IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received October 2, 2019, accepted October 29, 2019, date of publication November 5, 2019, date of current version November 15, 2019.

Digital Object Identifier 10.1109/ACCESS.2019.2951688

Performance Evaluation of Two Similar 100MW Solar PV Plants Located in Environmentally Homogeneous Conditions

SYED FAIZAN ALI SHAH[1], IRFAN A. KHAN[2], (Member, IEEE), AND HASSAN ABBAS KHAN[3], (Member, IEEE)

[1]Energy Department, Government of Punjab, Punjab 54000, Pakistan
[2]Marine Engineering Technology in a joint appointment with Electrical and Computer Engineering, Texas A&M University, Galveston, TX 77553, USA
[3]Electrical Engineering, Lahore University of Management Sciences, Lahore 54000, Pakistan

Corresponding author: Irfan A. Khan (irfankhan@tamu.edu)

The open access publishing fees for this article have been covered by the Texas A&M University Open Access to Knowledge Fund (OAKFund), supported by the University Libraries and the Office of the Vice President for Research.

ABSTRACT With recent steep decrement of Photovoltaic (PV) module prices, many utilities around the world are investing in large scale solar PV power plants to meet their energy needs. Countries with an ample amount of deserted areas tend to utilize it for the purpose of energy generation. This article reviews two equal power rated solar PV power plants with similar environmental conditions located next to each other with similar installed equipment but different output energy generation. Various factors affecting the generation of these technically similar power plants such as PV module tilt angle, inter row spacing, annual degradation effect, the negative temperature coefficient of power and other causes are explored evaluate the performance along with the assessment of reasons for deviation in the performance. The energy output trend and the percentage difference for each month for a complete year are graphed for analysis with and without considering the degradation effect to give a level playing field for both the PV plants under review. The efficient design of tilt angle, inter row spacing for the area of installation with the help of sun charts and shading occurrence diagram, is of utmost importance to maximize the energy yield. Any laxity in designing these parameters result in heavy financial losses to the investor which multiply over the life cycle of the project. Similarly, an improved and proper design can increase the energy output and have a positive impact on the financial savings of the investor which in this case is USD 0.85 million per annum.

INDEX TERMS Solar PV technology, inter row spacing, solar design, tilt angle, energy output, very large scale photovoltaic (VLS PV) systems, ground cover ratio (GCR).

I. INTRODUCTION

Many countries like China, USA, India and others in the Middle East region are heavily investing in solar energy to reduce the basket electricity prices and promote environmentally friendly technologies. The price of solar modules have decreased up to 86% from 2010 to 2017 [1], resulting in levelized cost of electricity (LCOE) as low as 0.03USD [2]. According to International Energy Agency (IEA), China, United States, India and Japan have installed 53GW, 10.6GW, 9GW and 7GW of solar PV power plants in the year 2017, respectively and these figures are expected to increase for 2018.

From a commercial perspective, every solar photovoltaic (PV) power plant developer intends to extract the maximum amount of energy from the available space of land or rooftop [3]. Many factors play a role in optimizing the maximum generation from the installed capacity [4], [5]. The selection of topologies of the PV systems along with grid configurations play a role in the overall power losses [6]. The optimized design of PV power plant is one of the most crucial aspects because the resource (sunlight) is not under user control unlike other conventional generation technologies such as thermal or Nuclear. Therefore, the major goal for very large scale photovoltaic (VLS-PV) system designers

The associate editor coordinating the review of this manuscript and approving it for publication was Qiquan Qiao.

is to maximize the performance ratio. With optimal design depending upon the geographical location of the installation area [7].

Sunlight varies from the Southern hemisphere to the Northern hemisphere. Thus, two solar PV plants of the same rated DC capacity may generate different energy due to varying Global Horizontal Irradiance (GHI) [8], [9]. Furthermore, a solar PV plant in Europe may require larger area (due to the larger number of PV modules) to generate the same amount of energy as compared to a solar PV Plant installed in Asia [10].

One of the requirements of a large scale solar PV system is suitable amount of area [11]. VLS PV systems over the last decade have become increasingly popular in areas with low-cost land [12]. Lower values of ground cover ratio (GCR) can be achieved in such areas [13] contributing to higher outputs and economic benefits. This is one of the reasons solar PV plants are more commonly found in the desert areas around the world [14], [15].

A general expectation is that two plants in close vicinity produce similar energy. However, this may not be the case as we analyze the data from two large plants in Pakistan.

It is worth highlighting that to the best of authors' knowledge, till date, there never has been a comparison of two VLS-PV Power systems installed in the same desert with the same environmental conditions. Such a comparison is essential in figuring out the shortcomings in design and penning down recommendations for designers and developers to avoid in the future development of VLS-PV systems in similar conditions, This paper compares the varying output from two solar PV power plants located in close vicinity of each other in Bahawalpur desert region of Pakistan and evaluates the reasons for mismatch. Subsequently conclusions and recommendations in design are proposed. Additionally, this paper outlines the factors affecting the output excluding the environmental factors and presents a detailed analysis for the reasons. Furthermore, it presents the area-specific recommendations for designers to cater to the GCR, tilt angles, sun charts in designing their PV systems optimally.

This paper contributes to the field of VLS-PV systems by presenting a detailed comparison of two similar PV Power Plants located in same area for exploring the reason of difference in energy yield by nullifying the environmental factors. Due to the closeness of location the environmental conditions are expected to be same. Important critical parameters influencing the energy generation of the installed PV systems are studied and the annual energy outputs for one year i.e., 2017 are analyzed. Subsequently, the difference in tilt angles, inter row spacing and GCR of the two power plants is also compared. Furthermore, financial losses of the power plant producing less energy are calculated. Finally, after comparison, recommendations for optimized parameter selection are discussed for future deployments.

The rest of the paper is organized in the following order. Section 2 highlights the solar market situation in Pakistan. Section 3 enlists the factors affecting the energy output of two plants located in close vicinity having similar environmental conditions. The energy output of Pakistan's two VLS PV systems are compared in section 4 and differentiating factors explored in section 5. Section 6 suggests the changes and reasons for these changes. Section 7 evaluates the financial losses and finally, conclusions are presented in section 8.

II. SOLAR MARKET OF PAKISTAN

Fortunately, Pakistan is blessed with receiving abundant sunlight with a global horizontal irradiance (GHI) level of over 1500 kWh/m^2 in 90% of the country [16]. With the increase in annual percentage rise of global temperature, the world decided to divert its direction from the fossil fuels to alternate energy. Considering this, 194 nations under the United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties 21 (COP21) in Paris in 2015 and agreed to commit to limit the global carbon emission levels and reduce the pace with which the annual rise in temperature is in- creasing. It was agreed; "*Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*" [17]. Like many other Asian countries, Pakistan also committed to reduce its carbon emissions and encourage the dependence on renewable energy and deploying methods for efficient energy utilization since energy is currently the largest contributing sector in Pakistan's emissions profile, contributing nearly 46 percent to total emissions and its share is likely to grow significantly in future [18].

Pakistan immediately increased its efforts in utilizing the natural resources. Although wind power plants had previously been set up in the Sindh province, it was the Government of Punjab who explored the feasibilities of setting up large utility scale solar power plants in Punjab. Quaid e Azam Solar Park (QASP) resulted from these efforts which currently has installed capacity of over 400MWp and is expected to reach 1000MWp within next couple of years. The distribution of these Solar Power Plants is mentioned in Table 1. This paper will consider the first two Solar PV power plants mentioned in Table 1 i.e. 100MW Quaid e Azam Solar Power Plant (QASPP) & 100MW Appolo Solar Power Plant (ASPP).

First four out of the six solar power plants are favorable for techno-economic comparison due to equal MWp capacity and similar operating conditions due to all being located in close vicinity in Quaid e Azam Solar Park (QASP), Punjab as shown in Fig.1.

III. FACTORS AFFECTING THE ENERGY OUTPUT OF THE SOLAR PV PLANT

One of the significant factors affecting the output of the solar PV Plant is the solar irradiation intensity incident on the installed PV panels. Since the radiation levels are different (or can be different) at various locations around the globe, the location of the installed PV plant plays an important role.

TABLE 1. Details of operational solar PV power plants in pakistan.

Sr. No	Name of PV Plant	Capacity(MW)	Location
1	Quaid e Azam Solar Power Plant	100	QA Solar Park Bahawalpur
2	Appolo Solar Power Plant	100	QA Solar Park Bahawalpur
3	Best Green Energy Power Plant	100	QA Solar Park Bahawalpur
4	Crest Energy Power Plant	100	QA Solar Park Bahawalpur
5	Harappa Solar	18	Sahiwal, Punjab
6	Aj Solar	12	AdhiKot, Khushaab, Punjab
7	Oursun	50	Gharo, Sindh

FIGURE 1. Location of the 4 × 100 MW Solar Power Plants in Quaid e Azam Solar Park Bahawalpur, Pakistan.

However, if the comparison is to be carried out for two very similar power plants located adjacent to each other with the same environmental conditions, then factors such as temperature, humidity level, cloud cover, rainfall, soiling effect etc. are considered similar. Subsequently, the remaining short-listed influential factors are given below:

i. Type of PV module
ii. Pitch of PV row
iii. Tilt of PV modules
iv. Degradation effect on PV Panels
v. Cleaning frequency of PV modules
vi. Balance of system (BoS) losses
vii. Power transmission losses through MV & HV system
viii. Non project missed volume (NPMV) due to outages of different transmission circuits

In the following sub-sections, each of these factors will be discussed in details.

A. TYPE OF PV MODULE

A wide range of PV technologies are currently available for utility scale installations. Some of the popular technologies are silicon-based mono and poly crystalline, thin-film technologies of amorphous silicon (a-Si), cadmium telluride (CdTe), copper-indium-gallium-diselenide (CIGS), multi- junction & emerging technologies such as Organic PV (OPV) and Concentrating PV (CPV) technologies. Crystalline silicon modules represent about 85% of the global PV market. Space requirements for crystalline PV are around 7–8 m^2/kWp (4.5 – 5 acres/MWp) and for thin-film PV, it is around 10–15 m^2/kWp (9–10 acres/MWp). Table 2 shows a comparison of common PV technologies [19].

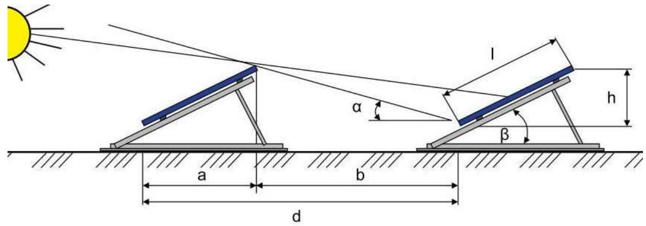

FIGURE 2. Explanation of essential parameters of solar inter row spacing.

B. PITCH OF THE PV ROW

The distance between rows of PV modules (the pitch) required to avoid significant inter-row shading varies with the site latitude. Sites should be chosen with sufficient area to allow the required capacity to be installed without having to reduce the pitch to levels that cause unacceptable yield loss. The maximization of annual energy generated by the facility is the objective function [20]. The reduced pitch will cause shading effect on the PV panels which is escalated in case of VLS-PV systems due to large number of rows.

Figure 2 explains the critical parameters for the inter-row spacing between two PV rows.

d : pitch of the rows
b : distance between the rows/inter row spacing
β: tilt angle
l : length of the PV Panel
α: Solar Elevation

C. TILT OF PV MODULES

The angle of a PV module from the horizontal ground is known as the tilt of the module. Global radiation on a tilted

TABLE 2. Comparison of common PV technologies.

Panel Type	Mono Si	Poly Si [a]	Thin Film
Efficiency	Most efficient (18-22%)	Less efficient (14-18%)	Least efficient (10-12%)
Manufacturing	From single Si Crystal	By fusing Si Crystals	Many layers of PV
Suitable for	Standard temperature	Moderately High tem-	High temperature
Area need/kW	Least	Less	Large
Energy yield per unit	High due to high Si content	High due to high Si content	Low due to low Si content
Performance at lowlight	Low	Low	Moderate
Gap between Voc&Vmp	15-20% (less is better)	15-20%	15-20%
Temperature Coefficients	High	High	Low (Low is better)
Fill Factor	70-80%(High is better)	70-80%	60-68%

surface consists of three components, i.e., beam radiation, diffuse radiation and reflected radiation. The tilt angle of a solar energy system is one of the essential parameters for capturing maximum solar radiation falling on the solar panels. This angle is site specific as it depends on the daily, monthly and yearly path of the sun. The accurate determination of the optimum tilt angle for the location of interest is essential for maximum energy production by the system [21]. The importance of the tilt angle of the PV Module in VLS PV systems can be considered by analyzing that the land requirement also increases in proportion to the tilt angles due to the spacing between PV rows. The increase in land requirement increases cable length. Even if all the cost factors are assumed to be similar, it is the first majority of the total investment cost.

It is the most expensive at 40° array tilt angle and the least at 10° array tilt angle, since the requirement of array support, foundation, and labor for system construction increases as array support is inclined [14]. Moreover, decreasing the tilt will decrease the ground cover ratio thereby increasing land cost, while decreasing the increasing the tilt will increasing inter row shading effecting the energy yield of the plant. General rule of thumb is that the value of tilt angle of PV modules in a region shall be close to the latitude of the region. However, it should be fine-tuned considering the sun chart of the subject region.

D. DEGRADATION EFFECT ON PV PANELS

Solar modules do not usually fail in a catastrophic way instead they experience a steady power degradation over time [22], [23]. This degradation process has been reported to undergo two different stages provided below:

- within the first year of exposure solar modules exhibit a rapid degradation (1–3%) [24]
- after that a slower linear degradation rate is observed (0.5–1%/year).

Degradation reduces the generated energy from the PV plant over the years. A specific clause in each Power Purchase Agreement (PPA) of the project is mentioned in order to ensure that efficient operation and maintenance is carried out and annual degradation is limited to agreed levels as mentioned above.

E. CLEANING FREQUENCY

PV installations in desert areas suffer from loss in efficiency due to the accumulation of dust and airborne dirt. The resultant soiling through dirt accumulation hinders the conversion of light into electricity, consequently degrading the PV performance. Hence, in order to maintain a steady performance, PV panels must be cleaned regularly. Washing of solar PV panels is traditionally known for effective cleaning using centralized cleaning facilities. For optimizing the performance, it is better to clean the panels early in the morning and using pressure-induced de-mineralized water. Various PV panel cleaning techniques have been developed which include manual washing, automated cleaning robots, vibration methods and other coating techniques. However, for desert based systems lack of water availability may affect cleaning techniques as well as frequency. Many researches and studies have been carried out for calculating the optimum frequency of cleaning of PV panels in desert region. PV module cleaning frequency for desert regions is approximately 20 days when the power output reduction and particle concentration equal to 5% and 100μg/m3, respectively. Based on these findings it is preferred to clean the PV modules twice a month for keeping the energy yield to optimum value.

F. BALANCE OF SYSTEM (BoS) LOSSES

The balance of systems includes wiring, switches, mounting systems, solar inverters, battery banks, battery chargers, maximum power point tracking (MPPT) systems, junction boxes with fuses and relays, power conditioners and metering system and other supporting equipment. It consists of all the components of the solar PV system except the PV modules. BoS can be set up in many different configuration by the designers of the PV system depending upon design constraints such as cost, space, efficient operation and maintenance [25].

G. POWER TRANSMISSION LOSSES THROUGH MV & HV SYSTEM

The voltage level of DC power after conversion to AC power (for each array installed in the PV area) is stepped up by step up transformers. This AC power is stepped up to a medium voltage range (11kV, 33kV or any other level according to the regional specifications being followed). The transfer of this AC power from each of the transformer to the medium voltage switchgear room consists of various configurations. This contributes to slight power losses in cables and other equipment such as transformer losses, switching losses. Additionally, prior to the metering equipment, this power undergoes another step up in voltage before dispatch to the national grid. All these losses are occurred prior to the metering equipment recording the export of energy to the national grid system.

H. NON PROJECT MISSED VOLUME (NPMV) DUE TO OUTAGES OF DIFFERENT TRANSMISSION CIRCUITS

When comparing two VLS PV systems, it is essential to consider the number of hours of outages of the utility system to which the PV plant is connected. Since the PV power plant is available for export of energy but is unable to export due to fault on the transmission network, the overall energy generated will decrease. In Pakistan, this energy is termed as Non Project Missed Volume (NPMV). Luckily, this energy is claimed through energy invoices assuring the availability of all the PV arrays and the utility operator confirming the non- availability of its network due to any reason, i.e. fault, maintenance or scheduled outage.

IV. COMPARISON OF ENERGY OUTPUT OF TWO SOLAR PV PLANTS

The factors mentioned in section III will be discussed for comparison purposes for the first two power plants mentioned in table 1 i.e.,

1) **100 MWp Appolo Solar Power Plant (ASPP)**
2) **100MWp Quaid e Azam Solar Power Plant (QASPP)**

The monthly energy generation output curve for each of the power plant for the year 2017 is produced in figure 3 for analysis purposes.

Trend line in Fig. 3 reveals that the 100MW Appolo solar power plant generates more energy than its counterpart 100MW Quaid e Azam solar power plant. However, deeper insights are required to understand the reasons behind such a contrast in the output.

V. REASONS FOR DIFFERENCE IN ENERGY OUTPUT

This section explores the reasons for the difference in energy output of two solar power plants by comparing each factor of section III.

A. TYPE OF PV MODULE

Both solar power plants under comparison have installed poly crystalline PV modules for generating energy. QASPP consists of 255W JA Solar (China make) modules whereas

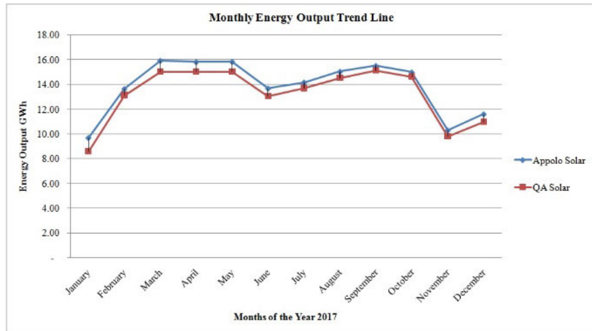

FIGURE 3. Trend Line for monthly energy generation of QASPP & ASPP for the year 2017 Source: National Electric Power Regulatory Authority Pakistan.

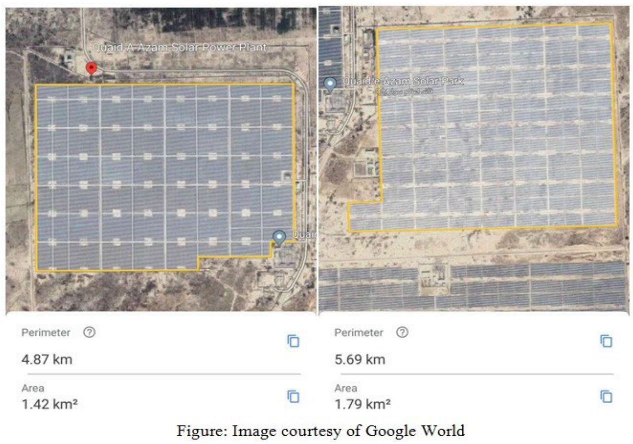

FIGURE 4. PV Area measurements of QASPP & ASPP.

ASPP utilizes 250W Trina Solar (China make) PV modules. The configuration of PV modules are 60 cell 3BB (busbar) in both the power plants. JA Solar and Trina Solar both belong to the tier 1 manufacturers of solar modules. Temperature related power degradation (%/°C) for JA Solar(-0.45%/°C) is higher than Trina Solar (−0.41%/°C) which shows that for every °C rise in temperature JA Solar will lose 0.04% more power than Trina solar beyond 25 °C.

B. PITCH OF PV ROW

The distance between rows of modules (the pitch) required to avoid significant inter-row shading varies with the site latitude. Sites should be chosen with sufficient area to allow the required capacity to be installed without having to reduce the pitch to levels that cause unacceptable yield loss. In our scenarios, the PV area of QASPP and ASPP is 350 and 442 acres, respectively as shown in Fig. 4.

Fig 4 shows that QASPP has utilized the lesser area for their 100MW Solar Power Plant than ASPP. The lesser PV area is because the inter-row spacing between the PV modules in QASPP is lesser than that of ASPP because the dimensions of the PV panel are the same. Inter-row spacing (b) for QASPP and ASPP is 3m and 3.8m respectively. For

TABLE 3. Years of operation for plants under comparison.

Sr. No	Name	Commercial Operation Date[a]	Years of operation
1	Quaid e Azam Solar Power Plant	July 15,2015	4th
2	Appolo Solar Power Plant	May 30, 2016	3rd

FIGURE 5. QASPP images showing inter-row spacing.

FIGURE 6. ASPP images showing inter-row spacing.

illustration purposes, please see figure 5 and 6 of each PV power plant.

It can also be seen from the naked eye that the space between the PV rows is higher in case of ASPP then in the case of QASPP.

QASPP = 3.5acre/MW

ASPP = 4.42acre/MW

C. TILT OF PV MODULES

The tilt of the modules in QASPP is 28° facing south whereas that of ASPP is 25° facing south. The three degree more tilt enables lesser inter- row shading during the sunset and sunrise periods and resultantly, extracts more energy from the PV panels.

Due to the tilt difference between the two power plants, the ground cover ratio (GCR) is also different for each of the two. GCR ratio can be defined as

$$GCR = \frac{A_{PV}}{A_{PV+L}} \tag{1}$$

where A_{PV} is the total PV area excluding land and A_{PV+L} is the total PV area including land. Furthermore, A_{PV} can be calculated as

$$A_{PV} = A_C \times N_C \times N_m \tag{2}$$

where A_c, N_c, N_m are the area of the PV cell, number of cells in a module and number of modules installed, respectively. Calculating GCR for both QASPP and ASPP as below:

1) GCR FOR QASPP

PV cell dimensions for QASPP are 156mm × 156mm and covered PV area including the row spacing is 1146000m^2. Using these values, GCR for QASPP calculates to 0.416 or 41.6%.

2) GCR FOR ASPP

PV cell dimensions for ASPP are also 156mm×156mm and covered PV area including the row spacing is 1789000m^2.Using these values, GCR for ASPP calculates to 0.336 or 33.6%. Difference in GCR shows that ASPP consumes 26% more land than QASPP.

D. DEGRADATION EFFECT ON PV PANELS

Another important aspect worth considering in the analysis is, that since the Commercial Operation Dates (COD) for both the power plants under study had a gap of approximately one year, the degradation in the generation of PV module should be considered. The maximum allowed degradation value in Energy Purchase Agreement (EPA) of these solar plants is 0.7%. However, in reality, the actual value is lesser than 0.7% due to efficient maintenance by respective operations and maintenance teams. However, for the analysis, annual degradation of 0.7% is assumed.

Seven-month degradation for Appolo is considered i.e., June 2017 to December 2017. Since one year from COD was achieved on end of May 2016. So one-time degradation factor applies to the remaining months of 2017 after May 2017 as shown in Fig. 7.

For QA Solar, from August through December the degradation effect is considered twice while it is taken once for the remaining months. The reason is the same, i.e. from 2015 July to 2016 July, no degradation applies. From August 2016 to July 2017 degradation applies once for the first time. Then a further degradation applies for the remaining months of 2017. Please see figure 8 for a better understanding. This is important because at the end of the analysis the trend line will be reproduced to see the variations after catering the degradation effects.

E. CLEANING FREQUENCY OF PV MODULES

The frequency of cleaning is twice per month for both the power plants. It is assumed that the standard procedures are followed for the cleaning of PV modules. The method of cleaning PV modules is manual washing with standard cleaning tools.

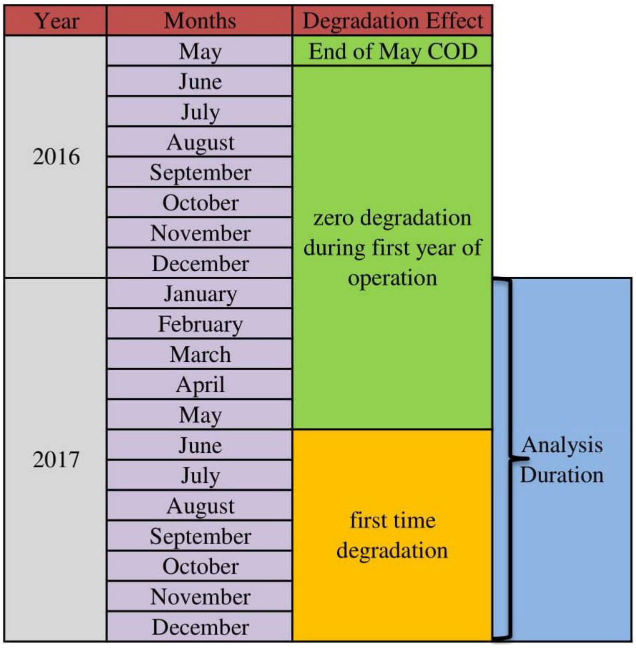

FIGURE 7. Degradation for ASPP.

F. BALANCE OF SYSTEM (BoS) LOSSES & POWER TRANSMISSION LOSSES THROUGH MV SYSTEM

The configuration adopted by QASPP and ASPP for BoS of the two power plants are typical central inverters with step up transformer. The step up transformers dispatches the AC power at 33kV voltage to MV switchgear. The power is dispatch to the national utility after undergoing a voltage step up from 33kV to 132kV through 2 number of 100MVA transformers. Since both power plants use the same topology it is assumed that the BoS and MV/HV transmission losses are the same.

G. NON-PROJECT MISSED VOLUME (NPMV) DUE TO AN OUTAGE OF DIFFERENT TRANSMISSION CIRCUITS

NPMV is the volume of electric energy (kWh) not delivered by the Complex due to

- Constraints on the export of energy
- Unavailability of the Grid System
- Grid failure or any fault in it
- Dispatch Instruction
- Any other circumstances not caused by the failure of the complex

There are many instances during the operation of the power plant where the grid system fails, or a fault occurs and the energy cannot be exported from the plant. Such instances limit the export of energy from the plant. QASPP and ASPP, although located adjacent to each other, the energy is exported on different transmission circuits. Both power plants are connected to the 132kV double circuit transmission line of Bahawalpur - Lal Suhanra substation. However, the circuits are not the same as shown in fig. 9 to view the interconnection circuits of two power plants.

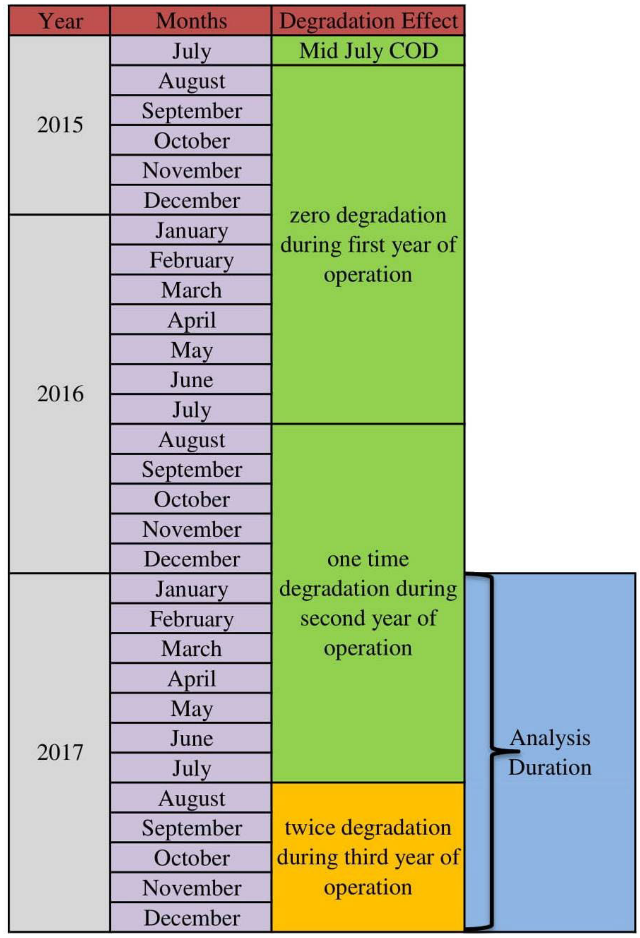

FIGURE 8. Degradation for QASPP.

During operations, it has been observed that the outages in these circuits are close to none. Moreover, outages are occurred simultaneously on both the circuits whenever it occurs. Accordingly, the influence of outage of one circuit and therefore non-export of energy from any one of the solar power plant is also ruled out.

H. MONTHLY ENERGY OUTPUT AFTER CONSIDERING THE FACTORS

Comparing fig. 10 with fig. 3 shows the slight narrowing of the gap between the two trend lines. Inspecting the trend lines clearly shows that the gap is least for September, October, November and February.

Figure 11 shows the trend line for monthly percentage difference in the energy outputs of the two solar plants. The percentage difference between the energy outputs of the power plants per month is graphed in figure 11. Average percentage difference for a complete year is a little above 4% as seen from the black horizontal line.

One of the observations of the trend lines in figure 11 is that percentage difference in energy is greatest for the January & December due to the Sun being low on the horizon and longer shadows. The annual energy difference between the

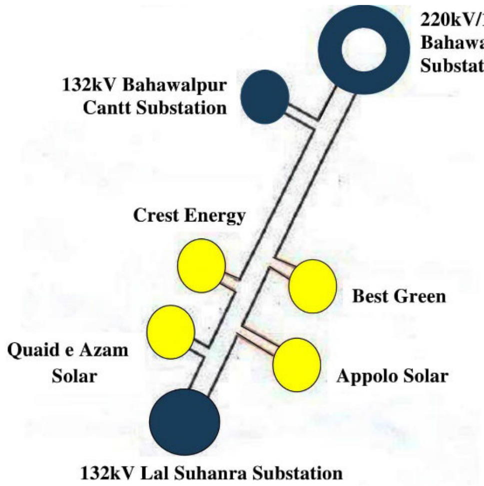

FIGURE 9. Interconnection Schemes of QASPP & ASPP.

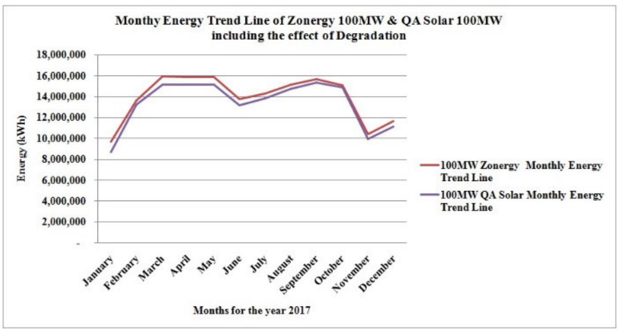

FIGURE 10. Energy Trend of QASPP & ASPP after considering Degradation effect.

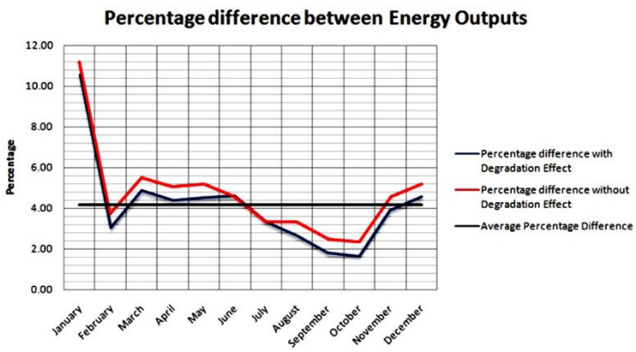

FIGURE 11. Monthly percentage difference between energy Outputs of QASPP & ASPP.

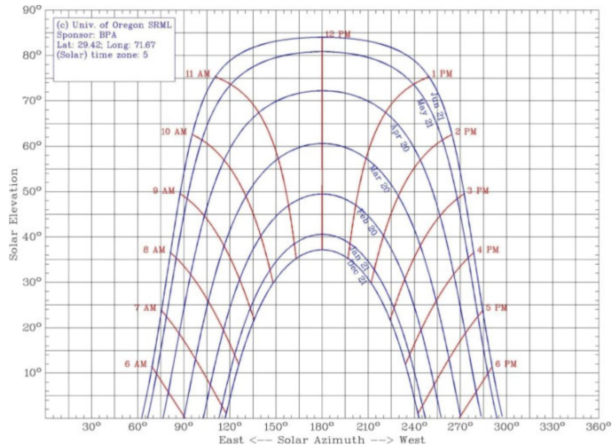

FIGURE 12. Sun Chart of Bahawalpur Region.

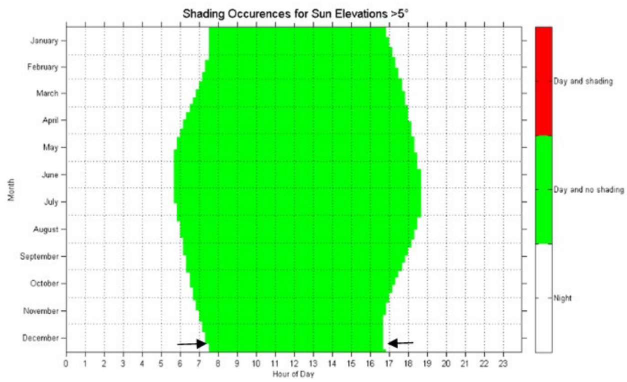

FIGURE 13. Shading Occurrences for Sun Elevation Angle above 5 degrees [26].

QASPP and ASPP with and without degradation effects is 6.6GWh and 7.5GWh respectively for the year 2017 with ASPP producing greater energy than QASPP.

It can be concluded that due to lesser inter-row spacing, greater tilt angle and lesser PV area, QASPP faces shadow effects during the sunrise and sunset especially, in the winter seasons. The difference in energy is also higher during these months. A greater tilt angle requires more area to reduce the shading effect. Whereas in this scenario QASPP has utilized a greater tilt with lesser PV area thereby reducing the energy yield. This can also be observed from the GCR calculation presented above where the GCR is lesser for ASPP then QASPP. Higher the GCR, lesser will be the energy yield at greater tilt angles.

VI. SUGGESTED CHANGES

Since the PV plants under observation have fixed tilt PV systems with government allocated PV areas of 500acre (2,023,428m^2) for each 100MW plant, QASPP has a remaining area of 607,428m^2 which is free and can be utilized. Similarly, ASPP has a remaining area of 234,428m^2.

In order to extract maximum energy due to the proper design of inter-row shading, we must investigate the ideal row spacing for the area so that the PV panels are least shaded. Initiating the investigation, we must observe the Sun chart of Bahawalpur. Fig. 12 and Fig. 13 show the Sun Chart of Bahawalpur (developed by the University of Oregon online Sun Chart maker) and the shading occurrence of Bahawalpur Region above sun elevation angle of 5° [25].

According to fig.13 during the winter solstice, the shading occurrences above 5-degree angle elevation occurs from 7:30 am in the morning till 4:30 pm in the late afternoon

TABLE 4. Comparison of important parameters.

Sr. No.	Parameter	100MW Quaid e Azam Solar Power Plant	100MW Appolo Solar Power Plant
1.	Panel Rating	255Wp	250Wp
2.	Installed Capacity	100MW	100MW
3.	Panel Manufacturer	JA Solar	Trina Solar
4.	Efficiency	15.59%	15.3% efficiency
5.	NOCT	47+/- 2%	44+/- 2%
6.	Temp Coefficient	-0.45%/°C	-0.41%/°C
7.	Tilt	28 degree	25°C
8.	Area	350 acres PV Area	442 acre
9.	Hectare /MW	1.41/MW	1.789/MW
10.	Length of Panel	1650mm	1650mm
11.	Row spacing	Less than 3m	3.8m

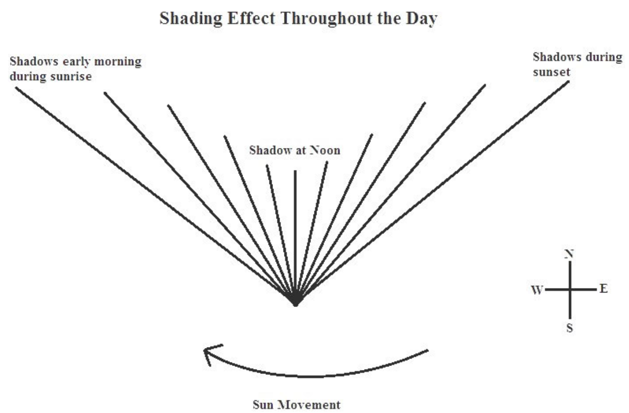

FIGURE 14. Shadings at morning, noon and sunset.

(as depicted by black arrows in the figure). Thus, we will consider design for angle above 5 and between these timings. The solar elevation angle (α) is approximately 12° for a time period of 8:00am to 4:00 pm on the sun chart in figure 12, for the December 21st Curve (seen by the black arrow to the y-axis). Therefore, α is taken as 12°. The module length is taken as 3.3m (1.65m × 2), due to double row configurations.

Due to larger shadows at sunrise and sunset, designing the PV systems catering overall shading effect will require a huge amount of space and render the PV system infeasible. Azimuth correction of angle is required to cater these shading effects in order to ignore some shades during the morning and late afternoon but to ensure there is no shade during the noon, i.e., the highest solar elevation angle. Drawing perpendicular lines intersect the x-axis on 125° and 235°. This is 55° from 180° on either side. Thus, 55° isused for the azimuth correction calculations. The calculations of minimum inter-row spacing using the above parameters are given for reference.

A. MINIMUM INTER-ROW SPACING FOR ASPP

Minimum inter-row spacing calculated for 7:30am to 4:30pm, winter solstice and degree tilt 25° as follows

$$H_t = \sin(\beta) \times L_m \times R_m \tag{3}$$

where H_t is the height difference, β is the tilt angle, L_m is the module length and R_m is number of module per row. H_t can be calculated as

$$H_t = \sin(25) \times 1.65 \times 2$$

$$H_t = 1.39\text{m}$$

Furthermore, module row spacing can be calculated as

$$L_{R-R} = \frac{H_t}{\tan\alpha} \tag{4}$$

where L_{R-R} is module row spacing and α is solar elevation angle, taken as 12° fromthe Sun Chart in Fig. 13.Using these values, L_{R-R} is calculated as $6.56m$.

Finally, Azimuth angle correction can be calculated as

$$L_{(R-R)min} = L_{R-R} \times cos(\alpha) \tag{5}$$

Using value of α as 55, $L_{(\mathrm{R-R})\mathrm{min}}$ is computed to 3.76^m. Therefore, minimum module row spacing of 3.76^m is sufficient to cater the shadows.

B. MINIMUM INTER-ROW SPACING FOR QASPP

It is noteworthy that only the tilt angle will be different for QASPP from ASPP. All remaining values will remain same for both solar power plants. Using 28° and following the same procedure as for ASPP, the minimum module row spacing comes out to be $4.15m$.

According to the above computations, QASPP should have a row spacing of $4.15m$ and ASPP of $3.76m$. However, QASPP and ASPP have an inter-row spacing of $3m$ and $3.8m$ respectively with tilt angles of 28° and 25°.The lower production of QASPP can be due to a steeper angle and lesser inter-row spacing due to which 4% monthly lesser energy on average is produced as depicted in the figure above.

In order to utilize the remaining area optimally, additional rows of PV modules can be placed at the available area at a minimum distance of 4.15m for QASPP for the same tilt angle of 28°. However, due to rated capacities of 100MW agreed in the Energy Purchase Agreements, the policies of the electric regulatory authority of Pakistan would need an amendment as the 25 years tariff is based on the 100MW rated capacity of the PV plant.

C. IMPORTANCE OF INTER ROW SPACING IN FIXED TILT PV SYSTEMS

Problem of self-shading between rows of PV modules has been analyzed in several early studies from the approach of incident energy. These analyses allowed a better understanding of the main design parameters involved in the shading effect. The optimum array spacing in stationary grid-connected PV systems installed on a horizontal land can be analyzed considering the following three parameters:

- Land availability
- Annual energy yield
- Economic objective function.

Increasing the array spacing implies higher annual energy output because of the reduced impact of shading, but at the same time, it raises costs of land purchase/preparation and wiring costs. However, if limited or fixed land is available to the developer then it is important to analyze the optimum inter row spacing that maximizes the annual energy yield.

A_{Land} = Area of land Available

$P_{Capacity}$ = Rated Capacity

The annual energy (E_Y) yield of a power plant is a function of different types of losses such as the inverter losses, thermal losses and transformation losses etc.

The developers aim is to maximize the energy generation given the land availability. For a fixed tilt angle of θ, reducing the inter row spacing d will certainly reduce the cost of land and other wiring expenses, however, it will also reduce the energy yield.

Thus for a fixed tilt θ, the following relation is true;

$$Ey \text{ directly proportional to } d$$

It can revealed from this research that on average 4% higher annual energy yield is observed in case of ASPP as compared to QASPP. The reason for difference in energy output is that ASPP is having an optimal inter row spacing i.e. 0.8m more inter row spacing than QASPP.

VII. FINANCIAL EFFECT DUE TO ENERGY DIFFERENCE

Based on 4% annual difference in energy, the financial loss of QASPP evaluates to approximately PKR 119million per year (PKR 18.0387/kWh for first ten years, i.e., PKR 1.19 billion for first ten years = USD 8.5million)

VIII. CONCLUSION

In this paper, factors affecting the energy output difference of two equally power rated similar VLS PV plants located in same environmental conditions are explored. It is observed that the critical difference is the inter-row spacing of the PV modules and the tilt angle. The average difference in the energy output of the two PV plants is 4% per annum with approximately 6.6GWh. It is further observed that the minimum distances according to the different tilts of the two power plants is 3.76m for ASPP and 4.15m for QASPP. QASPP inter-row spacing is found around 1m less than the calculated optimal one.

Due to Chinese EPC contractors for both PV Plants, it is assumed that the losses in BoS system are same owing to Chinese equipment i.e., cables, inverters, and transformers utilized. An improved and proper design can increase the energy output and have a positive impact on the financial savings of the investor which in this case is USD 0.85 million per annum.

There is a trade-off between saving some land space using a steeper tilt angle (greater GCR) at the expense of low energy output, and improved design with lower tilt and more area (lesser GCR) but high energy output. This tradeoff will be explored in our future works.

REFERENCES

[1] D. J. Feldman and R. M. Margolis, "Q2/Q3 2018 solar industry update," Nat. Renew. Energy Lab., Golden, CO, USA, Tech. Rep. NREL/PR-6A20-72810, 2018.
[2] S. Comello, S. Reichelstein, and A. Sahoo, "The road ahead for solar PV power," *Renew. Sustain. Energy Rev.*, vol. 92, pp. 744–756, Sep. 2018.
[3] L. F. L. Villa, D. Picault, B. Raison, S. Bacha, and A. Labonne, "Maximizing the power output of partially shaded photovoltaic plants through optimization of the interconnections among its modules," *IEEE J. Photovolt.*, vol. 2, no. 2, pp. 154–163, Apr. 2012.
[4] A. Gholami, A. Saboonchi, and A. A. Alemrajabi, "Experimental study of factors affecting dust accumulation and their effects on the transmission coefficient of glass for solar applications," *Renew. Energy*, vol. 112, pp. 466–473, Nov. 2017.
[5] M. Q. Raza, M. Nadarajah, and C. Ekanayake, "On recent advances in PV output power forecast," *Solar Energy*, vol. 136, pp. 125–144, Oct. 2016.
[6] A. Cabrera-Tobar, E. Bullich-Massagué, M. Aragüés-Peñalba, and O. Gomis-Bellmunt, "Topologies for large scale photovoltaic power plants," *Renew. Sustain. Energy Rev.*, vol. 59, pp. 309–319, Jun. 2016.
[7] R. Conceição, H. G. Silva, L. Fialho, F. M. Lopes, and M. Collares-Pereira, "PV system design with the effect of soiling on the optimum tilt angle," *Renew. Energy*, vol. 133, pp. 787–796, Apr. 2019.
[8] J. A. Ruiz-Arias and C. A. Gueymard, "Worldwide inter-comparison of clear-sky solar radiation models: Consensus-based review of direct and global irradiance components simulated at the earth surface," *Solar Energy*, vol. 168, pp. 10–29, Jul. 2018.
[9] R. Prăvălie, C. Patriche, and G. Bandoc, "Spatial assessment of solar energy potential at global scale. A geographical approach," *J. Cleaner Prod.*, vol. 209, pp. 692–721, Feb. 2019.
[10] S. Guo, T. M. Walsh, and M. Peters, "Vertically mounted bifacial photovoltaic modules: A global analysis," *Energy*, vol. 61, pp. 447–454, Nov. 2013.
[11] K. Kurokawa, *Energy From the Desert: Feasibility of Very Large Scale Power Generation (VLS-PV) Systems*. Evanston, IL, USA: Routledge, 2012.
[12] T. Kerekes, E. Koutroulis, D. Séra, R. Teodorescu, and M. Katsanevakis, "An optimization method for designing large PV plants," *IEEE J. Photovolt.*, vol. 3, no. 2, pp. 814–822, Apr. 2013.
[13] S. B. Efe and B. Kocaman, "Harmonic analysis of a wind energy conversion system with small-scale wind turbine," *Int. J. Energy Appl. Technol.*, vol. 5, no. 4, pp. 168–173, 2018.
[14] K. Kurokawa, K. Kato, M. Ito, K. Komoto, T. Kichimi, and H. Sugihara, "A cost analysis of very large scale PV (VLS-PV) system on the world deserts," in *Proc. 29th IEEE Photovolt. Spec. Conf.*, May 2002, pp. 1672–1675.
[15] K. Kurokawa, *Energy from the Desert: Practical Proposals for Very Large Scale Photovoltaic Systems*. London, U.K.: Earthscan, 2012.
[16] World Bank Group. (2015). *Solar Modeling Report*. [Online]. Available: http://documents.worldbank.org/curated/en/2015/03/24365411/solar-resource-mapping-pakistan-solar-modeling-report

[17] *Report of the Conference of the Parties on Its Twenty-First Session, Addendum Part Two: Action Taken by the Conference of the Parties at Its Twenty-First Session*, Paris, France, Nov./Dec. 2015 .
[18] *Pakistan's Intended Nationally Determined Contribution (Pak-INDC)*. Accessed: May 2019. [Online]. Available: https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Pakistan%20First/Pak-INDC.pdf
[19] K. V. Vidyanandan, "An overview of factors affecting the performance of solar PV systems," *Energy Scan*, vol. 27, pp. 2–8, Aug. 2017.
[20] J. R. Perez-Gallardo, C. Azzaro-Pantel, S. Astier, S. Domenech, and A. Aguilar-Lasserre, "Ecodesign of photovoltaic grid-connected systems," *Renew. Energy*, vol. 64, pp. 82–97, Apr. 2014.
[21] A. K. Yadav and S. S. Chandel, "Tilt angle optimization to maximize incident solar radiation: A review," *Renew. Sustain. Energy Rev.*, vol. 23, pp. 503–513, Jul. 2013.
[22] M. Vázquez and I. Rey-Stolle, "Photovoltaic module reliability model based on field degradation studies," *Prog. Photovolt., Res. Appl.*, vol. 16, no. 5, pp. 419–433, 2008.
[23] C. R. Osterwald, J. P. Benner, J. Pruett, A. Anderberg, S. Rummel, and L. Ottoson, "Degradation in weathered crystalline-silicon PV modules apparently caused by UV radiation," in *Proc. 3rd World Conf. Photovolt. Energy Convers.*, Osaka, Japan, May 2003, pp. 2911–2915.
[24] I. Lillo-Bravo, P. González-Martínez, M. Larrañeta, and J. Guasumba-Codena, "Impact of energy losses due to failures on photovoltaic plant energy balance," *Energies*, vol. 11, no. 2, pp. 363, 2018.
[25] *World Bank and ESMAP Site Evaluation Report of Quaid e Azam Solar Park Bahawalpur*, Energy Sector Manage. Assistance Program, Bahawalpur, Pakistan, 2015.

SYED FAIZAN ALI SHAH received the master's degree in electrical engineering from the University of Engineering and Technology, Lahore. He has more than ten years of experience in energy sector developing various EHV Substations and Transmission lines. He has experience of developing Pakistan's largest Solar PV Power Plants of 300MW in Quaid e Azam Solar Park Bahawalpur under China Pakistan Economic Corridor (CPEC). He is currently a Renewable Engineer Enthusiast and the Manager (Energy) Punjab with the Energy Department, Government of Punjab, Pakistan. He is a certified Project Management Professional (PMP). He is a member of the International Solar Energy Society (ISES).

IRFAN A. KHAN (S'14–M'18) received the Ph.D. degree in electrical and computer engineering from Carnegie Mellon University, USA.

He is currently an Assistant Professor of practice with the Electrical and Computer Engineering Department, Texas A&M University (TAMU), Galveston, TX, USA. He has published more than 20 refereed journal and conference papers in the smart energy systems related areas. His current research interests include control and optimization of smart energy networks, optimization of energy storage systems, DCMicrogrids, smart grids, and renewable energy resources. He is the member of PES. He is an active Reviewer of many esteemed journals and conferences, including the IEEE TRANSACTIONS ON POWER SYSTEMS, the IEEE TRANSACTIONS ON SMART GRIDS, IEEE ACCESS, the IEEE TRANSACTIONS ON INDUSTRY APPLICATION SYSTEMS, *IET Smart Grids*, *Electrical Power Components and Systems*, and *Energies*. He is the Vice Chair of the IEEE PES Joint Chapter of Region 5 Galveston Bay Section (GBS) where his responsibilities are to organize presentations, invite renowned experts from power and energy background for presentations to GBS members. He is also the Registration Chair at the IEEE sponsored International Symposium on Measurement and Control in Robotics that was organized at the University of Houston Clear Lake, in September 2019.

HASSAN ABBAS KHAN received the B.Eng. degree in electronic engineering from GIKI, Pakistan, in 2005, and the M.Sc. degree (Hons.) and the Ph.D. degree in electrical and electronic engineering from the School of Electrical Engineering, The University of Manchester, U.K., in 2010. He is currently serving as an Assistant Professor with the Department of Electrical Engineering, LUMS. He is also working on efficient and reliable solar PV deployments in urban settings to maximize their performance ratios. His current research interest includes renewable energy and its uptake in developing countries. His core focus is also involved in novel grid architectures for low-cost rural electrification through solar energy.