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ORIGINAL ARTICLE

Future of solar energy in Saudi Arabia

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Abstract The continued rise of electricity demand in Saudi Arabia means that power generation must expand. Conventional generation is a major cause of environmental pollution and negatively impacts human health through greenhouse gas emissions. It is therefore essential that an alternative method of generation is found that preserves the environment and health and would support existing conventional generation during peak hours. Saudi Arabia is geographically suitable because it is located in the so-called sun belt, which has led it to become one of the largest solar energy producers. Solar energy is a serious competitor to conventional generation when the indirect costs of fossil fuels are included. Thus, processing sunlight via photovoltaic cells is an important method of generating clean energy. This article proves that the cost of solar energy will be less than the cost of fossil fuel energy if the cost of the environmental and health damages is taken into account.

1. Introduction

The construction boom and growing population of Saudi Arabia result in the rise of the country's electricity demand. The ongoing high loads require appropriate and adequate power generation. However, it is well known that conventional generation by means of fossil fuels is a chief cause of environmental pollution and impacts human health through emissions of harmful gases such as nitrogen oxides (NO, NO_2 & N_2O), sulfur oxides (SO_2 & SO_3), and carbon oxides (CO & CO_2). Therefore, it is essential to find an alternative way to support current conventional generation in Saudi Arabia that also preserves the environment and human health. Saudi Arabia is geographically strategic because it is located in the so-called sun belt, and it has widespread desert land and year-round clear skies, which have led it to become one of the largest solar photovoltaic (PV) energy producers. The average energy from the sunlight falling on Saudi Arabia is 2200 thermal kWh/m^2 (Alawaji, 2001), and it is therefore worthwhile to attempt to generate clean energy in the country via direct sunlight through PV cells.

Applications of solar energy in Saudi Arabia have been growing since 1960. A systematic major research and development work for the development of solar energy technologies was started by King Abdulaziz City for Science and Technology (KACST) in 1977. The Saudi Solar Radiation Atlas project was initiated in 1994 as a joint research and development project between the KACST Energy Research Institute and the US National Renewable Energy Laboratory (Said et al., 2008).

The solar village project site is located 50 km northwest of Riyadh and supplied between 1 and 1.5 MWh of electric

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energy per day to three rural villages. It was the biggest project of its type in 1980 and cost \$18 million (Sayigh et al., 1998).

In 2007, the Ministry of Higher Education established a Center of Research Excellence in Renewable Energy at the King Fahd University of Petroleum and Minerals. The aim of the center is to further scientific development in renewable energy with an emphasis on solar energy.

At the King Abdullah University for Science and Technology, 2 MW PV cells were installed. This solar power plant is located in Thuwal, north of Jeddah, and started operations in May 2010. It has 9300 modules of 215 Wp over 11,600 m^2 and is intended to produce 3300 MWh of clean energy annually while saving up to 1700 tons of annual carbon emissions. The total cost of this photovoltaic grid-connected (PVGC) power plant was approximately 65 million Saudi riyals (SR) (National Solar Systems, 2010).

The Farasan solar power plant, with a capacity of 500 kWp, was constructed in Saudi Arabia over an area of 7700 m^2 (National Solar Systems, 2010). This solar power plant is a stand-alone system intended to feed Farasan Island, south of Saudi Arabia, and has been in operation since June 2011 (National Solar Systems, 2010).

The world's largest solar parking project, the North Park Project located in Dhahran, Saudi Arabia, at the headquarters of the oil company Saudi Aramco, has a 10 MW carport system with a capacity to cover 200,000 m^2.

Because solar energy is an important renewable energy source, many organizations and countries have made efforts in terms of research and investment in solar energy as a key alternative to burning fossil fuels.

The scope of the research is about how to transfer solar energy into electrical energy through PV cells then inject it directly into the power transmission lines and thus this article does not mention about storage energy. However, some studies have mentioned it (Al-Ali et al., 2012; Mansouri et al., 2013).

2. Environmental and health issues

Unpolluted air is a basic condition necessary to preserving human health, but air pollution remains a threat to public health around the world. The conventional electricity-generating industry is a main contributor to the production of harmful gases polluting the environment. Low-quality fuels and the methods of generation typical in Saudi Arabia (such as crude oil with high sulfur content in power plants with negligible emission controls) emit a variety of pollutants that contribute to public health issues (Alnatheer, 2005a). Conventional power plants emit greenhouse gases such as CO_2, SO_2, and NO_x, which are known contributors to global warming. Saudi Arabia leads the Gulf Cooperation Council (GCC) countries in its CO_2 emissions, contributing 56% (Qader, 2009), and has been ranked 14 in the world for CO_2 emissions (US Energy Information Administration, 2010). The relationship between electricity consumption and CO_2 emissions (US Energy Information Administration, 2010) (Fig. 1) is approximately linear. Accordingly, future use of conventional generation will increase the levels of CO_2 emissions in Saudi Arabia proportional to the expansion of its generation capacities. Power plants will therefore play a large role in reducing such emissions through the use of alternative electricity production such as PV power.

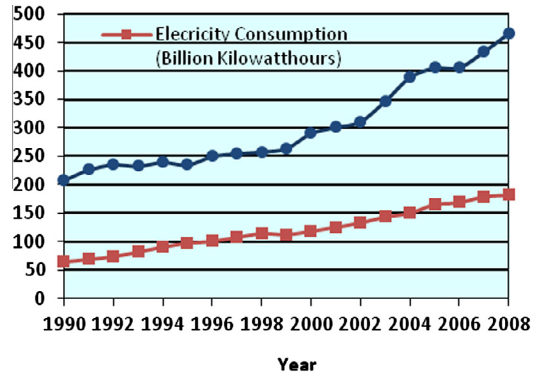

Figure 1 CO_2 emission from electricity consumption.

As per environmental protection standards in Saudi Arabia – managed by the Presidency of Meteorology and Environment – the average concentration of PM must not exceed 80 μg/m^3 per year at any site (Presidency of Meteorology and Environment in Saudi Arabia, 2001). However, PM concentration in Saudi Arabia is in reality 113 μg/m^3 (Booz et al., 2009). Concentrations of SO_2 must not exceed 85 μg/m^3 per year, and 100 μg/m^3 per year for NO_x, at any site (Presidency of Meteorology and Environment in Saudi Arabia, 2001). But the amounts of SO_2 released into the Saudi Arabian atmosphere exceed those reported for the Netherlands, Sweden, Finland, and Portugal (Al-Radady and Goknil, 1999). To analyze environmental costs, each kWh of energy produced can be linked to rates of emission for each pollutant. CO_2, SO_2, and NO_x emissions from fossil fuels used to generate electricity in Saudi Arabia are 180, 3.16, and 2.13 g/kWh, respectively (Rahman and de Castro, 1995). The cost of health impacts from gas powered plants in Germany is 0.0034 €/kWh (European Commission, 2003), and the equivalent cost of health impacts in Saudi Arabia is estimated to be 0.0178 SR/kWh (Gandayh, 2012).

3. Economics of solar energy

Solar energy costs have declined from approximately 90 ¢/kWh in 1980 to approximately 20 ¢/kWh today (Bull, 2001). The current cost of PV in the US ranges from 18 to 23 ¢/kWh, with the expectation that it will decrease to 5–10 ¢/kWh by 2015 (Thornton, 2009). The US has a target to make PV-generated electricity costs competitive with conventional energy sources by 2020 (Kroposki et al., 2009). Today, the cost of PV is approximately 2.5 \$/Wp and the target is to reduce this to approximately 1 \$/Wp (Kalogirou, 2009).

In 2008, the average overall cost in Saudi Arabia for a unit of conventional electricity generation (kWh) supported by the government was approximately SR 0.15 (Kroposki et al., 2009). The total cost of power generation for a typical GCC utility at US market prices is 12 ¢/kWh (Booz et al., 2009), which is equivalent to SR 0.45. One ton of petroleum is equal to 6.84 barrels and could provide 11,630 kWh of conventionally generated power (Plaz, 1978). World oil prices are expected to increase from \$70 to approximately \$95 per barrel by 2015 and \$108 per barrel by 2020 (US Energy Information Administration, 2010). This means that the production costs of electricity from conventional generation sources will increase

Table 1 Indirect costs of conventional generation.

External damage	Damage cost (SR/kWh)
CO_2	0.036
SO_2	0.027
NO_x	0.088
Health	0.0178
Total indirect costs = 0.1688 SR/kWh	

rapidly. The cost of power generation from renewable sources would be less expensive than from fossil fuels when the hidden costs of fossil fuels, such as environmental and public health costs, are considered (Qader, 2009).

Solar energy economics are at their best in regions with high solar radiation factors. Any comparison of solar energy and conventional generation is unfair if it does not include the indirect costs of conventional energy, which are defined by factors such as environment and health impacts. A summary of indirect costs per kWh of conventional generation is provided in Table 1 (Gandayh, 2012). The average external costs of CO_2, SO_2, and NO_x are 0.0001 SR/g, 0.0086 SR/g, and 0.0412 SR/g, respectively (Alnatheer, 2005a,b). Total indirect costs in Saudi Arabia are estimated to be 0.1688 SR/kWh (Gandayh, 2012).

In this paper, four approaches, A, B, C, and D, are considered to draw a financial comparison between conventional generation and solar PV systems (Gandayh, 2012). The comparison covers the years 2010–2020. Approach A represents the subsidized price of conventional generation, which is 0.15 SR/kWh excluding indirect costs versus PV-generated electricity costs. This approach shows that the average cost of solar energy will not be competitive with that of conventional systems until 2020. Approach B represents the non-government-supported price of conventional generation, which equals 0.45 SR/kWh excluding indirect costs versus solar energy systems. This cost will be competitive with that of solar energy by 2011. Approach C represents the government-supported price of conventional generation including indirect costs versus solar energy. The government-supported cost of conventional generation plus indirect costs is approximately 0.32 SR/kWh. The latest amount will be competitive with PV schemes by 2015, or by 2020 in the worst case scenario of high solar energy costs (Fig. 2). The final approach to comparison, D, represents the unsupported price of conventional generation including indirect costs versus solar energy. This price is approximately 0.62 SR/kWh and indicates that solar energy is currently more cost-effective than conventional generation when prices are unsupported by the government and indirect costs are included. Accordingly, the most convenient state is approach C because it is comparable to the current policy of energy in Saudi Arabia. Thus, solar energy is expected to be competitive with conventional generation by 2020.

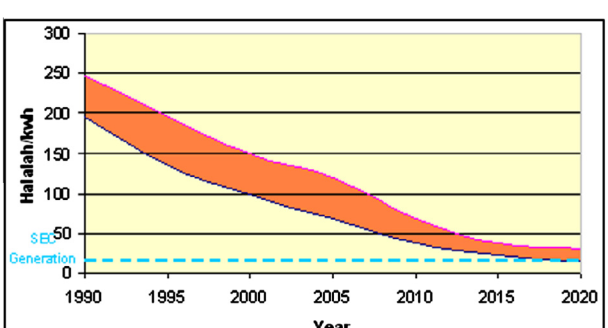

Figure 2 Forecasting of PV-generated electricity cost (100 Halalahs = 1 Saudi riyal) (Rahman and de Castro, 1995).

4. Geographical and meteorological issues

The area between latitudes 40°N and 40°S is a so-called sun belt, and Saudi Arabia lies in it, between latitudes 31°N and 17.5°N. Saudi Arabia is conveniently located in the sun belt to take advantage of solar energy. Insulation is the most important aspect to consider when selecting suitable sites to build PV power plants. Average solar radiation in Saudi Arabia varies between a maximum of 7.004 kWh/m^2 at Bisha and a minimum of 4.479 kWh/m^2 at Tabuk (Fig. 3). The higher values of solar radiation are observed in most parts of the southern region of the country, such as Bisha, Nejran, and Sulayyil.

Solar insulation H in $kWh/m^2/day$ can be converted to average solar irradiance h in W/m^2 by applying Eq. (1), or by simply multiplying by a conversion factor of 41.66666 (Gandayh, 2012).

$$h(W/m^2) = H(kWh/m^2/day) \times (1000)/(24\,h) \tag{1}$$

The top-ten locations of solar radiation intensity in Saudi Arabia (Rehman, 1998) are shown in Fig. 4.

Meteorological data such as solar radiation, sunshine hours, ambient temperature, relative humidity, and amount of cloud cover are important for estimating average global solar radiation. The duration of sunshine varies between a maximum and minimum of 9.4 and 7.4 h/day (Rehman, 1998), and average daily sunshine duration is approximately 8.89 h/day.

A PV cell converts a large amount of solar energy into electricity at low temperatures (Patel, 2006). The maximum power available at lower temperatures is higher than that at higher temperatures. Therefore, the effect at high operating temperatures is a reduction in output power. This effect can be calculated via Eq. (2):

$$P = P_{25^\circ C}[-0.5\% \times (T - 25^\circ C)] \tag{2}$$

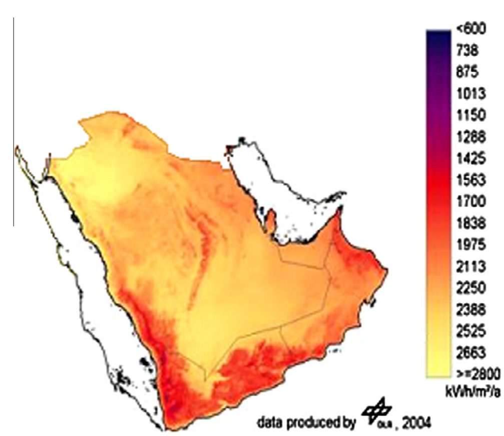

Figure 3 Annual solar insulation in Saudi Arabia (Plaz, 1978).

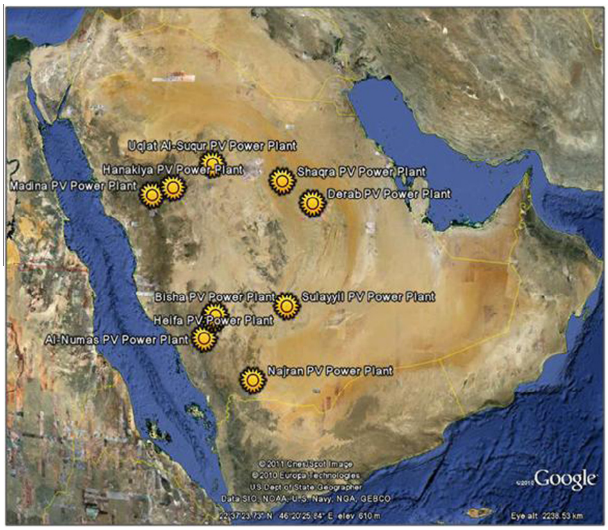

Figure 4 Top-ten locations of PV power plants according to solar irradiation (Rahman and de Castro, 1995).

where $P_{25^\circ C}$ is the manufacturer's rated power output of the PV module, and T is the ambient temperature.

The performance of PV modules is affected by the presence of dust on their surface. Dust accumulation changes the I/V characteristics of PV cells depending on the amount of dust accumulated per unit area of the module surface (g/m^2). Accordingly, PV modules must be kept clean in order to maintain PV power plants at maximum efficiency.

Some areas of Saudi Arabia are not suitable for use as foundations for PV modules because of their geomorphologic features. Areas of sand dunes and shifting sands are inappropriate for the erection of PV modules because the sand cones do not form a strong compound. Locations of shifting sands (Fig. 5) are mostly concentrated in Al-Dahna desert, Al-Nafud desert, and the Empty Quarter (Gandayh, 2012).

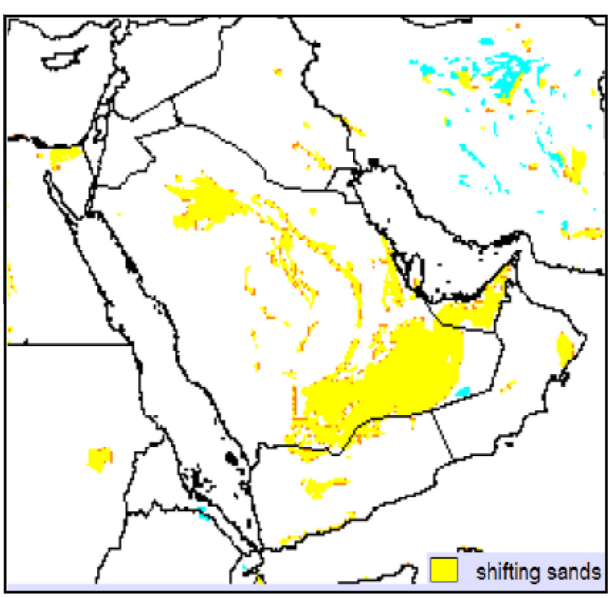

Figure 5 Locations of shifting sands in Saudi Arabia (Rehman, 1998).

5. Forecasting electrical loads

One of the most important determinants of the need for solar energy is the projected future demand for electrical loads. Usually, the first aspect that the designer must estimate is the electrical load and the load profile that the PV system should meet. Forecasting electrical loads involves formulating, analyzing, and evaluating alternative plans for adding to the capacity of a system in order to serve future loads (Abdullah, 1979). The demands on electrical loads have been growing since 2000 (Fig. 6). These loads require sufficient power generation capacity. The population growth rate is a major driving factor of electricity demand. By 2020, Saudi Arabia is projected to have a population of 34 million, based on intermediate estimates of the World Population Prospect of the United Nations (German Aerospace Center (DLR), 2009).

In Saudi Arabia, peak load demands occur on sunny days because of the heavy use of air conditioners. The peak load coincides with the maximum incident solar radiation, and hence PVGC systems produce the highest power. Load profiles in Saudi Arabia show that the period of peak loads lies mostly from 12:00 P.M. to 5:00 P.M. Accordingly, solar power plants may serve to extend the peak load capacity and provide a part of the spinning reserve capacity for the daytime period. This is known as peak saving (Figs. 7 and 8).

Thus, total power demand from conventional sources in Saudi Arabia may be reduced in particular during peak periods, and the peak saving pattern shows the amount required from conventional generation.

Usually, most electrical loads increase from 7:00 A.M. and decline from 6:00 P.M., particularly during workdays (Fig. 7), while solar radiation is available from approximately 6:00 A.M. to 6:00 P.M. Peak loads in Saudi Arabia are mostly observed from May to September, when the monthly pattern of sunshine duration matches that of peaks in electrical loads.

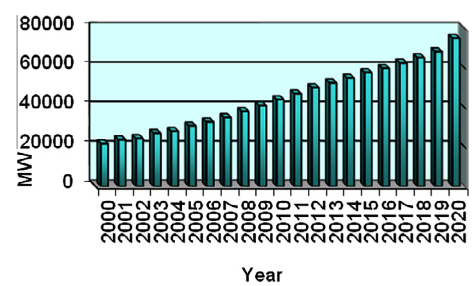

Figure 6 Annual growth of forecasted peak loads (Rahman and de Castro, 1995).

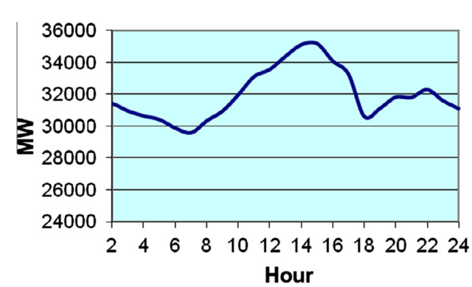

Figure 7 Load pattern in Saudi Arabia (Rahman and de Castro, 1995).

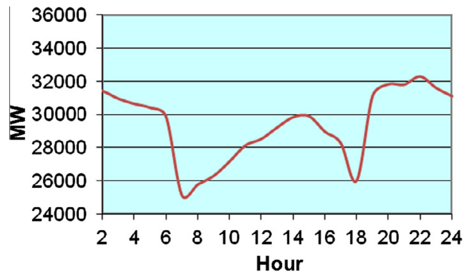

Figure 8 Peak saving pattern (Rahman and de Castro, 1995).

6. Conclusion

This paper has discussed the importance of using solar energy to generate electricity in particular through the use of PV systems. We have considered environmental and health effects, the economics of solar energy, the geographical location of solar power plants, and load forecasting in Saudi Arabia. We have shown that air pollution represents a danger to public health around the world and that conventional generation is a large contributor to the production of dangerous gases polluting the environment. A reduction in greenhouse gas emissions will reduce environmental pollution and save expenditures on public health care. Moreover, the cost of solar energy is less than that of conventional generation if the indirect costs of fossil fuels are included, such as environmental costs and health costs. The period of peak loads in Saudi Arabia is 12:00 P.M. to 5:00 P.M., while solar radiation is available from approximately 6:00 A.M. to 6:00 P.M. Accordingly, peak saving during peak hours could be achieved through the contribution of PVGC systems in conjunction with existing power generation systems. Thus, by 2020, Saudi Arabia is expected to be fully ready to establish PVGC power plants in partnership with conventional power plants to support its national grid and meet the expected required loads.

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