

Analyzing the potential and progress of distributed generation applications in Saudi Arabia: The case of solar and wind resources



Makbul A.M. Ramli^{a,*}, Ssennoga Twaha^b, Zakariya Al-Hamouz^c

^a Department of Electrical and Computer Engineering, King Abdulaziz University, Jeddah 21589, Saudi Arabia

^b Energy and Sustainability Division, Faculty of Engineering, University of Nottingham, NG7 2RD, United Kingdom

^c Electrical Engineering Department, King Fahd University of Petroleum & Minerals, Dhahran 31261, Saudi Arabia

ARTICLE INFO

Keywords:

Distributed generation

Solar energy

Wind energy

Energy resource potential analysis

ABSTRACT

In this paper, the potential of solar and wind energy-based distributed generation (DG) in Saudi Arabia is simultaneously analyzed with the aim of maximizing the utilization of available resources. It begins with an analysis of DG application potential for wind and solar energy resources in various regions of Saudi Arabia. The progress of DG applications in terms of research, planning, and exploitation of wind and solar energy resources is then presented. An assessment of the DG contribution to the energy sector of Saudi Arabia has been conducted and the barriers and challenges for the implementation of DG systems in the country are discussed with suggested measures to overcome the challenges. The main findings are that with the huge potential of wind and solar resources for DG applications the country has targeted 50 GW of wind and solar capacity by the year 2040. The Saudi government is expected to provide full support in the form of financial incentives for solar and wind energy projects in order to boost renewable energy development.

1. Introduction

Saudi Arabia's electric energy consumption is now about 256 TWh/y, the highest consumption of all Gulf Cooperation Council (GCC) countries. However, the fossil fuels on which the country mainly depends for energy needs are limited, and are projected to be exhausted within 100–150 years. Additionally, the carbon emission released by burning fossil fuels is responsible for releasing greenhouse gas (GHG) emissions which lead to global warming and therefore to climate change, which all raise environmental concerns. Renewable energy systems are an alternative method of reducing dependence on fossil fuels. Wind energy systems have been used since ancient times, such as the wind-driven waterwheels from the fourth century [1], which are still in use today, especially in the coastal areas [2]. Among renewable resources, solar energy systems are being used through different configurations—such as hybrid and stand-alone—to improve the energy supply of different countries [3,4], as well as the use of feed-in tariffs to reduce the adverse effect of fossil-based energy systems on the environment [5]. Distributed generation (DG) systems based on renewable resources including wind and solar are crucial in countries like the Kingdom of Saudi Arabia (KSA) which mainly depends on fossil fuels for energy needs.

With DG, many power companies can invest in small scale renew-

able energy systems (RES) such as solar photovoltaic (PV), wind, small hydro turbines, combined heat and power (CHP) or a hybrid of different renewable energy resources [6]. DG is a small-scale energy generation and is established close to the consumer's location [7]. The amount of energy generated from DG system depends on the potential of the natural and man-made energy resources available in a given area. Therefore, it is quite important to know the energy production potential of a given area for proper planning and exploitation of the available energy resources. To assess whether DG systems offer substantial benefits, it is important to investigate the previous research and implementation of DG in the region [8] as well as the previous and current work on DG applications in the Kingdom. If such information is available, energy planning teams and policy makers can easily estimate the resources necessary to boost the renewable energy sector. For example, incentive programs and tax rebate schemes can be extended to small scale DG operators to offset the high initial investment costs of RES and support their application in KSA [9]. The multitude of barriers for the implementation of such systems can also be assessed and initiatives can be suggested to overcome them [10].

Studies on the application, development and consequences of renewable energy systems are being conducted continuously, and a pool of studies have examined the advantages of RE, such as the reduction of GHG emissions primarily through simulating models

* Corresponding author.

E-mail addresses: mramli@kau.edu.sa (M.A.M. Ramli), ssennogatwaha2007@gmail.com (S. Twaha).

relating to renewable energy penetration (REP) [11]. Environmental issues are imperative considerations when dealing with energy production since they carry costs to humanity that are rarely reflected in the price that consumers pay for electricity [12]. National and international efforts exist to incorporate the cost of emissions in energy production costs. Approaches to incorporating ecological and environmental costs and the economic value of electricity system expansion in Saudi Arabia have been and are being made. For example, in [13] a projection of energy consumption and CO₂ emissions in the electricity sector of Saudi Arabia was conducted in which solar PV and carbon capture and storage are deliberated as the case study. Aldossary et al. presented an analysis and discussion that focused on household energy consumption trends in different locations in the KSA, which has large energy consumption and GHG emission rates [14]. Although measures to reduce GHG through enhancing carbon capture and storage are not available yet [15], the development of research in renewable energy development and production is intensifying in the KSA. Since the early 1970s, the country has been leading research and development (R & D) of wind and solar energy. As an example, two major international joint R & D programs were financed, in collaboration with the United States and Germany, to advance RE technology and increase its application by implementing various demonstration projects around several parts of the country. Hence, in 2001 an assessment of the work related to solar and wind energy for the previous 20 years was conducted, and its possible contribution of renewable energy appraised in 2005 [16,17].

There is also increasing interest in DG mainly due to utility restructuring and increased needs for power [18]. Energy resources can be developed as stand-alone systems or arranged to operate as hybrid systems, such as wind/PV, wind/PV/biomass, or PV/wind/diesel systems. Hybrid DG systems are preferred to bridge the difference between power generation and supply caused by uncertainty in demand [19]. Any combination of DG resources to make a hybrid system may have varying performance compared to others. Nevertheless, for comprehensive financial evaluation, it is essential to accurately characterize the energy resource in terms of wind and solar power exploitability and scheduling, with levels of excess and shortages before the practicability of alternatives can be evaluated [20]. For example, Ramli et al. carried out an economic analysis of a PV/diesel hybrid system with flywheel energy storage, focusing on the impact of utilizing a flywheel on power generation, energy cost, and net present cost for certain configurations of the hybrid system [21]. It was found that flywheel use in hybrid systems greatly reduced the cost of energy and the CO₂ emissions.

The availability of the required level of solar radiation for the target energy generation should also be assessed to plan suitable implementation. Although some research papers have reported the study and analysis of typical energy systems that can be implemented in different regions of Saudi Arabia, a comprehensive study on the potential and progress of DG systems is still necessary to access the level of R & D and policy frameworks which are necessary to boost the implementation of DG systems in the country. Therefore, this paper aims to provide an analysis of the energy production potential of wind and solar in various regions of Saudi Arabia, and to discuss the progress of DG applications in the KSA. An assessment of the contribution of DG to the energy sector of Saudi Arabia is conducted, and the barriers as well as the challenges for the implementation of DG systems in the KSA are discussed.

2. The potential of solar energy

A summary of key energy and economic information for Saudi Arabia is given in Table 1. The country faces rising energy demand. The current level of domestic consumption of fossil fuels for transportation, industry, and electricity combined is 3.4 MBOE, and is expected to increase to 8.3 MBOE by 2028. Peak power demand is expected to grow from 55 GW to 121 GW by 2032, with a gap of 61 GW between the

Table 1

Summary of key energy and economic information for Saudi Arabia: Modified from [22].

Economic output (UNDP 2013)	
GDP (2005 PPP,10 ⁹ \$) 2011	601.8
GDP per capita (PPP) (2005 PPP \$) 2011	21,430
Oil and gas (OAEPEC, 2013)	
Proved oil reserves (10 ⁹ m ³) at end of 2011	42.195
Proved natural gas reserves (10 ⁹ m ³) at end of 2011	8150
Electric energy (generation/consumption) (IEA, 2012; OAEPEC, 2013)	
Electric energy consumption (GWh)	256,331
Peak electric load (MW) (2012)	51,965
Installed electric generation capacity (MW)(2012)	62,132
Per capita electric consumption (kWh/y)(2010)	7967
Per capita CO ₂ emissions (103 kg) (2008)	16.6

output of planned projects and the expected volume of demand. It is worthwhile to reduce the rising domestic consumption of oil, such that a greater proportion of oil is reserved for more lucrative export. Luckily, Saudi Arabia has resources that can be exploited to cover this gap. It is said that the zone lying between latitudes 40°N and 40°S on the world map is known as the “sunbelt,” and Saudi Arabia lies exactly in the center of this region [22]. Therefore, solar energy can be used to address the projected energy consumption needs if appropriate efforts and technologies are applied to convert solar energy into electrical energy.

Solar PV power penetration is expected to rise rapidly in many countries in future. PV has average annual growth rate of more 50% over the past five years, and is predicted to reach 11% global penetration by 2050 [23,24]. Approaching 2030, the International Energy Agency estimates that the global cumulative installed PV capacity will reach 900 GW. In other words, in 2030 the PV power capacity will be nine times that in 2012 [25]. In Saudi Arabia and the Middle East and North Africa (MENA) countries, the regional demand for solar PV power in 2013 recorded 625% increase from the previous year [26,27]. Table 2 shows the target of Saudi Arabia energy generation from non-hydrocarbon resources, which will contribute to 50% of total energy capacity. The country targets PV expansion to achieve around 41 GW–25 GW concentrated solar power (CSP) and 16 GW PV—of solar energy capacity by 2040 [28], which is projected to support the country's plan for increasing electricity generation capacity to 120 GW [29].

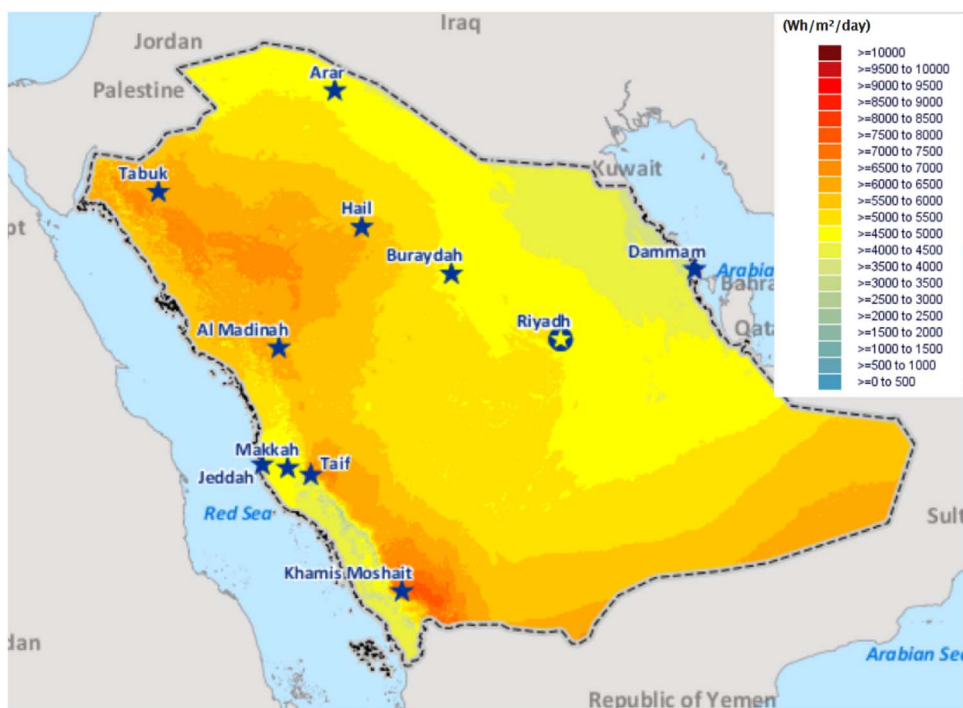
GCC countries fall into a region of between 2000 and 2500 kWh/m² a year of solar potential [30,31]. With an average annual solar radiation of about 2200 kWh/m², Saudi Arabia receives most intense range of sunlight. This level of radiation is relatively high enough to generate energy from sunlight if the required technology is applied efficiently to achieve maximum power at all times, especially if maximum power tracking systems are used [32].

Global solar radiation (GSR) totals are necessary to plan the kind of solar systems to be implemented. In Saudi Arabia, several studies on global solar radiation have been conducted for different regions

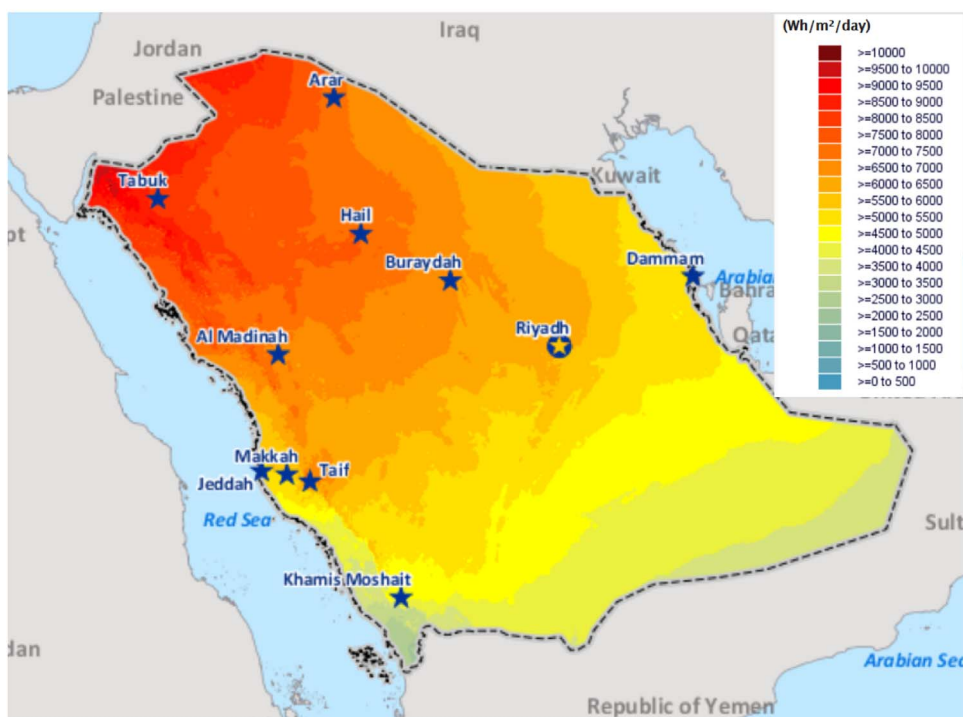
Table 2

Non-hydrocarbon power capacity target for Saudi Arabia by 2040 [28].

	Proposed capacity (GW)	Total capacity (%)
Concentrated solar power (CSP)	25	17.5
Photovoltaic	16	11.2
Wind	9	6.3
Waste-to-energy	3	2.1
Geothermal	1	0.7
Nuclear	17.6	12.2



(a)



(b)

Fig. 1. Solar radiation intensity in Wh/m² for (a) January 2015 and (b) January 2015. Source: [35].

including seeking the most suitable locations for solar energy applications [33,34]. For example, 35 solar resource monitoring stations were installed throughout the country to collect and monitor high-quality data of solar resource [35]. Global horizontal radiation is a total of diffused horizontal irradiance (DHI) and direct normal irradiance (DNI). Fig. 1 shows a comparison of direct normal irradiance (DNI) in January and July 2015. July represents summer, while January is

considered to be winter [36]. The selected range of the dataset is based on the latest data available in the Renewable Resource Atlas. Clearly, in July 2015 the northern region receives solar radiation at a higher intensity than other regions, with a range of 8.5–9.5 kWh/m²/day. In January 2015, solar radiation intensity is significantly lower throughout the country. The western and northern regions receive 6–7 kWh/m²/day, which is higher than the eastern region with 4–4.5 kWh/m²/

day. It can be observed that the solar energy potential in the country is enough to enable even large capacity solar energy systems. This energy potential can be utilized to supplement fuel-based power generation. Alternatively, the prediction of solar radiation using a support vector machine and artificial neural networks was accomplished in the case study locations of Jeddah and Qassim [37]. Results indicate that machine learning methods can accurately predict solar radiation on tilted surfaces.

The KSA initiated a major effort to tap into solar energy with the objective of preserving its vital oil commodity for export. By 2011 the KSA was producing more than 50% of power from oil, using up to an eight of total oil harvest of the KSA. With the cost of oil at \$10 per barrel, the loss of oil to electricity generation was not felt particularly; however, oil cost rises towards \$100 per barrel made it more reasonable and attractive for the Kingdom to invest in renewable resources to generate clean energy, and export the saved oil to the world market to generate more income. This is possible given the fact that the KSA is one of the leading net exporters of crude oil. In addition, it has been projected that electricity consumption in Saudi Arabia will double by the year 2020 [38]. Therefore, concerted efforts should be undertaken to boost electrical energy production.

In Saudi Arabia, CO₂ emissions are high since electricity is mainly generated by using fossil fuels. Fig. 2 shows that in 1990, CO₂ emissions were 208 million metric tons, an increase of about 17.5% from 1980. In 2000, CO₂ was 290.5 million metric tons, a 39.5% increase compared to 1990, and in 2010, CO₂ was 468.7 million metric tons, a 61.3% increase from 2000. This analysis indicates that the amount of CO₂ has been significantly increasing over the past decade due to the rapid industrialization and development [39]. The use of renewable energy generation system is one of the ways to reduce CO₂ emissions.

Several studies on the modeling and simulation of wind, solar, and hybrid wind/solar systems have also been conducted for Saudi Arabia. Ahmad et al. demonstrated a misting system powered by solar energy in which the system is used to cool down an open area in Madinah, Saudi Arabia [41]. The best PV array configuration, suitable to supply a DC helical pump with the optimal amount of energy under the outdoor conditions of Madinah places was determined [42]. PV water pumping systems act as a suitable alternative to drain water in the isolated desert areas for household and livestock consumption. A desalination system based on reverse osmosis which is fed with energy from a hybrid wind/solar is simulated and analyzed in [43]. The results of the simulation are used to improve the system for the least cost per cubic meter of desalinated water and the analysis indicates that the best system that powers a 1-kW RO system for 12 h/day yields a minimum leveled cost of energy (LCOE) found to be 0.624 \$/kWh. An attempt is made to use wind power for pumping water in areas located far away from the national grid. Micro-turbines in the range of 1–10 kW power capacity are selected with Gould 45 J type water pumps to generate wind energy and pump water in the Rawdat Ben Habbas, Arar, and Juaymah areas in the KSA [44].

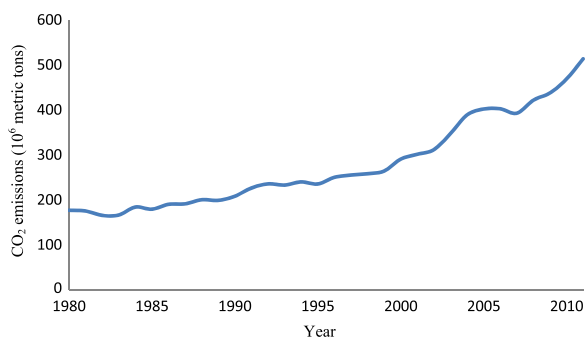


Fig. 2. CO₂ emissions of Saudi Arabia [40].

Several studies have been conducted in past years on solar energy for Saudi Arabia in the technical literature. An early study [45] discusses a hybrid PV/diesel/battery system for a remote village in the north-eastern region of the country. The study concluded that the hybrid system is more cost-effective compared to a stand-alone diesel system. The tendency was to substitute diesel with solar. Later, another suggestion for utilizing a PV/diesel/battery hybrid system is also offered for different provinces in Saudi Arabia. It is found that the penetration of PV is higher in northern and southern provinces for a given hybrid system [46]. Another comparative study of a PV system and hybrid PV/wind and hybrid PV/wind/fuel cell was conducted in Yanbu [47]. A PV system alone was found to be more economical than both hybrid systems. A particular case-study of a PV/Hydrogen fuel cell hybrid system for a typical house in the country was conducted to estimate its return on investment (ROI) [48]. Alrashed and Asif [49] recently conducted a research survey on the application of solar and wind energy in Saudi Arabia. The research results show that the residents chose PV technology as their preference.

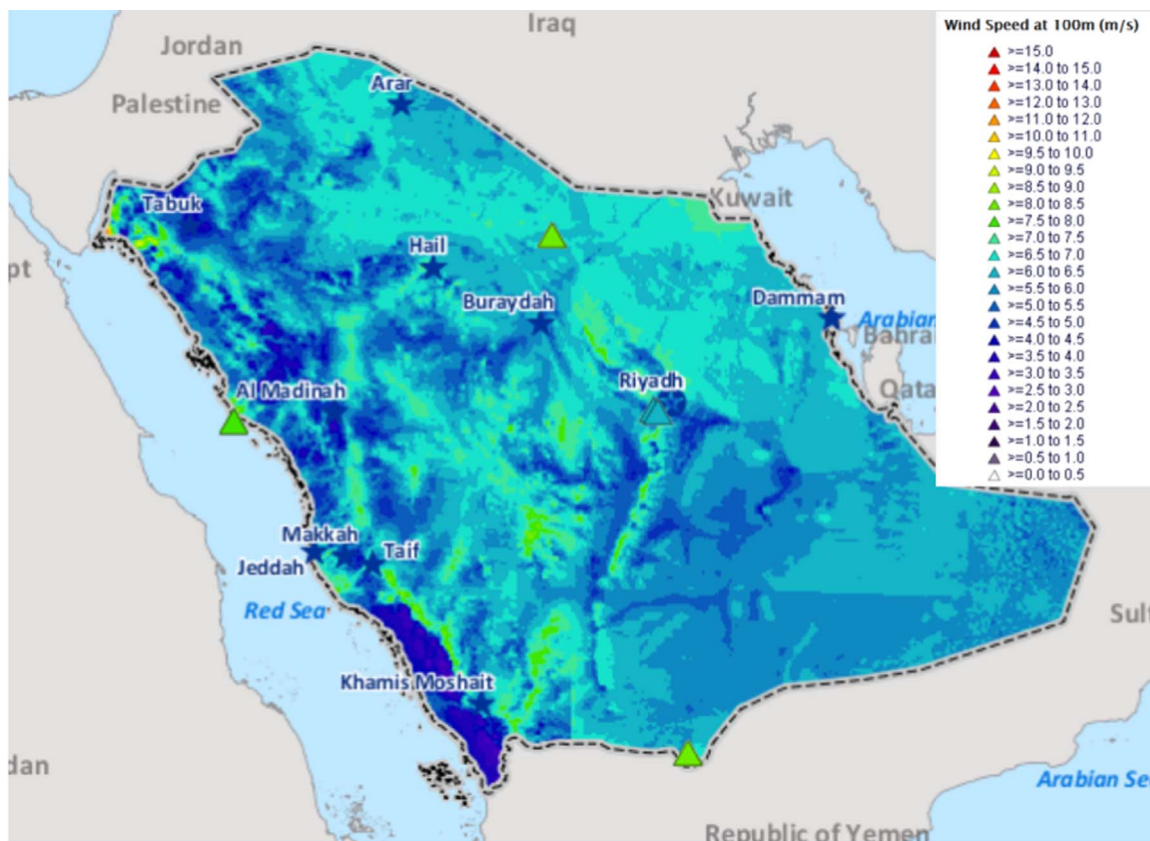
3. The potential of wind energy

Saudi Arabia is seriously considering exploring wind energy resources to generate power for its future energy supply. This option is in line with the important strategy to diversify energy resources and balance the energy mix of conventional and alternative energy resources [50]. As shown in Table 1, the country has targeted 9 GW of wind power generation by 2040, which will contribute to 6.3% of the total power capacity.

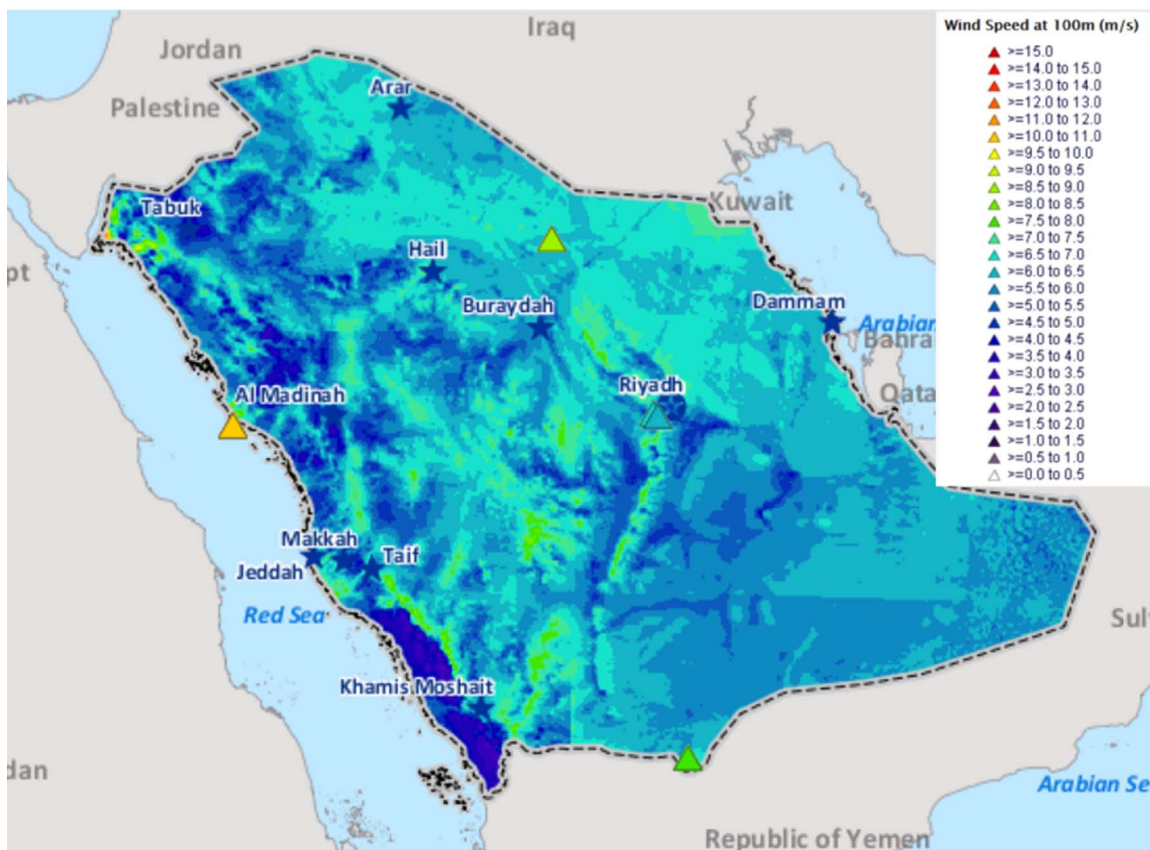
The development of wind power systems requires accurate and high-quality wind speed data for a successful feasibility study in the context of wind energy exploration projects. Fig. 3 shows the wind map for Saudi Arabia for February and August 2015. The five wind monitoring stations established by KACARE are Riyadh City site A, Riyadh City site B, Hafar Al Batin, Sharurah and Yanbu, each indicated with a Δ (delta) symbol. As seen in the map of February 2015, the average wind speed of the east coast Hafar Al Batin region was 7.5–8 m/s, slightly higher than for other regions, where wind speed ranged from 7 to 7.5 m/s in Yanbu on the west coast and Sharurah on the south coast, and 5.5–6 m/s in Riyadh on the central region. In August 2015 the average wind speed was higher in Yanbu and Riyadh but slightly lower in Sharurah. Yanbu on the western coast, had a wind speed in the range of 9.5–10 m/s, while Sharurah on the south coast recorded 6.5–7 m/s. The wind speed in Hafar Al Batin ranged from 7.5 to 8 m/s, while Riyadh was 5.5–6.5 m/s, the same as the wind speed in February 2015.

It can be observed that the wind energy potential in the country is enough to enable even large capacity wind energy systems. This energy potential can be utilized to supplement fuel-based power generation. The monthly wind speed at 60-m elevation for all wind monitoring stations between October 2013 and December 2015 is given in Fig. 4 [35]. This dataset is collected from five wind monitoring stations—established since October 2013—throughout the country.

It can be observed from Fig. 4 that wind speeds at Yanbu were the highest of all the five stations, with a maximum of 10.3 m/s taking recorded in September 2014, and the minimum of 6.4 m/s in December 2014. Hafar Al Batin recorded the next highest speeds however, they was far lower than those of Yanbu. Riyadh city stations exhibited the lowest wind speeds. From these observations it is clear that the wind speeds of stations vary significantly from month to month with those at Yanbu recording more variations than others. This implies that wind turbines used in this region should be able to operate with the minimum speeds of this station as the cut-in speed, and should continue to operate within other recorded wind speeds, which are below a turbine's cut-out speed. This turbine limitation match with wind speeds indicates they should be able to harvest a maximum of wind power for use.



(a)



(b)

Fig. 3. Average wind speed in m/s for (a) October 2014 and (b) February 2015. Source: [35].

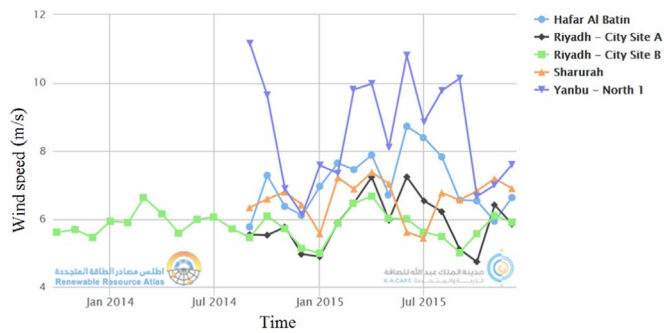


Fig. 4. Monthly average wind speed in October 2013–December 2015. Source: [35].

In an earlier work, an atlas of wind energy formed part of the earliest renewable energy development steps for Saudi Arabia. The atlas was initially formed with data collected from 20 weather stations. The atlas indicated speed profiles and wind power, and analyzed diurnal deviations of mean speeds. The frequency distribution of wind directions was also shown, and the speeds represented by contours. A number of works related to wind energy were based on the development of this atlas [51].

Table 3 shows the data composed of the coordinates, elevation, and the corresponding period of time wind data has been recorded for each location. Wind speeds were measured at a height of 10 m. The locations in Table 3 were strategically chosen. For example, Jeddah was chosen because measuring equipment was based there. Yanbu, Alwajh and Jizan were selected because as these are coastal areas, they were expected to have higher wind speed than other sites, and hence more wind power could be harvested. Makkah was selected because of its power requirements; it is a home to social and religious activities because it houses the Kaaba which receives many visitors and tourists throughout the year.

The King Abdullah City for Science and Technology (KACST) considered wind research in some locations, including some of those described above, in order to study their wind power potential. The data for some other selected sites is given in Table 4.

The wind speed data was taken at heights of 20 m, 30 m, and 40 m, while wind direction data was collected at 30 m and 40 m. The wind data was recorded hourly, daily, and monthly with average speeds calculated every 10 min at the Riyadh site, while a 30-min interval was used for the other stations. A standard deviation (STD) was computed and given in Table 5 with wind speeds 1, 2, and 3 representing those speeds at heights of 20 m, 30 m, and 40 m, respectively. Arar station is observed as the highest average speed at 4.40 m/s, while Qassim corresponds to the lowest speed of 3.4 m/s. The wind data discloses that if the height in Riyadh was increased by 10 m, there would be a corresponding increase in speed of 3–13% in daytime and 7–20% at night.

The wind direction is also indicated in Table 5, showing none of the stations experienced similar wind directions. The wind direction in Dhahran, Riyadh, and Arar flowed generally from the north—from the northeast and northwest—more than 40% of the time.

The wind speed frequency distribution indicates that for more than

Table 3
Coordinates, heights, and period of recording data for each location [51].

Location	Longitude (degrees)	Latitude (degrees)	Altitude (m)	Period of record (years)
Alwajh	36	26	19	16
Yanbu	37	24	6	12
Makkah	39	21	310	7
Jizan	42	16	5	14
Jeddah	40	21	17	16

Table 4
Geographical data for the selected locations [52].

Site	Latitude (degrees)	longitude (degrees)	Elevation (m)
Arar	30.8	41.3	550.0
Dhahran	26.1	50.1	3.0
Qassim	26.3	43.97	648.0
Riyadh	24.6	42.6	620.0
Dhulum	22.7	42.2	1117.0

80% of the time, speed ranged from 3 to 6 m/s for all locations and altitudes. On the other hand, a 4 m/s wind speed occurs 30% of the time. Unfortunately, a speed greater than 7 m/s was recorded in Arar in more than 15% of recorded intervals at 20 m, 24% at 30 m, and 25% at 40 m. Other sites show such speeds only 10% of all recorded period.

Table 6 shows the coordinates of the sites under consideration and the period for which the wind data was collected. As seen in Table 6, similar sites were studied as discussed in Table 3 above, however, Riyadh was not selected [53]. As seen from the table, different stations have different recording elevations. This is due to the geographical nature of the area under study. For example, wind speed at Dhulum was recorded at an elevation of 1117 m because it is located far below the sea level, while Dhahran station was set at 3 m because it is near sea level. The most important issue is to target the level at which a considerable amount of wind can be obtained for maximum harvest of wind power.

The maximum and mean values of wind speed at 40 m height during the collection periods at half-hour intervals are detailed in Table 7. It can be observed that the highest annual average speed occurs at Dhulum with 5.7 m/s which occurred more than 10 months a year followed by Arar with a speed of 5.4 m/s occurring more than 5 months. Since these two regions are remote with smaller populations, the wind speed suggests it is feasible to consider the establishment of a wind harvesting to provide wind power to households. The average speed recorded at Qassim was 4.3 m/s, while that at Yanbu was 4.7 m/s, both slightly lower than those of Arar and Dhulum. At Dhahran, the annual wind speed was 5.3 m/s, which is also suitable for wind power generation given a wind system with a hub cut-in speed of 5 m/s. The mean power density for Dhahran was found to be 154 W/m², Arar (164), Yanbu (134), Dhulum (186), and Qassim (81), which are proportional to the wind speeds discussed. Such power densities can be found to contribute a considerable amount of power to the renewable mix of the country.

The speed study helps to establish the cut-in and cut-out, survival and rated speeds for a wind power system to be used in a specified site. The energy in kWh obtained from a wind energy system is computed based on the wind duration expressed in terms of hours. Al-Hadrami evaluated the energy output and plant capacity factor (PCF) of small wind turbines in the ranges of 1–3 kW, 5–10 kW, 15–20 kW and 50–80 kW. He further studied the implication of varying hub heights on energy output and the PCF, and concluded that the horizontal axis wind turbines Fortis Passat with a PCF of 44.4% at 15 m hub height, the Aeolos-H 5 kW with a PCF of 20% at 20 m hub height, and the CF6e with a PCF of 32.5% at 20 m hub height were recommended for different load requirements [54]. Therefore, if necessary the power output can be modified by changing the hub height and PCF.

Wind was available for 85% of recorded times. The details of the civil construction specification, including the cost of concreting foundations and control room for the wind machines, are detailed in [55]. The present value cost (PVC) is about US\$0.97 million, \$1.32 million, \$1.97 million for the 600 kW, 1300 kW, and 2500 kW machines, respectively. It was found that the maximum energy was obtained at Yanbu corresponding to 4942 MWh for a 2500 kW wind machine, 263 MWh for 1300 kW, and 1295 MWh for a 600 kW machine. The minimum value of 1640 MWh was obtained at Nejran from a 2500 kW

Table 5
Wind data for different heights.

Location	Wind speed1 (m/s)	STD 1	Power density1 w/ m ²	Wind speed2 (m/s)	STD 2	Power density2 w/ m ²	Wind speed3 (m/s)	STD 3	Power density3 w/ m ²	Direction of wind
Arar	4.4	1.5	29.6	4.8	1.6	38.6	5.3	1.8	52.5	NW
Dhahran	4.0	1.2	22.2	4.3	1.3	27.0	4.5	1.4	30.4	E
Qassim	3.4	1.2	13.8	3.8	1.3	19.0	4.0	1.3	22.4	ESE
Riyadh	3.9	1.4	20.0	4.2	1.4	25.5	4.5	1.5	30.6	NW

Table 6
Sites location, height and period of data collection.

Station	Qassim	Arar	Yanbu	Dhahran	Dhulum
Longitude (deg E)	43.97	41.3	38.3	50.1	42.18
Latitude (deg N)	26.3	30.8	23.9	26.1	22.74
Elevation (m)	648	550	11	3	1117
Data collection period	Dec 5, 1995-Oct 24, 1998	Jun 6, 1995-Dec 31, 1998	Sep 17, 1996-Oct 21, 1999	Oct 4, 1995-Nov 30, 2000	Nov 1, 1998-Oct 12, 2002

machine, while 940 MWh and 469 MWh obtained from the other machines.

At coastal areas such as Dhahran, Al-Wajh, Yanbu, Jeddah, and Jizan, the wind was present above the necessary speed in excess of 50% of recorded intervals. On the other hand, at some inland locations such as Riyadh, Medina, Badana, Rafha, Qaisumah, Turaif, and Taif the required wind speed was present approximately 45% of the time. Moreover, at Taif, Al-Jouf, Qassim, Nejran, Hail, and Bisha the required wind was available only 35 ± 2% of periods per year. This further confirms that coastal areas are the priority candidates for wind power generation in this region. This can be additionally proved by the low cost of energy observed at these locations where by the minimum cost of electricity generated using 2500 kW, 1300 kW, and 600 kW machines at the coastal area of Yanbu was found to be 0.0234, 0.0295, and 0.0438 US\$/kWh respectively, while the corresponding maximum at the inland Nejran was 0.0706, 0.0829, and 0.121 US\$/kWh.

4. Development of DG applications in Saudi Arabia

As mentioned earlier, Saudi Arabia targets generation of 50 GW from solar and wind energy installations, a total largely dominated by

Table 7
Speed of the wind and power density for the five stations (Half-hour data).

Site			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Dhulum	Wind speed (m/s)	Max	17.4	22.7	23.9	19.6	20	15.1	23.7	17.2	16.6	16.5	16.4	17.3	23.7
		Min	6.1	6.6	6.7	5.9	5.7	5.8	6.5	5.8	5	5	5.7	5.8	5.7
	Power density (W/m ²)		197	249	278	197	176	165	226	166	114	109	175	178	186
Arar	Wind speed (m/s)	Max	16.4	15.2	19.2	18.6	20.7	14.6	15	12.5	18.2	16.5	16.2	20.1	20.7
		Min	5.2	5.1	6.1	5.7	5.4	5.8	6.3	5.3	5	5.1	4.5	4.9	5.4
	Power density (W/m ²)		142	159	241	200	182	181	211	148	129	143	107	125	164
Yanbu	Wind speed (m/s)	Max	14.4	15.4	15.2	15.1	14.2	14.7	14.4	15.1	14.4	12.8	17.2	14.3	17.2
		Min	4.7	4.9	5.3	5.1	4.9	4.7	4.7	4.9	4.8	4.6	4.3	4	4.7
	Power density (W/m ²)		122	149	184	178	142	137	142	152	130	96	95	76	134
Qassim	Wind speed	Max	12.9	13.5	15.3	17.5	22.7	11.5	12.3	11.1	10.9	11.4	11.5	12.3	22.7
		Min	4.3	4.8	4.9	4.9	4.3	4.3	4.3	4	3.9	4.1	3.9	4.1	4.3
	Power density (W/m ²)		78	104	125	125	91	72	73	57	55	66	63	68	81
Dhahran	Wind speed (m/s)	Max	15.8	15.8	16.2	19.2	19.3	16.1	18.5	15	16.5	13.1	16.2	13.2	19.3
		Min	5.2	5.7	5.8	5.9	5.2	5.7	5.7	5.1	4.8	4.7	5	4.9	5.3
	Power density (W/m ²)		145	179	197	207	151	200	188	137	114	95	123	112	154

solar, by the end of 2040. Of the 9 GW of wind power expected to be procured, just less than 2 GW is due to be tendered over this year (2016). Some 100–150 MW is expected to be contracted during the introductory round. Following this, 650 MW of wind power generation is expected to be tendered in the first round and 1.05 GW in the second round. The first and second rounds are planned and were launched between 2013 and 2016. A 20-year power purchase agreement with the state-owned Sustainable Energy Procurement Company has been completed to underpin each wind project [56]. To ensure these targets, initial procurements are set to be more than the projected periodic targets to allow for uncertainties. The key features of the proposed competitive procurement process (CPP) can be found in [57].

In the plan of proposed energy mix by 2040, wind energy is to be dedicated to powering desalination plants [58]. Over the past decade, the use of solar and wind energy for desalination plants has been dramatically growing. Several research works have been based on the application of wind and solar energy to water desalination in Saudi Arabia. For example, Mokheimer et al. [59] presented modeling and simulation of a wind/solar hybrid system for a reverse osmosis desalination system. The analysis of the system performance under Dhahran weather conditions was undertaken, and concluded that the proposed system has a minimum cost lower than that in the literature. In another work, analytical modeling and simulation was presented for a photovoltaic reverse osmosis (RO) water desalination system with experimental verification. The effect of PV panel slope and azimuth angle was investigated using PV and RO models [60]. A brief summary of literature review is presented by Hepbasli and Alsuhaibani [61] for solar energy development status in Saudi Arabia. Part of their review discusses the use of solar energy in water desalination plants, while the fuel subsidies for electricity generation are found to be the major barrier to solar energy deployment.

As wind energy is still under procurement process, one may notice there has been a multitude of research studies on the feasibility of wind energy throughout the KSA in the past few years. An early study (2007)

describes a quantitative assessment of wind resource based on hourly mean wind speed data in Dhahran on the eastern coast of Saudi Arabia [62]. The case study concluded that although wind power is viable for the city, large wind power systems are needed to meet the peak load in August–October, and that diesel generators and batteries should be integrated to overcome this requirement. Later, other studies were conducted for other parts of the country, including Dhulum in the western region [63], Al-Wajh, Jeddah, Yanbu, Jizan in coastal locations [64], the western province [65], and the three locations of Rawdat Bin Habbas (inland north), Juaymah (east coast), and Dhulum [66]. There has also been an assessment of wind resource and characteristics for Jubail industrial city, the Middle East's largest industrial base [67]. As a conclusion, those studies reveal that the western region has more potential for wind energy than other regions. These results are in agreement with the potential of wind energy described in the previous section.

In the first stage of implementation to achieve the projected targets Saudi Arabia, through the King Abdullah City for Atomic and Renewable Energy (KACARE) is targeting power generation of 500–800 MW from renewable energy resources. The planning is done in such a way that five to seven small projects of different technologies are presented to bidders at places which could easily be integrated to the grid network. The other two rounds are to target 2–3 GW and 3–4 GW respectively. It is anticipated that a sole round would last for about 6–10 months. Table 8 shows the renewable energy targets and current installed capacity in Saudi Arabia [68].

The King Abdullah University of Science and Technology (KAUST) Industry Collaboration Program (KICP) conducted a feasibility study on the future development of solar energy systems and components within the kingdom [69]. The KICP's annual strategic study's findings are divided into short, medium, and long-term potential depending on what can be achieved in that period.

The short-term is defined as two years, in which the employment of two or three PV industrial projects is expected to cost \$200–500 million in capital expenditure each, with the additional outcome of the creation of 1000 jobs. The ingots/wafers, silicon, and perhaps thin-film solar cells required for solar systems are the three major options

Table 8
Renewable energy targets and current installed capacity.

Electricity				
Sector	Technology	Value	Description	Year
Electricity	Solar PV	16 GW	Targeted total installed solar PV capacity	2040
Electricity	Solar PV	25 MW	Targeted total installed CSP capacity	2040
Electricity	Solar PV	6 GW	Targeted total installed solar PV capacity	2020
Electricity	Solar PV	1 GW	Targeted additional installed solar PV capacity	2013
Electricity	Solar PV	10,000 Units	Targeted additional installed solar PV panels	2013
Heating/cooling				
Heating/Cooling Solar	Heating/cooling	25 GW	Targeted total installed solar thermal capacity	2040
Not specified				
Electricity	Non-Technology specific	54 GW	Targeted total installed renewable capacity	2040
Primary energy				
Non-Sector specific	Non-Technology specific	23–30%	Targeted share of renewables in total primary energy supply	2040
Installed Capacity				
Electricity	Solar PV	12 MW	Total installed solar PV capacity	2013
Electricity	Solar PV	2 MWp	Total installed solar PV capacity	2010

anticipated to be produced in this period, according to the report's recommendations. Another CSP production project (> 50 MW) was expected in this period on condition that at least one solar power plant would be built in the country.

In the medium-term plan, it was observed that within at least five years from 2009, advancement of PV technology in KSA could be realized should the market be improved concurrently with PV development in the region. It was also anticipated that one fuel cell and PV module manufacturing project could be realized. Moreover, the study endorsed the development of a pure industrial solar cluster, including two to three prominent R & D institutes, two to three industrial parks, and numerous manufacturers and installation companies were realistically expected.

In the long-term potential, the study highlighted that more than five years from 2009, solar energy could have the capability to become a major industrial sectors providing roughly 50,000 jobs, sales worth US \$10 billion, and at least 50% of the KSA's export revenues. In that way, the solar industry could serve as a foundation for downstream industrial development in the KSA.

The report also recommended the Kingdom entice solar companies in the research field by creating attractive research environments such as that formed at KAUST. This could also involve extending financial facilities to state-of-the-art solar companies. The study also recommended the formation of a center for accreditation of solar-related products to enable updating these products for the international market, and to foster production of solar products on a commercial scale. The most applicable solar technologies and research areas for the KSA are identified in Fig. 5. The selection is based on the market potential and synergies for the Kingdom.

In the selection process, five solar technologies succeeded: crystalline silicon PV, CIGS thin-film PV, concentrated PV (HCPV), third generation PV, and solar thermal heat and solar thermal power (CSP). The study in [70] details the reason why they were recommended.

In an implementation driven through a recommendation in the report, some pilot solar PV parking lot projects have been established such as those discussed in the progress section. In addition, the Kingdom has increased the funding of research for higher institutions of learning such as universities and colleges through the establishment of the National Science, Technology and Innovation Plan (NSTIP), a body that invites and funds successful research proposals from researchers. To date, neither the above short-term nor the medium-term recommendations for industrial establishment have been implemented. We are yet to see what happens to the long-term recommendation in terms of execution.

Since the mid-seventies, Saudi Arabia has been conducting research and development for RES production, and more specifically in solar energy. The main pertinent accomplishments included the use of a PV system to provide electricity to run highway devices, and presenting and ordering the use of water heating systems powered by solar for household heating. As a result, about 1100 solar flat plate solar collectors were fitted on the rooftops of 380 homes in the campus of KACST in Riyadh during 1996 [71]. The other major implementations are discussed in the following subsections.

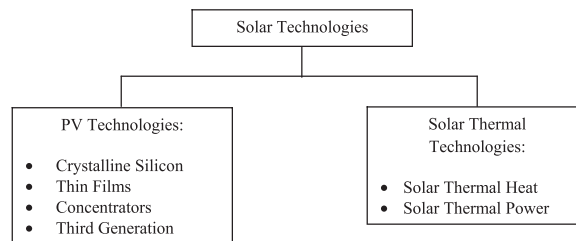


Fig. 5. Solar technologies for research and development in KSA [69].

4.1. Solar power station at Farasan Island

The first solar power project was inaugurated in October 2011 [72]. The solar plant is located in the neighborhood of Jizan, a town on the south eastern coast of the Red Sea. The plant comprises 6000 solar cells and is integrated to the power grid of the Jizan wing. It was built by Showa Shell Sekiyu (SSS), an energy company from Japan in close partnership with Saudi Electricity Company (SEC), a government utility company. The project is owned partially by SSS Company and by Saudi Aramco, a Saudi oil company. Being a remote location with limited access to the grid, the island was selected as the best alternative for solar power installation to provide electricity to the area. Therefore, it was chosen to reduce the oil consumption required to generate the distributed power for this region. According to the memorandum of understanding, SSS Company is to remain a partner of this project for 15 years, beyond which the ownership is to be shifted to SEC.

4.2. The 10 MW PV carpark system

A solar PV carpark system was constructed by Saudi Aramco at their offices in Dhahran. It consists of 10 MW capacity spanning spaces on the top of 4500 parking shades [73]. This solar power project is intended to provide the energy demand of Al-Midra Tower at Dhahran owned by Aramco. SSS company supplied the 120,000 PV panels which were used to accomplish the project [74]. This project was covered by a \$100 billion fund set aside by the kingdom in early 2011 to decrease oil-based power generation based on oil. This plant is believed to be the world's biggest solar facility on a parking lot.

4.3. The 2 MW PV plant at KAUST

The solar power plant was setup on the rooftop of KAUST by a German PV company, Conergy [75]. The farm was completed in 2010. The company built the power plant in collaboration with the kingdom's solar system integrator Saudi Arabian National Solar Systems (NSS). NSS provided the installation and operational management of the power plant, while Conergy was in charge of the design and components supply in addition to the development, planning, supervision, and commissioning of the power plant. The solar farm is formed by two portions of 1 MW solar PV installations each and comprises 9300 Conergy solar modules as well as Conergy 280 K central inverters. The power plant covers an acreage of 11,577 m² (124,600 square feet) and was expected to produce about 3332 MWh annually.

4.4. The 3.5 MW PV park in Riyadh

The Phoenix Solar Company planned and built the 3.5 MW PV project in January 2013 [76]. Solar PVs were installed on racks in an open space, and the project took 20 months to complete. Suntech Power Holdings provided the 12,684 PV modules, while SMA Solar Technology AG delivered the inverters. The division of tasks among different companies facilitated the speed of implementation of this project and the diversification of technology. The produced energy is fed straight into the grid which is at medium voltage at the station. However, the solar installation firm faced several challenges due to lack of data on solar projects in desert areas, as there are very few countries in the Gulf region that have implemented similar projects before, or with proper data records. As a solution to some of these challenges, the company established a distinct solution to accommodate the high temperatures and sand storms, whereby the PV system control boxes were enclosed in a well-insulated, air-conditioned inverter building. This method substantially enhanced the conditions of the power plant for easy maintenance, and ensured the long life of the PV system components.

4.5. Princess Noura University solar thermal plant

This plant uses 36,305 m² of solar arrays with a capacity of 25.4 MWth. It has been operating since 2012 and supplies 900,000 l of hot water for about 40,000 students in the campus area. The plant is the largest solar thermal plant in the world [22].

5. Challenges and policy framework

5.1. Challenges facing the exploitation of solar and wind energy in Saudi Arabia

The major challenges include the following:

- Although constant sunshine is good, solar panels become less efficient if they become too hot. The development of solar PV power systems may have challenges when implemented under extreme weather conditions such as at high temperatures. Therefore, in a large scale PV deployment in the region, comprehensive studies must be undertaken to ensure that suitable PV panels which can suit these temperatures are applied.
- Dust is a problem which results in partial shading, affecting power output and the overall performance of a PV system [77]. It is therefore important to track the maximum power point (MPPT) in all circumstances by automatically adjusting the control algorithms of the power electronic devices to achieve the maximum power output during time of variations of light level, shading, temperature, and PV characteristics [78]. This means considerable manpower may be necessary to continuously brush and clean solar panels, which may increase the operating cost of PV systems, especially if large PV farms are established [37]. However, several studies have been conducted on MPPT under partial shading condition [79–81], which suggest the use of soft computing techniques to track the MPPT efficiently. The main challenge may be increases in cost of PV systems with an embedded MPPT algorithm, which might limit the investment as well reducing the ROI of the PV system. This decrease in ROI may deter potential investors in Saudi Arabia.
- Natural gas has also been identified to pose a challenge as an alternative to solar energy to provide energy in KSA, which is similar to the U.S. where cheap natural gas is making it challenging for renewables to compete [77].
- There is also a problem of lack of data related to solar energy development within the Gulf region, as there are very few earlier solar projects completed and documented in these areas.
- Market technology: Konstantinos et al. observed that there is a challenge resulting from firm dispatch in grid operations [82]. Wind and solar power cannot easily be integrated and dispatched within the grid of a utility company because of the intermittent nature of their supply, and therefore this may require special dispatch measures.
- RE penetration is hindered by sub-optimal pricing for power, subsidies and delayed restructuring of power sectors, and delays in policymaking related to renewable energy applications. Streamlining RE tariffs is believed to promote energy conservation activities, and at the same time favor DG systems. Alternatively, in addition to restructuring the power sector, an RE policy is an important requirement to transform end user choice into a larger market share for RE technologies [83].

5.2. Policy frameworks

Nevertheless, policy frameworks have a significant role to play in the determination of hybrid DG systems. Therefore, to fully function, DG systems investors should be supported by national policies. A long-term vision of science and technology has been developed in the KSA through various initiatives [84]. The policy framework supports any

technologies leading to fuel economy, improved efficiency, reduced impact on the environment, and research for sustainable development. Some technology areas in this plan are GHG avoidance, renewable energy generation, and assessment and monitoring technologies. Hybrid DG systems operators can, therefore, easily obtain funding from funding agencies through government support, together with their collateral securities. The government is also expected to provide full support in the form of financial incentives for solar and wind energy projects in order to boost renewable energy development.

It is also necessary to embrace the feed-in-tariff (FIT) policy as suggested in [85]. Saudi Arabia has always been at the forefront of promoting research and development of RES, leading other countries in the GCC, and more generally in the Middle East. Therefore, the application of FIT is likely speed up RE development as it will attract more investment due to increased investment security and incentives that come with its implementation.

Some analysts suggest that the FIT may not be effective in countries such as Saudi Arabia because of the more centralized nature of the country's utilities, and the lack of tax systems. It is suggested that a possible alternative approach is the Renewable Portfolio Standard, which dictates that a portion of energy supply mix should come from specific technologies, such as solar and wind, or from renewables [86]. Such a policy may enforce the investment in renewable energy, especially it is backed by other government fiscal and financial policies.

There is a need to restructure the power utility of the country to introduce competition in the energy market to guarantee a higher quality of service and lower tariffs. This is because the limited extent of private competition for power generation reduces RE development [87]. In order to increase RE investments, a level playing field should be created by policy-makers between independent state-owned enterprises and power producers, as well as other network operators. However, this is likely to take considerable time to materialize given the nature of the current vertically-integrated power system in the country. This issue also applies to other Gulf countries such as Qatar and the United Arab Emirates, and therefore similar approaches can be applied.

To promote renewable energy further, as well to create unpolluted atmosphere within the country, fines should be introduced for conventional energy-generating companies which produce emissions greater than a specified cap. AlMasoud et al. observed that although environmental protection standards in Saudi Arabia stipulate the average concentration of particulate matter (PM) must not exceed 80 $\mu\text{g}/\text{m}^3$ per year at any site, in reality PM concentrations are 113 $\mu\text{g}/\text{m}^3$ in Saudi Arabia as reported [88]. Such policies should be enforced purposely to promote renewable energy systems and enforce environmental protection policies.

6. Conclusion

Development of wind and solar energy resources which do not threaten the environment because they have little or zero carbon emission is crucial. Saudi Arabia has long been depending mainly on power generated from fossil fuels. This paper has collectively discussed the potential of wind and solar energy-based DG in Saudi Arabia, which aims to maximize the utilization of the available sources. The analysis in this paper has pointed out that the country possesses enough potential in wind and solar energy resources to produce sustainable energy and save non-renewable resources, which are likely to diminish in the near future. The analysis further revealed that the Kingdom has been at the forefront of promoting renewable energy since early 1970s and several initiatives are underway to exploit available potential. Therefore, efforts to implement development programs should be intensified to achieve the target of 50 GW of solar and wind capacity by the year 2040. Some suitable policy frameworks to increase investment in renewable energy have also been suggested.

References

- [1] Yannopoulos SI, Lyberatos G, Theodossiou N, Li W, Valipour M, Tamburrino A, Angelakis AN. Evolution of water lifting devices (Pumps) over the centuries worldwide. *Water* 2015;7(9):5031–60.
- [2] Ramli MAM, Hiendro A, Al-Turki YA. Techno-economic energy analysis of wind/solar hybrid system: case study for western coastal area of Saudi Arabia. *Renew Energy* 2016;91:374–85.
- [3] Twaha S, Idris MH, Anwari M, Khairuddin A. Applying grid-connected photovoltaic system as alternative source of electricity to supplement hydro power instead of using diesel in Uganda. *Energy* 2012;37(1):185–94.
- [4] Twaha S, Ramli MAM, Murphy PM, Mukhtiar MU, Nsamba HK. Renewable based distributed generation in Uganda: resource potential and status of exploitation. *Renew Sustain Energy Rev* 2016;57:786–98.
- [5] Ramli MAM, Twaha S. Analysis of renewable energy feed-in tariffs in selected regions of the globe: lessons for Saudi Arabia. *Renew Sustain Energy Rev* 2015;45:649–61.
- [6] Aman MM, Jasmon GB, Mokhlis H, Bakar AHA. Optimal placement and sizing of a DG based on a new power stability index and line losses. *Int J Electr Power Energy Syst* 2012;43(1):1296–304.
- [7] Mirazimi SJ, Nematollahi M, Ashourian MH, Mirahmadi S. Reconfiguration and DG placement considering critical system condition. In: *Proceedings of the International Power Engineering and Optimization Conference*, 2013: 676–79.
- [8] Montoya FG, Montoya MG, Gómez J, Manzano-Aguilario F, Alameda-Hernández E. The research on energy in Spain: a scientometric approach. *Renew Sustain Energy Rev* 2014;29:173–83.
- [9] Amor MB, Pineau PO, Gaudreault C, Samson R. Assessing the economic value of renewable distributed generation in the Northeastern American market. *Renew Sustain Energy Rev* 2012;16(8):5687–95.
- [10] Pablo-Romero MP, Sánchez-Braza A, Pérez M. Incentives to promote solar thermal energy in Spain. *Renew Sustain Energy Rev* 2013;22:198–208.
- [11] El Fadel M, Rachid G, El-Samra R, Boutros GB, Hashisho J. Emissions reduction and economic implications of renewable energy market penetration of power generation for residential consumption in the MENA region. *Energy Policy* 2013;52:618–27.
- [12] Alnathier OA. Environmental benefits of energy efficiency and renewable energy in Saudi Arabia's electric sector. *Energy Policy* 2006;34(1):2–10.
- [13] Mansouri NY, Crookes RJ, Korakianitis T. A projection of energy consumption and carbon dioxide emissions in the electricity sector for Saudi Arabia: the case for carbon capture and storage and solar photovoltaics. *Energy Policy* 2013;63:681–95.
- [14] Aldossary NA, Rezgui Y, Kwan A. Domestic energy consumption patterns in a hot and humid climate: a multiple-case study analysis. *Appl Energy* 2014;114:353–65.
- [15] Rahman SM, Khondaker AN. Mitigation measures to reduce greenhouse gas emissions and enhance carbon capture and storage in Saudi Arabia. *Renew Sustain Energy Rev* 2012;16(5):2446–60.
- [16] Alawaji SH. Evaluation of solar energy research and its applications in Saudi Arabia – 20 years of experience. *Renew Sustain Energy Rev* 2001;5:59–77.
- [17] Alnathier O. The potential contribution of renewable energy to electricity supply in Saudi Arabia. *Energy Policy* 2005;33(18):2298–312.
- [18] Wang C, Nehrir MH. Analytical approaches for optimal placement of distributed generation sources in power systems. *IEEE Trans Power Syst* 2004;19(4):2068–76.
- [19] Iverson Z, Achuthan A, Marzocca P, Aidun D. Optimal design of hybrid renewable energy systems (HRES) using hydrogen storage technology for data center applications. *Renew Energy* 2013;52:79–87.
- [20] Chua KJ, Yang WM, Er SS, Ho CA. Sustainable energy systems for a remote island community. *Appl Energy* 2014;113:1752–63.
- [21] Ramli MAM, Hiendro A, Twaha S. Economic analysis of PV/diesel hybrid system with flywheel energy storage. *Renew Energy* 2015;78:398–405.
- [22] AlYahya S, Irfan MA. The techno-economic potential of Saudi Arabia's solar industry. *Renew Sustain Energy Rev* 2016;55:697–702.
- [23] International Energy Agency (IEA). FAQs: Renewable Energy. Available: (<http://www.iea.org/aboutus/faqs/renewableenergy/>). [accessed 02.01.16].
- [24] International Energy Agency (IEA). Technology Roadmap: Solar Photovoltaic Energy. Available: (http://www.iea.org/publications/freepublications/publication/pv_roadmap.pdf), [accessed 03.01.16].
- [25] International Energy Agency (IEA). Solar Photovoltaic Roadmap. Available: (http://www.iea.org/publications/freepublications/publication/pv_roadmap_foldout.pdf). [accessed 03.01.16].
- [26] NPD Solarbuzz. Emerging PV markets report: Middle East and Africa. Available: (http://www.solarbuzz.com/sites/default/files/SB_Sample_EmergingPVMarkets_MEA_web.pdf). [accessed 03.01.16].
- [27] Middle East–Africa Solar PV Demand Will Increase 625%. Available: (<http://cleantechica.com/2013/03/22/middle-east-africa-solar-pv-demand-will-reach-1-gigawatt-this-year-solarbuzz/>); 2016 [accessed 03.01.16].
- [28] REN21. Renewables 2015 Global Status Report. Available: (http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015_Onlinebook_low1.pdf); 2015 [accessed 02.01.16].
- [29] Middle East Economic Survey, KACARE Outlines Saudi Electricity Energy Source Scenario (May 3, 2013), page 7.
- [30] Bhatto AW, Bazmi AA, Zahedi G, Klemes JJ. A review of progress in renewable energy implementation in the Gulf Cooperation Council countries. *J Clean Prod* 2014;71:168–80.
- [31] Kinab E, Elkhoury M. Renewable energy use in Lebanon: barriers and solutions. *Renew Sustain Energy Rev* 2012;16(7):4422–31.

- [32] Benganem M. Optimization of tilt angle for solar panel: case study for Madinah, Saudi Arabia. *Appl Energy* 2011;88(4):1427–33.
- [33] Mohandes MA. Modeling global solar radiation using particle swarm optimization (PSO). *Sol Energy* 2012;86(11):3137–45.
- [34] Benganem M, Mellit A. Radial Basis Function Network-based prediction of global solar radiation data: application for sizing of a stand-alone photovoltaic system at Al-Madinah, Saudi Arabia. *Energy* 2010;35(9):3751–62.
- [35] Renewable Resource Atlas, King Abdullah City for Atomic and Renewable Energy (K.A.CARE), Saudi Arabia, (<https://rratlas.kacare.gov.sa>); 2015.
- [36] Alyahya S, Irfan MA. New solar radiation atlas for Saudi Arabia. In: Presented at ICRERA, Milwaukee USA; October 19–22; 2014.
- [37] Ramli MAM, Twaha S, Al-Turki YA. Investigating the performance of support vector machine and artificial neural networks in predicting solar radiation on a tilted surface: Saudi Arabia case study. *Energy Convers Manag* 2015;105:442–52.
- [38] Hargreaves S Saudi Arabia poised to become solar powerhouse. (http://money.cnn.com/2011/11/21/news/international/saudi_arabia_solar/index.htm). [accessed 03.01.16].
- [39] Rahman SM, Khondaker AN. Mitigation measures to reduce greenhouse gas emissions and enhance carbon capture and storage in Saudi Arabia. *Renew Sustain Energy Rev* 2012;16(5):2446–60.
- [40] EIA. Overview Data for Saudi Arabia. (<http://www.eia.gov>) [accessed 03.01.16].
- [41] Atieh A, Al Shariff S. Solar energy powering up aerial misting systems for cooling surroundings in Saudi Arabia. *Energy Convers Manag* 2013;65:670–4.
- [42] Benganem M, Daffallah KO, Joraid AA, Alamri SN, Jaber A. Performances of solar water pumping system using helical pump for a deep well: a case study for Madinah, Saudi Arabia. *Energy Convers Manag* 2013;65:50–6.
- [43] Modeling and optimization of hybrid wind–solar-powered reverse.pdf. 2013; pp. 86–97.
- [44] Rehman S, Sahin AZ. Wind power utilization for water pumping using small wind turbines in Saudi Arabia: a techno-economical review. *Renew Sustain Energy Rev* 2012;16(7):4470–8.
- [45] Rehman S, Al-Hadhrani L. Study of a solar PV/diesel/battery hybrid power system for a remotely located population near Rafha, Saudi Arabia. *Energy* 2010;35:4986–95.
- [46] Shaahid SM, Al-Hadhrani LM, Rahman MK. Review of economic assessment of hybrid photovoltaic-diesel-battery power systems for residential loads for different provinces of Saudi Arabia. *Renew Sustain Energy* 2014;31:174–81.
- [47] El Khashaba H, Al Ghamedy M. Comparison between hybrid renewable energy systems in Saudi Arabia. *J Electr Syst Inf Technol* 2015;2:111–9.
- [48] Atieh A, Al Shariff S. Case study on the return on investment (ROI) for using renewable energy to power-up typical house in Saudi Arabia. *Sustain. Cities Soc* 2015;17:56–60.
- [49] Alashed F, Asif M. An exploratory of residents' views towards applying renewable energy systems in Saudi dwellings. *Energy Procedia* 2015;75:1341–7.
- [50] The Vision, King Abdullah City of Atomic and Renewable energy (KACARE). Available: (http://www.kacare.gov.sa/en/?Page_id=84). [accessed 03.01.16].
- [51] Al-Abbad NM. Wind energy resource assessment for five locations in Saudi Arabia. *Renew Energy* 2005;30:1489–99.
- [52] Khogali A, Albar OF, Yousif B. Wind and solar energy potential in Makkah (Saudi Arabia) — Comparison with red Sea coastal sites. *Renew Energy* 1991;1(3–4):435–40.
- [53] Alawaji SH, Eugenio NN, Elani UA. Wind energy resource assessment in Saudi Arabia. *WREC* 1996; pp. 818–21.
- [54] Rehman S, Halawani TO. Statistical characteristics of wind in Saudi Arabia. *Renew Energy* 1994;4(8):949–56.
- [55] Rehman S, Halawani TO, Mohandes M. Wind power cost assessment at twenty locations in the kingdom of Saudi Arabia. *Renew Energy* 2003;28(4):573–83.
- [56] Windpower monthly. Analysis-Financing Saudi Arabia's wind energy plan. Available: (<http://www.windpowermonthly.com/article/1173394/analysis-financing-saudi-arabias-wind-energy-plan>) [accessed 05.01.16].
- [57] PV-Magazine, White paper unveils details of Saudi's 54 GW renewable energy plans, 2013. Available online: (http://www.pv-magazine.com/news/details/beitrag/saudi-arabia-targeting-109-billion-investment-for-solar_100008598/#axzz2z8yOWnT4) [accessed 03.01.16].
- [58] AlGhabban A. Saudi Arabia's renewable energy strategy and solar energy deployment roadmap. Presented at KACARE IRENA Lecture Program. Masdar, Abu Dhabi; March 26, 2013.
- [59] Mokheimer EMA, Sahin AZ, Al-Sharafi A, Ali AI. Modeling and optimization of hybrid wind–solar-powered reverse osmosis water desalination system in Saudi Arabia. *Energy Convers Manag* 2013;75:86–97.
- [60] Ahmad N, Sheikh AK, Gandhidasan P, Elshafie M. Modeling, simulation and performance evaluation of a community scale PVRO water desalination system operated by fixed and tracking PV panels: a case study for Dhahran city, Saudi Arabia. *Renew Energy* 2015;75:433–47.
- [61] Hepbasli A, Alsuhaibani Z. A key review on present status and future directions of solar energy studies and applications in Saudi Arabia. *Renew Sustain Energy Rev* 2011;15(9):5021–50.
- [62] Elhaddidy MA, Shaahid SM. Wind resource assessment of eastern coastal region of Saudi Arabia. *Desalination* 2007;209:199–208.
- [63] Rehman S, Al-Abbad NM. Wind shear coefficient, turbulence intensity and wind power potential assessment for Dhulom, Saudi Arabia. *Renew Energy* 2008;33:2653–60.
- [64] Shaahid SM, Al-Hadhrani LM, Rahman MK. Economic feasibility of development of wind power plants in coastal locations of Saudi Arabia – A review. *Renew Sustain Energy Rev* 2013;19:589–97.
- [65] Shaahid SM, Al-Hadhrani LM, Rahman MK. Potential of establishment of wind farms in Western province of Saudi Arabia. *Energy Procedia* 2014;52:497–505.
- [66] Mohandes MA, Rehman S. Short term wind speed estimation in Saudi Arabia. *J Wind Eng Ind Aerodyn* 2014;128:37–53.
- [67] Baseer MA, Meyer JP, Alam MM, Rehman S. Wind speed and power characteristics for Jubail industrial city, Saudi Arabia. *Renew Sustain Energy Rev* 2015;52:1193–204.
- [68] REN21 Renewables Interactive Map. Renewables interactive map country profile: Saudi Arabia. 2014.
- [69] KAUST Industry Collaboration Program (KICP). The KICP annual strategic study Saudi Arabia solar energy manufacturing and technology assessment. 2009: 2009, pp. 1–95.
- [70] Sundareswaran K, Peddapaty S, Palani S. MPPT of PV systems under partial shaded conditions through a colony of flashing fireflies. *IEEE Trans Energy Convers* 2014;29(2):463–72.
- [71] Doukas H, Patlitzianas KD, Kagiannas AG, Psarras J. Renewable energy sources and rationale use of energy development in the countries of GCC: Myth or reality?. *Renew Energy* 2006;31(6):755–70.
- [72] Saudi Gazette. Saudi Arabia's first solar power station inaugurated on Farasan Island. Available: (<http://www.saudigazette.com.sa/index.cfm?Method=home.region&contentID=20111003109859>); 2011 [accessed 03.01.16].
- [73] Saudi Gazette. World's largest solar parking lot in Saudi Arabia. Available: (<http://www.saudigazette.com.sa>). [accessed 03.01.16].
- [74] Bloomberg. Belectric wins contract for largest saudi solar plant in a parking lot. Available online: (<http://www.bloomberg.com/news/2011-04-04/belectric-wins-contract-for-largest-saudi-solar-plant-in-a-parking-lot.html>). [accessed 03.01.16].
- [75] Renewable energy news. Conergy completes 2 MW PV plant in Saudi Arabia. Available: (<https://renewables.seenews.com/news/conergy-completes-2-mw-pv-plant-in-saudi-arabia-68612>) [accessed 03.01.16].
- [76] PV-Magazine. 3.5 MW PV project completed in Saudi Arabia. Available: (http://www.pv-magazine.com/news/details/beitrag/35-mw-pv-project-completed-in-saudi-arabia_100010012/#axzz2z8yOWnT4). [accessed 03.01.16].
- [77] Balasubramanian IR, Ganesan SI, Chilakapati N. Impact of partial shading on the output power of PV systems under partial shading conditions. *IET Power Electron* 2014;7(3):657–66.
- [78] Eltawil MA, Zhao Z. MPPT techniques for photovoltaic applications. *Renew Sustain Energy Rev* 2013;25:793–813.
- [79] Hiyama T. Artificial neural network-polar coordinated fuzzy controller based maximum power point tracking control under partially shaded conditions. *IET Renew Power Gener* 2009;239–53.
- [80] Ishaque K, Salam Z. A deterministic particle swarm optimization maximum power point tracker for photovoltaic system under partial shading condition. *IEEE Trans Ind Electron* 2013;60(8):3195–206.
- [81] Ramli MAM, Twaha S, Ishaque K, Al-Turki YA. A review on maximum power point tracking for photovoltaic systems with and without shading conditions. *Renew Sustain Energy Rev* 2017;67:144–59.
- [82] Doukas H, Psarras J. Enhancing renewable energy in the Arab states of the Gulf: constraints & efforts. *Energy Policy* 2006;34:3719–26.
- [83] Srinivasan S. Subsidy policy and the enlargement of choice. 2009; 13: pp. 2728–33.
- [84] Ministry of Economy and Planning Kingdom of Saudi Arabia. National Science, Technology and Innovation Plan Administrative, technical and financial regulations. 2012.
- [85] Ramli MAM, Twaha S. Analysis of renewable energy feed-in tariffs in selected regions of the globe: lessons for Saudi Arabia. *Renew Sustain Energy Rev* 2015;45:649–61.
- [86] Dong CG. Feed-in tariff vs. renewable portfolio standard: an empirical test of their relative effectiveness in promoting wind capacity development. *Energy Policy* 2012;42(C):476–85.
- [87] Abdmouleh Z, Alammari RAM, Gastli A. Recommendations on renewable energy policies for the GCC countries. *Renew Sustain Energy Rev* 2015;50:1181–91.
- [88] Almasoud AH, Gandayh HM. Future of solar energy in Saudi Arabia. *J King Saud Univ – Eng Sci* 2015;27:153–7.