Potential of Photovoltaic Power Technology for Water Pumping in Hot Climatic Regions

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ABSTRACT

In the present paper, the potential of solar photovoltaic (PV) technology for water pumping in the K.S.A has been studied by analyzing long-term solar radiation data. To achieve this task, five geographically distinct sites covering different provinces/locations of the Kingdom have been selected. In general, long-term data indicates that the monthly average daily solar radiation/insolation of K.S.A. varies from 3.03 – 7.32 kWh/ m^2. Also, monthly average daily sunshine duration lies in the range 6.5 – 12.3 hours/day. The prevailing solar radiation intensity has been used as a means to assess the potential of using solar PV technology for water pumping. The study deals with estimation of monthly average daily and yearly amount of water that can be pumped (for a given water head and for a given PV power). The investigation also examines the impact of pumping heads (20m, 30m, 40m, 50 m) on amount of water pumped (m^3/day). Attempt has also been made to evaluate the effect of size of PV power (0.75 kWp, 1.6 kWp, 3 kWp, 6 kWp) on annual water output. It has been found that about 75m^3/day and 71m^3/day of water can be pumped in the month of July in northern and eastern regions of Saudi Arabia respectively (at a water head of 20m, with 1.6 kWp solar PV generator).

KEYWORDS: Solar radiation, Photovoltaic panels, Water head, Water pumping.

INTRODUCTION

Almost all technological development efforts/strides in both the developed and the developing nations depend on electrical energy. The sources of conventional means of electricity generation are finite and fast depleting. In this context, many countries are embarking on utilization of renewable/solar-PV energy as a way/option to avert impending energy crisis and to overcome the catastrophic effects of pollution on environment due to burning of fossil fuels. Solar energy is expected to be a promising alternative for conventional energy sources in foreseeable future. The high initial investment cost in PV systems is the main pressing barrier that hinders/precludes/prohibits promoting this technology in large-scale applications. However, technological breakthroughs (involving increase in efficiency and reduction in cost) may pave way for commercialisation of this technology and change the scenario. Solar energy (being inexhaustible, free, abundant, site-dependent, non-polluting, and potential source of renewable energy options) is being pursued by a number of countries with monthly average daily solar radiation (insolation/flux) in the range of 3kWh/m^2 – 6kWh/m^2, in an effort to reduce their dependence on fossil-based non-renewable fuels and to produce green electricity (Post et al., 1988; Mahmoud, 1990; Erhard et al., 1991; Richard, 1989; Martel, 2000; Frank et al., 1992; Greenpeace, 2005). Annual worldwide shipments of PV panels have grown from 2 megawatts peak (MWp) in 1975 to 135 MWp in 1998. World PV market grew by 26% in 2002 as compared to 2001. As a matter of fact, in the year 2003, the cumulative installed capacity of all solar PV systems around the world passed the landmark figure of 3,120 MWp. The global installed capacity of solar power is expected to reach 207 GWp by 2020 (the cost of solar modules is likely to go down to US$1 per Watt delivered). Also, the projections indicate that by 2020 solar energy can provide energy to over a billion people globally and provide 2.3 million full-time jobs (Greenpeace, 2005). The price of PV modules has dropped by a factor of 1/30 during the past 20 years. Germany, Japan and the Netherlands are leading the solar race (Greenpeace, 2005). Typical ratings of PV modules vary from 30 to 300Wp. Many international organizations such as World Bank Group, Bi-lateral Assistance Agencies, and UNO are providing funds for wide-spread dissemination of PV.

Saudi Arabia, being enriched with fairly high degree of solar radiation, is a prospective/potential candidate for deployment of solar driven power systems such as: PV systems. The electricity sector in the Kingdom of Saudi Arabia has grown remarkably over the last two decades. The number of consumers grew from 300,000 in early seventies to approximately 3.5 million in 2000. The installed generating capacity of the power plants in the Kingdom reached more than 27,000 MW in 2002 (Saudi Electricity Company, 2002). Increased rates of electric energy consumption is one of the major problems being faced by the electric companies in the Kingdom. An appreciable fraction of Saudi Arabia's energy demand may be captured/harnessed/exploited from indigenous solar energy. Solar radiation intensities of different provinces of Saudi Arabia are presented in Ref. (Saudi Arabian Solar Radiation Atlas, 1983). The use of renewable sources of energy reduces combustion of fossil fuels and the consequent CO_2 emission which is the principal cause of global warming. Literature indicates that 0.6 kg of CO_2 would be saved per kWh of output from a solar generator (Jeffrey, 1990; Coiante et al., 1996). Typical solar power applications/targets include: lighting electrical appliances, military installations, communication/gas stations, electricity for remote settlements, water pumping for irrigation or desalination, and cathodic protection of pipe lines, etc.

The application of PV in water pumping is becoming increasingly popular and is campaigned especially in remote areas where power supply is not available or is too costly to install (Amer et al., 2004; Sarkar et al., 2002; Mohammad, 200; Hamidat et al., 2001; Mousa et al., 2001; Zaringchang et al., 200; Amal, 2001). Water is the most needed commodity for the existence of life. The projected total water demand of K.S.A for 2004 was 22480 million cubic meters/year (Ministry of Planning, 2000). Traditionally water pumping employ diesel engines and electric grid powered motors (Sarkar et al., 2002). A PV based water pumping system with no-battery-storage is composed/comprised principally of a PV array, an electric motor and a water pump. If the pump is driven by an AC motor, a DC/AC inverter is included. The PV array (constructed of monocrystalline silicon cells) converts solar energy into direct current that powers/energies/feeds the motor either directly (in case of DC motors) or via the inverter (in case of AC motors). The motor (which is directly coupled to the water pump) drives the water pump. When the PV array generates enough electrical power, the motor produces mechanical torque and the pump draws water. A sufficient insolation level must be available for a PV pumping system to start its operation. More often, water is stored in storage tanks to bridge/cover the water demand during periods of low insolation. PV pump sets are quiet, need no fuel, life is about 20 years, can be expanded by addition of modules, and require little maintenance. Typical cost for PV panels is about $5/watt (other costs include: $300-400 for a controller, $600-800 for a tracker to increase solar array's power output, $100-200 for wiring and mounting fixtures, and $600-3000 for pumps). About 50,000 solar pumping systems have been deployed around the world (Sarkar et al., 2002). There are basically two types of solar pumps: positive displacement and centrifugal and these can both be subdivided into surface-mount and submersible categories. Water source dictates whether to use a surface- mount or submersible pump, while daily volume requirement and total dynamic head (TDH) determines whether to use positive displacement or centrifugal pump. In general, positive displacement pumps require less power and are used where TDH is high and the daily water volume requirement is low. The centrifugal pumps (need more power to push water all the way out of the well) are good in situations where the TDH is low and the daily volume requirement is high (Solar water pumping, 2005).

Work related to renewable energy in Saudi Arabia has been subject matter of several earlier studies (Elhadidy and Shaahid, 2000; Elhadidy and Shaahid, 1998; Elhadidy and Shaahid, 1999; El-Amin and Shaahid, 2004). In the present study, long-term (of the period 1971-1980, recent data could not be obtained) solar radiation data of different geographically distinct provinces/locations of K.S.A. has been analyzed to assess the potential of using solar photovoltaic technology for water pumping in K.S.A.

The solar radiation intensity has been used as a basis to evaluate the potential of utilizing solar PV technology for water pumping. The study deals with estimation of monthly average daily and yearly amount of water that can be pumped (for a given water head and for a given PV power). The study also addresses the impact of pumping/lifting heads (20m, 30m, 40m, 50m) on amount of water pumped (m^3/day). Attempt has also been made to evaluate the effect of size of PV array/power (0.75kWp, 1.6kWp, 3kWp, 6kWp) on annual water output.

BACKGROUND INFORMATION AND SOLAR RADIATION DATA

Solar PV systems are characterized by availability of solar insolation/regime/resource. The long-term (1971-1980) monthly average daily values/profiles of solar radiation of different locations considered in the study are demonstrated in Figure (1). In general, the monthly average daily values of solar global radiation/insolation (of the locations considered in the study) ranges from 3.03 – 7.32kWh/ m^2 (Saudi Arabian Solar Radiation Atlas, 1983).

The long-term monthly average daily sunshine hours of the above locations are presented in Figure (2). The monthly average sunshine duration lies in the range 6.5 – 12.3 hours/day. It can be depicted from Figure (1) that solar radiation is generally higher during the summer months (May to August) as compared to other months (this is due to topography). This implies that solar systems would produce appreciably more energy during summer time. This seasonal pattern/trend of solar radiation matches with the higher load requirements during summer period in Saudi Arabia. Relatively less load can be met/covered during non-summer months because of blocking of sun's rays by clouds.

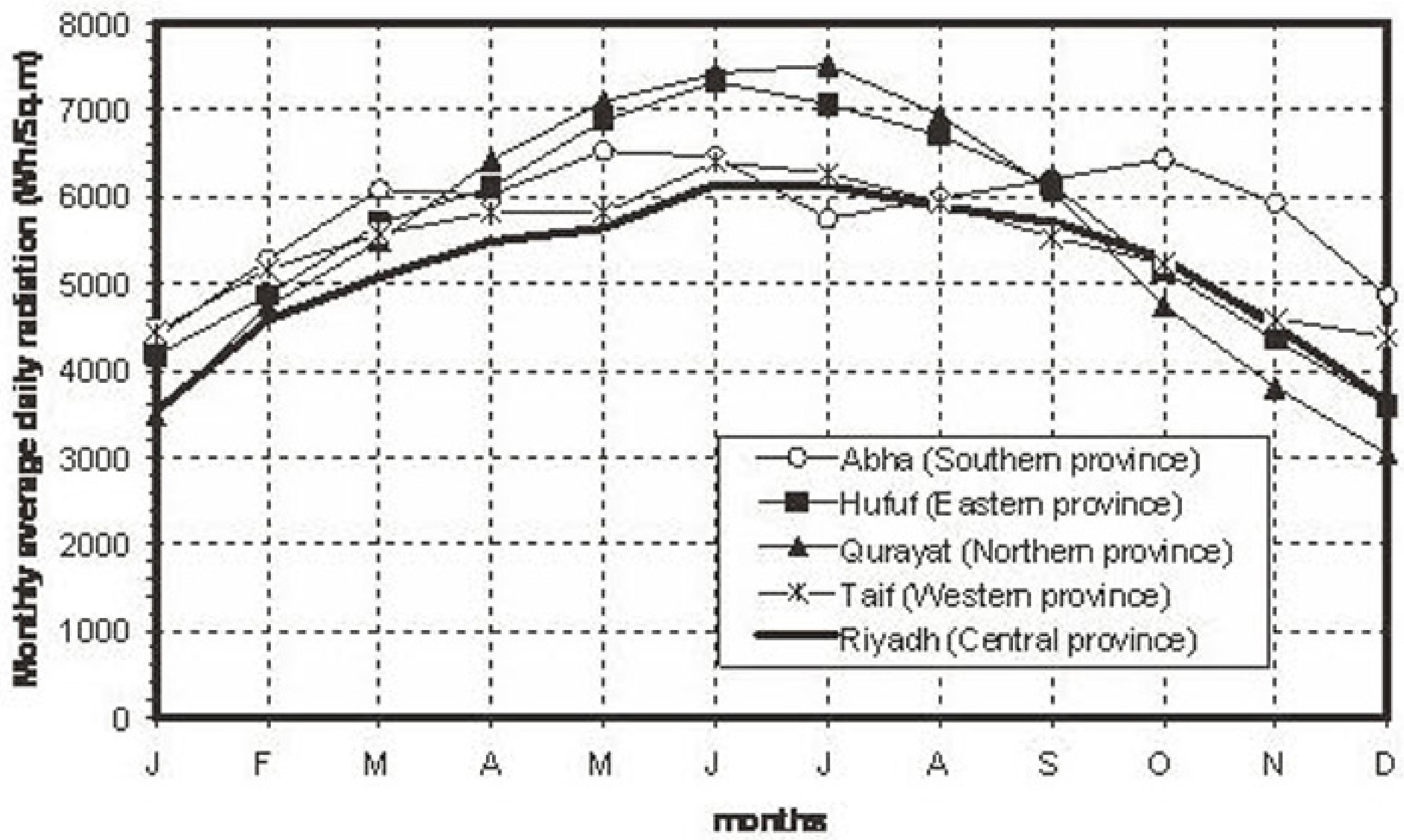

Figure 1. Monthly average daily solar radiation (long-term average) of different provinces/locations of Saudi Arabia

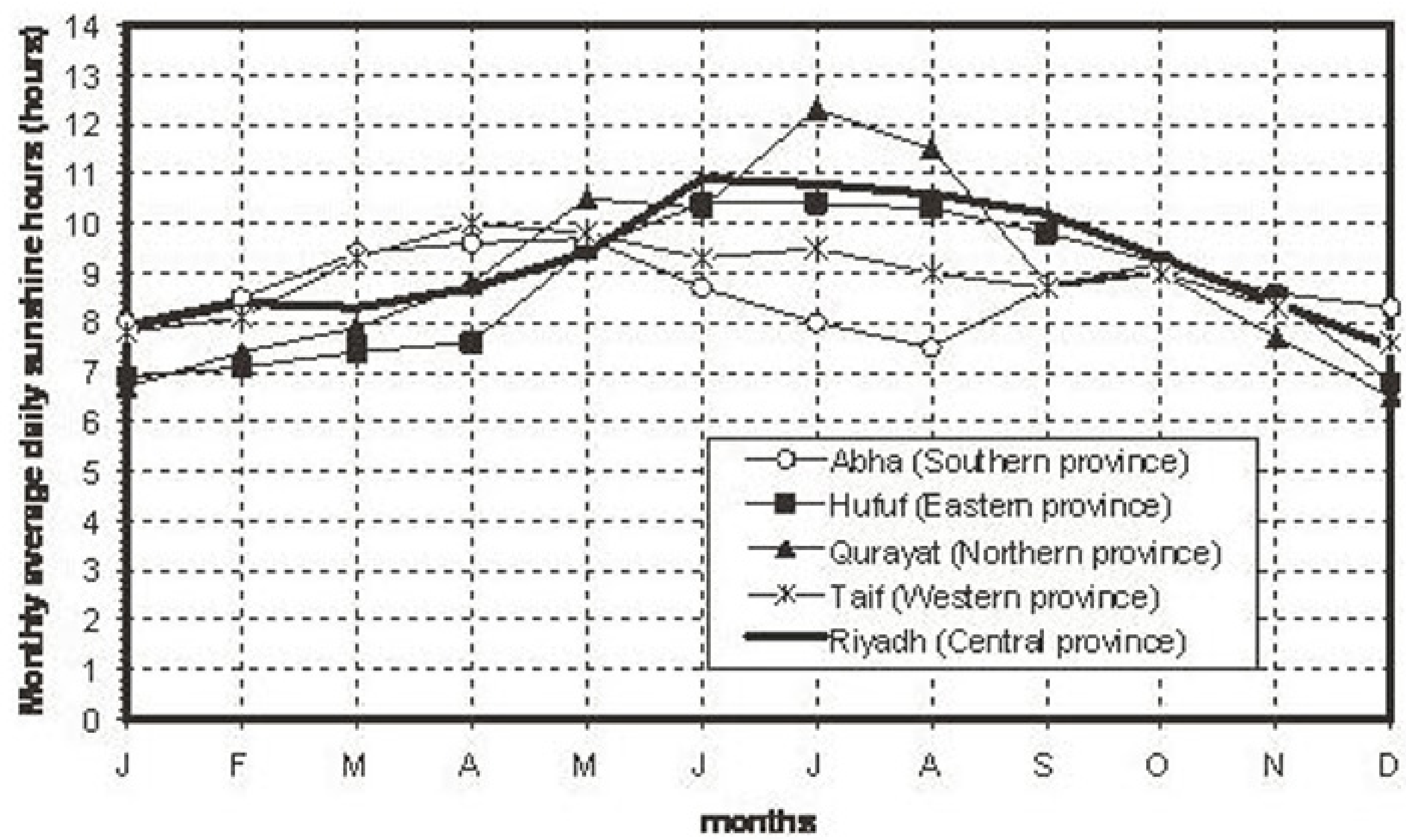

Figure 2. Monthly average daily sunshine hours (long-term average) of different provinces/locations of Saudi Arabia.

HYDRAULIC ENERGY CALCULATIONS FOR SOLAR WATER PUMPING

The hydraulic energy required to deliver a volume of water is given/governed by the formula (Solar Photovoltaic Water Pumping, 2005):

$$E_w = \rho_w g V H \quad (1)$$

Where E_w is the required hybraulic energy (kWh/day); ρ_w is the density of water (1000 kg/m^3); g is the gravitational acceleration (9.81m/s^2); V is the required volume of water (m^3/day); and H is the head of water (m).

The solar array power required is given by:

$$P_{sa} = E_w \div E_{sr}\, \eta\, F \quad (2)$$

Where P_{sa} is the solar array power (kWp); E_{sr} is the average daily solar irradiation (kWh/m^2 /day); F is the array mismatch factor (0.85); and η is the daily subsystem efficiency (0.4). Substituting Equation (1) in Equation (2), the following equation is obtained for the amount of water that can be pumped V (m^3/day):

$$V_a = P_{sa}\, E_{sr}\, \eta\, F \div \rho_w g H \quad (3)$$

From Equation (3), for given solar radiation (E_{sr},) the amount of water (V) that can be pumped can be determined for different selected PV array (P_{sa}) sizes and for different pumping heads (H). The characteristics of some of the commercial PV modules are documented in Table (1). Figure (3) shows the variation of daily water production with respect to average daily solar radiation (for a given PV power of 1.6kWp) at different pumping heads (20m, 30m, 40m, 50m). It is evident from this Figure that for a given solar insolation, the average water output decreases with increasing pumping head. More importantly, the volume of water pumped (or delivery flow rate) is proportional to the insolation level (Amer, 2004). In general, for a given water head of 20m, for an increase in insolation from 4 kWh/m^2 to 5 kWh/m^2, the volume of water pumped increases by about 20%. Figure (4) is a block diagram showing the layout of a typical solar water PV pumping system.

Table 1. Characteristics of some commercial PV modules

Module Size L x W x D	Rated Power (watts), Rp	Current (amps)	Voltage (volts)	Module Reference η
1113 x 502 x 50 (in mm)	60	3.5	17.1	0.107
1108 x 660 x 50 (in mm)	83	4.85	17.1	0.113
18.5" x 25.7" x 2.1" (in inches)	35	2.33	15.0	0.15
25.2" x 25.7" x 2.1" (in inches)	50	3.00	16.7	0.15
34.1" x 25.7" x 2.2" (in inches)	70	4.14	16.9	0.15
56.1" x 25.7" x 2.2" (in inches)	120	7.10	16.9	0.15
50.8" x 39.0" x 1.4" (in inches)	167	7.2	23.2	0.15

L : Length; W : Width; D : Dept

The above modules are High Efficiency Solar Electric Modules and Kyocera solar Modules. Power specifications are at standard test conditions of 1000W/Sq.m Solar Irradiance, 25° cell temperature.

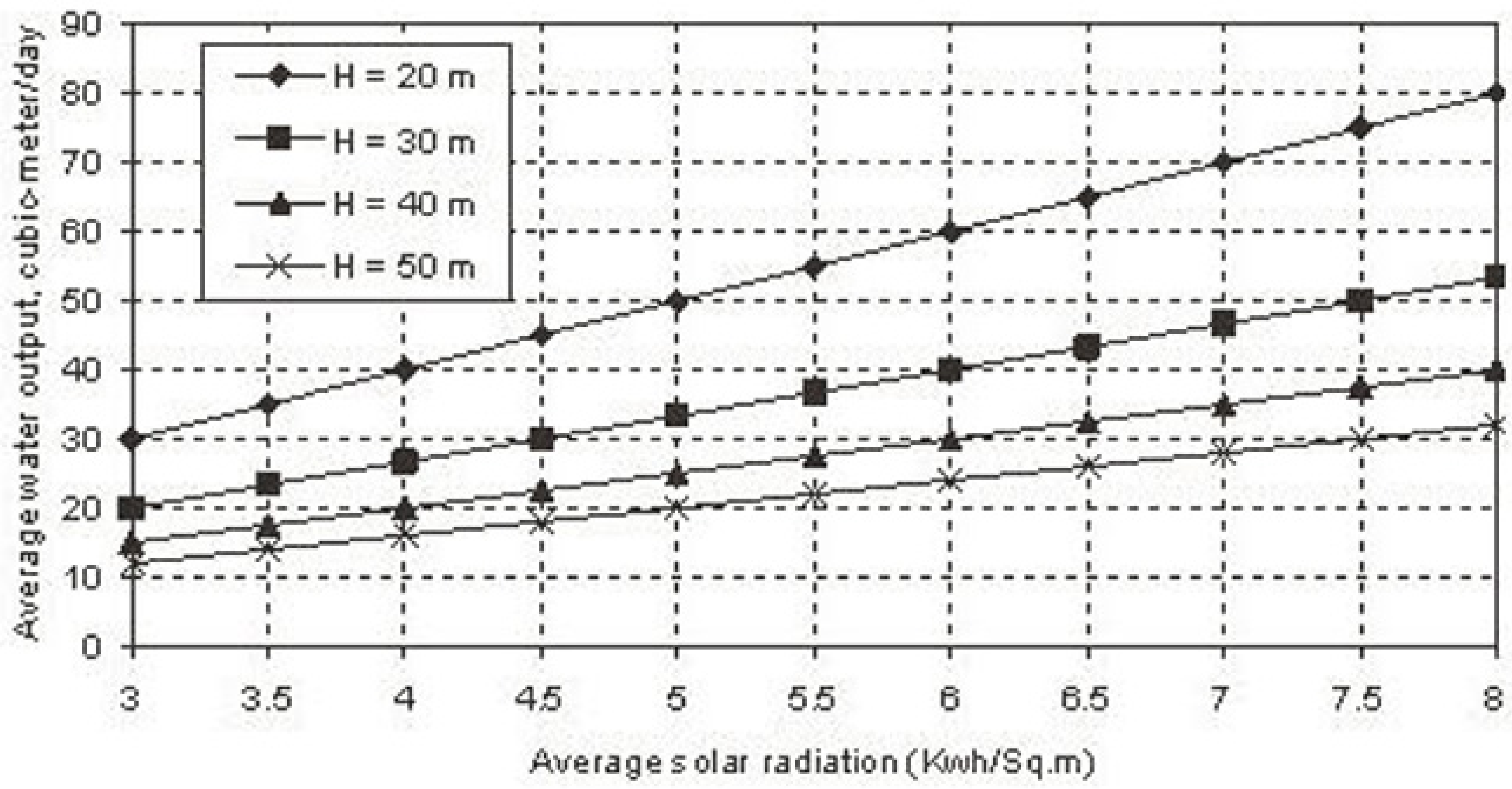

Figure 3. Daily water production versus daily solar radiation at different pumping heads (for given PV power of 1.6kWp

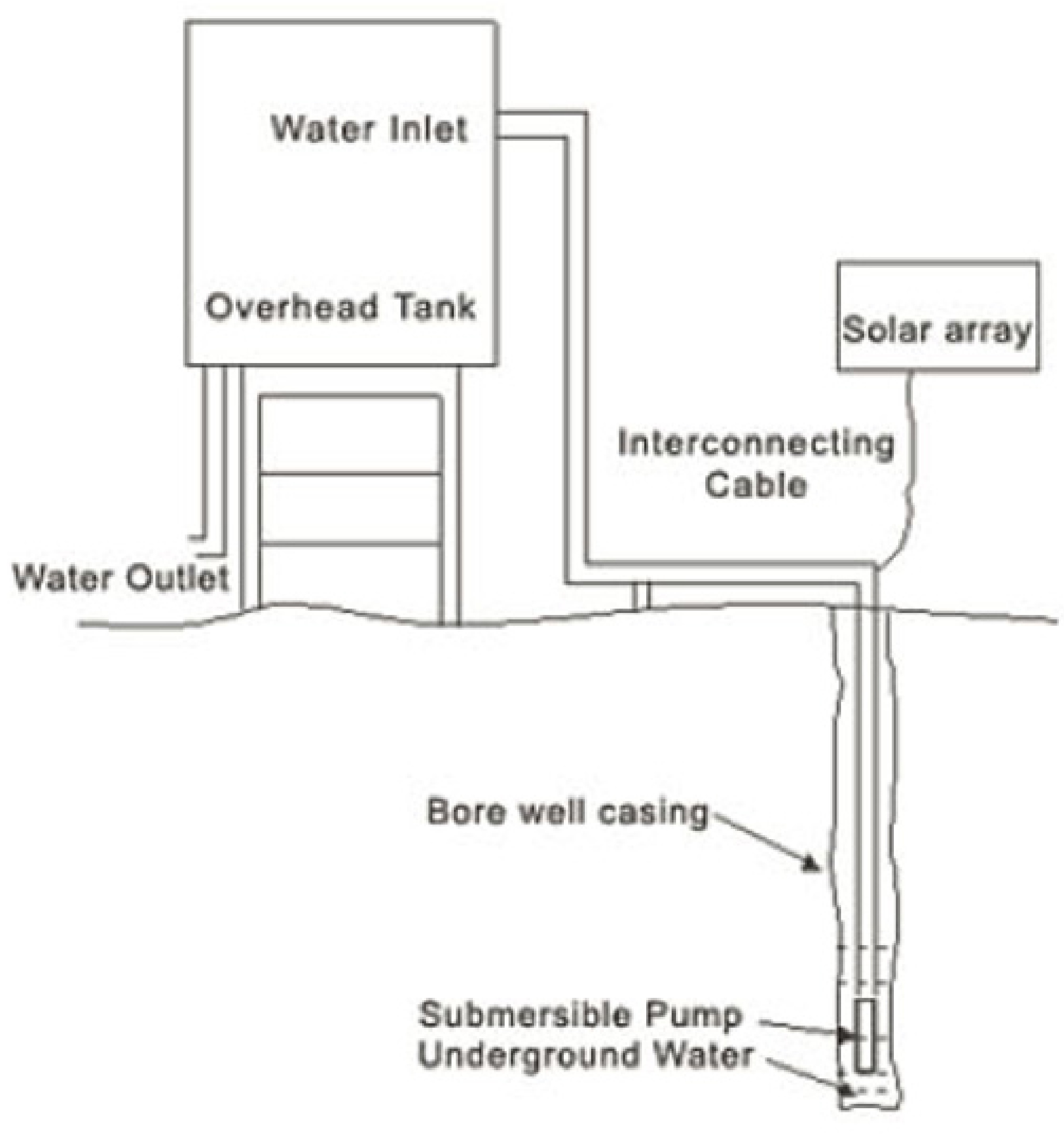

Figure 4. Block diagram of a typical solar water pumping system

RESULTS AND DISCUSSION

The performance analysis of solar PV water pumping system (with no-battery-storage) has been evaluated for different operating and performance parameters (such as: solar insolation, PV array sizes, water pumping heads, etc.) for different locations of K.S.A. by using indigenous solar insolation. Figure (5) shows the monthly average daily amount of water which can be pumped from all the five selected sites with a pumping head of 20m (for a given PV array power/size of

1.6kWp). In general (for all locations), it can be noticed that solar PV systems deliver/pump appreciably more water during summer months (May-August) as compared to other months of the year. As mentioned earlier, solar PV system can meet higher load (water demand) requirements during summer period. In particular, northern (Qurayat) and eastern (Hufuf) provinces produce more water during summer as compared to other locations. Northern and eastern provinces are more promising for water pumping during summer. About 75m^3/day and 71m^3/day of water can be pumped in the month of July in northern and eastern regions respectively (at a water head of 20m, with 1.6kWp solar PV power). However, during winter month (e.g. January), about 35m^3/day and 41m^3/day of water can be pumped in northern and eastern regions respectively (at a water head of 20m, with 1.6kWp solar PV power). The water pumped during winter months is approximately 52% of the water that can pumped during summer months.

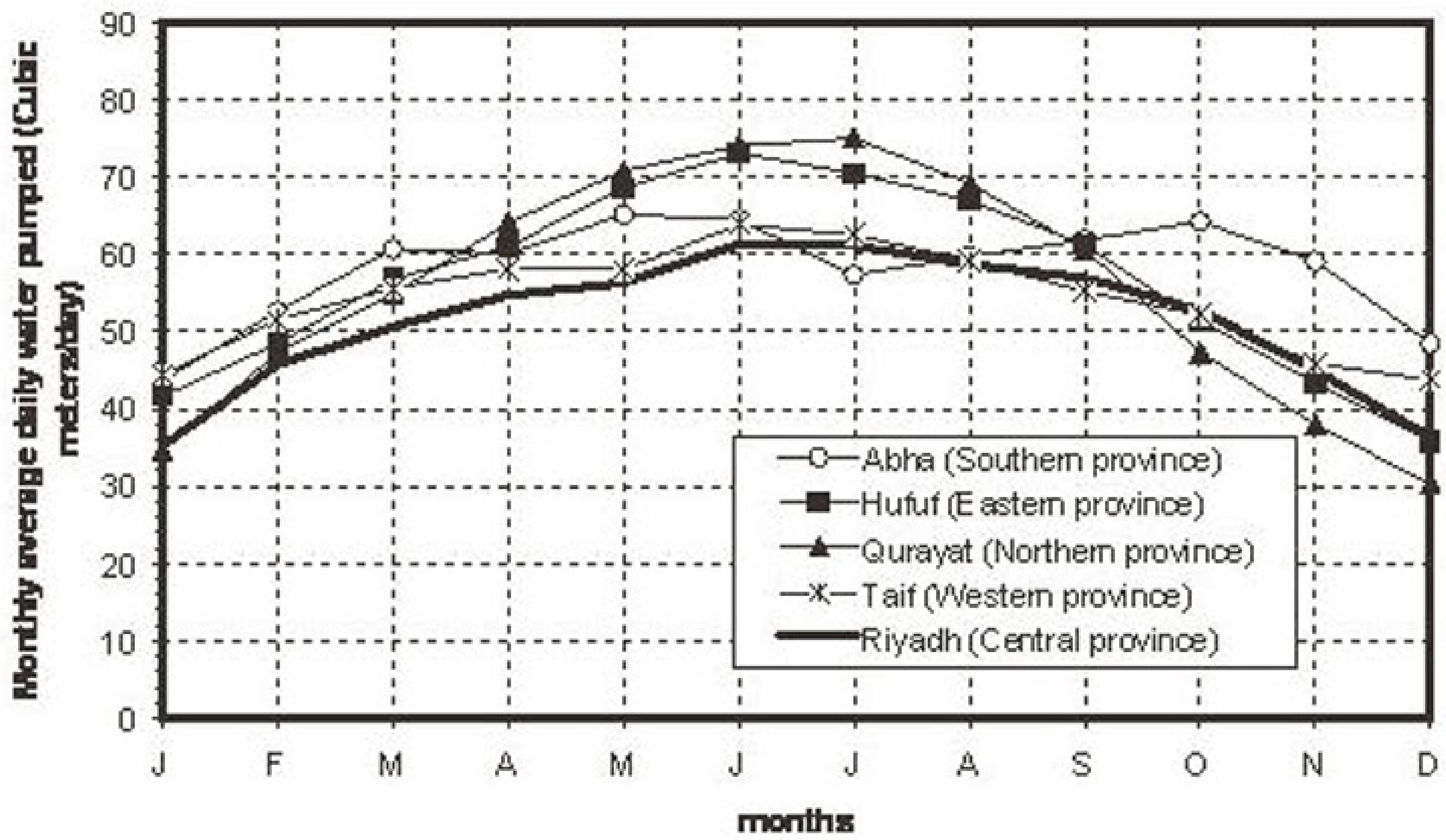

Figure 5. Monthly average daily water pumped to a height of 20m (for given 1.6kWp VP system) at different provinces/locations of Saudi Arabia

The annual amount of water which can be pumped from all the selected sites with a pumping head of 20m (for a PV generator of 1.6kWp) is demonstrated in Figure (6). It can be observed that annual amount of water output obtained from southern region (Abha) is relatively more as compared to other regions. It is interesting to note that, although northern and eastern regions show (Figure (5)) more potential for water pumping during summer, but their annual water output is less than southern region.

The annual water output of southern province is 21,215m^3. This annual output amounts to about to 21% of the water pumped from all sites combined together. The annual water outputs of northern and eastern provinces are 20,256m^3 and 20,650 respectively (at a water head of 20m, with 1.6kWp solar PV power). The annual water output of central province (Riyadh) is less (about 18,695 m^3) relative to other provinces. As a matter of fact, this is equal to about 18% of the water pumped from all the sites when combined together.

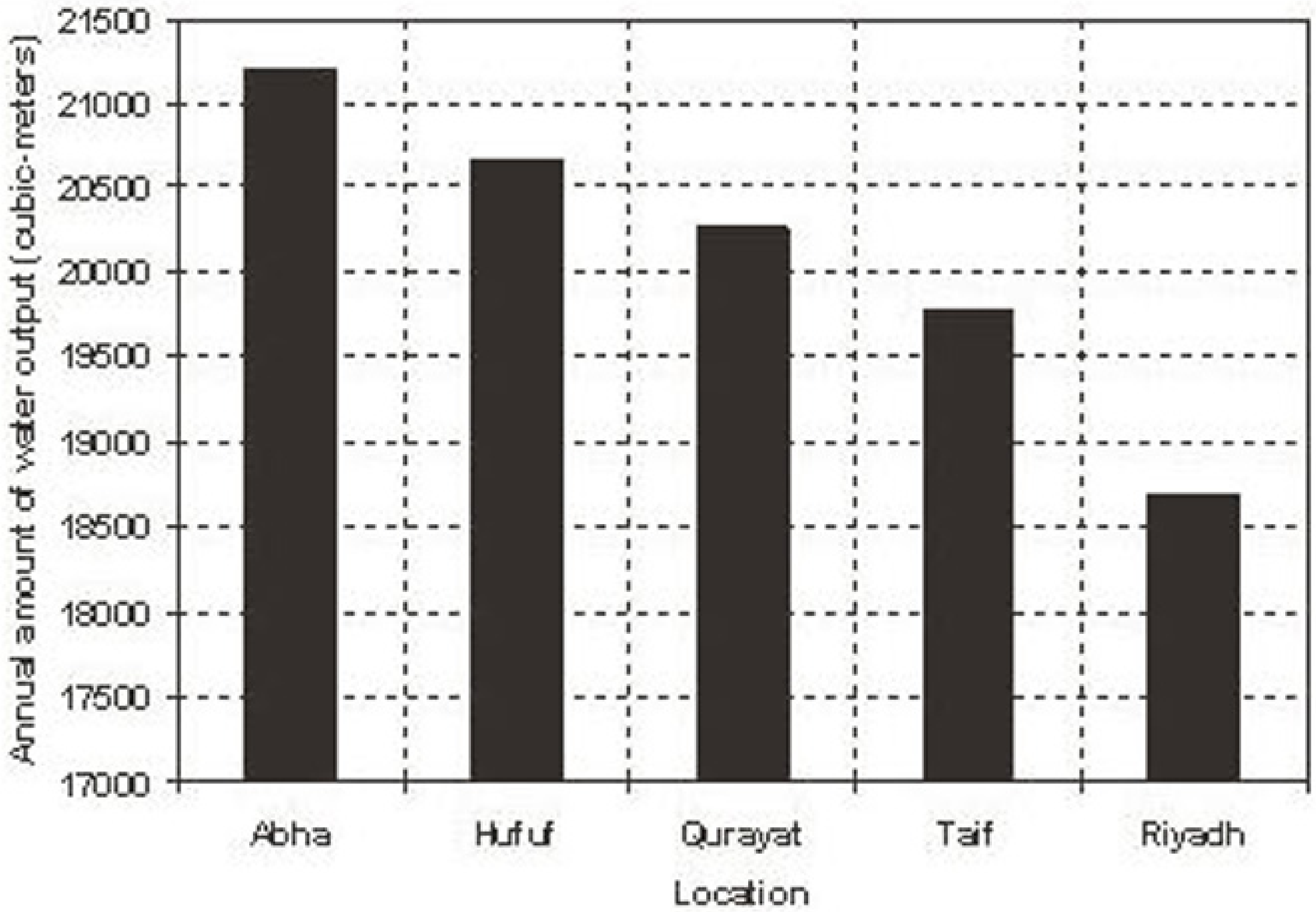

Figure 6. Annual amount of water pumped to a height of 20m for all selected locations (for given 1.6kWp PV system)

The annual water output/yield/delivery for different water heads (20m, 30m, 40m, 50m) and for different PV generator sizes (0.75kWp, 1.6kWp, 3kWp, 6kWp) for all the regions/provinces is furnished in Table (2). Expectedly/invariably the volume of water pumped increases with increase in PV power generator size. For a given location (southern region, for water head head of 20m) increase in PV size from 1.6kWp to 3.0kWp increases the annual water output by 46%.

As mentioned earlier, southern region shows more water potential as compared other regions. It is important to note (from Table (2)) that for a given PV power size the water output decreases with increase in water head. The annual water output decreases (e.g. PV power = 3.0kWp, for southern region), by 33% due to increase in water head from 20m to 30m. However, the decrease in water output is 25% by increasing the pumping head from 30 m to 40m.

Also, the decrease in water output is 20% by increasing the pumping head from 40m to 50m. To consolidate, it can be mentioned that the impact of pumping head on water is less pronounced/sensitive with higher pumping heads. The research/studies pursued in other parts of the world on solar water pumping indicate that many countries with average solar insolation in the range of 3 – 6kWh/m^2 are pursuing the option of solar PV for water pumping (Amer et al., 2004; Sarkar et al., 2002; Mohammad, 2001; Hamidat et al., 2001; Mousa et al., 2001; Zaringchang et al., 2001; Amal, 2001; Kala, et al., 2008; Pallav et al., 2008).

Table 2. Annual water output (m^3) pumped at different water heads for different solar PV sizes at various provinces/regions of K.S.A.

Province/Region (for PV power = 0.75kWp)	**Annual amount of water pumped (m^3) for different water heads**			
	H = 20m	**H = 30m**	**H = 40m**	**H = 50m**
Eastern region (Hofuf)	9680	6453	4840	3872
Western region (Taif)	9271	6180	4635	3708
Northern region (Qurayat)	9495	6330	4742	3798
Southern region (Abha)	9945	6630	4972	3978
Central region (Riyadh)	8763	5842	4381	3505
Province/Region (for PV power = 1.6.kWp)	**Annual amount of water (m^3) pumped for different water heads**			
	H = 20m	**H = 30m**	**H = 40m**	**H = 50m**
Eastern region (Hofuf)	20650	13767	10325	8260
Western region (Taif)	19778	13185	9889	7911
Northern region (Qurayat)	20256	13504	12128	8102
Southern region (Abha)	21215	14143	10607	8486
Central region (Riyadh)	18695	12463	9347	7478
Province/Region (for PV power = 3.0kWp)	**Annual amount of water (m^3) pumped for different water heads**			
	H = 20m	**H = 30m**	**H = 40m**	**H = 50m**
Eastern region (Hofuf)	38720	25813	19360	15488
Western region (Taif)	37084	24722	18542	14833
Northern region (Qurayat)	37981	25320	18990	15192
Southern region (Abha)	39778	26519	19889	15911
Central region (Riyadh)	35054	23369	17527	14021
Province/Region (for PV power = 6.0kWp)	**Annual amount of water (m^3) pumped for different water heads**			
	H = 20m	**H = 30m**	**H = 40m**	**H = 50m**
Eastern region (Hofuf)	77440	51626	38720	30976
Western region (Taif)	74168	49445	37084	29667
Northern region (Qurayat)	75962	50641	37981	30384
Southern region (Abha)	79557	53038	39778	31823
Central region (Riyadh)	70109	46739	35054	28043

CONCLUSION

In view of substantial monthly average daily global solar radiation (3.03 – 7.32kWh/sq.m), the study indicates that Saudi Arabia is a suitable/potential candidate for deployment of solar PV based water pumping systems. It has been noticed that about 75m^3/day and 71 m^3/day of water can be pumped in the month of July in northern and eastern regions respectively (at a water head of 20 m, with 1.6kWp solar PV power). Also, it has been found that annual amount of water output obtained from southern region (Abha) is relatively more as compared to other regions.The annual water output of southern province has been found to be 21,216m^3 (at a water head of 20m, with 1.6kWp PV power). It has been noticed that for a given PV power the water output decreases with increase in water head. For a given region (eg. Southern, with 3.0kWp PV), the annual water output decreases by 33% due to increase in water head from 20m to 30m.

The observations of the present work can be used as a tool for designing/sizing solar PV water pumping systems for other regions having climatic conditions similar to the locations considered in study. Also the outcome of the present study can be utilized as a basis for a detailed cost study.

ACKNOWLEDGEMENT

The author acknowledges the support of the Research Institute of the King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia.

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جهد تكنولوجيا القدرة الفولطاضوئية لضخ المياه في المناطق الحارة

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المملكة العربية السعودية.

الملخص

في هذا البحث تم دراسة جهد تكنولوجيا كهرباء الشمس (من خلال الأسطح الفولطاضوئية) لضخ المياه في المملكة العربية السعودية من خلال تحليل نتائج الإشعاع الشمسي المسجلة في السعودية منذ فترة طويلة. ولأجل الوصول إلى هدفنا فقد تم تقسيم المملكة إلى خمس قطاعات جغرافية تغطي مواقع مختلفة من الدولة. وبصفة عامة، فإن نتائج متوسط الإشعاع الشمسي الشهري لفترات طويلة في المملكة العربية السعودية تشير إلى تمرجحها من 3.03 إلى 7.32 كيلووات ساعة / متر^2 . كما أن المتوسط الشهري لساعات سطوع الشمس اليومي يتراوح من 6.5 إلى 12.3 ساعة / يوم. وقد تم استخدام القيمة السائدة للإشعاع الشمسي لتقدير جهد استخدام كهرباء الشمس (من خلال الأسطح الفولطاضوئية) لضخ المياه . وتتناولت هذه الدراسة تقدير المتوسط الشهري للقياسات اليومية في كل عام لكمية المياه الممكن ضخها من آبار ذات أعماق مختلفة (20 م ، 30 م، 40 م، 50 م) بوحدة م^3/يوم. كما سعى البحث إلى تقييم تأثير حجم قدرة الكهرباء الشمسية من الألواح الفولطاضوئية (0.75 كيلووات، 1.6 كيلووات، 3 كيلووات، 6 كيلووات) على الخارج السنوي من الماء. ولقد تم التوصل إلى أنه حوالي 75 م^3/ يوم و 71 م3/يوم من الماء يمكن ضخه في شهر يوليو في شمال و شرق المملكة العربية السعودية، على التوالي (عندما يكون عمق البئر 20 م و جهد اللواح الشمسية 1.6 كيلوات).