Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2016.1152511

57 (2016) 26552–26561
November

Thermoeconomic analysis of combined power cycle integrated with MSF/SWRO desalination plant

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Received 25 November 2015; Accepted 4 February 2016

ABSTRACT

A comprehensive thermo-economic study based on the exergy accounting method is conducted to evaluate the performance of a combined gas/steam power generation system integrated with a hybrid multistage flash (MSF)/sea water reverse osmosis (SWRO) desalination plants. The plant consists of five combined power generation cycles. Each cycle incorporates, two gas turbines (GT), two heat recovery steam generators, and one steam turbine. The total power generated is 2,645.5 MW. The combined power generation cycles are integrated with a hybrid MSF/SWRO desalination plant with a total water production of 1,000,000 m^3/d, of which 70% is produced by MSF and 30% by SWRO. The exergy accounting study revealed that the heat rate of the combined gas/steam power cycle is 6,388.94 kJ/kWh, corresponding to an overall thermal efficiency of 56.34%. On the other hand, the water specific fuel energy consumption of the hybrid SWRO/MSF plant is 33.74 kWh/m^3. The suggested exergy cost accounting method shows the water unit production cost varying from \$0.8258/m^3 to \$2.259/m^3 and the per unit electricity generation cost varying from \$0.02266/kWh to \$0.0966/kWh, as the oil price is increased from \$6/bbl to \$72/bbl, respectively.

Keywords: Dual purpose; Hybrid; Desalination; Combined cycle; Exergy; Thermo economic

1. Introduction

Most of the dual purpose plants currently engaged in the simultaneous production of water and electricity employ back pressure or a condensing extraction turbine integrated either with multistage flash (MSF) or MED desalination plants. Combined gas/steam power generation systems integrated with hybrid MSF/sea water reverse osmosis (SWRO) desalination plants can be considered as an attractive alternative for optimizing the specific energy consumption and maintaining the reliability of the desalination system [1–3]. Hybrid (membrane/thermal/power) configurations are characterized by flexibility in operation, less specific energy consumption, low construction cost, high plant availability, and better power and water matching [4–14].

Thermoeconomic analysis of dual purpose plants has been a controversial issue. A number of methods have been recommended for predicting how the fuel input is allocated between power and water [15–26].

Presented at the IDA 2015 World Congress (Desaltech 2015) 29 August–4 September, 2015 San Diego, CA, USA

The methods normally employed to allocate boiler fuel energy between water and electricity include: the reference cycle method, the power loss method, and the exergy method. The reference cycle method is based on a comparison between the heat consumption and efficiency of a dual-purpose power/desalination plant with the thermal efficiency of an appropriate reference cycle of similar power output [15–17]. The reference cycle should be a practical, single purpose generating plant cycle for the type of fuel available, operating under the same ambient conditions as the dual purpose plant. However, selection of reference cycle efficiency is to a great extent arbitrary. It should be set at anywhere from 32 to 46%, depending on the configuration and power output of the cycle. This method is simple and convenient for power and water purchase agreements. In the loss kilowatt method [18,23], the boiler fuel energy is split between electricity and water, with the assumption that the steam passed to the desalination unit could alternatively be utilized to generate a certain amount of electrical energy, if allowed to expand through a hypothetical condensing turbine. The fuel consumption corresponding to this amount of the hypothetical lost electrical power is to be charged to water. The loss kilowatt method is applicable for both back pressure and extraction condensing systems.

The exergy method is a rigorous allocation approach and based on second low thermodynamic [19–21]. For the exergy allocation method, each power/water cogeneration cycle was first divided into a number of separate subsystems which included the boiler, the turbine/generator, the condenser (if any), the desalter, and the other minor systems such as deaerator, feed water heaters, and pumps were lumped into one subsystem. The exergy content of each stream was then determined. An exergy balance was then carried out for each subsystem, to determine the exergy dissipation within the subsystem.

A comprehensive literature survey to critically assess and evaluate the different methods used for cost assignment in power/water cogeneration plants has been duly reported [21]. The two main approaches used for the thermoeconomic analysis of dual purpose plants are the micro-thermoeconomic analysis method, in which the cost of each stream is determined, and the direct cost allocation method, which is based on certain rules of thumb. Steam exergy costing involves the division of the cogeneration plant into an arbitrary number of components that may or may not coincide with the plant's physical structure. Cost evaluation of each stream is normally carried out sequentially in two steps. In the first step, a detailed energy/exergy analysis is followed by an economic analysis conducted at each component level. From this, the cost of each stream is calculated using an appropriate energy/exergy costing method such as the algebraic cost accounting method [27–29] or the structural theory of thermoeconomics [30–35].

In the direct cost allocation approach, capital and fuel costs are distributed between power and water on certain rules of thumb or criterion. Cost allocation can either be based on the exergy consumption of component aggregates responsible for water production or power generation [19,20]. Allocation of cost components between water and electricity based on functional considerations has been reported [18]. The costs of both commodities can be calculated on the basis of the lost electric power resulting from steam quantity passed to the desalination plant, instead of being expanded in the turbine to generate more power [27,36,37]. Distribution of expenditures to water and electricity according to the deviation from an ideal point has been reported [38,39]. The ideal point marks the point at which equivalent power is generated with steam demand to the desalination plant in an identical single purpose power or desalination plant. At this point, all expenditures are shared solely to the product they serve.

Few research studies have been reported to assess the thermal and economic performance of combined gas/steam power generation systems integrated with thermal or hybrid thermal/SWRO desalination plants. A comprehensive study on fuel allocation between power and water in a combined steam-injected gas turbine power generation and low temperature multi-effect thermal compression, has been reported [2]. A wide range of fuel allocations methods has been analyzed and compared and a fuel allocation analysis procedure was recommended. An economic study has been reported on an integrated power/water dual purpose scheme combining a gas turbine, heat recovery steam generator, and hybrid MSF/SWRO desalination plant [3]. The economic study was based on the present value of expenses over the economic life of capital and leveled cost of water. It has been concluded that RO can successfully coexist with MSF rather than a process that should replace it.

The reference cycle method is used for fuel allocation for a combined gas/steam power cycle with electrical output of 586.8 MW integrated with an MSF plant of 50 MIGD net capacity [17]. Darwish and Amer [40] reported the results of a simulation study to evaluate the techno economic performance of a combined gas/steam power cycle integrated with an MSF plant. Both the work loss and exergy methods are used for fuel allocation between water and electricity. Both methods give very close results.

A sensitivity analysis has been carried out to investigate the impact of variation of some operating parameters on desalination specific energy consumption and cost.

Darwish et al. [41] reported a comprehensive study comparing fuel consumption and cost for 14 combinations of power and desalination plants. The study revealed that the unit fuel cost of combined gas/steam power cycle (either coupled to hybrid SWRO/MED desalination plant or to hybrid SWRO/MSF) is comparable to fuel cost of the combined gas/steam power cycle driving SWRO plant.

Application of principles of thermoeconomics to optimize the design of a number of desalination and power configurations including gas turbine/MSF cogeneration system was reported [42]. The methodology applied begins with simple thermodynamic computations of a given system configuration on a trajectory leading to an optimal design via computations involving the disciplines of design, thermodynamics, and economics.

Literature review reveals that there is scarcity of information on thermoeconomic performance of combined power cycles when integrated with hybrid desalination plants. The objective of this paper is to conduct a comprehensive thermoeconomic analysis to assess thermal performance and quantify the thermal benefits of a combined gas/steam power generation cycle integrated with a hybrid MSF/SWRO desalination plant and predict the electricity and water unit production costs. The availability of sufficient design based thermodynamic and transport information of the whole power/water cycle provides a good opportunity to use the exergy concept.

2. System configuration

Fig. 1 shows the schematic diagram of the combined power cycle integrated with the hybrid MSF/SWRO desalination plant. The plant consists of five combined power generation cycles. Each cycle incorporates two gas turbines (GT), two heat recovery steam generators (HRSG), and one steam turbine. Each of the 10 gas turbines generates 199.7 MW and each of the five steam turbine generates 129.7 MW. The total power generated is 2,645.5 MW and the net power supplied to the grid amounts to 2,400 MW. The combined power generation cycles are integrated with a hybrid MSF/SWRO desalination plant with a total water production of 1,000,000 m^3/d, 70% of which is produced by MSF and 30% by SWRO. The MSF island consists of 8 MSF units of the brine recirculation, cross tube, and single deck design, each with a capacity of 20 MIGD, making them the world's largest single MSF units. The RO plant is subdivided in two independent modules, each with a modular set up.

3. Fuel allocation

A rigorous thermodynamic procedure based on the available energy accounting method is used to distribute the fuel energy supplied to the gas turbine system equitably between the two end products, electricity, and water. The cogeneration cycle was firstly subdivided into the major subsystems which included the gas turbines, HRSG, steam turbines, desalination plant, deaerator, and other auxiliaries as shown in Fig. 2. Table 1 shows the thermodynamic properties of each steam entering and leaving a subsystem. It also shows the corresponding specific exergy content of each stream as determined from a proprietary thermodynamic calculator [43]. An exergy balance was then carried out for each subsystem to determine the exergy dissipation within the subsystem.

A summary of the breakdown of fuel available energy supplied to the gas turbine (5,665.24 MW) among the major subsystems is shown in Fig. 3. The percentage of net electrical output that represents the net overall efficiency disregarding the fuel exergy utilized by the desalination plant is 42.36%. The gas turbine island represents the highest irreversible subsystem whereby 27.26% of the fuel available energy is dissipated followed by desalination plant and HRSG subsystems, consuming respectively, 13.93 and 13.1% of the available energy.

To distribute the fuel exergy input equitably between the two end products electricity and water, the total fuel input of the power/water cycle which is supplied to the gas turbine (5,665.244) is firstly divided into two parts, as shown in Fig. 4. The first part represents the sum of power generated in the gas turbine system (1,997 MW) and exergy losses in the gas turbine system (1,544.1 MW) and they are both completely allocated to power generation fuel consumption. The second part represents the fuel available energy of combustion gases exiting the gas turbine system (2,124.12 MW), that will be utilized by the remaining thermal units of the cogeneration cycle, which include HRSG, steam turbine, desalination plant, deaerator, and other auxiliaries.

The fuel available energy supplied to the remaining thermal units of the cogeneration cycle is then divided into three categories:

(1) The steam turbine grid net power output (403 MW) is allocated entirely to power generation fuel consumption.

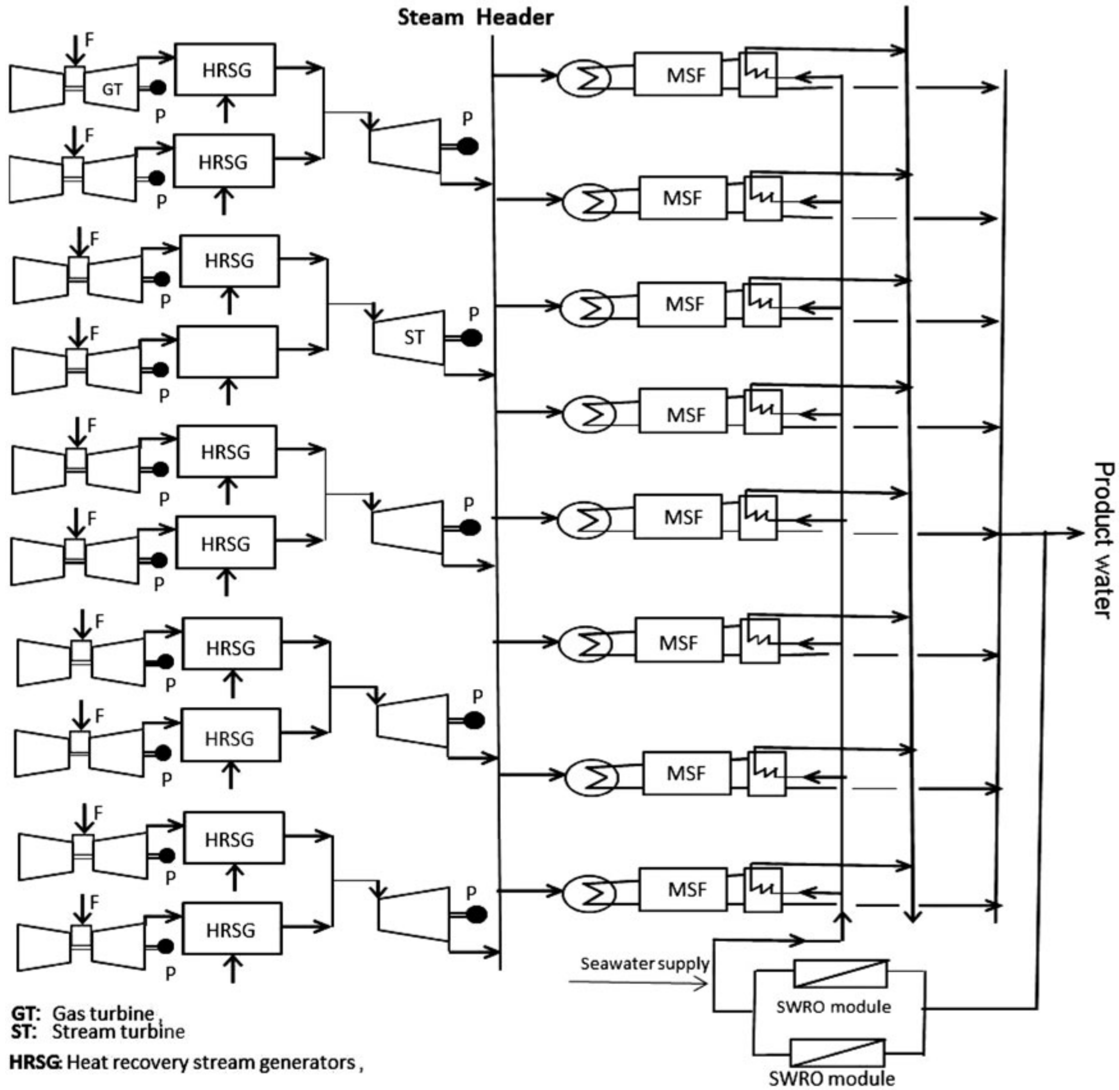

Fig. 1. Schematic diagram of the combined power cycle integrated with the hybrid MSF/SWRO desalination plant.

(2) The desalination plant available energy consumption (788.94 MW) is allocated entirely to water production.
(3) Fuel energy allocated to common equipment which is the summation of the exergy losses in the boiler, HRSG, steam turbine, deaerator, and pumping power for common equipment (932.18 MW) is distributed between water and electricity in proportion to the exergy consumption and utilization in the desalination plant and the steam turbine net power output. Accordingly, out of the 932.18 MW total exergy consumption of the common equipment, 315.17 MW was allocated to power generation and 617.01 MW for water production. A summary of fuel available energy allocation between water and electricity is shown in Fig. 4. Out of the 5,665.24 MW gas turbine fuel energy content, 4,259.29 MW (75.183%) was allocated to power generation and 1,405.95 MW (24.817%) to water production.

Based on the amount of fuel charged to power output, it has been determined that the heat rate of the combined gas/steam power cycle is 6,388.935 kJ/kWh, corresponding to an overall thermal efficiency of 56.34%. The heat rate of conventional, dual purpose incorporating backpressure or condensing extraction steam turbines coupled with thermal desalination plants is about 30 to 70% higher than the heat rate of the combined cycle integrated with an MSF/SWRO hybrid plant. This indicates a better fuel usage for the latter.

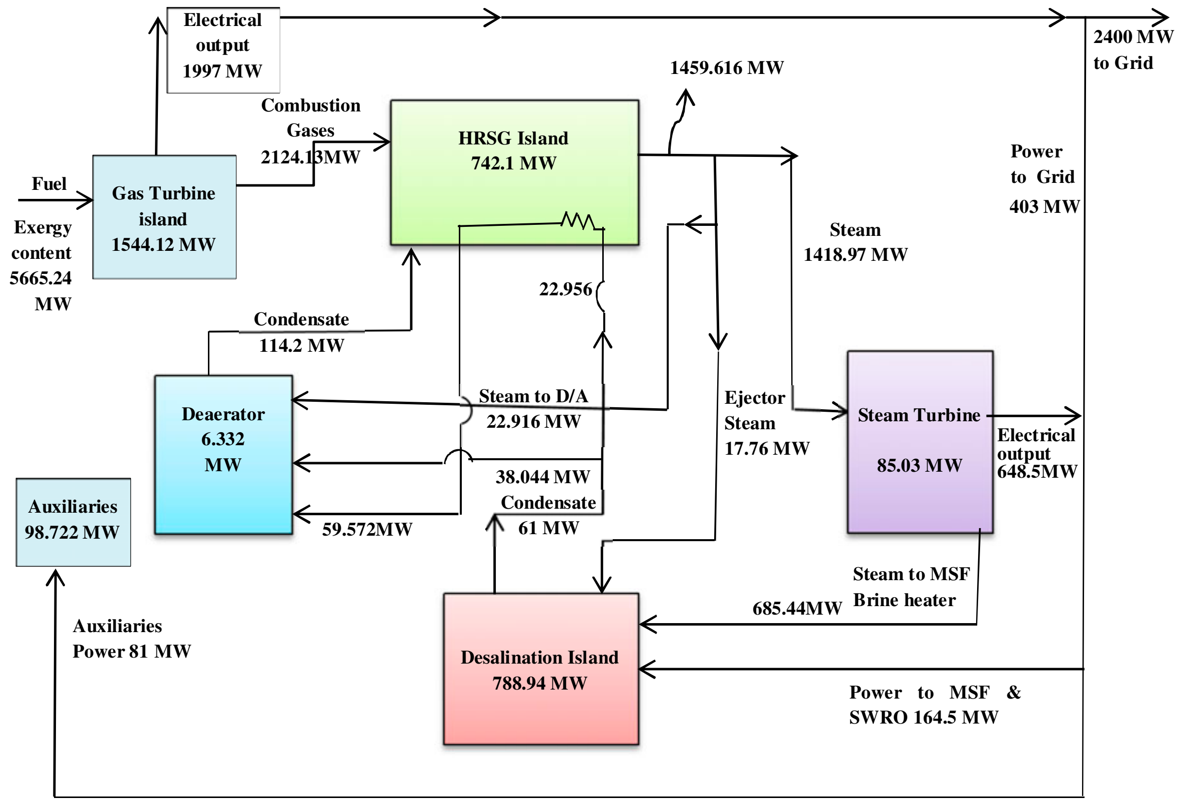

Fig. 2. Exergy flow diagram of the power/water cogeneration plant.

Based on the amount of fuel charged to water, the product water specific fuel energy consumption of the hybrid SWRO/MSF plant is 33.7 kWh/m^3. Fig. 5 shows a comparison of the boiler specific fuel energy consumption needed to produce desalinated water using various desalination configurations. The specific fuel energy consumption of the hybrid MSF/SWRO desalination plant operating within the context of combined gas/steam power cycle is 32.6% less than that of an MSF desalination plant integrated with a steam power cycle and more than double that of a standalone SWRO desalination plant.

The thermodynamic advantages of combining power and water production in a dual-purpose cycle can also be quantified by comparing between the total fuel supplied to standalone power and standalone water plants with the total fuel supplied to the dual purpose plant integrating synergistically the power and water plants and to produce the same power and water loads of the standalone plants. The exergy analysis reveals that the total fuel requirements of the whole integrated combined power cycle/hybrid MSF/SWRO desalination plant is around 27.3% less than that required by three standalone plants including combined power generation cycle, MSF, and SWRO desalination plants producing the same power and water loads of the integrated power/water plant.

4. Cost allocation

The cost accounting procedure selected for this study to determine the unit water and electricity production cost is based on rational thermodynamic considerations. The exergy destruction within the different components of the dual purpose power/water plant is used as a basis for cost allocation. The allocation of all the capital and operating expenses incurred to operate the whole dual purpose plant between electricity and water is based on the followings:

(1) The total capital depreciation and O & M expenditure of the MSF and SWRO plants are allocated entirely to water production cost. While the capital depreciation and O & M expenditure of the gas turbine system are allocated to electricity generation cost.
(2) The total cost of fuel supplied to the plant is divided between water and electricity based on the available energy accounting which is described in the fuel allocation section.

Table 1
Thermodynamic parameters of the streams entering and leaving each subsystem as indicated in Fig. 2

Stream no.	Stream description	Mass flow rate (kg/s)	Temperature (°C)	Pressure (bar)	Specific exergy (kJ/kg)	Exergy content (MW)
1	Fuel input (natural gas)	122.08	60	_	46,406	5,665.244
2	Combustion gases leaving gas turbine	5,363.97	613.2	1.045	396	2,124.132
3	Gas turbine power output	–	–	–	–	1,997
4	Steam leaving HRSG	950.89	539.1	77.98	1,535	1,459.6
5	Condensate return from MSF to HRSG for preheating	352.08	115.6	25	65.2	22.956
6	Condensate return from HRSG plant to deaerator	352.08	189.3	24.44	169.2	59.572
7	Condensate return from deaerator to HRSG	950.89	151.9	120.08	120.1	114.2
8	Steam entering steam turbine	925.6	538.4	76.5	1,533	1,418.94
9	Steam leaving steam turbine to MSF plant	924.3	157.2	2.98	741.9	685.74
10	Steam turbine power output	–	–	–	–	648.5
11	Steam supply from HRSG to MSF ejectors	17.76	230	18	1,000	17.76
12	Total condensate return from MSF plant to deaerator and HRSG	920	118.5		66.3	61
13	Power input to MSF & SWRO desalination plant	–	0	0	0	164.5
14	Condensate return from MSF plant to deaerator	587.8	115.6	24.99	65.2	38.32
15	Steam from HRSG to deaerator	14.8	230	18	1,000	14.8
16	Power input to auxiliaries	–	–	–	–	81

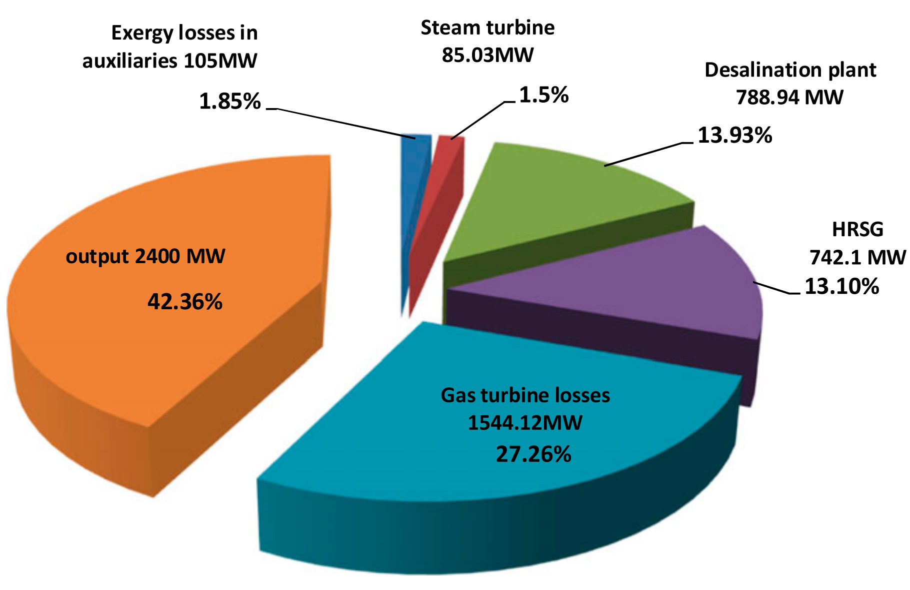

Fig. 3. Breakdown of fuel exergy among the major subsystem.

(3) The total capital depreciation cost of the steam turbine systems is divided between water and electricity in proportion to the amount of electricity consumed by the MSF and SWRO desalination plants and the net electricity generated by the steam turbine. The heat recovery and associated equipment capital cost are divided between electricity and water in proportion to the amount of exergy utilized in the steam turbine and desalination plant respectively.

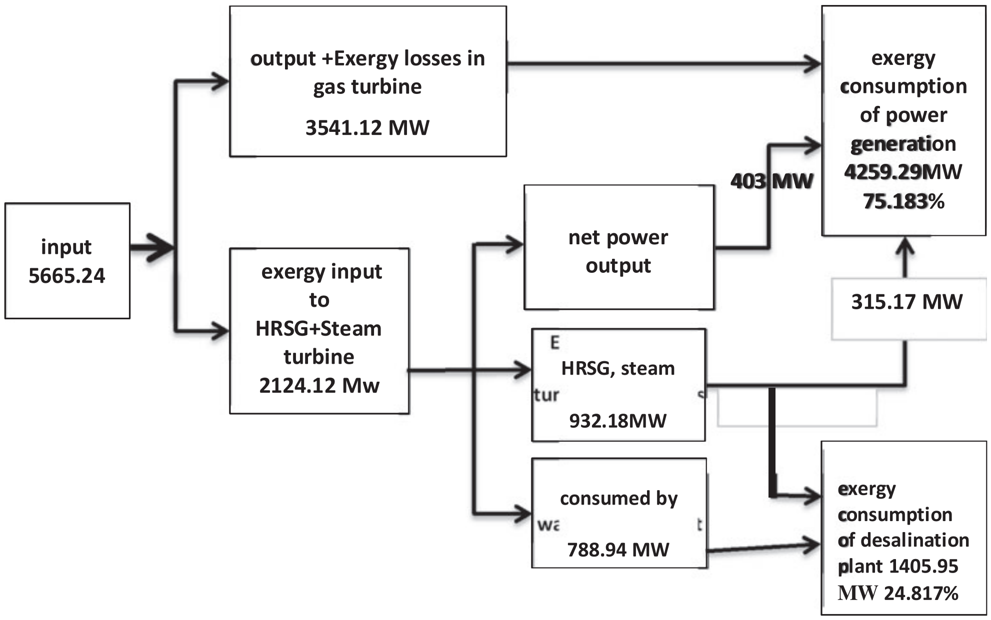

Fig. 4. Fuel available energy allocated between power and water.

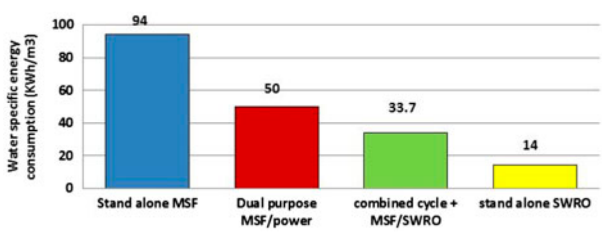

Fig. 5. The water specific fuel energy consumption of various desalination arrangements.

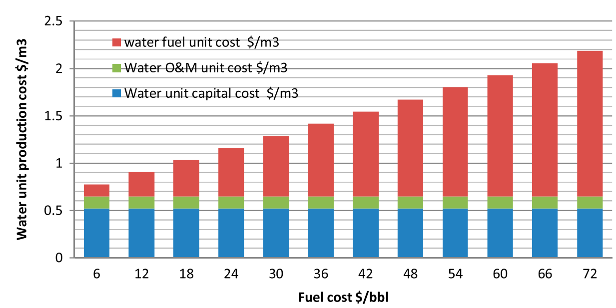

Fig. 6. Impact of variation of fuel unit cost ($/bbl) on water production unit cost.

The results of the economic study are shown in Figs. 6 and 7. They reveal that both the water and electricity unit production costs are highly influenced by the fuel energy cost. The cost of fuel energy is represented in terms of barrel oil equivalent (bbl), assuming that one barrel of oil produces 5.7 GJ heat. As shown in Fig. 6, the water unit production cost varies from \$0.777/m^3 to \$2.18/m^{3,} as the fuel energy cost is increased from a low energy value of \$6/bbl to a high energy cost of \$72/bbl. At the present oil cost of \$30/bbl, the water unit production cost is \$1.29/m^3 of which the fuel unit cost accounts for 49.63%, capital depreciation 40.44%, and O & M 9.93%.

Fig. 7 shows that the electricity unit generation cost varies from \$0.024/kWh to \$0.098/kWh, as the oil price is increased from of \$6/bbl to \$72/bbl. At the

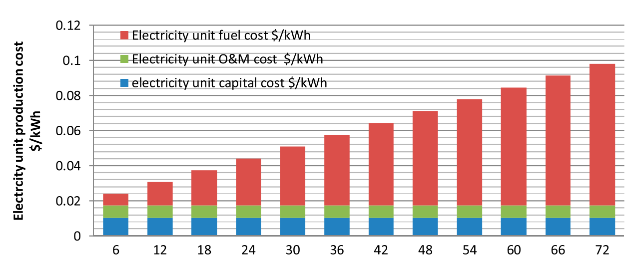

Fig. 7. Impact of variation of fuel unit cost ($/GJ) on electricity unit cost.

present oil cost of $30/bbl, the electricity unit production cost is $0.051/kWh, of which the fuel unit cost accounts for 66.1%, capital depreciation 20.16%, and O & M 13.74%.

5. Comparison between exergy and loss kilowatt cost accounting methods

The "lost kilowatt" is conventionally applied to determine the quantity of available energy that can be obtained, if steam passed to MSF distillers is hypothetically expanded through a condensing turbine. In the loss kilowatt method, boiler fuel energy is split between electricity and water according to the reasoning that steam passed to a desalination unit has the potential to generate a certain amount of electrical energy, if allowed to expand through a hypothetical low pressure condensing turbine. Fuel consumption corresponding to this amount of hypothetical lost electrical power is allocated to water [18].

Fuel energy is allocated to electricity m_f (elec) and water m_f (water) according to the following equations [18]:

$$m_f\ (\text{elec}) = m_f \frac{P_{net} + P_{power}}{P_{net} + P_{power} + P_{desal} + P_{cst}} \quad (1)$$

$$m_f\ (\text{water}) = m_f \frac{P_{desal} + P_{cst}}{P_{net} + P_{power} + P_{desal} + P_{cst}} \quad (2)$$

where m_f is the total amount of fuel supplied to the dual purpose plant (MW), P_{net} is the net electricity produced (MW), P_{power} is the power consumption of the power generation cycle (MW), P_{des} is the power consumption of desalination plant (MW), and P_{cst} is the amount of additional power which could have been generated by hypothetical condensing turbine (MW).

In this study it has been assumed that both steam discharged from the steam turbine and passed to the MSF brine heaters and steam passed to the ejector system are hypothetically expanded in a low pressure turbine at 8 kPa that shall generate 565.32 MW of electrical energy. The desalination plant power consumption is 164.5 MW. The net power output is 2,400 MW and the power consumption of the power generation cycle is 80.4 MW. Using Eq. (1), it has been found that 4,379.24 MW, which represents 77.3% of the total fuel energy input, is allocated to power generation and the remaining 22.7% (1,286 MW) to water production. Meanwhile, and as shown in the preceding section using the exergy method, 75.18% of the total fuel has been allocated to power generation and 24.82% to water production. Fuel allocation predictions of the lost kilowatt and exergy methods are to some extent comparable. Despite that the loss kilowatt method is much simpler and required thermodynamic and transport properties are limited, the exergy method is more precise, since exergy losses are quantified on the basis of the actual operating conditions of the desalination plant as well as of the power cycle.

Water and electricity unit cost are then calculated based on the amount of fuel allocated to water and electricity using the loss kilowatt method. Depreciation cost of the desalination plant is assigned to water production and depreciation cost of gas turbine is allocated to electricity. The steam turbine depreciation cost is split between water and electricity according to the amount of electricity consumed by the desalination plant and net electricity generated by the steam turbine, respectively. Depreciation of capital cost of the heat recovery steam generator and associated equipment are divided between electricity and water in proportion to the steam turbine and desalination plant capital cost, respectively [18].

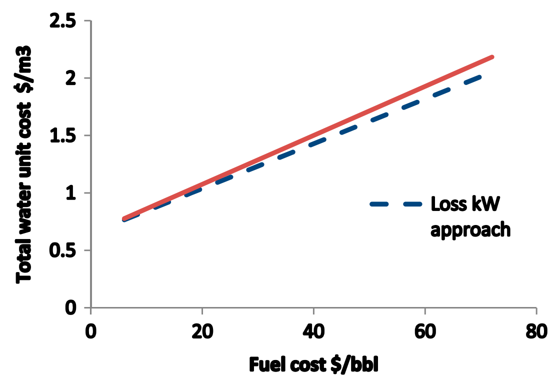

Fig. 8. Comparison between water production cost based on exergy and loss kilowatt approaches.

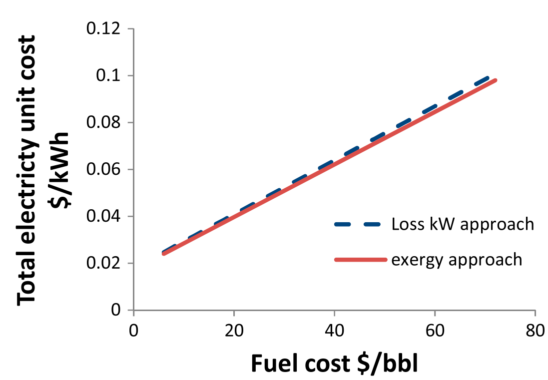

Fig. 9. Comparison between electricity production cost based on exergy and loss kilowatt approaches.

Fig. 8 shows that the exergy approach is consistently yielding a slightly higher water production cost. The difference between the two approaches increases from 1.4 to 6% as fuel cost increases from \$6/bbl to \$72/bbl. Meanwhile, Fig. 9 shows that the exergy approach yields around 2.9% lower electricity cost compared to the loss kilowatt approach. The difference in the predictions of the two approaches is primarily due to the fact that the exergy approach allocates more fuel to water production. The exergy approach allocates 24.82% of the total fuel supplied to the combined cycle to water compared to 22.7% using the loss kilowatt approach.

6. Conclusions

A rigorous thermodynamic study based on the exergy method is employed to quantify the thermal benefits and energy efficiency of a gas/steam combined power cycle integrated with a hybrid MSF/SWRO desalination plant. The study revealed that the heat rate of the combined gas/steam power cycle is 6,388.935 kJ/kWh, corresponding to an overall thermal efficiency of 56.34%, while the water specific fuel energy consumption of the hybrid SWRO/MSF plant is 33.7 kWh/$m^{3,}$ which is more than twofold that of a standalone SWRO plant and only about 67.4% of the water specific fuel consumption of a plant utilizing a conventional backpressure or extraction condensing turbine integrated with MSF unit. A rational cost procedure whereby the fuel and capital costs as well as O & M expenditures of the whole combined power cycle and hybrid desalination plant are equitably distributed between water and electricity is recommended in order to estimate the unit water and electricity unit production cost and examine the impact of the fuel energy cost.

A comparison between Exergy and conventional loss lilowatt cost accounting methods has also been made. Using the exergy approach, the fuel energy allocated to water is 8.5% higher than that determined by the loss kilowatt approach. Meanwhile, the fuel energy allocated to electricity is 2.85 lower. As a result, the exergy cost allocation approach yields around 1.4–6% higher water production cost than the conventional loss kilowatt approach. In spite of the fact that the loss kilowatt method is much simpler and the required thermodynamic and transport properties are limited, the exergy method is more precise, since exergy losses are quantified on the basis of the actual operating conditions of the desalination plant as well as of the power cycle.

References

[1] G. Calì, E. Fois, A.M. Lallai, Optimal design of a hybrid RO/MSF desalination system in a non-OPEC country, Desalination 228 (2008) 114–127.
[2] Y. Wang, N. Lior, Fuel allocation in a combined steam-injected gas turbine and thermal seawater desalination system, Desalination 214 (2007) 306–326.
[3] S.P. Agashichev, Analysis of integrated co-generative schemes including MSF, RO and power generating systems (present value of expenses and "levelised" cost of water), Desalination 164 (2004) 281–302.
[4] P. Jong Kyou, T. Seop Song, J.M. Hong, Application of Hybrid Technology to the Largest Desalination Plant, Fujairah, UAE, IDA Conference, Bahamas, 2003.
[5] A.M. Helal, A.M. El-Nashar, E. Al-Katheeri, S. Al-Malek, Optimal design of hybrid RO/MSF desalination plants Part II: Results and discussion, Desalination 160 (2004) 13–27.
[6] E. Cardona, S. Culotta, A. Piacentino, Energy saving with MSF-RO series desalination plants, Desalination 153 (2002) 167–171.
[7] L. Awerbuch, Power-desalination and the importance of hybrid idea's, IDA World Congress Conference, Madrid, 1997.
[8] M.AK. Al-Sofi, A.M. Hassban, E.E. El-Sayed, Integrated and non-integrated power/MSF/SWRO plants, Desalin. Water Reuse Part 1 2(3) (1992) 10–16; Part2: 2 (4) (1992) 42–46.
[9] L. Awerbuch, S. May, R. Soo-Hoo, V. Van Der Mast. Hybrid desaling systems, Proc. of the 4th World Congress on Desalination and Water Reuse, IDA, Kuwait, 1989.
[10] L. Awerbuch, V. Van der Mast, R. Soo-Hoo, Hybrid desalting systems—A new alternative, Desalination 64 (1987) 51–63.
[11] P. Jong Kyou, I. Seop Song, J.M. Hong, Application of Hybrid Technology to the Largest Desalination Plant, IDA, Fujairah, UAE, 2003, Bahamas.
[12] I.S. Al-Mutaz, M.A. Soliman, A.M. Daghthem, Optimum design for a hybrid desalting plant, Proc. of the 4th World Congress on Desalination and Water Reuse, IDA, Kuwait, 1989.
[13] M. Sherman, Hybrid Desalination System, MEDRC Series of R & D Reports, Project 97-AS-008b, Muscat, Oman, 2000.
[14] O.A. Hamed, Overview of hybrid desalination system-current status and future prospects, Int. J. Desalin., Elsevier, Amsterdam 184 (2006) 207–214.
[15] N.M. Wade, R.S. Fletcher, Energy allocation and other factors influencing water costs in desalination and dual purpose power/water plant, in: Proceedings of IDA World Congress vol. III, Abu Dhabi, 1995, pp. 363–379.
[16] N.M. Wade, Energy and cost allocation in dual-purpose power and desalination plants, Desalination 123 (1999) 115–125.
[17] N. Wade, J. Willis, J. McSorley, The Taweelah A2 independent water and power project, Desalination 125 (1999) 191–202.
[18] A.M. El-Nashar, Cost allocation in a cogeneration plant for the production of power and desalted water —comparison of the exergy cost accounting method with the WEA method, Desalination 122 (1999) 15–34.

[19] L. Breidenlbath, R. Rautanbaih, G.F. Tusel, Thermoeconomic assessment of fossil fuel fired dual purpose power water plants, IDA World Congress, Madrid, Spain, vol. 4, 1997, pp. 167–180.
[20] L. Breidenlbath, Thermoeconomic evaluation of a nuclear co-production nplant for electricity and potable water, in: Proceeding of an International Symposium on Desalination of Seawater with Nuclear Energy, Taeja, 1997, pp. 181–198.
[21] O.A. Hamed, H.A. Alwashmi, H.A. Alotaibi, Thermoeconomic analysis of a power/water cogeneration plant, Energy 31 (2006) 2699–2709.
[22] A.M. El-Nashar, Optimal design of a cogeneration plant for power and desalination taking equipment reliability into consideration, Desalination 229 (2008) 21–32.
[23] M.A. Darwish, E.M. Al-Awadhi, A.M. Darwish, Energy and water in Kuwait Part 1. A sustainability view point, Desalination 225 (2008) 341–355.
[24] R. Borsani, S. Rebagliati, Fundamentals and costing of MSF desalination plants and comparison with other technologies, Desalination 182 (2005) 29–37.
[25] K.V. Reddy, N. Ghaffour, Overview of the cost of desalinated water and costing methodologies, Desalination 205 (2007) 340–353.
[26] M.A. Darwish, Desalting fuel energy cost in Kuwait in view of $75/barrel oil price, Desalination 208 (2007) 306–320.
[27] R.A. Gaggioli, Y.M. El-Sayed, A critical review of second law costing methods, Proceedings of the IV International Symposium on Second Law Analysis of Thermal Systems, (ASME Book 100236), ASME N.Y., USA, 1987, pp. 59–73.
[28] A.M. El-Nasher, Cost allocation of electricity and water in a cogeneration plant, Desalination 85 (1992) 197–212.
[29] A.M. El-Nashar, Cost allocation for electricity and water for the umm al nar west cogeneration plant using the exergy accounting method, Desalination 71 (1989) 57–71.
[30] A. Valero, M.A. Lozano, L. Serra, G. Tsatsaronis, J. Pisa, C. Frangopoulos, M.R. von Spakovsky, C.G.A.M. Problem, CGAM problem: Definition and conventional solution, Energy 19(3) (1994) 279–286.
[31] A. Valero, C. Torres, F. Lerch, Structural theory and thermoeconomic diagnosis—Part 111: Intrinsic and induced malfunctions, Proceedings of the ECOS'99 Conference (ASME), Tokyo, Japan, 1999, 35–41.
[32] A. Valero, L. Correas, L. Serra, On-line thermo economic diagnosis of thermal power plants, in: A. Bejan, E. Mamut (Eds.), Thermodynamic Optimization of Complex Energy Systems, Kluwer Academic Publishers, Netherlands, 1999, pp. 117–136.
[33] A. Valero, C. Torres, L.A. Serra, General theory of thermo economics Part-1 structural analysis, Proceedings of the International Symposium: ECOS'92, Zaragoza, Spain (ASME Book 1Q033 1), New York, NY, 1992, 137–145.
[34] A. Valero, L. Serra, M.A. Lozano, Structural theory of thermo economic, AES, (ASME Book H00874), ASME 30 (1993) 189–198.
[35] M.A. Lozano, J.L. Bartohome, A. Valero, M. Reini, Thermo economic diagnosis of energy systems, Flowers 94, Florence World Energy Research Symposium, Florence, Italy, 1994, pp. 149–156.
[36] I. Kamal, Thermoeconomic modeling of dual purpose power/desalination plants: Steam cycles, IDA World Congress, vol. 4, Madrid, Spain, 1997, pp. 193–207.
[37] 1. Kamal, G.V. Sims, Thermal cycle and financial modeling for the optimization of dual purpose power-cum-desalination plants, IDA World Congress on Desalination and Water Reuse, vol. 3, Abu Dhabi, 1995, pp. 427–441.
[38] M.AK. Al-Sofi, M.M. Srouji, Fuel allocation in dual-purpose plants, Desalination 100 (1995) 65–70.
[39] M.A. Al-Ghamdi, M.M. Srouji, M.A. Al-Sulaiman, L.A. Al-Musallam, Cost allocation in dual purpose plants, Proceedings of IDA World Congress on Desalination and Water Reuse, Manama, Bahrain, 2002, pp. 1–14.
[40] M.A. Darwish, A.B. Amer, Cost allocation in cogeneration power-desalination plant utilizing gas/steam combined cycle (GTCC) in Kuwait, Int. J. Energy Res. 14 (2014) 275–302.
[41] M.A. Darwish, N.M. Al-Najem, N. Lior, Towards sustainable seawater desalting in the Gulf area, Desalination 235 (2009) 58–87.
[42] Y.M. El-Sayed, Water desalination revisited in changing physical and economic environments, in: N. Lior (Ed.), Chapter 1 in Advances in Water Desalination, John Wiley & Sons, Inc., Stamford, CT, 2013, pp. 1–78.
[43] K.S. Spiegler, Y.M. El-Sayed, A Desalination Primer, Balaban Desalination Publications, Santa MariaImbaro, 1994, 215 p.