ربط انظمة الطاقه الشمسيه المركزه مع محطات توليد الطاقه القديمه

جمال عثمان

شعبة الهندسه الميكانيكيه، نقابة المهندسين الاردنيين، عمان، الاردن

الملخص

تهدف هذه الدراسه الى تقييم الجوانب الفنيه والاقتصاديه والبيئيه لربط نظام المجمع الهلالي (Parabolic Trough Collector) مع مسخنات مياه تغذية المراجل لوحده بخاريه قديمه باستطاعته اسميه تبلغ 33 ميغاوات في محطة الحسين الحراريه في الاردن. حيث من المؤمل ان ربط مثل هذا النظام سيؤدي الى تحسين اداء وحدة التوليد وتقليل معدل استهلاك الوقود، وبالتالي خفض الانبعاثات الغازيه الملوثه للبيئه ومن ضمنها الغازات الدفيئه. ولتحقيق ذلك تم استخدام برنامج حاسوبي (System Advisor Model) لنمذجة الحقل الشمسي المطلوب وتحديد مساحة المجمعات والمركزات الشمسيه المطلوبه لتعويض استنزاف البخار من التوربينه واللازم لتسخين مياه تغذية المرجل. كما تم بناء نوذج رياضي خاص لكافة اجزاء دورة البخار (Rankine cycle) بالاعتماد على العلاقات الثيرموديناميكيه وميزان الكتله والطاقه. حيث تم دراسة عدة خيارات لتسخين مياه التغذيه ومقارنتها بالوضع الحالي والمتمثل باستنزاف كميات من البخار على ضغوط مختلفه لغايات تسخين هذه المياه. وقد تبين بأنه يمكن تحسين كفاءة وحدة التوليد البخاريه بما نسبته 3% وذلك بسبب زيادة انتاج التوربينه البخاريه كنتيجة مباشره لأزدياد كمية البخار المتدفق خلال المراحل الاخيره منها. بالاضافه الى خفض انبعاثات ثاني اكسيد الكربون بما يزيد على 10 الاف طن سنوياً. ولكن الجدوى الاقتصاديه لمثل هذا المشروع قد لا تكون مشجعه حالياً بسبب انخفاض اسعار النفط في الاسواق العالميه، حيث تقدر فترة استرداد رأس المال بأكثر من عشر سنوات.

الكلمات المفتاحيه: اعادة تأهيل المحطات، انظمة الطاقه الشمسيه المركزه، توليد الطاقه، الاردن.

Integrating CSP technology into existing old thermal power plants

Jamal Othman

Mechanical Division, Jordan Engineers Association, Amman, Jordan
Email: jojaber@gmail.com

Abstract

This study aims to investigate technical, economic and environmental aspects of integrating a Parabolic Trough Collector with existing feed-water heating system in an old "33 MW unit" in Al-Hussein Thermal Power Plant in Jordan. Such integration should improve the performance of the existing power plant and reduce the rate of fuel consumption, consequently the resultant pollutants', including GHG, emissions will be reduced. System Advisor Model software was used as a simulation tool in this study to optimize the required solar field aperture area and to predict the performance of employed solar system. Thermodynamic basic relations, energy and mass balances, are used to simulate various main components of the existing standard steam, Rankine, cycle. Different scenarios of feed-water heating arrangement with solar-replacement are presented and discussed. It was found that efficiency of the existing power unit could be increased by 3% due to higher turbine's output as a result of increased steam flow rate at later stages of the turbine. The estimated avoided GHG emissions exceed 10,000 ton CO_2 annually. But economics of such system may not be very attractive due to decreasing oil prices: at present the estimated payback period is more than 10 years.

Keywords: Repowering, CSP, Solar Energy, Thermal Power Plants, Jordan

1.   <u>Background</u>

Concerns of security of energy supplies, fossil fuels prices and resultant negative environmental impacts are main drivers behind moving towards utilizing indigenous energy resources including renewables. This is typically the case in Jordan, which is a non-oil producing country with limited natural resources and totally dependent on imported energy from Gulf States and Egypt. Recently the regional political upheaval which caused instability in the whole MENA region had impacted Jordan economically through:

1.   The sharp drop in natural gas supplies from Egypt which led to a surge in Jordan's current account and fiscal deficits; and

2. The large influx of refugees, especially from Syria, which increased the population by more than 25% and further straining Jordan's difficult fiscal position.

Thus, the government of Jordan (GOJ) has taken few actions aiming to develop the energy sector to and promote energy efficiency in all sectors of the economy in order to reduce dependence on imported oil and gas. It is aimed to cut the current level of approximately 97%, while increasing the share of renewable energy meeting to 10% (i.e. 600-100 MW wind, 300-600 MW solar and 30-50 MW biomass) of energy demand by 2020 as reported by the Minister of Energy and Mineral Resources at different occasions. However, in the past few years (2011-2014) electricity produced from renewable sources was less than 0.5% [1].

Among all renewable sources, solar and wind energy are most promising and could be used in green electricity generation. The annual solar intensity (2000-2500 kWh/m^2) in Jordan is among the highest in the world which supports the development of solar based central power plants either by using PV or CSP technologies. At present there is a long list of PV projects, as central power plants, either connected to the grid or in the pipeline and soon will be completed. But CSP technology is still not deployed due to the fact that the required capital investment is very high compared with other renewable or non-renewable technologies. In this study, repowering of an old 33 MW steam unit at Al-Hussein Thermal Power Plant (HTPP), in Jordan is presented. The repowering is achieved by integrating a parabolic trough collector (PTC) system with the feed-water heaters (FWHs) to substitute for steam extractions from the steam turbine. Such integration of a new technology will lead to improve the performance of the existing power plant and reduce its fuel consumption; consequently, the resultant pollutant emissions will be reduced. The paper is organized as follows: the next section presents the literature review related to the research subject; section 3 describes the adopted methodology in this research; the results and discussion are then introduced in section 4; and section 5 presents some concluding remarks.

2. Introduction

The early works about hybridization of Rankine cycle with solar thermal energy started in 1975 with Zoschak and Wu studying seven alternatives of absorbing solar energy as direct input to 800 MW fossil-fuelled steam power plant [2]. It was reported that combined evaporation and superheating is the preferred option for hybridization. Gupta and Kaushik [3,4] analyzed exergy characteristics for different components of a proposed conceptual solar thermal power plant and they concluded that heating feed-water using solar energy is more advantageous than using the same solar energy in a stand-alone solar thermal power plant. Hu et al. [5] studied the advantages of the solar aided power generation (SAPG) concept using THERMOSOLV software. They proved that energy and exergy efficiencies of a power station can be improved by using solar energy to replace the extracted steam for heating feed-water. Qin Yan et al. [6] studied the overall efficiencies of the SAPG with different solar systems to substitute partially for steam extraction in the regenerative cycle. It was found that solar integration assisted the existing power plant in reducing coal consumption and pollution emissions due to increased net power output. Suresh et al. [7] analyzed energy, exergy, economic, and environmental impacts of hybrid solar-coal-fired power plants, in India, by using the Cycle Tempo software. It was shown that there is an instantaneous fuel conservation of about 5-6% with the substitution of turbine bleed streams to the feed-water heaters. Popov

[8] modeled three options to repower an existing 130 MW steam power plant with solar heating using THERMOFLEX software. The off-design calculations indicated that the most attractive option, especially for existing power plants, is the replacement of high pressure (HP) heaters with an adequate solar field to raise boiler feed-water temperature up to the desired approach temperature.

Xiuyan et al. [9] proposed using solar steam as an auxiliary thermal source of a 600 MW coal-fired supercritical unit, by integrating solar system with the de-aerator. Yang et al. [10] demonstrated SAPG through a case study of a 200 MW coal-fired power plant, and discussed different replacement schemes. Reddy et al. [11] carried out a comparative energetic and exergetic analysis of a solar aided coal-fired supercritical thermal power plant. It was reported that there was an instantaneous increase in power generation capacity up to 20% when substituting turbine bleed streams for all the LP- and HP-FWHs. Yan et al. [12] developed a model to evaluate SAPG, studying energy and economic benefits if integrating solar system to preheat feed-water in the range from 90°C to 260°C. Their results indicated that the benefits of SAPG vary for different steam extraction positions and power plant configuration: in general, the larger the power plant, the higher the benefit for the same level of integrated solar power.

There are various options for integrating CSP technologies with a steam cycle. In the current investigation, the boiler and feed-water heaters are the only sources of thermal energy in the cycle; however, all steam is generated in the boiler. Integrating solar system with the boiler requires a high-temperature solar technology like solar tower or advanced parabolic trough collectors, in addition to controls complexity. But the integration with feed-water heaters to replace steam extraction from the steam turbine appears to be a more practical option due to relatively medium temperature required in this case. Benefits of solar-aided power plant, i.e. hybridization or solar repowering, are nemours but the most important are:

1. Reduce consumption of fossil fuel(s) and resultant emissions
2. Improve cycle efficiency
3. Lower capital cost than solar-only plants
4. Guarantee full capacity plant operation

In the market, there are four CSP technologies available and used; these are (i) Stirling-dish engine, (ii) Central Receiver System (CRS), (iii) Parabolic Trough Collectors (PTC) and (iv) Linear Fresnel reflectors (LFR). In this study the PTC has been considered as preferred technology for producing the required heat for FWHs due to the followings:

1. Proven technology in commercial projects
2. Low cost
3. Low relative area required (m^2/kW)

In future research, LFR system will be considered and final results should be compared with findings of the study in hand. PTC could work with heat transfer fluid (HTF) such as thermal oils where oil transfers thermal energy to the water to produce saturated or superheated steam, or water can be used as a heat transfer fluid with direct steam flashing (below 100 bar steam). As the objective here is simply to heat FWHs with steam outlet conditions below 100 bar, then a direct steam generation (DSG) option, without any type of thermal storage, was considered due to the following advantages [13].

1. No need for additional heat exchangers
2. Reduced size of the solar field
3. Low investment cost as well as O&M costs
4. No danger of pollution or fire

The present investigation is the 1st attempt in Jordan to study the integration of CSP with an existing thermal power plant. For this purpose, researchers have developed a tailor-made simulation of an old steam unit of 33 MW$_e$, which was installed in the second half of 1970s at HTPP near Zarqa in Jordan, based on principles of thermodynamics and energy conversion. This model was used to evaluate the performance (energy balance, consumption, power output, efficiency, etc.) of this power station. Then a concentrated solar power system (CSP) is introduced to preheat boiler feed-water instead of live-steam extraction from the steam turbine and compared to the base case scenario. But it should be remembered that it is not the aim of this research work to redesign the steam cycle or its components, rather providing a techno-economic and environmental assessment of such hybrid systems.

3. Methodology

The HTPP is an old power plant, located nearby Zarqa, approximately 30 km northeast of the Capital Amman. The plant site is situated at 560 m above sea level. It consists of seven generating units and split into two groups: old 3×33 MW and new 4×66 MW steam units. The nominal design efficiency of old 33 MW units was 33%. Such low efficiency is due to the fact that air-cooled condensers are used because of lack of fresh water supplies. The plant was connected to the grid and came on commercial operation in 1977, and after 38 years of operation the real efficiency dropped to 26%, as reported by the Central Power Generation Company [14]. In this study, one of these 33 MW units has been selected and analyzed. The employed thermal cycle is a standard regenerative Rankine cycle, in which the boiler feed-water heating system consists of four closed and single open feedwater heaters. Fig.1 shows the original heat and mass balance and flow diagram for this unit, with heavy fuel oil being the prime fuel. The blocks in red dashed-line are main components: fuel-fired boiler, multi-stage steam turbine, condenser, water pumps, feed-water heaters and other accessories.
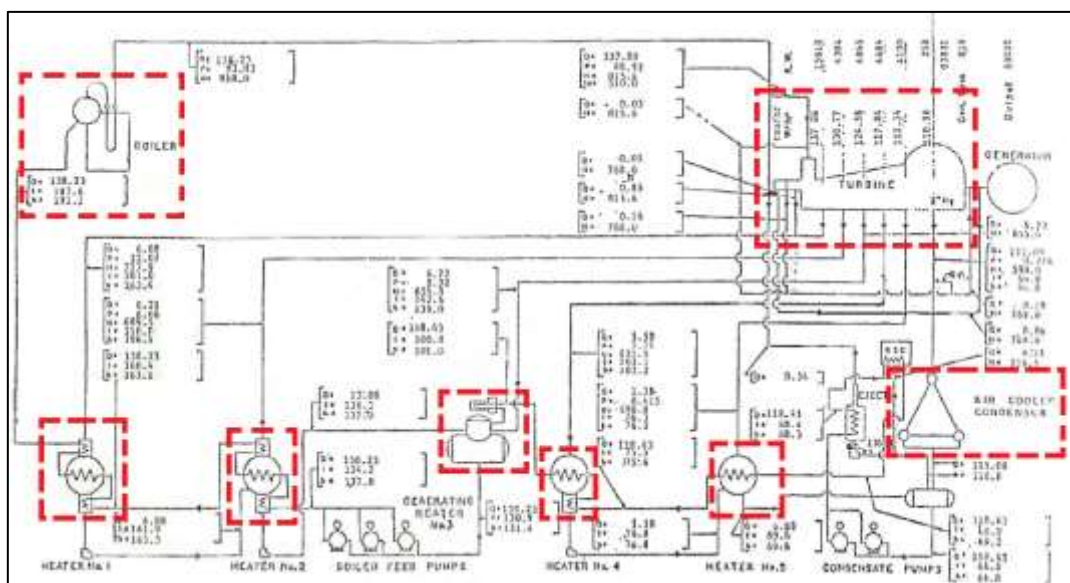

Fig. 1: Heat balance and flow diagram for the 33 MW steam-unit

The design point energy and mass balances are presented for each component; which represent the base case in the current study, i.e. before integrating the proposed CSP system. Based on this diagram, a detailed thermodynamic analysis was carried using a tailor-made simulation program, which enabled calculating all properties such as temperature, pressure, enthalpy, and flow rate, etc., at each point of the cycle and for each component. Followed by discussing different scenarios for integrating the selected CSP technology with the existing cycle. The simulation of CSP technology is conducted by using the System Advisor Model (SAM) software, which is developed by the National Renewable Energy Laboratory (NREL) of USA, to study and analyze the performance of the CSP system as part of the hybrid Solar-Rankine cycle.

SAM software, which is used to evaluate the CSP system, requires a resource data file describing the solar energy source and weather conditions on site such as hourly values of solar radiation and weather data. These include but not limited to solar and weather parameters (GHI, DNI and DHI) and dry/wet ambient temperatures, relative humidity, atmospheric pressure, wind speed, direction and albedo, in addition to latitude, longitude and elevation as summarized in Table 1. The reference solar parameter, DNI, employed in this study is shown in Fig. 2. The basic assumptions used in this study are (i) average DNI 950 W/m^2, (ii) ambient temperature 20°C, and (iii) wind velocity 10 m/s.

Table 1: Solar and weather data for plant location

State, City	Zarqa, Al-Hashemyyeh
Country	Jordan
Time Zone	GMT 2
Elevation (m)	560
Data Source	TMY3
Latitude (°)	32.07 N
Longitude (°)	36.07 E
GHI (kWh/m^2/day)	5.13
DNI (kWh/m^2/day)	6.39
DHI (kWh/m^2/day)	1.04
Avg. Temperature (°C)	18.6
Avg. Wind Speed (m/s)	10.4

The input parameters, for simulation with SAM, for all proposed options are summarized in Table 2, each option is taken as a separate case in order to calculate the optimal area required for the PTC solar field. This enabled the determination of best and optimal performance with feasible initial/capital costs. But it should be remembered here that the land area depends on different factors such as the distance between the PTC rows and aperture area. The later depends on required thermal capacity, DNI, ambient temperature, wind velocity and solar multiple (SM), etc.

Table 2: Parameters for different FWHs replacement options

Replacement Option		Mass Flow Rate (ton/h)		Thermal Energy Rate (kcal/h)	Thermal Energy (MW)	Water/Steam Inlet Temp. (°C)	Water/Steam Outlet Temp. (°C)	Water/Steam Inlet Pressure (bar)
FWH #1		6.88		4,939,152	5.74	281.0	161.9	12.07
FWH #1+2	#1	6.88	13.09	9,220,947	10.72	281.0	161.9	12.07
	#2	6.21				218.0	136.3	6.66

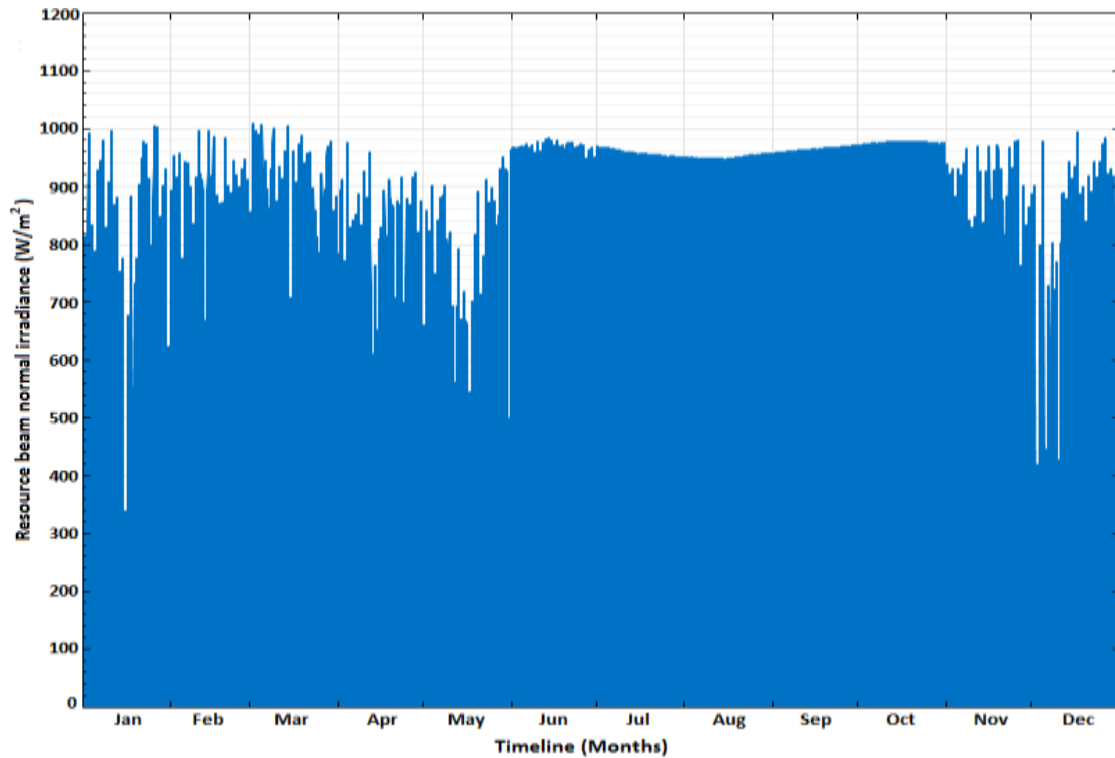|								
FWH #1+2+3	#1	6.88	19.81	13,627,923	15.85	281.0	161.9	12.07
	#2	6.21				218.0	136.3	6.66
	#3	6.72				142.6	130.9	2.92
FWH #1+2+3+4	#1	6.88	25.31	17,046,173	19.82	281.0	161.9	12.07
	#2	6.21				218.0	136.3	6.66
	#3	6.72				142.6	130.9	2.92
	#4	5.50				102.1	76.8	1.11
FWH #1+2+3+5	#1	6.88	21.19	14,442,123	16.79	281.0	161.9	12.07
	#2	6.21				218.0	136.3	6.66
	#3	6.72				142.6	130.9	2.92
	#5	1.38				76.3	69.6	0.42
FWH #4+5	#4	5.50	6.88	4,232,450	4.92	102.1	76.8	1.11
	#5	1.38				76.3	69.6	0.42
FWH #5		1.38		814,200	0.95	76.3	69.6	0.42
All FWHs		26.69		17,860,373	20.77	281.0	69.6	0.42 - 12.07

Fig. 2: Resource beam normal irradiance (DNI) in Zarqa around the year

In this study, integration of CSP system with feed-water heaters is considered and eight different options of replacing feed-water heaters are presented and discussed, as follows:

1- Feedwater heater No.1 (one high pressure FWH).
2- Feedwater heaters No.1 and No.2 (two high pressure FWHs).
3- Feedwater heaters No.1 to No. 3 (two high pressure FWHs and one open FWH).
4- Feedwater heaters No.1 to No. 4 (two high pressure FWHs, one open FWH and one low pressure FWH).
5- Feedwater heaters No.3 to No. 5 (one open FWH and two low pressure FWHs).

6

6- Feedwater heaters No.4 and No.5 (two low pressure FWHs).
7- Feedwater heater No.5 (one low pressure FWH).
8- All feedwater heaters (five FWHs).

In all of these scenarios, there will be no water/steam mixing between the solar system and the steam unit due to using a closed-loops system which should provide FWHs with adequate steam/water flow rate at the specified conditions. The obtained results are presented and discussed in the following section, with the basic assumption applying for all these scenarios is that the plant running at full load in order to simplify calculations. Bearing in mind that the aim of this research is to demonstrate the impacts of integrating the proposed CSP system with an existing steam unit, and not to redesign the power plant or its components.

4. Results and Discussion

Energy and Mass Balance

In this study, all engineering calculations for supplying the required heat as steam, generated by the PTC to the FWH No.1, was taken as a sample for the rest of FWHs (see Fig. 1). Such solar add-on would eliminate steam extraction from the steam turbine, consequently more steam mass flow expand in later stages of the turbine. Finally, this will produce more network output to the generator.

The effect of first replacement (i.e. FWH No.1) on the T-s diagram is shown in Fig. 3. It is clear that steam at point 1 is no longer extracted from the turbine, since the required heat load is supplied by the PTC system. Based on thermodynamic principles and analysis, after establishing mass and energy balances, the predicted effect on different cycle parameters ($\dot{Q}_{in@Boiler}$, $\dot{W}_{Turbine}$, $\dot{W}_{Pumps}$, $\dot{Q}_{out@condenser}$, etc.) is determined and the final efficiency (η) of the steam cycle can be estimated.

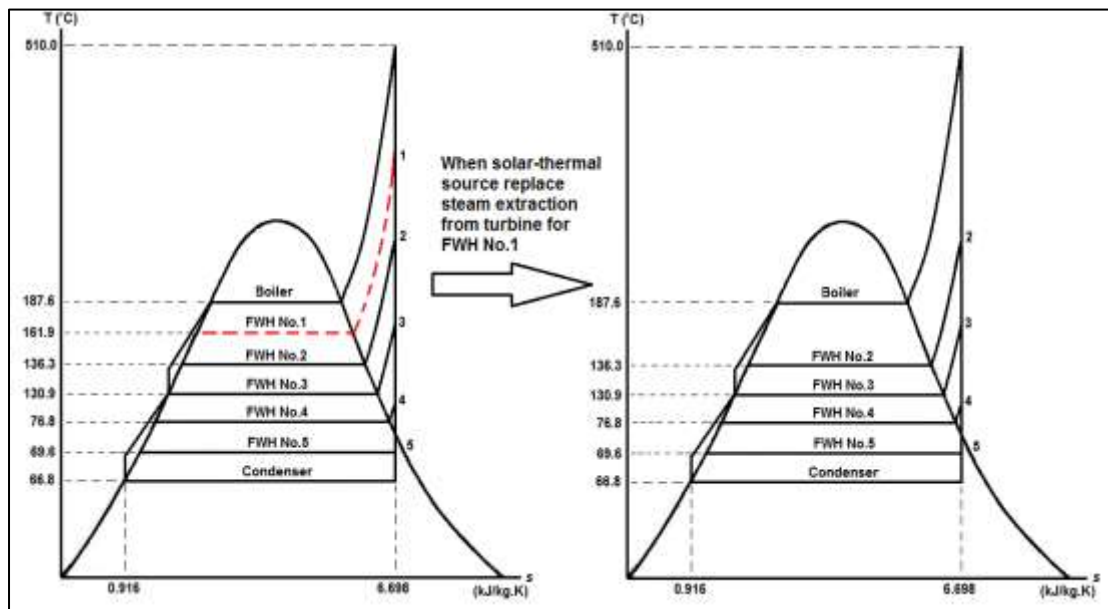
Fig. 3: Replacement of FWH No.1on T-s diagram

This replacement of source of steam, to FWH No.1, showed positive effect on turbine's output, which is reflected on the cycle efficiency: increased cycle's efficiency by about

1.04%. Similar procedure was followed for the rest of proposed options (see Figs.4 & 5). Close look at these two figures clearly confirms that substitution for FWH No. 5 would result in least improvement on the cycle due to the fact that needed steam here is at low pressure and mass-flow rate, which has insignificant influence on the work produced by the turbine. While supplying all FWHs with steam generated by the PTC system would increase the final efficiency by approximately 3%. Main performance indicators of the cycle for all studied options are summarized in Table 3. It is clear that replacing all FWHs, or high (1&2) and low (3&4) pressure, is the best option. Since the steam will continue expansion in the turbine resulting in more output instead of being extracted for feedwater heaters.
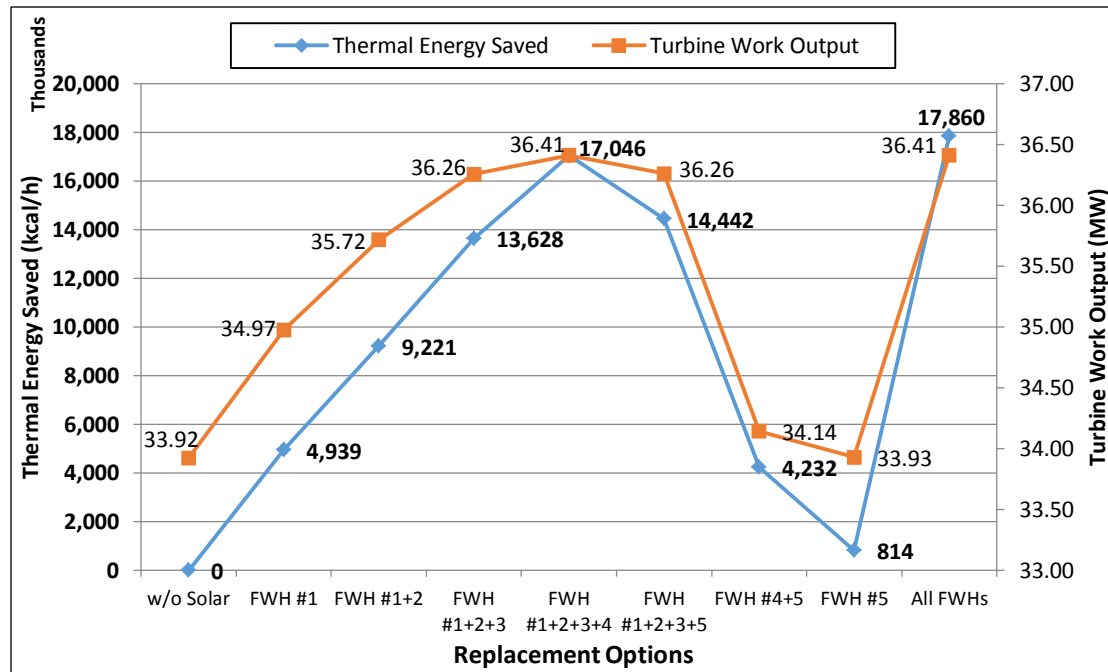

Fig. 4: Saved thermal energy and turbine work output for various replacement options of FWHs
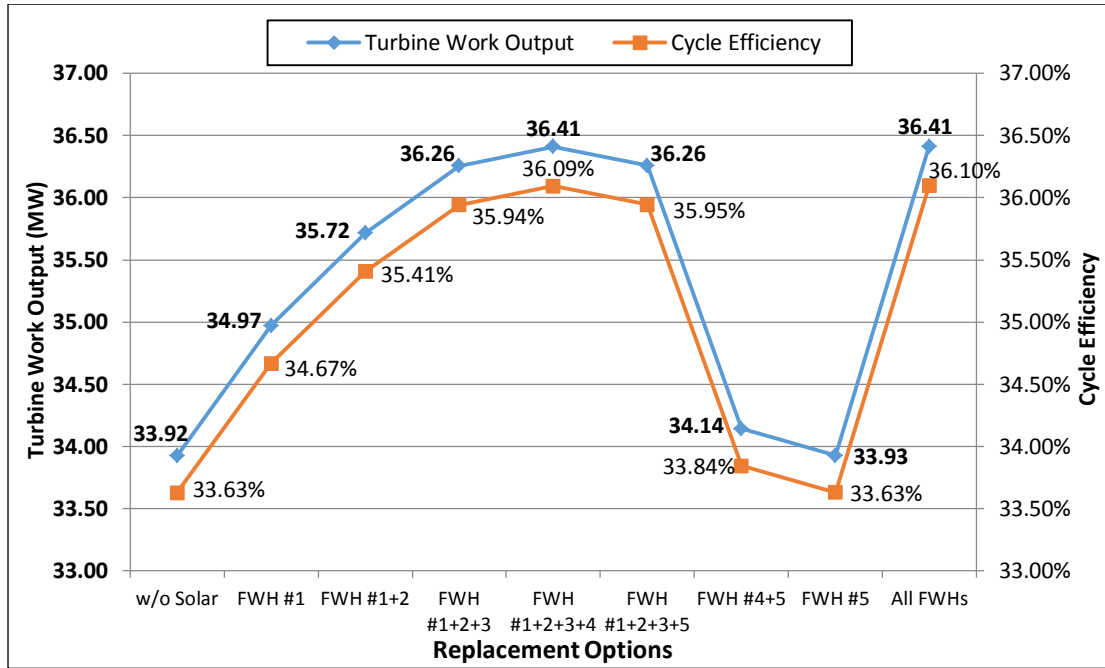
Fig. 5: Steam turbine work output and cycle efficiency for various replacement options of FWHs

Table 3: Main performance indicators for all studied options

Replacement Option	Saved Steam (ton/h)	FWH(s) Thermal Energy (kcal/h)	$\dot{W}_{Turbine}$ (MW)	$\dot{Q}_{Condenser}$ (MW)	$\dot{W}_{Cond.Pump}$ (kcal/h)	η (%)
Base Case	0	---	33.92	67.21	2.6×10^{-3}	33.63%
FWH #1	6.88	4,939,152	34.97	71.38	2.7×10^{-3}	34.67%
FWH #1+2	13.09	9,220,947	35.72	75.14	2.9×10^{-3}	35.41%
FWH #1+2+3	19.81	13,627,923	36.26	79.22	3.0×10^{-3}	35.94%
FWH #1+2+3+4	25.31	17,046,173	36.41	82.55	3.0×10^{-3}	36.09%
FWH #1+2+3+5	21.19	14,442,123	36.26	80.05	3.0×10^{-3}	35.95%
FWH #4+5	6.88	4,232,450	34.14	71.38	2.6×10^{-3}	33.84%
FWH #5	1.38	814,200	33.93	68.05	2.6×10^{-3}	33.63%
All FWHs	26.69	17,860,373	36.41	83.39	3.0×10^{-3}	36.10%

Required Solar Field

Optimization of required solar field aperture area and performance prediction of the proposed PTC system was achieved by employing SAM, as a simulation tool, as illustrated previously. Fig. 6 shows the schematic-flow diagram of the steam-unit after integrating the PTC system with FWH No.1 and simulation results are summarized in Table 4. The minimum value of solar multiple is assumed to be 1.5 to ensure that the system will work all over the year at its

rated capacity. The field thermal energy produced by the PTC system over the year is shown in Fig. 7.

Table 4: Simulation data of PTC for FWH No.1

Replacement Option	Input Parameters			Output of PTC		
	Solar Multiple (SM)	Required Thermal Power Output (MW$_{th}$)	Steam Output/Input Temperatures (°C)	Solar Field Aperture (m^2)	Active Hours[1] (hour)	Out of Service Days[2]
FWH#1	1.50	5.74	300/160	13,160	2,043	91

1: Active hours (out of 8,760 hours)
2: Out of service days (out of 365 days)

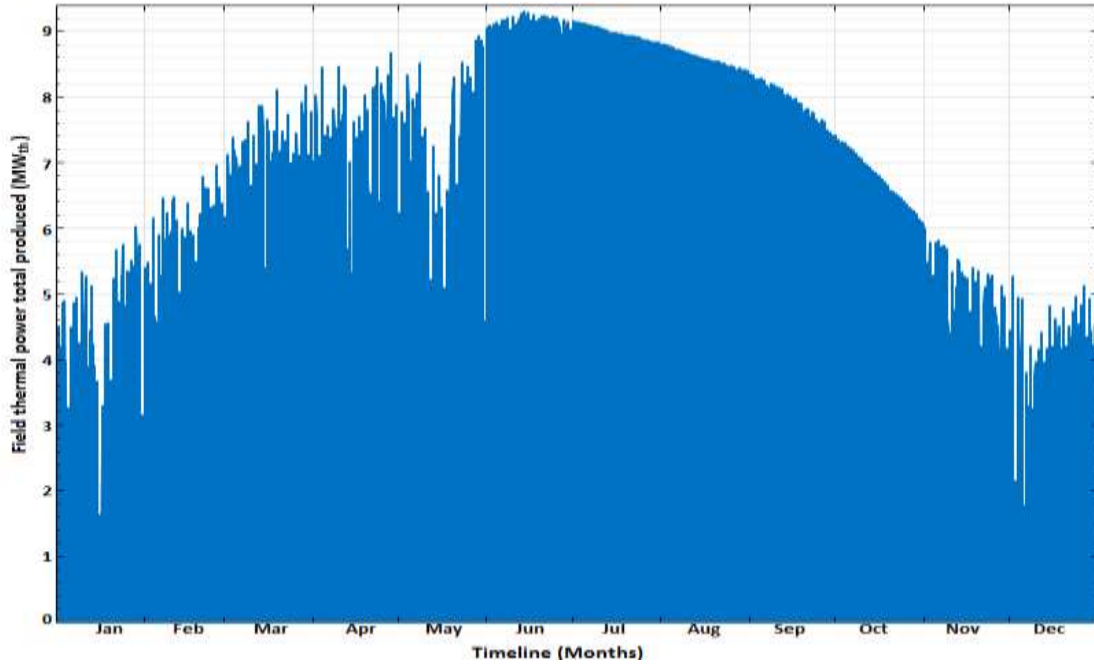Fig. 6: Schematic diagram with PTC system to supply FWH No.1

Fig. 7: Field thermal power produced for FWH No.1 with SM = 1.5 over a year

In order to meet the minimum required thermal energy demand all around working days, i.e. during winter season and cloudy days, and to increase active hours of the proposed PTC system, the SM factor should be enlarged to satisfy the demand. In this study, to calculate the optimal solar field aperture area, different trials were carried out, for FWH No. 1, by changing the SM value between 1.50 and 2.75 with a step of o.25. Same procedure applied for all FWHs replacement options and sample of results of FWH No.1 option are summarized in Table 5.

Table 5: Simulation results of FWH No.1 with variant SM values

Input Parameters			Output of PTC		
Solar Multiple (SM)	Required Thermal Power Output (MW$_{th}$)	Steam Output/Input Temperatures (°C)	Solar Field Aperture (m^2)	Active Hours[1] (hour)	Out of Service[2] (Days)
1.50			13,160	2,043	91
1.75			15,275	2,426	55
2.00	5.74	300/160	17,390	2,703	26
2.25			19,505	2,911	8
2.50			21,855	3,080	7
2.75			23,970	3,168	3

1: Active hours (out of 8,760 hours)
2: Out of service days (out of 365 days)

It is clear from the tabulated figures in Table 5 that solar field aperture area for any replacement option is directly proportional to solar multiple as well as PTC system's active hours. Doubling SM factor would lead to a sharp drop in the out of service days, i.e. from 91 to 3, but the aperture area almost doubled which will increase the required capital investment and O&M costs. This direct proportional relationship between SM value and aperture area is shown in Fig. 8, for all replacement options.
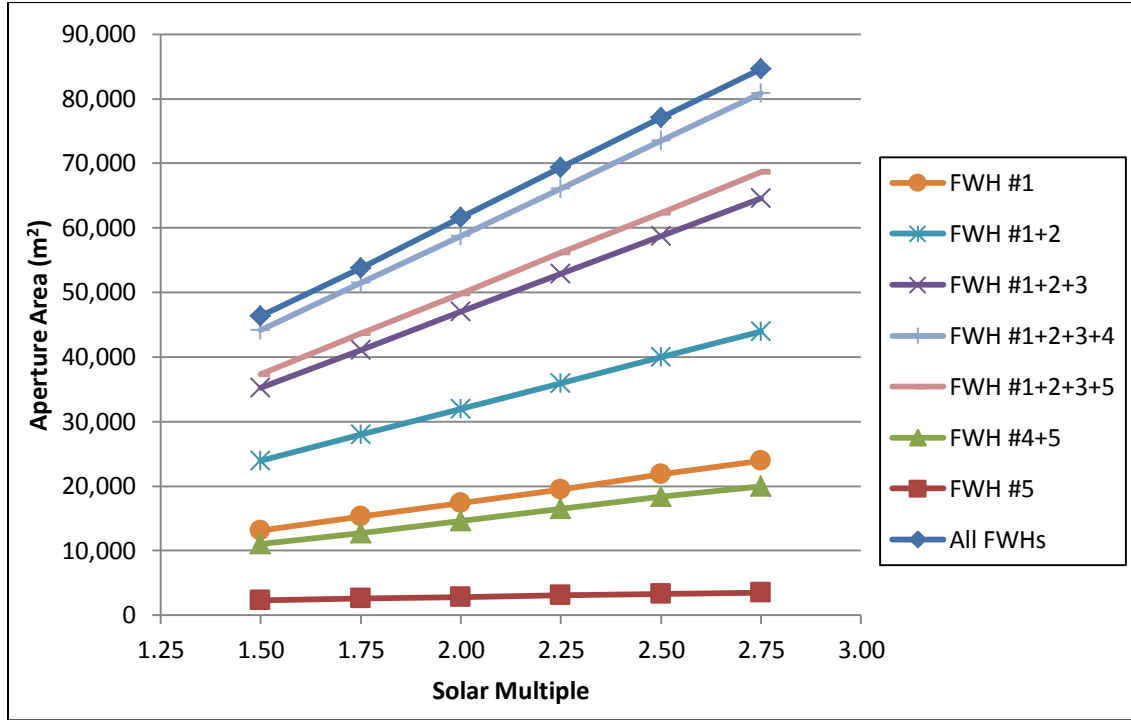
11

Fig. 8: Relationship between solar multiple and solar field aperture area

Configuration of PTC system and number of collectors in each of preheating, evaporation and superheating sections of the solar field are not part of this work. Only models of each collector and receiver are mentioned here. So a commercially available system "SCHOTT PTR 70" is selected as receiver and "Luz LS-2" as collector. Characteristics of receiver and collector are shown in Table 6 [15] and Table 7 [13].

Table 6: Characteristics of "SCHOTT PTR 70" receiver

Absorber steel pipe outer/inner diameter (m)	0.070 / 0.066
Glass envelope outer/inner diameter (m)	0.120 / 0.115
Inner roughness of steel absorber pipes (m)	4.5×10^{-5}
Absorber absorption	0.96
Absorber emittance	0.095
Glass envelope transmittance	0.97
Selective coating	Black Cr
Heat losses (W/m)	58.29
Thermal losses (W/m and W/m^2)	77.03 / 15.40
Optical efficiency	0.75

Table 7: Characteristics of "Luz LS-2" collector

Solar collector assembly (SCA) length (m)	50
SCA aperture (m)	5
SCA aperture reflective area (m^2)	235
Distance between SCAs in row (m)	1
Row spacing; center to center (m)	15
Number of SCAs per Row	4
Deploy angle ($^\circ$)	10
Stow angle ($^\circ$)	170

Average focal length (m)	1.8
Solar tracking accuracy ($^{\circ}$)	0.10
Maximum wind velocity to operate (km/h)	56
Mirror reflectivity	0.935
Aperture angle	80
Geometric accuracy	0.98
Dust on envelope	0.98

Economic Analysis

In open literature there is limited information about cost breakdown of CSP systems. In addition to lack of local experience in such new systems from EPC point of view which prevents making reasonable assumptions. The only dependable available sources are the World Bank report, 2011, which included the investment cost of different subsystems of Andasol-1 plant in Spain [16] and the cost model developed by the National Renewable Energy Laboratory (NREL) with assistance from Worley Parsons Group Inc., for use with NREL's System Advisor Model (SAM) [17]. Based on these reports, estimates of capital and running costs factors of the proposed PTC system are summarized in Table 8.

Table 8: Estimated capital and annual running cost factors for the proposed PTC system

Parameter	Cost Factor
Direct Capital Cost	
Site Improvement (US$/m^2)	10.0
Solar Field (US$/m^2)	400.0
HTF System (US$/m^2)	5.0
Contingency (% of total direct cost)	3%
Indirect Capital Cost	
Engineering, procurement and construction (% of total direct cost)	10%
Annual Running Cost	
O&M (labor and material) (US$/kW-year)	12.0

Based on basic assumptions provided in Table 8 and previous calculations, the total capital cost of PTC system needed to replace FWH No.1 (with SM = 1.5 and aperture area of 13,160 m^2) are assessed as shown in Table 9. This could provide an initial projection of costs related to integrating a CSP system with an existing steam power unit. The share of each of main components of the proposed PTC system in the total capital cost is shown in Fig. 9.

Table 9: Total capital cost of PTC for FWH No.1 (SM = 1.5)

Parameter	Cost (US$)
Direct Capital Cost	
Site Improvement	131,600.0
Solar Field	5,264,000.0
HTF System	65,800.0
Contingency	163,850.0
Indirect Capital Cost	
EPC Contract	562,530.0
Total	**6,187,780.0**

It is clear that solar field cost is the major one with sharing ratio of 85%, while all other items represent less than 15%. Table 10 summarizes total capital costs and cost per energy unit produced by the new system (US$/kW$_{th}$) for replacing FWH No.1, with variable SM values as discussed previously. Based on previous calculations and assumptions, the projected simple payback period for this project is not very attractive since it exceeded 11-12 years. But with prevailing low oil prices in the international market, in 2016, the payback period is much longer. In Fig. 10 which illustrates the relation between SM, capital cost and SPBP for FWH No.1 replacement option, it is obvious that the optimal SM values is around 1.75 and estimated SPBP not less than eleven years.
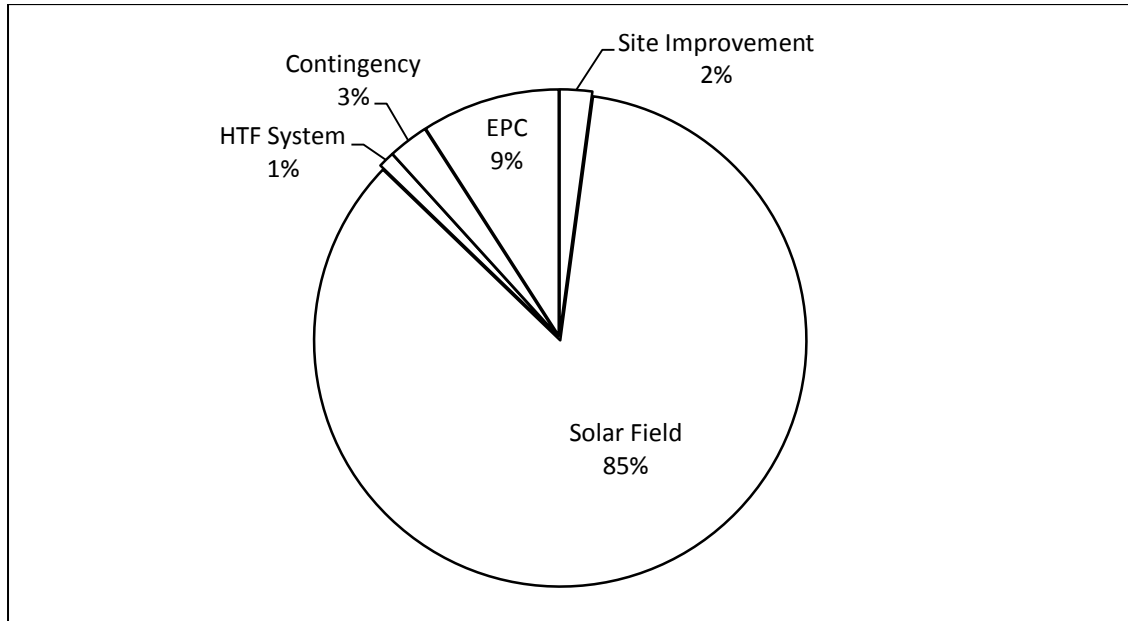

Fig. 9: Cost share of main components of proposed PTC system to replace FWH No.1

Table 10: Cost analysis for replacement FWH No.1 option

SM	Aperture Area (m^2)	Capital Cost (10^6 US$)	Unit Energy Cost (US$/kW$_{th}$)	Actual Active Hours (hour)	Thermal Energy Saved* (kcal×10^9/yr.)	Fuel Saving** (US$/yr.)	Simple Payback Period (year)
1.50	13,160	6.188	1,077	2,002	11.237	541,046	11.44
1.75	15,275	7.182	1,251	2,377	13.344	642,476	11.18
2.00	17,390	8.177	1,424	2,649	14.868	715,834	11.42
2.25	19,505	9.171	1,597	2,853	16.012	770,918	11.90
2.50	21,855	10.276	1,789	3,018	16.941	815,674	12.60
2.75	23,970	11.271	1,962	3,105	17.425	838,979	13.43

*Calorific value of HFO (fuel used in 33 MW unit of HTPP) = 10,139 kcal/kg [18]

**HFO price used for power generation based on fuel prices in Jordan considered as US$ 488.2/ton as in March 2015 [19]
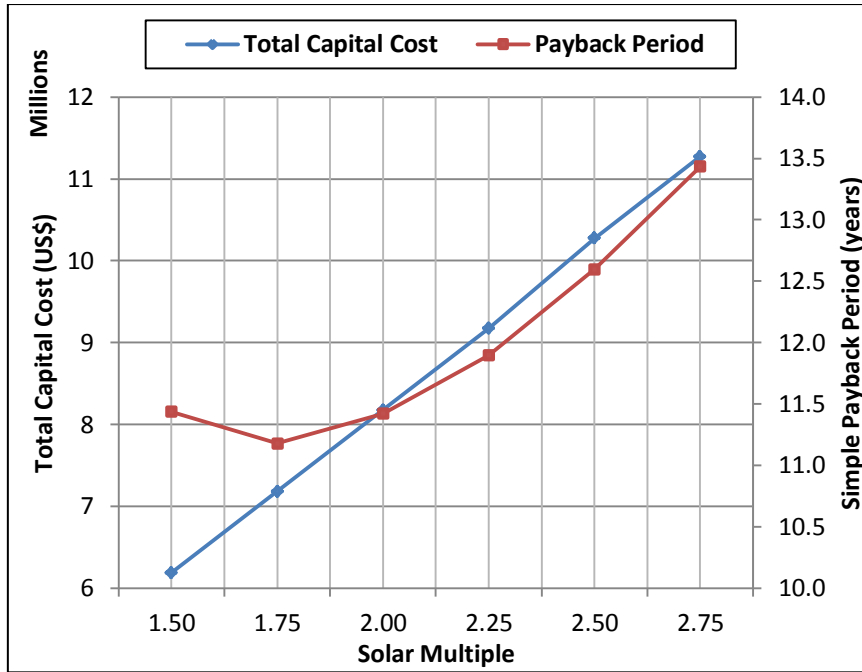
Fig. 10: Relation between SM, capital cost and SPBP for FWH No.1 replacement option

Same procedure was applied for all studied options, taking also different SM values. It was found that SPBPs for any replacement option range between 10 and 14 years and the optimum SM between 1.75 and 2.0.

For such long-term project, calculating SPBP is enough to judge on its economics and thus the cash flow over the lifetime of the proposed PTC system should be considered. The long-term investment analysis presented by cash-flow diagram and Net Present Value (NPV) of money were simulated for all cases of FWHs replacement, with various financial parameters as shown in Table 11. The results of such simulation are presented in Figs. 11 and 12 which show annual net cash flow and cumulative cash flow, respectively.

Table 11: Financial parameters and assumptions for investment analysis

Financial Parameter	Value	Notes
Project lifetime (investment period)	20 years	---
Inflation rate	5%	Average value for years (2010-2014) in Jordan [20]
Discount rate	7%	---
Net salvage value	10%	% of total capital cost (Conservative assumption for the value of the project at the end of the lifetime)
Income tax rate	14%	Income tax rate in Jordan due to date 2015 [21]
Insurance	0.3%	% of total capital cost
Debt ratio	70%	% of total capital cost

| Loan term | 10 years | --- |
| Loan rate | 6% | --- |

Based on net yearly values cash flow diagram (Fig. 11); NPV at a discount rate of 7% was about +191,503 US$. While PBP based on cumulative cash flow diagram (Fig. 12) was about 12 years and 6 months. But since the NPV has a positive value, then project is acceptable and may prove to be feasible in the future.
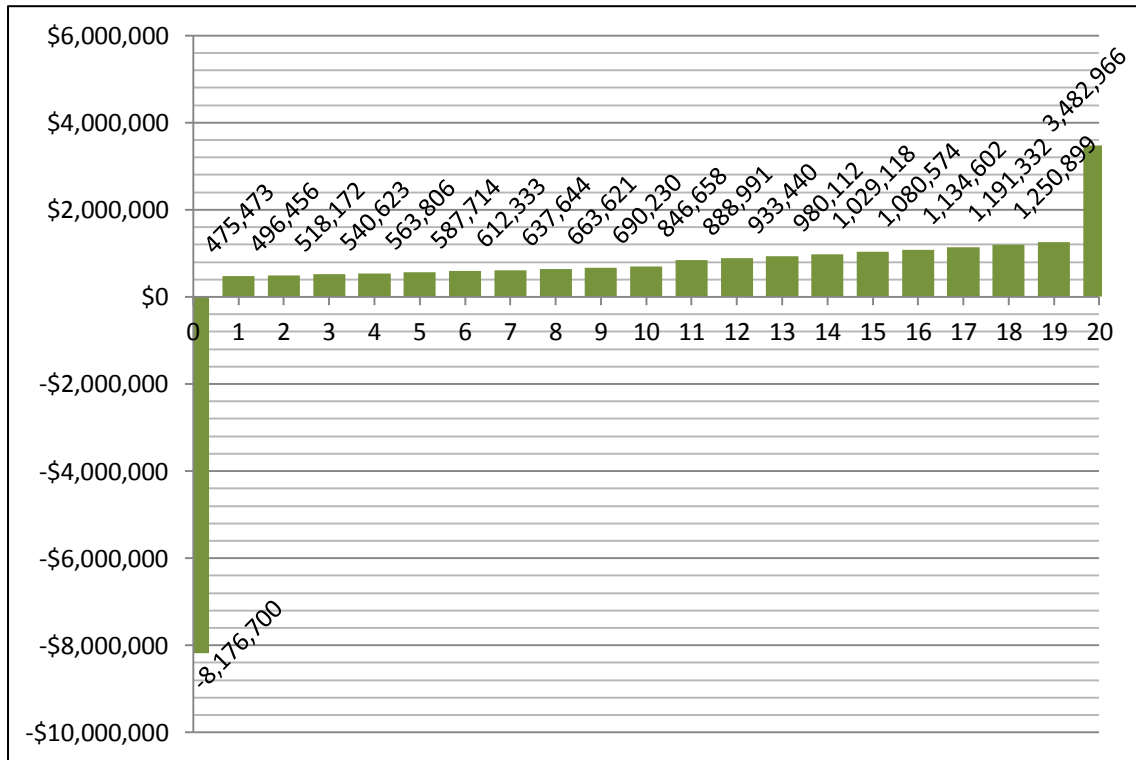

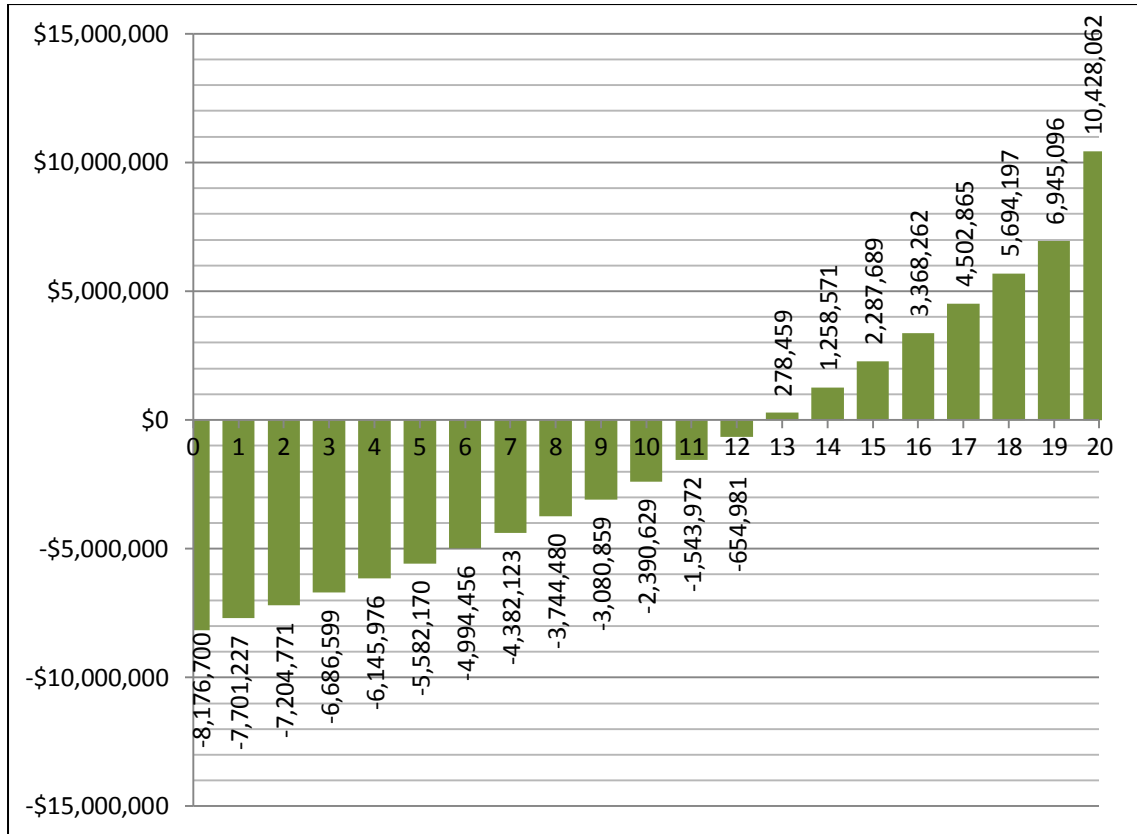Fig. 11: Net values cash flow diagram for FWH No.1 (SM = 2)

Fig. 12: Cumulative cash flow diagram for FWH No.1 (SM = 2)

But, any change in the proposed financial parameters and basic assumptions would have a significant change on NPV and PBP calculations, e.g. increasing debt fraction to 100% of total capital cost will reduce NPV to only +52,011 US$ and increase PBP by 3 months or more. Since such economic analysis was conducted based on variables and assumptions that are uncertain, then sensitivity analysis was carried out in order to test the robustness of obtained results and understand better the relationships between most influential input and output variables. As shown in Fig. 13 that most important two variables are capital cost, represent by the cost of required solar field and fuel prices. Followed by other less important factors such as construction cost.
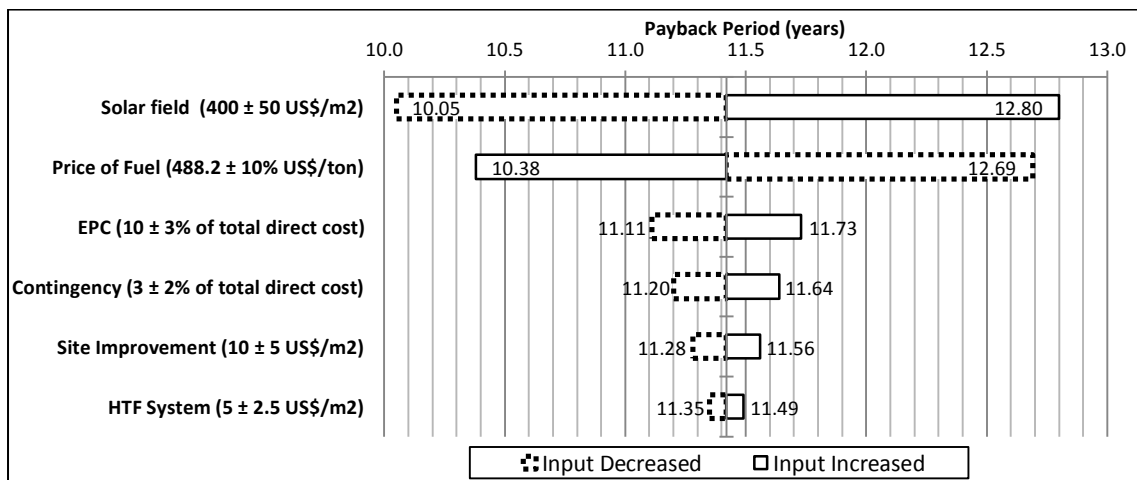

Fig. 13: Sensitivity analysis of key parameters and their influence on SPBP

17

When looking at the financial parameters, as expected the most important factor on economics of this project is the discount rate (when increased by 1%, the NPV decreased to about -610,000 US$ and therefore the project is not accepted and invest in such project is not feasible) followed by the local inflation rate and other factors as illustrated in Fig. 14.
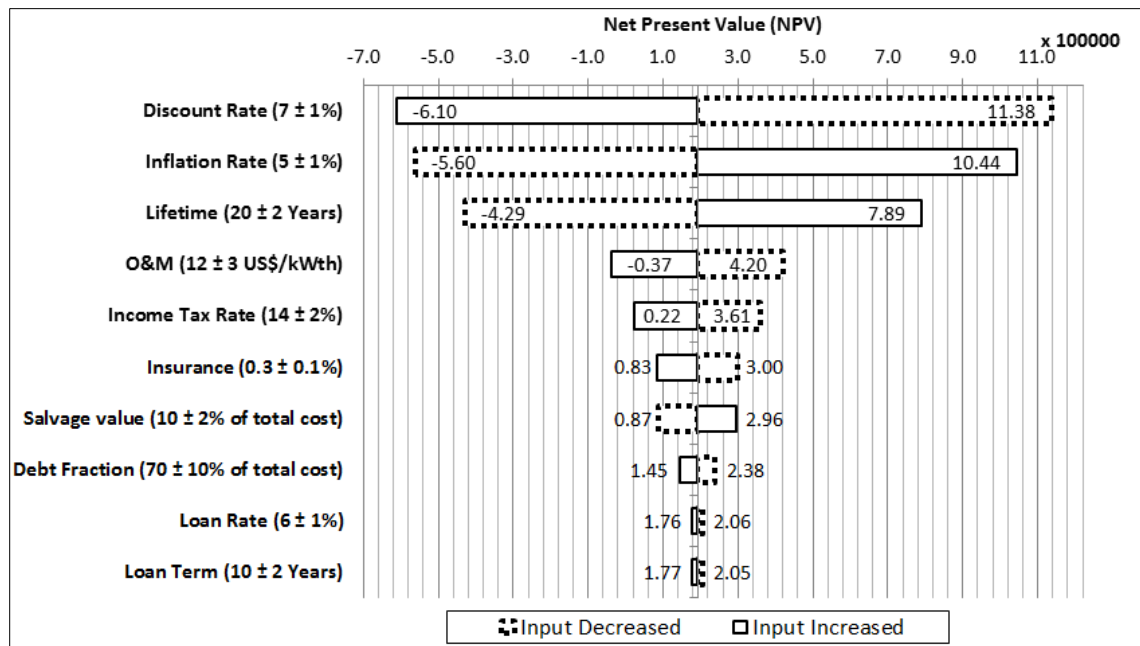

Fig. 14: Sensitivity analysis of NPV in relation with employed financial parameters

GHG Emissions

As demonstrated earlier that the new CSP integration with existing steam plant saved energy, represented by the amount of HFO needed to generate steam, consequently there will be net reduction of pollutant gases including GHG emissions. The amount of avoided GHG emissions, represented by CO_2 equivalent was calculated using an emission factor of 77.4 ton CO_2/TJ [22]. Nevertheless, cost reduction of such project could be achieved through financing from grants and/or CO_2 emissions trading. Based on the European Union Emissions Trading Scheme (EU ETS), each ton of CO_2 avoided could be sold in the international market for approximately 26 US$ [23]. When such cost is taken into consideration and added to fuel savings, then the SPBP is reduced significantly, by about 15%, as shown in Fig. 15.
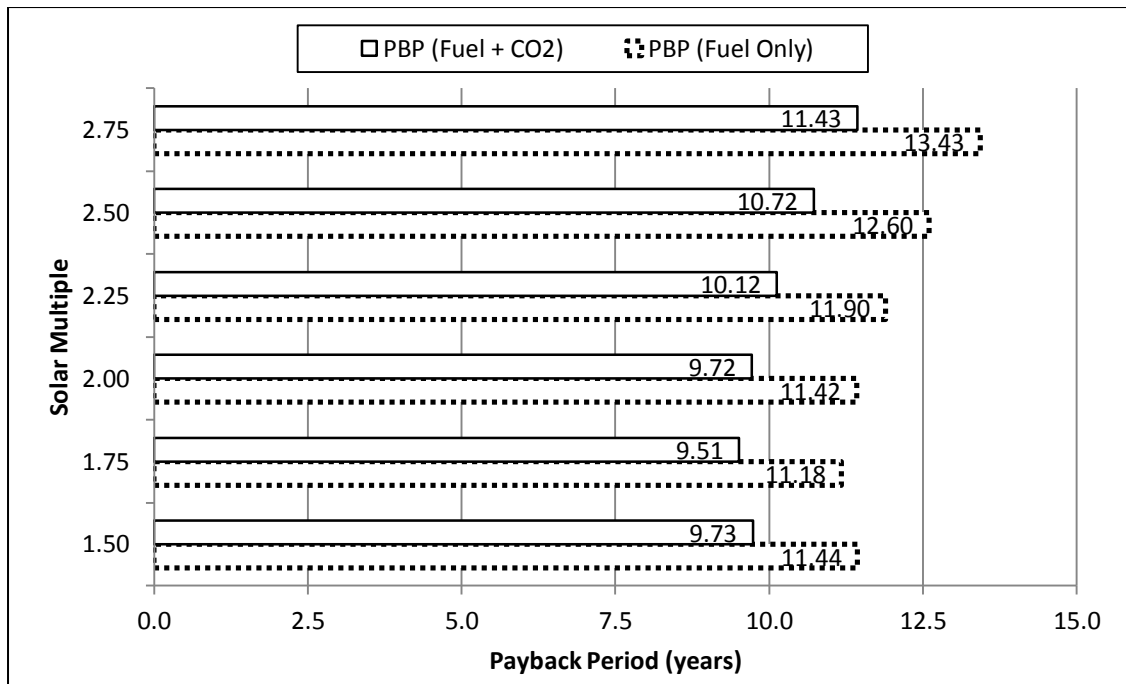
Fig. 15: Calculated SPBP for FWH No.1 before and after considering CO_2 emissions

5. Conclusion

In this work, the integration of CSP technology with an old HFO fired steam (standard Rankine cycle) unit of 33 MW is proposed based on a parabolic trough collector system (PTC). This will be used to heat boiler's feed water heaters instead of extracting the required steam from the steam turbine. Technical, economic and environmental analyses were conducted for different scenarios for such integration. Each of the studied scenarios has different thermal capacity; consequently dissimilar solar field aperture areas were required. To conduct such analysis a trailer-made simulation tool was developed based on basics of thermo-fluids relations. The PTC solar field aperture areas and its performance as well optimal solution were conducted by using the System Advisor Model (SAM) software. The introduced PTC system has increased efficiency by 2.5% due to the net increase (of 7.5%) in turbine's work output and reduced rate of fuel consumption. But this value varied as different FWHs integration scenarios were assumed. The economics of such system under studied circumstances were found not encouraging since the SPBP ranged between 10 and 12 years for different scenarios. The environmental impacts are positive since pollutant emissions were reduced significantly: about 17,500 ton/year of CO_2 could be avoided.

References

[1] Jaber JO, Elkarmi F, Alasis E, Kostas A. Employment of renewable energy in Jordan: current status, SWOT and problem analysis, Renewable & Sustainable Energy Reviews, Vol. 49, pp. 490-499, 2015.

[2] Zoschak RJ, Wu SF. Studies of the direct input of solar energy to a fossil-fueled central station steam power plant", Solar Energy, Vol. 17, pp. 297-305, 1975.

[3] Gupta MK, Kaushik SC. Exergetic utilization of solar energy for feed water preheating in a conventional thermal power plant, International Journal of Energy Research, Vol. 33, pp. 593-604, 2009.

[4] Gupta MK, Kaushik SC. Exergy analysis and investigation for various feed water heaters of direct steam generation solar-thermal power plant, Renewable Energy, Vol. 35, pp. 1228-1235, 2010.

[5] Hu E, Yang Y, Nishimura A, Yilmaz F, Kouzani A. Solar thermal aided power generation, Applied Energy, Vol. 87, pp. 2881-2885, 2010.

[6] Qin Yan YY, Nishimura Akira, Kouzani Abbas, Eric Hu. Multi-point and multi-level solar integration into a conventional coal-fired power plant, Energy Fuels, Vol. 24, pp. 3733-3738, 2010.

[7] Suresh MVJJ, Reddy KS, Kolar AK. 4-E (energy, exergy, environment, and economic) analysis of solar thermal aided coal-fired power plants, Energy for Sustainable Development, Vol. 14, pp. 267-279, 2010.

[8] Popov D. An option for solar thermal repowering of fossil fuel fired power plants, Solar Energy, Vol. 85, pp. 344-349, 2011.

[9] Xiuyan W, Mengjiao W, Xiyan G. Thermal performance analysis of solar steam aided coal-fired power generation, Materials for Renewable Energy & Environment (ICMREE), International Conference, pp. 209-212, 2011.

[10] Yang Y, Yan Q, Zhai R, Kouzani A, Hu E. An efficient way to use medium or low temperature solar heat for power generation-integration into conventional power plant, Applied Thermal Engineering, Vol. 31, pp. 157-162, 2011.

[11] Reddy V, Kaushik S, Tyagi S. Exergetic analysis of solar concentrator aided coal fired super critical thermal power plant (SACSCTPT)", Clean Technologies and Environmental Policy, pp. 1-13, 2012.

[12] Yan Q, Hu E, Yang Y, Zhai R. Evaluation of solar aided thermal power generation with various power plants, International Journal of Energy Research, Vol. 35, pp. 909-922, 2011.

[13] Romero-Alvarez M, Zarza E. Concentrated solar thermal power in "Energy Conversion" edited by Goswami D & Kreith F, 1st edition, CRC Press, USA, pp. 38, 2008.

[14] Anon, Central Electricity Generation Company, Annual Report 2014, Amman, Jordan.

[15]: Official website of "SCHOTT PTR®70" receiver:
http://www.schott.com/csp/english/download/schott_ptr70_4th_generation_datasheet.pdf

[16] Ernst & Young Global Limited Co., (France), Goswami Institute for Solar Energy Systems (ISE) and Fraunhofer Institute for Systems and Innovation Research (ISI), Middle East and North Africa Region assessment of the local manufacturing

potential for concentrated solar power (CSP) projects, Energy Sector Management Assistance Program (ESMAP), The World Bank, Washington, DC, USA, 2011.

[17] Turchi C. Parabolic trough reference plant for cost modeling with the System Advisor Model (SAM), Technical Report No. NREL/TP-550-47605 by NREL, Department of Energy, USA, 2010.

[18] Average calorific value of petroleum products, internal report, personal contact with Laboratories Dept., Jordan Petroleum Refinery Co. Ltd., Jordan, November 2013.

[19] Fuel prices in Jordan, March 2015, Al-Manaseer Oil and Gas Co., Amman, Jordan [http://www.mgc-gas.com/fuel-prices/].

[20] Inflation rate: http://www.tradingeconomics.com/jordan/inflation-cpi

[21] Income tax in Jordan, 2015 http://www.tradingeconomics.com/jordan/personal-income-tax-rate

[22] CO_2 emission factor for stationary combustion in the energy industries by Darío R. Gómez and John D. Watterson, Chapter 2: Stationary combustion from 2006 IPCC (International Panel on Climate Change) Guidelines for National Greenhouse Gas Inventories, Switzerland.

[23] Fact sheet: Carbon pricing around the world:
http://www.eesi.org/papers/view/fact-sheet-carbon-pricing-around-the-world?/fact-sheet-carbon-pricing-around-world-17-oct-2012