OPPORTUNITIES AND CHALLENGES OF SOLAR ENERGY IN SAUDI ARABIA

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ABSTRACT

Saudi Arabia has one of the highest direct normal irradiation (DNI) resources in the world. Saudi Arabia is planning for significant deployment for both photovoltaic (PV) and concentrated solar power (CSP) in order to harvest this high DNI and produce energy from a renewable, clean and sustainable source. This will help conserve hydrocarbon resources that are currently being consumed in significant quantities to generate electricity and desalinate seawater in the country. However, high DNI combined with extreme summertime ambient temperatures represent a major technical challenge for the PV systems since the efficiency of these systems decreases when operating at high temperatures. This necessitates the development of cooling mechanisms suitable for the environment in the region. On the other hand, this high DNI is more favorable for the CSP systems, but high dust loadings may have a greater impact on reflectors. CSP in Saudi Arabia is being considered for both electricity generation as well as direct thermal applications in industrial processes such as water desalination. This paper will highlight the challenges and opportunities of solar energy in Saudi Arabia, including overheating and potential cooling mechanisms as well as solar thermal process heat and desalination opportunities.

Key words: temperature effect, photovoltaic, concentrated solar power and desalination.

1. INTRODUCTION

Using current projection, electricity demand in Saudi Arabia is anticipated to grow from 40 GW[1] up to 120 GW[2] between years of 2010 and 2028. This will contribute to the projected increase in hydrocarbon use from 3.4 million barrels of oil equivalent (MBOE) per day to 8.3 MBOE in the same period[3]. Water demand is also expected to grow based on increasing population and industrialization. A large share of the world desalinated water is produced in Kingdom of Saudi Arabia primarily using oil-fired thermal processes.

Therefore, Saudi Arabia is planning to introduce renewable energy as part of the Kingdom's energy mix, in order to reduce the demand on exportable hydrocarbons. Solar energy will be a key technology, due to the high DNI resource of an average 2200 $kwh/m^2/y$[4]. However, Saudi Arabia's climate conditions such as high temperatures and dust will create many challenges and opportunities; one of the challenges is the temperature and dust effect on photovoltaic plants and Concentrated Solar Power (CSP) plants. This paper will focus on the high temperature effect on solar cells and how could it be solved; the opportunity of utilizing solar thermal energy in seawater desalination and the potential fuel savings will be evaluated also.

2. TEMPERATURE EFFECT ON PV MODULES

As the PV surface is exposed to the sunlight, the module temperature increases. High ambient temperatures along with long sunlight exposure time increases the temperature impact on PV cells efficiency. The PV cell consists of a p-n junction, there are different types of cells, where electrons and holes are injected from the junction layers to the cell surface to be collected in the collectors. The increased temperature in the cell increases atoms vibration (phonons) which obstruct charge carriers movement and decrease cell efficiency. Hence, the output power is reduced by 2%-26.4% considering different mounting and weather conditions[5-7]. Moreover, other elements like the encapsulations and wires are affected and rapidly degraded[8.9]. It has been reported that temperature losses in PV modules mounted on a roof was 11.3% where module temperature reached 85°C and the ambient temperature was 30°C[5]. Also, it was reported 10% reduction in efficiency of the building integrated photovoltaic (BIPV) while it is less in the ground mounted PV[6]. The power reduction depends on the temperature coefficient of the module which depends on the cell type and is provided by the supplier by %/ °C, see table 1.

TABLE 1: POWER REDUCTION RATE DUE TO TEMPERATURE FOR DIFFERENT TYPES OF PV[7]

PV type	Power reduction (% / °C)
Thin film Si	0.48
c-Si	0.45
a-Si single junction	0.13
CIGS	0.36

To estimate temperature losses, it is required to calculate the module temperature[10]. The module temperature depends on ambient temperature, irradiation level and wind speed[8]. The effect of these individual factors varies from site to site. In Riyadh, it is found that the effect of wind speed, irradiance and other variables other than the ambient temperature is relatively small[8] . Notably, module operating temperature is affected by the aging process where the exposure to high temperatures for a short time might age rapidly PV modules encapsulants or even these encapsulants will not withstand at high temperatures about 96°C[8].

Poly-crystalline modules have temperature coefficient of -0.5% / °C[6]. Standard Test Conditions (STC) for cells are at 1000w/m^2, 1.5 air mass and cell temperature equal to 25 °C. Saudi Arabia with its large area has different average monthly *high* temperatures which vary from more than 40°C in Riyadh in June, July, August and September and less than 30°C in Abha for the same months[11]. The cell temperature could be estimated using equation (1)[10]. Therefore, the effective temperature which used to calculate the power loss would be equal the ambient temperature, equation (2)[10].

$$T_{cell} = T_{ambient} + 25 \quad (1)$$

$$T_{effective} = T_{cell} - 25 = T_{ambient} \quad (2)$$

However, other reports based on measurements and modeling stated higher than 25°C temperature difference between module and ambient. In Florida, testing CIGS PV modules, the measured module temperature was 70.6°C while the ambient temperature was 34.4°C[8]. The difference is 36°C.

Module temperature in Riyadh was estimated to be from 40.3- 52.9°C where the average annual temperature is 26°C[8]. However, the average annual *high* temperature is 33°C[11] which might be considered as the effective average temperature because the average *high* temperatures are during the day whereas the average ones consider all the day and night while the PV works only in the day. For the Poly-crystalline PV modules which loss 0.5% / °C will result in 16.5% reduction in the output power.

2.1 Case Study:

In order to examine the potential power loss due to temperature conditions in Saudi Arabia, a typical case was modeled. A hypothetical 10 MW polysilicon PV power plant in Riyadh, Saudi Arabia was selected. It was assumed the modules will be tilted 20° facing south, which results in a capacity factor of 21.4%[12]. Other directions like south-west-south, south-west and west-south-west have been examined using the same calculator[12] and the results showed that south direction has the highest irradiation ,see table 2.

TABLE 2: AVERAGE DAILY TOTAL IRRADIATION BY PANEL DIRECTION IN RIYADH.

Panel direction	south	south-west-south	south-west	west-south-west
Irradiation (KWh/m^2/day)	5.88	5.73	5.59	5.15

Lowest module prices for poly Si is $1/W[13]. However, all the system cost with choosing a higher module price ($2/W) will be $4/W. The plant lifespan is 25 years. Saudi Arabia electricity prices are heavily subsidized. Thus, a high-end U.S. electricity price of $0.20 KWH was used[13] .

2.2 Results:

RETscreen tool was used to estimate the revenues of the 10 MW PV plant. The annual production from this hypothetical case is 18,746 MWH and the electricity price was $200/MWH. So the yearly income is $3,749,299. However considering the temperature effect in this plant, it will have an estimated 16.5% reduction in energy yield and will reduce the production to15.653 MWh and the income to $3,130,600 annually. As a result, the income loss could be $618,699 annually.

2.3 Possible Cooling Mechanisms:

Many cooling mechanisms have been tested; for example, fins, ducts and water tanks[5, 14-16] .PV cooling could limit the temperature loss to less than 3%[5]. Cooling BIPV has more attention because these PVs are more affected by temperature. However, these mechanisms are affected by variable factors. It was found that different fin sizes have different effects where larger fins have greater effect than the smaller ones[14]. Although the reduction in temperature was 1°C by the large fins, fins cooling efficiency increases as there are some wind speed and high temperature gradient (i.e. large difference between module temperature and ambient temperature)[14].

Another mechanism is using air ducts attached to the back of the PV panels where results showed that larger duct thickness allows more heat transfer at high irradiation levels and therefore higher cooling efficiency[15]. This technique showed more than 10°C reduction in the panel temperature[15]. Water tank below the PV panels could be used to absorb the heat and resulted in 12% increase in energy yield[16]. The drawback is that its heavy weight 200 kg/module which is not practical for roof mounted PV systems[16]. Another mechanism could be cooling through flowing water on the top of the surface[16]. This solution resulted in 22°C reduction in cell temperature, 10.3% increase in energy output (8-9% increase in energy yield)[16]. The disadvantage of these last two options are the significant water use, a challenge in dry Saudi Arabia conditions. A key area of future research and technology development for Saudi Arabia is dry cooling technologies.

3. SOLAR THERMAL DESALINATION *

Saudi Arabia is the world leader in water desalination with 30% of the overall global desalination capacity[17]. The desalinated water is heavily subsidized by the government at every stage. For the present analysis, the actual cost of fuel for water desalination in Saudi Arabia was compared with the international prices. The calculations are based on the annual report of operation and maintenance of Saline Water Conversion Corporation (SWCC) in 2009[18]. SWCC used five types of fuels: natural gas (54.3%), heavy fuel oil 180 (15.4%), heavy fuel oil 380 (7.8%), crude oil (9.2%) and diesel(4.4%) (the shares are cost-wise[18]).
The overall water production in 2009 was 1,014 million m^3 and the unit cost of fuel was \$ 0.152/ m^3, [18] therefore the overall fuel cost is around \$ 154.13 million. Table 3 shows the calculations of the unit cost of each type of the fuels while table 4 shows a comparison between the calculated local fuel prices and the international fuel prices and the opportunity cost for one year (the international prices here are average approximations[19-20]).

It's shown that there is a huge opportunity cost in this field, around \$ 3 billion/year because of the heavy subsidization of the fossil fuels. Based on these numbers, utilizing renewable energy resources in water desalination is a promising field to save the natural resources of the kingdom, however, further studies are needed to compare between the renewables and fossil fuels to show the economic and technical feasibility of this approach. There are many studies in the literature in this regard.

TABLE 3: THE CALCULATIONS OF FUEL UNIT COST

Fuel Type	Share[18]	Cost (USD)	Quantity[18]	Unit cost(USD)	Unit cost (USD)
Natural Gas	54.3 %	83,708,764	279,260 MMCF	300 /MMCF **	0.3 \$/MMBTU ***
HFO180	15.4 %	23,740,607	2,179,738 ton	11 /ton	1.57 /barrel
HFO380	7.8 %	12,024,463	1,093,909 ton	11 /ton	1.57 /barrel
Crude Oil	9.2 %	14,182,700	896,505 ton	16 /ton	2.28 /barrel
Diesel	4.4 %	6,783,030	129,839 ton	52 /ton	7.43 /barrel
Imported Power	4.4 %	NA			
Internal Power	4.5 %	NA			
Total	100 %	154,159,786			

** Million cubic feet. *** Million British thermal unit,

* Some of the results in this section are expected to be presented in ARWADEX conference in April 2012.

TABLE 4: LOCAL FUEL PRICES VERSUS INTERNATIONAL FUEL PRICES AND THE OPPORTUNITY COST

Fuel Type	Local Prices	International Prices[19-20]	Local/ Int.	Opportunity Cost ($)
Natural Gas	300 $/MMCF	4080 $/MMCF	7.35%	1,055,602,800
HFO180	11 $/ton	444 $/ton	2.48%	943,826,554
HFO380	11 $/ton	424 $/ton	2.59%	451,784,417
Crude Oil	2.28 $/barrel	80 $/ barrel	2.85%	487,698,720
Diesel	52 $/ton	735 $/ ton	7.07%	88,680,037
Total				3,027,592,528

This section will discuss two possible cases -large plant with water and power production (co-generation) and small remote plant with water production only- to utilize solar thermal energy in water desalination and an estimated cost analysis for each approach. Other methods of solar desalination such as combining photovoltaic with reverse osmosis is being tested in Saudi Arabia by KACST and IBM[21]. However, other options to integrate renewable energy with desalination exist, including wind power, geothermal energy, biomass or other energy sources[22-24].

3.1 Large Scale Dual-Purpose Power and Water Production plant (Co-generation):

The configuration of this approach is shown in figure 1, the heat is transferred from the solar field to run the turbines to produce the electricity; the waste heat coming out from the turbines is directed to the multi effect distillation unit (MED) for water desalination. In this case, parabolic Trough technology will be chosen to examine the validity of the CSP-desalination (CSP-D) approach because it is the most mature CSP technology.

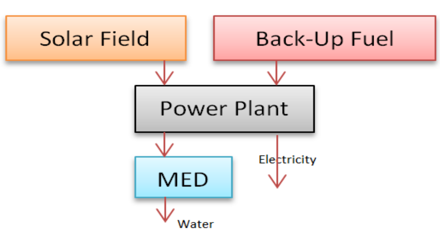

Fig. 1: The Configuration of Co-Generation Plant

Here is a very simple comparison based on a study and analysis made by FICHTNER [25] and the SWCC annual report[18] between two desalination plants of the same production capacity. The first plant is conventional MED plant powered by fossil fuel (the cost of the fuel here is the calculated opportunity cost in table 4). The second plant is CSP + MED plant with solar share of 38.8 % and fossil fuel share of 61.2%. To simplify the comparison, the following assumption were considered:

1- Cost of the power block was the same of the previous part to simplify the comparison.
2- O&M costs were neglected
3- Fuel cost is the opportunity cost calculated in table 4.
4- The water tariff and electricity tariff is $ 0.027 /m^3 and /kwh .
5- No interest rate.
6- Plant production capacity is 100,000 m^3/ day and 719 GWh_{el}/ year.
7- Plant lifetime is 30 years with 5%/year degradation in the production through the last five years.

As shown in figures 2 and 3, utilizing solar thermal energy in desalination would save around $ 1.5 billion over the life time of the plant.

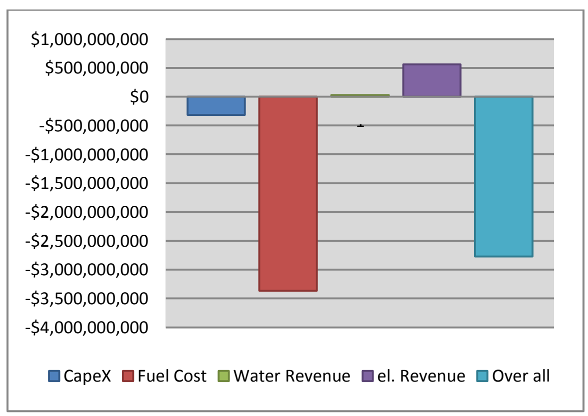

Fig. 2: The Expenditures & Revenues in a Conventional Plant over 30 years

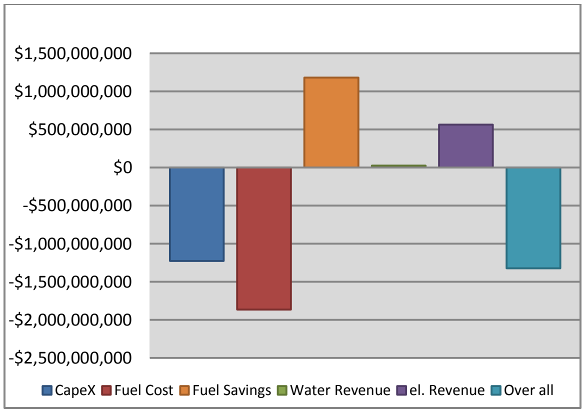

Fig. 3: The Expenditures &Revenues in a CSP + D Cogeneration Plant

3.2 CSP + MED for Water Production Only (Small Plant in Remote Location):

In this approach, the thermal energy will be directed from the solar field which is a group of medium heat thermal collectors to the MED. The desalination plant here is considered to be a satellite plant with a daily production of 5000 m^3/day. Cost comparison between a conventional satellite plant and a solar thermal plan is shown here.

Generation of electricity is the majority application of CSP technologies as the temperature it might exceed up to 800 °C while desalination plant done not need more than 130 °C for evaporation process. Because of that, Mid-concentrated reflectors with low efficiency can be used which affects magnificently on the total cost. As the main scope of this study is to validate CSP-D, Mid-temperature parabolic trough collectors have been studied to produce heat in range of 150 °C up to 300 °C.

The estimated cost of solar plant that produce heat in range 130 °C up to 300 °C is $ 13 million including absorber tube and steel components with total used land of 60,000 m^2 [25]. It is worth mentioning that, the cost of MED plant that produces 5000 m^3/day in this concept is triple MED cost in the previous concept as it works 8 hours/day because it totally depends on sun rays. Furthermore, pipes and integration components have been add to the total cost by assuming it is 10% of the CSP plant cost.

Among all above, the total CSP-D plant estimated cost is about $58 million divided into 23% goes for CSP plant and the rest for the MED.

To sum up, CSP-D saves about $ 86 million compared to the conventional approach which loses $ 156 million as shown in figures 4&5. CSP-D approach should be taken in consideration as it might bring a tremendous advantage to the Kingdom by reducing the oil consumption to be used for other purposes.

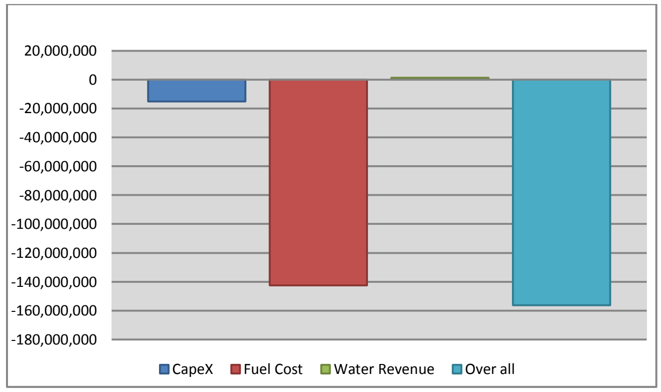

Fig. 4: The Expenditure and Revenues in a Conventional Plant for Water Production

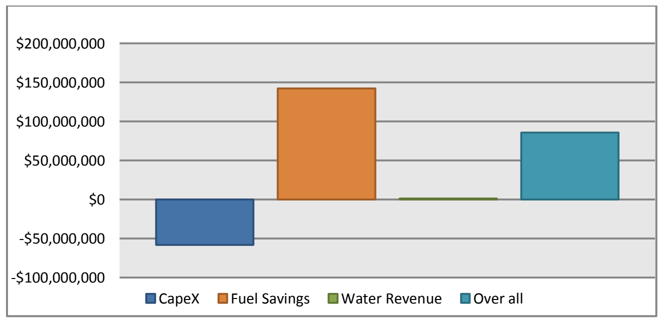

Fig. 5: The Expenditure and Revenues in a CSP-D for Water Production

4. SUMMARY:

This paper discussed two of the many challenges and opportunities in the field of solar energy in Saudi Arabia. The energy reduction due to temperature effect only in the hypothetical PV plant in Riyadh was calculated to be 16.5%. However, implementing a cooling mechanism in this PV plant power plant would be energy efficient. The paper also showed the economical promise of the solar thermal energy application in seawater desalination on two different approaches comparing to the conventional fossil fuel-powered desalination plants which will results in saving the natural resources of the Kingdom of Saudi Arabia.

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