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Retrofit of Steam Power Plants in Eco-industrial Parks

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This article presents a systematic methodology for the retrofit of steam power plants in eco-industrial parks, which offers the opportunity of energy integration among companies. Components of this work include the energy reallocation and the retrofitted design of steam systems. In the present study, the current strategy of energy utilization for existing sites is assessed. Retrofit is taken into account to evaluate the potential energy for the integration. The problem is formulated as a mixed integer nonlinear program based on a superstructure approach. The result of an industrial case study shows that the energy integration among plants is benefit, which provides incentive to promote the cooperation of companies in the vicinity.

1. Introduction

Steam systems are an important part of most processing sites, where energy consumption influences the costs enormous and, therefore, has always been of notable concern. The cost of fuel and power is very significant and better energy management of utility system can lead to remarkable cost savings. Such cost savings can be accomplished by more effective energy regulation of the system or more closely energy integration with neighbouring sites in the industrial park.

Much work has been published on the design and optimization of steam systems. Nishio et al. (1980) and Chou and Shih (1987) introduced the methodology based on thermodynamic principles and heuristics rules to design the steam distribution network (SDN) of steam plants. Papoulias and Grossmann (1983a) presented the superstructure-based mathematical formulation, proposing mixed-integer linear programming (MILP) method and considering the total annual cost (TAC) as the objective to find the best network design. Later, Bruno et al. (1998) developed a mixed-integer nonlinear programming (MINLP) method to have sufficient accuracy for the implementation to actual industrial problems. It should be noted that studies mentioned above addressed the design of SDN assuming all units operate at full load or at fixed efficiency to satisfying demands and conditions. Thence, Aguilar et al. (2007) and Chen and Lin (2010) proposed a robust computational tool to address design and operational problems for flexible utility plants, considering structural and operational parameters as variables to be optimized simultaneously.

The design of total processing systems which includes the utility plants and the processing plants was discussed by Papoulias and Grossmann (1983b), where the transshipment model was embedded into formulation to account for the possible heat integration and the utility consumption. Afterward, Dhole and Linnhoff (1993) introduced the total site integration of heat systems, based on the concept of the site heat source and heat sink profiles, to describe a set of processes served by a central steam system. And the targeting procedure was developed for sites involving several processes. Thereafter, Hui and Ahmad (1994) extended this concept to address a similar problem using exergetic techniques for the total site integration. Subsequently, some publications have addressed the steam system design with the total site integration. Klemeš et al. (1997) and Bandyopadhyay et al. (2010) applied the

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site utility grand composite curve to estimate the cogeneration potential of a total site. Varbanov et al. (2005), and Chen and Lin (2011a) embedded pinch technology or transshipment model in the steam systems. However, the studies focused on only the network design of SDN. Accordingly, Chen and Lin (2011b, 2012) developed the systematic method to discourse upon the energy transfer of an entire energy system, simultaneously synthesizing both steam system network and heat recovery network.

In an Eco-Industrial Park (EIP), the basic idea is that businesses cooperate with each other in an attempt to reduce waste and pollution, efficiently share re-sources (such as materials, water, energy, and natural resources), and increase economic gains and improve environmental quality to help achieve sustainable development. In this context, the work is to develop an approach following this concept, taking into account energy integration among companies. The proposed steam system model has ability to tackle not only the operational problem but also the retrofit design in industry.

2. Problem statement

The production of steel is composed of an energy-intensive process. Therefore, during the last few decades, finding new ways of maximizing energy efficiency is an increasing emphasis. However, there still remains a wide margin for improvement. More specifically, a large amount of waste heat is only recovered and converted into power without inter-company partnering so that the best application of waste heat is not to accomplish. Nowadays, the idea of energy share in an EIP is much acceptable for most industrialists, which, hence, provides the opportunities for the best energy utilization. The problem addressed in this paper can be briefly stated as follows:

Consider a steel mill that has several utility plants to provide the utility demands. For each site, the layout is given. There exist a set of boilers ($b \in B$), a set of steam turbines ($t \in T$), and a set of steam headers ($i \in I$). The plants supply steam and power to satisfying utility demands, where the excess energy is exported by steam or electricity to neighbouring plants or public grid. Due to the prevalence of EIP in recent years, the original energy policy of utility plants must be reviewed. This work discusses how to retrofit sites in a steel mill to enhance the performance of the steam power plants and to maximize the profit by exporting steam to vicinal companies.

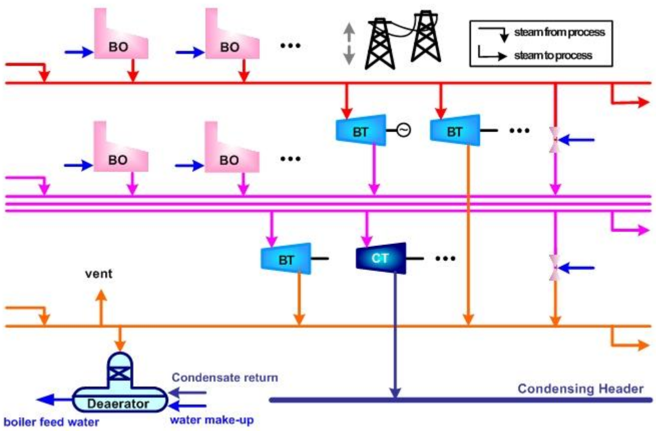

Figure 1: A typical steam distribution network

3. Model formulation

Figure 1 presents a typical SDN, which is the combination of types of units and all possible flow connections. According to the network, steam is generated in steam boilers, and collected and distributed through steam headers. When steam is expanded in steam turbines, the units produce power and steam at high, medium, or low pressures, which can satisfy requirements of inside processing plants. Moreover, to provide the chance of energy integration with company-partnering, steam and power which are imported or exported are allowable.

3.1 Boiler

$$f_b^{\mathrm{bfw}} = \sum_{i \in I} f_{bi} + \sum_{i \in I} f_{bi}^{\mathrm{bd}} \qquad \forall b \in B \tag{1}$$

$$f_b^{\mathrm{bfw}} H^{\mathrm{deaer}} + q_b = \sum_{i \in I} f_{bi} h_{bi} + \sum_{i \in I} f_{bi}^{\mathrm{bd}} H_i^{\mathrm{sat,l}} \qquad \forall b \in B \tag{2}$$

$$f_{bi}^{\mathrm{bd}} = \varphi f_{bi} \qquad \forall b \in B, i \in I \tag{3}$$

$$f_{bu} = \frac{Z_{bu} q_b}{\eta_b H_u^{\mathrm{LHV}}} \qquad \forall b \in B, u \in U \tag{4}$$

3.2 Steam turbine

$$\sum_{\substack{i,i' \in I \\ i<i'}} w_{ii't} = \sum_{j \in J} w_{tj} \qquad \forall t \in TS \tag{5}$$

$$z_t \geq \sum_{j \in J} z_{tj} \qquad \forall t \in TS \tag{6}$$

$$\underline{\Gamma}_t z_{tj} \leq w_{tj} \leq \overline{\Gamma}_t z_{tj} \qquad \forall t \in TS, j \in J \tag{7}$$

$$z_t \geq z_{ii't} \qquad \forall i,i' \in I, i < i', t \in T \tag{8}$$

$$\underline{\Omega}_t z_{ii't} \leq f_{ii't} \leq \overline{\Omega}_t z_{ii't} \qquad \forall i,i' \in I, i < i', t \in T \tag{9}$$

$$\underline{\Gamma}_t z_{ii't} \leq w_{ii't} \leq \overline{\Gamma}_t z_{ii't} \qquad \forall i,i' \in I, i < i', t \in T \tag{10}$$

3.3 Steam header

$$\sum_{b \in B} f_{bi} + \sum_{\substack{i' \in I \\ i'<i}} \sum_{t \in T} f_{i'it} + \sum_{\substack{i' \in I \\ i'<i}} f_{i'i} + f_i^{\mathrm{ld}} + F_i^{\mathrm{ps}} + f_i^{\mathrm{imp,s}} = \sum_{\substack{i' \in I \\ i'>i}} \sum_{t \in T} f_{ii't} + \sum_{\substack{i' \in I \\ i'>i}} f_{ii'} + F_i^{\mathrm{pd}} + f_i + f_i^{\mathrm{vent}} + f_i^{\mathrm{exp,s}} \qquad \forall i \in I \tag{11}$$

$$\sum_{b \in B} f_{bi} h_{bi} + \sum_{\substack{i' \in I \\ i'<i}} \sum_{t \in T} f_{i'it} h_{i'it} + \sum_{\substack{i' \in I \\ i'<i}} f_{i'i} h_{i'} + f_i^{\mathrm{ld}} H^{\mathrm{deaer}} + F_i^{\mathrm{ps}} H_i^{\mathrm{ps}} + f_i^{\mathrm{imp,s}} H_i^{\mathrm{imp,s}} = \Big(\sum_{\substack{i' \in I \\ i'>i}} \sum_{t \in T} f_{ii't} + \sum_{\substack{i' \in I \\ i'>i}} f_{ii'} + F_i^{\mathrm{pd}} + f_i + f_i^{\mathrm{vent}} + f_i^{\mathrm{exp,s}}\Big) h_i \qquad \forall i \in I \tag{12}$$

3.4 Power balance

$$\sum_{t \in TS} w_{tj} + \sum_{m \in M} w_{mj} = W_j^{\mathrm{dem,s}} \qquad \forall j \in J \tag{13}$$

$$\sum_{\substack{i,i' \in I \\ i<i'}} \sum_{t \in TE} w_{ii't} + w^{\mathrm{imp,e}} = W^{\mathrm{dem,e}} + \sum_{m \in M} \sum_{j \in J} \frac{w_{mj}}{\eta^{\mathrm{m}}} + w^{\mathrm{exp,e}} \tag{14}$$

3.5 MINLP model

$$\min_{\mathbf{x}\in\Omega}\left(\begin{array}{l} C^{\mathrm{w}} f^{\mathrm{w}} + \sum_{t\in T} C^{\mathrm{cw}} q_t + \sum_{b\in B}\sum_{u\in U} C_u f_{bu} \\ + \sum_{i\in I} C_i^{\mathrm{imp,s}} f_i^{\mathrm{imp,s}} - C_i^{\mathrm{exp,s}} f_i^{\mathrm{exp,s}} + C^{\mathrm{imp,e}} w^{\mathrm{imp,e}} - C^{\mathrm{exp,e}} w^{\mathrm{exp,e}} \end{array}\right) t^{\mathrm{hrs}} \tag{15}$$

$$\mathbf{x} \equiv \left\{\begin{array}{c} f_{bi}, f_{bi}^{\mathrm{bd}}, f_b^{\mathrm{bfw}}, f_{bu}, f_{ii't}, f_{ii'}, f_i, f_i^{\mathrm{ld}}, f_i^{\mathrm{vent}}, f^{\mathrm{c}}, f_i^{\mathrm{exp,s}}, f_i^{\mathrm{imp,s}}, f^{\mathrm{w}}, \\ h_{bi}, h_{ii't}, h_i, q_b, q_t, w_{ii't}, w_{mj}, w_{tj}, w^{\mathrm{exp,e}}, w^{\mathrm{imp,e}}, \\ z_{bi}, z_b, z_{ii't}, z_m, z_{tj}, z_t, z^{\mathrm{exp,e}}, z^{\mathrm{imp,e}} \\ \forall b\in B, i\in I, j\in J, m\in M, t\in T, u\in U \end{array}\right\}$$

4. Industrial case study

In this section, the proposed model is applied to address a practical industrial case. On account of the side-products produced from the steel mill process, utility plants are able to buy synthesis gas (SG) from coke processing plants as cheap fuel input and the amount is 75.5 t/h. Figure 2 shows the steam system layouts of a steel mill, in which two steam power plants are there to provide internal and external plants with steam and power. Four steam header levels are available for each plant, and two of them are linked together. There are four boiler groups in sites, where boiler workshop 1 (B1) produces 128 kg/cm^2 steam, boiler workshop 2 (B2) produces 60 kg/cm^2 steam, and boiler workshops 3 and 4 (B3, B4) produce 94 kg/cm^2 steam. It is noted that B3 uses coal, and the others use SG as their fuel input. Seven steam turbines (STs) are equipped to generating power, where two turbines generate shaft work and the others generate electricity. Tables 1 and 2 present the site conditions and utility demands. Here, these two systems are regarded as part of industrial park to integrate by the transfer of steam and power.

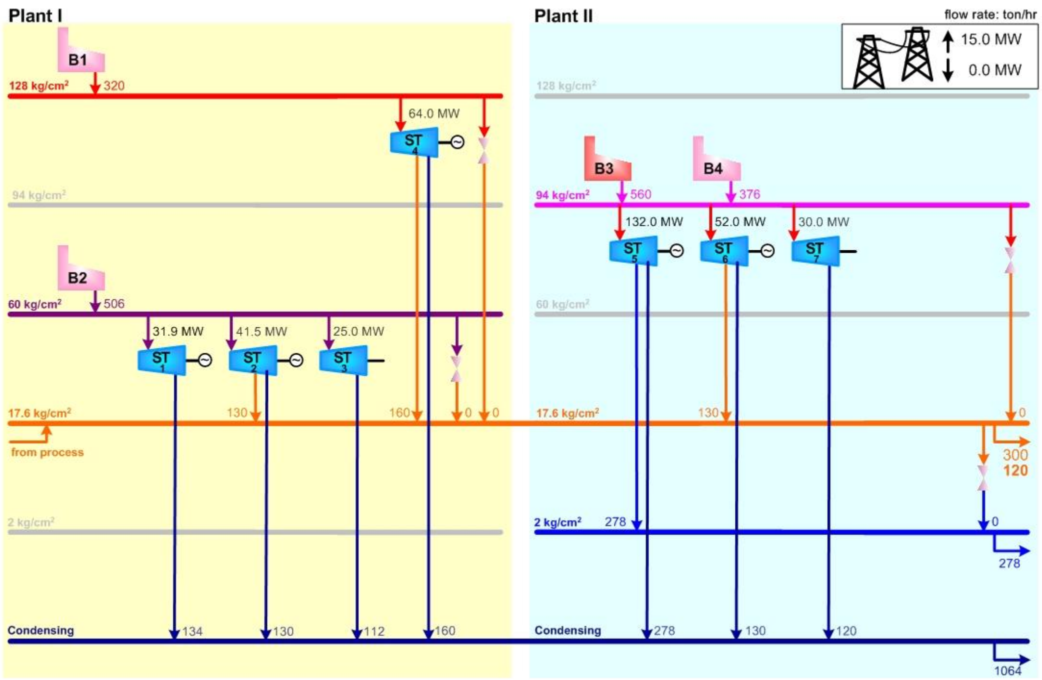

Figure 2: The configuration of utility plants (current operating status)

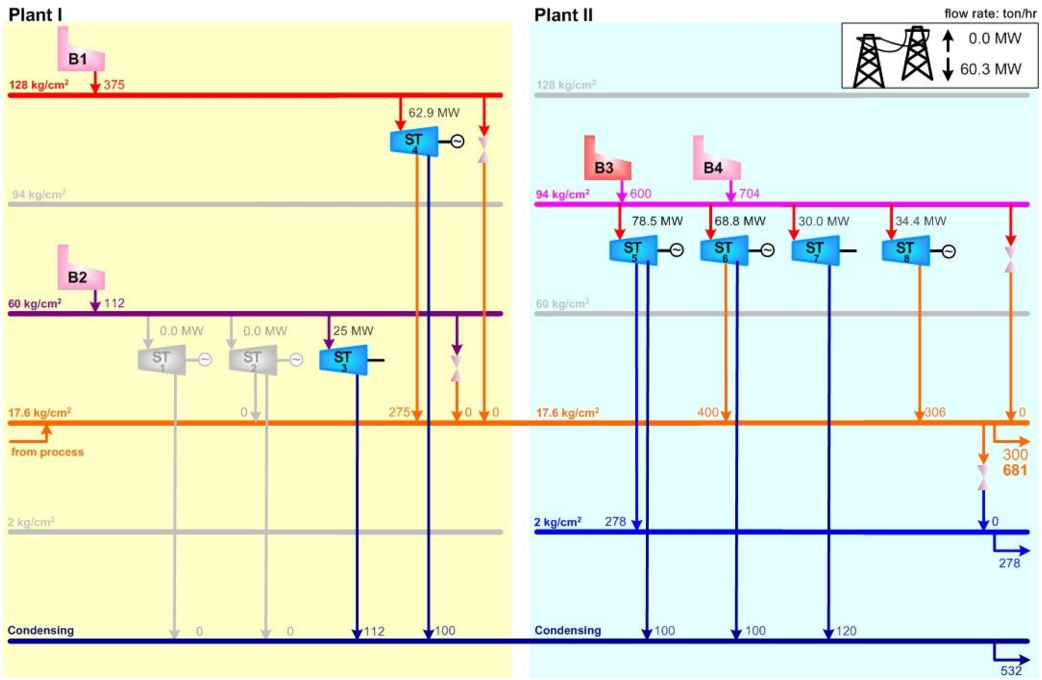

Figure 3: Retrofit of utility plants

Table 1: Site conditions

Total working hours	8,600 h/y
Synthesis gas LHV	52,000 kJ/kg
Coal LHV	28,000 kJ/kg
Electricity price	2.5 NT$/kWh
Steam price (export)	1,000 NT$/t
Synthesis gas price	5,760 NT$/t
Coal price	3,600 NT$/t

Table 2: Steam and power demands

Steam demands (17.6 kg/cm^2)	300 t/h
Steam demands (2.0 kg/cm^2)	278 t/h
Power demands	300 MW
Shaft power demand 1	25 MW
Shaft power demand 2	30 MW

The optimal configuration of utility plants is shown in Figure 3. One additional steam turbine (ST8) is installed and located between 94 and 17.6 kg/cm^2 headers. From the result, compared to the base case, sites can increase steam export from 120 to 681 t/h. However sites must import 60.3 MW power. B2 decreases steam production from 506 to 112 t/h and B4 increases that from 376 to 704 t/h. Also note that most SG is supplied to B4. Now, the amount of SG for B2 is to maintain the operating of ST3. For steam turbines, not only ST1 but also ST2 are turned off. The additional new ST8 is applied to increase the amount of steam export with 306 t/h and to enhance electricity generation. ST8 is more efficient than ST2 so that power import from electric grid can be reduced. In this case, the sites produce around 79.9 % of the required electricity. The retrofit result corresponds to a 67.5 % reduction in overall operating cost (NT$ 1604 M/y) in comparison with the base case. The trend of result recommends that the best strategy is to export steam and to import power in the existing systems.

5. Conclusion

A systematic methodology has been proposed for optimizing the steam and power generation system in a steel mill. In this present, the two major elements of the energy share contain steam and electricity. In this industrial case, the utility plants are integrated with vicinal companies' energy system, which allows evaluating the trade-off for energy import or export. Significant reductions have achieved in operating cost by 67.5 % by considering inter-factory energy integration, which provides incentive to promote the cooperation of neighbouring companies in the industrial park. Also, the result recommends that the existing utility plants to export steam are more profitable than to generate power. According to the market research, the supply amount of steam export from sites is still not enough in the studied industrial park even if the result shows that sites can export steam up to 681 t/h, which presents the proposed policy is feasible. It is important to note that different plants may have different results or strategies since their energy systems are not always the same. However, this paper provides a powerful tool and can be readily extended to various circumstances.

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