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Solar Energy Resource Analysis and Evaluation of Photovoltaic System Performance in Various Regions of Saudi Arabia

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Abstract: According to Vision 2030, the Kingdom of Saudi Arabia (K.S.A) plans to harness 9.5 GW of energy from renewable energy sources, which includes a major part of solar PV generation. This massive implementation of solar projects requires an accurate assessment and analysis of solar resource data and PV site selection. This paper presents a detailed analysis of one-year solar radiation data and energy output of 100 kW PV systems at 44 different locations across the K.S.A. Coastal areas have a lower amount of global horizontal irradiance (GHI) as compared to inland areas. Najran University station gives the highest annual electrical output of 172,083 kWh, yield factor of 1721, and capacity utilization factor of 19.6%. Sharurah and Timma TVTC are second and third best with respect to annual PV performance. Similarly, during high load summer season (April–October), Tabuk station is the best location for a PV power plant with an electrical output of 110,250 kWh, yield factor of 1102, and capacity utilization factor of 21.46%. Overall, the northern province of Tabuk is the most feasible region for a solar PV plant. The basic approach presented in this research study compares solar resource pattern and solar PV system output pattern with the load profile of the country. The site selected based on this criterion is recommended to be economically most feasible which can reduce the stress on electricity companies during high load seasons by clipping the peak load during daytime in the hot summer period.

Keywords: renewable energy; solar energy; photovoltaic; GHI; Saudi Arabia

1. Introduction

The K.S.A has a unique electrical load profile. The electrical load is low in the winter season from November to March, and increases very quickly from April onward and reaches a peak value in June and July. The electrical load remains on the higher side until October. Peak load in the summer season is two times higher than winter peak load. This unique characteristic of electrical load is developed by cooling load in residential and commercial buildings in the hot summer season. Residential and commercial buildings in K.S.A use about 50% of the total electricity consumed [1–3]. According to World Energy Council statistics, an average household in K.S.A consumed 23.81 MWh of electricity in 2014 which is third highest consumption rate in the world, while the overall average in the world was 3.35 MWh [4,5]. In 2015, K.S.A generated 328.1 billion kWh of electricity, which is 6.4% more than that generated in 2014 and almost twice that in 2006 (181.4 billion kWh) [6]. The demand for electricity is rising at a very brisk rate. The number of subscribers are increasing at an average rate of 5.2%. Electricity demand growth of the industrial sector is 6.9%. This has resulted in more combustion of fossil fuels, which will eventually release a greater amount of CO_2 into the atmosphere. Environmental pollution and global warming is considered a serious threat to life on our planet [7–9]. It is becoming an accepted fact that the amount CO_2 emissions resulting from fossil fuels burning is so huge that a technical fix to this problem is inevitable [10–14]. In 2013, the K.S.A released 458.8 million tons of CO_2 into the atmosphere due to combustion of fossil fuel as compare to 429.8 million tons in 2012 [15]. The annual average growth rate of CO_2 emissions in the K.S.A between 1971 and 2013 was 5.8% [16,17]. Electricity demand growth has been increasing at a high rate of around 7.5% per annum in the last decade or so [18]. This increasing demand for electrical energy is one of the main problems being faced by the power companies in the K.S.A. Saudi Arabia is among the 26 countries accounting for three-quarters of global energy demand [19]. The renewable energies share in primary consumption is less than 0.1% in the K.S.A as compared to 12.9% in the rest of the world [20]. Unless renewable energy resources are explored and adopted, fossil fuel demand for power generation is estimated to increase from 3.4 mb/d in 2010 to 8.3 mb/d in 2028 [6]. This will result in a significant reduction in the country's export revenue.

In order to overcome energy crises in future, the K.S.A has plans to include renewable resources to diversify its power generation. The K.S.A has massive oil reserves and at the same time, the Kingdom is blessed with other resources, like solar energy, that could solve all the energy crises in the future. Annual solar irradiance in the country is around 2000–2450 kWh/m^2 [21], along with the vast empty land areas available to host solar installation, which makes the K.S.A an ideal location for both PV and CSP generation [22–25].

Average annual solar radiation in the Arabian Peninsula is about 2000 kWh/m^2 [26]. Only around 0.1% land area of the country is required to meet the projected demand for electricity for 2050 [27]. The barrier to the adoption of solar power generation is its huge capital cost but unlike other renewables, solar power is abundant and everywhere. Renewable energy is essential in the Gulf Cooperation Council (GCC) countries, but government policies to subsidize fossil fuels are the major barriers in the way of renewable energy [28]. Increasing solar share in energy mix increases the cost of the solar system but fuel cost, cost of emissions and emissions itself get reduced [29]. Solar PV can be installed domestically on rooftops and commercially in or near cities to avoid losses due to long distance transmission. This makes solar power the most feasible resource in the renewable category. Germany has the second highest installed solar PV capacity in the world. Interestingly, minimum solar irradiation in Saudi Arabia (2000 kWh/m^2) is more than maximum irradiation in Germany (1200 kWh/m^2). The installed capacity of solar PV in Germany is 32,509 MW_P.

Current projects, related to solar power generation in the K.S.A, have been based on outdated and limited solar resource data, mostly relying on estimated data from satellite-based observations of the atmosphere. The K.S.A has set an initial target of generating 9.5 gigawatts of renewable energy. This large-scale expansion of renewable projects, as planned in vision 2030 [30], requires precise, long-term ground-based real data. In order to obtain long-term accurate ground-based data, the K.S.A has established a Renewable Resource Monitoring and Mapping (RRMM) network [31]. The data used in this paper was taken from The King Abdullah City of Atomic and Renewable Energy (K.A.CARE). K.A.CARE has established a RRMM network of 46 stations across the country.

A recent study on solar radiation data in the K.S.A reports an assessment of solar radiation resources at 30 locations across the country [32]. The GHI, direct normal irradiance (DNI), and their variabilities are discussed over a one-year period but no seasonal load variations and solar radiation variations were analyzed at the same time. Another study presents a techno-economic review of rooftop solar PV for Al Majmaah city, province of Riyadh, Saudi Arabia and feasibility of the system was proven based on annual production of PV energy and payback period, but seasonal load profile variations were not considered in the feasibility analysis [3]. Sherif S. Rashwan et al. performed an environmental and economic study of a small-scale PV power plant for a small building in Dhahran, K.S.A [33]. Sulaiman AlYahya et al. compared solar radiation data from K.A.CARE for two locations in K.S.A (K.A.CARE Headquarter Riyadh and Qasim University Stations) with long-term estimates by GeoModel [34]. Hisham El Khashab et al. investigated renewable energy source applications for a hybrid system (PV, wind turbine, and fuel cell systems) at Yanbu, K.S.A and cost of energy in three systems was compared [35]. Abdullah Al-Sharaf et al. investigated the potential for power generation via wind and solar PV at five different locations in the K.S.A [36]. Another study investigates a PV-diesel hybrid power system with battery backup for a remote village in Saudi Arabia [37].

The existing research focuses on either a general scenario of solar radiations and feasibility of solar PV generation at a particular location. None of the existing study compared solar PV feasibility over a large number of locations across each and every corner of the country. None of the existing work explored the most feasible location while taking into account the shape of the annual load profile of the K.S.A.

Most of the existing research work focuses on solar radiation levels and other weather related factors while finding the best site for solar PV generation in a country. One very important missing aspect is to consider the load profile of the country as well. Here in this paper, most feasible region for solar PV generation is explored and shape of load profile is considered as a very important parameter in the site selection. This approach is very useful to locate the best site for solar PV station in a country where the load is high over a period of few months and electricity companies are overstressed during that period. A site selected using this approach will have an added advantage to further clip the load peak and release stress on electricity companies.

2. Materials and Methods

2.1. Data Collection

In order to find the most feasible regions for solar PV generation, a careful and accurate collection of data is very important. The data used in this study is one full year (December 2015 to November 2016) of solar radiation data gathered from 46 different locations in the K.S.A. The data is collected from King Abdullah City for Atomic and Renewable Energy (K.A.CARE). K.A.CARE has a RRMM network, which focuses on monitoring and mapping solar, wind, geothermal, and waste-to-energy resources in the K.S.A [31]. In order to acquire data for the spatial and temporal variability of solar resources, RRMM network has established solar resource monitoring stations (SRMS) at various locations throughout the Kingdom. Based on types and quantities of monitoring instrumentations, SRMS are classified into three tiers.

2.1.1. Tier 1 Research Stations

Tier one stations are most complete and complex stations with the highest accuracy of data. These stations provide data with low uncertainty of ±2%. Tier 1 stations are cleaned and checked on a daily schedule. All Tier 1 stations comply with the measurement practices described in the World Meteorological Organization (WMO) Baseline Surface Radiation Network (BSRN). These stations are further classified into three configurations:

- Configuration A—Research and Development Laboratory—These stations contain a full complement of radiometric instruments with independent and redundant solar radiation component data. This configuration also contains basic meteorological instruments plus horizontal visibility and dust deposition measuring instruments as well.
- Configuration B—Solar Broadband and Spectral Monitoring Station—This configuration contains all broadband solar radiometers, selected solar spectral radiometers, photometers, and pyranometers. This configuration also contains basic meteorological instruments plus horizontal visibility and dust deposition measuring instruments as well.
- Configuration C—Broadband Baseline Monitoring Station—This configuration contains basic meteorological instruments and other instruments to provide fundamental solar irradiance data (GHI, DNI, and GHI).

2.1.2. Tier 2 Mid-Range Stations

These stations provide solar resource and surface meteorological data with a baseline uncertainty of ±5%. These stations are cleaned and checked twice a week and provide one-minute data, averaged to hourly and daily data for ease of use.

2.1.3. Tier 3 Simple Stations

Tier 3 stations are arranged in a cluster of eight instruments measuring solar irradiance and temperature, surrounding a single rotating shadowband radiometer (RSR). The instruments on a simple station are clustered in approximately 4 km^2 area to characterize rapid solar resource variations.

2.1.4. Data Quality Assurance

The quality of data is assured on daily bases by visually inspecting all resources and stations operation data via graphs to make sure that data is within the acceptable established range and reasonably follows the acceptable patterns. This daily inspection approach helps to pinpoint the operational issues and reduce the harmful effects of distorted data. K.A.CARE used a more robust approach to ensure the quality of data by installation of a backup pyranometer of the same make and same model as the primary. The secondary pyranometer provides a redundant measurement of GHI at all the stations. This redundancy of GHI measuring instruments helps to trigger appropriate investigative measures and corrective actions in case one of the sensors may have an issue and sensors are reading in disagreement with high uncertainties. The three components of solar radiation (GHI, DNI, DHI) are analyzed with the help of an automated program SERI QC, utilizing the secondary redundant sensors, and viewing long-term pattern tendency and parameter ratios. Short duration data irregularities resulting from known cleaning periods are filled with values through interpolation or by using two known components to calculate the third one [32].

2.1.5. Solar Resource Monitoring Stations Network

K.A.CARE has planned 53 SRMSs across the country, out of which 46 stations are already established in all provinces of Saudi Arabia. Distribution of these stations in various provinces is shown in the Map in Figure 1 [38]. Table 1 provides the detailed information about all 46 installed stations locations with station name, city name, province name, and station type. It can be observed in Figure 1 and Table 1 that the bulk of the stations are installed in the central region and western coastal areas. The northern part of the K.S.A has fewer SRMSs. There are only a few stations in the eastern part of the country. A summary of all existing and planned stations, their types, and installation status are shown in Table 2. It can be seen in Table 2 that no Tier 3 simple stations have been installed yet. There are 18 Tier 1 (research) stations with a low-level uncertainty of ±2% and 28 Tier 2 (mid-range) stations with medium level uncertainty of ±5% [38].

Table 1. Solar resource monitoring stations details

Province Name	City	Station Name	Station Abbreviation	Station Type (Tier)
Al Baha	Al Baha	Al Baha University	Al Baha-University	1C
Al Jouf	Al Jouf	Al Jouf College of Technology	Al Jouf-TVTC	1C
Asir	Abha	Abha Technical Institute	Abha-TVTC	1B
	Al Farshah	Tuhamat Qahtan Technical Institute	Al Farshah-TVTC	2
Eastern Province	Al Ahsa	King Faisal University	Al Ahsa-KFU	1C
	Al Dhahran	King Fahd University of Petroleum and Minerals	Al Dhahran-KFUPM	2
	Al Dammam	Imam Abdulrahman Al Faisal University	Dammam-IAFU	1B
	Hafar Al Batin	Hafar Al Batin Technical College	Hafar Al Batin-TVTC	2
	Al Jubail	Saline Water Conversion Corporation (Jubail)	Al Jubail-SWCC	2
	Al Khafji	Saline Water Conversion Corporation (Al Khafji)	Al Khafji-SWCC	1C
Hail	Hail	Hail College of Technology	Hail-TVTC	1C

Table 1. *Cont.*

Province Name	City	Station Name	Station Abbreviation	Station Type (Tier)
Jazan	Farasan Island	Saline Water Conversion Corporation (Farasan)	Farasan-SWCC	2
	Jazan	Jazan University	Jazan-University	C
Madinah	Al Hanakiyah	Al Hanakiyah Technical Institute	Al Hanakiyah-TVTC	2
	Al Madinah	Taibah University	Taibah-University	1C
	Yanbu	Royal Commission of Jubail and Yanbu	Yanbu-RCJY	1C
Makkah	Hada Al Sham	King Abdulaziz University (East Hada Al Sham Campus)	Hada Al Sham-KAU	2
	Jeddah	King Abdulaziz University (Main Campus)	Jeddah-KAU	2
	Rania	Rania Technical Institute	Rania-TVTC	1C
	Makkah	Umm Al Qura University	Makkah-UQU	1C
	Osfan	King Abdulaziz University (Osfan campus)	Osfan-KAU	2
	Al Qunfudhah	Al Qunfudhah Technical Institute	Al Qunfudhah-TVTC	2
	Taif	Taif University	Taif-University	1C
	Thuwal	King Abdullah University of Science and Technology	Thuwal-KAUST	2
Najran	Alkherkheer	Al Kherkheer	Al Kherkheer	2
	Najran	Najran University	Najran-University	2
	Sharurah	Sharurah Technical Institute	Sharurah-TVTC	2
Northern Borders	Arar	Arar Technical Institute	Arar-TVTC	1C
Qassim	Qassim	Qassim University	Qassim-University	1B
Riyadh	Afif	Afif Technical Institute	Afif-TVTC	2
	Al Dawadmi	Al Dawadmi College of Technology	Al Dawadmi-TVTC	2
	Al Kharj	Prince Sattam bin Abdulaziz University	Al Kharj-SAU	2
	Layla	Al Aflaaj Technical Institute	Al Aflaaj-TVTC	2
	Majmaah	Majmaah University	Majmaah-University	2
	Riyadh	K.A.CARE Building Olaya St	Riyadh-K.A.CARE HQ	2
	Riyadh	K.A.CARE City Site Tier 2	Riyadh-K.A.CARE City T2	2
	Riyadh	King Saud University	Riyadh-KSU	2
	Riyadh	Princess Norah University	Riyadh-PNU	2
	Riyadh	Al Uyaynah Research Station	Riyadh-Al Uyaynah	1A
	Shaqra	Shaqra University	Shaqra-University	2
	Wadi Addawasir	Wadi Addawasir College of Technology	Wadi Addawasir-TVTC	1C
Tabuk	Duba	Duba Technical Institute	Duba-TVTC	2
	Hagl	Saline Water Conversion Corporation (Hagl)	Hagl-SWCC	2
	Tabuk	Tabuk University	Tabuk-University	1C
	Timaa	Timaa Technical Institute	Timaa-TVTC	2
	Umluj	Saline Water Conversion Corporation (Umluj)	Umluj-SWCC	2
	Al Wajh	Al Wajh Technical Institute	Al Wajh-TVTC	1C

Table 2. Network Statistics.

Station Type	# Stations Planned	Stations Online
Tier 1—Research Stations	18	18
• Configuration A—Research and Development Laboratory	-	1
• Configuration B—Solar Broadband and Spectral Monitoring Stations	-	3
• Configuration C—Broadband Baseline Monitoring Station	-	14
Tier 2—Mid- Range Stations	32	28
Tier 3—Simple Stations	3	0
Total	**53**	**46**

Figure 1. Map of solar resource monitoring stations (SRMS) network by province.

2.2. Analysis of GHI Solar Data for 46 Stations

One-year data for 46 installed stations was collected from K.A.CARE. Data from 44 stations is complete for the one-year study period from December 2015 to November 2016. Two stations have incomplete or no data. Princess Noora University Riyadh station has no data for the given period and Taif University station has one month of missing data (November 2016). GHI data for all the 44 stations is presented in Table 3. We analyzed the data in Table 3 to know the station wise pattern and trends of GHI in each region. It can be observed in Table 3 that a minimum average daily total GHI of 5542.6 Wh/m^2 is at Al Dhahran station, which is a Tier 2 station. Al Dhahran is a coastal area station in the eastern province with high water vapor and more cloudy weather, which is one of the factors to lower the level of GHI in this area. Jazan University station has the second lowest average daily total GHI during the study period followed by Farasan Island station at third lowest. Both of these stations are also coastal area stations in Jazan province in the western region of Saudi Arabia. Al Qunfudhah TVTC, again a coastal area station in Province of Makkah in the western region of K.S.A, has the fourth lowest average daily total GHI. AlKhafji—SWCC and Al Jubail—SWCC stations are placed in the fifth and sixth lowest positions. Both AlKhafji—SWCC and Al Jubail—SWCC stations are also coastal area stations situated in the coastal area of the eastern province. Here, the trend shows that coastal area stations on both eastern and western regions of Saudi Arabia have lower levels of GHI, which is linked to cloudy and humid weather of these areas.

Sharurah station has the highest average daily total GHI of 6654.5 Wh/m^2 and it is a Tier 2 station. The second highest average daily total GHI is observed at Najran University station, which has 6623.3 Wh/m^2 of GHI. Both of these stations are located in the province of Najran in the southern region of Saudi Arabia. Timaa TVTC station is third highest on the list with average daily total GHI of 6448.4 Wh/m^2. This station is located in the northwest part of the country in Tabuk province. Afif-TVTC with 6423.6 Wh/m^2 and Riyadh—K.A.CARE City T2 with 6413.9 Wh/m^2 are placed at fourth and fifth respectively in the top-ranked list. Both of these stations are in the central part of the K.S.A. Layla Al Aflaaj—TVTC and Wadi Addawasir—TVTC are the next two highest on the list and are also in the central region. There is one common thing in all of the high average daily total GHI stations that all of them are located in the areas where the weather is dry and humidity level is very low.

Table 3. Average daily total GHI data $\left(\mathrm{Wh/m^2}\right)$ for 44 stations across the country.

Station \ Month	December	January	February	March	April	May	June	July	August	September	October	November	Average Daily Total
Al Baha	4223.4	5070.6	6012.5	6591.5	6059.1	6705.1	7496	6798.5	6535.4	6462.6	6673.5	5533.8	6180.2
Al Jouf	3576.5	4213.8	5347.5	5948.5	7395.3	8115.6	8536.2	8453.7	7474.4	6718.2	5355.4	4137	6272.7
Abha	4382	4443.6	6304.7	7063.6	5620.9	6656	6928.4	5808.7	6086	6106.8	6740	5512.5	5971.1
Al Farshah	4675.5	4775.1	6013.9	6540.5	5483.1	6733.4	6396.2	5290.1	5831.2	5985.6	6538.4	5404.1	5805.6
Al Ahsa	3938.9	4301.5	5306.3	5333.2	6294.6	7453.5	7881.4	7623.2	7239	6594.9	5798.4	4401.5	6013.9
Al Dhahran	3372.4	3829	4866	4869.8	6110.4	7067.9	7548.6	7134	6657.1	6086.6	5182	3787.1	5542.6
Al Damam	3576.7	4081.6	5285	5248.1	6403.9	7434.1	7966.8	7557.4	7035.4	6546.2	5505.8	4005.1	5887.2
Hafar Al Batin	3238.3	3738.1	5090.2	5373.2	6927.2	7943.1	8240.1	8278.9	7491.3	6618.7	5601.5	4071.6	6051
Al Jubail	3303.6	3946.3	5158.3	5232.4	6536.5	7343.5	7835.6	7405.3	6870.2	6327.5	5290.4	3843.4	5757.7
Al Khafji	3139.4	3794.7	4999.2	5130.7	6579.8	7395.3	7745.7	7535.4	7022	6333.9	5186.6	3750.9	5717.8
Hail	3758.8	4217.2	5427.8	5794.1	6860.2	8047.6	8423.9	8393.4	7434.7	6720.4	5655.3	4304.2	6253.1
Farasan Island	4152.5	4190.3	5270.4	6143	6501.1	6512.5	6381.7	5615.9	5871.3	5966.7	5937.9	4823.2	5613.9
Jazan	4218.6	4235.5	5312	6044.4	6345.3	6515	6228.3	5356.4	5858.1	5986.7	5986.5	4942	5585.7
Al Hanakiyah	4035.4	4631.2	5625	5820.5	7143.3	7936.4	8066.3	7897.7	7040.3	6728.5	5894.3	4954.3	6314.4
Al Madinah	4028.	4523.5	5526.2	5727.6	6767	7868.4	7865.4	7847.6	7077.9	6520.7	5666.9	4840.6	6188.3
Yanbu	4234.1	4603.1	5635.1	5790.3	7261.2	7949.1	7829.2	7612.5	7001.8	6455.4	5458.7	4860.8	6224.3
Hada Al Sham	3618.6	4255.7	5279	6068.4	6687.3	7445	7498.2	6974.6	6517.7	6098.9	5723.7	4795.6	5913.6
Jeddah	3769.1	4295.1	5262.7	5906.9	6825.4	7375.7	7235	6776.9	6267.6	6132.4	5452.1	4578.8	5823.1
Rania	4316.3	4839	5862.7	6030.7	5990.8	7311.7	7679.3	7206.3	7089.5	6638.8	6483.3	5313	6230.1
Makkah	3901.2	4282.6	5375.6	6185.1	6718	7421.1	7510	6936.1	6461.4	6003.9	5778.5	4782.2	5946.3
Osfan	3909.7	4306.9	5352	5972.8	6987	7530.2	7368.4	6923.7	6418.1	6071.6	5525.2	4648.7	5909.5
Al Qunfudhah	4007.6	4440.9	5305.2	6228.4	6540.1	6707.4	6526.9	6143.1	6057.8	5890.7	5548.7	4917	5667.8
Thuwal	3840.6	4414.8	5339.1	6040.3	6923.1	7541.1	7365.2	6869	6498.6	6099.4	5491.9	4731.8	5929.6
Najran	4979.2	5358.7	6569.4	6892	6318.5	7646.9	7765.3	6958.8	7062.7	6960.6	6977.1	5990.8	6623.3
Sharurah	5088.4	5368.9	6383.1	6898.6	6639.4	7768.4	7642.5	7167	7106.1	7104.1	6862.1	5825.4	6654.5
Arar	3307.9	3819.5	5121.6	5858.8	7190.8	8008.5	8357.9	8472	7303.8	6663.9	5204.4	3974.8	6106.9
Qassim	3422	4250.7	5510.9	5637.6	6867.8	7839.4	8155.3	8182.6	7395.5	6606.2	5856.9	4392.2	6176.4

Table 3. *Cont.*

Station \ Month	December	January	February	March	April	May	June	July	August	September	October	November	Average Daily Total
Afif TVTC	4121.5	4740	5844	5999.2	6962.3	7820.6	8067.8	7836.5	7324.3	6881.8	6300.1	5185.5	6423.6
Al Dawadmi	4078.1	4706.5	5788	5882.7	6856.9	7791.8	8100	7802.9	7153.9	6803.7	6181.2	4572.5	6309.8
Al Kharj	3924.4	4494.3	5439.2	5644.2	6555	7162.1	7685.2	7490.3	6983.3	6468.1	5834	4284.4	5997
Layla Al Aflaaj	4265.1	4695	5936	6174.8	6563.9	7596.7	7967.4	7749.3	7299.6	6933	6385	5124.4	6390.8
Majmaah	3428.6	4326.5	5414.6	5387.3	6687.1	7605.3	7986.1	7888.1	7054.1	6549.6	5867.5	4240.4	6036.3
Riyadh Olaya	3812.2	4353.6	5280.1	5476	6618.7	7211	7668.1	7600.1	6930.2	6429.9	5790.5	4191.6	5946.8
Riyadh City T2	4150.4	4718.7	5761.5	5999.7	7053.4	7803.9	8179.8	8131	7465.4	6874.9	5255.2	4572.9	6413.9
Riyadh KSU	3943.3	4519.5	5507.8	5715.6	6880.5	7507.5	7997.9	7922.3	7282.8	6714.5	6044.9	4720.5	6229.8
Riyadh Al Uyaynah	3941.5	4496.8	5578.3	5628.5	6865.8	7558	8006.1	7938	7215	6665.7	6065.4	4419.7	6198.2
Shaqra	3894.6	4631.8	5638	5675.8	6974.2	7755.9	8069.9	7991.4	7329.5	6740.5	6081.6	4461.2	6270.4
Wadi Addawasir	4473.7	4942.1	6079.7	6390	6266.4	7327.2	7670.7	7228.2	7139.6	6798.5	6534.1	5510.3	6363.4
Duba TVTC	4067.8	4390.5	5492.1	5774	7230.4	7834.5	8077.6	7826.5	7013.3	6561	5395.1	4353.7	6168
Hagl	3662.5	3976.2	4953.1	5708.8	7115	7728	8031.3	7935.9	7073	6440.9	5108.5	3936.1	5972.5
Tabuk	3902.6	4352.4	5446.4	5922.6	7356.2	8055.9	8437	8322.8	7420.2	6833.7	5486.8	4239.6	6314.7
Timaa	3908.9	4514.6	5675.1	5978.2	7416	8294.1	8543.4	8335.9	7546.7	6895	5603.9	4668.5	6448.4
Umluj SWCC	4188.2	4483.7	5583.6	5733.2	7214.3	7835.1	7912.4	7648.3	6863.2	6385	5307.7	4710.3	6155.4
Al Wajh	4247.5	4228.4	5517.5	5860.7	7311.2	7982.2	8274.4	8038	7170.1	6713.8	5597.1	4681.9	6301.9

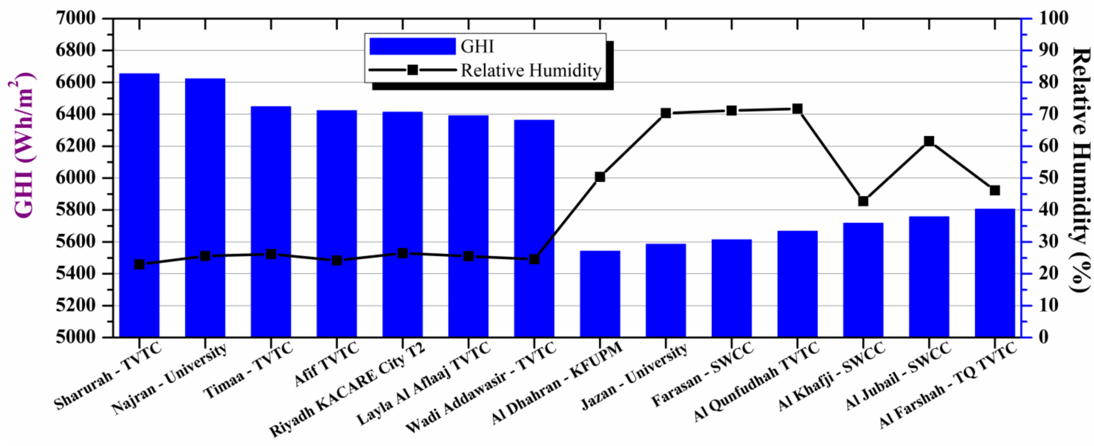

Figure 2. Average daily total GHI vs. relative humidity for the top seven and bottom seven stations with respect to GHI.

A plot of the average daily total GHI and relative humidity levels of the seven highest and seven lowest (GHI wise) stations is shown in Figure 2. Figure 2 clearly depicts that stations with low relative humidity have high daily average of GHI and vice versa. Six out of seven stations with low GHI are coastal area stations on both eastern and western coastal lines of Saudi Arabia. Eastern coastal area stations have relatively lower humidity level as compared to western coastal areas. Nevertheless, all the coastal area stations have relative humidity level of more than 50% except Alkhafji-SWCC station, which has a relative humidity level of 42.5%. Sea breeze brings a lot of moisture resulting in increased level of relative humidity. The relatively low level of humidity is due to wind direction and speed at Alkhafji. Wind speed at Alkhafji-SWCC station is 3.1 m/s and average wind direction is 236° (SW) as compared to Jubail-SWCC station with an average wind speed and wind direction of 3.6 m/s and 258° (WSW), respectively. Cross-wind at Jubail-SWCC brings lot of moisture from sea as compared to Alkhafji-SWCC station with lesser wind speed and different wind direction angle. This has resulted in lower relative humidity level at Alkhafji-SWCC as compared to Jubail station. None of the seven top-ranked stations are located in coastal areas. In fact, all of them are located in the dry areas with very low relative humidity levels of under or around 25%. A high level of relative humidity not only affects the GHI but it also affects solar PV modules and their efficiency as well. Although water vapors in the atmosphere are not visible to human eye, yet they are visible to solar cells. Corrosion is one of the major effects of humidity on solar cell and it becomes a grave issue if temperature is also high at the same time. In humid weather, the corrosion phenomenon may deteriorate the titanium–silver contact on silicon solar cells. High temperatures in the range of 40 °C–60 °C may result in long-term deterioration of these contacts [39]. Typically, the corrosion process accelerates under high humidity and high temperature conditions because of the presence of minute quantities of ionization contaminate (e.g., salts). Another effect of higher humidity is growth of fungus. High humidity levels around 75% to 95% and temperatures in the range of 20–40 °C result in higher growth rate of fungi [39]. Other effects include the formation of a sticky surface film of moisture that catches dust and dirt particles.

2.3. Methodological Approach towards Identification of Most Feasible Region for Solar PV System

The K.S.A's electric load has a unique aspect that country's load almost becomes double in the summer-time as compared to winter. In order to meet this high load demand in summer, a high penetration of renewable energy is inevitable. Over the last decade, peak load and consumption of electricity are growing at a rapid pace. Peak load is growing at an average pace of more than 7% [18]. Under the given economic and demographic trends, peak load is expected to be tripled by 2030 [40]. In order to find the regions which are most suitable for solar PV power generation, the stations with high GHI over one annum and stations with high GHI during high load summer season from April to October are analyzed and compared in this study.

Solar radiations and ambient air temperature are the two most important factors, which affect the performance of the PV system [41]. Solar radiation is a measure of the amount of sunlight falling on a given surface. The higher the solar radiation incident on a solar cell, the more energy a cell will produce. Other factors such as tilt angle of PV panels, fog, passing clouds, and dust accumulation effect the solar radiation hitting the PV surface. Ambient air temperature is another important parameter to be considered for PV energy output calculations [41]. Solar cells operate at much higher temperatures than ambient air temperature. As the ambient temperature increases, cell temperature further increases. The hotter the cell material is, the more resistance there is and the slower the electrons can move through it. The energy output of PV module decreases as the cell temperature increases. All of these factors differ from one site to another and from time to time over the span of one year. Similarly, the feasibility of PV system at a particular location depends on how effectively the PV system generated power can be used to clip the peak demand for electricity in high load season. Therefore, the shape of load profile is taken as an important parameter for the selection of a most feasible region for PV system. The solar resource data for the study period of one year is collected from RRMM network of K.A.CARE. There is not enough data for dust accumulation, therefore it is assumed that PV panels are regularly cleaned.

A 100 kW PV power system is designed in HOMER (Hybrid Optimization Model for Electric Renewable) software. It is a micro-grid computer modeling program which is developed by the National Renewable Energy Laboratory (NREL). It is a very powerful tool to evaluate the feasibility of renewable energy based system. Simulations are performed to evaluate the performance of the proposed 100 kW PV system at 44 locations across the Kingdom. The PV system is tested at each location and following performance analysis are considered for identification of the most feasible location for PV power generation:

- PV system total energy output over the period of one year;
- PV system total energy output during high load summer season;
- Annual yield factor (YF), which represents the number of times the PV system can produce its rated power over a period of one year;
- Summer season yield factor (YF), which represents the number of times the PV system can produce its rated power during a high load summer season;
- Annual capacity utilization factor (CUF), which measures the percentage of usability of a proposed PV system over a period of one year;
- Summer season capacity utilization factor (CUF), which measure the percentage of usability of a proposed PV system during a high load summer season.

3. Results and Discussion

3.1. K.S.A Load Curve vs. Solar Irradiance Pattern

A very important angle of analyzing GHI values is to match the pattern of GHI over the period of one year with annual load curve of the country. It is very important that solar radiation patterns follow the load curve. If high solar radiation is available during those months of the year when the load of the country is high, then this high radiation can really help to cut the peak of the load curve by the inclusion of solar PV power in the system. Figure 3 shows the annual load curve of Saudi Arabia for two consecutive years 2014 and 2015 [42]. It can be seen in the load curve that the load is high during summer from the month of April to October. The load is almost double during summer months.

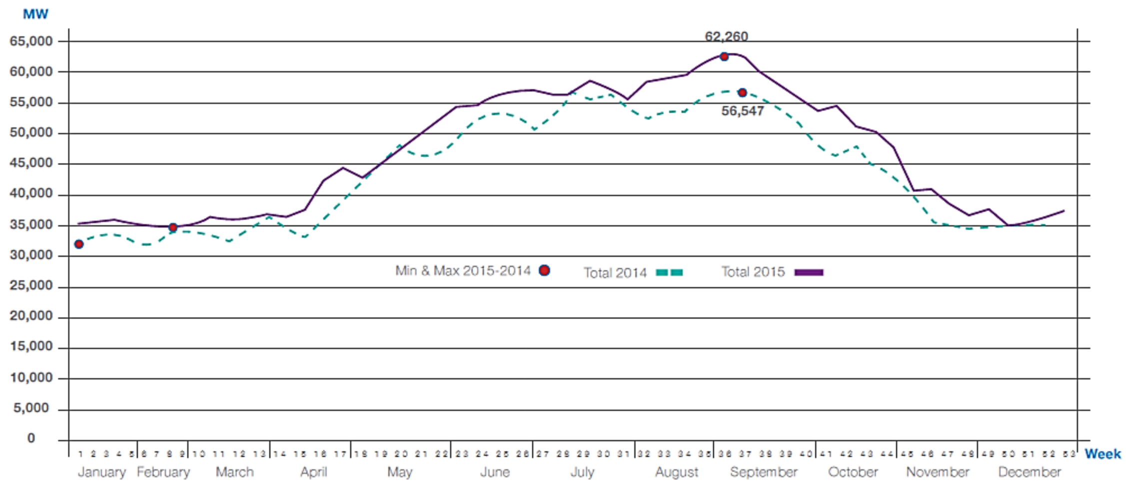

Figure 3. Annual load profile of Saudi Arabia.

Figure 4 presents total daily average GHI curve of 44 stations over the period of one year. It is evident from Figure 4 that solar irradiance of most of the stations follow the load pattern and GHI is on the higher side from April to October. There are few stations where the GHI does not follow the load pattern and their high value does not follow the high load months.

In order to find the most feasible stations from solar irradiance point of view, we need to compare average daily total GHI of all the stations in high load season from April to October. Figure 5 shows average daily total GHI during summer-time high load from April to October. Al Farshah TQ TVTC, Jazan University, Farasan SWCC, Abha TVTC, Al Qunfudhah TVTC stations do not follow the load pattern and have low GHI during the peak load season. It can also be observed in Figure 4 as well. Al Farshah TQ TVTC and Abha TVTC stations are located in Abha province. This province has humid weather. Jazan University and Farasan SWCC stations are in Jazan province. Both of these stations are located in the southwest coastal area. Al Qunfudhah is located in the southwest of Makkah province and it is a coastal area station as well.

Timaa TVTC, AlJouf TVTC, Tabuk University, Riyadh K.A.CARE City T2, Hail TVTC, Arar TVTC, and Afif TVTC stations are the top-ranked stations with very high GHI values during the summertime. Timaa TVTC and Tabuk University stations are located in Tabuk province. Tabuk province is in the northwest region of the country. Arar TVTC is located in the northern border province. AlJouf TVTC, Riyadh K.A.CARE City T2, and Afif TVTC stations are located in the central province of Riyadh. Hail TVTC station is in Hail province, which is also central region of the country. From here, we can conclude that central and northern regions have high GHI during the high load summer period. These stations follow the load pattern very well. High GHI during the high load season indicates that solar PV power generation is suitable to replace the high peak load of the country during summertime.

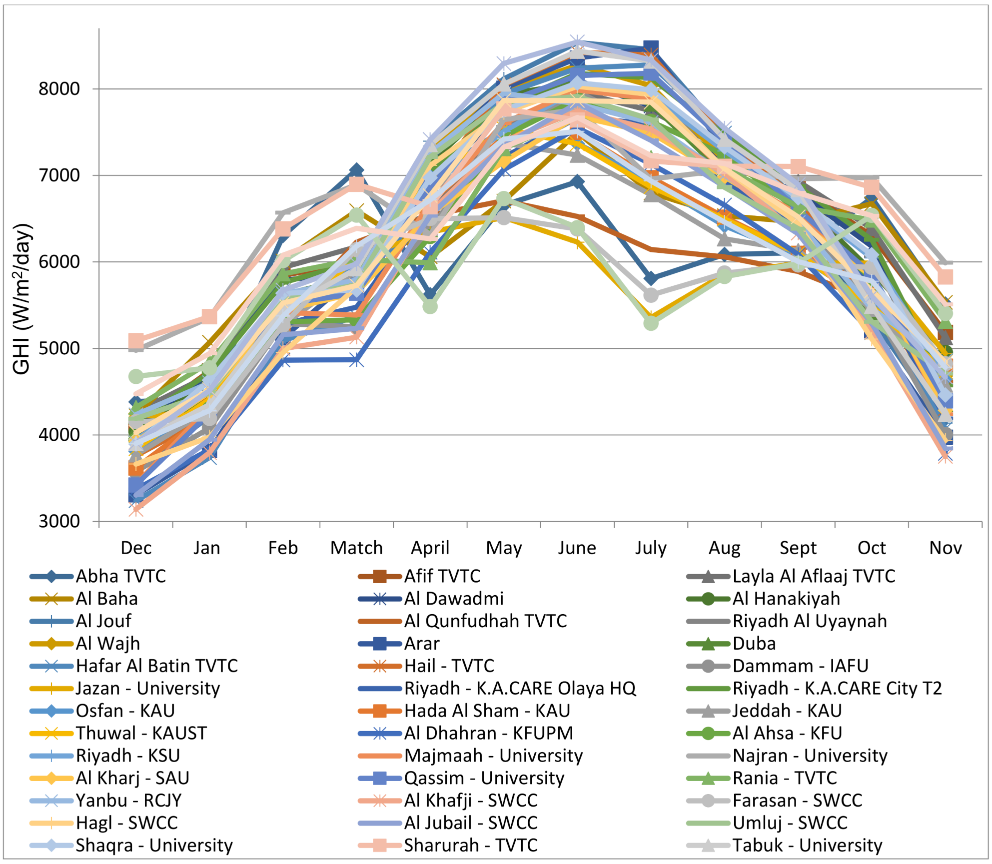

Figure 4. Average daily total GHI of 44 stations over the one-year study period.

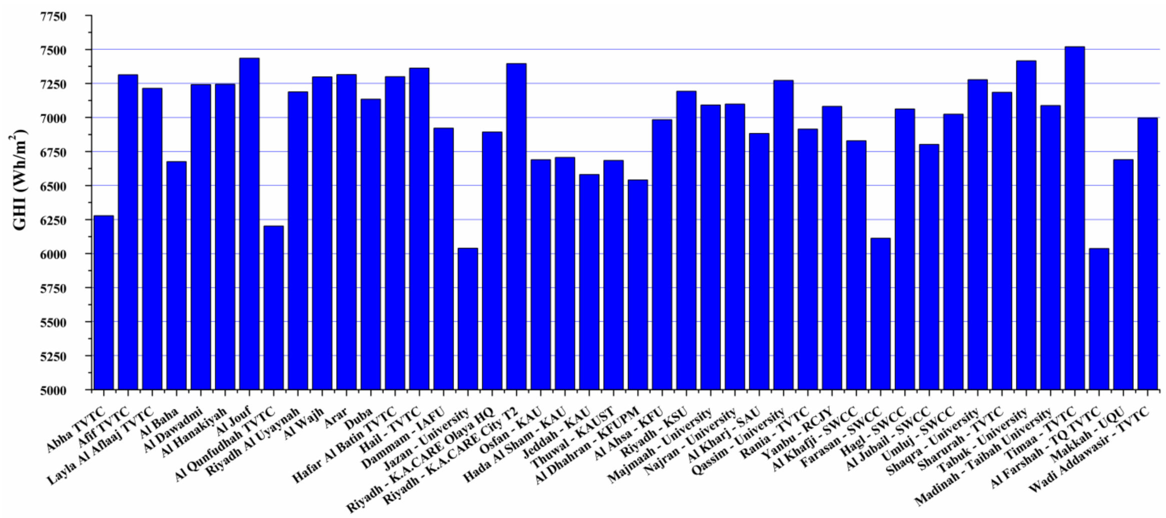

Figure 5. Average daily total GHI during high load summer season (April to October).

The best site for solar PV generation is the one with high GHI in peak load season as well as high GHI throughout the year. In order to find the regions, which are most suitable for solar PV power generation, we compare the stations with high GHI over one annum and stations with high GHI during high load summer season from April to October. Names and GHIs of the top 10 stations over the period of one year and top 10 stations during of high load season are summarized in Table 4. We can identify four stations in Table 4, which have high GHI in both one-year period and summertime high load period. These stations exhibit very good average daily total GHI during summer and they have high average daily total GHI over the whole year as well. Looking at the load pattern of Saudi Arabia, it can be concluded that these four stations could be the best candidate sites for Solar PV generation.

Table 4. Top 10 stations with highest average daily total GHI over the period of one year and during high load summer season.

Average Daily Total GHI over the Period of One Year		**Average Daily Total GHI during High Load Summer Season (April to October)**	
Station Name	**GHI (WH/m^2)**	**Station Name**	**GHI (WH/m^2)**
Sharurah TVTC	6654.5	Timaa TVTC	7519.3
Najran University	6623.3	Al Jouf TVTC	7435.4
Timaa TVTC	6448.4	Tabuk University	7416.1
Afif TVTC	6423.6	Riyadh K.A.CARE City T2	7394.8
Riyadh K.A.CARE City T2	6413.9	Hail TVTC	362.2
Al Aflaaj TVTC	6390.8	Arar TVTC	7314.5
Wadi Addawasir TVTC	6363.4	Afif TVTC	7313.3
Tabuk University	6314.7	Hafar Al Batin TVTC	7300.1
Al Hanakiyah TVTC	6314.4	AlWajh TVTC	7298.1
Al Dawadmi TVTC	6309.8	Shaqra University	7277.6

3.2. Performance Analysis of Photovoltaic System at Each Station

HOMER Pro software is used to find out the electrical energy production capacity of solar PV system at each station in various part of the Kingdom. A 100 kW solar PV system is designed in HOMER to obtain the PV power output at 44 different locations across the country. Flat plate mono-crystalline silicon modules are used in the analysis for HOMER software. The details about the module are provided in Table 5.

Table 5. PV module specifications.

Model Name	PV-MLU250HC Modules
Cell type	Monocrystalline Silicon 78 × 156 mm
Maximum power rating Pmax (Pmax)	250 W
Open circuit voltage V_{OC}	37.6 V
Short circuit current I_{SC}	8.79 A
Maximum power voltage (V_{mp})	31 V
Maximum power current (I_{mp})	8.08 A
Module Efficiency	15.4%
Normal operating cell temperature (NOCT)	45.7 °C

3.2.1. Analysis of PV System at 44 Locations

Figure 6 shows the total annual electrical energy produced by the proposed 100 KW solar power plant for 44 locations across the K.S.A. It is observed that Sharurah TVTC station gives the highest annual electrical energy output of 194,264 kWh followed by Najran University station with 193,351 kWh output. Timaa TVTC station produces third highest annual electrical output. Similarly, the three stations with the lowest annual electrical energy output are Al Dhahran KFUPM (161,793 kWh), Jazan University (163,053 kWh), and Farasan SWCC (163,875 kWh).

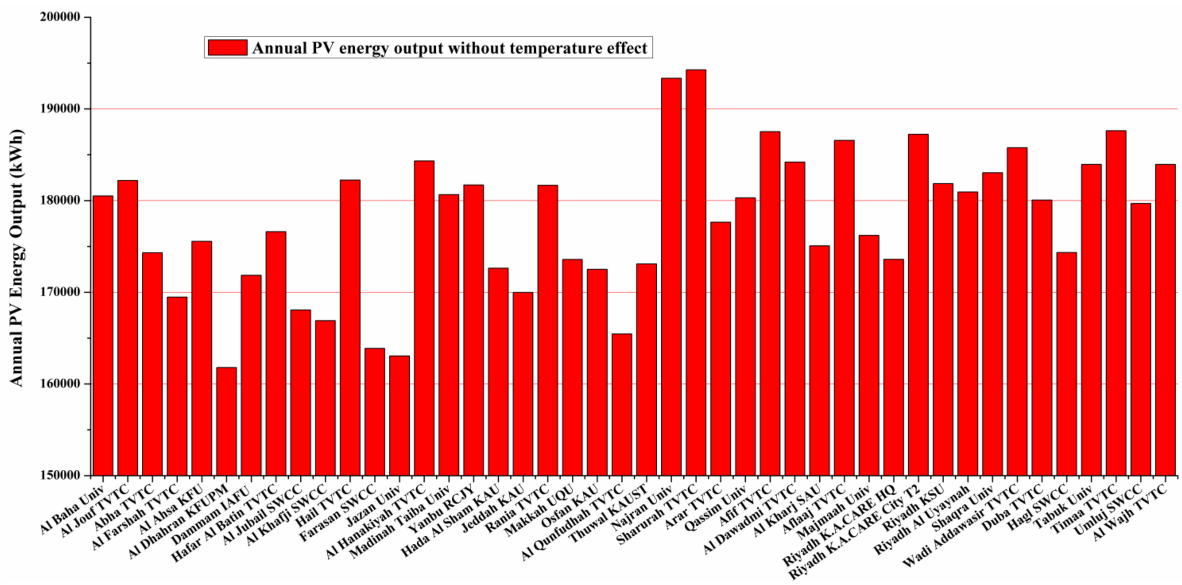

Figure 6. Electrical Energy (kWh) generated by 100 KW solar PV system at each station without temperature effect.

Temperature plays a pivotal role in the energy output productivity of PV modules. The output of the PV module decreases with increasing temperature. The ambient air temperature and daytime temperature of solar cells are not equal. As solar cells are dark in color, they absorb more sun energy, which causes a rise in cell temperature. As a result, solar cells operate at much higher temperature than the ambient air temperature. As the ambient temperature increases, cell temperature further increases and short circuit current somewhat increases but at the same time, open circuit voltage, fill factor (FF), maximum power output, and the efficiency decreases. Maximum output power of PV module decreases linearly with temperature [43]. The temperature coefficient of power for the selected module for this research is $-0.45\%/^{\circ}\mathrm{C}$ [44]. The output power of PV array is given by the equation

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,\, STC}} \right) \left[1 - \alpha_p (T_C - T_{C,\, STC}) \right] \tag{1}$$

where:

Y_{PV} : power output of PV array under standard testing conditions [kW]
f_{PV} : PV derating factor [%]
G_T : solar radiations incident on PV array in the current time step [kW/m^2]
$G_{T,\, STC}$: incident radiations at standard test conditions [1 kW/m^2]
α_p : temperature coefficient of power [%/°C]
T_C : PV cell temperature in the current time step [°C]
$T_{C,\, STC}$: PV cell temperature at standard test conditions [°C]

If we ignore the temperature effect on PV output then the above equation of PV out will reduce as under

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,\, STC}} \right) \tag{2}$$

Figure 6 shows the PV output of 100 kW solar power plant without considering the effect of temperature. The K.S.A is a country with very hot and long summer season. The temperature in some areas reaches 50 °C during summer season. It can be observed in Equation (1) that PV output decreases linearly with increasing temperature, therefore, it is very important to consider the effect of temperature while finding the most feasible sites for solar PV generation. Table 6 shows the average monthly daytime temperatures of 44 locations under study [38].

Table 6. Daytime ambient temperature (°C) at 44 stations across the country.

Station \ Month	December	January	February	March	April	May	June	July	August	September	October	November	Average Daily Total
Al Baha Univ	18.2	18	20.1	25.2	22.1	29.1	33.2	31.9	31.7	30.4	25.4	21.3	25.6
Al Jouf TVTC	11.3	12.0	16.5	20.3	26.2	29.5	35.5	36.6	37.7	33.0	28.1	18.5	25.3
Abha TVTC	15.2	14.5	16.6	20.5	17.9	23.4	26.0	24.6	23.4	23.6	19.9	16.8	20.2
Al Farshah TVTC	26.2	25.2	27.6	31.8	28.5	32.7	35.3	33.0	31.4	33.2	30.8	27.7	30.3
Al Ahsa KFU	19.2	18.7	21.3	25.9	29.2	36.5	40.0	41.8	41.3	38.0	31.9	25.7	30.8
Al Dhahran KFUPM	19.7	18.6	20.9	25.1	28.8	35.8	39.0	40.4	39.8	36.7	31.5	25.9	30.2
Dammam IAFU	19.6	18.3	20.2	24.4	27.9	34.2	37.4	38.8	38.4	35.7	30.7	25.3	29.2
Hafar Al Batin TVTC	13.9	14.5	18.9	23.7	28.7	35.2	39.7	41.8	42.5	37.8	31.3	22.0	29.2
Al Jubail SWCC	19.1	18.1	19.7	24.2	27.2	33.4	36.8	38.3	37.9	35.5	30.1	25.1	28.8
Al Khafji SWCC	16.0	15.6	18.5	22.9	26.4	32.3	36.9	38.6	37.8	34.6	28.9	22.0	27.5
Hail TVTC	12.6	13.3	17.0	20.9	25.3	30.7	35.0	36.7	37.2	33.8	28.4	20.0	25.9
Farasan SWCC	31.0	30.1	30.6	31.8	33.5	35.4	36.8	36.4	35.9	36.5	34.5	32.1	33.7
Jazan Univ	30.6	29.5	30.0	32.1	33.5	34.9	36.3	35.1	34.4	35.4	33.5	31.5	33.1
Al Hanakiyah TVTC	18.3	19.2	21.9	27.4	27.8	34.5	38.7	38.7	39.7	37.5	30.9	25.1	30.0
Madinah Taiba Univ	21.1	21.9	24.4	30.1	29.9	36.3	40.0	38.9	39.8	39.1	33.8	28.5	32.0
Yanbu RCJY	24.9	24.2	26.7	28.9	30.9	32.6	34.6	34.2	34.6	34.2	32.3	30.0	30.7
Hada Al Sham KAU	27.7	26.9	29.4	32.7	32.8	35.7	38.5	37.4	37.0	36.9	34.2	32.5	33.5
Jeddah KAU	28.5	27.6	29.5	32.1	34.6	36.0	37.8	38.4	37.2	36.5	34.5	33.0	33.8
Rania TVTC	20.8	20.4	22.6	29.4	25.4	34.5	37.8	38.4	37.9	35.5	28.9	24.4	29.7
Makkah UQU	28.4	27.1	29.6	33.6	33.1	37.5	40.1	38.6	37.5	37.9	34.6	32.3	34.2
Osfan KAU	27.3	26.0	28.8	30.2	34.5	35.3	36.8	37.1	36.3	35.5	33.6	31.8	32.8
Al Qunfudhah TVTC	30.5	29.2	29.8	32.1	33.9	34.7	35.7	35.6	35.5	35.4	33.3	31.8	33.1
Thuwal KAUST	27.0	25.9	27.7	29.4	31.3	32.8	33.4	34.7	34.6	34.0	31.8	31.0	31.1
Najran Univ	20.3	20.3	22.3	29.6	26.0	32.8	35.2	36.5	35.1	33.2	26.5	23.2	28.4
Sharurah TVTC	22.6	22.9	24.1	32.0	30.7	36.5	38.4	38.8	37.9	36.5	29.3	26.3	31.3
Arar TVTC	10.4	10.6	15.3	19.5	25.5	29.6	35.4	37.0	38.3	32.5	27.0	17.1	24.8

Table 6. *Cont.*

Station \ Month	December	January	February	March	April	May	June	July	August	September	October	November	Average Daily Total
Qassim Univ	15.1	15.9	19.2	24.4	27.1	33.7	37.8	39.4	39.5	36.4	29.6	22.0	28.3
Afif TVTC	16.9	17.3	19.7	25.7	24.8	32.6	36.0	37.2	37.0	34.9	28.3	22.7	27.8
Al Dawadmi TVTC	16.4	16.4	19.6	26.1	25.5	32.9	36.9	38.6	38.3	35.9	29.0	22.5	28.2
Al Kharj SAU	17.8	17.4	20.3	26.5	28.1	35.5	38.1	40.7	39.9	36.2	28.8	22.7	29.3
Aflaaj TVTC	19.7	19.3	21.7	27.9	28.8	36.8	39.4	41.1	40.5	37.5	30.6	24.9	30.7
Majmaah Univ	14.8	14.9	18.1	23.4	26.3	33.3	36.8	38.4	38.2	34.9	27.9	21.0	27.3
Riyadh K.A.CARE HQ	17.8	18.3	20.9	25.7	28.6	36.4	39.9	41.8	41.6	38.4	31.7	24.7	30.5
Riyadh K.A.CARE City T2	15.6	15.9	18.8	23.5	25.7	33.2	36.9	38.5	38.1	34.9	28.6	21.8	27.6
Riyadh KSU	17.5	17.5	20.6	26.4	28.3	35.8	38.8	41.1	40.6	37.2	30.3	24.2	29.9
Riyadh Al Uyaynah	15.5	15.8	18.1	23.2	25.7	33.1	36.3	37.8	37.6	34.7	27.7	20.0	27.1
Shaqra Univ	17.0	16.8	20.0	26.3	27.0	34.0	38.2	40.0	39.8	37.0	29.9	23.1	29.1
Wadi Addawasir TVTC	20.4	20.1	21.7	29.0	27.4	35.1	37.0	39.1	38.4	35.2	27.7	23.6	29.6
Duba TVTC	23.3	21.3	24.7	27.9	30.5	32.8	37.1	34.8	34.7	34.4	32.2	29.2	30.2
Hagl SWCC	20.5	18.8	22.9	24.2	29.5	30.2	33.9	33.9	33.7	31.9	29.8	26.2	28.0
Tabuk Univ	12.5	12.6	17.4	21.7	26.3	28.9	34.0	34.0	34.5	31.1	26.8	20.2	25.0
Timaa TVTC	13.4	13.7	18.8	23.7	27.1	31.0	35.9	36.6	37.7	34.2	29.4	21.8	26.9
Umluj SWCC	24.9	23.0	25.5	28.3	30.5	31.9	34.9	34.8	34.4	33.4	32.1	29.9	30.3
Al Wajh TVTC	22.5	21.1	24.2	26.7	28.8	30.6	33.3	33.0	32.7	31.4	30.3	28.3	28.6

3.2.2. Analysis of PV System at 44 Locations Including Temperature Effect

Figure 7 shows the total annual electrical energy output of the proposed 100 kW solar PV plant by taking into account the effect of temperature on PV output at 44 locations across the Kingdom. It is observed that Najran University station gives the highest annual electrical output of 172,083 kWh followed by Sharurah TVTC station with 170,184 kWh output energy. It was the other way around when temperature effect was not included in the analysis. The reason behind the shift in top-ranked stations is the higher temperature in Sharurah and moderate temperature in Najran during the summer season. The average daytime temperature of Sharurah over one year study period is 31.3 °C and average daytime temperature at Najran is 28.4 °C. Timaa TVTC is the third best with 166,957 kWh output. It can be observed by comparing energy production of the proposed PV plant in two cases (with and without temperature effect) in Figures 6 and 7 that if we consider the temperature effect, then ranking of most feasible stations may change. A particular station might have a good solar GHI but at the same time temperature at that site could be on the higher side and it will cause a reduction in the total annual output energy at that site. As Saudi Arabia is a hot country with very high temperature in the long summer season, so temperature plays a vital role in the selection of feasible PV sites.

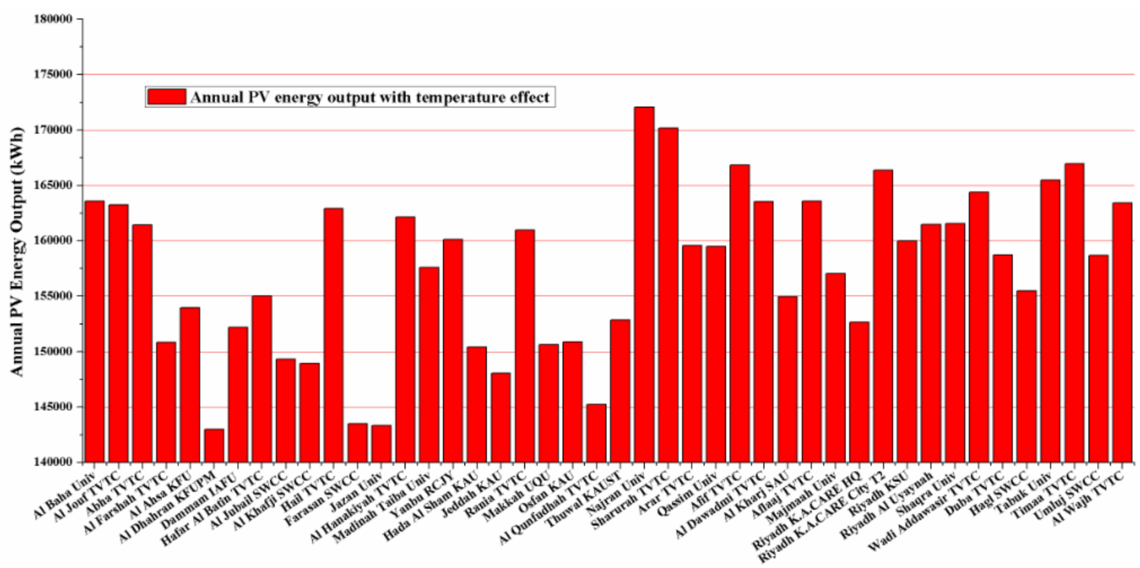

Figure 7. Electrical Energy (kWh) generated by 100 KW solar PV system at each station including temperature effect.

Figure 8 shows the yield factor (YF) of the proposed PV system at 44 locations. Figure 8 indicates that Najran University station has the highest YF of 1721 followed by Sharurah TVTC station with a YF of 1701.8 and the lowest YF is observed in Al Dhahran station which is 1429.9. Figure 9 shows the capacity utilization factor (CUF) of the proposed PV system at 44 locations, which is the measure of percentage usability of the PV system. Najran University station has the highest CUF of 19.6% followed by Sharurah TVTC station with 19.4%, and the lowest CUF is observed in Al Dhahran station, which is 16.3%.

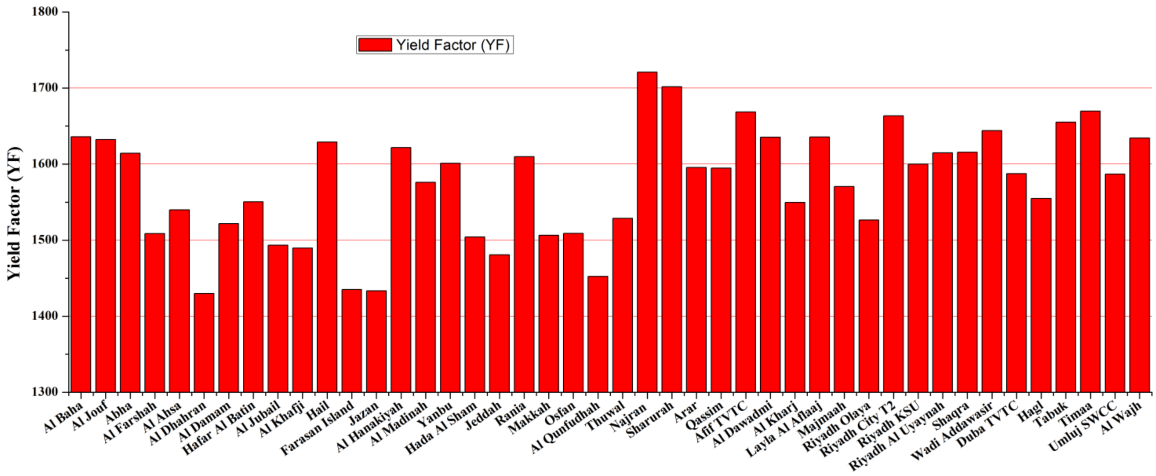

Figure 8. Annual yield factor (YF) of the proposed PV system at 44 locations.

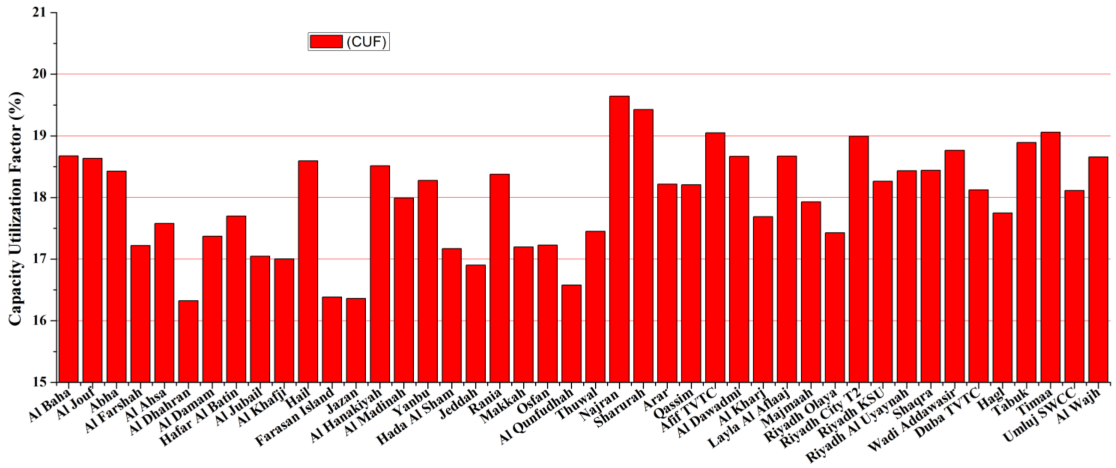

Figure 9. Annual capacity utilization factor (CUF) of the proposed PV system at 44 locations.

3.2.3. Analysis of PV System at 44 Locations in High Load Summer Season

The K.S.A has a unique load profile with the long summer season of high electric load from April to October. In order to find most feasible sites for solar PV generation, it is very important to consider the load profile as well. The K.S.A has to meet high load demand in the summer season, which is a very difficult task for electricity companies in the Kingdom. In this paper, one of the proposed selection criteria for the best site is to look for the solar PV feasible sites, which have high PV energy potential in the high load summer season. For this approach, the energy output production of a 100 kW PV plant is simulated in the high load summer season from April to October.

Figure 10 shows the energy output of the proposed PV plant at 44 locations during the high load summer months including the temperature effect. It can be observed in Figure 10 that Tabuk University station has the highest annual energy output of 110,250 kWh for the proposed 100 kW PV system during high load season and Timaa TVTC is at the second place with 110,148 kWh. Although Timaa TVTC has better GHI in the high load summer season as compared to Tabuk University station, but the high temperature at this location has pushed it down in the ranking. The average daytime temperature at Tabuk in high load summer season (April to October) is 30.8 °C and at Timaa is 33.1 °C. Al Jouf TVTC and Riyadh K.A.CARE City T2 are the next two in the list with 109,235 kWh and 108,647 kWh respectively.

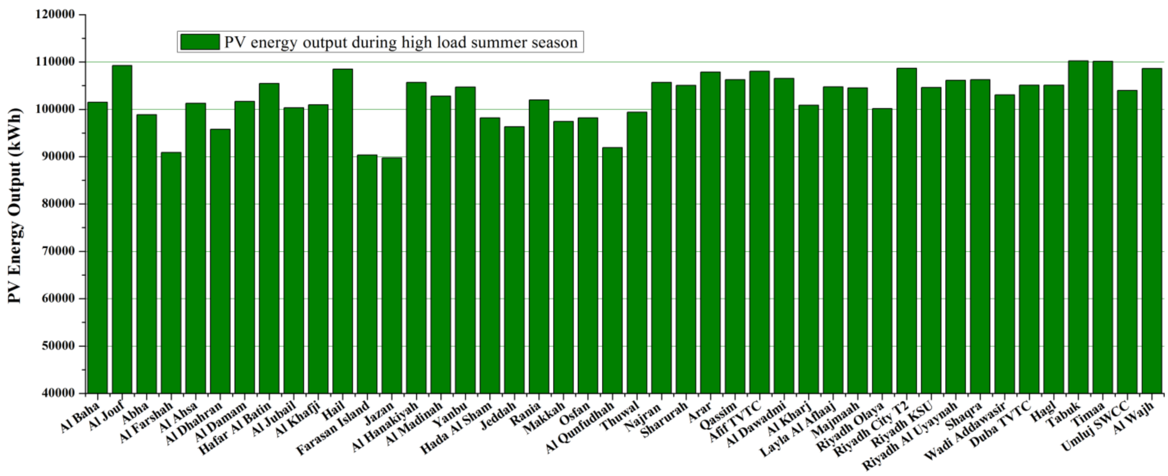

Figure 10. Electrical energy (kWh) generated by 100 KW solar PV system at each station during high load season including temperature effect.

Figure 11 shows the YF of the proposed PV system at 44 locations during high load summer season. It can be observed in Figure 11 that Tabuk has the maximum YF and Timma TVTC has the second best YF during high load summer season. Jazan has the minimum YF of 987.2 during high load summer season. Capacity utilization factor of proposed PV system during high load summer season at 44 locations is presented in Figure 12. Tabuk and Timma are closely placed at the first and second positions with PV CUF of 21.46% and 21.44% respectively followed by Al Jouf TVTC with third best CUF of 21.27%. Jazan has the lowest CUF of 17.47%.

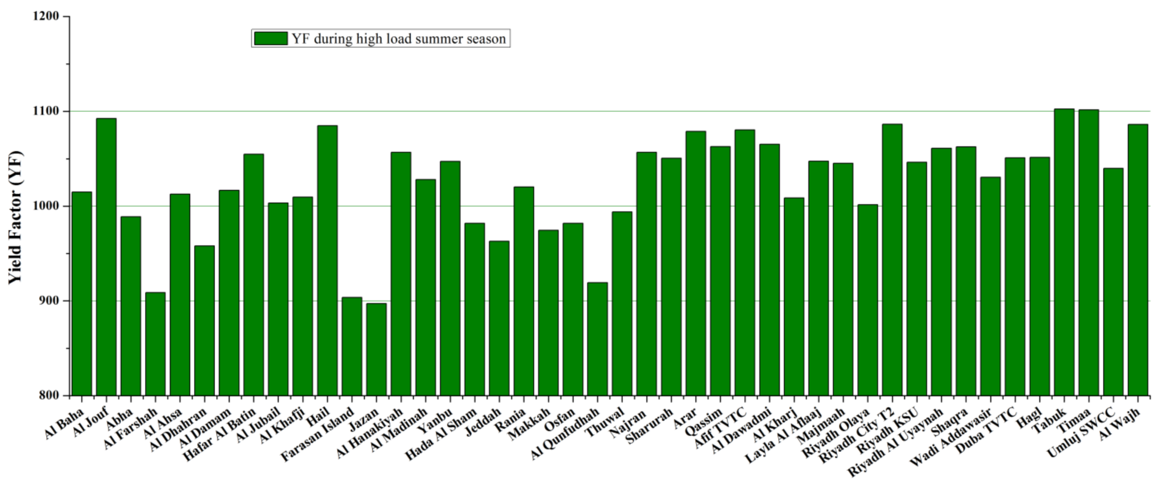

Figure 11. Yield factor (YF) of the proposed PV system at 44 locations during high load summer season.

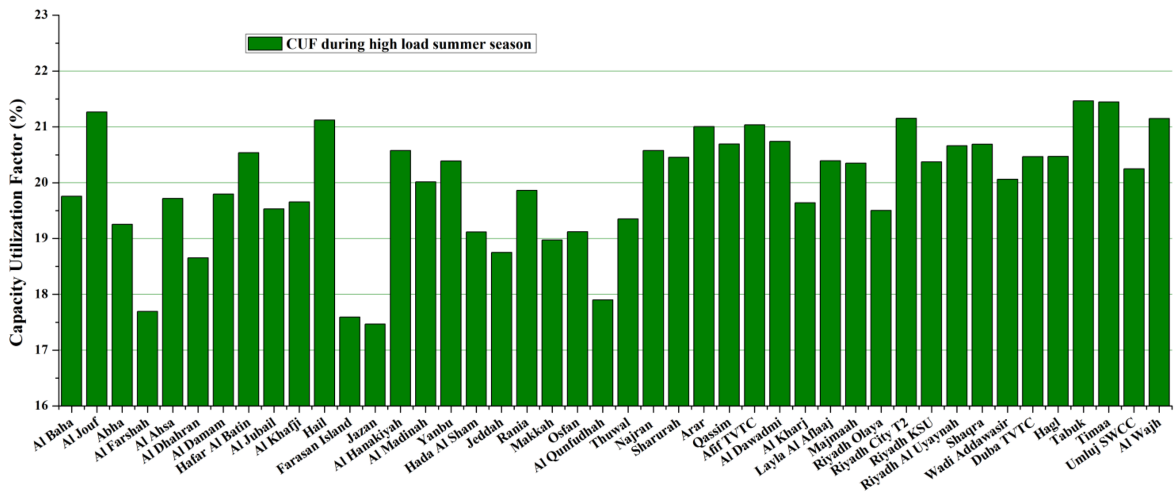

Figure 12. Capacity utilization factor (CUF) of the proposed PV system at 44 locations during high load summer season.

3.3. Ranking of Stations

Figure 13 shows the ranking of 44 station sites under study based on the average daily total GHI, annual energy output, and CUF of a proposed 100kW PV system at each location over the period of one year. Here, it can be observed that the top-ranked stations with respect to average daily total GHI do not share the same ranking position in annual PV energy output and CUF ranking. Therefore, it can concluded that a station with highest average daily total GHI does not guarantee to be the best station for solar PV power production because ambient temperature at the site plays a vital role in PV output energy production. Sharurah TVTC is the top-ranked station with highest average daily total GHI but when this station is tested with a 100 kW PV plant, then it is moved to second place with respect to energy output and CUF. Najran University station, which has the second highest average daily total GHI but it is the top-ranked station when it comes to PV energy output and CUF because of the moderate temperature in Najran as compared to Sharurah. Similarly, Tabuk University station has moved up from eighth to sixth position above Layla Al Aflaaj and Wadi Addawasir stations. On the other hand, Layla Al Aflaaj has the sixth highest average daily total GHI but it is moved down to ninth place with respect to PV energy output and CUF. The reason again is the moderate temperature at Tabuk and relatively higher temperature at Wadi Addawasir and Layla Al Aflaaj stations. Daytime average temperature at Tabuk station is 25 °C, while daytime average temperatures at Wadi Addawasir and Layla Al Aflaaj stations are 29.6 °C and 30.7 °C respectively. Al Hanakiyah has the ninth best average daily total GHI but it is not in the top 10 PV energy output stations. Similarly, Al Baha station is not in the 10 best daily GHI stations but it is at number 8 in the top 10 stations with respect to PV energy output and CUF of PV plant. Daytime average temperature at Al Hanakiyah and Al Baha stations are 30 °C and 25.5 °C respectively. Out of top 10 stations with respect to GHI, 4 have different rankings when listed with respect to their CUF and PV energy output.

Figure 14 shows the ranking of 44 stations during high load summer season based on the average daily total GHI, PV energy output, and CUF of proposed 100 kW PV system at each location. There are a greater number of shifts in the position of top-ranked stations when a comparison is performed during high load summer season. With respect to GHI, 7 out of top 10 stations have different rankings when they are listed with respect to their PV energy output and CUF in high load summer season and 2 stations even do not find a place in top 10 PV energy output and CUF stations. Hafar Al Batin and Shaqra University stations have the 8th and 10th best GHI in K.S.A in summer season but they are not in the top 10 PV energy output and PV CUF stations ranking. Greater number of shifts here is due to very hot summer in the K.S.A.

Figure 13. Ranking of stations based on average daily total GHI, annual PV energy output, and capacity utilization factor.

A comparison of the top 10 stations with respect to GHI and top 10 stations with respect to PV energy output, and shift in the position of stations over the period of one year and during the high load summer season is presented in Table 7. It is clear that high average daily total GHI is not a sufficient criterion to find the best location for a PV plant because there are other factors which affect the PV energy output as well. The magnitude of the impact of other factors could be different under different weather conditions in different countries. As the K.S.A has hot weather, impact of temperature on PV energy output is greater.

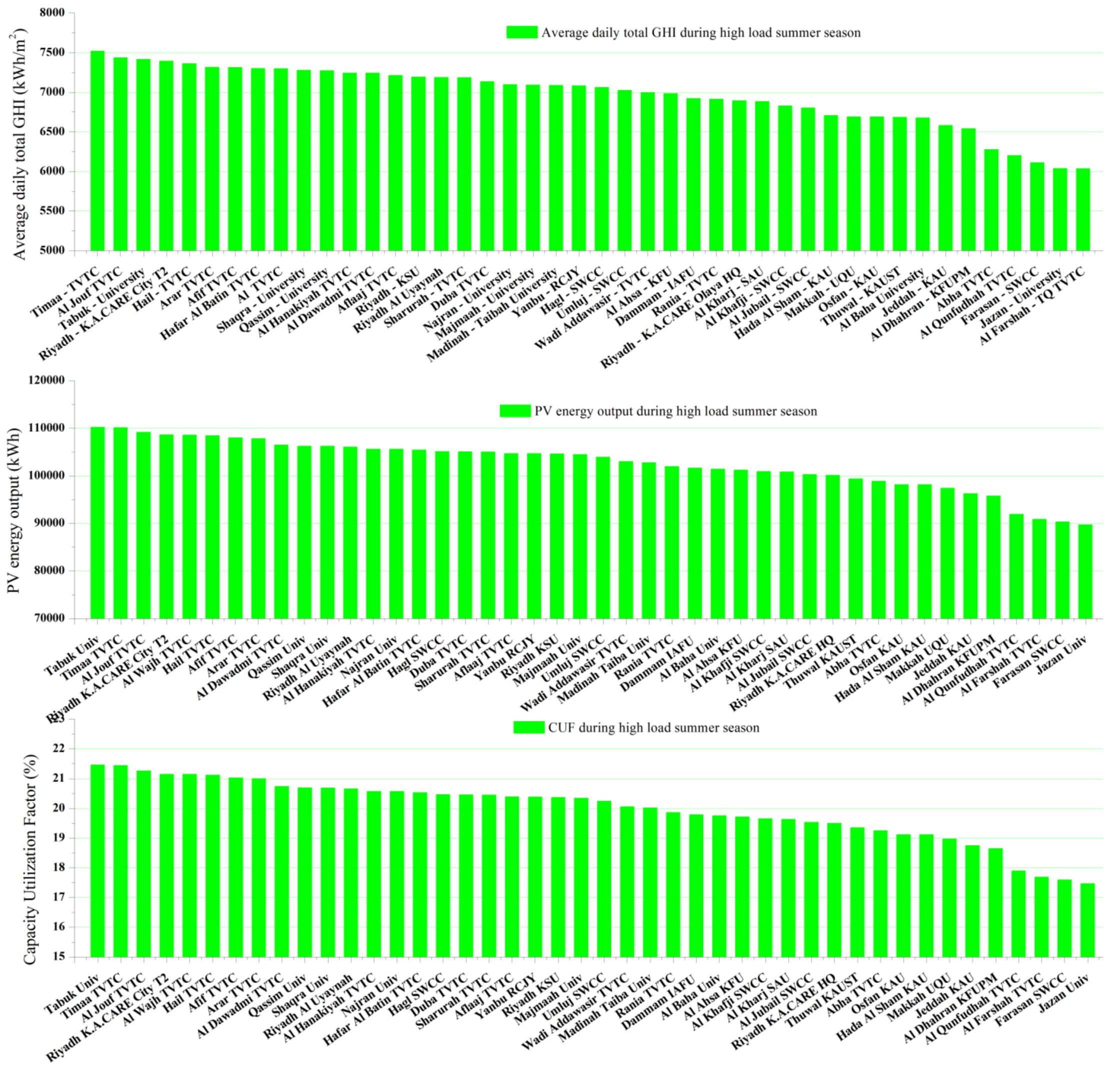

Figure 14. Ranking of stations based on average daily total GHI, annual PV energy output, and capacity utilization factor.

The proposed criterion to choose the most feasible sites is to select only those sites, which find their place in top-ranked stations in both cases (high annual and high summer). The sites selected based on this criterion are feasible both economically and clipping the high load peaks in summer months. The scores of top-ranked sites in each case (high annual and high summer) and their rankings are shown in Table 8. Timaa TVTC, Tabuk University, and Al Wajh TVTC stations are located in the northern province of Tabuk. Riyadh K.A.CARE City T2, Afif TVTC, and AL Dawadmi TVTC stations are located in the Central province of Riyadh. Tabuk province in the northern region and Riyadh province in the central region are the two most feasible regions for solar PV generation. The overall score of Tabuk province is 38 (Timaa TVTC: 17, Tabuk University: 15 and Al Wajh TVTC: 6) and an overall score of the central province, Riyadh, is 27 (Riyadh K.A.CARE City T2: 13, Afif TVTC: 11 and AL Dawadmi TVTC: 3). From here, it is concluded that northern province of Tabuk is the most feasible region for solar PV generation. Two of the top three stations in Tabuk region are Tier 1 stations with low level uncertainty of ±2% and all three stations of Riyadh region are Tier 2 stations with medium level uncertainty of ±5%. The results for the Tabuk region are relatively more accurate than the Riyadh region. The Tabuk region lead by a big margin, so this small uncertainty in the measured data in the Riyadh region does not affect the final results.

Table 7. Top 10 stations (both annually and high load season) with respect to GHI and top 10 stations with respect to PV energy output.

Average Daily Total GHI and PV Energy Output Ranking over the Period of One Year			Average Daily Total GHI and PV Energy Output Ranking during High Load Summer Season (April to October)		
Average Daily total GHI Stations	**PV Energy Output Stations**	**Change in Ranking**	**Average Daily Total GHI Stations**	**PV Energy Output Stations**	**Change in Ranking**
Sharurah TVTC	Najran University	1 ▲	Timaa TVTC	Tabuk University	2 ▲
Najran University	Shahrurah TVTC	1 ▼	Al Jouf TVTC	Timaa TVTC	1 ▼
Timaa TVTC	Timaa TVTC	0	Tabuk University	Al Jouf TVTC	1 ▼
Afif TVTC	Afif TVTC	0	Riyadh KACARE City T2	AlWajh TVTC	5 ▲
Riyadh KACARE City T2	Riyadh KACARE City T2	0	Hail TVTC	Riyadh KACARE City T2	1 ▼
Aflaaj TVTC	Tabuk University	2 ▲	Arar TVTC	Hail TVTC	1 ▲
Wadi Addawasir TVTC	Wadi Addawasir TVTC	0	Afif TVTC	Afif TVTC	0
Tabuk University	Al Baha University	12 ▲	Hafar Al Batin TVTC	Arar TVTC	2 ▼
Al Hanakiyah TVTC	Aflaaj TVTC	3 ▼	AlWajh TVTC	Al Dawadmi TVTC	4 ▲
Al Dawadmi TVTC	Al Dawadmi TVTC	0	Shaqra University	Qassim University	0
	Al Hanakiyah TVTC	5 ▼		Shaqra University	1 ▼
				Hafar Al Batin TVTC	7 ▼

[1] ▲ Increase in ranking, ▼ Decline in ranking.

Table 8. Score of top-selected sites.

Station Name	Annual Performance Ranking	Score	Summer Season Performance Ranking	Score	Total Score
Timaa TVTC	3	8	2	9	17
Tabuk University	6	5	1	10	15
Riyadh K.A.CARE City T2	5	6	4	7	13
Afif TVTC	4	7	7	4	11
Al Wajh TVTC	11	0	5	6	6
Al Dawadmi TVTC	10	1	9	2	3

4. Conclusions

This paper analyzes and compares solar radiation and PV system performance at 44 locations in different areas of Saudi Arabia. This research has several key findings about the selection of the best site for a solar PV system. The criterion proposed in this paper compares GHI and PV energy production with the load profile while taking into account a key factor (temperature) which is also responsible for very high load in the country during summer season. Most of the locations in the K.S.A have high GHI, which are well suited for solar PV generation. However, some areas have very high temperatures, which degrade the performance of PV technologies; as a result, those sites have lesser

PV energy output in spite of having very good solar resources. Very interesting results were observed when a comparison of GHI and PV system performance, over the period of one-year vs. the high load summer season, was performed. Some of the top ranked sites with excellent GHI resource are not even in the top 10 sites in the country when it comes to real PV system performance. The best-selected sites are those which have high annual PV energy output and high output during the high load season. Tabuk province in the northern region and Riyadh province in the central region are the two most feasible regions for solar PV generation. The overall score of Tabuk province is 38 and the overall score of the central province of Riyadh is 27. From these results, it is clear that the northern Province of Tabuk is the most feasible region for solar PV generation. A site selected based on this criterion will be economically most feasible out of the lot and at the same time, it will release the stress on electricity companies during high load season by clipping the peak load during daytime in the hot summer period. The data and analysis presented in this paper will be beneficial for policymaking as well as for planning the best locations for solar PV. The results of this research are critical in guiding policies, reducing the risks for deploying solar facilities, and providing judicious information for construction of solar facilities. The same approach can be used in other countries where a correlation between solar resource, PV energy output, and load profile exists.

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