The Economics of Solar Thermal Electricity (STE) in Libya

M. E. Mashena
Department of Mechanical Engineering
University of Tripoli
m.mashena@uot.edu.ly

N. A. Alkishriwi
Department of Mechanical Engineering
University of Tripoli
n.alkishriwi@uot.edu.ly

***Abstract*--** **This paper investigates the technical and economic feasibility analysis for the development of solar energy power plants to generate electricity using large scale Parabolic Trough Collector PTC Power Plants through investments or government funding in Libya. In this study, investment using parabolic trough with Molten Salt technology is investigated. This storage technology is considered as one of the most advanced thermal energy storage systems. With the aim of developing investment guidelines using concentrated solar power CSP, this paper presents the technical and economic feasibility analysis for three selected locations representing three major climatic regions in Libya (Tripoli, Sabha, and Alkufra). Solar resources from ground stations and/or from the available satellite measurements for the three different locations were collected and assessed. A detailed technical and dynamic analysis has been made using a specially designed Microsoft Excel sheets and SAM software issued by the national renewable energy laboratory NREL revealing productivity for every hour throughout the whole year. The analysis showed that, the maximum productivity of a proposed 50 MW PTC power plants (without storage) are 89.2, 120.3, and 143.7 GWh respectively for the three locations respectively, while the Levelized Costs of Energy LCOE are \$162.7, \$118.3, and \$91.1/MWh respectively depending on the location (Direct Normal Irradiation DNI) and energy storage. Analysis estimated that the LCOE of a PTC plants declines by around 4% for every 100 kWh/m^2/year of the DNI radiation that exceeds 1800 kWh/m^2/year.**

***Index Terms*--** **Concentrated Solar Power CSP; Parabolic trough, Libyan resources; feasibility analysis of CSP plants; Cost analysis**

1. Introduction

Energy consumption in Libya has been increasing at an annual rate of 8%. Population growth has resulted in the need for new infrastructure, especially in the field of electricity generation. This has resulted in a dramatic increase in the electrical power demand, and therefore has raised challenges for adopting alternative sources.

The relationship between energy consumption and environmental pollution has become clear due to the negative results such as high levels of carbon dioxide and climate change. During the latter years of the 20th century, the climate change was heavily observed and a more efficient usage of energy was recommended as one of the main areas for improvement to create a cleaner environment. One of the most powerful initiatives in the world to create an environment containing a long-term sustainable production of electricity is the massive solar power development. Electric power industry is characterized as one of the industries that can have a substantial impact reducing carbon emissions by increasing the percentage of electricity from renewable sources. This also lead to reducing the dependence on fossil fuels, which in turn will ensure economic stability. Libyan electric power generation system is totally dependent on hydrocarbon resources while the country enjoys a climate with the highest solar intensity level worldwide. Adopting a balanced energy resource mix can certainly help in overcoming the persisting shortage that resulted in long hours of power shedding. Therefore, to explore the opportunity for wider energy mix, solar energy will be one possible options.

Libya has the largest proven oil reserves in Africa as well as a huge potential for renewable energies. However, despite excellent solar radiation and wind conditions, renewable options have never been seriously considered in the past. Since the country has enormous potential, solar energy is an attractive renewable option for the Libyan energy generation system. With a potential of 139,600 TWh/year (DNI > 1800 kWh/m^2/y), Libya is considered one of the countries with the highest potential for solar power not only in North Africa and Middle East but worldwide (Libya is one of the sun-belt countries with high Direct Normal Irradiance DNI, [1].

The Parabolic Trough Collector PTC solar thermal power plant is one of the attractive technologies to produce electricity from thermal solar energy. Parabolic trough collector is the most mature concentrated solar power CSP technology, and further improvements in performance and cost reductions are expected. Parabolic trough technology accounts for more than 90 percent of the CSP capacities installed worldwide [2]. The first commercial plants in operation were built in the United States (410 MW) and Spain (100 MW). Globally, there will be around 5000 MW in operation by the end of 2016 as shown in Fig. (1), [3], [4].

After a gap in interest between 1990 and 2000, CSP deployment has been growing over the past decade. CSP plants offer an integrated solution of concentrating the solar radiation and low-cost thermal energy storage to provide power on demand [5] and more imported at the peaks as shown in Fig. 2. In this situation, CSP plants can supply electricity to match the load during sunshine time and peak times even when sun is not shining where electricity is delivered from the thermal storage equipment. Nevertheless, only strong direct sunlight can be concentrated to reach required temperatures for electricity generation in concentrating solar plants. The generally accepted minimum DNI technical operational limit of a CSP plant is 1,800 kWh/m^2/year, while the generally accepted threshold for commercial CSP projects is 2,000 kWh/m^2/year, which accounts for slightly more than 5 kWh/m^2/day [1]-[6].

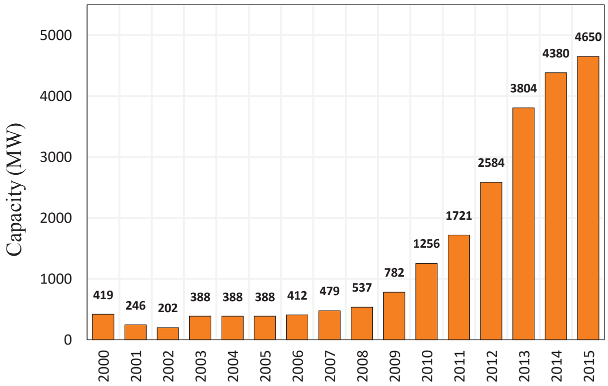

Fig. 1. Installed concentrated solar power capacity in world

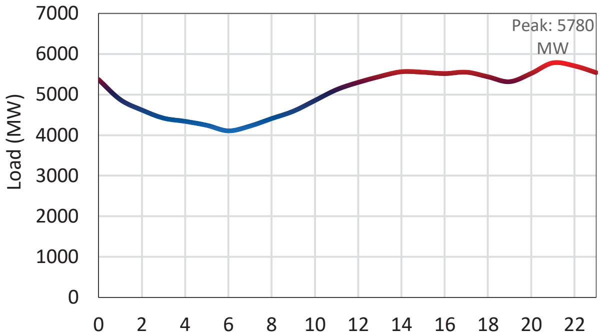

Fig. 2. Daily load curve for Libya (June 21st 2014).

The paper focused on the analysis of the parabolic trough power plants without and with a thermal storage of 6 hours capacity at three locations with an annual DNI between 2000 and 3000 kWh/(m²a). CSP power plants are capital intensive, but have virtually zero fuel costs. Parabolic trough plants without thermal energy storage have capital costs as low as 4300 $/kW, with low capacity factors between 0.2 and 0.33. Adding six hours of thermal energy storage increases capital costs to between 7400 $/kW to 8300 $/kW, but allows capacity factors to be almost doubled as will be shown in analysis of the selected cases.

2. Levelized Costs of Electricity

Levelized Cost of Electricity LCOE is defined as total costs of a system over its lifetime divided by the expected energy output over its useful lifetime. LCOE includes all costs throughout the lifetime of a plant: initial investment, operations and maintenance cost, and cost of fuel. It is a measurement of the cost of producing energy from a technology and is an important parameter to measure commercial viability of any electricity generation technology. LCOE is the threshold selling cost of unit energy that marks the profitability or loss of the project. The Levelized Cost of Electricity LCOE for the proposed parabolic trough plants in Libya was estimated using the following formula:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+i)^t}}$$

where:

LCOE = average lifetime Levelized cost of electricity generation
I_t = investment expenditures in the year t
M_t = operations and maintenance expenditures in the year t
F_t = fuel expenditures in the year t
E_t = electricity generation in the year t
i & n = discount rate and life of the system respectively

3. Solar Energy Resources in Libya

Each second, the sun turns more than four million tonnes of its own mass into energy, producing neutrinos and solar radiation. A half a trillionth of this energy falls on Earth after travelling 150 million kilometers, which takes a little more than eight minutes. The solar irradiance (solar constant) is 1368 W/m^2 at that distance, with only 1000 W/m^2 arrives at the surface of the earth when the sun is at zero incident angle. The solar radiation reaching the earth's surface has two components: direct or "beam" radiation, which comes directly from the sun's disk; and diffuse radiation, which comes indirectly [7].

The primary resource for CSP technologies is the DNI. It refers to the "amount of electromagnetic energy arrives at Earth´s flat-surface perpendicular to the sun's beam with surrounding diffuse sky radiation blocked, and it is equivalent to the solar constant minus the atmospheric losses due to absorption and scattering [8].

CSP plants require direct solar radiation in order to generate electricity, given that only strong direct sunlight can be concentrated to the temperatures required for electricity generation. This limits the use of CSP to hot, dry regions. The insulation time over the most of the national territory exceeds 2500 h annually and may reach 3900 h in high plains and Sahara. To be economic at present requires a CSP plant with direct normal irradiance levels DNI of 2000 kWh/m^2/year or more, although there is no technical reason why CSP plants cannot run at lower levels. CSP plants in areas with high DNI will have a lower LCOE, compared to one located in an area with a lower DNI. Higher levels of DNI have a strong impact on the LCOE, [5]. Figure 3 shows the distribution of average annual DNI across Europe and the MENA region where Data interpolated from a global dataset produced by NASA's Surface meteorology and Solar Energy (SSE) program. Areas with DNI above 5 kWh/m^2/day are preferred for CSP operation and are denoted by the hatch pattern. While Europe exhibits good solar resources in southern Spain and Turkey during some periods of the year, far greater potential lies in the MENA countries to the south [9].

Figure 4 shows the Potential for CSP around the world. The excellent DNI resources in the world fall in sun belt region in which Libya occupy a large part.

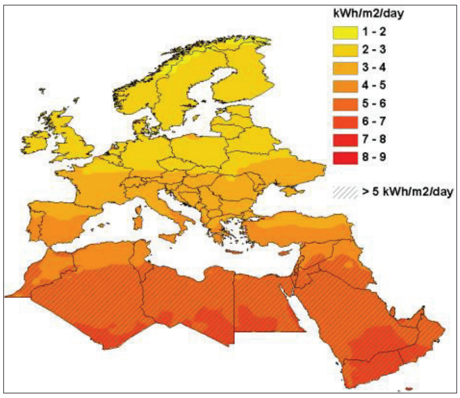

Fig. 3. Average Annual DNI in Europe and MENA Region, [10].

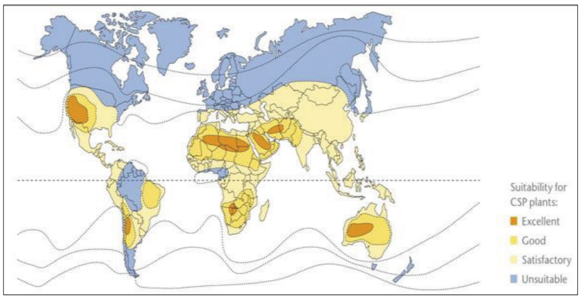

Fig. 4. Potential for CSP around the world map, [11].

Figure 5 demonstrates the DNI Libyan map. It shows areas with the highest potential for CSP, that are suitable for large-scale, year-round operation of CSP facilities. The first region is characterized as a coastal plain, located between latitudes 32-28° North. The range of solar radiation insolation in this region is between 1800-2100 kWh/m^2 per year. The second region which is located between 28 and 25° North with an annual solar radiation on horizontal ranges between 2100-2500 kWh/m^2. The third region is located between latitudes 25-19° North with the highest intensity of solar radiation in Libya exceeding 2900 kWh/m^2 per year. In general, Libya, with solar radiation ranging between 1800-2900 kWh/m^2/year, has an average solar radiation of 2700 kWh/m^2/year.

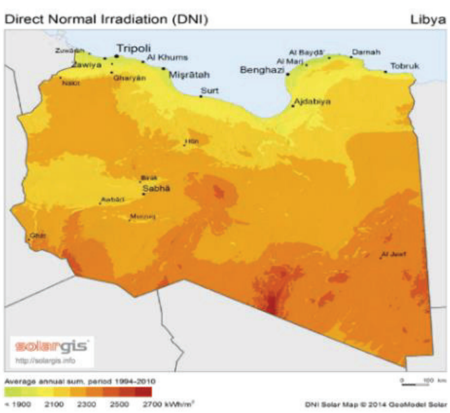

Fig. 5. Annual DNI Irradiation in kWh/m²

4. Concentrating Solar Power CSP Plant Components

Concentrating solar power is a power generation technology that uses mirrors or lenses to concentrate the direct solar radiation to heat a fluid and produce steam. The steam is then used to drive a turbine and generates electricity in the same way as conventional power plants. There are four major CSP technologies: parabolic troughs and linear Fresnel reflectors (concentrated on a linear collector system), power towers and parabolic dish (concentrated on central focal point). Each of these types can be integrated with thermal storage. When equipped with thermal storage, the capacity factor of the CSP plant and the dispatchability of the generated electricity increases, thus providing grid integration and economic competitiveness to fossil power plants. Figure 6 demonstrates a schematic diagram of a typical configuration of CSP power plant which shows the main three parts of the plant namely: (i) the solar field that collects and concentrates the solar radiation using parabolic trough collectors (PTC), (ii) the thermal storage unit, and (iii) the power block that converts the heat collected from the sun to electricity.

This work considers the analysis of a 50 MW power plants located at the three representative locations by using parabolic trough collector technology.

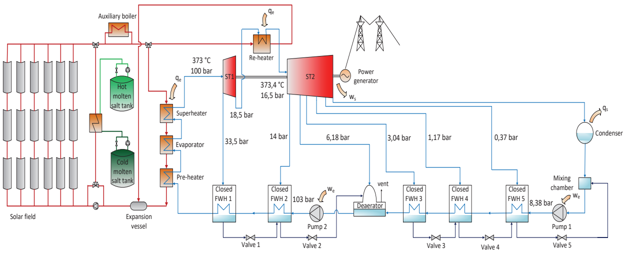

Fig. 6. Reheat regenerative Rankine cycle based on the commercial PTC CSP plants, typical configuration, [12]

5. Results and Discussion

A. Technical Analysis

The calculations of the expected annual energy yield of the proposed 50 MW (PTC) power plants were analyzed using the available data for the three selected locations (Tripoli, Sebha, and AlKufra) representing different DNI solar intensities and climate conditions in Libya. Analysis was performed using a specially designed Microsoft Excel sheets and SAM software issued by the national renewable energy laboratory NREL [13]. To investigate the effect of including a storage system to the plant on the feasibility of the project, two cases were considered: (i) no storage and (ii) a storage that allows the plant to operate 6 additional hours. It was assumed that the plant will be unavailable for 4% of the operating time due to scheduled outages allocated basically for maintenance activities. Sizing the three solar fields of a parabolic trough system were done. The optimal solar field aperture area for each system at each location was determined by taking into consideration two major objectives: (i) maximizing the amount of time in a year that the field generates the required thermal energy to drive the power block at its rated capacity and (ii) minimizing the installation and operating costs which leads to lowering LCOE. Figures 7 and 8 show the results of the optimization of the solar field at Alkufra location for the two cases without and with thermal storage respectively. The frequency distribution in which the power block generates electricity at its rated capacity is shown in Fig. 7. It is clear that the plant generates electricity at its rated capacity during about 60% of the time. For systems with thermal energy storage the optimization involves finding the combination of field area and storage capacity that results in the lowest LCOE. In this case, about 80% of the time the power plant is running at its rated capacity as indicated in Fig. 8. The annual simulation results are shown in Fig. 9 and Fig. 10. It can be seen from Fig. 9 that the maximum produced energy from each of the three fields is realized in June as it has the maximum solar irradiation. Figure 10 provides a visual and numerical representations of the different energy conversion through the complete electricity generation process. The analysis showed that, the proposed 50 MW PTC power plants without storage based on weather conditions for the three proposed locations, have a maximum productivity of 89.2, 120.3, and 143.7 GWh respectively, which is equivalent to a capacity factor of 20.6, 27.7, and 33.1% respectively while the electric energy produced for the power plants with storage case are 144.0, 181.2, and 224.3 GWh respectively. Results of the technical analysis is listed in Table I.

B. Financial Analysis

The Levelized Costs of Energy LCOE incorporates all capital and operational expenses into the cost of the unit of energy produced. Table II showed the specific cost of the major cost elements. A specific capital cost range from 4276\$/kW to 8256\$/kW for the case of the 50 MW PTC in the three selected locations are considered. The differences in the capital specific costs are mainly due to the different values of solar multiple, (1.3 to 2.0), because the project in Alkufra requires less collector area to drive the power plant than the project in Sebha and Tripoli.

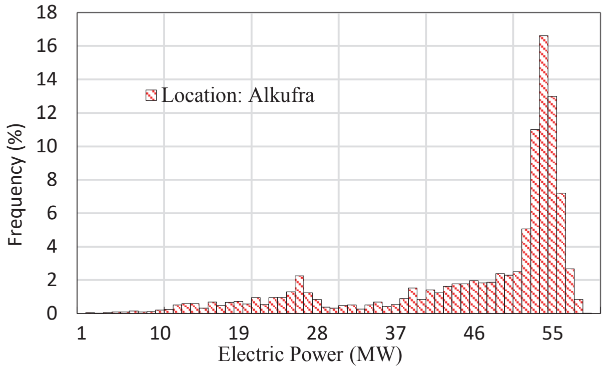

Fig. 7. Power histogram (Frequency distribution) of CSP power plant using PTC without storage at Alkufra area with an optimum solar multiple of 1.3.

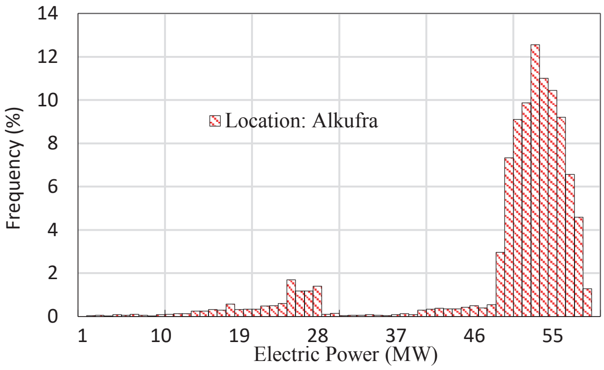

Fig. 8. Power histogram (Frequency distribution) of CSP power plant using PTC with storage at Alkufra area with an optimum solar multiple of 2.

Operation and Maintenance capacity-based expenses are fixed annual costs proportional to the system's rated capacity while operation and maintenance production-based expenses are variable annual cost proportional to the system's total annual electrical output in megawatt-hours.

. TABLE I
Summary of technical parameters of Both Cases with and without Storage

Description	Tripoli		Sebha		Alkufra	
Full load hours of TES	0 hours	6 hours	0 hours	6 hours	0 hours	6 hours
Total field reflector area	0.353 km^2	0.50 km^2	0.333 km^2	0.451 km^2	0.271 km^2	0.40 km^2
Storage volume	0 m^3	11746.3 m^3	0 m^3	11746.3 m^3	0 m^3	11746.3 m^3
Total land area	1.25 km^2	1.80 km^2	1.17 km^2	1.60 km^2	1.0 km^2	1.45 km^2
Heat transfer fluid	Hitec solar salt	Hitec solar salt	Hitec solar salt	Hitec solar salt	Hitec solar salt	Hitec solar salt
Solar multiple	1.6	2	1.6	2	1.3	2
Direct Normal irradiation (DNI)	1800 kWh/(m^2a)	1800 kWh/(m^2a)	2400 kWh/(m^2a)	2400 kWh/(m^2a)	3000 kWh/(m^2a)	3000 kWh/(m^2a)
Annual energy of the first year	89.2 GWh	144.0 GWh	120.3 GWh	181.4 GWh	143.7 GWh	224.5 GWh
Energy yield/kW	1802 kWh/kW	2910	2430 kWh/kW	3664 kWh/kW	2900 kWh/kW	4535 kWh/kW
Gross-to-net conversion	91.0%	91.2%	92.1%	92.2%	92.4%	92.5%
Capacity factor	20.60%	33.2%	27.70%	41.8%	33.10%	51.8%
Annual Water Usage	25,026 m^3	36,978 m^3	27,255 m^3	38,478 m^3	26,765 m^3	40,465 m^3

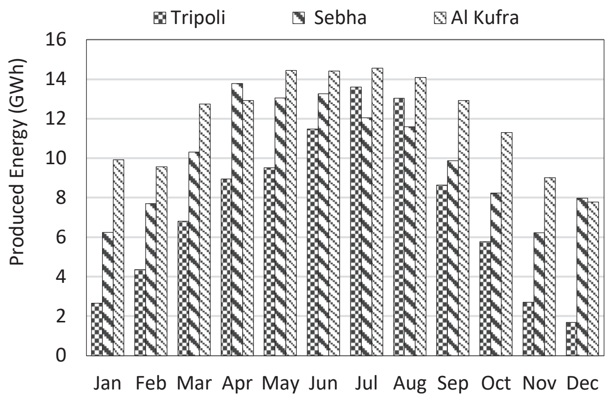

Fig. 9. Monthly net electric output of the proposed plants.

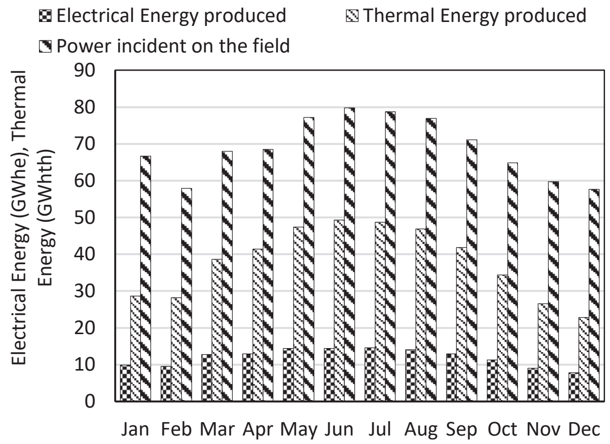

Fig. 10. Monthly energy flow through the proposed plant in Alkufra.

TABLE II

Summary of specific costs

Description	Costs
Site Improvements	50.0 \$/m^2
Solar Field	295.0 \$/m^2
HTF System	80.0 \$/m^2
Storage	100.0 \$/kWht
Power Plant	1500.0 \$/kWe
OPEX capacity-based expense	70.0 \$/kW-year
OPEX production-based expense	3.0 \$/MWh

Table III shows the LCOE of the three proposed PTC Plants. It is evident from the LCOE results the effect of DNI for both cases with and without storage. Alkufra, having the highest DNI has the best potential for using PTC plants for both cases which is reflected in the lowest LCOE as well as the lowest difference in the unit cost between the cases without and with storage; 0.29¢/kWh when compared 0.46 and 1.37 \$/kWh for both Sebha and Tripoli locations respectively. The results confirm limits indicated in the literature for the viability, [1], [6].

Analysis of the three locations estimated that for every 100 kWh/m^2/year that the DNI radiation exceeds that in Tripoli which is 1800 kWh/m^2/year the LCOE of a PTC plants declines by an average of 4.12% and 3.68% for the cases of without and with storage respectively.

C. Economic Analysis

The economic analysis has been conducted based on essential international economic data for PTC plants. Major input economic parameters, such as: plant life time, and unit energy selling rice (PPA tariff), as well as economic output indicators expressed in terms of the payback period, internal rate of return IRR, and the net present value NPV are all listed in Table III.

All the three economic indicators for Alkufra location stressed again on the potential of the location thus showing a stronger feasibility for using PTC plants covering base time as well as peak load period of up to 6 hours.

Figure. 11 presents the annual profit, cumulative annual profit and the cumulative annual cash flow for the proposed plant at Alkufra, which shows a payback period of little longer than 9.6 years. The IRR and the Payback period of Alkufra plant suggests that investing in PTC plants is competitive with current conventional technologies being in operation in Libya.

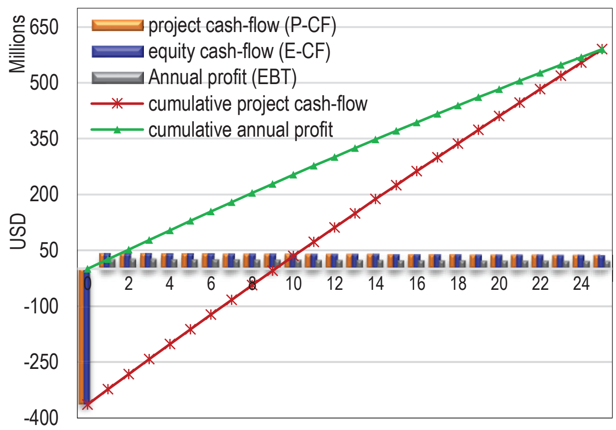

Fig. 11. Cash flow, annual, cumulative, and annual profit of the proposed plant in Alkufra [14].

The study also incorporated some sensitivity analysis to show the effect of changes in three major cost parameters; investment costs (CAPEX), the operating costs (OPEX) and the project lifetime on the economic indicators; on internal rate of return IRR and the net present value NPV, Figs (12 and 13). Fig (12) shows the effect of input parameters (CAPEX, OPEX and lifetime of the plant) variation with up to ±30% of its values given in Tables II and III on the net present value of the project (in million USD), which is a direct indicator to the profitability of the project. Fig. (13) gives the effect of variation in the same parameters on the IRR. The figure shows that the capital investment has the major effect on the economics of the project, however, the specific cost considered in the study is a conservative one in comparison to the international prices and taking into consideration the price trend in the last few years, which makes the results more reliable.

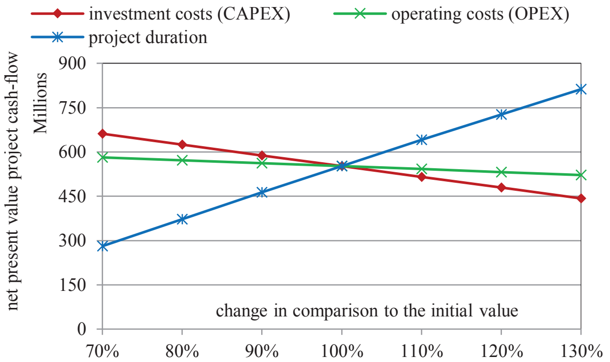

Fig. 12. Monthly energy flow through the proposed plant in Alkufra.

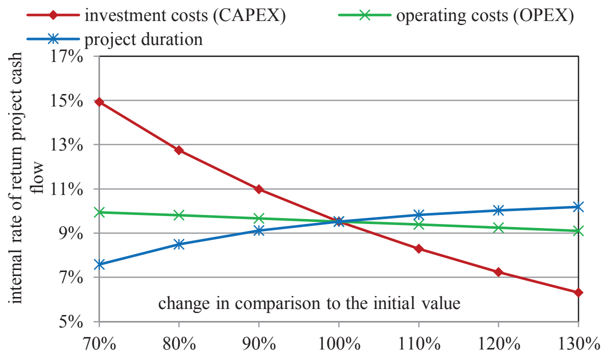

Fig. 13. Monthly energy flow through the proposed plant in Alkufra [14].

TABLE III

Summary of results of Both Cases with and without Storage

Description	Tripoli		Sebha		Alkufra	
Full load hours of TES	0 hours	6 hours	0 hours	6 hours	0 hours	6 hours
Life time	25 years	25 years	25 years	25 years	25years	25 years
Capital cost (CAPEX)	\$248,278,512	\$408,712,032	\$239,952,320	\$386,406,528	\$211,698,704	\$364,101,056
Specific investment Cost	5027\$/kW	8256\$/kW	4847\$/kW	7806\$/kW	4276\$/kW	7355\$/kW
Operating cost (OPEX)	3,732,614 \$/year	3,825,881 \$/year	3,896,095 \$/year	3,897,143 \$/year	4,009,131 \$/year	4,138,416 \$/year
PPA price	20.0 ¢/kWh	20.0 ¢/kWh	20.0 ¢/kWh	20.0 ¢/kWh	20.0 ¢/kWh	20.0 ¢/kWh
LCOE	**16.27 ¢/kWh**	**14.9 ¢/kWh**	**11.83 ¢/kWh**	**11.37 ¢/kWh**	**9.11 ¢/kWh**	**8.82 ¢/kWh**
Net present value (NPV)	\$78,500,000	\$173,120,000	\$231,650,000	\$368,600,000	\$368,500,000	\$590,900,000
Payback period	19.6 year	18.2 year	13.3 year	13.3 year	9.6 year	9.6 year
IRR at end of project	2.3%	3.0%	6.24%	6.17%	10.28%	9.68%

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