

The cost benefit analysis of the implementation of photovoltaic solar system
in Saudi Arabia

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Abstract

The Middle Eastern Kingdom of Saudi Arabia (KSA) is the 14th largest country in the world and one of countries that burn crude oil directly for power generation. In response to the rising costs of the fossil fuels used in generating the electricity required to meet its continuously increasing electricity demand and the negative environmental impact of burning fossil fuels, Saudi Arabia is planning to more than double its available generating capacity from 58 GW to 120 GW by developing solar and nuclear power generation. This paper demonstrates the economic feasibility and viability of a 3.5 MW photovoltaic solar energy station at the investment cost of \$4/kW, 15% efficiency, and 10% interest rate. A cost-benefit analysis demonstrates that when the savings in fossil fuels and the decrease in CO₂ emissions of an oil-fired generating plant are taken into account, the levelized cost of electricity of a photovoltaic solar energy system and that of an oil-fired generating plant are the same at \$0.07/kWh. The results of the cost-benefit analysis is further strengthened when one looks at the learning curve of the photovoltaic technology, which predicts that the levelized cost of electricity of a photovoltaic solar energy system will be lower than that of any traditional technology used in generating electricity, including coal-fired and gas-fired generating plants.

1. INTRODUCTION

The Middle Eastern Kingdom of Saudi Arabia (KSA) is the 14th largest country in the world, the second largest member of the Organization of the Petroleum Exporting Countries, and it has the fifth-largest proven natural gas reserves. Saudi Arabia holds 18% of the world's proven petroleum reserves, and it is classified as the largest exporter of petroleum. The economy of Saudi Arabia is the largest economy in the Arab World. The oil and gas sector account for about 50% of Saudi Arabia's GDP, and 70% of her exports' incomes. In 2016, the natural resources of KSA was valued at US\$34.4 trillion, the third highest in the world [1,2].

According to the Joint Organizations Data Initiative (JODI), Saudi Arabia is one of The Middle East countries that burn crude oil directly for power generation. During the summer, Saudi Arabia typically experiences an increase in electricity consumption as domestic demand for air conditioning rises. Saudi Arabia used on average 0.7 million barrels of crude oil per day for power generation during the summers of 2009 to 2013. During that same period, Iraq and Kuwait, the next two largest users of crude oil for power generation in the Middle East, each averaged roughly 0.08 million barrels of crude per day in power generation. Saudi Arabia has no domestic coal production, and most of its natural gas is associated gas, which is produced along with oil from the same wellbore. At the same time, net electricity consumption in Saudi Arabia has more than doubled since 2000, reaching an estimated 232 billion kilowatt-hours (kWh) in 2012 (the latest data available). Saudi Arabia's economy also continues to grow. The GDP growth in Saudi Arabia in the first quarter of 2014 was 4.7% per annum in contrast with the 3.8% growth per annum in the first quarter of 2013. In addition, Saudi Arabia's Central Department of Statistics & Information estimates that the country's population will grow 2.6% in 2014 to more than 30 million residents, further increasing electricity demand. Saudi Arabia plans to diversify its power generation sources and improve overall energy efficiency. Saudi Arabia is planning to more than double – by 2032 – its available generating capacity from 58 gigawatts (GW) to 120 GW by developing solar and nuclear power generation. New and planned petroleum refineries are expected to be customized to produce larger amounts of diesel, a portion of which may be allocated for power generation to replace crude oil” [3].

Several studies on electricity demand and renewable energy in Saudi Arabia have been carried out recently. Per Yasir Abdulkarim Alturki and Abdel- Aty Edris (2015) looked for alternative energy resources that meet Saudi Arabia's growing demand. Said Nachet and Marie-Claire Aoun (2015) reviewed Saudi Arabia's demands for electricity and examined the developments of the power sector. All these studies showed the consumption of oil in the power sector. Mohammad Ramdhan and Adel Naseeb (2010) carried out a cost benefits analysis of implementing a solar energy system in Kuwait to meet its growing demand for electricity. In this paper, I replicate the analysis of these researchers for Saudi Arabia.

According to El-Nakla *et al.* in the article “Renewable Energy in Saudi Arabia: Current Status, Initiatives and Challenges”, May 2017, Saudi Arabia, with its favorable geographical location and climate, is an excellent candidate for renewable energy projects. In particular, solar energy is one of the most satisfactory renewable energy source that Saudi Arabia can exploit because the kingdom is blessed with around 3,000 hours of sunshine per year and 2,450 kwh/m² annual insolation levels. For comparison with a country with a well-developed solar energy system,

Germany's insolation levels reach 1,700 kWh/m² in Freiburg; has a total photovoltaic (PV) capacity of 40 GW; and generated 38.5 TWh of electricity in 2015. Grasping the enormous potential of solar energy, The King Abdallah City for Atomic and Renewable Energy plans to generate electricity from PV (16GW) and CPS (Concentrated Solar Power Thermal) (25 GW) by 2032. Due to the environmental and climatic conditions of Saudi Arabia, the PV and CSP solar energy systems provide a solution to the problem of electricity supply in the short term. Following Mohammad Ramadhan and Adel Naseeb (2010), I will study the benefits of implementing a solar energy system in the Kingdom of Saudi Arabia.

The paper is organized as follows. Section 2 provides some background on Saudi Arabia. Section 3 presents a description of the PV system. Section 4 gives a brief account of the evolution of the PV world market and the downward trend of PV prices. Section 5 discusses the levelized cost of electricity (LCOE), an important concept used in comparing the advantages of various electricity generating technologies. Section 6 contains a discussion of the viability of a PV solar energy system in Saudi Arabia. Section 7 contains a cost benefit analysis of a solar energy system in KSA. And finally, some recommendations and concluding remarks are given in Section 8.

2. THE BACKGROUND ON SAUDI ARABIA

The Kingdom of Saudi Arabia lies at the southwest corner of Asia between 16° to 33° N latitudes and between 34° and 56° longitudes. The Kingdom is bordered by [Jordan](#) and [Iraq](#) to the north; [Kuwait](#) to the northeast; [Qatar](#), [Bahrain](#), and the [United Arab Emirates](#) to the east; [Oman](#) to the southeast; and [Yemen](#) to the south. Its total land area, estimated by the Central Intelligence Agency World Factbook, is 2,149,690km². Saudi Arabia is dominated by the Arabian Desert, connected with semi-desert, shrubland, mountain ranges, and highlands. The weather is characterized by desert climate, very high temperatures in daytime and a sharp drop at night. The temperature range between summer and winter in KSA is 0°C to around 50°C [2].

According to Sultan Abu Ashwan, et al. (2012), the population of KSA increased from 6,167,308 in 1974 to 27,136,997 by 2010, and this means the population growth between 1974 and 2010 was 340% [4]. The enormous population growth is due to immigration and improvements of the infrastructure to facilitate citizen daily life and transportation between cities. From 1969 to 2018, the GDP growth rate in Saudi Arabia was 4.12% [3].

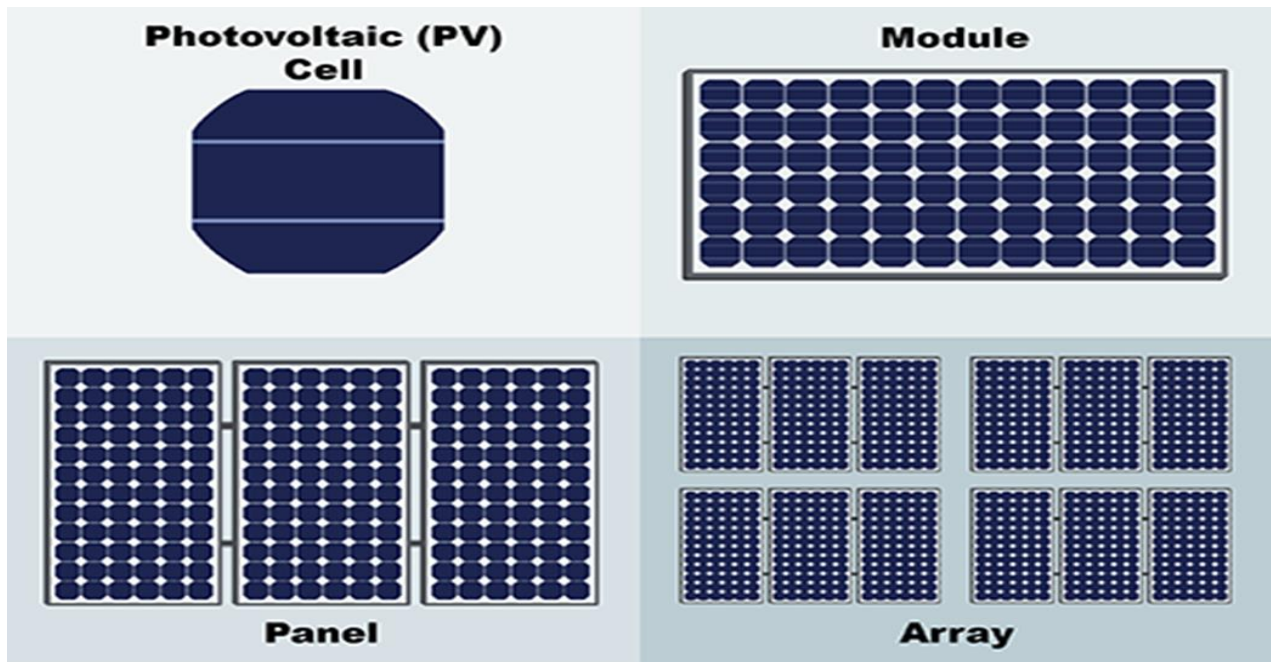
According to the Independent Statistics & Analysis, a U.S. Energy Information Administration report (2018), Saudi Arabia is considered the second largest holder of oil reserves in the world, owning 18% of the world's total reserves. KSA was the largest exporter of oil, the second largest petroleum producer, and second largest lease condensate producer in 2016. The economy of the Kingdom depends primarily on petroleum exports. The oil and gas sector accounts for about 50% of GDP and 70% of export incomes. The average crude oil production in Saudi Arabia, according to Trading Economics data (Saudi Arabia Crude Oil Production, Trading Economics, 2018), is 8101.63 BBL/D/1K during the time period 1973-2018, reaching a peak of 10720 BBL/D/1K in November 2016 and dropping to a low of 2340 BBL/D/1K in August of 1985[4].

According to the report "The Saudi Electricity Sector: Pressing Issues and Challenges", IFRI Centre Energie-30 March 2015, by Said Nchet and Marie-Claire Aoun, Saudi Arabia is the largest

oil consumer in Middle East with more than 3 million barrels per day of domestic oil consumption. The domestic energy consumption in KSA was growing faster than its GDP, and the electricity sector is the main consuming sector of oil, and its consumption reached around 700,000 bbl/d in summer peak's demand. The electricity use has increased by 7-8% annually over the last decade. By 2032, it is expected that the generation capacity of electricity in Saudi Arabia will attain 120GW.

3. PHOTOVOLTAIC SYSTEMS

Solar cells – also called photovoltaic cells – convert sunlight into electricity. Traditional solar cells are flat plates made from semiconducting materials similar to those used in computer chips. When sunlight is absorbed by these materials, the energy from the sun knocks electrons loose from their atoms, allowing the electrons to flow through the material and generate electricity. This process of converting light (photons) into electricity (voltage) is called the photovoltaic (PV) effect. Second-generation solar cells are called thin-film solar cells because they are made from amorphous silicon or non-silicon materials such as cadmium telluride. Thin film solar cells use layers of semiconductor materials only a few micrometers thick. Because of their flexibility, thin film solar cells can double as rooftop shingles and tiles, building facades, or the glazing for skylights. Third-generation solar cells are being made from a variety of new materials besides silicon, including solar inks using conventional printing press technologies, solar dyes, and conductive plastics. Some new solar cells use plastic lenses or mirrors to concentrate sunlight onto a very small piece of high efficiency PV material. The PV material is more expensive, but because so little is needed, these systems are becoming cost effective for use by utilities and industry. However, because the lenses must be pointed at the sun, the use of concentrating collectors is limited to the sunniest parts of the country.



These flat-plate PV arrays can be mounted at a fixed angle facing south, or they can be mounted on a tracking device that follows the sun, allowing them to capture the most sunlight over the course of a day. Several connected PV arrays can provide enough power for a household; for large electric utility or industrial applications, hundreds of arrays can be interconnected to form a single, large PV system. Nowadays, most PV systems – ranging from small building-integrated systems to large utility-scale power stations of hundreds of megawatts – are grid-connected, while stand-alone systems constitute only a small part of the market.



In 2018, after tax credits, a solar panel in the US costs from \$11,380 to \$14,900, and the price per watt for solar panels ranges from \$2.71 to \$3.57. In general, the larger the area of a module or array, the more electricity it can produce, and thus the cost of a PV solar energy installation can also be expressed in the price per square meter.

Some solar cells are designed to operate with concentrated sunlight. These cells are built into concentrating collectors that use a lens to focus the sunlight onto the cells. This approach has both advantages and disadvantages compared with flat-plate PV arrays. The main idea is to use very little of the expensive semiconducting PV material while collecting as much sunlight as possible. But because the lenses must be pointed at the sun, the use of concentrating collectors is limited to the sunniest parts of the country. Some concentrating collectors are designed to be mounted on simple tracking devices, but most require sophisticated tracking devices, which further limit their use to electric utilities, industries, and large buildings.

The performance of a solar cell is measured in terms of its efficiency at turning sunlight into electricity. Only sunlight of certain energies will work efficiently to create electricity, and much of it is reflected or absorbed by the material that make up the cell. Because of this, a typical commercial solar cell has an efficiency of 15% – about one-sixth of the sunlight striking the cell generates electricity. Low efficiencies mean that larger arrays are needed, and that means higher cost. Improving solar cell efficiencies while holding down the cost per cell is an important goal of the PV industry, NREL (The National Renewable Energy Laboratory) researchers, and other U.S.

Department of Energy (DOE) laboratories, and they have made significant progress. The first solar cells, built in the 1950s, had efficiencies of less than 4%.

4. THE GLOBAL PHOTOVOLTAIC SOLAR ENERGY MARKET

4.1. *Historical Development*

Applications of concentrated solar power and solar thermal energy had existed for quite some time, but photovoltaic solar energy only emerged when US scientists at Bell Labs developed the silicon PV cell in 1954, and the first silicon PV cell achieved an efficiency of 6%. In 1958, Vanguard 1, the fourth Earth orbital satellite was launched, and Vanguard 1 had six solar cells producing about 1W of power. Although the efficiency of silicon solar cells continued to improve in research labs, the successful mass production of solar cells was only made possible by Sharp in 1963, which brought down from space satellites to the general public. The Arab oil embargo, which took place in 1973, spurred research in solar energy, and the price of a solar panel dropped from \$100/watt to \$20/watts.

In 1974, The Solar Energy Industries Association (SEIA) was formed, and since 1974, SEIA has worked to promote, develop, and expand the use of solar energy in the United States. In 1980, ARCO Solar became the first solar panel manufacturer to attain the 1MW level of yearly production. Two years later, this company installed the first multi-megawatt solar energy project in California. In 1986, ARCO Solar released the first commercial thin-film power module made of amorphous silicon. Six years later, thin-film modules made of cadmium telluride hit 15.9% efficiency. In 1993, Pacific Gas & Electricity became the first US utility to support distributed systems with a 500kW PV array in Kerman, California.

In 2000, global PV installations passed the milestone of 1GW. In 2007, Nanosolar shipped the first commercialized CIGS thin-film modules, and its solar panels were sold at the price of \$0.99/W, the lowest-cost solar panel at the time. At the end of 2009, the cumulative installed PV capacity worldwide was approaching 24GW. One year later, it was 40.7GW; and at the end of 2011, it was 71.1GW. In 2012, more than 100GW of PV capacity had been installed worldwide, and the volume of electricity that can be produced from this capacity more than meets the electricity needs of 30 million European households.

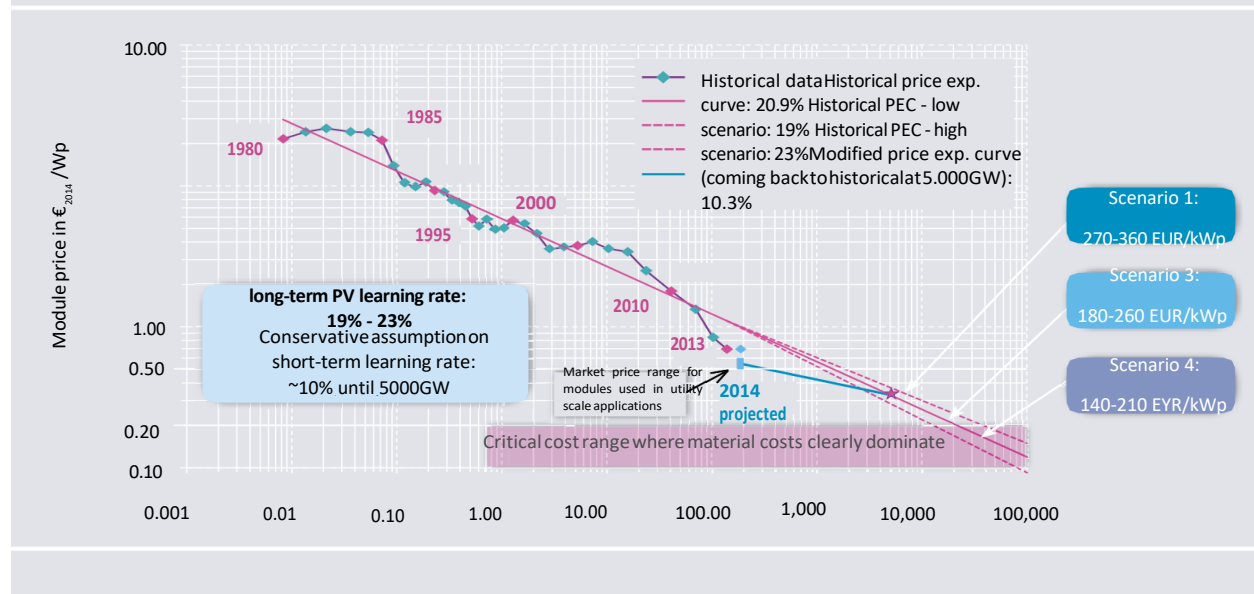
In terms of cumulative installed capacity, Europe was the leading region in 2012, with more than 70GW, which accounted for 70% of the world's cumulative installed capacity. Next in the ranking came China (8.3 GW), the USA (7.8 GW), and Japan (6.9 GW). Outside the EU, many countries – in particular, China, the USA, Japan, Australia (2.4GW), and India (1.2GW) – have only exploited a small part of their enormous solar energy potential. Countries with high insolation levels in Africa, the Middle East, South East Asia, and Latin America have started developing their solar energy resources. As of 2012, the cumulative installed capacity outside the EU was 30GW.

By the end of 2016, 303GW had been installed worldwide. Also, in 2016, the global PV market was 75MG, with China (34.54GW) as the largest, to be followed by the USA (14.72GW), and Japan (8.6GW) Twenty-four countries had at least 1GW of cumulative PV capacity at the end of 2016.¹ According to GTM Research, in 2017, the global solar energy market increased by 9%, reaching 85GW.² China, the US, India, and Japan will continue to be major players on the demand side; however, their overall share in the global market will shrink from 82% in 2017 to 72% in 2018.³

4.2. The Falling Prices of Modules and The Forecast Levelized Cost of Electricity

The cost developments in the PV technology in the last decade have been dramatic. The following figure – reproduced from the study “Current and Future Costs of Photovoltaics, p. 6” by Agora Energiewende⁴ – represents the learning curve for future module prices in Germany, one of the most developed markets for photovoltaic power plants worldwide. The analysis based on this learning curve shows that PV solar energy will soon be the cheapest form of electricity in many regions of the world.

Future module prices in different scenarios based on the historical “learning rate”



¹ Global PV Market 2016-IEA PVPS, www.iea-pvps.org/.../report/statistics/Snapshot_2016_-_Infographic.pdf . PDF file

² GTM Research: global solar market to see 9% growth in 2017, <https://www.pv-magazine.com/2017/04/13/gtm-research-global-solar...>

³ 10 Trends That will Shape the Global Solar Market in 2018, <https://www.greentechmedia.com/articles/read/solar-trends-2018-gtm>.

⁴ <https://www.scribd.com/.../Current-and-Future-Cost-of-Photovoltaics>

The following table – also reproduced from the study “Current and Future Costs of Photovoltaics, Table 5, p. 65” by Agora Energiewende⁵ – gives the forecast levelized costs of electricity for a number of countries including Saudi Arabia.

ICoe, in euR ₂₀₁₄ ct/kwh																								
year	2015						2025						2035						2050					
	5%		7,5%		10%		5%		7,5%		10%		5%		7,5%		10%		5%		7,5%		10%	
	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
Argentina	5,5	12,5	6,6	15,1	7,8	17,9	4,1	10,0	4,9	12,1	5,7	14,3	3,0	8,6	3,5	10,4	4,1	12,4	1,9	6,9	2,2	8,5	2,6	10,2
Australia	4,6	8,9	5,5	10,8	6,5	12,8	3,4	7,1	4,1	8,6	4,8	10,2	2,5	6,1	3,0	7,4	3,5	8,9	1,6	4,9	1,9	6,1	2,2	7,3
brazil	4,7	8,2	5,7	9,8	6,7	11,7	3,5	6,5	4,2	7,9	4,9	9,3	2,6	5,6	3,0	6,8	3,6	8,1	1,6	4,5	1,9	5,5	2,3	6,7
Canada	5,8	10,4	7,0	12,6	8,3	14,9	4,3	8,3	5,2	10,0	6,1	11,9	3,2	7,2	3,8	8,7	4,4	10,3	2,0	5,8	2,4	7,1	2,8	8,5
China	4,8	8,2	5,8	9,8	6,9	11,7	3,6	6,5	4,3	7,9	5,1	9,3	2,6	5,6	3,1	6,8	3,7	8,1	1,7	4,5	2,0	5,5	2,3	6,7
France	5,5	9,4	6,6	11,3	7,8	13,4	4,1	7,5	4,9	9,0	5,7	10,7	3,0	6,4	3,5	7,8	4,1	9,3	1,9	5,2	2,2	6,4	2,6	7,7
india	4,6	6,7	5,5	8,1	6,5	9,6	3,4	5,4	4,1	6,5	4,8	7,7	2,5	4,6	3,0	5,6	3,5	6,6	1,6	3,7	1,9	4,5	2,2	5,5
korea, south	6,3	7,2	7,5	8,7	8,9	10,3	4,7	5,8	5,6	7,0	6,6	8,3	3,4	5,0	4,1	6,0	4,8	7,1	2,2	4,0	2,6	4,9	3,0	5,9
morocco	4,6	6,3	5,5	7,5	6,5	9,0	3,4	5,0	4,1	6,0	4,8	7,2	2,5	4,3	3,0	5,2	3,5	6,2	1,6	3,5	1,9	4,2	2,2	5,1
Russia	5,5	11,0	6,6	13,3	7,8	15,8	4,1	8,8	4,9	10,6	5,7	12,6	3,0	7,6	3,5	9,2	4,1	10,9	1,9	6,1	2,2	7,5	2,6	9,0
saudi Arabia	4,5	6,1	5,4	7,3	6,3	8,7	3,3	4,8	4,0	5,8	4,7	6,9	2,4	4,2	2,9	5,0	3,4	6,0	1,5	3,3	1,8	4,1	2,1	4,9
south Africa	6,5	9,4	7,8	11,3	9,3	13,4	4,8	7,5	5,8	9,0	6,8	10,7	3,5	6,4	4,2	7,8	4,9	9,3	2,3	5,2	2,7	6,4	3,1	7,7
spain	4,5	6,9	5,4	8,4	6,3	9,9	3,3	5,6	4,0	6,7	4,7	7,9	2,4	4,8	2,9	5,8	3,4	6,9	1,5	3,8	1,8	4,7	2,1	5,7
thailand	5,3	6,9	6,4	8,4	7,5	9,9	3,9	5,6	4,7	6,7	5,5	7,9	2,9	4,8	3,4	5,8	4,0	6,9	1,8	3,8	2,2	4,7	2,5	5,7
turkey	4,8	6,9	5,8	8,4	6,9	9,9	3,6	5,6	4,3	6,7	5,1	7,9	2,6	4,8	3,1	5,8	3,7	6,9	1,7	3,8	2,0	4,7	2,3	5,7
uganda	4,8	6,5	5,8	7,8	6,9	9,3	3,6	5,2	4,3	6,2	5,1	7,4	2,6	4,4	3,1	5,4	3,7	6,4	1,7	3,6	2,0	4,4	2,3	5,3
united kingdom	7,4	11,7	8,9	14,1	10,5	16,8	5,5	9,4	6,5	11,3	7,7	13,4	4,0	8,1	4,8	9,8	5,6	11,6	2,6	6,5	3,0	8,0	3,5	9,6
united states	4,3	6,9	5,2	8,4	6,2	9,9	3,2	5,6	3,9	6,7	4,5	7,9	2,4	4,8	2,8	5,8	3,3	6,9	1,5	3,8	1,8	4,7	2,1	5,7

5. LEVELIZED COSTS OF ELECTRICITY

Levelized costs of electricity (LCOE) are convenient summary measures of the overall competitiveness of different generating technologies. The LCOE of a generating plant over an assumed life time. Key inputs to calculating LCOE include capital costs, fuel costs, fixed and variable operations and maintenance (O&M) costs, financing costs, and an assumed utilization rate for each plant type.⁵ The importance of these factors varies among the technologies. For technologies such as solar and wind generation that have no fuel costs and relatively small variable

⁵<https://www.scribd.com/.../Current-and-Future-Cost-of-Photovoltaics>

O&M costs, LCOE changes in rough proportion to the estimated capital cost of generation capacity. For technologies with significant fuel cost, both fuel cost and overnight cost estimates significantly affect The levelized cost of electricity (LCOE) of a generating plant is computed according to the following formula:

$$LCOE = \frac{I_0 + \sum_{t=1}^n \frac{A_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}}$$

Here n is the lifetime (in years) of the generating plant;

I_0 is the investment expenditures;

A_t = annual cost in year t (fuel cost + operations cost + maintenance cost);

E_t is the electricity output in year t; and

r is the rate of discount.

Note that in the preceding formula used to compute the LCOE the output is also discounted. rate of discount. The idea behind the discounting of electricity output is that future outputs reflects future earnings, and the farther earnings are in the future, the lower are their present value. Another possible justification for discounting the yearly output of electricity is to identify the yearly output of electricity with the social utility obtained in a year, and the social welfare obtained from the project is thus the present value of the stream of social welfare yielded by the project over its lifetime. Under this interpretation, LCOE is the cost per unit of social welfare. Solar cells are typically combined into modules that hold about 40 cells; a number of these modules are mounted in PV arrays that can measure up to several meters on a side.

Table 1 presents the levelized costs of electricity and the costs of carbon emissions for some generating technologies.⁶

Table 1
Levelized Costs of Electricity for Some Generating Technologies

Type of System	Plant Size (MW)	Capital (Investment)(€m) Cost	Initial Investment per unit of Capacity (\$m/MW)	Fixed Cost FC (\$/MWh)	Fuel Cost (\$/MWh)	Operational and Maintenance Cost (\$/MWh)	Carbon Emission Cost (\$/MWh)	Full Cost (\$/MWh)
Geothermal	50	1932.7	38.65	26.4	-	22	-	48.4
Coal	1600	1210	0.75	14.3	23.1	5.5	9.9	52.8
Nuclear	1000	3300	3.3	39.6	5.5	7.7	-	52.8
Combined cycle gas plant	750	770	1.02	9.9	37.4	4.4	5.5	57.2
Wind (Onshore)	100	1430	14.3	50.6	-	13.2	-	63.8
Wind (Offshore)	200	2618	13.09	81.4	-	26.4	-	107.8

⁶ M. Bonass and M. Rudd. *Renewables: A Practical Handbook*. London: Globe Law and Business, 2010, pp. 51.

Solar (Concentrated)	10	5170	517	210.1	-	19.8	-	229.9
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6. THE INTRODUCTION OF PHOTOVOLTAIC SOLAR ENERGY IN SAUDI ARABIA

6.1. *The Levelized Cost of the 3.5MW Photovoltaic Solar Energy Station in King Abdullah City*

King Abdullah Economic City (KAEC) is a modern, healthy lifestyle city, which offers a safe family environment. KAEC plans to construct an electricity power system in Saudi Arabia through the use of renewable energies – a wind power stations, solar power stations and solar PV station. The largest completed PV station in Saudi Arabia has been constructed on a land area of 55,000m² belonging to the largest oil research center the “King Abdullah Petroleum Studies and Research Center” in Riyadh, and it has a capacity of 3.5 MW. According to Smestad GP (2009), the main economic concept for PV installations is that the useful energy produced during the lifetime of PV should recover its cost. The levelized cost of electricity (LCOE) can be measured from the total life cycle cost to the total lifetime energy production,

The CRF or Capital recovery Factor is the amortization of capital cost. This model has been used in the study of the cost benefits analysis of implementing PV system in Kuwait (Mohammad Ramadhan, Adel Nasseb 2010), and also in studying the analysis of economic feasibility of PV system in Qatar (Marafia Hamid 2001).

The following example illustrates the calculations of the LCOE for the 3.5MW photovoltaic solar energy station of King Abdullah Economic City. The data used in the calculations are as follows:

Average insolation/m²/year = 2200kWh,
 Efficiency = 15%,
 Project life = 20 years,
 O&M = \$48,400 (22\$/kWh/year),
 Capital Cost = 500\$/m² or (5\$/Watt),
 Interest Rate = 5%,
 Station Capacity = 55,000 m².

The above data allow us to compute the following values of I_0, A_t, E_t :

$$\text{Installation cost} = I_0 = (500\$/m^2) \times 55,000m^2 = \$27,500,000,$$

$$\text{Annual cost} = A_t = \$48,400,$$

$$\text{Annual output} = E_t = \left(\frac{2200kWh}{m^2} \right) \times 0.15 \times 55,000m^2 = 18,150,000 kWh, t(\text{year}) = 1,20.$$

With the above values of outputs and costs, the levelized cost of electricity for the KAEC project is $LCOE = \$0.124/kWh$.

Per Mohammad Ramadhan and Adel Nasseb (2010), used a different procedure to obtain the LCOE:

$$\text{Station Annual Output} = \text{Average Annual Insolation} \times \text{Model Efficiency} \times \text{Station Capacity},$$

Installation Cost = Capital Cost × Station Capacity,

Annual Cost = (Installation Cost × CRF) + (O&M),

$$LCOE = \frac{\text{Annual Cost}}{\text{Annual Output of the Station}}$$

Note that the procedure uses CRF (Capital Recovery Factor) to compute the annual cost. The procedure used by these researchers yields a LCOE of 0.12\$/kWh for a 3.5 MW PV station priced at 5\$/Watt. Because the difference between their calculated LCOE and ours is insignificant, in what follows, we shall use the calculated LCOE of these researchers in our cost-benefit analysis of the 3.5MW photovoltaic solar energy station in Saudi Arabia.

6.2. The Economic Feasibility of a 3.5 MW Photovoltaic Solar Energy Station

Table 2 shows the LCOE generated by 3.5 MW PV station in King Abdullah city established under different assumptions of price/W and discount rates. As per Mohammad Ramadhan, Adel Nasseb. “The PV solar systems are compared on the basis of their levelized electricity costs (LCOE), which depend on the capital cost of the plant, the efficiency of modules, region solar radiation, system output, annuity factor, and annual operations and maintenance costs. Using the same parameters in the above example, with a different set of PV prices and discount rates of 5% and 10% yields the results in Table 2.”

The results in Table 2 enhance the concept that the PV price/W, the efficiency of the cells, and the discount rates are the main factors in establishing the cost of generated electricity (Mohammad Ramadhan, Adel Nasseb, 2009). The results in Table 2 show clearly that the LCOE drops as the price/W decreases and that the LCOE is also responsive to the discount rates. At 5% discount rate, the LCOE declines from \$0.17 to \$0.10 when the price per square meter falls from \$700 to \$400. At 10% discount rate, the LCOE drops from \$1.27 to \$0.07 when the price per square meter falls from \$700 to \$400. In the Kingdom of Saudi Arabia, the average electricity cost is 7.7 cents/kWh (\$0.077/kWh) when the fuel prices are deregulated.⁷ With the module price at \$5/W and a discount rate of 5% the LCOE is estimated to be around \$0.12/kWh, which is much higher than \$0.07/kWh, the cost of electricity generated from local fossil fuels. However, at 10% discount rate and installation costs of \$4/W, the LCOE of the PV project and the cost of electricity using the local fuel oil are the same (\$0.07/kWh). As per Walid Matar and Murad Anwer (2017) the PV project will be cost competitive when the oil price is at \$30/bbl. Since the oil price is expected to increase worldwide in the future, and PV modules are expected to become more efficient, we can conclude that the LCOE of PV systems will be close or less than fossil fuel electricity in the near future.

⁷ Based on Walid Matar and Murad Anwer, “Jointly reforming the prices of industrial fuels and residential electricity in Saudi Arabia”, Energy Policy- Volume 109, October 2017, Pages 747-756.

Table 2

Expected LCOE for 3.5 MW PV station in Saudi Arabia.

Price/W	Price \$/m ²	LCOE at 5% interest	LCOE at 10% interest
7	700	\$0.17	\$1.27
6	600	\$0.14	\$0.11
5	500	\$0.12	\$0.09
4	400	\$0.10	\$0.07

7. THE COST-BENEFIT ANALYSIS OF PHOTOVOLTAIC SOLAR ENERGY

Mohammad Ramadhan and Adel Naseed (2009) suggested that the valuation of the renewable energy projects should not be based solely on financial returns. A renewable energy project – besides financial returns – also yield social and environmental benefits. One major advantage of renewable energy is that it will not run out because it is easily replenished. It also requires less maintenance, and produces little or no waste products, such as carbon dioxide. A renewable energy project also creates more job opportunities for example the solar power industry alone created double workplaces than oil or coal industry together [10], preserves local fossil fuels, and reduces the import and export of fuel oil. In a study entitled “Cost Reduction study for Solar Thermal Power Plants”, published by the World Bank (1999), Enermodal Engineering Limited explained that Cost-Benefit Analysis provides the methodological framework which allows for an overall evaluation of projects and policies by taking into account all costs and benefits, both those referring to the investment itself (internal costs and benefit) and those attributed to the external economic and natural environment (external costs and benefits).

7.1. Benefits of CO₂ Emissions Reduction

Solar energy is an alternative to fossil fuels; it is a renewable and non-polluting source of energy. It generates no greenhouse gases, especially carbon dioxide (CO₂), which leads to a rise in the global temperatures and climate change [7]. According to the economists Nicholas Muller, Robert Mendelsohn and William Nordhaus (2011), CO₂ emissions are available for electric power generation,⁸ and the estimated social costs of the CO₂ emissions, long-term damage done by a tone of Carbon dioxide

⁸ The data are provided by the US Energy Information Administration.

emissions, range from \$19 to \$68 per ton. In this paper, I will use the general conservative estimate value of \$27 per ton, which, according to Nordhaus (2007), is a rather conservative estimate [8]. Implementing the photovoltaic and concentrated solar power in the Kingdom of Saudi Arabia will reduce the emissions of CO₂ and other pollutants. Following Mohammad Ramadhan and Adel Naseeb (2009), Table 3 provides estimates of the value of CO₂ emissions eliminated for different sizes of PV system. Per Hannah Ritchie and Max Roser (2018), we assume that 263.88kg of CO₂ are emitted for each megawatt-hour of electricity produced by burning crude oil. For PV stations of sizes 3.5MW, 10MW, 50MW, and 100MW, the CO₂ emissions will be reduced by approximately 2 tons, 6 tons, 29 tons, and 58 tons, respectively. Under these assumptions, the cost of reduction in CO₂ emissions ranges from \$57 to \$1562 per year (around \$0.007/kWh).

Table 3

Reduction in CO₂ Emissions by the PV Systems.

Station Type	Station Output Capacity (MW)	Annual Output (MWh)	CO ₂ Emission (factor = 0.263)	Annual emission at 27\$/ton
PV	3.5	8	2.1	56.80
	10	22	5.8	156.22
	50	110	28.9	781.11
	100	220	57.9	1562.22

7.2. Economic Benefits of a Photovoltaic System

The electricity produced by a PV system replaces the electricity produced using crude oil. In the case the oil can be conserved or exported – and Saudi Arabia is planning to replace the energy produced using fuel oil – the oil thus conserved can be used in the future. To compute the economic profit of a PV solar system, we should consider the opportunity cost of using fossil fuels to produce electricity and count the implicit cost of environmental pollution. The true economic benefit of implementing a PV solar system in the Kingdom of Saudi Arabia is estimated according the below assumptions:

- The production cost of electricity using crude oil (light and heavy) in Saudi Arabia is around \$0.004kWh.⁹
- Saudi Arabia will lower its CO₂ emissions cost by 0.007\$/kWh.

⁹ According to King Abdullah Petroleum Studies and Research Center.

Table 4 shows the economic benefits of implementing a 3.5MW photovoltaic solar energy station in Saudi Arabia under different installation costs (\$/Watt).

Table 4

Economic benefits of PV Solar Energy.

Price \$/W	LCOE	Energy Savings	CO ₂ Emission	Economic Cost
7	0.17	\$0.004	\$0.007	\$0.15
6	0.14	\$0.004	\$0.007	\$0.12
5	0.12	\$0.004	\$0.007	\$0.10
4	0.10	\$0.004	\$0.007	\$0.08

As can be seen from Table 4, the true economic LCOE of a PV system will decrease significantly when the price per watt of the installation falls. The economic LCOE will range from \$0.08/kWh to \$0.15/kWh, and this means in the Kingdom of Saudi Arabia, the LCOE produced by a PV system is financially feasible and economically viable.

7.3. The Economic Feasibility of the 3.5MW Photovoltaic Solar Energy

Station in King Abdullah City

Solar power will become a viable alternative to fossil fuels ahead of coal, hydro, and nuclear within a decade, says the International Energy Agency (Paul Rodgers, ‘Solar Power Viable Within a Decade, Says IEA’, September 2014). And by 2050, solar energy will be the world’s largest source of electricity, said the Paris-based agency, which is better known to business for its oil price forecasts. The economics of the switch will drive a \$44-trillion investment boom, a staggering sum compared to the \$900 billion a year pumped into fossil fuels at the present time” [9]. The most significant benefits of solar energy systems are:

- Opening new job opportunities. (specially that Saudi Arabia’s population is increasing);
- Reducing CO₂ emission because of the decreasing use of fossil fuels for generating electricity;
- Electricity produced by PV systems will be cheaper than electricity produced from any other source of energy, including oil, coal, natural gas.

Saving of natural resources (gas, oil, ...).

8. CONCLUDING REMARKS

Solar energy is the most suitable alternative to conventional power in the Middle East due to the high solar irradiation in this region. A solar system in Saudi Arabia can be three times more effective from the same system in other country. The analysis demonstrates that the positive radiation in the kingdom plays a major role in making the implementation of a photovoltaic solar energy system economically feasible. A photovoltaic system is usually used to generate electricity power, while a solar thermal system is used to generate heat for water heating and for building heating systems.

The Kingdom of Saudi Arabia has a plan to wean its economy off oil. Saudi Arabia's goal is to expand the use of solar energy systems at both the national and regional level, and to keep up with the growing electricity demand. The feasibility of a 3.5 MW photovoltaic solar energy station can be achieved under the price of 4\$/kWh, 15% efficiency, and 10% interest rate, where its LCOE and the LCOE generated from local fossil fuels are equal (\$0.07/kWh). The LCOE of a 3.5 MW station is around \$0.12/kWh. When the value of the saved fossil fuels used in generating electricity is \$0.004/kWh¹⁰ and the cost of CO₂ emissions is \$0.007/kWh, the true LCOE of a photovoltaic system will fall from \$0.15 to \$0.08/kWh. In the case of a PV station with a cost of \$5/kWh, the economic benefit will lower the LCOE from \$0.12/kWh to \$0.10/kWh. The new project in Saudi Arabia is to produce 200 gigawatts of power through 2030. In that manner, if Saudi Arabia produces electricity using a PV system, it can sell more its own oil and increase the oil exportations that lead to more income for the kingdom. Finally, Saudi Arabia in implementing a PV system, will improve its international image by decreasing its CO₂ emissions as well as decrease its dependence on fossil fuels to produce electricity. Based on this preliminary analysis, the study recommends the implementation of PV solar systems in the Kingdom of Saudi Arabia – and all the Gulf Club countries – in order to diversify sources of energy, decrease global air pollution, and save the finite stocks of oil reserves from premature exhaustion.

¹⁰ according to the crude oil prices since it is the most used oil in the production of electricity.

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