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DESALINATION

Desalination 214 (2007) 306–326

www.elsevier.com/locate/desal

Fuel allocation in a combined steam-injected gas turbine and thermal seawater desalination system

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Received 4 December 2006; Accepted 15 January 2007

Abstract

Fuel allocation in a combined steam-injected gas turbine (STIG) power generation and multi-effect thermal vapor compression (METVC) desalination system is studied, using seven methods: (1) Products Energy Method, (2) Products Exergy Method, (3) Power-Generation-Favored Method, (4) Heat-Production-Favored Method, (5) Basic Exergetic Cost Theory, (6) Functional Approach and (7) Splitting Factor Method. The latter three are thermo-economics-based. Two sample cases are calculated. The methods and results are compared and discussed. The main conclusions are: it is important to carefully choose suitable methods to perform fuel allocation in a dual purpose desalination systems (here a combined STIG-METVC system) since different methods produce very different results; The results obtained from Methods (1) and (5) are unreasonable, and those from Methods (3) and (4) set the range within which the fuel allocation values must reside; Although thermoeconomic methodologies are considered to be the most rational for cost attribution of multi-product systems, false results could be reached if they are not suitably used; When sufficient information is unavailable for performing a thermoeconomic analysis, Method (2) can be taken as an approximation for fuel allocation, as well as for the distribution of fuel cost and combustion pollutant emission, between power and water in a STIG-METVC system. A recommended fuel allocation analysis procedure, based on this study and with some generality for other gas-turbine power plant dual purpose thermal desalination systems, was outlined.

Keywords: Fuel allocation; Dual-purpose power and water system; Steam-injected gas turbine; Multi-effect thermal vapor compression desalination; Exergetic cost

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0011-9164/07/$– See front matter
doi:10.1016/j.desal.2007.01.001

1. Introduction

Combined power and water systems (often called dual-purpose systems), in which high-grade energy is used to produce power in a power plant, and low-grade power plant output heat to run a thermal desalination unit to produce fresh water from saline water, is generally a more energy-, economy- and environment-profitable way when compared with separate power-only and water-only systems [1,2]. For instance, coupling multi-stage flash (MSF) desalination with a steam turbine plant showed in a typical study 37% fuel saving and 45% water cost reduction compared with a water-only MSF unit run by the steam from a fuel-fired boiler [1]. A life-cycle assessment showed that the life-cycle environmental load (the negative environmental impact associated with the plant construction, operation, maintenance, and final disposal), of thermal desalination technologies is reduced by about 75% when operating in a hybrid combined cycle plant [2].

Although economics play a major role for the plant consumers and vendors point in their plant choice, it is still interesting to study the fuel allocation between power and water in a dual-purpose system. Such a study clarifies how and to what extent the cogeneration influence the fuel consumption of the power and water production, and to thus produce better thermodynamic understanding on the system and thereby also provide guidance for further improvement of fuel utilization.

Theoretically, all the fuel allocation methods proposed for power+heat cogeneration systems can also be used in dual-purpose power and water systems, because in a dual-purpose system, the products of the power plant are also power and thermal energy. Main allocation methods proposed for power+heat cogeneration systems are briefly described below.

1. Products Energy Method — based on the *energy* content of the products [3,4]:

$$y_P = \frac{P}{P+Q} \tag{1}$$

$$y_Q = \frac{Q}{P+Q} \tag{2}$$

where P and Q are the produced power and thermal energy, respectively, and y_P and y_Q the corresponding fuel allocation ratios. This method treats different forms of energy equally, and will result in an unreasonably high fuel allocation to the heat production [5].

2. Products Exergy Method — based on *exergy* content of the products [3,4]:

$$y_P = \frac{P}{P+E_Q} \tag{3}$$

$$y_Q = \frac{E_Q}{P+E_Q} \tag{4}$$

where E_Q is the exergy of the thermal energy. This method is more reasonable than the one based on energy, since it considers the quality difference between power and heat.

3. Power-Generation-Favored Method — giving the benefit of the fuel saving by cogeneration to the power generation part [3,4]:

$$y_P = 1 - \frac{F_{heat-only}}{F} \tag{5}$$

$$y_Q = \frac{F_{heat-only}}{F} \tag{6}$$

where F is the fuel consumption rate of the cogeneration plant, and $F_{heat\text{-}only}$ the fuel consumption rate when the heat is produced in a conventional fuel-fired boiler. Giving the entire benefit of fuel saving by cogeneration to the power output, this method results in a low value of y_P, and simultaneously a high value of y_Q.

4. Heat-Production-Favored Method — giving the benefit of fuel saving by cogeneration to the heat production part [3]:

$$y_P = \frac{F_{power-only}}{F} \tag{7}$$

$$y_Q = 1 - \frac{F_{power-only}}{F} \tag{8}$$

where $F_{power\text{-}only}$ is the fuel consumption rate when the power is produced in a power-only plant. Contrary to Method (3), giving the entire benefit of fuel saving by cogeneration to the heat production, this method results in a high value of y_P and a low value of y_Q.

5. Thermoeconomics Methods — based on thermoeconomics as elaborated below.

By analyzing the cost formation process from fuel to the final products, "thermoeconomics" (in that sense) is considered to be the thermodynamically most rational way for allocating costs among the products in a multi-product system. Both exergetic cost, which is the fuel exergy consumption for producing unit product, and monetary cost, can be studied, and following the above-mentioned objective of this paper, only the former is studied here, to analyze the fuel allocation between power and water in a dual-purpose system.

Several thermoeconomic methodologies have been proposed, such as Exergetic Cost Theory [6,7], Functional Approach [8], and Specific-Cost Exergy-Costing Approach [9], and the basic equation of the exergetic cost balance for the methodologies is

$$\Sigma k_{input} E_{input} = \Sigma k_{output} E_{output} \tag{9}$$

where k represents the exergetic cost of an exergy stream, and the subscripts *input* and *output* refer to the exergy streams input to and output from the control volume studied. This equation is suitable for each control volume (may consists of one or several physical components, or a conceptual one), and of course, the whole energy system studied.

Usually, the unit of k is (kJ fuel exergy)/(kJ stream exergy). Other units can also be used according to the specific situation. For instance, in a dual-purpose system, the interest is in the quantity of the produced fresh water, not its exergy. Consequently, in that case the exergetic cost balance equation of a dual-purpose system would be

$$k_f E_f = k_P P_{net} + k_W m_{net} \tag{10}$$

where E_f is the fuel exergy rate consumed, P_{net} is the net power production, m_{net} is the net mass flow rate of produced water, and k_f, k_P, and k_W are the exergetic costs of fuel, power, and fresh water, having the units of (kJ fuel exergy)/(kJ fuel exergy), (kJ fuel exergy)/(kJ power), and (kJ fuel exergy)/(kg fresh water), respectively. Obviously, $k_f = 1$.

Three thermoeconomics-based methods — the basic Exergetic Cost Theory [7], named Method (5), the Functional Approach [9], named Method (6), and the Splitting Factor Method [10], named Method (7) — were applied in this paper, with the details described in Section 4, where all of the pertinent equations are listed. Space does not permit a more detailed description of the principles of all these thermoeconomic methodologies in this paper, but they are known and have been described well [6–10].

Several other methods for fuel allocation have also been proposed, for instance, the proportional saving distribution method [11], which distributed energy saving proportionally on the basis of two comparable single-purpose systems, and the reference cycle method [12], which was based on a reference power plant, and can be categorized as the above-described Method (4). The work loss method [13] and the enthalpy drop method [5] are some of the other allocation methods which are more suitable for use in a steam turbine-based system rather than a gas turbine based one we treat in this paper, and will thus not be discussed or used here.

The objective of this paper is to study the fuel allocation between power and water in a combined steam-injected gas turbine (STIG) power generation and thermal seawater desalination system. The thermal desalination plant used here is a low-temperature multi-effect thermal vapor compression (METVC) unit, which features low corrosion rate, low electrical power consumption and low capital cost compared with commonly used MSF plants [14]. After introducing the configuration of the STIG-METVC system and the parameters of the two sample cases used, seven methods are applied to calculate the fuel allocation. The methods and results are compared and discussed.

2. System configuration and parameters

Fig. 1 schematically shows a STIG-based dual-purpose power and water system, in which part of the saturated steam (10) produced in the heat recovery steam generator (HRSG) run by the exhaust gas (4) from the gas turbine (GT) is used to operate a thermal desalination unit (TDU), and the remainder (11) is superheated and then injec-

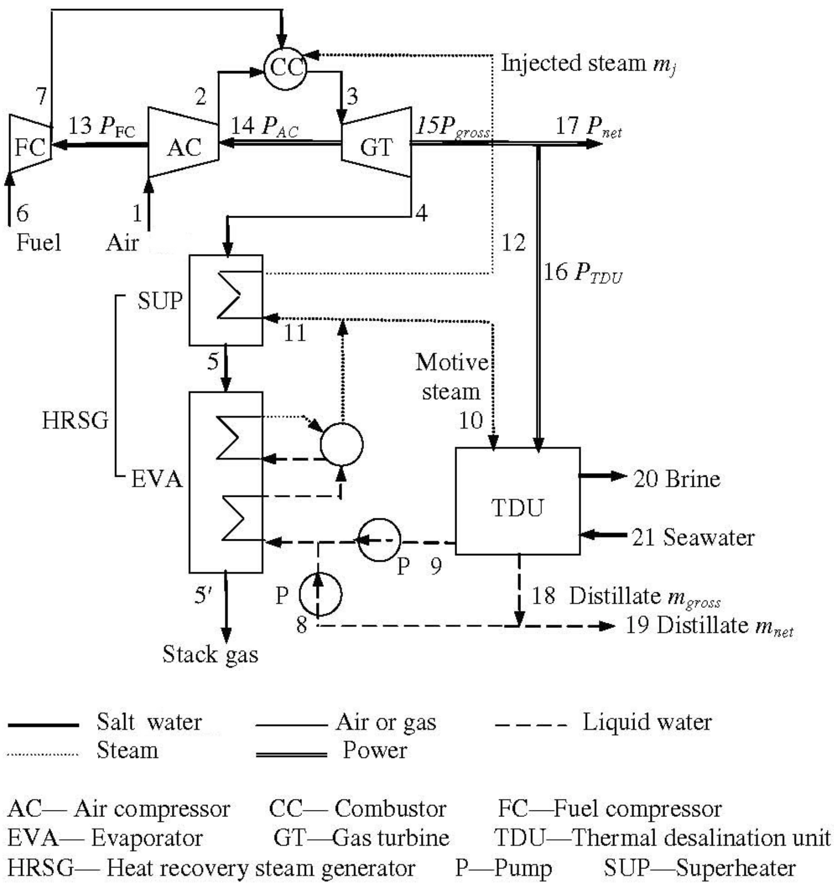


Fig. 1. STIG-based power and water combined system considered in this study.

ted into the combustor (CC) to enhance power output. Fig. 2 schematically illustrates a METVC unit which is the combination of a steam jet ejector and a multi-effect evaporation (MEE) unit.

Compared with conventional (dry) gas turbine plants, STIG plants have advantages such as higher efficiency, higher specific work output, lower NO_x emission, and improved performance at part-load and high ambient temperature [15]. A major disadvantage of STIG plants is high water consumption, which restricts its use, especially in water-short areas. An LM5000 STIG™ plant commercialized by General Electric Co., for instance, consumes about 29 tons water a day per MW power output (1450 tons water per day with a power output of 50.7 MW) when running under a full STIG pattern [16]. Combining STIG with thermal seawater desalination by using the low-level steam produced in the HRSG to run a desalination unit to produce fresh water from seawater for both injection and general use, can not only help solve the water problem for STIG, but more importantly, help obtain good synergy in the power and water production [17]. Because of the high pressure (1MPa or higher) of the steam provided by the STIG plant, a METVC unit was chosen, as previously done [17,18]. The strong influence of the steam mass injection rate on the production ratio of power and water offers also the advantage of good flexibility of design and operation of such combined systems [17]. Detailed information on the characteristics as well as energy and exergy utilization of such a STIG-METVC system can be found in [17], and on the operational model and economics in [18].

The analysis is based on two sample cases, described in Table 1. The performance of the METVC unit used in Case 1 is computed by using the program developed by the authors [17], and that used in Case 2 is based on the cases previously introduced [19,20]. The commercial Aspen Plus [21] code was used to carry out the simulation of the STIG cycle. The computerized models were validated by (1) examining the relative errors of mass and energy balance of each

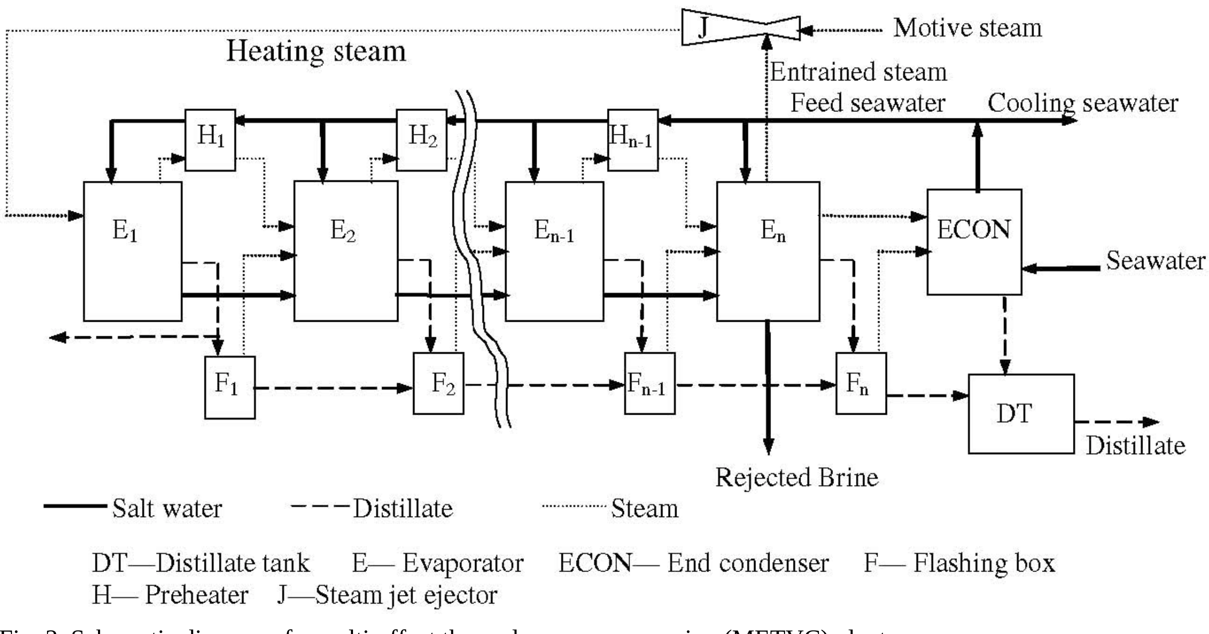


Fig. 2. Schematic diagram of a multi-effect thermal vapor compression (METVC) plant.

Table 1
Calculation conditions of the two STIG-METVC system cases analyzed in this paper

Descriptions	Case 1	Case 2
STIG plant		
Pressure ratio	20	30
Turbine inlet temperature (°C)	1110	1300
Air conditions at the compressor inlet	25°C, 1 atm saturated air	
Dead state for exergy analysis	25°C, 1 atm saturated air; 25°C, 1 atm water	
Fuel	CH_4	
Pressure drop in combustor	3% of inlet pressure	
Pressure drop in superheater	1% of inlet pressure	
Pressure drop in evaporator	2% of inlet pressure	
Pressure drop in stack	1% of inlet pressure	
Combustor efficiency	0.99	
Isentropic efficiency of compressor	0.85	0.88
Isentropic efficiency of gas turbine	0.88	0.90
Minimum pinch point temperature difference in HRSG (°C)	15	15
Minimum temperature difference in superheater (°C)	100	50
Minimum temperature of stack gas (°C)	140	130
Pressure of injected steam (MPa)	2.76	3.5
Mass ratio of injected steam and compressed air	0.06	0.07
METVC unit		
Number of effects	6	12
Pressure of motive steam (MPa)	2.845	3.608
State of motive steam	Saturated steam	Saturated steam
Condensation temperature of heating steam (°C)	72	64.5
Condensation temperature in end condenser (°C)	45.2	37
Pressure of heating steam (MPa)	0.034	0.024
Performance ratio [(kg fresh water)/(kg motive steam)]	9.216	15
Power consumption [kJ/(kg distillate)] [24]	7.2	7.2

component and the entire system, and adjusting the computational conditions till they were found to be $<10^{-4}$, and (2) comparing the simulation results with others [22,23]. For one case [22], our model gave a power output of 44.8 kW and an exergy efficiency of 44.8% under the same calculation conditions, very close to the 44.4 kW and 44.4%; for the other case [23], the corresponding values from our model were 50.0 MW and 37.1%, and those were 50.55 MW and 37.4%.

The parameters obtained, including mass, temperature, pressure and exergy, of each point are shown in Table 2. The results corresponding to each point obtained from fuel allocation Method (5) and Method (7) are also shown in Table 2, with the calculation principles described in detail in Section 4.

3. Fuel allocation between power and water in a STIG-METVC system using Methods (1)-(4)

In a STIG-METVC system, its two subsystems, STIG and METVC, are interconnected. The STIG provides both thermal energy and pumping work for the METVC, and the METVC

Table 2
Parameters of the two STIG-METVC system cases

Descriptions		Thermodynamic parameters				Method (5)	Method (7)			
		m kg/s	T °C	p MPa	E kW	k kJ/kJ	E^P kW	E^Q kW	k^P kJ/kJ	k^Q kJ/kJ
Case 1										
1	Air	1	25	0.101	0	1	0	0	1	1
2	Air	1	477.9	2.026	448.7	2.017	448.7	0	2.327	1
3	Combustion gas	1.078	1110	1.966	1176	1.774	1019	156.4	2.048	1.468
4	Combustion gas	1.078	518.2	0.105	295	1.774	138.3	156.4	2.048	1.468
5	Combustion gas	1.078	496.4	0.104	276.1	1.774	119.7	156.4	2.048	1.468
5	Combustion gas	1.078	140	0.102	58.0	0	43.8	14.1	0	0
6	CH_4	0	25	0.101	941.8	1	712.2	229.6	1	1
7	CH_4	0.018	331.0	2.76	956.1	1.015	726.5	229.6	1.026	1
8	Water	0.06	25	0.101	0	1	0	0	1	1
9	Water	0.114	72	0.034	1.6	3.088	0	1.6	1	2.1
10	Saturated steam	0.114	230.9	2.845	109.2	3.088	0	109.2	1	2.1
11	Saturated steam	0.06	230.9	2.845	57.4	3.088	57.4	0	4.515	1
12	Superheated steam	0.06	418.2	2.76	71.2	2.954	71.2	0	4.176	1
13	Fuel compression work				15.2	1.891	15.2	0	2.182	0
14	Air compression work				478.6	1.891	478.6	0	2.182	0
15	Gas turbine plant work				332.8	1.891	332.8	0	2.182	0
16	TDU work consumption				7.6	1.891	7.6	0	2.182	0
17	Net work output				325.2	1.891	325.2	0	2.182	0
18	TDU water production	1.052				k_W=329.5 kJ/kg			k_W=234 kJ/kg	
19	Net water production	0.992								
Case 2										
1	Air	1	25	0.101	0	1	0	0	1	1
2	Air	1	550.1	3.04	533.9	1.743	533.9	0	1.907	1
3	Combustion gas	1.093	1300	2.949	1491	1.595	1327	163.3	1.746	1.397
4	Combustion gas	1.093	543.4	0.105	334	1.595	170.9	163.3	1746	1.397
5	Combustion gas	1.093	510.7	0.104	305.4	1.595	142	163.3	1.746	1.397
5	Combustion gas	1.093	130	0.102	65.8	0	53.1	12.7	0	0
6	CH_4	0.023	25	0.101	1181	1	953.2	228.3	1	1
7	CH_4	0.023	355.6	3.5	1201	1.013	972.9	228.3	1.02	1
8	Water	0.07	25	3.608	0	1	0	0	1	1
9	Water	0.12	64.5	0.024	1.2	2.696	0	1.2	1	2
10	Saturated steam	0.12	244.3	3.608	117.9	2.696	0	117.9	1	2
11	Saturated steam	0.07	244.3	3.608	68.9	2.696	68.9	0	3.742	1
12	Superheated steam	0.07	493.5	3.5	91.8	2.524	91.8	0	3.356	1
13	Fuel compression work				20.9	1.664	20.9	0	1.821	0
14	Air compression work				559.1	1.664	559.1	0	1.821	0
15	Gas turbine plant work				528.8	1.664	528.8	0	1.821	0
16	TDU work consumption				12.9	1.664	12.9	0	1.821	0
17	Net work output				515.9	1.664	515.9	0	1.821	0
18	TDU water production	1.797				k_W=187.1 kJ/kg			k_W=140.2 kJ/kg	
19	Net water production	1.727								

provides injection water for the STIG. Because the STIG plant itself is a power and heat cogeneration system, Eqs. (1)–(8) can be used first to calculate the fuel allocation ratios of power and heat, y_P and y_Q, and then based on the relation of power, heat and water in the dual-purpose system, the fuel allocation ratios of power and water, z_P and z_W, can be calculated.

Referring to Fig. 1, the power output P, the thermal energy production Q, and the exergy of the thermal energy E_Q, needed in the equations of Methods (1) and (2) are:

$$P = P_{gross} \tag{11}$$

$$Q = m_{10}(h_{10} - h_9) \tag{12}$$

$$E_Q = m_{10}[(h_{10} - h_9) - T_0(s_{10} - s_9)] \tag{13}$$

where h and s are specific enthalpy and entropy, respectively, and T_0 is the temperature of the surroundings (the dead state here).

In Method (3), $F_{heat\text{-}only}$ is needed. Assuming that Q is produced in a fuel-fired boiler with an efficiency of 0.9, then

$$F_{heat-only} = \frac{Q}{0.9 q_f} \tag{14}$$

where q_f is the low heating value of the fuel. Similarly, in Method (4), in order to calculate $F_{power\text{-}only}$, a power-only STIG plant is assumed that produces the same amount of power P as the cogeneration plant, and in which all the steam produced in the HRSG is injected into the combustor at the highest temperature allowed by the working condition of the HRSG (for maximal power efficiency). Aspen Plus [21] was also used here to carry out the simulation and calculate the exergy efficiency ε_e, which is the ratio of the power output to fuel exergy input, of the power-only STIG plant. ε_e of 42.4% and 51.4% was obtained for Case 1 and Case 2, respectively. Then,

$$F_{power-only} = \frac{P}{\varepsilon_e e_f} \tag{15}$$

where e_f is the specific exergy of fuel.

The fuel allocation ratios of power and heat, y_P and y_Q, can be calculated from Eqs. (1)–(8) and (11)–(15), and the results for Case 1 and Case 2 are shown in Table 3. If E_f is the fuel exergy rate input to the combustor, the fuel exergy rate allocated to power and heat production will be:

$$E'_{f,P} = y_P E_f \tag{16}$$

$$E'_{f,Q} = y_Q E_f \tag{17}$$

Fig. 3 illustrates the relation of fuel, power, heat and water in a STIG-METVC system. The fuel exergy E_f is devided into two parts: $E'_{f,P}$ spent on power production P, and $E'_{f,Q}$ on heat production Q. This Q is then, together with a small part of power P_D, used to run the desalination unit, and part of the produced water, m_j, is used as injection water.

To make it possible to properly compare the results from Methods (1)–(4) with those from Methods (5)–(7), the definitions of exergetic cost of power and water production, k_P and k_W [Eq. (10)], are also used here. From Fig. 3, the exergetic cost balance equations of power and water production in a STIG-METVC system are

$$E'_{f,P} + k_W m_j = k_P(P_{net} + P_D) \tag{18}$$

$$E'_{f,Q} + k_P P_D = k_W(m_{net} + m_j) \tag{19}$$

k_P and k_W can thus be obtained from the solution of Eqs. (18) and (19), and then the fuel exergy rate allocated to power and water will be

$$E_{f,P} = k_P P_{net} \tag{20}$$

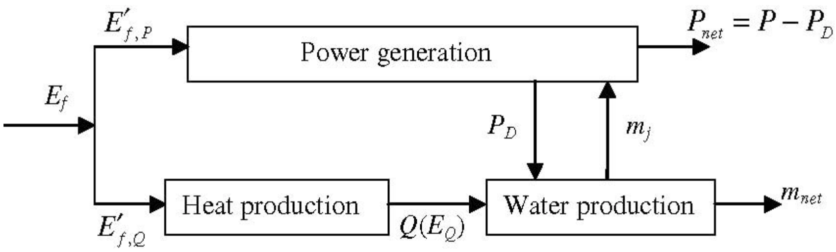


Fig. 3. Relation of fuel, power, heat and water in the STIG-METVC system considered in this study.

Table 3
Fuel allocation in a STIG-METVC system using different allocation methods

Descriptions	y_P %	y_Q %	k_P kJ fuel exergy/(kJ power)	k_W kJ fuel exergy/(kg water)	z_P %	z_W %
Case 1						
(1): Products Energy Method	53.8	46.2	1.638	425	55.2	44.8
(2): Products Exergy Method	75.6	24.4	2.181	234.4	75.3	24.7
(3): Power-Generation-Favored Method	65.2	34.8	1.903	325.3	65.7	34.3
(4): Water-Generation-Favored Method	83.3	16.7	2.444	166.7	82.4	17.6
(5): Basic Exergetic Cost Theory			1.891	329.5	65.3	34.7
(6): Functional Approach			2.065	272.5	71.3	28.7
(7): Splitting Factor Method			2.182	234	75.4	24.6
Case 2						
(1): Products Energy Method	63.6	36.4	1.453	250.1	63.5	36.5
(2): Products Exergy Method	81.9	18.1	1.848	132.2	80.7	19.3
(3): Power-Generation-Favored Method	70.5	29.5	1.603	205.5	70	30
(4): Water-Generation-Favored Method	87.1	12.9	1.959	98.8	85.6	14.4
(5): Basic Exergetic Cost Theory			1.664	187.1	72.7	27.3
(6): Functional Approach			1.773	154.6	77.4	22.6
(7): Splitting Factor Method			1.821	140.2	79.5	20.5

$$E_{f,W} = k_W m_{net} \tag{21}$$

and the fuel allocation ratios, z_P and z_W, of power and water production in a STIG-METVC system will be

$$z_P = E_{f,P} / E_f \tag{22}$$

$$z_W = E_{f,W} / E_f \tag{23}$$

k_P, k_W, z_P and z_W for Methods (1)–(4) can be calculated by the above-described analysis, and the results for Case 1 and Case 2 are shown in Table 3.

It is noteworthy that heat is the major fraction of the METVC unit energy consumption. For instance, in Case 1 the pumping work needed is 7.2 kJ/(kg distillate), while the needed heat is 271.2 kJ/(kg distillate) and the corresponding thermal exergy is 102.3 kJ/(kg distillate).

The results obtained from Methods (3) and (4) set ranges of exergetic costs of power and water, as well as the ranges of the fuel allocation ratios of the two. In Method (3), the thermal energy for desalination is assumed to be provided by a fuel-fired boiler. In fact, the thermal energy for desalination in a dual-purpose system is provided by low-temperature heat from the power plant, and not the high-level chemical energy of fuel as in the conventional boiler. Method (3) hence assigns the upper limit to the fuel consumption for water production, and correspondingly the low limit to the power production. Similarly, by assuming that power is generated in a power-only plant, while in dual-purpose systems part of the fuel consumed is shared by water production, Method (4) assigns the upper limit to the fuel consumption of power, and correspondingly the low limit to the water production. It is thus clear that, the fuel allocation of power and water should be within the ranges set by Methods (3) and (4). An allocation method producing values outside this range will hence be unreasonable.

From Table 3, we can see that, based on the results from Method (3) and Method (4), the ranges of z_P for Case 1 and Case 2 are 65.7%–82.4% and 70%–85.6%, respectively, and correspondingly, that of z_W are 17.6–34.3% and 14.4– 30%, respectively. The values of z_W obtained from Method (1), 44.8% for Case 1 and 36.5% for Case 2, are much higher than the top limits set by Method (3) because in this energy-based method, the fuel consumption for producing 1 kJ power is assumed to be the same as that of producing 1 kJ low-temperature heat, leading to an unreasonably high y_Q of heat production, and then an unreasonably high z_W of water production. The z_W values obtained from Method (2), 24.7% for Case 1 and 19.3% for Case 2, are within the ranges set by Methods (3) and (4), because in this exergy-based method, the fuel consumption of producing 1 kJ power is assumed to be the same with that for producing 1 kJ thermal exergy, which is thermodynamically much more reasonable than Method (1).

4. Fuel allocation between power and water production in a STIG-METVC system using thermoeconomic methods [Methods (5)–(7)]

Several methodologies of thermoeconomic analysis have been proposed, and three of them: the basic Exergetic Cost Theory [7], the Functional Approach [8] and the Splitting Factor Method [10], are used in this study, with calculation principles described in detail in Sections 4.1, 4.2 and 4.3 respectively, and discussions on the methods and results in Section 4.4. All of the variables used in the equations are defined in the nomenclature.

The commercial software EES (Engineering Equation Solver) [25] was used to solve the equation systems of Methods (5)–(7). The mathematical models were validated by (1) checking the balance of the exergetic cost equation of each component where the relative error was found to be $<10^{-5}$, and (2) examining if the results obtained satisfy Eq. (10) which is the exergetic cost equation of the STIG-METVC system and not included in the equation systems solved by EES.

4.1. Fuel allocation using the basic Exergetic Cost Theory [Method (5)]

Based on a set of propositions, the Exergetic Cost Theory [7] allows evaluation of the exergetic cost for each exergy stream, material or not, of an energy system. Following the methodology of the basic Exergy Cost Theory [7], the STIG-METVC system is separated into 7 control volumes: air compressor, fuel compressor, gas turbine, combustor, superheater, evaporator, and desalination unit. The water pumps in the gas turbine plant are not considered because of their negligible influence on the performance of the whole system. The exergetic cost balance equations of each control volume are shown in Table 4. According to previous propositions [7], some supplementary equations are added, to make the equation system solvable.

Table 4
Eqs. (24)–(42) for the basic Exergetic Cost Theory [Method (5)]

Air compressor	$k_1 E_1 + k_{14} E_{14} = k_2 E_2$					(24)
Fuel compressor	$k_6 E_6 + k_{13} E_{13} = k_7 E_7$					(25)
Combustor	$k_2 E_2 + k_7 E_7 + k_{12} E_{12} = k_3 E_3$					(26)
Gas turbine	$k_3 E_3 = k_4 E_4 + k_{13} E_{13} + k_{14} E_{14} + k_{15} E_{15}$					(27)
Superheater	$k_4 E_4 + k_{11} E_{11} = k_5 E_5 + k_{12} E_{12}$					(28)
Evaporator	$k_8 E_8 + k_W m_j + k_9 E_9 + k_5 E_5 = k_{10} E_{10} + k_{11} E_{11} + k_{5'} E_{5'}$					(29)
Thermal desalination unit	$k_8 E_8 + k_W m_j + k_9 E_9 + k_W m_{net} = k_{10} E_{10} + k_{16} E_{16}$					(30)
Supplemental equations	$k_1 = 1$	(31)	$k_6 = 1$	(32)	$k_f = 1$	(33)
	$k_3 = k_4$	(34)	$k_4 = k_5$	(35)	$k_{5'} = 0$	(36)
	$k_8 = 1$	(37)	$k_{10} = k_{11}$	(38)	$k_9 = k_{10}$	(39)
	$k_{13} = k_{14}$	(40)	$k_{13} = k_{15}$	(41)	$k_{16} = k_{15}$	(42)

The equation system was solved using EES [25]. The exergetic costs of each exergy stream obtained are shown in Table 2, and the results of fuel allocation in Table 3.

4.2. *Fuel allocation using the Functional Approach [Method (6)]*

The Functional Approach method [8] is based on the division of exergy, the concept of junctions and distributors of exergy, and the definition of the function of each component in the energy system. Following this methodology, Fig. 4 shows the functional diagram of the STIG-METVC system.

The function of the air compressor (unit 1) is to increase the exergy of air from state 1 to state 2, which consists of thermal and mechanical exergy (due to temperature and pressure increase respectively):

$$r_1 = E_2 - E_1 = (E_2^T - E_1^T) + (E_2^M - E_1^M) \quad (43)$$

where E_i^T and E_i^M represent thermal exergy and mechanical exergy in exergy stream i, respectively. Taking air as ideal gas, then

$$E_2^T - E_1^T = m_a \left[\int_{T_1}^{T_2} c_{pa} \mathrm{d}T - T_0 \int_{T_1}^{T_2} c_{pa} \frac{\mathrm{d}T}{T} \right] \quad (44)$$

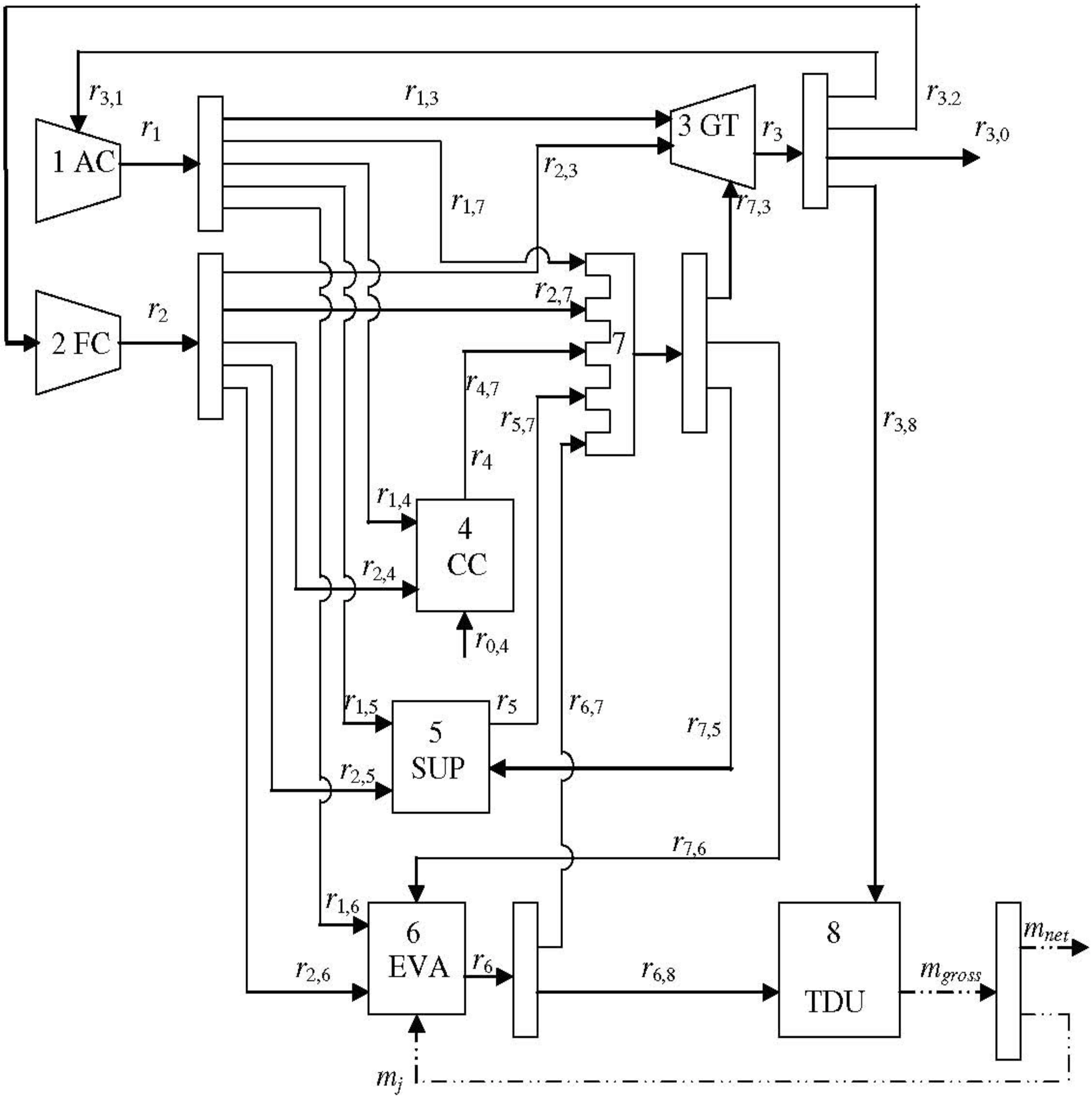
that is combined with thermal exergy from the combustor and HRSG in the junction (unit 7, which is conceptual, i.e. it does not correspond to a real component of the plant), and

$$E_2^M - E_1^M = m_a R_a T_0 \ln \frac{p_2}{p_1} \quad (45)$$

that is distributed to (consumed by) the combustor, the gas turbine and the HRSG [Eqs. (47)–(50) in Table 5].

Similar to the air compressor, the function of the fuel compressor (Unit 2) is to increase the exergy of the fuel and the corresponding equations are shown by Eqs. (52)–(57).

The function of the gas turbine (Unit 3) is to produce shaft power, r_3 [Eq.(58)], by using mechanical exergy $r_{1,3}$ and $r_{2,3}$ [Eqs. (47) and (53)] and thermal exergy $r_{7,3}$ [Eq. (72)].



AC (Unit 1)—Air compressor FC (Unit 2)—Fuel compressor GT (Unit 3)—Gas turbine
CC (Unit 4)—Combustor SUP (Unit 5)—Superheater EVA (Unit 6)—Evaporator
JUN (Unit 7)—Junction TDU (Unit 8)—Thermal desalination unit

Fig. 4. Functional diagram of the STIG-METVC system considered in this study.

Table 5
Eqs. (46)–(100) for the Functional Approach [Method (6)]

Function equations	$r_1 = E_2 - E_1$	(46)	$r_{1,3} = m_a R_a T_0 \ln \frac{p_2}{p_3}$	(47)	$r_{1,4} = m_a R_a T_0 \ln \frac{p_3}{p_4}$	(48)
	$r_{1,5} = m_a R_a T_0 \ln \frac{p_4}{p_5}$	(49)	$r_{1,6} = m_a R_a T_0 \ln \frac{p_5}{p_{5'}}$	(50)	$r_{1,7} = E_2^T - E_1^T$	(51)
	$r_2 = E_7 - E_6$	(52)	$r_{2,3} = m_f R_f T_0 \ln \frac{p_7}{p_3}$	(53)	$r_{2,4} = m_f R_f T_0 \ln \frac{p_3}{p_4}$	(54)
	$r_{2,5} = m_f R_f T_0 \ln \frac{p_4}{p_5}$	(55)	$r_{2,6} = m_f R_f T_0 \ln \frac{p_5}{p_{5'}}$	(56)	$r_{2,7} = E_7^T - E_6^T$	(57)
	$r_3 = E_{13} + E_{14} + E_{15}$	(58)	$r_{3,1} = E_{13}$	(59)	$r_{3,2} = E_{14}$	(60)
	$r_{3,8} = E_{16}$	(61)	$r_{3,0} = r_3 - r_{3.1} - r_{3.2} - r_{3.8}$	(62)		
	$r_{0,4} = E_f$	(63)	$r_4 = E_3^T - E_2^T - E_7^T - E_{12}$	(64)		
	$r_{4,7} = r_4$	(65)	$r_5 = E_{12} - E_{11}$	(66)		
	$r_{5,7} = r_5$	(67)	$r_6 = E_{10} + E_{11} - E_8 - E_9$	(68)		
	$r_{6,7} = E_{11} - E_8$	(69)	$r_{6,8} = E_{10} - E_9$	(70)		
	$r_7 = E_3^T - E_{5'}^T$	(71)	$r_{7,3} = E_3^T - E_4^T$	(72)		
	$r_{7,5} = E_4^T - E_5^T$	(73)	$r_{7,6} = E_5^T - E_{5'}^T$	(74)		
Exergetic cost balance equations	AC: $k_P r_{3,1} = k_{r_1} r_1$	(75)	$k_{r_{1,3}} = k_{r_1}$	(76)	$k_{r_{1,4}} = k_{r_1}$	(77)
	$k_{r_{1,5}} = k_{r_1}$	(78)	$k_{r_{1,6}} = k_{r_1}$	(79)	$k_{r_{1,7}} = k_{r_1}$	(80)
	FC: $k_P r_{3,2} = k_{r_2} r_2$	(81)	$k_{r_{2,3}} = k_{r_2}$	(82)	$k_{r_{2,4}} = k_{r_2}$	(83)
	$k_{r_{2,5}} = k_{r_2}$	(84)	$k_{r_{2,6}} = k_{r_2}$	(85)	$k_{r_{2,7}} = k_{r_2}$	(86)
	GT: $k_{r_{1,3}} r_{1,3} + k_{r_{2,3}} r_{2,3} + k_{r_{7.3}} r_{7,3} = k_P r_3$			(87)		
	CC: $k_{r_{1,4}} r_{1,4} + k_{r_{2,4}} r_{2,4} + k_{r_{0.4}} r_{0,4} = k_{r_4} r_4$			(88)	$k_{0,4} = 1$	(89)
	$k_{r_{4,7}} = k_{r_4}$			(90)		
	SUP: $k_{r_{1,5}} r_{1,5} + k_{r_{2,5}} r_{2,5} + k_{r_{7.5}} r_{7,5} = k_{r_5} r_5$			(91)	$k_{r_{5,7}} = k_{r_5}$	(92)
	EVA: $k_{r_{1,6}} r_{1,6} + k_{r_{2,6}} r_{2,6} + k_{r_{7.6}} r_{7,6} + k_W m_j = k_{r_6} r_6$					(93)
	$k_{r_{6,7}} = k_{r_6}$			(94)	$k_{r_{6,8}} = k_{r_6}$	(95)
	JUN: $k_{r_{1,7}} r_{1,7} + k_{r_{2,7}} r_{2,7} + k_{r_{4.7}} r_{4,7} + k_{r_{5,7}} r_{5,7} + k_{r_{6,7}} r_{6,7} = k_{r_7} r_7$					(96)
	$k_{r_{7,3}} = k_{r_7}$	(97)	$k_{r_{7,5}} = k_{r_7}$	(98)	$k_{r_{7,6}} = k_{r_7}$	(99)
	TDU: $k_P r_{3,8} + k_{r_{6,8}} r_{6,8} = k_W m_{gross}$			(100)		

Table 6
Values of exergy streams and exergetic costs from Method (6)

r (kW)	Case 1	Case 2	r (kW)	Case 1	Case 2	k[a]	Case 1	Case 2	k[a]	Case 1	Case 2
r_1	448.7	533.9	$r_{3,0}$	325.2	515.9	k_{r_1}	2.202	1.857	$k_{r_{0,4}}$	1	1
$r_{1,3}$	253.3	288.4	$r_{3,8}$	7.6	12.9	$k_{r_{1,3}}$	2.202	1.857	k_{r_4}	1.472	1.399
$r_{1,4}$	2.6	2.6	$r_{0,4}$	941.8	1181	$k_{r_{1,4}}$	2.202	1.857	$k_{r_{4,7}}$	1.472	1.399
$r_{1,5}$	0.9	0.9	r_4	645.0	848.6	$k_{r1,5}$	2.202	1.857	k_{r_5}	2.492	2.079
$r_{1,6}$	2.6	2.6	$r_{4,7}$	645.0	848.6	$k_{r_{1,6}}$	2.202	1.857	$k_{r_{5,7}}$	2.492	2.079
$r_{1,7}$	189.3	239.3	r_5	13.8	23.0	$k_{r_{1,7}}$	2.202	1.857	k_{r_6}	2.518	2.184
r_2	14.3	19.7	$r_{5,7}$	13.8	23.0	k_{r_2}	2.198	1.833	$k_{r_{6,7}}$	2.518	2.184
$r_{2,3}$	8.2	11.7	r_6	165.0	185.6	$k_{r_{2,3}}$	2.198	1.883	$k_{r_{6,8}}$	2.518	2.184
$r_{2,4}$	1.0	0.6	$r_{6,7}$	57.4	68.9	$k_{r_{2,4}}$	2.198	1.883	k_{r_7}	1.826	1.644
$r_{2,5}$	0.03	0.04	$r_{6,8}$	107.6	116.7	$k_{r_{2,5}}$	2.198	1.883	$k_{r_{7,3}}$	1.826	1.644
$r_{2,6}$	0.09	0.1	r_7	852.5	1121	$k_{r_{2,6}}$	2.198	1.883	$k_{r_{7,5}}$	1.826	1.644
$r_{2,7}$	5.0	7.2	$r_{7,3}$	619.3	856.4	$k_{r_{2,7}}$	2.198	1.883	$k_{r_{7,6}}$	1.826	1.644
r_3	826.5	1109	$r_{7,5}$	17.7	28.0	k_p	2.065	1.773	k_W	272.5	154.6
$r_{3,1}$	478.6	559.1	$r_{7,6}$	215.4	236.8						
$r_{3,2}$	15.2	20.9									

[a]The units of k_{r_i} and $k_{r_{i,j}}$ are: kJ fuel exergy/(kJ stream exergy), those of k_P are: kJ fuel exergy/(kJ power), and those of k_W are: kJ fuel exergy/(kg water).

The combustor increases the thermal exergy of the working fluid [Eq. (64)] by consuming the fuel chemical exergy [Eq. (63)], and the combustor function is given to the junction (Unit 7) [Eq. (65)].

The HRSG, composed of superheater and evaporator (Units 5 and 6), increases the thermal exergy of water/steam [Eqs. (66) and (68)] by using the thermal exergy from the exhaust gas [Eqs. (73) and (74)], and part of the output, $r_{6,8}$ [Eq. (70)], is used to run the thermal desalination unit, and part, $r_{5.7}$ and $r_{6,7}$ [Eqs. (67) and (69)], to the junction.

The function of the junction is to increase the thermal exergy of the working fluid from state 1 to the maximum state (State 3). However, only part of this increase, r_7 [Eq. (71)], is used in the system, while the rest is rejected to the environment. This is an external irreversibility, which occurs in the interaction of the energy system with the environment, in the STIG-METVC system being the irreversibility of the process in which the stack gas at State 5 eventually reaches both physical and chemical equilibrium with the ambient.

Table 5 shows the functional equations [Eqs. (46)–(74)] and the exergetic cost balance equations [Eqs. (75)–(100)] of the STIG-METVC system based on Method (6). Solving the equation system by using EES [25] gives the values of r and the corresponding exergetic costs shown in Table 6, and those of the fuel allocation to power and water production shown in Table 3.

4.3. Fuel allocation using the Splitting Factor Method [Method (7)]

The Splitting Factor Method [10] is based on the definition of the contribution of each physical component in the system. According to this method, some of the components in the gas turbine-based power-heat cogeneration system are exclusively assigned to power production, and their exergetic or monetary cost is charged to power only. A typical example is the air compressor, in which the mechanical work (exergy) is used for compressing air, so as to make it possible for the working fluid to expand in the gas turbine and thus produce power. This compression process in this specific system is unnecessary for heat production because only liquid is pumped in a conventional heat-only boiler, thus requiring very little energy. The compression irreversibility raises the air temperature at the compressor outlet, which reduces fuel consumption; this fuel reduction is considered to influence only the fuel consumption of power production.

Splitting factors are defined for each component according to the extent that the component serves the production of the final products. For instance, the splitting factors of the air compressor for power and heat production are $x_{AC}^P = 1$ and $x_{AC}^Q = 0$, whereby the cost of irreversibility and the consumed mechanical work of the air compression process is charged only to power generation. Each exergy stream in the system is thereby divided into two parts, one for power and the other for heat generation:

$$E_i = E_i^P + E_i^Q = x_i^P E_i + x_i^Q E_i \tag{101}$$

where E_i^P and E_i^Q are the exergy of E_i distributed to power and heat production, respectively, and x_i^P and x_i^Q are the corresponding splitting factors.

The first step of the method is to define the function of each component. In a STIG-based cogeneration system, the air compressor, fuel compressor, gas turbine, and superheater are assumed to serve only power production because it is unnecessary to use these components in the heat production process, while the combustor and evaporator serve both power and heat production. The splitting factors of each component are shown in Table 7 [Eqs. (102)–(111)]. The contribution allocations of the evaporator to power and heat production is defined according to the exergy obtained by the injection steam for power generation [Eq. (110)], and the motive steam for desalination [Eq. (111)], respectively. Based on the definition of the function of each component, Fig. 5 schematically illustrates the exergy streams related to the power and heat production of the STIG plant.

The second step is to determine the exergy split of each stream, as shown in Table 7 [Eqs. (112)–(147)]. The method for obtaining these equations can be found in the literature [10]. Here, the external irreversibility between power and heat is split based on the percentage of the fuel allocated to each [Eqs. (130) and (131)].

The third step is to define the exergetic cost balance equations separately for heat and power production, as shown by Eqs. (148)–(159) which are obtained for the configuration shown in Fig. 5. To make the equation system solvable, several supplemental equations [(161)–(170] are added by applying the propositions of the Exergetic Cost Theory [7]. The power, heat and water production are linked by the equations of the evaporator [Eqs. (158) and (159)] that provides motive steam for desalination and accepts fresh water from the desalination unit for injection into the combustor, and of the desalination unit [Eq. (160)] that consumes heat and power for water production and provides fresh water for injection into the combustor.

The equation system was solved using EES [25]. The resulting values of E_i^P and E_i^Q, as well as the corresponding exergetic cost k_i^P and k_i^Q, of each point in the system are shown in

Table 7
Eqs. (102)–(170) for the Splitting Factors Method [Method (7)]

Splitting factors for components	AC: $x_{AC}^{P}=1$ (102) $x_{AC}^{Q}=0$ (103) FC: $x_{FC}^{P}=1$ (104) $x_{FC}^{Q}=0$ (105)
	GT: $x_{GT}^{P}=1$ (106) $x_{GT}^{Q}=0$ (107) SUP: $x_{SUP}^{P}=1$ (108) $x_{SUP}^{Q}=0$ (109)
	EVA: $x_{EVA}^{P}=(E_{11}-E_{8})/(E_{11}-E_{8}+E_{10}-E_{9})$ (110)
	$x_{EVA}^{Q}=(E_{10}-E_{9})/(E_{11}-E_{8}+E_{10}-E_{9})$ (111)
Exergy splitting of streams	Based on AC: $E_{2}^{P}=E_{1}^{P}+x_{AC}^{P}(E_{2}-E_{1})$ (112) $E_{2}^{Q}=E_{1}^{Q}+x_{AC}^{Q}(E_{2}-E_{1})$ (113)
	$E_{1}^{P}=x_{AC}^{P}E_{1}$ (114) $E_{1}^{Q}=x_{AC}^{Q}E_{1}$ (115)
	Based on FC: $E_{7}^{P}=E_{6}^{P}+x_{FC}^{P}(E_{7}-E_{6})$ (116) $E_{7}^{Q}=E_{6}^{Q}+x_{FC}^{Q}(E_{7}-E_{6})$ (117)
	$E_{6}^{P}=x_{FC}^{P}E_{6}$ (118) $E_{6}^{Q}=x_{FC}^{Q}E_{6}$ (119)
	Based on CC: $E_{3}^{P}=E_{2}^{P}+E_{7}^{P}+E_{12}^{P}+y_{P}(E_{3}-E_{2}-E_{7}-E_{12})$ (120)
	$E_{3}^{Q}=E_{2}^{Q}+E_{7}^{Q}+E_{12}^{Q}+y_{Q}(E_{3}-E_{2}-E_{7}-E_{12})$ (121)
	Based on GT: $E_{4}^{P}=E_{3}^{P}-x_{GT}^{P}(E_{3}-E_{4})$ (122) $E_{4}^{Q}=E_{3}^{Q}-x_{GT}^{Q}(E_{3}-E_{4})$ (123)
	Based on SUP: $E_{5}^{P}=E_{4}^{P}-x_{SUP}^{P}(E_{4}-E_{5})$ (124) $E_{5}^{Q}=E_{4}^{Q}-x_{SUP}^{Q}(E_{4}-E_{5})$ (125)
	$E_{12}^{P}=E_{11}^{P}+x_{SUP}^{P}(E_{12}-E_{11})$ (126) $E_{12}^{Q}=E_{11}^{Q}+x_{SUP}^{Q}(E_{12}-E_{11})$ (127)
	Based on EVA: $E_{5'}^{P}=E_{5}^{P}-x_{EVA}^{P}(E_{5}-E_{5'})$ (128) $E_{5'}^{Q}=E_{5}^{Q}-x_{EVA}^{Q}(E_{5}-E_{5'})$ (129)
	Emission loss: $E_{5'}^{P}=y_{P}E_{5'}$ (130) $E_{5'}^{Q}=y_{Q}E_{5'}$ (131)
	Others:
	$E_{8}^{P}=E_{8}$ (132) $E_{9}^{P}=0$ (133) $E_{10}^{P}=0$ (134) $E_{11}^{P}=E_{11}$ (135)
	$E_{13}^{P}=E_{13}$ (136) $E_{14}^{P}=E_{14}$ (137) $E_{8}^{Q}=0$ (138) $E_{9}^{Q}=E_{9}$ (139)
	$E_{10}^{Q}=E_{10}$ (140) $E_{11}^{Q}=0$ (141) $E_{13}^{Q}=0$ (142) $E_{14}^{Q}=0$ (143)
	$E_{15}^{P}=E_{15}$ (144) $E_{15}^{Q}=0$ (145) $E_{16}^{P}=E_{16}$ (146) $E_{16}^{P}=0$ (147)
Exergetic cost equations	AC: $k_{1}^{P}E_{1}^{P}+k_{P}E_{14}^{P}=k_{2}^{P}E_{2}^{P}$ (148) $k_{1}^{Q}E_{1}^{Q}=k_{2}^{Q}E_{2}^{Q}$ (149)
	FC: $k_{6}^{P}E_{6}^{P}+k_{P}E_{13}^{P}=k_{7}^{P}E_{7}^{P}$ (150) $k_{6}^{Q}E_{6}^{Q}=k_{7}^{Q}E_{7}^{Q}$ (151)
	CC: $k_{2}^{P}E_{2}^{P}+k_{7}^{P}E_{7}^{P}+k_{12}^{P}E_{12}^{P}=k_{3}^{P}E_{3}^{P}$ (152) $k_{2}^{Q}E_{2}^{Q}+k_{7}^{Q}E_{7}^{Q}=k_{3}^{Q}E_{3}^{Q}$ (153)
	GT: $k_{3}^{P}E_{3}^{P}=k_{4}^{P}E_{4}^{P}+k_{P}(E_{13}^{P}+E_{14}^{P}+E_{15}^{P})$ (154) $k_{3}^{Q}E_{3}^{Q}=k_{4}^{Q}E_{4}^{Q}$ (155)
	SUP: $k_{4}^{P}E_{4}^{P}+k_{11}^{P}E_{11}^{P}=k_{5}^{P}E_{5}^{P}+k_{12}^{P}E_{12}^{P}$ (156) $k_{5}^{Q}E_{5}^{Q}=k_{4}^{Q}E_{4}^{Q}$ (157)
	EVA: $k_{8}^{P}E_{8}^{P}+k_{W}m_{j}+k_{5}^{P}E_{5}^{P}=k_{11}^{P}E_{11}^{P}+k_{5'}^{P}E_{5'}^{P}$ (158)
	$k_{9}^{Q}E_{9}^{Q}+k_{5}^{Q}E_{5}^{Q}=k_{10}^{Q}E_{10}^{Q}+k_{5'}^{Q}E_{5'}^{Q}$ (159)
	TDU: $k_{8}^{P}E_{8}^{P}+k_{W}m_{j}+k_{9}^{Q}E_{9}^{Q}+k_{W}m_{net}=k_{10}^{Q}E_{10}^{Q}+k_{P}E_{16}^{P}$ (160)
	Supplemental equations:
	$k_{1}^{P}=1$ (161) $k_{6}^{P}=1$ (162) $k_{5'}^{P}=0$ (163) $k_{3}^{P}=k_{4}^{P}$ (164)
	$k_{1}^{Q}=1$ (165) $k_{6}^{Q}=1$ (166) $k_{5'}^{Q}=0$ (167) $k_{4}^{P}=k_{5}^{P}$ (168)
	$k_{8}^{P}=1$ (169) $k_{10}^{Q}=k_{9}^{Q}$ (170)

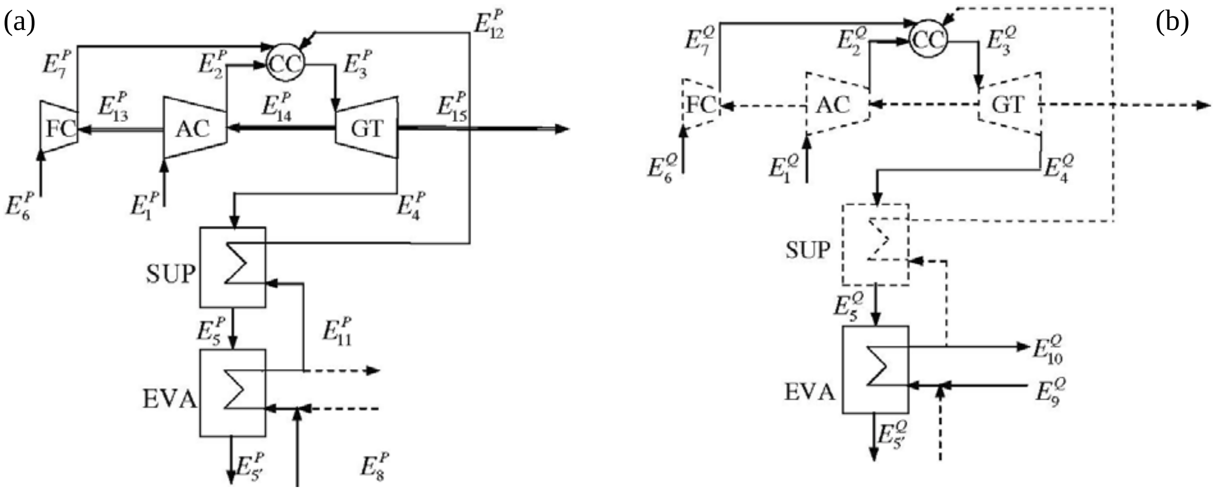


Fig. 5. Flowsheets showing the separate generation of power and thermal energy. (a) Exergy stream flowsheet for power generation. (b) Exergy stream flowsheet for heat production. The dashed lines represent components/streams that have no role in the production of the desired product.

Table 2, and those of the fuel allocation to power and water are shown in Table 3.

4.4. Discussion on the results obtained from the three thermoeconomic methods

As seen in Table 3, the results obtained from the three thermoeconomic methods are different from each other. The exergetic costs and fuel allocation ratios using Method (5) for the power are the lowest, and those of the water the highest. Contrarily, Method (7) produces the highest values for power, and the lowest for water. The values from Method (6) fall in the middle of the two.

From Method (5), in Case 1, z_W equals to 34.7%, higher than the high limit, 34.3%, set by method (3), and correspondingly, k_W equals to 329.5kJ/kg, higher than that of the boiler-run water-only unit, 325.3kJ/kg. Based on the discussion in Section 3, Method (5) is thus considered to be unsuitable for use in the STIG-METVC system. In Case 2, even though z_W, 27.3%, is within the range, 14.4%–30%, set by Method (3) and Method (4), we thus feel that it is higher than the value should be. To ascertain this point, we calculated several additional cases. One case is based on the same conditions as Case 1 except that the steam injection rate (the mass flow ratio of the injected steam to that of the compressor inlet air), is higher, 0.082 kg/(kg air) rather than 0.06 kg/(kg air), resulting in a k_W of 357.6 kJ/kg, much higher than the 325.3 kJ/kg consumed in the water-only system. Another case has the same conditions as Case 2 except that steam injection rate is again higher, 0.10 kg/(kg air) rather than 0.07 kg/(kg air), resulting in a k_W of 202.6kJ/kg, only slightly lower than the 205.5kJ/kg of a water-only system. It is thus clear that, from the above analysis, Method (5) produces much lower k_p and z_p, and correspondingly, much higher k_w and z_w than should be, so is not suitable for use in the fuel allocation of a STIG-METVC system.

In Method (6), k_p and z_p increase and k_w and z_w decrease compared to those obtained from Method (5). The reasons for this are twofold. First, the exergy is divided into mechanical and thermal parts in Method (6), which makes it possible to define the contribution of different parts of exergy to power and heat production, as shown in Fig. 4 and by Eqs. (46)–(74). Steam production in the evaporator consumes mainly thermal exergy which is mainly produced by the combustor at the expense of fuel with relatively low exergetic cost (k_f = 1), resulting in a lower exergetic cost of the saturated steam (State 10), and then a lower k_w and z_w, while the gas turbine consumes most of the mechanical exergy which has a higher exergetic cost than thermal exergy, resulting in a higher k_p and then a higher z_p. Second, the external irreversibility is shared by power and heat through the junction in Method (6). From Fig. 4 and Table 5, the exergy input to the junction is $E_3^T - E_6^T - E_1^T - E_8$, while the exergy output is $r_7 = E_3^T - E_5^T$, lower than the input value. The difference between the two is caused by the external irreversibility, which increases the exergetic cost of r_7. r_7 is consumed in the gas turbine and HRSG, thus assigning the external irreversibility to power and heat more reasonably than Method (5). In Method (5), by setting the exergetic cost of the stack gas (state 5) to zero [Eq. (36)], according to the proposition of the methodology [7], the external irreversibility is assigned only to the evaporator, causing a higher exergetic cost of the saturated steam produced [Eq. (29)], and then a higher exergetic cost of fresh water.

Similarly, the reasons for the higher k_p and z_p and lower k_w and z_w with Method (7) than Method (5) are mainly also two. The exergy is also divided into two parts in Method (7): one part for power and the other for heat production. The division is based on the definition of the contribution of each component in the system to the production of the two products. This is different from Method (6), in which the exergy is divided into mechanical and thermal parts, and heat production is considered to consume mainly thermal exergy and power production the both. As to the distribution of the external irreversibility, Method (7) applies a very rational way, as indicated in Section 4.3, which is based on the fuel allocation ratios between power and heat.

The results obtained from Methods (6) and (7) are within the ranges set by Methods (3) and (4) mainly because that, as discussed above, the split of exergy makes it possible to define the contribution of different parts of exergy with different exergetic costs to power and heat production, and the existence of the junction [in Method (6)] or the definition of the emission loss according to the fuel allocation ratios [in Method (7)] results in a more reasonable distribution of the external irreversibility.

Clearly, different thermoeconomic methods produce different results, of which some are rational, and some not. It is very difficult to evaluate the reasons for the differences in the results obtained by the different thermoeconomics-based methods because they differ in their foundations. The readers are referred to the literature [26] to find relevant discussions. The Functional Approach, the Exergetic Cost Theory, the Disaggregating Methodology, the Exergoeconomics Methodology, and their variations, were applied to calculate the cost of power and heat in a simple gas turbine cogeneration system, and the result changes from \$6.95/kJ to \$8.18/kJ for power and \$15.6/kJ to \$7/kJ for heat [26]. The great difference between the results from different thermoeconomic methods in [26] and this paper indicates that more comparison, evaluation and unification work is needed in the thermoeconomics field.

It is noteworthy that, as seen in Table 3, the results from Method (2) are the closest to those from Methods (6) and (7). More information is needed to perform a thermoeconomic analysis, including not only the basic information such as power output, water production, fuel consumption and desalination work consumption of the system, but also detailed information such as temperature, pressure, mass rate and composition of each point in the system. When there is not enough information available, the results from Method (2) can be taken as an approximation, because: (a) this method is thermodynamically more reasonable than Methods (1), (3) and (4); (b) the results from Method (2) are within the ranges set by Methods (3) and (4), and very close to those from Methods (6) and (7); (c) only the basic information of the system is needed to perform the calculation [Eqs. (3), (4), (11), (13), (16)–(23)]. This approach can thus be taken for the monetary cost evaluation of fuel consumption of the two products when full thermoeconomic analysis is impossible due to insufficient information. Similarly, Method (2) also provides an approximate way to allocate the pollutant emission caused by fuel combustion.

The analysis above was done on the STIG-METVC system, but the basic (though not the specific quantitative) conclusions should be applicable to other combined power and thermal desalination systems based on gas turbine cycles (e.g., humid air turbine cycle, simple gas turbine cycle, regenerative gas turbine cycle) because very similar components, processes, and operating conditions are used.

5. Conclusions

Seven methods are used in this paper to study the fuel allocation between power and water in a STIG-METVC system. Method (1), the Products Energy Method, is deficient since it treats power and heat equally. Method (2), the Products Exergy Method, is more reasonable since it considers the quality difference between power and heat by treating power and thermal exergy equally. Method (3), the Power-Generation-Favored Method, in which the desalination unit is assumed to be run by the thermal energy from a conventional boiler with the pumping work obtained from a power plant, sets the upper limit of fuel allocation to the water production. Method (4), the Heat-Generation-Favored Method, in which power is assumed to be generated in a power-only plant, sets the low limit of fuel allocation to the water production. Methods (3) and (4) are not suitable for use in fuel allocation of a STIG-METVC system, but they set the range within which the fuel allocation values must reside. Method (5), the Basic Exergetic Cost Theory [7], Method (6), the Functional Approach [8], and Method (7), the Splitting Factor Method [10], are all thermoeconomics-based, but only the latter two gave reasonable results, as discussed in Section 4. So although thermoeconomic methodologies are considered to be the most rational, false conclusions could be reached if they are not suitably used.

The calculation results of two sample cases show that different allocation methods produce very different results [for example, the fuel allocation ratio to water production in Case 1 is 44.8% using Method (1), and 17.6% using Method (4)], which emphasizes the importance of understanding the fuel allocation methods and choosing the suitable one.

Based on this study, and until more fundamental and general knowledge becomes available, we recommend the following fuel cost allocation procedure for dual-purpose desalination plants:

- Calculate the fuel allocation using Methods (3) and (4) to determine the upper and lower limits, respectively, of fuel allocation to the power and water production,
- Then use thermoeconomic Method (6) and/or Method (7) or other thermoeconomic methods, depending on the specific application, to find the fuel allocation between the above two limits.

When sufficient information is unavailable for performing a thermoeconomic analysis, Method (2) can be taken as an approximation on fuel consumption allocation, as well as of the distribution of fuel cost and combustion pollutant emission, between power and water.

Although the calculation and analysis were done specifically on the STIG-METVC system, the basic conclusions (though not the specific quantitative ones) are applicable to other gas turbine thermal desalination dual purpose systems.

6. Symbols

c_{pa} — Specific heat of air at constant pressure [kJ/(kg•K)]
e_f — Specific exergy of fuel [kJ/kg]
E — Exergy rate[kW]
E_f — Fuel exergy rate [kW]
$E_{f,P}$ — Fuel exergy rate allocated to power production in a dual-purpose system [kW]
$E_{f,W}$ — Fuel exergy rate allocated to water production in a dual-purpose system [kW]
$E'_{f,P}$ — Fuel exergy rate allocated to power in a power+heat cogeneration system [kW]
$E'_{f,Q}$ — Fuel exergy rate allocated to heat in a power+heat cogeneration system [kW]
E_Q — Exergy of thermal energy rate Q [kW]
E_i^P — Exergy rate allocated to power production in exergy stream *i* [kW]
E_i^Q — Exergy rate allocated to heat production in exergy stream *i* [kW]
E_i^M — Mechanical exergy in exergy stream *i* [kW]
E_i^T — Thermal exergy in exergy stream *i* [kW]
F — Fuel mass rate [kg/s]
$F_{heat\text{-}only}$ — Fuel consumption rate of a boiler-run heat-only system [kg/s]
$F_{power\text{-}only}$ — Fuel consumption rate of a power-only plant [kg/s]
h — Specific enthalpy [kJ/kg]
k_i — Exergetic cost of exergy stream *i* [(kJ fuel exergy)/(kJ stream exergy)]
k_P — Exergetic cost of power [(kJ fuel exergy)/(kJ power)]
k_W — Exergetic cost of fresh water [(kJ fuel exergy/(kg distillate)
k_i^P — Exergetic cost of E_i^P [(kJ fuel exergy)/(kJ stream exergy)]
k_i^Q — Exergetic cost of E_i^Q [(kJ fuel exergy)/(kJ stream exergy)]
m — Mass flow rate [kg/s]
m_j — Mass rate of injection steam [kg/s]
m_{gross} — Gross mass rate of produced water in a dual-purpose system [kg/s]
m_{net} — Net mass rate of produced water in a dual-purpose system [kg/s]
p — Pressure [MPa]
$P(P_{gross})$ — Power production in a power+heat cogeneration system [kW]
P_D — Power consumption of desalination unit [kW]
P_{net} — Power production of a dual-purpose system [kW]
q_f — Low heat value of fuel [kJ/kg]
Q — Heat production rate in a power + heat cogeneration system [kW]
r_i — Exergy stream from unit *i* [kW]
$r_{i,j}$ — Exergy stream going from unit *i* to unit *j* [kW]
R_a — Gas constant of air [kJ/(kg•K)]
R_f — Gas constant of fuel [kJ/(kg•K)]
s — Specific entropy [kJ/(kg•K)]
T — Temperature [°C] [K]
T_0 — Temperature of the ambient [K]
x_i^P — Exergy splitting factor of power production in exergy stream or component *i*
x_i^Q — Exergy splitting factor of heat production in exergy stream or component *i*
y_P — Fuel allocation ratio of power production in a power + heat cogeneration system [%]
y_Q — Fuel allocation ratio of heat production in a power + heat cogeneration system [%]
z_P — Fuel allocation ratio of power production in a dual-purpose system [%]
z_W — Fuel allocation ratio of water production in a dual-purpose system [%]
ε_e — Exergy efficiency of power-only plant [%]

Acknowledgement

The authors gratefully acknowledge the support of the National Natural Science Foundation of China (Project No. 50676023) and the Science Foundation of Jimei University, China.

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