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Fuel utilization of steam power cycles integrated with multi-stage flash (MSF) desalination plants

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ABSTRACT

Fuel utilization of power/water cogeneration cycles employing extraction condensing or backpressure steam turbine configurations are evaluated and compared. The thermal assessment study includes two operating dual purpose plants incorporating extraction (condensing) steam turbine cycles integrated with multi-stage flash (MSF) desalination plants. They were commissioned in the early eighties and with a power to water ratio of 12.6 and 15.5 MW/MIGD, respectively. It also includes two operating backpressure steam turbine cycles integrated with MSF desalination plants with a power to water ratio of 5.2 and 7.8 MW/MIGD commissioned in 1983 and 2000, respectively. A rigorous thermodynamic approach based on available energy (exergy) reveals that water specific fuel energy requirement ranging from 50.8 to 61.1 kWh/m^3 and power heat rate ranging from 11,126 to 11,401 kJ/kWh for the extraction condensing turbine systems. The water specific fuel energy consumption of cogeneration systems employing backpressure turbines range from 58.8 to 69.8 kWh/m^3 with power heat rate ranges between 8,402 and 9,201 kJ/kWh. The study also reveals that actual annual fuel energy consumption of the four power/water cycles is around 10.4% and 30.9% higher than total design-based annual fuel energy consumption.

Keywords: Dual purpose; Desalination; Efficiency; Exergy

1. Introduction

The majority of large scale desalination plants in Saudi Arabia operate within the context of dual purpose arrangements for simultaneous production of two end products, water and electricity. Such cogeneration arrangements use either backpressure or extraction condensing turbines. Cogeneration cycles used till 1982 employed extraction condensing turbines with power to water ratio's ranging from 10.2 to 17.5 MW/MIGD. From 1983 onwards extraction condensing turbines were replaced by backpressure turbines in all new cogeneration plants. Backpressure turbines give lower power to water ratio (high water demand) and are characterized by high thermal efficiencies. They make the best use of low-grade heat that would otherwise be rejected by the power generating plant cycle.

A number of allocation procedures have been suggested to distribute boiler fuel input of dual purpose plants equitably between electricity and water [1–20]. The three most fuel allocation methods are reference cycle, loss kilowatt and exergy methods. The reference cycle method is based on comparing efficiencies of dual-purpose power/desalination plant with thermal efficiency of an appropriate reference single-purpose power cycle operating under the same ambient conditions [1–3]. Although the reference cycle method is simple, selection of reference cycle efficiency is to a great extent arbitrary. In the loss kilowatt method [4,9], boiler fuel energy is distributed between electricity and

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water according to the assumption that the steam which passed to the desalination unit has the potential to generate a certain amount of electrical energy, had it been allowed to expand through a hypothetical condensing turbine. The fuel consumption corresponding to lost electrical power is to be charged to water. The exergy method is a rigorous allocation approach based on the second law of thermodynamics [5–7,16,17,20]. In the exergy allocation method, each power/water cogeneration cycle is first divided into a number of subsystems. The exergy content of each stream is then determined. An exergy balance is then carried out for each subsystem to determine exergy dissipation within the subsystem.

An appropriate method to allocate fuel energy consumption of multi-purposed power/desalination plants equitably between power and electricity based on consumption of primary energy is reported [16,17]. A comprehensive exergy destruction analysis is performed to major subsystems of a cogeneration plant incorporating a combined power cycle and a desalination plant. A common platform for expressing the efficacy of a desalination process based on primary energy, has been developed [16,17]. The efficacy of the desalination plant is expressed as the mass ratio of potable water product to the primary energy input derived from the desalination plant.

The wide diversity and uniqueness of the design features of the Saline Water Conversion Corporation (SWCC) Company's dual purpose plants provide the opportunity to assess and evaluate fuel utilization of these plants. The majority of these plants have been in for more than 30 years. Assessment of current operational performance will indicate to which extent these plants are ageing and deviating from the design specifications. Consequently such an assessment will serve as a guide to predict longevity of these plants. Information on thermal performance can also be used as a guide to select appropriate and cost-effective design and operating features for new cogeneration plants.

2. Plant description

Table 1 shows major design characteristics of four examined power/water cogeneration plants which are owned and operated by SWCC. Two cogeneration plants Al Jubail 1 and Yanbu 1 employ extraction condensing steam turbines integrated with multi-stage flash (MSF) distillers. Al Jubail 1 consists of six power/water cycles. Each cycle incorporates one extraction condensing steam turbine coupled to an MSF distiller that has a power to water ratio (PWR) of 12.57 MW/MIGD. Yanbu 1 consists of five power/water cycles. Each cycle incorporates one extraction condensing turbine coupled to an MSF distiller with PWR of 15.3 MW/MIGD.

The remaining two cogeneration plants Al Jubail-II and Al Khobar-III employ backpressure steam turbines integrated with MSF distillers. Al Jubail-II consists of 10 power/water cycles. Each cycle incorporates one backpressure condensing turbine coupled to four MSF distillers with PWR of 5.08–6.44 MW/MIGD. Al Khobar-III consists of four power/water cycles. Each cycle incorporates one backpressure condensing turbine coupled to two MSF distillers with PWR of 7.88 MW/MIGD.

3. Methodology

3.1. Determination of water and specific fuel energy consumption

For each of the four examined steam power/water cycles, the design specific fuel available energy consumption of each desalination and power plant is first determined by the analysis of heat and mass balance flow charts as supplied by each plant manufacturer and when the plants are supposed to operate at maximum continuous rating (MCR). A rigorous thermodynamic approach based on the available energy (exergy) accounting method is employed to distribute total fuel available energy supplied to the power/water cycle equitably between water and power. The dual purpose

Table 1
Major design features of the power/water co-generation cycles

Plant	Khobar-III	Yanbu-I	Jubail- I	Jubail-II
Commissioning date	2000	1981	1982	1983
Turbine type	Backpressure	Extraction condensing	Extraction condensing	Backpressure
Power generation				
Power maximum/turbine	118.2	71.4	63.6	127–134
No. of turbines	4	5	6	10
No. of boilers	4	5	6	12
No. of preheaters per cycle	2	1	2	2
Cycle power to water ratio MW/MIGD	7.88	15.3	12.57	5.08–6.44
Water production				
No. of distillers	8	5	6	40
No. of distillers per cycle	2	1	1	4
TBT (range) °C	105	121	90.6	90.6–112.8
Distiller capacity MIGD	7.5	4.67	5.06	5.2–6.25
PR (range) kg/2,326 kJ	6.5	11	8	8–9.5
Scale control procedure	Additive	Acid/Additive	Additive	Additive

plant is first divided into major thermal subsystems which included the boiler, turbine/generator, desalination plant and other common equipment. The exergy content of each stream entering or leaving each subsystem is quantified. Exergy losses associated with each subsystem are then determined. The power/water cycle total fuel primary energy input is then divided into three portions:

1. Fuel exergy allocated entirely to power generation which is the summation of exergy losses in the turbine/generator and the net electrical output.
2. Fuel exergy allocated entirely to water production which is the summation of exergy consumption of the MSF distillers and useful chemical exergy of product water.
3. Fuel exergy allocated to common equipment which is the summation of exergy losses in the boiler, feed water heaters, steam/air preheater, deaerator and pumping power for common equipment. Exergy consumption of common equipments distributed between water and electricity in proportion to exergy consumption and utilization in MSF distillers and the turbine/generator.

3.2. Fuel energy saving factor

Dual-purpose plants reduce fuel consumption when compared with the fuel needed for two separate power and water plants. For a cogeneration plant producing net electrical power, W_{net}, and an amount of process heat to be utilized in the desalination plant, Q_d, and consuming an amount of fuel Q_f, the fuel energy saved, ΔQ_f, is defined by the following relationship:

Fuel energy saved = (fuel energy required by single-purpose conventional power plant) + (fuel energy required by single-purpose water plant coupled directly to a conventional boiler) – (fuel energy requirement of a dual purpose plant). (1)

$$\Delta Q_f = (Q_d + W_{net}) - Q_f \quad (2)$$

The fuel energy saving factor (FESF) is defined as the ratio of the saving (ΔQ_f) to the fuel energy required in the single-purpose power and water plant.

$$\text{FESF} = \frac{[(Q_d / \eta_b) + (W_{net} / \eta_f)] - Q_f}{[(Q_d / \eta_b) + (W_{net} / \eta_f)]} \quad (3)$$

where Q_d = heat supplied to the desalination plant, kJ/s; Q_f = fuel supply to boiler, kJ/s; W_{net} = rate of power output, kW; η_b = efficiency of boiler directly operating to desalter; η_f = efficiency of single-purpose power plant.

3.3. Fuel utilization factor

The actual energy efficiency of the four operating dual purpose plants is assessed by determining the fuel utilization factor (FUF).

Fuel utilization factor (FUF) = (actual fuel energy consumption of the operating power/water plant) /(total design-based fuel energy consumption of the desalination and power plants).

4. Results

For each of the four cogeneration cycles, exergy content of all thermally involved streams was determined. As a basis for comparison between the four cycles, boiler primary fuel input is considered to be 100 MW. As an example, Fig. 1 shows the exergy flow diagram of Al Khobar-III power/water cogeneration cycle based on the supply of 100 MW of boiler primary fuel energy input.

Table 2 also shows a summary of the break-down boiler fuel exergy input either wasted in the different subsystems of the cogeneration cycle or utilized as useful exergy gained by the two end products water and electricity. The boiler was the most inefficient subsystem where 53.56%–56.64% of total

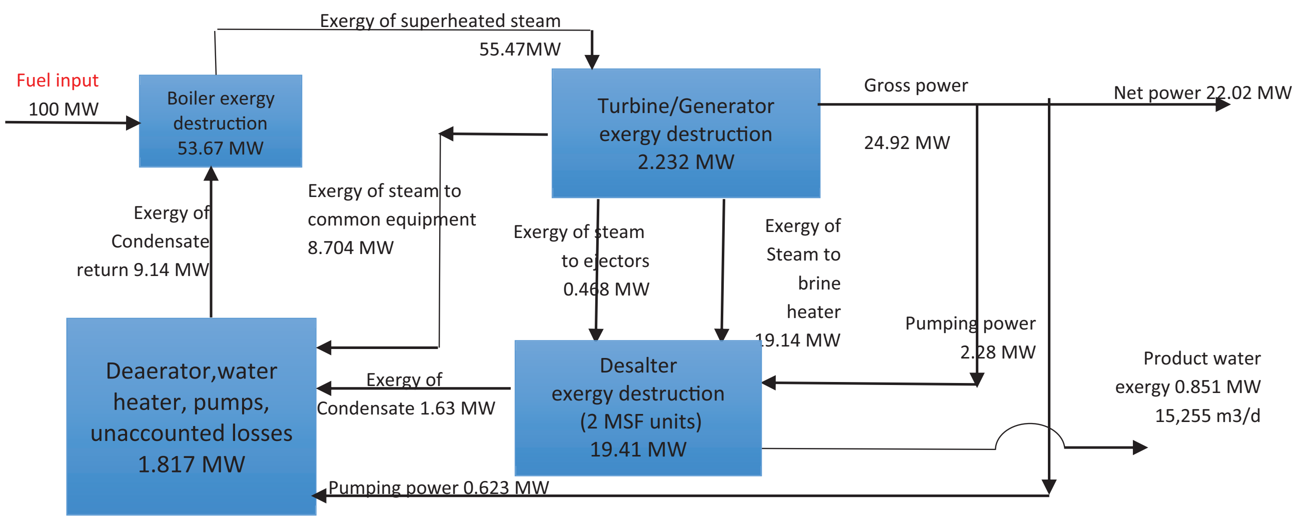

Fig. 1. Exergy flow diagram of Al Khoba-III power-water cogeneration cycle at MCR based on the supply of 100 MW of boiler fuel energy.

Table 2
Subsystem exergy analysis (basis 100 MW of fuel input)

Co-generation cycle	Boiler fuel exergy input (MW)	Exergy losses						Exergy content of net power output and water production		Water production (MIGD)	Second law efficiency (%)	Net power to water ratio (MW/MIGD)
		Boiler exergy consumption (MW)	Turbine/generator exergy consumption (MW)	Desalination plant exergy consumption (MW)	Condenser exergy consumption (MW)	Deaerator heaters and pumps exergy consumption (MW)	Total exergy losses (MW)	Net power output (MW)	Product water exergy (MW)			
Al Jubail-I	100	56.64	5.1	10.5	2.4	1.66	76.3	23.15	0.612	2.325	23.76	10
Yanbu-I	100	56.6	6.2	5.82	3.7	1.6	74.1	25.4	0.48	1.843	25.88	13.78
Al Khobar-III	100	53.67	2.23	19.41	–	1.82	77.14	22.02	0.85	3.234	22.87	6.8
Al Jubail-II	100	53.56	3.47	18.61	–	1.68	77.32	21.64	1.048	3.98	22.69	5.437

exergy destruction in the cogeneration cycles occurs. The next two subsystems of major irreversibility were the MSF distiller and the turbine generator. Minor losses due to the irreversibilities of other subsystems which include deaerator, feedwater heaters, condenser and pumps for power generation collectively account for about 5% of total losses.

Based on the exergy losses associated with each subsystem as shown in Fig. 1, the boiler primary fuel energy input of each power/water cycle is then divided equitably between water and electricity. Fig. 2 shows allocation of primary fuel between water and electricity of Al Khobar-III. The primary fuel energy input (100 MW) is first divided into three portions. The first portion (24.252 MW) that includes exergy losses in the turbine/generator and the net electrical output is allocated entirely to power generation. The second portion (20.261 MW) that includes exergy consumption of the MSF distillers and useful chemical exergy of product water is allocated entirely to water production. The third and last portion (55.487 MW) of common equipment that includes exergy losses in the boiler, feed water heaters, steam/air preheater, deaerator and pumping power is distributed between water and electricity in proportion to exergy allocated entirely to water and electricity production.

The exergy allocation procedure revealed that for plants operating within the context of backpressure steam turbines (Al Jubail-II and Al Khobar-III), 43.91% and 45.5% of the total boiler primary energy input is allocated to water production, respectively. Meanwhile, for plants that employ extraction condensing turbine (Al-Jubail-I and Yanbu-I), with a relatively high power to water ratio, primary energy allocated to water production ranges between 28.23% and 15.15% of total boiler fuel energy, respectively.

Figs. 3 and 4 show design water and electricity specific fuel energy consumption when the four plants are operating at a MCR. The water-specific primary fuel energy consumption ranges between 50.8 and 69.81 kWh/m^3. Darwish et al. [18] reported that for an MSF plant integrated with an extraction condensing turbine, the specific fuel energy consumption using the loss kilowatt method is 208.2 kJ/kg (57.833 kWh/m^3). This is within the range obtained in this study. It has also been reported that average specific fuel consumption of MSF plants operating within the context of dual purpose configurations is around 200 MJ/m^3 (55 kWh/m^3) [19]. When an MSF plant is integrated with a combined power cycle and all benefits of the dual purpose plants are allocated to water production, the specific water fuel consumption will be around 34 kWh/m^3 [21].

The efficacy of the four examined desalination plants when expressed as a ratio of potable water product to the primary energy input derived from the desalination plant ranges between 0.0143 and 0.0197 m^3/kWh. It has been reported that the ideal production of a desalination plant when operated at the thermodynamic limit and consuming the minimum separation work is 1.282 m^3/kWh [16]. The efficacy of the MSF plants examined in this study ranges between 1.11% and 1.5% the thermodynamic limit which reveals high associated irreversibility.

It has been reported that the water specific fuel energy consumption of hybrid SWRO/MSF plant integrated with a gas/steam power cycle is 33.74 kWh/m^3 [22]. The ratio of potable water product to primary energy input derived from the desalination plant shall then be 0.03 m^3/kWh which is

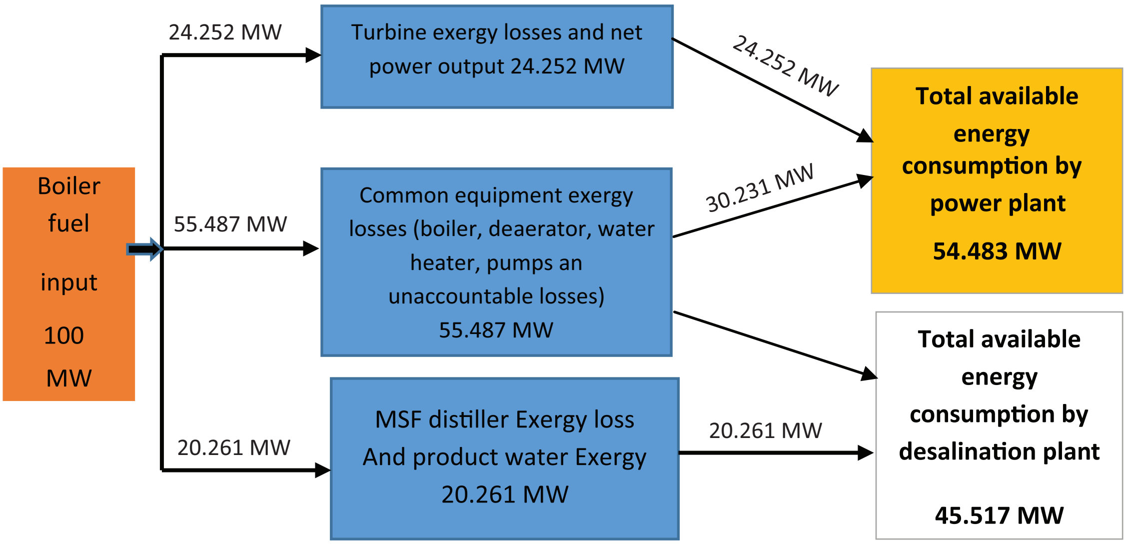

Fig. 2. Allocation of boiler available energy between power and water of Al Khobar III.

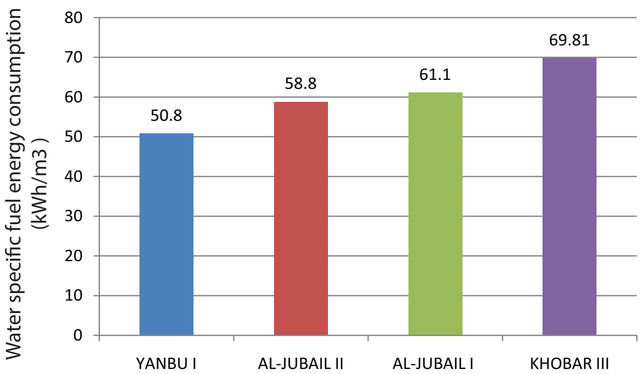

Fig. 3. Design-based water specific fuel energy consumption.

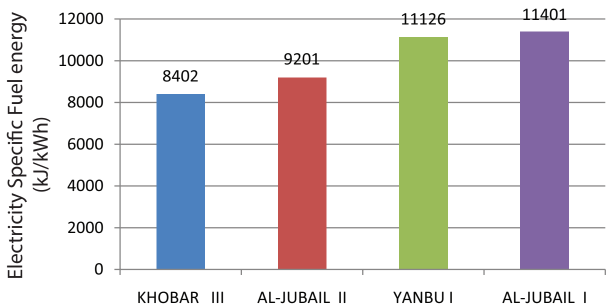

Fig. 4. Design-based electricity specific fuel energy consumption (heat rate).

around 50%–100% higher than that of MSF plants combined with steam power cycles.

4.1. Fuel energy saving factor

Fig. 5 shows the FESF of the four power/water cycles. It shows that fuel requirements of the power/water cogeneration cycles are around 16.8%–36.3% lower than fuel requirements of the corresponding single-purpose power

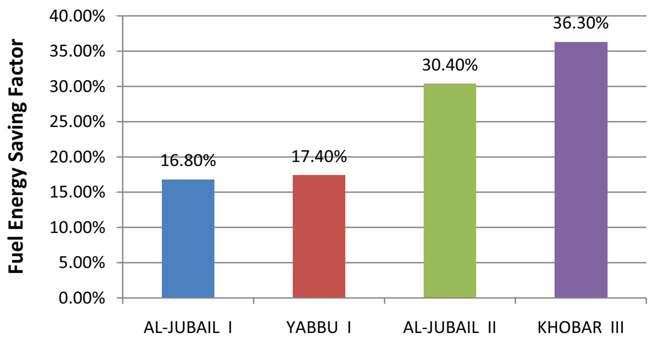

Fig. 5. Fuel energy saving factor.

and desalination plants. Yanbu phase I and Al Jubail phase I power/water cycles with extraction condensing turbine arrangements yield the lowest fuel energy savings. A considerable amount of energy is rejected in the turbine condenser as waste heat. Conversely, Al Khobar phase III cogeneration cycle with the backpressure turbine arrangement and high power to water ratio yields the highest energy fuel savings. It can thus be concluded that better fuel energy saving can be obtained with use of dual purpose plants with a backpressure turbine arrangement and a relatively high power to water ratio.

4.2. Actual operational fuel utilization performance

The actual fuel energy consumption of each of the four operating dual purpose power/water plants is compared with corresponding MCR design values. The design-based fuel energy consumption is determined from the water specific energy consumption and power generation heat rate for each plant that is based on the heat and mass balance flow charts information supplied by plant manufacturers. The actual total annual fuel consumption, water production and power generation covering a 1-year period are shown in Table 3. Assuming that each cogeneration plant maintains the design-based water specific energy consumption and power

Table 3
Comparison between the actual and design-based fuel energy consumption

Plants	Annual net power (kWh)	Annual water production (m^3/year)	Annual fuel input (kWh)	Design heat rate (kJ/kWh)	Design water specific (kWh/m^3)	Design-based power fuel input (kWh)	Design-based water fuel input (kWh)	Total design fuel input (kWh)	Actual fuel input/design-based input
Al-Jubail-I	2,562,305,000	47,680,319	12,410,744,440	11,203	61.1	7,256,113,237	2,913,267,491	10,169,380,728	1.2204032
Al-Jubail-II	7,738,602,000	317,477,187	40,464,932,435	9,201.5	58.8	17,999,483,093	18,667,658,596	36,667,141,689	1.1035748
Al-Khobar-II	2,891,930,000	75,032,416	14,895,009,000	8,402.3	69.81	6,142,212,703	5,238,012,961	11,380,225,664	1.3088501
Yanbu-I	1,932,908,000	26,203,297	8,733,599,071	11,125.2	50.8	5,435,730,321	1,331,127,488	6,766,857,808	1.2906432

generation heat rate and as determined by the available energy (exergy) accounting method, the total annual design fuel energy consumption is calculated using the following relationship:

Total design fuel energy consumption of the whole cycle = (actual annual water production * design-based water specific energy consumption) + (actual power generation * design-based heat rate).

Table 3 shows that the actual annual fuel energy consumption of the four power/water cycles is around 10.4% and 30.9% more than the total annual fuel energy consumption based on the design water specific energy consumption and design power generation heat rate.

5. Conclusions

A rigorous thermodynamic approach based on the available energy (exergy) accounting method has been developed to assess the irreversibility associated with power/water cogeneration cycles. The study revealed that the boiler is the most inefficient subsystem where 53.56%–56.64% of the total exergy destruction in the cogeneration cycles occurs. The next two subsystems of major irreversibility are the MSF distiller and the turbine generator.

Thermodynamic analysis shows that water specific fuel energy requirement ranges from 50.8 to 61.1 kWh/m^3 and power heat rate ranges between 11,126 and 11,401 kJ/kWh for the extraction condensing turbine systems. Meanwhile water specific fuel energy consumption of cogeneration systems employing a backpressure turbine ranges from 58.8 to 69.8 kWh/m^3 with power heat rate ranging from 8,402 and 9,201 kJ/kWh.

It can be concluded that better fuel energy saving can be obtained with the use of dual purpose plants with a backpressure turbine arrangement and with relatively high power to water ratio.

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