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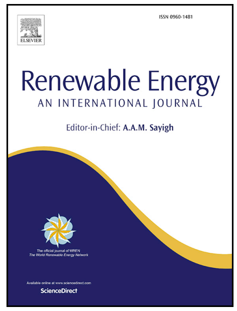

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Investor Focused Placement and Sizing of Photovoltaic Grid-Connected Systems in Pakistan

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Abstract

The world is moving toward renewable rich electricity generation systems. Pakistan being the sixth most populous country in the world and having median age of 21 years requires extensive resources for the next couple of decades to fulfill its energy requirements. Punjab is the largest province of Pakistan with 60% of total population and consumes about 80% of the electricity. The province does not have a lot of hydro and wind potential, but it has tremendous opportunity to utilize solar energy to fulfill its energy needs. In this paper, we explore the solar energy production possibilities in the province. Our objective in this paper is to find the best locations to install utility-scale solar power plants to fulfill 30% of energy needs by 2030. In addition to the technical feasibility of solar PV power plants, we also look at the economic aspects of such plants. To this end, we look at the complete life cycle of a solar PV power plant. Using data from an existing solar PV power plant we derive Profitability Index (PI) of various possible locations. According to our results, the transmission line losses range between 0.7% to 12.2% depending on the load and length of the transmission lines. Using data from transmission line losses the PI of potential utility-scale solar PV sites ranges between -9.11% to 69.65% based on various economic factors. These results provides detailed information on the best places to establish utility-scale power plants from technical as well as economic perspective.

Keywords: Investor-focused, Photovoltaics, Profitability Index, Distributed Power Generation, Transmission Line Losses.

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1. Introduction

Pakistan is a developing country in South Asia with an estimated population of 207.7 million. The country has one of the youngest population on the planet with a median age of 21 years. In 2016, the peak electricity[1] demand of the country was around 33 GW which is 30% more than its generation capacity of 24 GW. To counter the shortfall, the government has initiated many energy generation projects on a fast track basis, and the country is expected to have a generation capacity of around 33 GW by early 2018. Subsequently, between 2018 and 2022 the country's generation capacity is set to increase to 59 GW with numerous generation plants. Most of the new generation plants are based on coal, natural gas, and hydroelectric energy. Wind and solar will only contribute 5% and 3% respectively in the new energy generation mix by 2022.

With growing population and industrialization, the government expects the peak electricity demand to increase to 113 GW by the year 2030 [20]. Due to international agreements such as COP21, it is not possible for the country to keep on adding fossil fuel based generation sources in the years following 2022 to fulfill its energy needs. Fossil fuel sources are not only harmful to the environment, but it also increases the fuel import bill of the country to exorbitant amounts as most of the fuel types, i.e., coal, oil, and natural gas have to be imported from abroad. Pakistan is also considered among the ten most vulnerable countries from climate change. With the present population growth and industrialization, Pakistan is expected to quadruple its emissions in the next decade. Therefore, there is a need to focus on renewable energy resources for future energy resource planning in the country.

Pakistan has a huge potential of renewable energy sources (RES), i.e. hydro, solar and wind. Hydro has a potential of more than 60 GW, the average solar potential is around 2.142 kWh of solar irradiance/m^2/year, and wind energy has a potential of 50-100 GW [18, 17]. Out of this RES potential, Pakistan will be utilizing a significant proportion of its hydro potential by 2022. This leaves solar and wind sources that are widely available and could be utilized massively for the energy needs of the country.

[1] Energy and Electricity are used interchangeably in this paper.

Geographically Pakistan is divided into five provinces namely Punjab, Sindh, Balochistan, Khyber Pakhtunkhwa, and Gilgit Baltistan. Some other territories like capital Islamabad, Federally Administered Tribal Areas (FATA), and Azad Jammu and Kashmir (AJK), are also part of the country's political map as shown in Fig. 1. Population wise Punjab is the largest province of the country where around 60% of the country's population resides. In Punjab, the demand for energy is concentrated in five demand centers run by five utility companies [2] namely LESCO, MEPCO, FESCO, IESCO[3] and GEPCO as shown in Fig. 3. Based on present proportions of peak electricity demand, out of the 113 GW peak electricity demand of the country in 2030 [20], almost 93 GW is expected to be required by these five utility companies in the province of Punjab. The province does not have a lot of hydro and wind potential but has ample resources for solar energy. Our goal in this paper is to explore how 30% of the generation sources used by these companies should come from the solar energy produced in the province. As shown in Fig. 10, there are two peaks of the maximum electricity demand that occurs in a day. We cover mid-day peak of the demand which is almost equal to 30% of total electricity demand. To cover this mid-day peak demand, we plan generation of 30% from these solar PV power plants.

Punjab province is the main agricultural land of the country. Therefore, there is a requirement that any utility-scale solar PV power plant installations do not erode into the agricultural land of the province. The population of the province is also concentrated in these areas due to economic opportunities associated with agriculture. But despite being the main agricultural land and food basket of the country, there are ample empty spaces in the province that could be utilized to establish utility-scale solar PV power plants. To this end, we have identified four regions in the province that are either deserts or barren land and could be used for producing solar energy. These four areas are Cholistan desert region, Thal desert region, Pothohar plateau region and Koh e Suleman region as shown in Fig. 2. Together these four regions cover around 40% of the province's land area thus provide ample opportunity to set up large-scale solar PV power plants.

[2]Lahore Electric Supply Company, Multan Electric Power Company, Faisalabad Electric Supply Company, Islamabad Electric Supply Company, Gujranwala Electric Power Company

[3]IESCO also covers the Islamabad capital territory which is outside the limits of Punjab. We will consider Islamabad as part of Punjab from an energy distribution perspective.

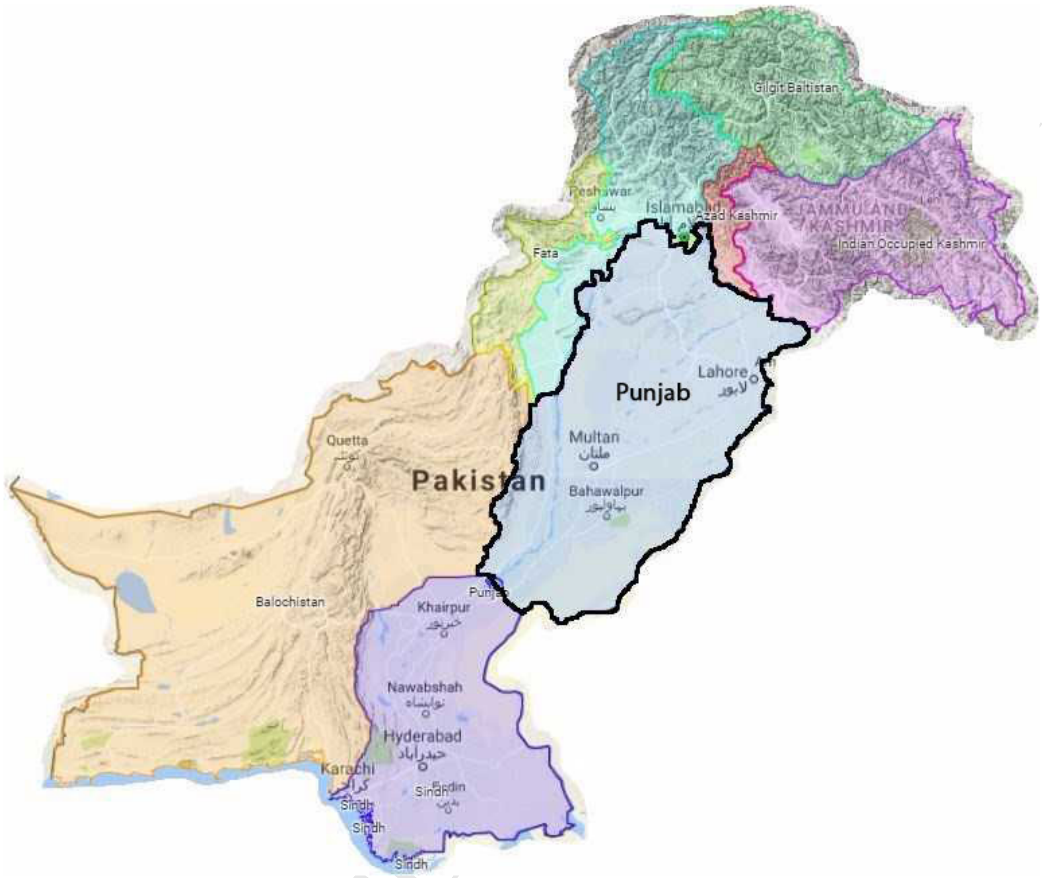

Figure 1: Map of Pakistan showing boundaries of Punjab province.

Other areas of the country provide better solar potential than Punjab province as shown in Fig. 4. The reason for choosing the province's land is following: Three main transmission lines will run parallel from north to south in the province. One of them is currently operational while two of them will be operational in the near future. Therefore, any utility-scale power plant in the province does not require long transmission lines to connect to the main transmission infrastructure of the country. Secondly, since 80% electrical load of the country is used in the province, the energy losses caused due to long distance transmission could be reduced if the plants are established close to the load centers. Finally, according to the recent amendment to the constitution of Pakistan, provinces are encouraged to rely on their natural resources first before depending on the country-wide natural resources.

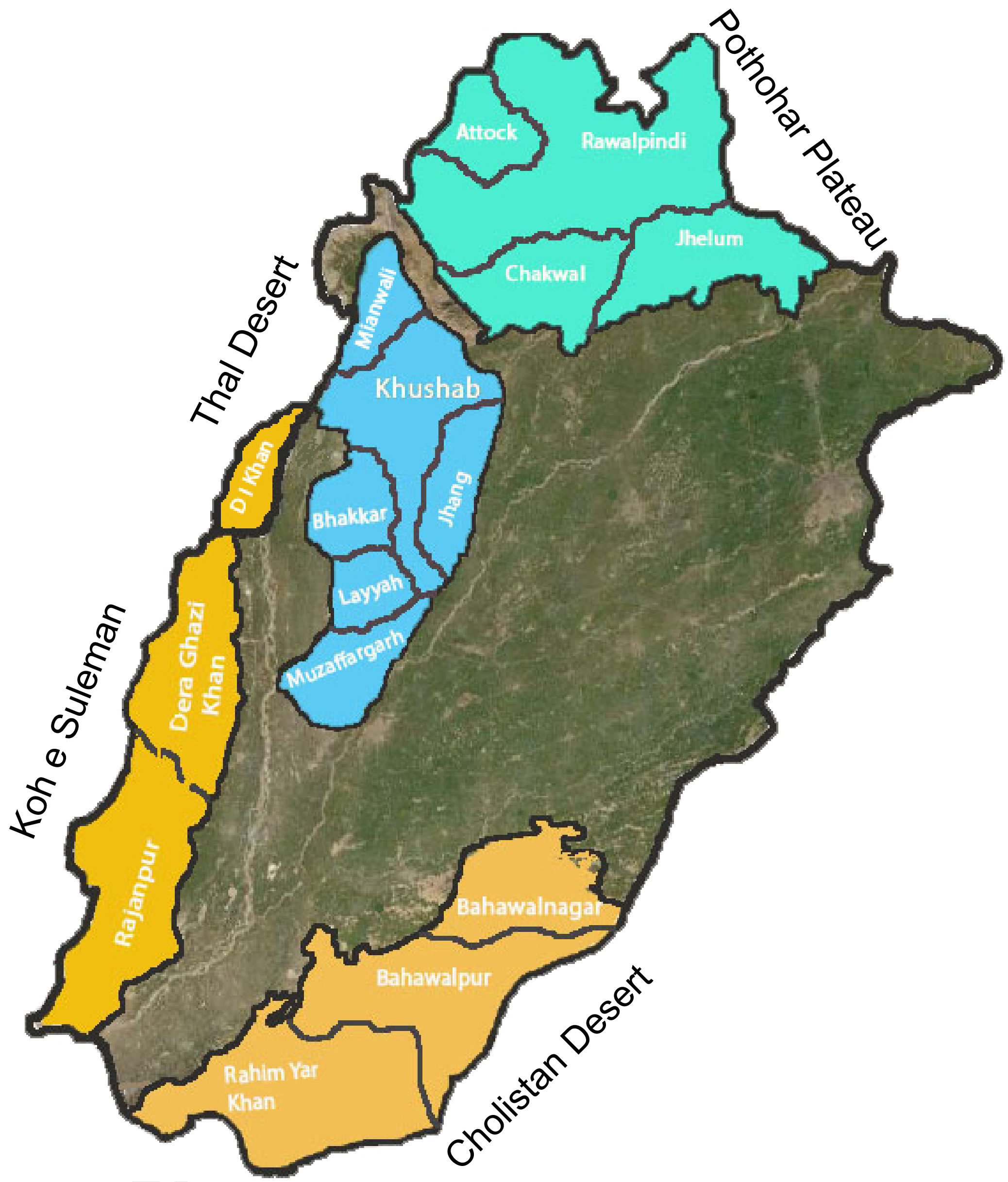

Figure 2: Sixteen selected locations from where solar PV data is available from ground stations.

In this paper, our goal is to develop a profile of the best places to generate large-scale solar PV energy in the province. We take into account the

Figure 3: Service areas for five DISCOs of Punjab[4].

technical factors such as PV output potential, transmission line losses from generation to load centers as well as the economic factors such as the capital, operational and maintenance cost and others. With all these technical and economic factors, our goal is to find locations where utility-scale PV power plants should be established which totals to 30% electricity needs of the province by 2030. The 30% is an arbitrary percentage which could be adjusted up or down depending on the need and targets of renewable energy in the province. Since the province does not have a renewable energy policy or target as yet, we have chosen 30% to be a starting point for discussion as the daytime peak demand of electricity is around 30% more than the base demand in the province. As mentioned earlier, the objective of the paper is to look at best possible places of utility-scale solar PV installations. The available area at each of the four possible geographical regions is not the inhibiting factor in increasing the share of solar PV. Thus a share of more than 30% is very well possible.

To our knowledge, such study has not been carried out. Therefore, our goal in this paper is to review the best ways to carry out such a study and apply it to the province of Punjab in Pakistan.

The rest of the paper is organized as follows. In section 2, we discuss other related efforts in installing large-scale solar PV power plants. In section 3, we provide details of data sources utilized in this paper. In section 4, we discuss the approach. In section 5, we describe problem formulation and methodology. Section 6 describes the detailed overview of our results. Section 7 discusses the results and their limitations. Finally, in section 8, we conclude the paper with an outlook of the future.

2. Related Work

An interesting problem associated with solar PV systems is to determine the optimal size for such systems. The size optimization of a stand-alone PV system is a complex optimization problem, and some researchers have presented numerous techniques to solve it.

Gomez et al. present binary particle swarm optimization for finding the optimal location and size for a Photovoltaic Grid-Connected System (PVGCS). This method also uses profitability index as a fitness function. They apply the proposed technique on the province of Jaen which is divided into 20,992 parcels, all of them with the same area ($S_i = 1\ km^2$) and find out the optimal location and size for PVGCS. Also, they compare different numerical techniques for the same problem. From simulation results, the authors verified the performance of the best method for the proposed problem [8].

Lopez et al. present an artificial intelligence (AI) based method to determine the optimal supply area and location for an electric generation system based on biomass. They proposed that a proper planning technique must consider the technical constraints of the network, the voltage regulation being one of the principal problems to be addressed for distributed generation (DG) systems [13].

[4] http://www.pdip.pk/discos-stakeholders/

[5] http://globalsolaratlas.info/downloads/pakistan

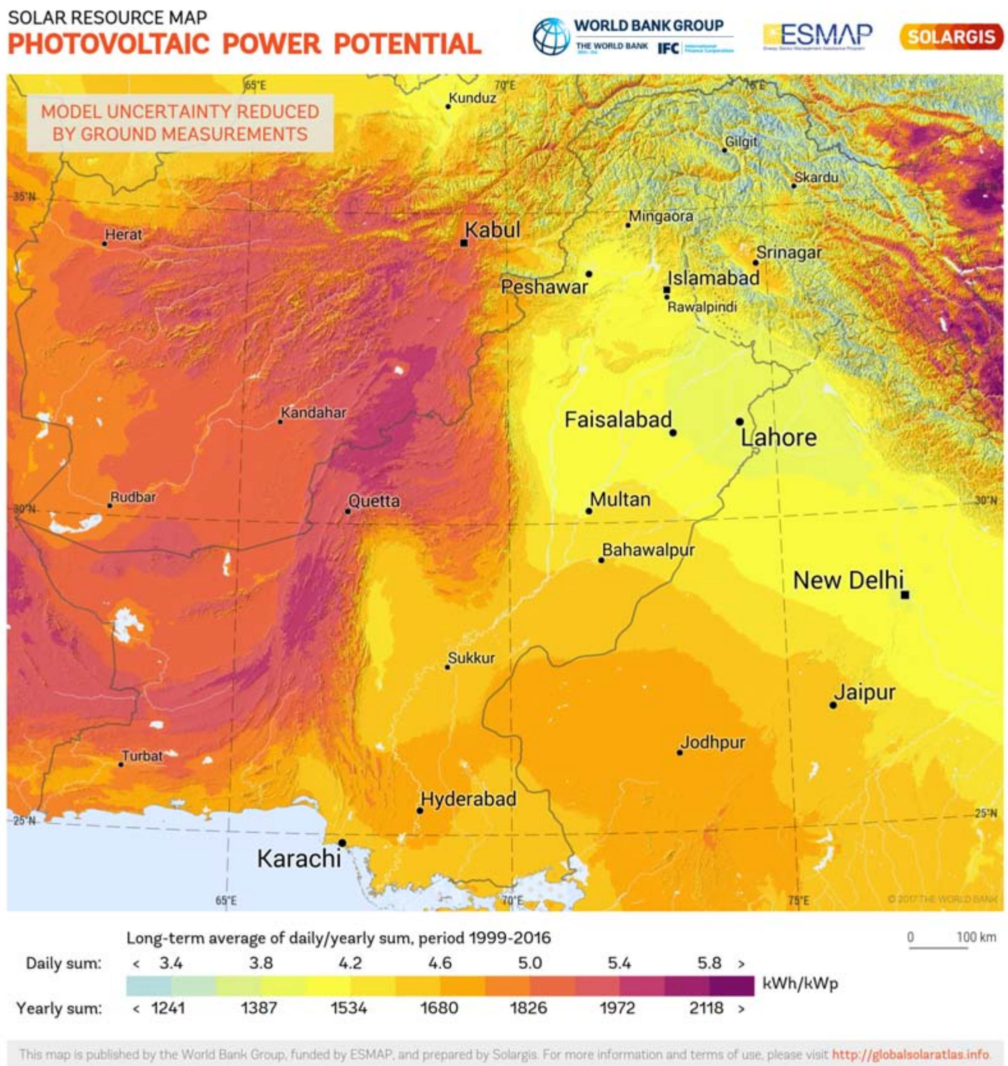

Figure 4: Solar PV potential of Pakistan[5].

Lopez et al. in their other paper presents a new approach using a discrete binary version of particle swarm optimization technique to determine the optimal supply area and location for an electric generation system based on biomass. They apply the proposed algorithm using a region composed of 16,384 parcels, all of them with the same area ($S_i = 2\ km^2$) [12].

Mellit et al. analyzed different artificial intelligence (AI) techniques for sizing of different types of photovoltaic (PV) systems, i.e., stand-alone PVs, grid-connected PV systems, PV-wind hybrid systems, etc. [16].

Mellit et al. in another paper applied artificial neural network-based genetic algorithm (ANN-GA) model which was developed for generating the sizing curve of a stand-alone photovoltaic systems. The proposed approach needs only the geographical coordinates and the specified loss of load probability for generating the sizing curve, from which optimal size pair can be estimated which allows the calculation of the number of PV modules and batteries needed for a given location and load in Algeria [15].

Li et al. dealt with the sizing optimization problem of a stand-alone photovoltaic power systems using hybrid energy storage technology. The results indicate that maximizing the system efficiency while minimizing system cost is a multi-objective optimization problem. As a trade-off solution to the problem, the proposed PV/FC/Battery hybrid system is found to be the configuration with lower cost, higher efficiency and fewer PV modules as compared with either single storage system [11].

Yang et al. proposed a sizing method to optimize the capacity sizes of different components of hybrid solar-wind power generation systems employing a battery bank. A hybrid solar-wind system is simulated by running the HSWSO program, and its relationships with system configurations are also analyzed. The optimal configurations of the hybrid system are obtained regarding different desired system reliability requirements and the LCOE [26].

Thiaux et al. applied non-dominated sorting genetic algorithm II (NSGA-II) to optimize a stand-alone photovoltaic system with the aim of quantifying the gross energy requirement reduction by minimizing the storage capacity [24].

Kornelakis and Koutroulis analyzed the optimization of photovoltaic grid-connected systems. The proposed methodology is to suggest, among a list of commercially available system devices, the optimal number and type of the PV modules and the DC/AC converters, the PV modules optimal tilt angle, the optimal arrangement of the PV modules within the available installation area and the optimal distribution of the PV modules among the DC/AC converters, such that the total net economic benefit achieved during the system operational lifetime period is maximized [9].

Kornelakis and Marinakis also applied particle swarm optimization (PSO) to the same problem as discussed in Kornelakis and Koutroulis paper. The optimization's goal is the maximization of the investments net present value (NPV). Proper location of DGs in power systems is essential for obtaining their maximum potential benefits [10].

Wang et al. present analytical methods to determine the optimal location to place a DG in radial as well as networked systems to minimize the power loss of the system. Simulation results are given to verify the proposed analytical approaches [25].

Askarzadeh et al. propose an artificial bee swarm optimization (ABSO) based parameter identification technique based on the single and double diode models for a 57 mm diameter commercial (R.T.C. France) silicon solar cell. The results obtained by ABSO algorithm are quite promising and outperform those found by the other studied methods [4].

3. Data Sources

To study the best places for utility-scale solar PV power plants installation in Punjab province, we need two types of data. The first type of data is the solar potential of various selected regions in the province and the second type of data is estimating the peak electricity demand of the five utility distribution companies (DISCOs) in 2030.

3.1. Solar irradiance data

Many variables affect the amount of solar irradiance that reaches the earth surface. The main contributing factors are the latitude, longitude, the day of the year and conditions of the atmosphere. However, additional variables such as elevation, orientation, slope and shading also affect the solar irradiance [7].

Three different methods are typically used for mapping the solar irradiance: satellites based estimation, geographic information system (GIS) based solar radiation models and the geostatistical estimates [3].

In addition to these measurements, ground-based detailed data provide the actual measurements that could then be correlated with above methods [21].

In this work, we take solar irradiance data from the National Solar Radiation Database (NSRDB) which was developed by the National Renewable Energy Laboratory (NREL) and the National Climatic Data Center (NCDC) [1].

The data available in NSRDB uses one of the two models: the Physical Solar model and the SUNY Semi-Empirical model. Physical Solar model is used for US-NSRDB data whereas SUNY Empirical model is used for the

Table 1
Peak demand of DISCOs in 2017 and projected demand in 2030 [20].

DISCOs	Peak Demand (GW) (2017)	Peak Demand (GW) (2030)
LESCO	5	26.6
MEPCO	3	23.1
FESCO	3	17.6
IESCO	2	14.8
GEPCO	4	13.1

Indian subcontinent. SUNY Empirical model was developed using the semi-empirical satellite model in collaboration with India-US energy dialogue. This model consists of hourly visible frames from a geostationary satellite covering Indian subcontinent. The satellite data have a ground resolution of 0.1 by 0.1 degrees, approximately 10 km x 10 km for the considered region [1].

In this work, ground-based data is considered for the proposed regions. This data includes all the information of our considered four regions having a total of sixteen stations. The data for all sixteen stations are created by using SUNY Empirical model which is averaged from the hourly model output for over 12 years. Here, the data taken from a geostationary satellite is considered for the whole region, and the potential of each station is matched to the ground base station data for determining the solar potential of adjoining area of each station.

3.2. Electricity demand data

As stated earlier, the peak electricity demand of Punjab province comes from the five distribution companies, i.e., LESCO, MEPCO, FESCO, IESCO, and GEPCO. The National Transmission and Dispatch Company (NTDC) that is the main transmission company of the country estimates that the country would need 113 GW peak electricity in 2030 [20]. Based on the present proportions of the five DISCOs, we estimate the peak electricity demand of the five DISCOs as 93 GW in 2030. Each DISCO is expected to have the peak electricity demand as shown in Table 1.

This estimate is based on the population growth, GDP growth and other related factors. The peak electricity demand of the five DISCOs and their load fulfillment through solar energy at 30% is shown in Fig. 5.

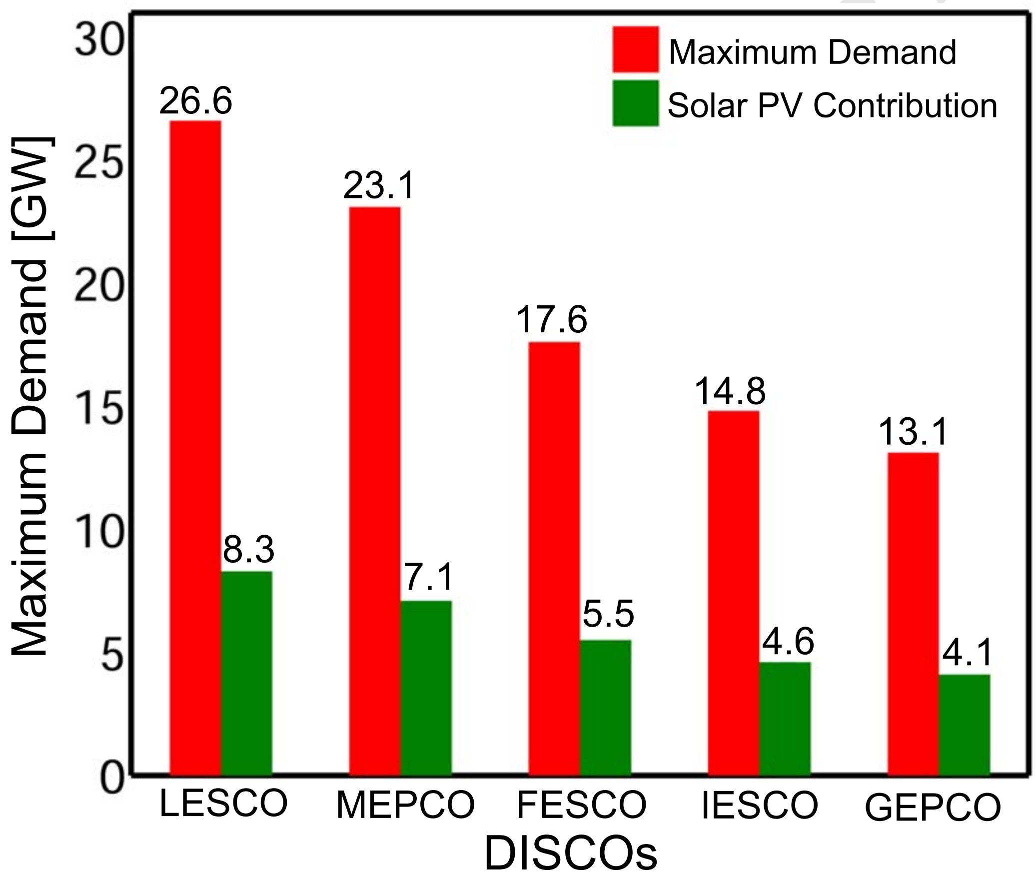

Figure 5: Maximum projected demand of DISCOs in 2030 and expected share of solar PV generation.

4. Approach

4.1. Regions identification

To find the best locations for utility-scale solar PV power plants installation to generate electricity and cover 30% peak electricity demand of the province from these sources, we first identified the regions where agriculture is sparse. In total, we were able to identify four such regions namely as given in Table 2.

Table 2
Four selected regions with total available area [5].

Regions	Total Area (sq.km)
Koh e Suleman	30,938
Cholistan Desert	26,300
Pothohar Plateau	22,254
Thal Desert	20,093

Following the identification of the regions, we then identified solar PV stations that provided us with the expected solar PV output of these regions. In total, we were able to identify sixteen such places where we got detailed hourly based information of solar irradiance and PV potential. These sixteen locations along with their equivalent peak sunlight hours (EPSH) per day are given in Table 3. For some area in Punjab adjacent to DI Khan, we used the readings from DI Khan station. Please note that DI Khan is not in Punjab but is close enough that its readings could be utilized for determining the PV potential of adjacent areas of Punjab province.

Following identifying the sixteen locations, we now discuss the technical and economic factors that we take into account in our approach.

4.2. Technical factors

4.2.1. Solar PV ouput

Equivalent peak sunlight hours (EPSH) per day for each station is calculated which ranges from 4.86 to 5.50 depending upon the solar insolation at each location as shown in Table 3. From EPSH per day values, we calculate annual energy production for each location which is discussed in section 5.1.

Table 3
Equivalent peak sunlight hours (EPSH) for sixteen selected locations [1].

PV Power Plant Location	EPSH
Bhakkar	5.24
Jhang	5.14
Khushab	5.04
Layyah	5.22
Mianwali	5.18
Muzaffargarh	5.30
Attock	5.02
Chakwal	4.96
Rawalpindi	4.94
Jhelum	4.86
DG Khan	5.32
DI Khan	5.26
Rajanpur	5.46
Bahawalpur	5.37
Bahawalnagar	5.27
Rahim Yar Khan	5.50

4.2.2. Transmission line losses

For these sixteen locations, we took the average output of each hour of the year. This results in 8760 readings for each location. Electrical power losses occur in the process of supplying power from the generating station to load centers due to the dissipation of energy in conductors and equipment used for transformation and distribution of power. These losses are naturally present in the system and can be further subgrouped depending upon the transformation and transmission system. Technical losses in electrical power system mean power losses incurred by physical properties of components in the power system infrastructure. The average power loss in a transmission line can be expressed as:

$$P_{loss} = P_{source} - P_{load} \tag{1}$$

Where P_{source} is the average power that the source is sending into the transmission line and P_{load} is the power consumed by the load at the receiving end of the transmission line [2].

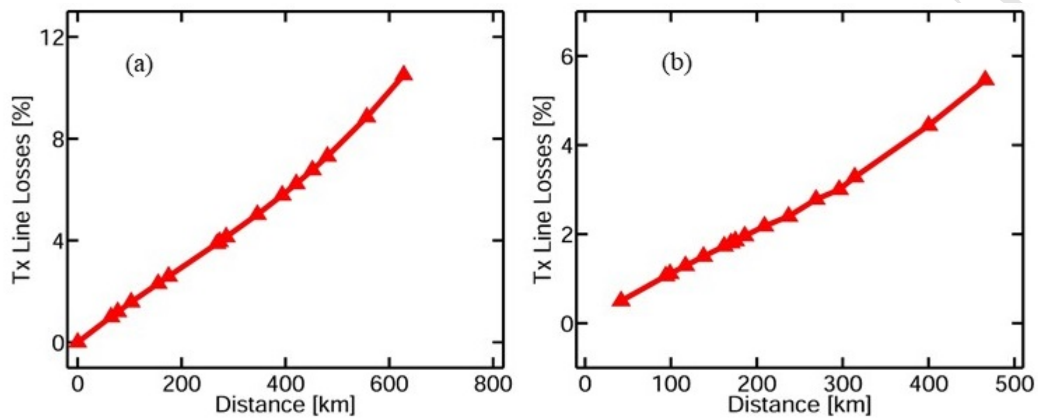

Figure 6: Transmission line losses as a function of distance and load for different source to load combinations.

Transmission line losses play a vital role while transmitting the generated power from the source to load centers. While transmitting power, the losses occur in transmission lines which depends upon the transmission parameters. It mainly includes the resistance of transmission lines as current is passing through it [2]. These losses can be calculated by using the following relation.

$$P = I^2 R \quad (2)$$

Here P is the total power loss in the transmission line conductor, I is the current flowing in the conductor and R is the resistance of the conductor which depends upon the length and area of the conductor. Electrical losses in a power system are caused by power flowing in transmission lines as heat. The power flowing in transmission lines result in power loss in the system, which also depends on the distance between the generating station and the load centers. For example, transmission line losses are lower when a generating station is located near to load center and greater if the same generating station is far away from the load center which is shown in Fig. 6. This is because the power from a remote generating station has to flow through a long transmission line to reach to the load center and fulfill its demand.

Simulations performed in this work takes different parameters into account such as voltage, power and power factor whose values are known. First of all distance between each generating station and load center is determined by computing the losses between them. Simulation tool ETAP (Electrical Transient and Analysis Program) is used for load flow analysis which is viewed as an industrial strength electrical power flow analysis tool. By using ETAP load flow analysis, we find out the transmission line losses. Additionally, through load flow analysis we analyze voltage, current, power and reactive power at different points. As the transmission line losses depend on the distance between generating source and load; it gives distinctive results for each source to load combination as given in Table 9 to Table 13 in the appendix.

4.3. Economic factors

For any power plant to be attractive for the investment, we need to calculate its profitability index (PI) [8]. Many factors such as initial investment, cash inflows, cash outflows, net present value, debt, land cost, equipment cost, maintenance and operation cost, scrap value, interest rate, etc. determine the profitability index (PI). Some of these parameters such as initial investment, cash inflows, cash outflows and net present value are discussed in detail in section 5. Here we discuss economics related parameters given in Table 4 specifically for all sixteen locations.

Recently, Punjab has installed its major utility-scale solar PV power plant named Quaid-e-Azam Solar Power Plant (QSP). This power plant which is capable of producing 100 MWp is located in the Cholistan desert. In this paper, we used data from QSP to determine the numbers for economic factors.

The initial investment or capital cost is the sum of land and equipment cost. Land cost is the cost of land where the power plant is installed. We used 25000 $/MW as land cost. Equipment cost depends on the plant production and it varies with the size of the power plant. We consider that all plants capacity varies between 2600 MW and 3100 MW. Thus, the value of the large-scale power plant comes out 1.57 Million $/MW. The M&O cost is taken as 1.5% of the cash inflows. The proposed financial arrangement for each case is based on debt to equity ratio which is taken as 75%:25%. The scrap value is the plant value at the end of the lifetime which is considered 10% of the initial investment. The interest rate is taken as 9%. After adjusting all these parameters, we calculate the net present value for each source to load combination.

Table 4
Economics related parameters and their description.

Economics Parameters	Description
Capital cost of land/MW	25000 $/MW
Capital cost of equipment/MW	1.57 Million $/MW
Electricity price per kWh	0.18 $
Plant factor	17.5%
Annual increase in electricity price	3%
Annual panel degradation	0.7%
Our investment	25% of INV
Loan	75% of INV
Interest rate	9%
WACC	11%
Tax rate	2.75%
Return on equity (IRR)	17%
Maintenance cost	1.5%
Scrap value	10% of INV
Lifetime of PV power plant	25 Years

We need to optimize for maximum overall PI while considering the constraint that none of the individual load source PIs should be negative. In other words, we may not prefer a solution with higher overall PI, which has any individual PI as negative, over a solution with lower overall PI in which all individual PIs are positive. The reason for this is that no power plant can sustain locally if it has a negative PI due to financial constraints, despite the overall solution being of higher PI. For sixteen source locations and five load centers from the five utilities, a total of $2^{16}C_5 = 1.007284468 * 10^{22}$ combinations are possible if we keep the generation and the demand as constant. This is because each load has to be balanced by one or more than one sources, hence we need to consider five sets of sources, one for each load from all possible sets of sources (i.e., the power set of the set of all sources) such that no source is repeated within the selected five set of sources to balance the five loads and each assigned set completely balances the loads.

Our objective function is maximizing the profitability index (PI) of each plant that we establish at any of these sixteen locations. PI depends upon the transmission line losses and economics parameters like net present value (NPV) and the present value of the initial investment (PVI). By adjusting the transmission line losses for each source to load combination, we calculate PI for each source to load by using the following relation [19].

$$PI = \frac{NPV}{PVI} = \frac{PV_{IN} - PV_{OUT}}{PVI} - 1 \quad (3)$$

An investment is profitable when PI>0. Therefore, PI less than zero is neglected in this work.

5. Problem Formulation and Methodology

5.1. Electricity production capacity of solar PV power plants

We calculate the annual total electricity E_g (kWh) generated from a solar PV power plant by using the following equation [23, 14].

$$E_g = G \cdot PR \cdot P_p \quad (4)$$

Where P_p is the unit peak power installed, PR is the system performance ratio or efficiency and G is the annual sum of global horizontal irradiance vertical or inclined plane of the PV module (kWh/m^2).

The PR is the best-known parameter for evaluating the energy efficiency of a PVGCS in real conditions of operation. This parameter includes the total losses of the normalized system. In general, these losses are due to the temperature of the modules, an incomplete utilization of radiation or failures or inefficiencies of the components of the system [22, 6]. Also, PR is influenced by the climatic conditions that occur for different latitudes.

5.2. Evaluation of the profitability of utility-scale solar PV power plants

We present the economic factors and their formulation for our optimization [19].

5.2.1. Initial investment

The initial investment (INV) for the design and construction of the power plant and its required equipment is expressed as [19]:

$$INV = (INV_f + INV_v) \cdot P_p \quad (5)$$

Where INV_f is the capital cost of land (\$/kWp), INV_v is the capital cost of equipment (\$/kWp) and P_p is the installed power capacity of the plant (kW).

5.2.2. Cash inflows

The present value of cash inflows (PV_{IN}) is obtained from the sold electrical energy (kWh) during the useful lifetime, V_u [19]. It can be written as:

$$PV_{IN} = P_g \cdot E_g \cdot \frac{K_g(1 - K_g^{V_u})}{1 - K_g} \tag{6}$$

Where P_g is the selling price of the electrical energy (units) supplied to the network (\$/kWh), E_g is the sold and produced electric energy (kWh/year) and $K_g = (1 + r_g)/(1 + d_a)$, r_g being the annual increase rate of the sold energy price which we have taken 3% in our case for finding PI for each power plant. On average, this is a historical increase in the electricity prices in Pakistan. However, we have now provided PI based on 5% and 7% annual increase rate of electricity too which is given in Table 6 and Table 7 in our results.

5.2.3. Cash outflows

The present value of cash outflows (PV_{OUT}) is the sum of the following costs during the useful lifetime of the PV power plant: annual leasing cost, L_C, and annual maintenance and operation costs, MO_C.

The annual cost of leasing of the necessary terrain is $L_C = L_{Cu_i} \cdot P_p$; where L_{Cu_i} is the leasing unit cost in parcel i (\$/kWp).

The annual maintenance and operation costs are $MO_C = MO_{Cu_i} \cdot P_p$; where MO_{Cu_i} is the average maintenance and operation cost in region i (\$/kWp) [19].

Finally, the present value of cash outflows is:

$$PV_{OUT} = \begin{cases} L_C \cdot \frac{K_L(1-K_L^{V_u})}{1-K_L} + \\ MO_C \cdot \frac{K_{MO}(1-K_{MO}^{V_u})}{1-K_{MO}} \end{cases} \tag{7}$$

Where $K_L = (1 + r_L)/(1 + d_a)$ and $K_{MO} = (1 + r_{MO})/(1 + d_a)$, r_L being the annual increase rate of L_C and r_{MO} is the annual increase rate of MO_C.

5.2.4. Net present value

The net present value (NPV) of an investment from the viewpoint of the investor is defined as the present value of cash inflows (PV_{IN}) minus the present value of cash outflows (PV_{OUT}) and the present value of initial investment (PVI) during the useful lifetime of the power plant plus the scrap value (SC_V) of the PV power plant at the end of the useful lifetime [19]. Therefore, it is expressed as:

$$NPV = PV_{IN} - PV_{OUT} - PVI + SC_V \tag{8}$$

5.3. Finding PI through genetic algorithm

Genetic algorithms (GAs) are search methods based on principles of natural selection and genetics. Genetic algorithm solves optimization problems by creating a population or group of possible solutions to the problem. The algorithm repeatedly modifies a population of individual solutions as shown in Fig. 7.

Genetic algorithm uses three main types of rules at each step:

i. Selection rules select the individuals, called parents.

ii. Crossover rules combine two parents to form children.

iii. Mutation rules apply random changes to individual parents to form children.

The genetic algorithm solves the problem by allowing the fewer fit individuals in the population to eliminate and selectively breeding the fittest individuals. This process is called selection. The genetic algorithm will take two fit individuals and mate them. The offspring of the mated pair will receive some of the characteristics of the mother, and some of the father.

Working of genetic algorithm:

The genetic algorithm starts by generating a random selection of S solutions, out of which top N solutions are selected after applying the fitness function to get the initial population. In our case, the fitness function is the maximization of the profitability index. After the initial population of N solutions is ready, all pairs of the initial population are considered for crossover and the novel solutions thus generated are mutated with a small probability after which top K is selected by applying the fitness function. This cycle of crossover, mutation and selection of the top K in each iteration is repeated until the same top K solutions are encountered in two consecutive iterations or the max number of iterations t_{max} is reached.

Solution:

A solution consists of a set of loads of all DISCOs each of which contained a set of sources that the corresponding load was balanced with in such a way that no source is repeated and no load is balanced with such a source which has a negative PI.

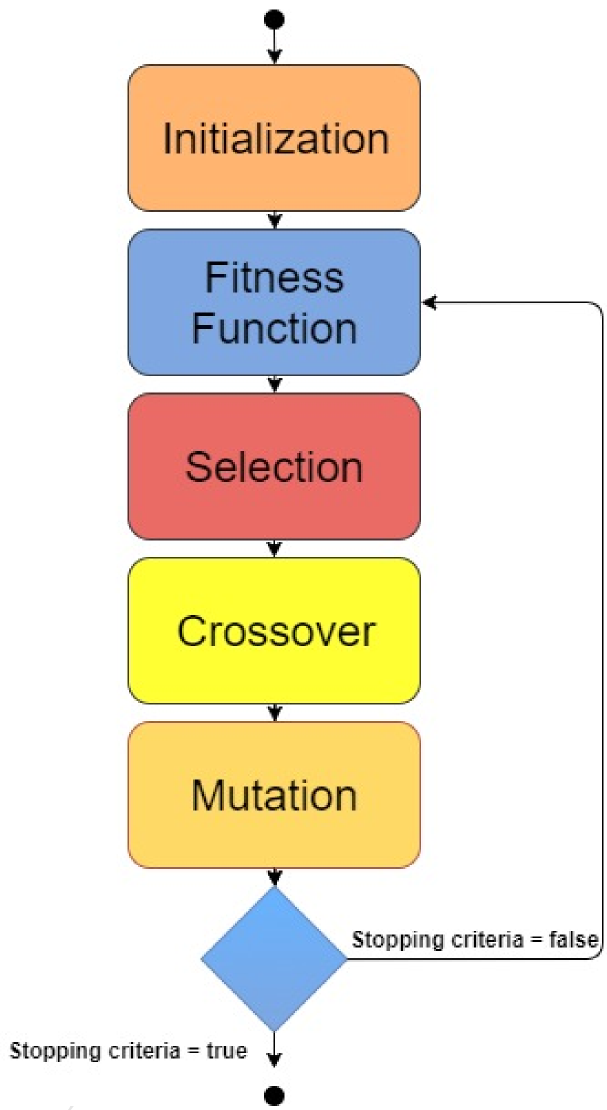

Figure 7: Genetic algorithm (GA) flow chart.

Fitness function:

460 The fitness function of a solution was taken to be the overall weighted PI of the solution.The details of PI are following.

- **Individual PIs:** PI of every (load, source) combination was known. For instance, from Table 8, the individual PI of (MEPCO, Rajanpur) as a (load, source) combination is 11.75%.

- **Weighted load PI:** The weighted PI of a load was obtained by taking the average of the PI values for all sources used to balance this load weighted by the percentage contribution of each source to the load. For instance, consider the load FESCO from Table 8, which is balanced by the sources Layyah and Bahawalpur, their individual PIs for FESCO are 5.65% and 8.43% respectively. The percentage contributions of Layyah and Bahawalpur to the FESCO load are 49.32% and 50.67% respectively, which are used as weights to average the PI of the load FESCO which comes out to be 7.06%.

- **Overall weighted PI:** Overall weighted PI of a particular solution was obtained by taking an average of the PI values of each load weighted by the percentage contribution of each load to the total load. For instance consider all the loads, i.e., LESCO, MEPCO, FESCO, IESCO, and GEPCO from Table 8, their load PIs are found out to be 4.08%, 11.12%, 7.06%, 6.04%, and 7.33% respectively. The percentage contributions of these loads to the total production of 34.6 GW are 24.84%, 25.72%, 16.74%, 16.50%, and 16.21% respectively, which are used as weights to average the overall PI which comes out to be 7.24%.

Crossover:

A crossover between two solution was obtained by considering each load to be balanced by either the sources from the first solution for that load or the second one thus giving rise to a new solution. The solution thus obtained is kept only if it is valid and avoids repetition of sources.

Mutation:

The mutation was done by randomly selecting a load and then randomly choosing a source balancing that load. This source is then replaced by a random unselected source. The solution thus obtained is kept only if it is valid and all loads are satisfied.

6. Results

The region selected for the proposed method is the province of Punjab. In Punjab, four distinctive regions are chosen for installation of utility-scale solar PV power plants which will supply electrical energy to all the DISCOs having different electricity demand capacity. Table 5 to Table 7 gives the peak power production of each generating station and PI for each source to load combination for 3%, 5%, and 7% annual increase rate in the electricity price per kWh for five DISCOs in Punjab. The generation of Cholistan desert region is comparatively higher than other three regions. Different sets of generating station either in combination or individually will provide the electrical energy to the specified load centers.

The effect of distance in electricity transmission is obvious in our results as given in Table 9 to Table 13 in the appendix. The southern regions are the best-suited places for electricity production, but they are not suitable to supply electricity to northern DISCOs. For example, Bahawalpur could supply MEPCO with PI of 11.50%, but to IESCO the PI drops to 4.35% and further drops to 3.07% for LESCO.

Table 5
Profitability index of electricity transmission from sixteen selected source locations to five DISCOs with 3% annual increase rate of electricity.

PV Power Plant Locations	Generating Capacity (MW)	LESCO (%)	FESCO (%)	IESCO (%)	GEPCO (%)	MEPCO (%)
Bhakkar	2866	0.96	6.44	5.53	6.31	5.92
Jhang	2812	1.35	6.13	3.14	5.06	3.78
Khushab	2758	**-3.52**	2.63	2.38	2.76	**-1.51**
Layyah	2859	**-0.20**	5.65	3.96	5.26	7.21
Mianwali	2833	**-1.48**	4.85	5.75	5.10	1.75
Muzaffargarh	2905	5.92	7.24	4.60	6.19	11.34
DG Khan	2911	0.62	6.85	4.46	5.92	10.42
DI Khan	2880	0.94	6.58	6.32	6.32	5.79
Rajanpur	2986	1.68	8.48	5.35	7.67	11.75
Bahawalnagar	2884	4.88	7.90	4.35	7.24	6.45
Bahawalpur	2937	3.07	8.43	4.95	7.76	11.50
Rahim Yar Khan	3010	1.02	8.01	4.17	6.91	11.16
Attock	2748	**-4.66**	**-0.91**	3.47	8.40	**-5.91**
Chakwal	2716	**-3.35**	**-0.14**	1.59	0.60	**-5.70**
Rawalpindi	2701	**-5.35**	**-2.15**	2.40	**-0.55**	**-7.69**
Jhelum	2661	**-4.63**	**-3.42**	**-1.60**	**-1.36**	**-9.11**

Table 6
Profitability index of electricity transmission from sixteen selected source locations to five DISCOs with 5% annual increase rate of electricity.

PV Power Plant Locations	Generating Capacity (MW)	LESCO (%)	FESCO (%)	IESCO (%)	GEPCO (%)	MEPCO (%)
Bhakkar	2866	24.37	30.92	29.83	30.76	30.29
Jhang	2812	24.89	30.59	27.03	29.32	27.79
Khushab	2758	19.12	26.46	26.16	26.61	21.52
Layyah	2859	22.99	29.98	27.96	29.51	31.84
Mianwali	2833	21.49	29.04	30.12	29.35	25.34
Muzaffargarh	2905	30.27	31.85	28.69	30.59	36.73
DG Khan	2911	23.92	31.36	28.51	30.25	35.63
DI Khan	2880	24.35	31.07	30.76	30.76	30.13
Rajanpur	2986	25.13	33.25	29.51	32.27	37.14
Bahawalnagar	2884	29.03	32.64	28.41	31.85	30.91
Bahawalpur	2937	26.83	33.22	29.07	32.42	36.90
Rahim Yar Khan	3010	24.32	32.66	28.08	31.36	36.43
Attock	2748	17.77	22.25	27.47	24.34	16.27
Chakwal	2716	19.36	23.20	25.26	24.08	16.56
Rawalpindi	2701	16.98	20.80	26.24	22.71	14.19
Jhelum	2661	17.88	19.33	21.49	21.78	12.53

Table 7
Profitability index of electricity transmission from sixteen selected source locations to five DISCOs with 7% annual increase rate of electricity.

PV Power Plant Locations	Generating Capacity (MW)	LESCO (%)	FESCO (%)	IESCO (%)	GEPCO (%)	MEPCO (%)
Bhakkar	2866	54.37	62.26	60.94	62.07	61.51
Jhang	2812	55.04	61.91	57.62	60.39	58.54
Khushab	2758	48.14	57.00	56.63	57.18	51.03
Layyah	2859	52.72	61.14	58.71	60.58	63.39
Mianwali	2833	50.93	60.03	61.33	60.40	55.58
Muzaffargarh	2905	61.45	63.35	59.55	61.83	69.23
DG Khan	2911	53.79	62.75	59.32	61.42	67.90
DI Khan	2880	54.33	62.44	62.06	62.06	61.31
Rajanpur	2986	55.17	64.96	60.46	63.78	69.65
Bahawalnagar	2884	59.98	64.32	59.22	63.37	62.24
Bahawalpur	2937	57.28	64.97	59.97	64.01	69.40
Rahim Yar Khan	3010	54.18	64.23	58.72	62.66	68.77
Attock	2748	46.52	51.92	58.22	54.44	44.72
Chakwal	2716	48.47	53.10	55.59	54.17	45.09
Rawalpindi	2701	45.62	50.22	56.78	52.53	42.25
Jhelum	2661	46.74	48.48	51.10	51.45	40.29

Table 8
Optimal placement of solar PV power plants for each DISCO in Punjab province.

DISCOs	Load (MW)	PI (%)	Assigned Sources
LESCO	8255	4.08	Jhang, Muzaffargarh, Bahawalnagar
MEPCO	7175	11.12	DG Khan, Rajanpur, Rahim Yar Khan
FESCO	5447	7.06	Layyah, Bahawalpur
IESCO	4586	6.04	Mianwali, DI Khan
GEPCO	4093	7.33	Bhakkar, Attock

Fig. 5 demonstrate the maximum load demand of all DISCOs in Punjab which will be covered by solar PV and includes, LESCO, MEPCO, FESCO, IESCO and GEPCO.

Fig. 6 indicates transmission line losses concerning distance and loads. One can see that as we vary the distance between sources and loads, the losses vary proportionally.

Fig. 8 shows the convergence curve of the simulated genetic algorithm. The simulation tool used for this optimization technique is MATLAB. The data used in our simulations are: Selection size, S=1500, Initial population, N=10 and the maximum number of iterations, t_{max} =1000, Top K=10, Max PI of solution = 7.24%. These maximum results are obtained by applying different iterations and selection of random values initially. The PI obtained is the overall weighted percentage. The mutation probability and the selection rate have been fixed to be 0.1 and 0.8 respectively [8].

Fig. 8 demonstrate the graph of the improving population as the genetic algorithm progresses. Max represents the best of the solutions at a particular iteration having the highest PI; Min represents the worst of the solutions at a particular iteration having the lowest PI and Average shows the mean of all solutions at a particular iteration. Iteration -1 shows the initial random selection of S solutions, iteration 0 shows the hence selected initial population of N solutions using the fitness function and all subsequent iterations show the top K solutions at each step after applying crossover and mutation. The best solution achieved in our work corresponds to the results presented in Table 8 which has twelve optimal locations out of sixteen locations where utility-scale solar PV power plants would be installed. These locations are shown in Fig. 9.

Table 8 shows the optimal solution for the overall installation of utility-

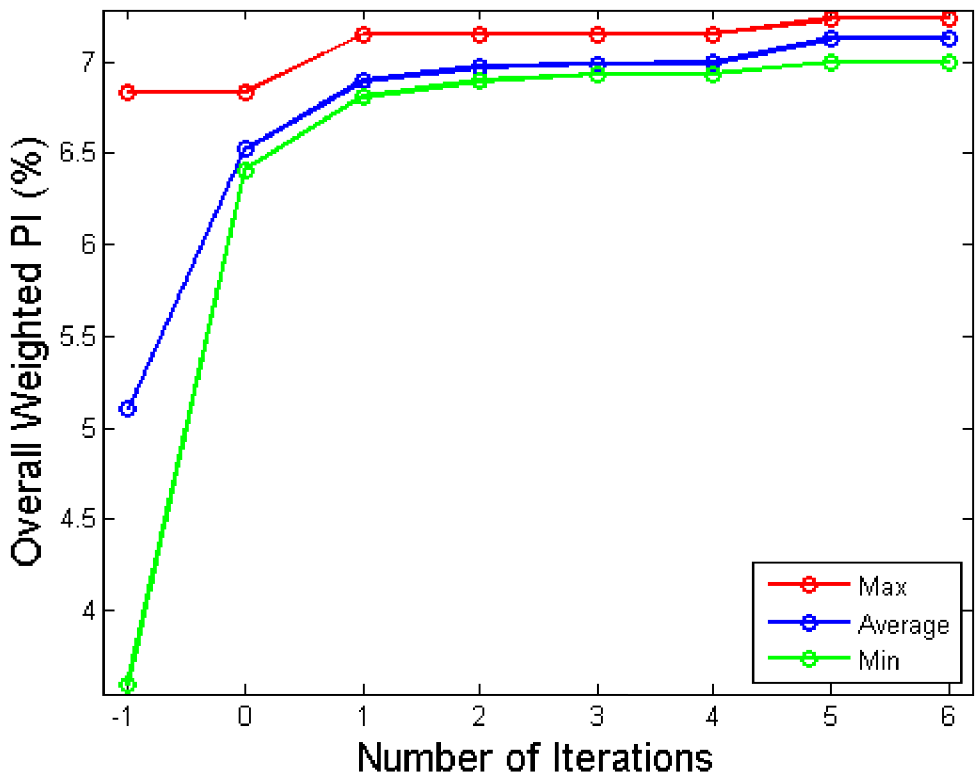

Figure 8: Convergence curve of genetic algorithm.

scale solar PV power plants. The overall weighted PI is around 7.24% for all the DISCOs combined.

7. Discussion

According to the results, the best locations for installing utility-scale solar PV power plants are in the south of the province. Not only these locations receive a better solar insolation, but they also have the highest number of sunny days in the province. For MEPCO, supplying electricity from these locations is on average will give PI of 11.12%. One would think that if this region has so much potential for solar power, why not install all the PV plants here. The problem is that when going up the country, the transmission line losses makes the energy less profitable. Therefore, in Table 8, the region selected for each DISCO is based on the proximity of the DISCO with the

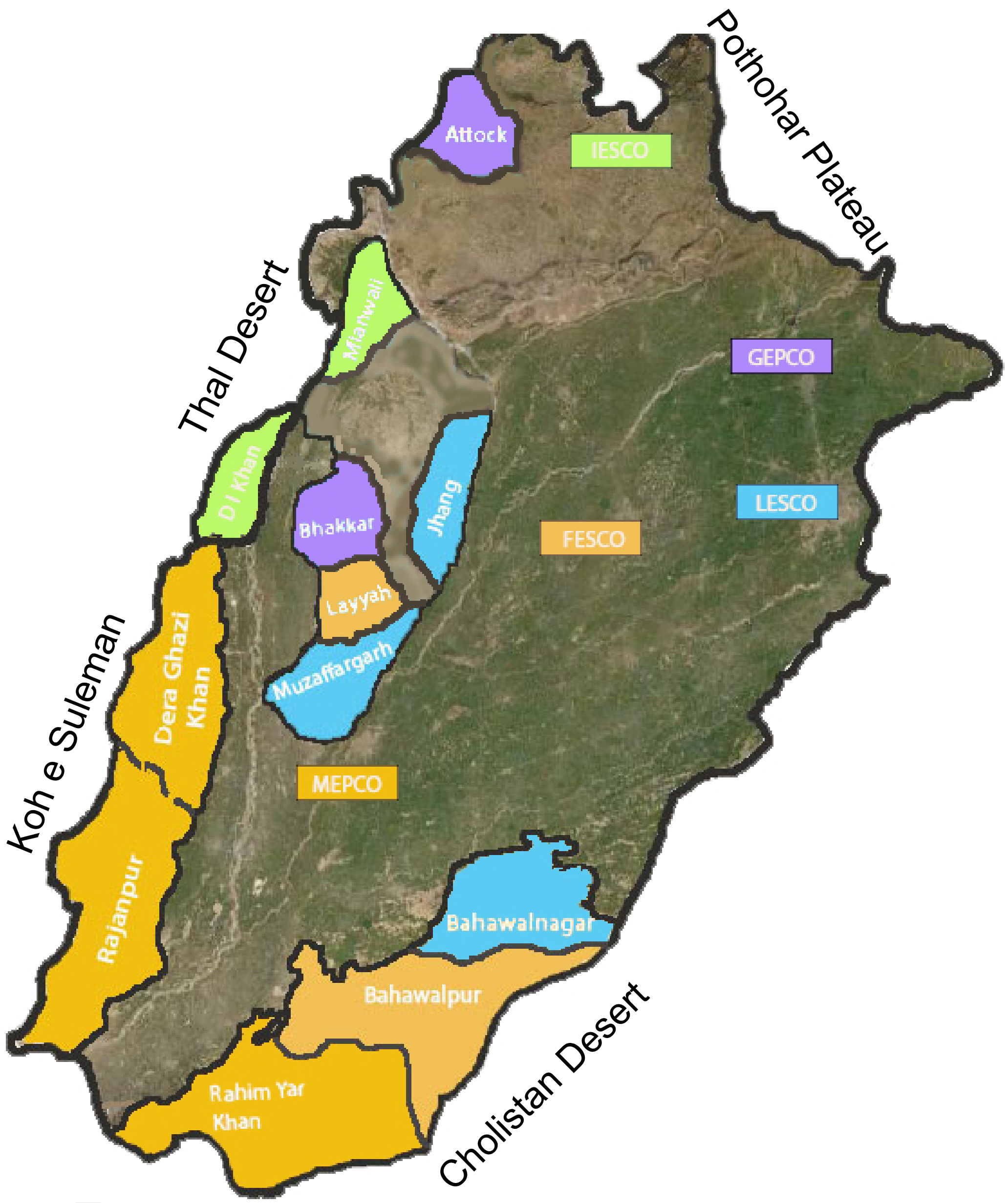

Figure 9: Twelve optimal regions for utility-scale solar PV power plants placement in Punjab.

selected region. Moreover, distributing the solar power plants, it is necessary to deal with the climatic variation across the province.

The peak load of the DISCOs is 25-35% more than the base load. Because of hot summers, the peak load is usually positively correlated with the temperature. Therefore, the solar energy could provide an ideal solution for fulfilling the needs of energy during the daytime for most of the summer season. However, this claim needs further investigation as it requires hourly analysis for the whole year vis-a-vis solar energy generation.

In Pakistan, typically two load peaks occur, one at mid-day and the other during evening hours. Our focus is to use the solar PV to fulfill the daily mid-day peak. Since the peak load in Pakistan is around 20,000 MW, and the base load is around 12,000 MW, we assume that the utility-scale solar PV power plants will fulfill the first peak of the day while the second peak will be fulfilled by using mainly hydro resources as well as through demand-side management. One question could come that the solar doesnt exactly match the peak, especially during the summer. Again some demand-side management has to be carried out to utilize solar energy in full. Our future work would be to map demand and PV production on an hourly basis which gives us even better and accurate results for matching demand and supply. Fig. 10. shows the normalized seasonal distribution of Punjab average electricity demand vs. its matching with the solar PV output. At this time, since the peak load is matching very closely with the PV output, we are not considering storage of solar PV energy. However, this will be a research direction we plan to pursue in our future work.

There are certain limitations related to our work, some of them are following:

First in this work, connecting the utility-scale solar PV power plants with existing installed transmission lines are not studied. The connection of available transmission lines to the utility-scale solar PV power plant is one of the major limitation. As 132 kV transmission lines are passing through these areas, we can easily connect our power plant to these lines, but a detailed study is needed before identifying a specific location. Second is dust accumulation which is also a major problem in installing a utility-scale solar PV power plants in these areas of Punjab. We are uncertain up to how much extent dust accumulation factor would affect the power output of these plants. Third, since these are remote areas, the roads network in these areas are minimal. So we have to look at the roads network availability to establish utility-scale solar PV power plants in these areas.

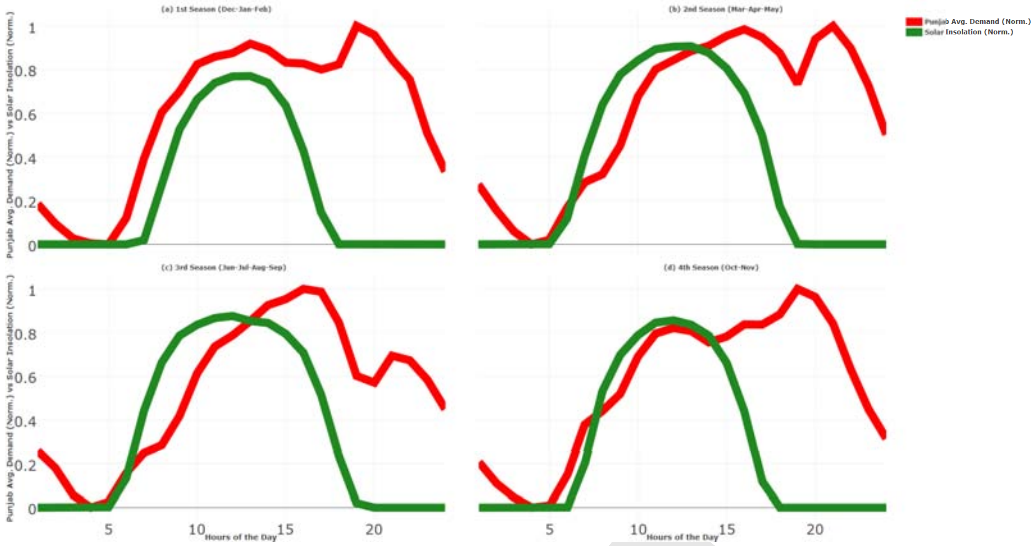

Figure 10: Normalised seasonal distribution of Punjab average electricity demand vs. solar insolation.

8. Conclusion and Future Work

To our knowledge, this paper is the first attempt at combining the solar energy and its economic aspects from an investor's perspective in Pakistan. We were able to find multiple locations in the province that provide PI of up to 69.65% while not eroding into the agriculture or population centers of the province. We were also able to identify ideal solar locations for supplying solar power to each DISCO of the province.

Our future work will look at balancing hourly demand at DISCOs and supply from solar PV power plants. Moreover, in this work, we fixed the size of the solar PV power plants between 2600 MW and 3100 MW, and a single location is supplying the electricity to a single DISCO only. In our future work, we will relax these restrictions and will be able to get a better sizing of the solar PV power plants based on the hourly demand and supply as well as economic factors.

In our future work, we will also look at the effects of various climatic factors on the performance of the solar PV power plants such as dust, fog and other generation inhibiting factors. We will also look at different types of solar power plants such as solar thermal in southern regions, rooftop solar PV for cities, floating PV for canals and dams and others to fulfill the energy needs of the province. Additionally, we will also look at the effects of solar PV on the biodiversity of the province.

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[1] , . Solar resource assessment: Databases, measurements, models, and information sources (fact sheet) report. URL: `https://digital.library.unt.edu/ark:/67531/metadc898674/`. accessed April 10, 2017.

[2] ALAMIN, A.A., 2013. ELECTRICAL POWER DISTRIBUTION LOSSES IN SUDAN. Ph.D. thesis. University of Khartoum.

[3] Alsamamra, H., Ruiz-Arias, J.A., Pozo-Vázquez, D., Tovar-Pescador, J., 2009. A comparative study of ordinary and residual kriging techniques for mapping global solar radiation over southern spain. Agricultural and Forest meteorology 149, 1343–1357.

[4] Askarzadeh, A., Rezazadeh, A., 2013. Artificial bee swarm optimization algorithm for parameters identification of solar cell models. Applied Energy 102, 943–949.

[5] BS, 2015. Land utilization and agricultural farms. URL: `http://bos.gop.pk/system/files/Dev-2015.pdf`.

[6] Drif, M., Pérez, P., Aguilera, J., Almonacid, G., Gomez, P., De la Casa, J., Aguilar, J., 2007. Univer project. a grid connected photovoltaic system of¡ span¿¡ img height=. Solar Energy Materials and Solar Cells 91, 670–683.

[7] Geiger, R., 1965. The climate near the ground.

[8] Gómez, M., López, A., Jurado, F., 2010. Optimal placement and sizing from standpoint of the investor of photovoltaics grid-connected systems using binary particle swarm optimization. Applied Energy 87, 1911–1918.

[9] Kornelakis, A., Koutroulis, E., 2009. Methodology for the design optimisation and the economic analysis of grid-connected photovoltaic systems. IET Renewable Power Generation 3, 476–492.

[10] Kornelakis, A., Marinakis, Y., 2010. Contribution for optimal sizing of grid-connected pv-systems using pso. Renewable Energy 35, 1333–1341.

[11] Li, C.H., Zhu, X.J., Cao, G.Y., Sui, S., Hu, M.R., 2009. Dynamic modeling and sizing optimization of stand-alone photovoltaic power systems using hybrid energy storage technology. Renewable energy 34, 815–826.

[12] López, P.R., González, M.G., Reyes, N.R., Jurado, F., 2008a. Optimization of biomass fuelled systems for distributed power generation using particle swarm optimization. Electric Power Systems Research 78, 1448–1455.

[13] López, P.R., Jurado, F., Reyes, N.R., Galán, S.G., Gómez, M., 2008b. Particle swarm optimization for biomass-fuelled systems with technical constraints. Engineering Applications of Artificial Intelligence 21, 1389–1396.

[14] Lorenzo, E., 1994. Solar electricity: engineering of photovoltaic systems. Earthscan/James & James.

[15] Mellit, A., Kalogirou, S.A., Drif, M., 2010. Application of neural networks and genetic algorithms for sizing of photovoltaic systems. Renewable Energy 35, 2881–2893.

[16] Mellit, A., Kalogirou, S.A., Hontoria, L., Shaari, S., 2009. Artificial intelligence techniques for sizing photovoltaic systems: A review. Renewable and Sustainable Energy Reviews 13, 406–419.

[17] Mirza, U.K., Ahmad, N., Majeed, T., Harijan, K., 2007. Wind energy development in pakistan. Renewable and Sustainable Energy Reviews 11, 2179–2190.

[18] Mirza, U.K., Ahmad, N., Majeed, T., Harijan, K., 2008. Hydropower use in pakistan: past, present and future. Renewable and Sustainable Energy Reviews 12, 1641–1651.

[19] Nofuentes, G., Aguilera, J., Muñoz, F., 2002. Tools for the profitability analysis of grid-connected photovoltaics. Progress in Photovoltaics: Research and Applications 10, 555–570.

[20] NTDC, 2008. Electricty demand forecast. URL: http://www.ntdc.com.pk/LoadForecast.pdf.

[21] Perez, R., 1998. The strength of satellite-based solar resource assessment, in: In: Production of Site/Time-specific Irradiances from Satellite and Ground Data, Report 98-3. New York State Energy Research and Development Authority, Corporate Plaza West, 286 Washington Evenue Extension, Citeseer.

[22] Standard, I., et al., 1998. Photovoltaic system performance monitoring-guidelines for measurement, data exchange and analysis. BS EN 61724.

[23] Šúri, M., Huld, T.A., Dunlop, E.D., Ossenbrink, H.A., 2007. Potential of solar electricity generation in the european union member states and candidate countries. Solar energy 81, 1295–1305.

[24] Thiaux, Y., Seigneurbieux, J., Multon, B., Ahmed, H.B., 2010. Load profile impact on the gross energy requirement of stand-alone photovoltaic systems. Renewable Energy 35, 602–613.

[25] Wang, C., Nehrir, M.H., 2004. Analytical approaches for optimal placement of distributed generation sources in power systems. IEEE Transactions on Power systems 19, 2068–2076.

[26] Yang, H., Lu, L., Zhou, W., 2007. A novel optimization sizing model for hybrid solar-wind power generation system. Solar energy 81, 76–84.

Appendix

The transmission line losses depend on the distance between generating source and load. Also, it depends on load as well. It gives distinctive results for each source to load combination as given in Table 9 to Table 13. One can see that as we vary the distance between sources and loads, the losses vary proportionally.

Table 9
LESCO transmission line losses.

PV Power Plant Locations	Distance to LESCO (km)	Transmission Losses (%)
Bhakkar	312	7.4
Jhang	207	5.1
Khushab	287	6.9
Layyah	332	7.9
Mianwali	344	8.1
Muzaffargarh	198	4.8
DG Khan	393	9.2
DI Khan	330	7.8
Rajanpur	472	11.0
Bahawalnagar	204	5.0
Bahawalpur	351	8.3
Rahim Yar Khan	525	12.2
Attock	312	7.4
Chakwal	210	5.1
Rawalpindi	260	6.3
Jhelum	163	4.0

Table 10
MEPCO transmission line losses.

PV Power Plant Locations	Distance to MEPCO (km)	Transmission Losses (%)
Bhakkar	166	3.6
Jhang	145	3.2
Khushab	252	5.3
Layyah	101	2.2
Mianwali	268	5.6
Muzaffargarh	33	0.7
DG Khan	83	1.8
DI Khan	190	4.1
Rajanpur	165	3.6
Bahawalnagar	174	3.8
Bahawalpur	91	2.0
Rahim Yar Khan	226	4.8
Attock	406	8.4
Chakwal	335	7.0
Rawalpindi	397	8.2
Jhelum	370	7.7

Table 11
FESCO transmission line losses.

PV Power Plant Locations	Distance to FESCO (km)	Transmission Losses (%)
Bhakkar	194	3.2
Jhang	77	1.4
Khushab	115	2.0
Layyah	208	3.4
Mianwali	192	3.2
Muzaffargarh	236	3.8
DG Khan	280	4.5
DI Khan	213	3.5
Rajanpur	373	6.0
Bahawalnagar	161	2.7
Bahawalpur	263	4.3
Rahim Yar Khan	435	7.1
Attock	272	4.4
Chakwal	150	2.5
Rawalpindi	229	3.7
Jhelum	180	3.0

Table 12
IESCO transmission line losses.

PV Power Plant Locations	Distance to IESCO (km)	Transmission Losses (%)
Bhakkar	286	3.9
Jhang	268	3.7
Khushab	155	2.2
Layyah	346	4.7
Mianwali	175	2.5
Muzaffargarh	421	5.8
DG Khan	452	6.3
DI Khan	273	3.7
Rajanpur	557	8.3
Bahawalnagar	394	5.4
Bahawalpur	481	6.9
Rahim Yar Khan	628	9.9
Attock	64	0.9
Chakwal	77	1.1
Rawalpindi	15	0.7
Jhelum	103	1.5

Table 13
GEPCO transmission line losses.

PV Power Plant Locations	Distance to GEPCO (km)	Transmission Losses (%)
Bhakkar	270	3.3
Jhang	177	2.2
Khushab	150	1.9
Layyah	303	3.7
Mianwali	247	3.0
Muzaffargarh	374	4.6
DG Khan	412	5.2
DI Khan	305	3.7
Rajanpur	497	6.6
Bahawalnagar	261	3.2
Bahawalpur	389	4.8
Rahim Yar Khan	564	7.9
Attock	247	3.0
Chakwal	152	1.9
Rawalpindi	195	2.4
Jhelum	97	1.3

Table 14
Nomenclature

Nomenclature			
AI	artificial intelligence	NPV	net present value ($)
AJK	azad jammu and kashmir	NREL	national renewable energy laboratory
COP	conference of the parties	NSRDB	national solar radiation database
DISCOs	distribution companies	P	transmission line losses (kW)
E_g	annual total electricity generated from PV power plant (kWh)	S	selection size
EPSH	equivalent peak sunlight hours per day	P_{load}	power provided to load by source (kW)
ETAP	electrical transient and analysis program	P_{loss}	average power loss (kW)
FATA	federally administered tribal areas	P_{source}	average power provided by source (kW)
FESCO	faisalabad electric supply company	P_g	selling price of electrical energy ($/kWh)
G	sum of global horizontal irradiation (kWh/m^2)	P_P	peak power installed (kW)
GA	genetic algorithm	PI	profitability index
GDP	gross domestic product	PV	photovoltaic
GEPCO	gujranwala electric power company	PVGCS	photovoltaic grid-connected system
GIS	geographic information system	PVI	present value of initial investment ($)
I	current passing through a transmission line conductor (A)	PV_{IN}	cash inflow ($)
IESCO	islamabad electric supply company	PV_{OUT}	cash outflow ($)
INV	initial investment ($/kW)	PR	performance ratio
INV_f	capital cost of land ($/kW)	R	resistance of conductor (Ω)
INV_v	capital cost of equipment ($/kW)	r_g	annual increase rate of sold energy price
L_c	annual leasing cost ($/kW)	r_L	annual increase rate of L_c
LESCO	lahore electric supply company	r_{MO}	annual increase rate of MO_c
M&O	maintenance and operation cost	R & D	research and development
MO_c	annual maintenance and operation cost	REG	renewable energy generation
MEPCO	multan electric power company	RES	renewable energy sources
N	initial population	SC_v	scrap value ($)
NCDC	national climatic data center	V_u	useful lifetime

Highlights

- Pakistan has a rapidly increasing population which demands more energy resources
- Solar PV is a widely available resource for electricity generation which has not been utilized yet
- We look at technical and economic factors to determine the best locations for utility scale solar PV plants in the province of Punjab
- Solar PV energy could be produced with a Profitability Index of as high as 69.65% in certain areas of the province