The Potential of Diesel Cycle and Gas Turbine Cogeneration in the Thai Industrial Manufacturing Sector

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ABSTRACT

This study assesses the potential of diesel and gas turbine cogeneration in the Thai Industrial Manufacturing Sector, numbering more than 27,000 factories in 1994.

The appropriate system for each industry has been analyzed technically and financially according to heat and electrical demand, operating hours of each industry, together with data on cogeneration costs and other economic parameters.

Over 500 different cases have been investigated with natural gas, heavy oil, and distilled oil being assumed as cogeneration fuels .

Two methods have been adopted to assess the potential industrial application of cogeneration: First, a nomogram was made from the incremental heat rate (IHR) and the generated electricity cost with different kinds of fuel, considering the internal rate of return (IRR) for each fuel, based on a minimum expectation of a 25% return. Using the stand alone system calculations were based on the thermal-matched method .

Secondly, mixed-integer linear programming was used, considering the thermal-match and electrical-match to find the maximum benefit. In this method there are auxiliary boilers to supply supplementary heat and reduce cost.

1. INTRODUCTION

The following industries were surveyed: chemicals; rubber production; car and motorcycle tyre production; gloves; machine belts; plastics production; chemical substance production; food processing; soft drinks; alcohol; wine; whisky; brandy; beer; animal feed; pellets; vegetable oil; cassava flour; food preservatives; milk production; noodles; pre-cooked noodles; food canning; petro-chemicals; paper; fiber making; spinning; dyeing and oil refining [8].

The heat and power cogeneration plant is one of the most significant technological elements in achieving energy conservation. A gas turbine cogeneration plant combines gas turbine generators and waste heat boilers. Whereas in diesel cycle cogeneration, diesel generators are used. The basic design efficiency lies in the cascade use of energy to optimize economy. An optimal plant configuration is determined by selecting the total number and scale of each type of equipment.

The trial and error method has been adopted based on the minimum heat and electrical power demand.

The objectives of this study are: to study the heat and electrical demand characteristics in the industrial manufacturing sector in Thailand; to construct a nomogram in order to facilitate the selection of the appropriate technology for each sector ; and finally to use a mixed-integer linear programming method to determine the optimal plant configuration, together with the optimal operational policy for each plant based on the annual cost method and to assess the potential of diesel and gas turbine cogeneration in all industrial manufacturing sectors.

2. DATA USED

Information from more than 500 companies has been obtained by a survey. The data include: electrical demand; heat demand; boiler capacity; operating hours; steam pressure; fuel consumption per month; electrical cost per month; maximum kW. The data was fed into an IBM compatible 486DX2-66 on a mixed-integer linear program with objective functions and constraints.

3. CALCULATION PROCEDURE

1. To Find the Appropriate Technology for an Industry.

The method for making a preliminary assessment considers the technical and economic performance of cogeneration. The assessment, which is based on a nomogram, indicates how to find the appropriate technology.

The nomogram was produced by relating IHR [1] and cogenerated electricity cost with different kinds of fuel, considering the IRR for each fuel, based on a minimum expectation of a 25% return.

The IHR equation is shown below:

$$Q_f = 1{,}000 \frac{F - (\frac{H}{\eta_b})}{P_e} \tag{1}$$

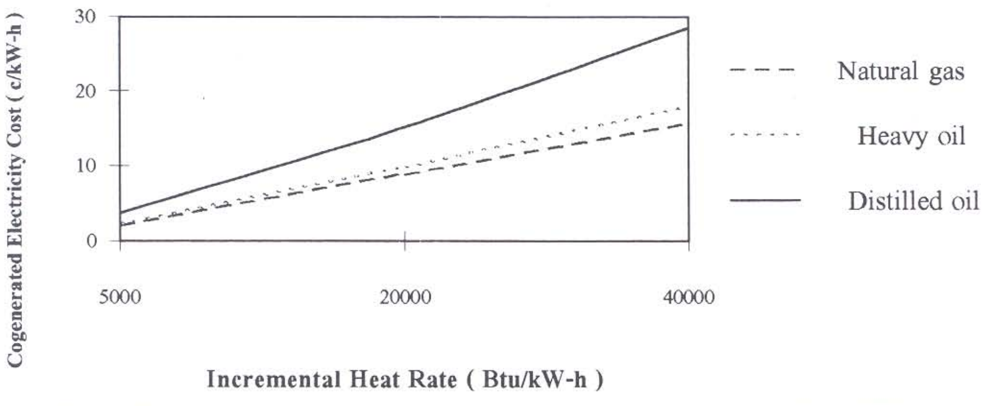

Fig 1. This nomogram shows the relation between Incremental Heat Rate (HR) and cogenerated electricity cost for different kinds of fuel.

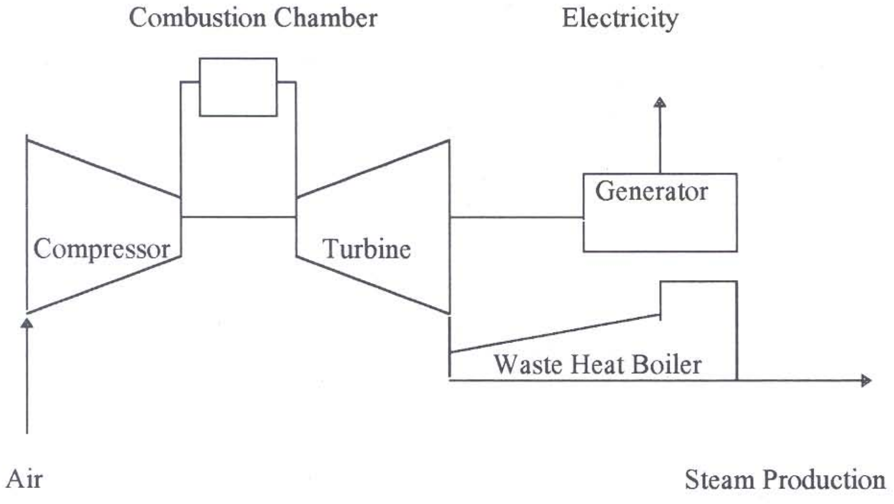

Fig. 2a. Gas turbine unit (Topping cycle) [6],

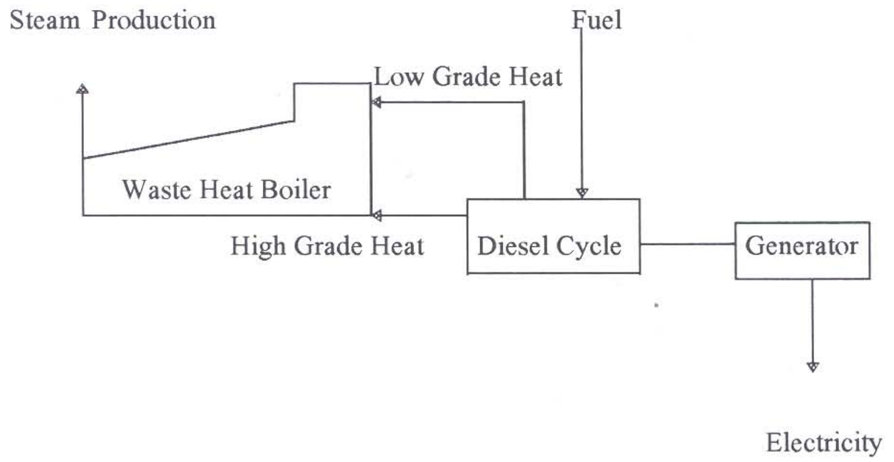

Fig. 2b. Diesel engine (Topping cycle) [3] .

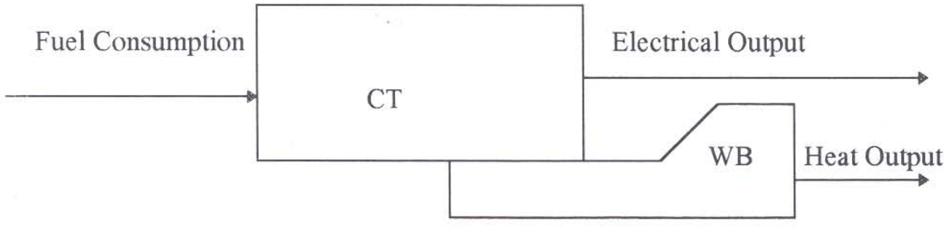

Fig. 2c. Equivalent system for a diesel cycle or gas turbine cogeneration unit .

2. Structure of the Plant .

Figs. 2a and 2b show the unit system of gas turbine and diesel cycle cogeneration (CT) with the waste heat boiler (WB). The size of the waste heat boiler in each case is determined according to the capacity of the gas turbine or diesel engine generator. Although the generating efficiency of this CT/WB unit is not high, exhaust heat recovery ensures sufficient thermal efficiency. Fig. 2c shows the equivalent system for both units.

Fig. 3 shows the structure of the CT/WB cogeneration plant studied. In the diagram AB means the auxiliary boilers, which are installed in the plant in order to supplement heat output from the waste heat boilers [4] .

The plan of the plant consists of 28 diesel cycle cogeneration systems which divide into four of each of the following: 2.18 MW, 5.24 MW, 7.86 MW, and 14 MW. The 32 gas turbine cogeneration systems [5] divides into four ofeach of the following: 2.21 MW, 7.5 MW, 10.8 MW, 21 MW, 34 MW, 74.3 MW, 144 MW and 198 MW, to cover the requirements of every industry.

There are 12 auxiliary boilers which divide into two of 1.38 MW, 1.71 MW, 2.84 MW, 5.4 MW, 9.95 MW and 18.5 MW. The equipment included in the fundamental structure is more than would be needed in any industry. However, the structure should provide enough equipment for computer software to freely select the optimal structure for each industrial group. The combination of boilers, gas turbine or diesel cycle cogeneration will be selected to obtain the best configuration for the power plant.

3. Performance Characteristics

There exist various types of CT/WB units with different scales developed for miscellaneous applications. The relation between fuel consumption, power and heat output can be approximated by the following linear equations [5] , as given in Eqs. 2-4 in Appendix 1.

4. Energy Equilibrium Equation

The energy and mass flow balance of the plant shown in Fig. 3 can be described as given in Eqs. 5-9 in Appendix 1 .

5. Optimal Solution

(a) Assumptions

The following assumptions are implied in the formulation of the optimal solution.

1. The Energy demand patterns of heat and power are known from the survey.
2. The power purchased from the national grid supplements the shortage of the generated power of the CT within the value of the maximum contract demand for the purchased power. However, it is assumed that if excess power is generated by the CT, it can be sold.
3. The long-term economics of the plant are evaluated by the annual cost method.
4. The useful life of a diesel cycle cogeneration system is 15 years and for a gas turbine cogeneration system 20 years.

(b) Methodology

In principle, the economics of alternative plants in which *N* units of CT and *L* units of AB are installed are compared, 0-1 integer variables are defined to on / off for each piece of equipment as given in Eqs. 10-16 in Appendix 1 .

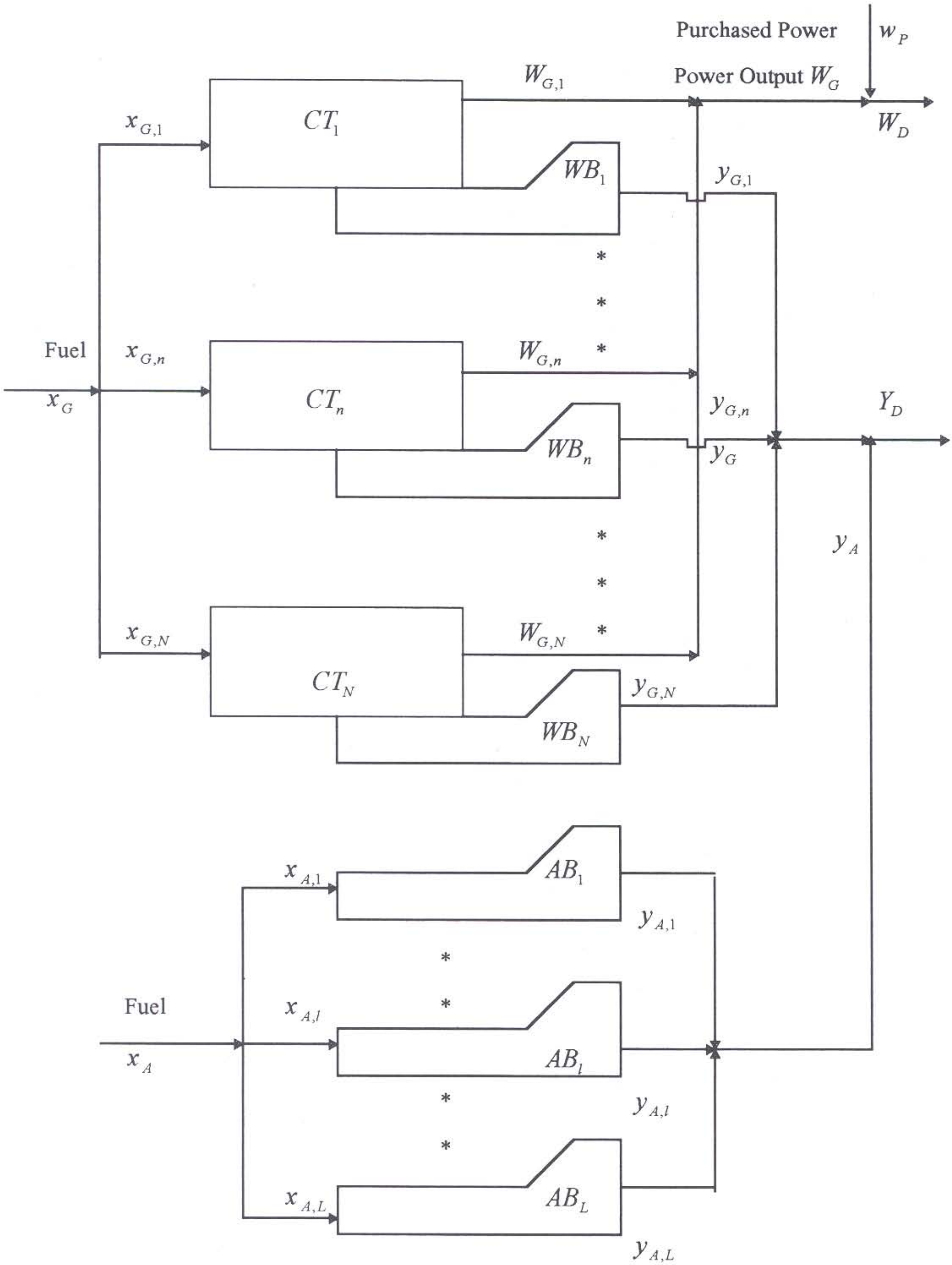

Fig. 3. Fundamental structure of a gas turbine or diesel cycle cogeneration plant.

(c) The Objective Function

The main objective of optimization is to choose the most suitable equipment to be used in the power plant in order to obtain the maximum benefit for each industry.

The maximum benefit is defined as the overall income minus the total expenditure which can be shown as given in Eqs. 17-20 in Appendix.

(d) The Constraints

By considering the energy and mass balance of the fundamental power plants (Fig. 3), the following relationships can be obtained as given in Eqs. 21-26 in Appendix 1.

1. Electricity which is produced by cogeneration must be equal to or greater than the power demand of the plant.
2. The heat which is produced by cogeneration and the auxiliary boilers must be sufficient in each industrial application.
3. Cogeneration should run within its lower and upper limits.
4. The boiler should run within its lower and upper limits.
5. Cogeneration should be involved in the considered alternatives before switching it on or off.
6. The auxiliary boiler should be involved in the considered alternatives before switching it on or off.

4. ILLUSTRATIVE EXAMPLE

For the purpose of illustrating the methodology used to obtain the optimal alternative, an illustrative example can be based on the data of a rubber production factory: For a car tyre production factory in which the productivity is more than 1 million units/year, the following are the main procedures and results obtained.

1. Input Data

Input data set for the numerical study are as follows:

(a) Power and heat demand from data received (Table 1).

Table 1. Power and heat demand used in car tyre production (with an output of more than 1,000,000 tyres/year).

Productivity	Oph (h/yr.)	Wp (MW)	Wd (MW)	Yd (MW)
>/= 1,000,000	84,000	4.85	4.07	11.01

(b) Fuel and purchased power: Natural gas, heavy oil, and diesel oil are used as fuels for the CT/WB and AB. The unit price of natural gas is US$ 3.037 /M Btu; for heavy oil US$ 4.14 / M Btu; and for diesel oil US$ 8.99 / M Btu [7]. The unit cost of purchased power is US$ 0.056 /kW-h, and the unit cost necessary for maximum contract demand of the purchased power is US$3.788/kW.

(c) Data related to economics (Table 2).

Table 2. Data related to economics [2][9].

	Boiler	Diesel Cogeneration	Gas turbine Cogeneration
Useful life (yrs)	15	15	20
Remainder rate (p)	0.1	0.2	0.25
Annual maintenance cost ratio	0.1	0.16	0.14
Annual interest rate	0.12	0.12	0.12

2. Numerical Results

Given the assumptions (Section 5) , the result of the optimization shows that the most suitable configuration is a Diesel cycle cogeneration system using natural gas as a fuel . This can produce a net benefit of US$ 1.2 million per year from an investment of US$ 7.80 million , with an IRR of 27.57 %. The break even point is after three and a half years .The summary of the equipment selected to be used in the optimal configuration is presented in Fig. 4 .

5. DISCUSSION

The analysis of the over 500 factories considered provided the following information: energy consumption; fuel price; steam consumption; direct heat usage and for each process that uses direct heat-load factor and recorded fuel data. From the data gathered a nomogram can be constructed. It shows the relation between the IHR and the cogenerated electricity cost with different kinds of fuel. The information from the nomogram indicates that the appropriate technology for each industry depends on IHR.

From the received information detailing planning problems to determine the optimal configuration of a cogeneration plant, those which are constructed by combining gas turbine and diesel cycle generators, waste heat boilers and an auxiliary boiler were studied.

The planning problem has resulted in a mixed-integer linear programming solution, and branch and bound algorithms have been adopted to find the optimal solution.

The objectives of this study were: to study the heat and electrical demand in Thai industry; to study and use a nomogram to select the appropriate technology for the each manufacturing sector: to use a mixed-integer linear programming method to determine the optimal plant configuration together with the optimal operational policy of each plant based on the annual cost method and to assess the potential of diesel and gas turbine cogeneration in the Thai industrial manufacturing sector.

6. CONCLUSION

The relation between the IHR and the cogenerated electricity price for three kinds of fuel: natural gas, heavy oil, distilled oil (Eq. 1), can show how to select a cogeneration technology with an IRR of over 25%.

The diesel cycle cogeneration system using natural gas generates 13 453>IHR>10 086 Btu / kWh

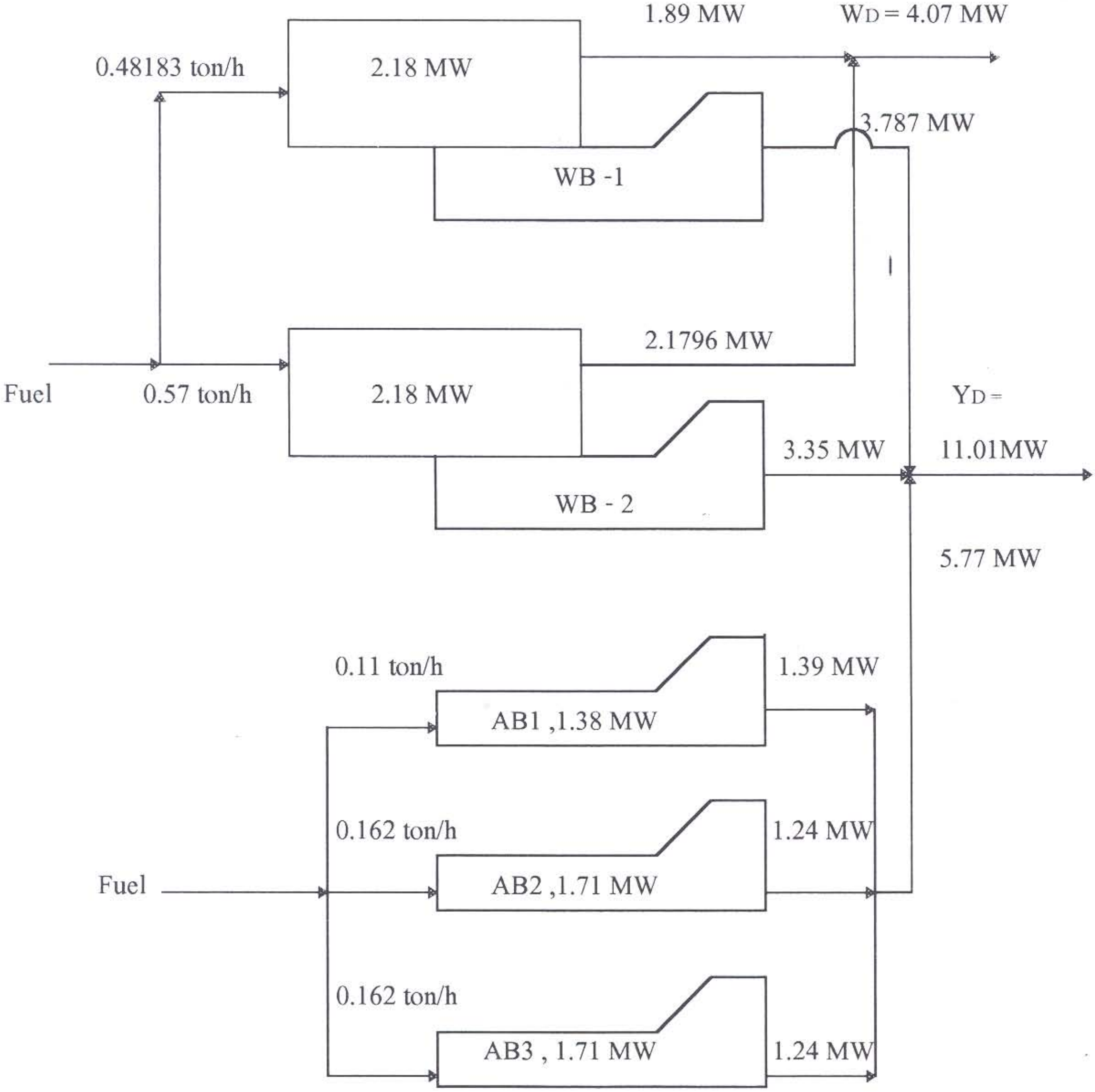

Fig. 4 . The optimal configuration for a power plant in the car tyre production industry in which the productivity is over 1,000,000 tyres/year .

and can produce 26.3<IRR<44%. Using heavy oil it can generate 13268>IHR> 7225 Btu/ kW-h . and can produce 25.8 < IRR < 39%. With distilled oil no factory generates an IRR over 25%.

The gas turbine cogeneration system using natural gas generates 9,484 > IHR > 3,139 Btu / kW-h with the return on investment 25 < IRR < 57.1 %. Using heavy oil it can generate 9,226 > IHR > 3,138 Btu / kW-h . and can give 25.02 < IRR < 48.7%. Using distilled oil it can generate 6,693 > IHR > 3,138 Btu / kW-h . and can produce 25.20 < IRR < 32.4 %.

By the above method, the potential of diesel cycle and gas turbine cogeneration in the Thai industrial manufacturing sector can be estimated by using the mixed-integer linear programming method the results of which show that:

1. for the chemical industry group, there is potential for gas turbine cogeneration of 105 MW, and for diesel cycle cogeneration of 51.18 MW.
2. for the food industry group, there is potential for gas turbine cogeneration of 660.84 MW. and for diesel cycle cogeneration of 145.3 MW.
3. for the petro - chemical industry group, there is potential for gas turbine cogeneration of 555.6 MW. and for diesel cycle cogeneration of 181.31 MW.
4. for the paper industry group, there is potential for gas turbine cogeneration of 732.6 MW, and no potential for diesel cycle cogeneration.
5. for the fibre spinning and dyeing group, there is potential for gas turbine cogeneration of 184.5 MW. and for diesel cycle cogeneration of 87.7 MW.
6. for the oil refinery group, there is potential for gas turbine cogeneration of 447.8 MW, and no potential for diesel cycle cogeneration.

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NOMENCLATURE

η_G	generator efficiency; %
x_G	cogeneration fuel consumption; (ton/h)
x_A	auxiliary boiler fuel consumption; (ton/h)
W_G	cogeneration power output (MW)
y_G	cogeneration heat output (MW)
y_A	auxiliary boiler heat output (MW)
w_P	purchased power (MW)
W_D	power demand (MW)
Y_D	heat demand (MW)
CT	cogeneration technology
WB	waste heat boiler
AB	auxiliary boiler
Z_R	annual variable cost for the divers plants (US$/yr)
Z_F	annual fixed cost for the divers plants (US$/yr.)
Z_S	standby charge cost of cogeneration (US$/yr)

C_B	buy back rate cost (US$/kW-h)
C_P	unit cost of the purchased power (US$/kW-h)
O_{PH}	annual operation hours (h/yr)
C_F	unit fuel price for cogeneration (US$/ton)
R_G	rate of return for cogeneration (1/yr)
R_A	rate of return for an auxiliary boiler (1/yr)
I_G	initial equipment cost of a CT/WB unit (US$)
I_A	initial equipment cost of an AB unit (US$)
γ_G	the ratio of the annual maintenance cost of a cogeneration system to the initial installation cost of a cogeneration system (1/yr)
γ_A	the ratio of the annual maintenance cost of an auxiliary boiler system to the initial installation of an auxiliary boiler system (1/yr)
τ_G	the economically useful life of a CT/WB unit
τ_A	the economically useful life of an AB unit
r	annual interest rate
ρ_G	the salvage value of the waste heat boiler of cogeneration at the end its the economically useful life.
ρ_A	the salvage value of the auxiliary boiler at the end of its economically useful life.
Q_f	incremental heat rate (Btu/kW-h)
F	fuel used (Btu/h)
H	steam heat content (Btu/h)
η_b	boiler efficiency (%)
P_e	power output (MW)

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APPENDIX A

Linear Equation for Diesel Cycle and Gas Turbine Cogeneration

$$w_{G,n} = \begin{cases} a_{G,n} x_{G,n} + b_{G,n} & : \underline{X}_{G,n} \le x_{G,n} \le \bar{X}_{G,n} \\ 0 & : x_{G,n} \end{cases} \tag{2}$$

$$y_{G,n} = \begin{cases} \alpha_{G,n} x_{G,n} + \beta_{G,n} & : \underline{X}_{G,n} \le x_{G,n} \le \bar{X}_{G,n} \\ 0 & : x_{G,n} \end{cases} \tag{3}$$

$$1 \le n \le N$$

Where $\underline{X}_{G,n}$ and $\bar{X}_{G,n}$ are the lower and upper limits respectively of the fuel consumption of the n^{th} CT/WB unit installed in the plant and $a_{G,n}$, $b_{G,n}$, $\alpha_{G,n}$, $\beta_{G,n}$ are constants .

$$y_{A,l} = \begin{cases} \alpha_{A,l} x_{A,l} & : \underline{X}_{A,l} \le x_{A,l} \le \bar{X}_{A,l} \\ 0 & : x_{A,l} \end{cases} \tag{4}$$

$$1 \le l \le L$$

Where $\underline{X}_{A,l}$ and $\bar{X}_{A,l}$ are the lower and upper limits, respectively, of the fuel consumption of the AB installed in the plant, $\alpha_{A,l}$ is the constant.

$$x_G = \sum_{n=1}^{N} x_{G,n} \tag{5}$$

$$x_A = \sum_{l=1}^{L} x_{A,l} \tag{6}$$

$$w_G = \sum_{n=1}^{N} w_{G,n} \tag{7}$$

$$y_G = \sum_{n=1}^{N} y_{G,n} \tag{8}$$

$$y_A = \sum_{l=1}^{L} y_{A,l} \tag{9}$$

$$\varepsilon_l = \begin{cases} 1: l^{th}\ AB\ (1 \le l \le L)\ is\ operating\ . \\ 0: AB\quad is\ stopping \end{cases} \tag{10}$$

$$\delta_n = \begin{cases} 1: n^{th}\ CT/WB\ \ (1 \le n \le N)\ is\ \ operating \\ 0: CT/WB\ \ is\ \ \ stopping \end{cases} \tag{11}$$

From the Eqs. (1)-(3) adopting these 0-1 integer variables can be expressed thus :

$$w_{G,n} = a_{G,n} x_{G,n} + b_{G,n} \delta_n \tag{12}$$

$$y_{G,n} = \alpha_{G,n} x_{G,n} + \beta_{G,n} \delta_n \tag{13}$$

$$\underline{X}_{G,n} \delta_n \le x_{G,n} \le \bar{X}_{G,n} \delta_n \qquad (1 \le n \le N) \tag{14}$$

$$y_{A,l} = \alpha_{A,l} x_{A,l} \tag{15}$$

$$\underline{X}_{A,l} \varepsilon_l \le x_{A,l} \le \bar{X}_{A,l} \varepsilon_l \quad (1 \le l \le L) \tag{16}$$

Benefit (Z) = overall income - annual variable cost - annual fixed cost - reserves

$$\text{Benefit (Z)} \quad = I - Z_R - Z_F - Z_S \tag{17}$$

$$I = (W_G - W_D)C_B O_{PH} + C_P O_{PH} W_D \tag{18}$$

$$Z_R = \{C_F \sum_{n=1}^{N} x_{G,n} + C_F \sum_{l=1}^{L} x_{A,l} + C_P W_D - C_P \sum_{n=1}^{N} (a_{G,n} x_{G,n} + b_{G,n}\delta_n)\} O_{PH} + \bar{C}_P \bar{w}_P \tag{19}$$

$$Z_F = \sum_{n=1}^{N} R_G I_{G,n} + \sum_{l=1}^{L} R_A I_{A,l} + \gamma_G \sum_{n=1}^{N} I_{G,n} + \gamma_A \sum_{l=1}^{L} I_{A,l} \tag{20}$$

$$\sum_{n=1}^{N} (a_{G,n} + b_{G,n}\delta_n) \geq W_D \tag{21}$$

$$\sum_{n=1}^{N} (\alpha_{G,n} x_{G,n} + \beta_{G,n}\delta_n) + \sum_{l=1}^{L} x_{A,l}\alpha_{A,l} \geq Y_D \tag{22}$$

$$x_{G,n} \geq \underline{x}_{G,n} \; ; \; x_{G,n} \leq \bar{x}_{G,n} \quad (1 \leq n \leq N) \tag{23}$$

$$x_{A,l} \geq \underline{x}_{A,l} \; ; \; x_{A,l} \leq \bar{x}_{A,l} \quad (1 \leq l \leq L) \tag{24}$$

$$\delta_{G,n} - \sigma_{G,N} \leq 0 \tag{25}$$

$$\varepsilon_{A,l} - \sigma_{A,l} \leq 0 \tag{26}$$