the plant was about 52% lower than during off-peak hours. Electricity from the national grid was not required during the operation of the cogeneration plant, whose maximum daily profit was 838.49 USD.

Actual daily profits achieved by a constant bagasse feeding schedule of 60 tonne/h during the same month rose by 5.14%, from 797.49 to 838.49 USD.

3.1 Sensitivity Analysis

The sensitivity analysis investigated how various model variables affected the estimation of daily profit. The direct economic parameters such as the price of electricity for an electric utility (*p*), the cost of electricity generation (*c*), and the indirect economic parameter the low heating value of bagasse (LHV) were selected to study their uncertainty in the estimated daily profit. The calorific value of 8,022 MJ/tonne bagasse is most commonly used as a boiler fuel [20] while that of 50% wet mill bagasse moisture is reduced to 7,360 MJ/tonne. When moisture content in bagasse was removed by a dryer before introducing to a boiler in cogeneration plant, the feed rate of bagasse was saved to 2.23 tonne/h resulting in improved efficiency of the steam generation unit [21]. In other words, efficient combustion of bagasse depends on its moisture content. Compared to the parametric values of the base case, the LHV, *p* and *c* varied between +10% and −17%, −1% and +3% and −1% and +3%, respectively, as shown in Fig. 3.

An increase in the LHV of bagasse did not affect maximum daily profit. When LHV was reduced, 11% of the base case value caused maximum daily profit to decrease by 11%. A 17% LHV decrease caused maximum daily profit to drop by 82%. The cost of electricity purchased by an electric utility (*p*) depends on numerous factors such as electricity pricing policies, the global electricity market pricing, price and demand forecasting, transmission capacity, and the CO_2 emission allowances price [22].

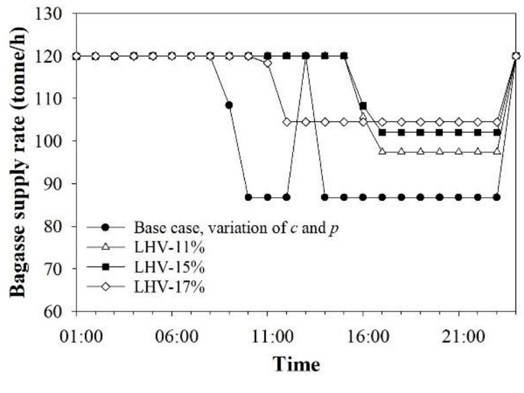

Fig. 3. Bagasse Feeding Trajectory for Each Scenario.

A 1% and 3% decrease in *p* caused a maximum daily profit decline of about 27% and 80%, respectively. The cost of electrical energy (*c*) is significantly influenced by feedstock costs. Since the sugarcane price is estimated by cane weight and sucrose content in the juice, the price of bagasse depends on the harvest period [23]. The same 1% and 3% cost reduction (*c*) increased maximum daily profit by about 21% and 72%, and a 1% and 3% increase of *c* decreased maximum daily profit by about 26% and 77%. Amongst these three parameters, *p* had the greatest impact on the maximum daily profit. However, the purchase of electricity from electric utilities depended on government policies. Similarly, because of unexpected growth in the renewable energy market, the cost of biomass-based fuel was unpredictable. Viewing the operation of a cogeneration plant from a practical perspective, LHV had the most direct effect on the maximum daily profit. Therefore, bagasse containing excessive moisture, with an LHV less than 6550 MJ/tonne, can lower maximum daily profits.

In the early period of calculation, the maximum daily profit was achieved by supplying cogeneration plants with the maximum value of fuel feed rate due to numerical adjustment approaching the target.

During peak hours, from 10 AM to 11 PM, fuel supply rate profiles for the base case and for variations of scenarios *p* and *c* decreased 27.71%, from 120 to 86.75 tonne/h, as shown in Fig. 4. However, the fuel supply rate profile of a varied LHV scenario, from 4 PM to 11 PM, moved down 15 to 19% of the maximum fuel supply rate. This result showed that the required fuel hourly supply rate was proportional to the heat demand of load (H_D).

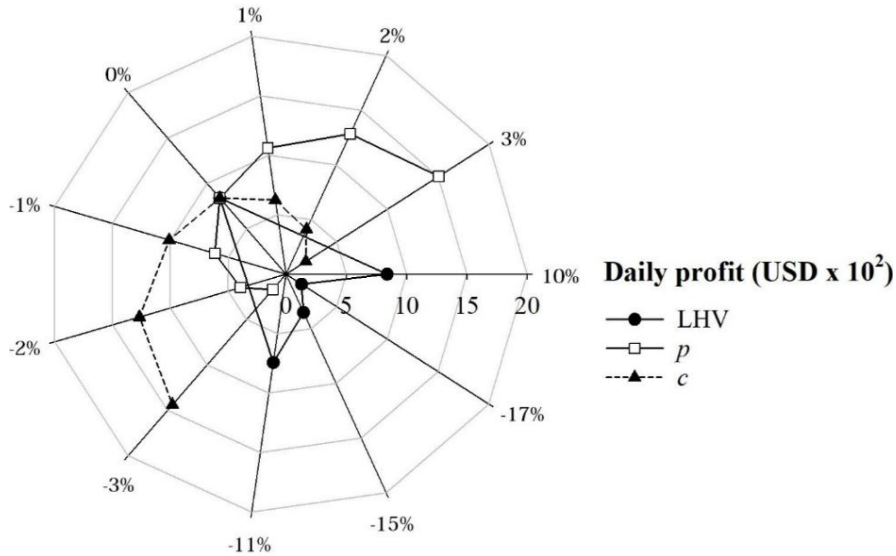

Fig. 4. Sensitivity Analysis of Maximum Daily Profit.

4. Conclusions

Daily profits from selling electricity using excess bagasse can be improved by 5.14% with optimal bagasse hourly feeding trajectory in a limited-capacity cogeneration plant. Such a plant can be more profitable by maintaining a suitable bagasse moisture content and by saving electric demand for the sugar refining process.

Acknowledgement

This work was financially supported by Thammasat University, Thailand (grant number TP10/1/2558).

Nomenclature

Index

t time index (h) of periods

Variables

E_L electric generation delivered from cogeneration to load (kWh)

E_S electric generation delivered from electric utility to load (kWh)

E_U electric generation delivered from cogeneration to electric utility (kWh)

Parameters

c cost of electricity generation (USD/kWh) {0.07}

$E_D^{\min}$ minimum electric demand of load (kWh) {4,000}

$E_D^{\max}$ maximum electric demand of load (kWh) {14,000}

$E_G^{\min}$ minimum electric generation of cogeneration (kWh) {5,000}

$E_G^{\max}$ maximum electric generation of cogeneration (kWh) {125,000}

$F^{\min}$ minimum bagasse supply rate (tonne/h) {40}

$F^{\max}$ maximum bagasse supply rate (tonne/h) {2,780}

$H_B^{\min}$ minimum heat generation of boiler (MJ) {249,130}

$H_B^{\max}$ maximum heat generation of boiler (MJ) {830,000}

$H_D^{\min}$ minimum heat demand of load (MJ) {120,000}

$H_D^{\max}$ maximum heat demand of load (MJ) {435,000}

H_L heat generation delivered from cogeneration to load (MJ)

H_W waste heat from process (MJ)

LHV lower heating value of 50% bagasse moisture (MJ/tonne) {7,360}

T_E total electric demand (kWh) {100,000}

T_H total heat demand (MJ) {6,016,000}

Constants

p buying rate of electricity by an electric utility (USD/kWh) {0.131 (P^*) and 0.0876 (OP^*)}

r selling rate of electricity by an electric utility (USD/kWh) {0.143 (P^*) and 0.114 (OP^*)}
P* and OP* represent peak (09:00–22:00) and off-peak hours (22:00–09:00), respectively.

Greek symbols

α conversion factor from fuel supply to electricity (kWh/tonne) {0.11}

β conversion factor from fuel supply to heat (MJ/tonne) {0.89}

Appendix

Estimation of α value

$$\alpha = \frac{\text{Plant capacity}(\text{MW}) \times \text{Annual operating hour}(\text{h/y}) \times 3,600(\text{sec/h})}{\text{Bagasse suply rate}(\text{tonne/y}) \times \text{LHV}(\text{MJ/tonne})}$$
$$= \frac{(12.5\text{MW}) \times (8,500 \text{ h/y}) \times (3,600 \text{sec/h})}{(476,106 \text{ tonne/y}) \times (7,360 \text{ MJ/tonne})}$$
$$= 0.11$$

Estimation of β value

$$\beta = 1 - \alpha = 1 - 0.11 = 0.89$$

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