

Article

Optimization of Steam Pressure Levels in a Total Site Using a Thermo-economic Method

Shahin Shamsi and Mohammad R. Omidkhah *

Department of Energy and Environment, Science and Research Branch, Islamic Azad University, Tehran 14778, Iran; E-Mail: shaahinshams@gmail.com

* Author to whom correspondence should be addressed; E-Mail: omidkhahm@gmail.com; Tel.: +98-21-82883334; Fax: +98-21-88005040.

Received: 30 January 2012; in revised form: 3 March 2012 / Accepted: 6 March 2012 /

Published: 12 March 2012

Abstract: The present study aims to develop a thermo-economic-based approach for optimization of steam levels in a steam production and distribution system by use of the specific exergy costing (SPECO) method for determining optimum steam levels to minimize the cost caused by exergy destruction. In the field of total site optimization, incremental cost of the utility system caused by exergy destruction has been selected as an objective function and the result is compared with the case that energy minimization has been selected as the prime objective. The steam levels are optimized considering steam demand at each level, output power generated by turbines, boiler duty, fuel and cold utility requirements as well as capital cost of equipments. The analysis showed that thermo-economic (exergoeconomic) approach in optimization not only can change the optimum structure of steam levels but also may reduce the total cost of utility system up to 8%.

Keywords: thermo-economics; exergoeconomics; total site

Nomenclature:

$\dot{C}$	Cost rate, Cost rate associated with exergy [\$/h]
C_o	Heat flowing out of the temperature interval control volume to heat sink zone
c	Cost per unit of exergy [\$/GJ]
$\dot{E}$	Exergy flow rate [kW]
F	Heat flowing out of the steam level control volume to the steam turbine
G	Heat flowing out of the steam level control volume to the heat sink
H_i	Heat provided by process heat source to temperature interval control volume in heat source zone

H_o	Heat flowing out of the temperature interval control volume in heat source zone
HP	High Pressure
LP	Low Pressure
MP	Medium Pressure
RC_i	Heat flowing into temperature interval control volume from a higher temperature interval into heat sink zone
RC_o	Residual heat flowing out of temperature interval control volume in heat sink zone
RH_i	Heat flowing into temperature interval control volume from a higher temperature interval into heat source zone
RH_o	Residual heat flowing out of temperature interval control volume in heat source zone
S	Heat flowing into the steam level control volume from steam turbine
VHP	Very High Pressure

Subscripts

B	Boiler
D	Destruction
e	Exit
F	Fuel
i	Inlet
is	Isentropic
max	Maximum, refers to capacity
P	Product
q	Heat loss
sat	Saturation
sys	System
T	Turbine
w	Power

1. Introduction

In recent years, many practical and theoretical studies have been conducted on optimization of energy-intensive sectors of chemical processes such as utility systems, separation sections and heat exchanger networks. When talking about the optimization of a chemical process plant, it could not be considered apart from the system of power and heat generation and the optimization often contains the total site. In such cases the cost of power and heat generation should be considered under different operating conditions, which include some steam levels such as VHP, HP, MP, LP and operation units between the levels. Usually thermodynamics and mathematical programming or combined approaches are used for this purpose, each of which has its own strengths and weaknesses. The early work of Nishio [1] was further developed by other researchers. In this method a simple LP algorithm for turbine allocation and heuristics for minimizing the exergy loss in the system were used. Nishio [2] considered the problems of selecting optimum header pressure levels, and a direct search approach was presented by him.

A decomposition strategy has been suggested by Petroulas and Reklaitis [3]. In this method the design task was decomposed into two sub-problems—header selection and driver allocation—and a

linear programming technique was used. For constant demand of process heat and power for a site Papoulias and Grossmann [4], described an approach using Mixed Integer Linear Programming (MILP).

Mavromatis [5], and Mavromatis and Kokossis [6], have developed a method for estimation of power production by steam turbines, which have been applied to the design of steam turbine networks. The steam turbine model was further extended by Shang [7], to have some useful features enabling construction of optimization models of complete utility systems so the effect of equipment size on performance could be seen. This model included boiler and gas turbine models too. Methods for selecting of optimal header pressure and utility network design are also involved. Shang and Kokossis [8], proposed a transshipment model of a steam network which uses a boiler hardware model (BHM) and a turbine hardware model (THM). Their proposed model was MILP that used constraints based on energy equations. This model was improved by Varbanov *et al.* [9]. The exergoeconomic approach has not been used in their work. To achieve an effective energy saving scheme one should try to somehow minimize irreversibility and exergy destruction in the system under consideration. In this respect, a good initial design is of prime importance, as the best operation practice or even deployment of high tech equipment may not have the capacity to overcome the massive exergy destruction caused by an improper design.

Keenan [10] propounded the exergy and cost flow concepts for the first time. He demonstrated that the real value of steam and electricity is in the availability, not in the magnitude of energy. Therefore, the basics of exergoeconomics as a branch of engineering and science were founded.

The Specific Exergy Costing (SPECO) approach [11] is one of the subcategories in exergoeconomics which is based on the definition of “Fuel” and “Product” for each component of the system and the cost equations is obtained by applying basic laws. An exergoeconomic analysis and optimization for a cogeneration system was done by Sahoo [12]. He improved the performance of the system in a cost effective way using evolutionary programming.

Abusoglu and Kanoglu [13] presented the formulation for exergoeconomic analysis of diesel engine powered cogeneration (DEPC). In their work, a DEPC plant was considered with all associated components. Mass, energy, and exergy balances were applied to each system component and subsystem. Exergy destruction was yield by exergy balance formulations. The formulations for the cost of products, and cost formation and allocation within the system were developed based on exergoeconomic analysis (energy and exergy).

In another paper, Abusoglu and Kanoglu [14] considered an actual DEPC for application of the developed formulation. The exergoeconomic analysis was based on specific cost method (SPECO). Exergy destructions and various exergoeconomic performance parameters were determined for the entire plant.

The current paper is based on transshipment, and a MINLP model with constraints based on energy and exergy (exergoeconomic) equations for the optimization of steam generation and distribution network in a total site. The model also uses a SPECO approach for this purpose. Two case studies have been used.

2. Model Representation

2.1. Transshipment Model of a Steam Network

In the transshipment model of a steam network [8], heat is considered as a commodity to be shipped from a process heat source (origin) to steam levels (nodes) and from there to process heat sinks (destinations) through temperature intervals. According to the Second Law of Thermodynamics, heat flows as a result of this driving force and only from higher to lower temperatures, thus these constraints have to be accounted for in the network model. The network consists of three cascades of temperature intervals: heat source cascade, steam level cascade, and heat sink cascade.

2.2. Exergoeconomics

Tsatsaronis [15] defined exergoeconomics as a branch of engineering that incorporates exergy analysis at the system component level, into the economic laws to provide useful information for the designer or operator to cost-effectively design or operate the system. It should be noted that this information cannot be obtained using regular energy or exergy analysis, and/or economic analysis separately. Among the various existing methods in literature, the SPECO approach is chosen for this study and is explained in the next section.

2.2.1. SPECO Method

Specific exergy costing (SPECO) method includes three steps: in the first step, all energy and material flows that cross the control volume of each component must be identified. Flows of exergy are obtained from exergy analysis applied on all energy and material streams crossing the boundary of the component.

In the second step, fuel and product exergy for each component will be calculated. The quantity of resources that must be identified through mass or energy flows are known as “Fuel”, while “Product” is the desired output of a component. According to the Fuel-Product model, the product of one component is used as fuel for another component or as part of the total production of the plant [16].

The exergetic cost rate balance and auxiliary equations for each subsystem should be derived separately in the third step. Cost rate balance formulation for the K^{th} component is the summation of cost rates of all output and input exergy flows associated with cost rates of investment, $\dot{Z}_k^{CI}$, plus operation and maintenance, $\dot{Z}_k^{OM}$. The relevant equation is:

$$\dot{Z}_k = \dot{Z}_k^{CI} + \dot{Z}_k^{OM} \quad (1)$$

Neglecting the exergy loss in each component, three aforementioned steps can be rewritten as [12]:

$$\dot{E}_{F,k} = \dot{E}_{P,k} + \dot{E}_{D,k} \quad (2)$$

$$c_{P,k} \dot{E}_{P,k} = c_{F,k} \dot{E}_{F,k} + \dot{Z}_k \quad (3)$$

Eliminating $\dot{E}_{F,k}$ from Equation (3), it is presented as follows:

$$(c_{P,k} - c_{F,k}) \dot{E}_{P,k} = c_{F,k} \dot{E}_{D,k} + \dot{Z}_k \quad (4)$$

The right hand side of Equation (4) includes the cost rate of exergy destruction. Generally, for the K^{th} component, the rate of exergy destruction can be obtained according to Equation (5):

$$\dot{E}_{D,k} = \sum \dot{E}_{i,k} - \sum \dot{E}_{e,k} \quad (5)$$

For the whole system the Equation would be as follows:

$$\dot{E}_{D,sys} = \sum \dot{E}_{D,k} \quad (6)$$

The cost rate of exergy destruction for the K^{th} component ($\dot{C}_{D,k}$) is:

$$\dot{C}_{D,k} = c_{F,k} \dot{E}_{D,k} \quad (7)$$

In the same manner, for the whole system, cost rate of exergy destruction ($\dot{C}_{D,sys}$) would be:

$$\dot{C}_{D,sys} = \sum c_{F,k} \dot{E}_{D,k} \quad (8)$$

Equations (9–12) are also related to cost rates of the K^{th} component:

$$\dot{C}_{i,k} = c_i \dot{E}_{i,k} \quad (9)$$

$$\dot{C}_{e,k} = c_e \dot{E}_{e,k} \quad (10)$$

$$\dot{C}_{w,k} = c_w \dot{W}_k \quad (11)$$

$$\dot{C}_{q,k} = c_q \dot{E}_{q,k} \quad (12)$$

where c_j ($j \in [i, e, w, q]$) is the levelized cost per exergy unit associated with the input, output, work and heat loss. In general, the cost balance equation for the K^{th} component is given by Equation (13):

$$\sum (c_i \dot{E}_i)_k - \sum (c_e \dot{E}_e)_k \pm c_{q,k} \dot{E}_{q,k} \pm c_{w,k} \dot{W}_k + \dot{Z}_k = 0 \quad (13)$$

when the component produces heat and work is also generated, the minus sign is used for the third and fourth terms in Equation (13). In Equation (13) it is assumed that the costs per exergy unit are known for all inlet streams. These costs are known from the upstream components. The cost of inlet stream to the process (no upstream component) would be at its purchased cost.

2.2.2. Auxiliary Equations

To write the cost balance equations for each component, if the number of outlet streams from the component is more than one, then Equation (13) is not enough and auxiliary equations should be applied through the “fuel and product” rules.

The fuel rule refers to the removal of exergy from an exergy flow within the component being regarded, for this flow, the exergy difference between inlet and outlet is considered in the definition of the fuel. The fuel rule states that the total cost associated with this removal of exergy should be equal to the cost, at which the excluded exergy was supplied to the same flow in upstream component.

On the other hand, the product rule refers to the supply of exergy flow within the specific component. The product rule indicates that each exergy unit is supplied to any flow associated with the

products at the same average cost c_P . This cost is calculated using the cost balance and the other equations obtained by applying the fuel rule.

3. Optimization of Network

Optimization of a steam network is a mixed integer non linear problem (MINLP). This system contains boiler(s), steam pressure levels, steam turbines in each expansion zones. The network also includes process streams which are capable of generating or consuming steam within each temperature interval. The objective function is defined as to minimize a total cost function $\dot{C}_{sys}$ that contains terms of capital cost and exergy destruction cost for all components [12]:

$$\dot{C}_{sys} = \alpha/\tau \sum (Z_T + Z_B) + \dot{C}_{D,sys} \quad (14)$$

where α is annualized factor and can be obtained from Equation (15):

$$\alpha = i(1+i)^N / ((1+i)^N - 1) \quad (15)$$

where “ i ” is the interest rate, “ N ” the project life time in year; and τ is the total annual number of hours of system operation at full load.

3.1. Constraints

Constraints of the problem are those constraints related to energy and exergy flows, cost balance equations for the boiler and steam turbines, and thermodynamic constraints applied to each of the temperature intervals in three areas: location of steam generation by process streams, location of steam levels, and finally location of steam usage for heating.

3.2. Decision Variables

Optimization problem determines the amount of fuel requirement for boiler (directly relates to the boiler duty), the optimum steam level in each main pressure levels of steam, cold utility requirement, and the power output from each steam turbine at each expansion zone.

4. Case Studies

Applying the SPECO method for optimization of a steam network to a total site is illustrated in the following case studies. Investigational efforts for optimization of utility system were conducted using two approaches. The first was considering the objective function of energy, and the second approach was exergy destruction cost, followed by capital cost function in both cases. The optimum steam levels, heat balance of steam levels and steam turbines, output power of steam turbines, boiler duty, fuel and cold utility requirements, were calculated through solving an optimization problem.

4.1. Case Study 1

4.1.1. Definition of Problem and Superstructure

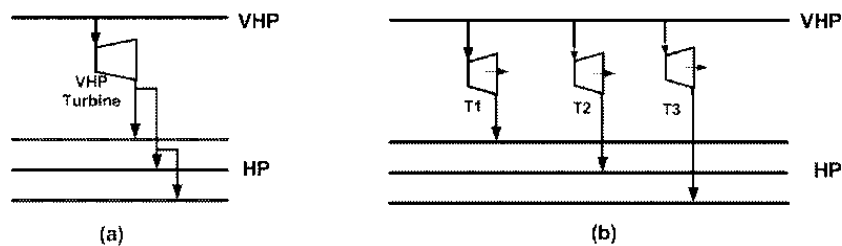
The total site profile contains four main steam levels: VHP, HP, MP, and LP. The boiler works at VHP (9000 kPa and 500 °C). The HP, MP, and LP steam can be produced either through throttling higher levels of steam or being generated against some process streams and will be used as heating media. Heat required above the temperature interval (1,1) is 4 MW and the surplus heat of process heat sources below the temperature interval (3,3) is 9 MW and also, power requirement of the site is 15 MW.

Table 1. Data of the case study 1.

Heat Provided (MW)	Heat Required (MW)	Interval (i,j)	Pressure Steam Level (kPa)
12	1	(1,1)	5498.7
2	3	(1,2)	4688.6
6	20	(1,3)	3973
9	8	(2,1)	1906.3
3	0.8	(2,2)	1553.8
10	9	(2,3)	1254.4
9	3	(3,1)	270.1
5	40	(3,2)	198.5
2	7	(3,3)	143.3

A back pressure steam turbine is used in each expansion zone. The exiting steam from the turbine can enter into sublevels of the next main steam level. The expansion zone between VHP and HP steam levels is shown in Figure 1a.

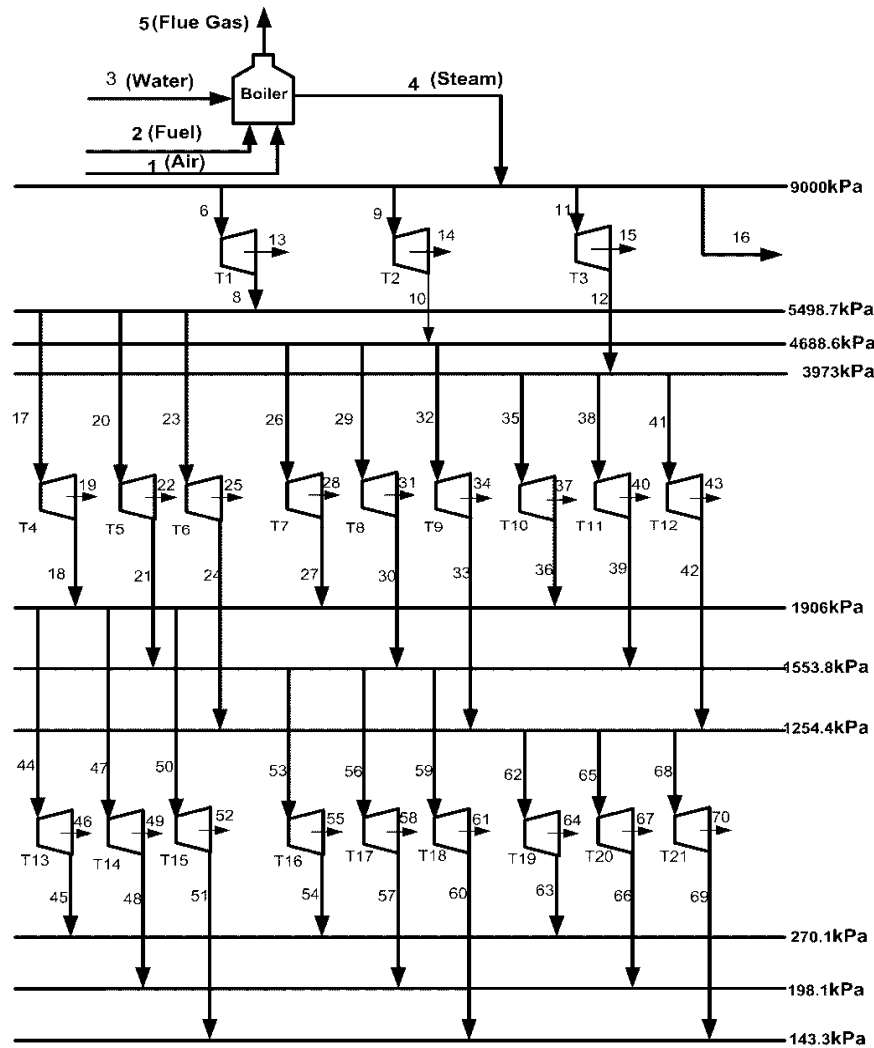
Figure 1. The schematic representation block diagram of steam turbines: (a) Expansion zone between VHP and HP steam levels; (b) Expansion zone between VHP and HP steam levels with three back pressure steam turbines one alternative must be selected.



It can be assumed that Figure 1a comprises three back pressure steam turbines between the VHP and HP steam levels which only one of them should be selected (Figure 1b). Therefore, there are nine possible alternatives of steam turbines between the HP and MP steam levels which one of them should be selected. This is also true for the case between the MP and LP steam levels.

The resulting superstructure is shown in Figure 2. The numbers beside the arrowed-headlines in Figure 2 are related to the corresponding exergy streams.

Figure 2. Superstructure of the steam network for the case study 1.



4.1.2. Derivation of Constraints

4.1.2.1. Steam Turbine

The improved THM model [9] was used for steam turbines according to Equations (16–18):

$$W = nm - W_{int} \quad (16)$$

$$n = L + 1/B (\Delta h_{is} - A/m_{max}) \quad (17)$$

$$W_{int} = L/B (\Delta h_{is} m_{max} - A) \quad (18)$$

where W is the shaft power of steam turbine; Δh_{is} the isentropic enthalpy change; m_{max} the steam turbine capacity; A and B the regression parameters; and finally L is the steam turbine intercept ratio.

4.1.2.2. Boiler

The boiler hardware model [8] was applied to describe the performance of the boiler. BHM relies on the size of the boiler and describes the operation of unit over its entire range. Fuel requirement is obtained from Equation (19):

$$Q_{fuel} = (C_p \Delta T_{sat} + q)[(1 + b)m_B + am_{Bmax}] \quad (19)$$

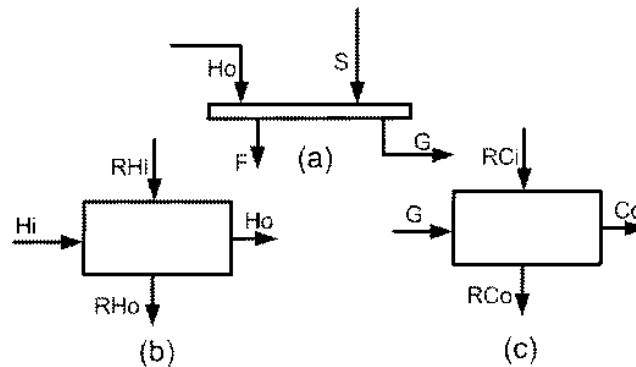
where Q_{fuel} is the fuel required by the boiler; q the specific heat load of the steam from its superheated temperature to its saturation temperature; m_B the steam load of the boiler; m_{Bmax} the boiler capacity; ΔT_{sat} the temperature difference between produced saturated steam and entering water to the boiler; and finally, a and b are the regression parameters usually provided by vendors.

4.1.2.3. Energy Balance of Steam Levels

Each steam level is regarded as a control volume (Figure 3a) and energy balance of control volume is according to Equation (20) [8]:

$$H_o + S - F - G = 0 \quad (20)$$

Figure 3. Energy balances: (a) control volume around a pressure steam level; (b) Control volume around a temperature interval in the heat source zone; (c) Control volume around a temperature interval in heat sink zone.



4.1.2.4. Energy Balance of Temperature Intervals

Each temperature interval in the area of steam generation by process streams is regarded as a control volume (Figure 3b). Energy balance of this control volume is according to Equation (21) [8]:

$$H_i + RH_i - RH_o - H_o = 0 \quad (21)$$

Each temperature interval in the area of steam usage for heating is regarded as a control volume (Figure 3c) and energy balance of this control volume is according to Equation (22) [8]:

$$G + RC_i - RC_o - C_o = 0 \quad (22)$$

4.1.2.5. Exergy and Cost Equations

Exergy and cost flow equations along with auxiliary equations for streams around boiler and the turbine 1 in Figure 2 are according to Equations (23–27):

$$\dot{E}_1 + \dot{E}_2 + \dot{E}_3 - \dot{E}_4 - \dot{E}_5 = \dot{E}_{D_b} \quad (23)$$

$$\dot{E}_6 - \dot{E}_8 - \dot{E}_{13} = \dot{E}_{D_{T1}} \quad (24)$$

$$\dot{C}_1 + \dot{C}_2 + \dot{C}_3 - \dot{C}_4 - \dot{C}_5 + \dot{Z}_B = 0 \quad (25)$$

$$\dot{C}_6 - \dot{C}_8 - \dot{C}_{13} + \dot{Z}_{T1} = 0 \quad (26)$$

$$\dot{C}_5 / \dot{E}_5 = \dot{C}_2 / \dot{E}_2 \quad (27)$$

Exergy and cost flow equations along with auxiliary equations for other steam turbines are obtained in a similar way.

4.1.3. Objective Function

As mentioned before, objective function is regarded as Equation (28) where Z_T is obtained from Equation (29):

$$\dot{C}_{sys} = (Z_T + Z_B)\alpha / \tau + \dot{C}_{D,sys} \quad (28)$$

$$Z_T = \sum Z_{T_i}, \quad i \in [1, 2, \dots, 21] \quad (29)$$

4.1.4. Assumptions

Some assumptions have been taken for case studies are presented as follows:

- Exergy costs of entering air and water to the boiler are negligible.
- Exergy losses in all components are negligible.
- Steam has no chemical exergy.
- All condensates are returned to the boiler (no condensate losses and no blow down).
- Maintenance costs of the components are not accounted for.
- Boiler utilizes natural gas with Heat Value (HV) of 13,856 kWh/t as fuel. The price of natural gas and cooling water with $\Delta T = 20^\circ\text{C}$ is as 223 USD/t and 0.005 USD/t, respectively. The price of electricity is assumed as 0.12 USD/kWh.
- Investment costs (USD) of the boiler (Z_B) and steam turbine (Z_T) are according to Equation (30) and Equation (31) in which m_B and P_T are mass flow rate of steam (kg/s) and power output (kW), respectively:

$$Z_B = 30337.015m_B^{1.5} + 1407058.4 \quad (30)$$

$$Z_T = 151.13P_T + 356250 \quad (31)$$

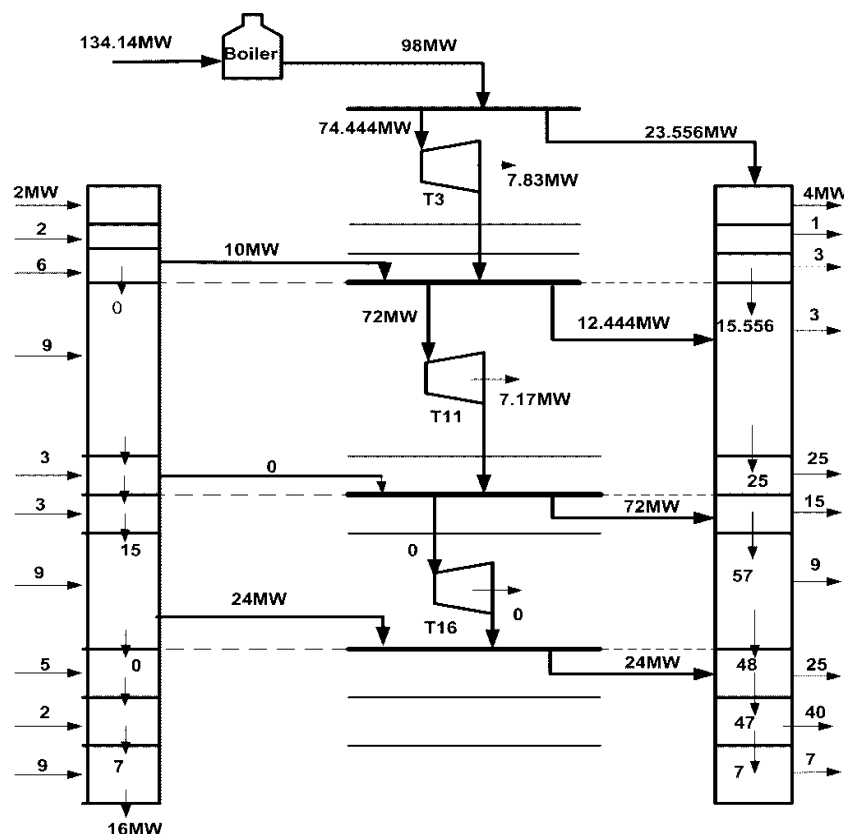
Equations (30) and (31) were obtained from the regression process based on the data reported by the website of Equip Cost [17] and Loh *et al.* [18], respectively.

- Marshall and Swift equipment cost index for the process industries in the first quarter of 2011 is 1549.8 [19].
- Annual system operation time at nominal capacity is 7008 hours.

All the equations presented for determination of turbines function and boiler was applied. Also, all the equations of mass and energy balance for components and steam level were extracted and finally MINLP model was achieved for each case study separately. To solve the model, DICOPT Program (Framework for solving MINLP models) was used. To select back pressure steam turbines in expansion zones and pressure levels of the steam, binary variables were used.

In the first case, the objective function involving energy cost, the optimum steam levels are according to pressures 3973, 1553.8, and 270.1 kPa (Figure 4), while all required power is produced in the site. In this case two steam turbines, placed in the VHP-HP and HP-MP areas, operate and the steam turbine in the MP-LP area does not contribute in the power generation.

Figure 4. Optimal structure of the case study1 when energy and capital costs are considered as objective functions.



At this condition, the provided energy by fuel to the boiler is 134.14 MW and according to the operational conditions of boiler, the VHP steam with 98 MW thermal energy is given to the entire system, of which 23.556 MW participates directly in heating of the cold streams in high temperature intervals in heat sink zone and the remaining after producing power with the produced steam by the hot streams in heat source zone is used for heating the streams in lower temperature intervals.

The total amount of the required heating of the streams in heat sink zone is 132 MW in which boiler share in producing steam for heating is 74% and to produce steam for producing power is 88%.

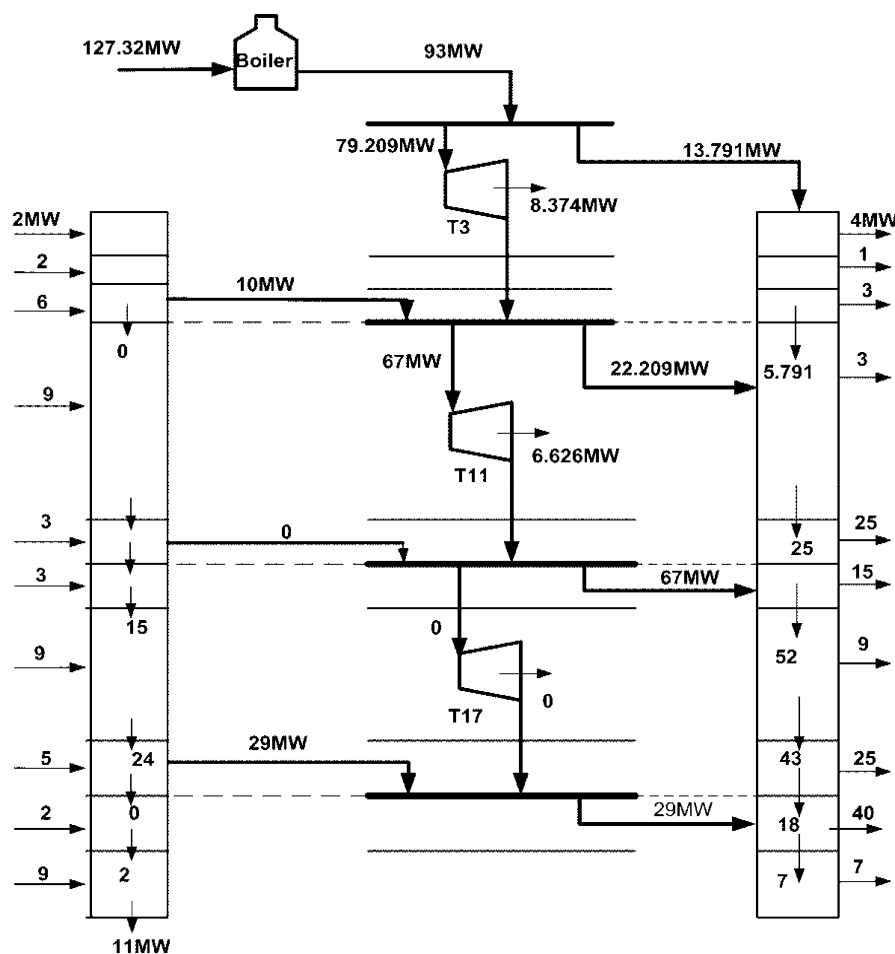
The amount of heat being removed by cold utility is 16 MW. The fuel and cold utility cost is 15,154 and 24.142 kUSD/yr, respectively and the power saving is 11,833 kUSD/yr. The total cost of the network is 19,159.73 kUSD/yr.

In the second case (objective function involves exergy destruction and capital cost) the optimum steam levels are 3,973 kPa, 1,553.8 kPa, and 198.5kPa (Figure 5). All required power is produced in the site while there is a possibility of power purchasing from outside.

At this condition, the provided energy by fuel to the boiler is 127.32 MW and according to the operational conditions of boiler, the VHP steam with 93 MW thermal energy is given to the entire system that is reduced to the previous case. Thus, in this case, boiler share in producing steam for heating is 70% and the share of the produced steam by the current flows in heat source zone is increased 4% compared to the previous case that shows better use of the existing resources in this state. Also, the amount of the heat being removed by cold utility is reduced to 11 MW compared to the previous one.

In this case the fuel cost, cold utility, and the total cost of the network is 14,361, 16,598, and 18,209 kUSD/yr, respectively. This demonstrates a reduction of about 5% in the total cost of utility system.

Figure 5. Optimal structure of the case study 1 when exergy destruction and capital costs are considered as objective functions.



4.2. Case Study 2

In the second case study, the boiler applied in the first case study operates under the same conditions and produces superheated steam. New values for the heat generated and required by the processes in predefined temperature intervals, are shown in Table 2. Heat required above the temperature interval (1,1) is 0.5 MW and the surplus heat of process heat sources below the temperature interval (3,3) is 9 MW.

Table 2. Data of the case study 2.

Heat Provided (MW)	Heat Required (MW)	Interval (i,j)	Pressure Steam Level (kPa)
0.5	0.5	(1,1)	6411.7
0.5	12	(1,2)	5498.7
18	1	(1,3)	4688.6
6	1.5	(1,4)	3973
18	2	(2,1)	2317.8
9	12.5	(2,2)	1906.3
3	17.5	(2,3)	1553.8
3	4.5	(2,4)	1254.4
18	5	(3,1)	270.1
5	35	(3,2)	198.5
2	3.5	(3,3)	143.3

The optimum steam levels were acquired as the same with the two conditions discussed in the case study 1. Figure 6 shows the conventional structure with the optimum steam levels which possess the pressures of 5498.7, 1906, and 270.1 kPa. The required power is 13.5 MW which is generated by three steam turbines. The power saving is 11,352.960 kUSD/year. Amount of heat provided by the boiler is 33.2 MW and the fuel cost is 5170.4 kUSD/year. The cost of cooling water is 44,882 USD/year.

In the second case, the optimum steam levels have the pressures of 3973 kPa, 1906 kPa, and 270.1 kPa, as shown in Figure 7. The power saving is the same as the first case and the heat provided by the boiler is 30.6 MW which, as compared to the previous case, demonstrates an approximately 2.6 MW reduction.

The fuel cost is 4776.3 kUSD/year which shows about 400 kUSD/year reduction. Also, the cost of cooling utility is 41,015 USD/year.

There was the possibility of purchasing power from the main network in both case studies, but after optimization operation, it was observed that all the production power was done inside the steam network while by increasing the cost of electricity production, for each kilowatt inside the network; it is possible to need purchasing power from the overall network.

Figure 6. Optimal structure of the case study 2 when energy and capital costs are considered as objective function.

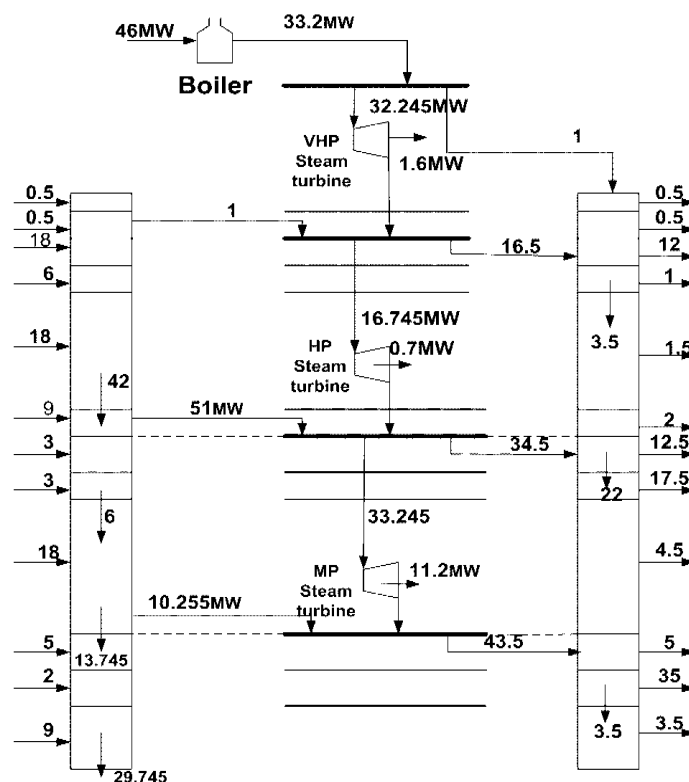
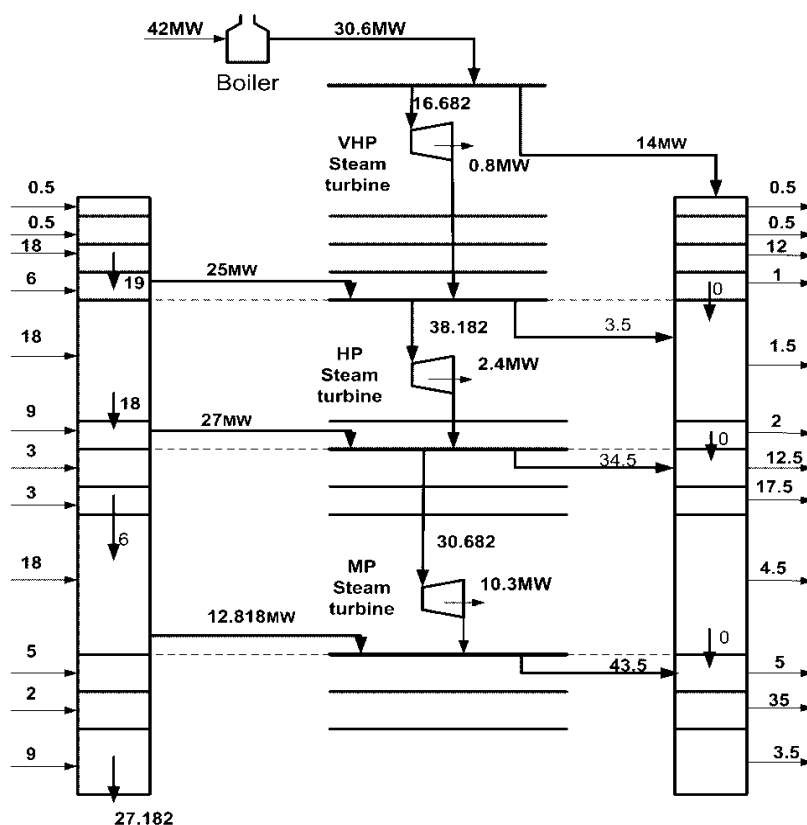


Figure 7. Optimal structure of the case study 2 when exergy destruction and capital costs are considered as objective function.



5. Conclusions

Exergoeconomics approach has the capability to provide the designer with a thorough understanding of the system in order to develop a cost effective structure. Modelling of the steam generation and distribution network in preliminary design of a total site utility system can be considered as a transshipment model. Both the model and the optimization procedure have been illustrated with two case studies. Results obtained from the case studies demonstrated that optimization of the transshipment model with exergoeconomic technique, as compared to the conventional method, yields a different network with respect to its structure and distribution-related features. Considering the results of case studies, it was observed that by reducing fuel consumption as a source of hot utility, the amount of cold utility was reduced and this is due to more use of the existing thermal potential inside the system in the new approach. Furthermore, this optimized method can reduce the energy cost up to 8%. Exergoeconomic is a promising tool for cost effective utilization of energy and capital resources in an energy systems. It was shown that application of the objective function involving the exergy destruction cost as compared with the energy cost terms gives more reliable solution. Furthermore, the SPECO method in the light of “fuel” and “product” principles in the construction of cost flow and auxiliary equations can be used effectively in the model to determine the optimum structure.

References

1. Nishio, M. Computer aided synthesis of steam and power plants for chemical complexes. Ph.D. Thesis, The University of Western, Ontario, Canada, 1977.
2. Nishio, M.; Itoh, J.; Umeda, T. A thermodynamic approach to steam-power system design. *Ind. Eng. Chem. Proc. Des. Dev.* **1980**, *19*, 306–318.
3. Petroulas, T.; Reklaitis, G.V. Computer-aided synthesis and design of plant utility systems. *AIChE J.* **1980**, *30*, 69–78.
4. Papoulias, S.A.; Grossmann, I.E. A structural optimisation approach in process synthesis-I. Utility systems. *Comput. Chem. Eng.* **1983**, *7*, 695–706.
5. Mavromatis, S.P. Conceptual design and operational of industrial steam turbine networks. Ph.D. Thesis, The University of Manchester, Manchester, UK, 1996.
6. Mavromatis, S.P.; Kokossis, A.C. Conceptual optimisation of utility networks for operational variations-1: targets and level optimisation. *Chem. Eng. Sci.* **1998**, *53*, 1585–1608.
7. Shang, Z. Analysis and optimisation of total site utility systems. Ph.D. Thesis, The University of Manchester, Manchester, UK, 2000.
8. Shang, Z.; Kokossis, A. A transshipment model for the optimisation of steam levels of total site utility system for multiperiod operation. *Comput. Chem. Eng.* **2004**, *28*, 1673–1688.
9. Varbanov, P.S.; Doyle, S.; Smith, R. Modelling and optimization of utility systems. *Chem. Eng. Res. Des.* **2004**, *82*, 561–578.
10. Keenan, J.H. A steam chart for second law analysis. *Mech. Eng.* **1932**, *54*, 195–204.
11. Lazzaretto, A.; Tsatsaronis, G. SPECO: A systematic and general methodology for calculating efficiencies and costs in thermal systems. *Energy* **2006**, *31*, 1257–1289.

12. Sahoo, P.K. Exergoeconomic analysis and optimization of a cogeneration system using evolutionary programming. *Appl. Therm. Eng.* **2008**, *28*, 1580–1588.
13. Abusoglu, A.; Kanoglu, M. Exergetic and thermoeconomic analyses of diesel engine powered cogeneration: Part 1—Formulations. *Appl. Therm. Eng.* **2009**, *29*, 234–241.
14. Abusoglu, A.; Kanoglu, M. Exergetic and thermoeconomic analyses of diesel engine powered cogeneration: Part 2—Application. *Appl. Therm. Eng.* **2009**, *29*, 242–249.
15. Tsatsaronis, G. Definitions and nomenclature in exergy analysis and exergoeconomics. *Energy* **2007**, *32*, 249–253.
16. Abusoglu, A.; Kanoglu, M. Exergoeconomic analysis and optimization of combined heat and power production: A review. *Renew. Sust. Energy Rev.* **2009**, *13*, 2295–2308.
17. Equip Cost: Boiler Cost. Available online: <http://www.matche.com/EquipCost/Boiler.htm> (accessed on 1 July 2011).
18. Loh, H.P.; Jennifer, L.; Charles, W.W. *Process Equipment Cost Estimation*; Final Report for National Energy Technology Center. Available online: <http://www.chemeng.lth.se/ket050/Arkiv/KostnadsDataProcessutrustning2002.pdf> (accessed on 9 March 2012).
19. Marshall & Swift Equipment Cost Index. Available online: <http://business.highbeam.com/408261/article-1G1-254419142/marshall-amp-swift-equipment-cost-indexFigure.1> (accessed on 1 July 2011).

© 2012 by the authors; licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (<http://creativecommons.org/licenses/by/3.0/>).