Off-Grid Electrification Strategy through Night-Time Satellite Imagery

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Session 2018-2020

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THESIS ACCEPTANCE CERTIFICATE

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Dedication

I dedicate my thesis to my ***Parents*** for their endless prayers, love, and encouragement.

Abstract

In Pakistan, various studies have been conducted for the electrification of off-grid areas through the solar photovoltaic system. However, the lack of analysis of load centers, solar energy potential, and the relevant economics related to these studies have been the major barriers to their practical applications. In this context, the unelectrified areas of Sindh and Punjab were analyzed using night-time satellite imagery and the obtained results were further examined through the database of the Pakistan Bureau of Statistics. Subsequently, an evaluation of solar potential as well as the project's economic viability was conducted in the selected areas. The study finds that the unelectrified rural areas of South Punjab and Sindh have sufficient solar energy potential that can be utilized for the electrification of rural communities. Moreover, economic analysis based on the Levelized Cost of Energy revealed that the per-unit cost of electricity through Solar PV system is PKR 10.7/kWh whereas, the cost of generation through conventional energy resource is PKR 20.79/kWh. The deployment of solar PV systems in unelectrified regions also helps in the mitigation of CO_2. Hence, based on the findings, the study proposes a comprehensive framework strategy for rural electrification through a Solar PV system involving all the concerned stakeholders. The outcomes and recommendations of this study will provide a basis for the formulation of an off-grid electrification policy in Pakistan.

Keywords: Sustainable development; Economic Analysis; Off-grid PV systems; CO_2 Mitigation

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List of journal papers/conference papers

M. A. Alizai, H. Zahid, W. Ajaz, A. A. Kazmi and S. Kumar, **"Techno-Economic Framework for Solar Electrification Using Night-time Satellite Imagery in Punjab - Pakistan,"** 2020 IEEE 23rd International Multitopic Conference (INMIC), 2020, pp. 1-6, doi: 10.1109/INMIC50486.2020.9318053.

List of Abbreviation

ADB	Asian Development Bank
PBS	Pakistan Bureau of Statistics
PSLMR	Pakistan Standard Living Measurement Report
SDG	Sustainable Development Goal
IFC	International Finance Corporation
NASA	National Aeronautics and Space Administration
NEPRA	National Electric Power Regulatory Authority
GHG	Green House Gases
GDP	Gross Domestic Product
IRENA	International Renewable Energy Agency
ADB	Asian Development Bank
AEDB	Alternative Energy Development Board

Chapter 1

Introduction

1.1 Overview

The Sustainable Development Goal (SDG #7) laid out by the United Nations is recognized as a basic human right that ensures the access of sufficient, affordable, reliable, and cost-effective energy supply for all including expansion in the share of renewable energy in the global energy mix by 2030 [1]. Surpassing 1.6 billion people, with the majority living in rural areas, a third of the world's population live without access to electricity. The World Bank reported that in developing countries more than 67 percent of the population lives without access to electricity [2]. Likewise, according to the last census result, Pakistan has a population of more than 220 million people, and a large portion has no electricity or lives in the areas where there is no electricity infrastructure in places [3].

Moreover, with economic development and social uplift, this demand continues to increase and requires further addition of generation capacity to ensure adequate supply for meeting current and future electricity demands. In this research, we examined geospatial data to analyze a lengthy time- series of nighttime satellite imagery to detect the presence, absence, and variability of outdoor lighting in rural communities across Sindh and Punjab. Data from these night-time images are compared with high-resolution data on human settlements and census results from the Pakistan Bureau of Statistics which identified the areas and off-grid population. In addition to that, based on the result of the unelectrified regions, a techno-economic framework of the PV solar system is presented by analyzing the solar profile of these regions from the NASA database [4]. Furthermore, a comprehensive off-grid electrification strategy of these regions is proposed.

1.2 Problem Statement

The following problem statement has been formulated based on the problems identified during the literature review.

As per Pakistan Census 2017, 63.62 percent of the total population lives in rural areas [5]. Currently, only 73 percent of the population has access to electricity, [6]. According to International Finance Corporation (IFC) and other independent agencies estimates, 38 percent of the grid-connected population, about 78 million people, receive low-quality energy [2]. About 31 percent of the population does not have access to electricity. According to the NEPRA [3], more than 30,000 villages in the country continue to remain without access to the electricity grid. For a number of remote villages, integration into the national electricity grid may not be viable both technically and financially.

1.3 Aim & Objectives

The aim and objectives of the study are as follows:

Aim:

To provide a comprehensive off-grid electrification Strategy in rural areas of Punjab & Sindh.

Objectives:

- Data sets extraction related to off-grid areas using Night-time satellite imagery.
- Evaluation of technical & economic viability of the photovoltaic system in the stated regions.
- Devising a rural electrification framework using Solar PV Systems.

1.4 Thesis Motivation

To date, no initiative has been undertaken to implement an effective off-grid electrification strategy across all the provinces. However, few pilot projects were done on targeted sites with the help of donor agencies but never implemented on a national scale. The remote nature of sites, lack of infrastructure, non-availability of exact and reliable data about a number of un-electrified villages, assessment of energy needs to communities and villages depending upon their domestic and economic needs are the leading impediments for national-level implementation. In addition to that lack of involvement of various government departments which include distribution companies and regulatory bodies is also resulting in electrification policy failure.

1.5 Thesis Contribution

The main contributions are listed as follows:

- The issue of off-grid site identification has been brought to light and associated barriers.
- Through research, it has been shown that unmet need areas located in night-time satellite imagery and census result complimented each other.
- Studied the solar system design for off-grid population-based on energy needs. Hence mitigating the costs associated with grid extension.
- Through the proposed system it has been shown that mitigation of carbon emission can be achieved.
- Discussed the implications of the non-existent off-grid electrification strategy which should provide a road map to electrify the off-grid areas.
- Presented a comprehensive plan of off-grid electrification which includes various government departments and agencies for national-level implementation.

1.6 Thesis Organization

The organization of the thesis is presented as follows. Chapter 2 presents the literature review of the important concepts related to this thesis. In chapter 3, the research methodology followed during the research has been discussed. In chapter 4 results and analysis were presented. In chapter 5, the proposed strategy, as well as recommendation, is presented for future off-grid electrification projects.

Summary

In this chapter basic concepts and strategy is introduced regarding off-grid electrification of Punjab and Sindh province. It gives an overview of the aim and scope of the thesis and presents the main objectives of the research work with the overall thesis organization. In the next chapter, we will look at the literature that has been conducted for the thesis.

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Chapter 2

Literature Review

2.1 Pakistan's Energy Sector

The demand for electricity in Pakistan rose to 24000 MW in recent years and is predicted to cross 40000 MW by 2030 [1]. So far, the major resources for electricity generation that constitutes the overall energy mix of Pakistan are Oil of 21.91 percent oil, coal 12.44 percent, nuclear 3.88 percent, wind 3.59 percent, solar 1.16 percent, natural gas 29.02 percent, Hydro 28.00 percent as shown in Figure 2.1 [2].

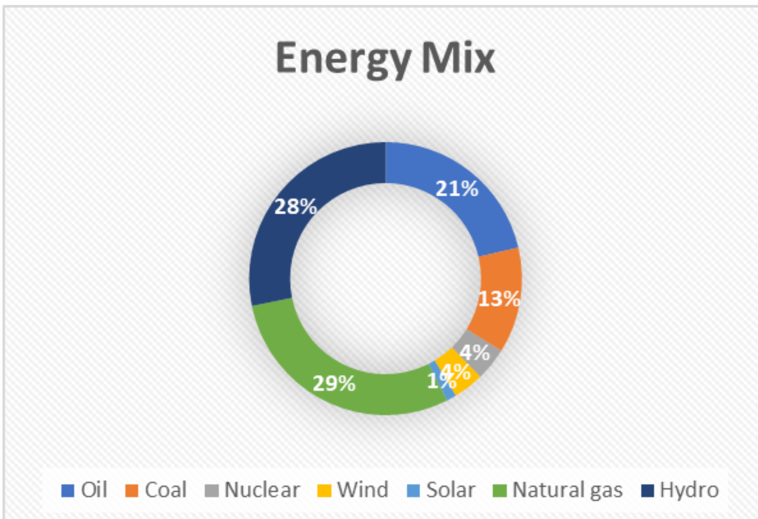

Figure 2.1: Energy Mix of Pakistan [2]

Furthermore, the domestic oil and gas reserves are forecasted to last 13 to 15 years resulting in enhancing the risk of energy security [3]. Similarly, the import-driven energy policy of Pakistan is also not sustainable in the long run resulting in increasing the insecure energy sector [4]. Whereas, to improve the global ranking in Green House Gas mitigation Pakistan must revisit its energy policy and exploit the alternative energy resources in rural as well as Urban areas [5]. So far, the renewable energy deployment particularly solar in rural areas is very low due to various reason which is discussed briefly one by one below.

2.1.1 Circular Dept and Electricity Rates

Last year Pakistan's electricity sector suffered an overall loss of Rs 5 trillion which is about 12 percent of GDP [6]. This surge in circular debt was due to the usage of expensive electricity resources and charging of lower consumer tariffs [7]. Apart from that this increase is also related to the issues of Policy formulation and administrative incompetence. Hence, the increase eventually led to the rise of electricity per unit price throughout the country resulting in power outages of 12 to 20 hours a day in both rural and urban communities [9]. The increase of circular debt also hampers the investment in this sector thereby increasing the overall cost [8]. Moreover, the world bank also highlighted the structural issues of utilities and their failure to collect the revenue resulting intolerable levels of circular debt [10].

2.1.2 Investment Barriers

In the 2014-2015 finance bill, a tariff of 32 percent tariff was imposed on the import of Solar panels [14]. However, due to the high domestic demand for solar panels by the private sector, the government reversed its decision. This complexity of Pakistan's energy sector also results as a repelling factor for the private sector to invest in renewable energy generation. The rise of upfront costs of projects, discount rates, dilapidated electricity infrastructure, remoteness of affected areas, and absence of resource potential assessment plays a key role in creating these investment barriers [11][12]. In addition to that, ADBI also reported that the structure and regulations of the Pakistan energy market do not help the small-scale companies in establishing small-scale solar home systems [13].

2.1.3 Lack of Coordination

According to the study [15], most of the energy policies are made in isolation and there is a lack of coordination among nation policies and programs and hence the power mix in the country has an overall negative impact on the environment. In addition to that, a lack of reliable data about present and potential future energy consumption results in the excessive drainage of resources and hampers the overall investment opportunities [16]. Moreover, the solar PV system deployment in rural communities is very low, the National Electric Power Regulatory Authority (NEPRA) stated that 30000 villages in the country are still unelectrified [17]. One of the reasons is the lack of coordination among different government organizations [18]. The absence of inter-departmental engagement creates barriers among three domains which are institutional, economic, and policy sectors. Hence, the electrification projects of these villages remain neglected.

2.1.4 Lack of Awareness Methods

There has always been a direct relationship between the community's access to electricity and their quality of life and health [19] whereas public opinion about different energy resources is also very critical for the planning of future energy resources [20]. According to the study [21], awareness-raising campaigns by electronic media and subsidies by the government are not effective in promoting solar PV systems in rural areas. Instead, the rural population can be compelled by in-person interaction, experimental learning, and targeted village awareness campaigns as shown in Figure 2.2.

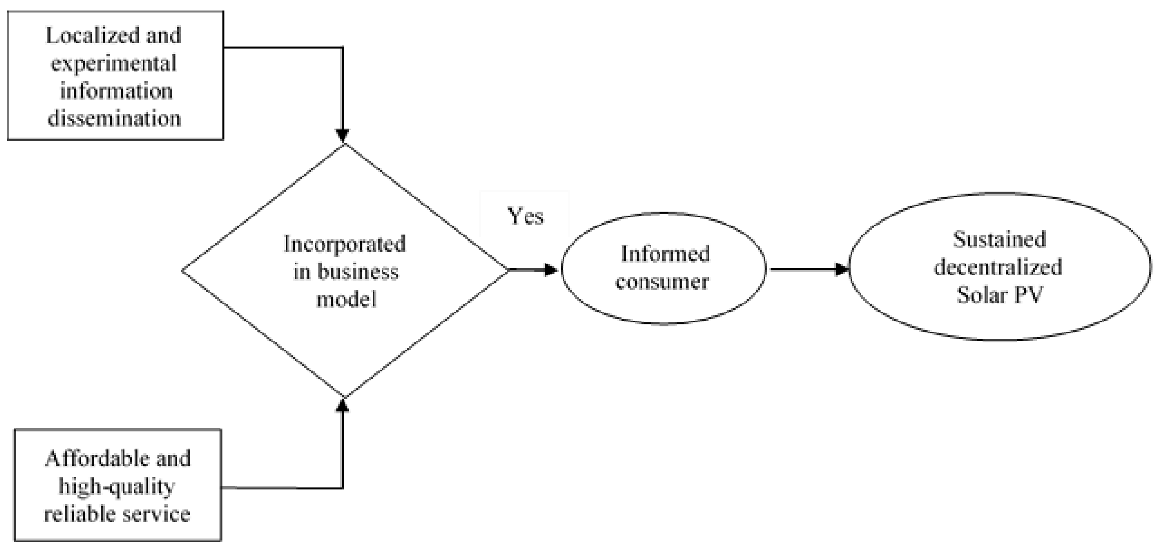

Figure 2.2: Rural Awareness Framework

2.2 Renewable Energy Resource in Pakistan

Pakistan has a huge potential for both renewable and non-renewable energy sources [22]. The known potential to generate electricity from renewable energy sources are Solar (2900GW), Wind (346 GW), Hydropower (5GW), and biomass (5 GW) as shown in figure 2.3 [23]. Furthermore, the total solar energy potential of Pakistan is forecasted to reach up to 169 GW by 2050 [24]. Despite this fact, Pakistan is still experiencing blackouts in rural as well as urban areas and sustainable energy planning still dependent upon fossil fuel generation units even though it is blessed with a tremendous amount of renewable energy resources which can be harnessed [25][26] In this study the criteria for renewable resource assessment is done through socio-political, environmental, technical and environmental aspects.

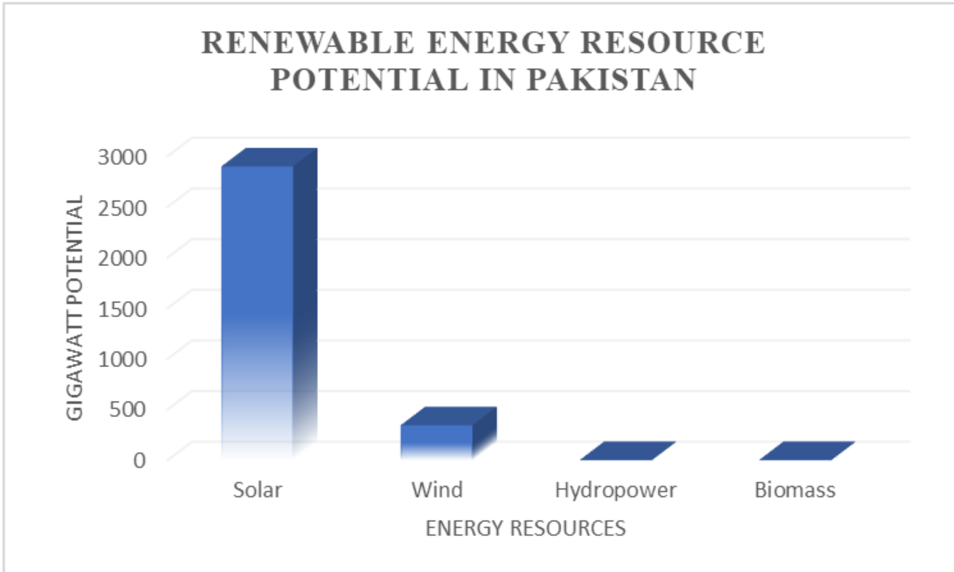

Figure 2.3: RE-Source Potential

2.2.1 Off-grid Solar Electrification

Throughout the year, the regions of south Punjab and Sindh receive abundant energy from solar irradiation [27]. Both of these provinces blessed with huge solar energy potential, having solar irradiation of 1900-2200 kWh/m^2 annually [28]. Furthermore, the study also highlighted the absence of resource management and infrastructure planning in rural areas. In relation to the feasible options for a particular region, multiple studies were conducted which compared the different power generation system that includes hybrid systems, diesel generation units, and Solar PV. The conclusion of these studies suggested that technically as well as economically Solar Photo Voltaic system is one of the most foremost options for residential electrification. [29] [30].

2.2.2 Cost-Effectiveness of Solar

The induction of solar PV systems saves multiple costs associated with other generation technologies. The on-site resource management help in eliminating the substitute costs well as fuel transportation cost associated with other conventional generation resources [31]. The studies have been conducted around life cycle analysis as well as projects environmental benefits and net energy generation, which revealed that, for off-grid electrification communities, PV technology is a feasible option [32][33]. Moreover, solar PV generation systems will replace hybrid systems in the future because of the costs associated with managing hybrid generation units [34].

2.2.3 Socio-Economic Development

There has always been a strong relationship between socioeconomic indicators and affordable and sustainable energy supply irrespective of available energy resources [35]. The induction of solar PV systems by rural communities is dependent on demographic as well as on institutional factors which help them in the transition from conventional energy resource to unconventional ones. Moreover, a study was conducted which analyzed the impacts of the Solar PV system on socio-economic conditions of the rural communities and concluded that the living standard of rural communities improved after this transition [36] [37]. The ADB and IRENA also endorsed off-grid electrification through the Solar PV system [38] [39]. In another study, they have analyzed the off-grid communities based on the price they pay for lighting sources and have concluded that unelectrified rural communities can leapfrog to Solar PV and will eliminate the cost related to lighting generation sources at night i.e., Kerosene. Furthermore, the costs associated with traveling for electricity access can also be eliminated [40].

2.2.4 Rural Household Profile

The electricity demand usually lies between 50W to 100W for rural households [41] [42]. The total load is comprised of few numbers of fans, charging ports for mobile, and a couple of LED lights. The rural household usually has 2 rooms and extending the electricity transmission to these houses with minimum load requirements is quite expensive and not feasible. Similarly, conventional energy sources like diesel generators do not provide an economically feasible option due to transportation issues associated with remote rural regions and environmental impacts associated with its use [43]. Hence, the provision for other electrification solutions must be analyzed for off-grid areas.

Summary

This chapter covers the background and the related work of the thesis. The related literature has been presented along with an analysis of the studies previously conducted. Previous research work and schemes used in the literature helps in formulating the solution to the identified problem. In the following chapter, we will discuss the research methodology that has been followed during the thesis.

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Chapter 3

Research Methodology

In this paper, a detailed methodology as well as the criteria's have been discussed. More specifically, it presents the sequence of research approach carried out during this study. In addition to that, data collection and analysis techniques have also been presented. Figure 3.1 presents the overall flowchart of our research methodology. Starting off with the data collection followed by identification of unelectrified districts, number of off-grid people, evaluation of solar potential and economic feasibility analysis related to the regions. Based on the above methodology as well as literature reviewed, a comprehensive electrification strategy is devised.

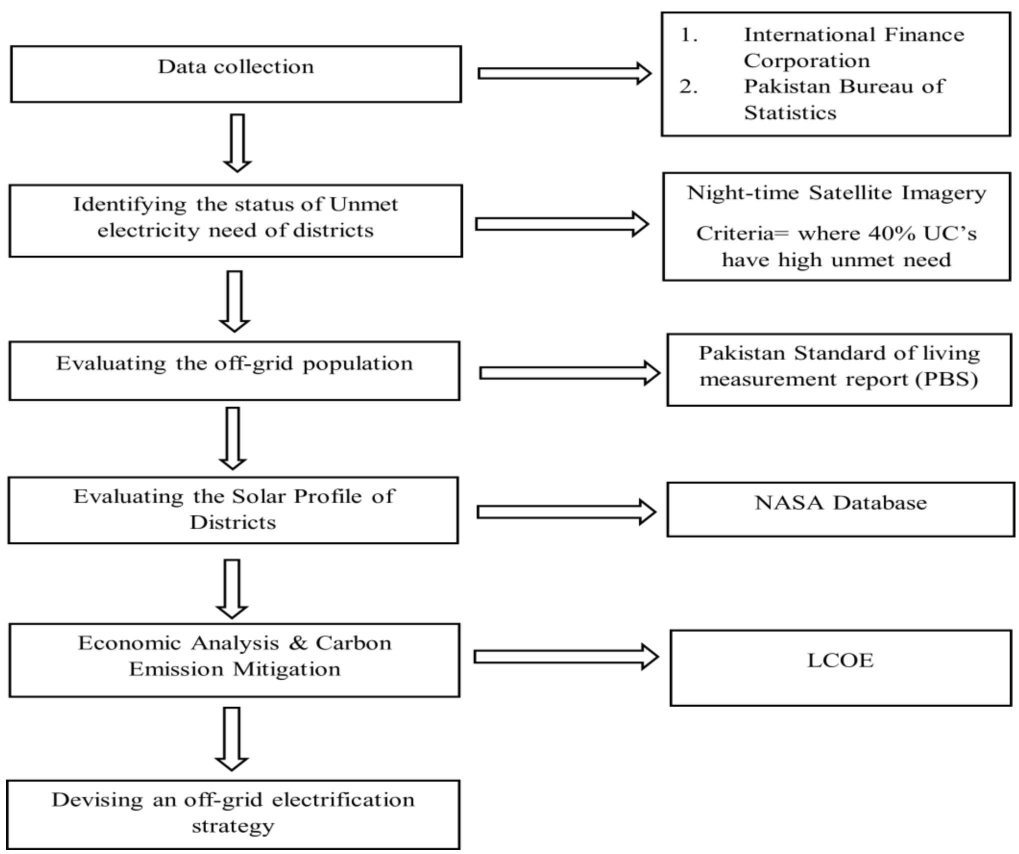

Figure 3.1: Research Flowchart

3.1 Region Selection through Night-time Satellite Imagery

The location of electrified settlements has been marked using Nigh-time Satellite Imagery. The data relating to the electrification status of the council and union council of districts has been acquired from the International Finance Corporation. It includes areas, average lighting, and energy needs. Moreover, further analysis has been done to shortlist and prioritize the union council with high unmet electricity demand. Due to the limitation of data, the research has been carried out on two provinces namely: Punjab and Sindh.

3.1.1 Status of Unmet Need in Punjab Province

After the analysis on Punjab province, 7 districts out of 36 districts were prioritize based on a deficiency in energy needs. In these 7 districts, more than 40 percent of union councils has a high ratio of unmet needs. These shortlisted districts were further analyzed through the Pakistan Bureau of Statistics PSLM report to account for the unelectrified people [1].

Table 3.1 shows the Unmet need/km^2 based on which districts of Punjab were selected. The data of unmet need of every union council in 36 districts were analyzed and criteria for selection was defined. After that based on the energy deficiency of union councils of more than 40% the above districts were selected.

Table 3.1: Status of Unmet Need in Punjab

Regions	**Light Output / km^2**			**Average Unmet Need/km^2**
	Maximum	**Minimum**	**Average**	
Bhakkar	1.56	1.04	1.10	1.02
Chakwal	1.35	1.06	1.11	1.00
D G Khan	1.94	1.04	1.13	0.99
Layyah	1.32	1.05	1.11	1.03
Mianwali	1.78	1.06	1.20	0.99
Muzaffargarh	1.50	1.04	1.15	1.03
Rajanpur	1.75	1.03	1.10	1.00

Similarly, Figure 3.2 shows actual satellite imagery from a source file acquired from IFC lightning Global. Whereas Figure 3.3 represents the mapping of districts based on energy needs. Both figures were analyzed for Table 3.1 summarization.

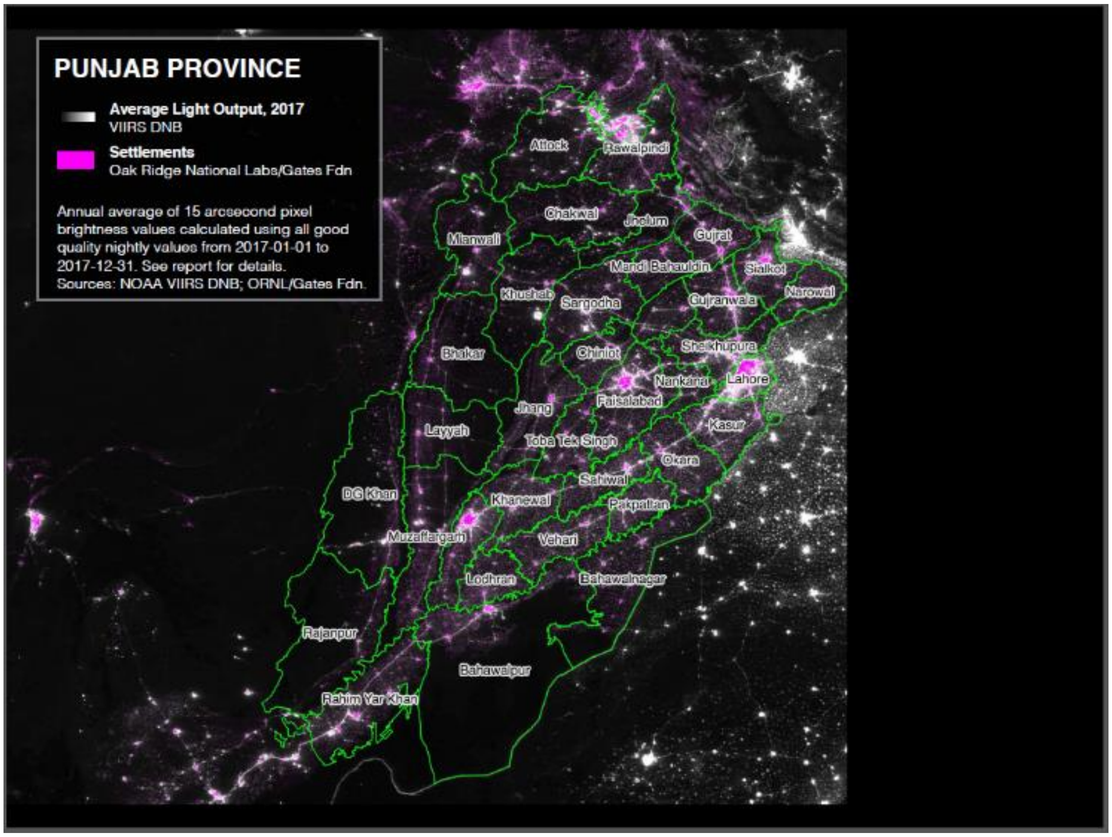

Figure 3.2: Punjab Night-time Satellite Imagery

3.1.2 Status of Unmet Need in Sindh Province

Similarly, out of 29 districts of Sindh, 9 districts are selected based on a deficiency in energy needs. The criteria of selection are the same as that of Punjab. Due to the remote nature of most of these regions and scattered human settlements, the number of selected districts in Sindh is higher than Punjab under the same criteria.

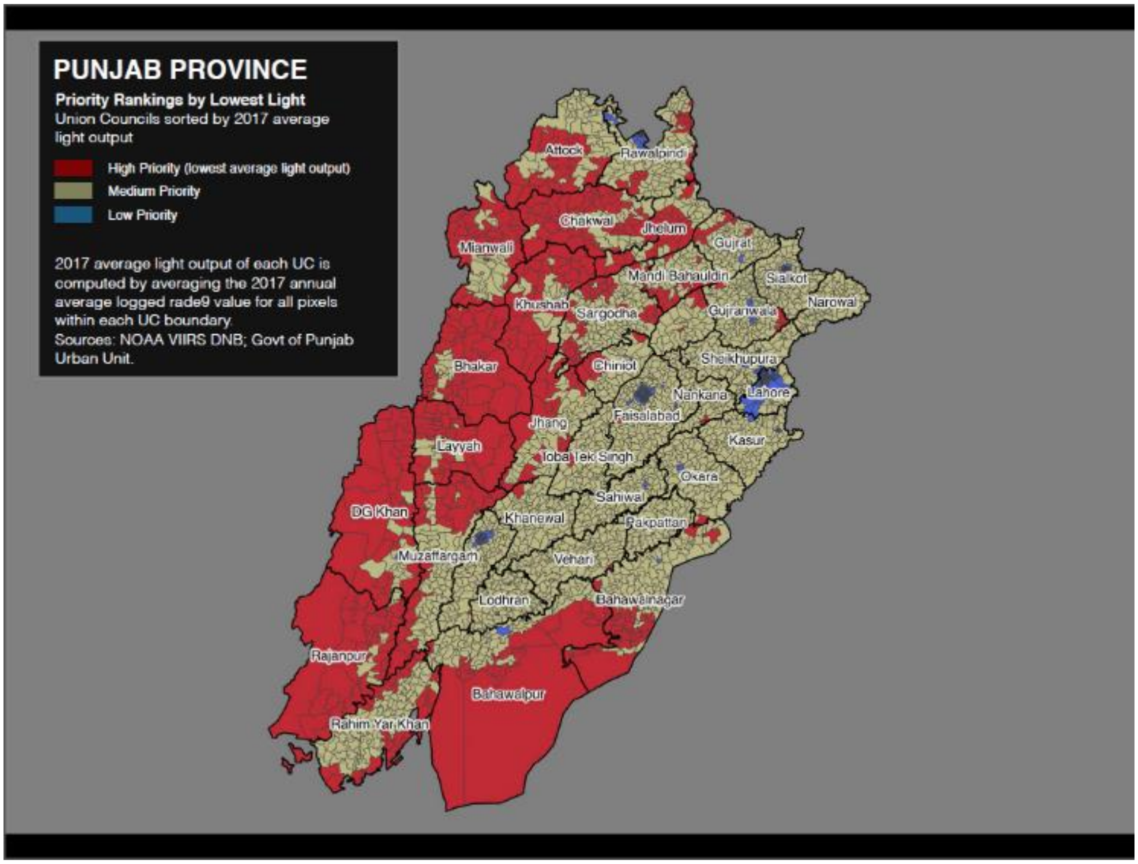

Figure 3.3: Punjab Map of Priority Rank

Here, Table 3.2 represents the unmet need/km^2 of Sindh province districts. The data of union councils of 29 districts were analyzed and based on the results Table 3.2 is summarized.

Table 3.2: Unmet Need of Sindh Districts

Regions	Light Output / km^2			Average Unmet Need km^2
	Maximum	Minimum	Average	
Badin	1.95	1.00	1.07	1.01
Jamshoro	2.47	1.02	1.16	0.88
Tando M. Khan	1.60	1.02	0.99	0.99
Thatta	1.74	1.00	1.07	1.01
Mirpur Khas	2.39	1.02	1.09	1.04
Sujawal	1.40	1.00	1.04	0.98
Tando Allah Yaar	1.87	1.04	1.16	0.98
Tharparkar	1.12	1.01	1.03	1.07
Umar Kot	1.58	1.02	1.06	1.06

Figure 3.4 represents the night-time satellite imagery of Sindh province whereas Figure 3.5 represents the mapping of districts of Sindh based on energy needs. Both figures were also obtained from the source file of IFC lightning global.

Furthermore, the number of districts listed in Table 3.2 is higher as compared to Table 3.1 while the criterion for selection remains unchanged. Hence, the clear indication from the analysis above is the need to electrify the off-grid community of both provinces and priority must be given to the Sindh province first.

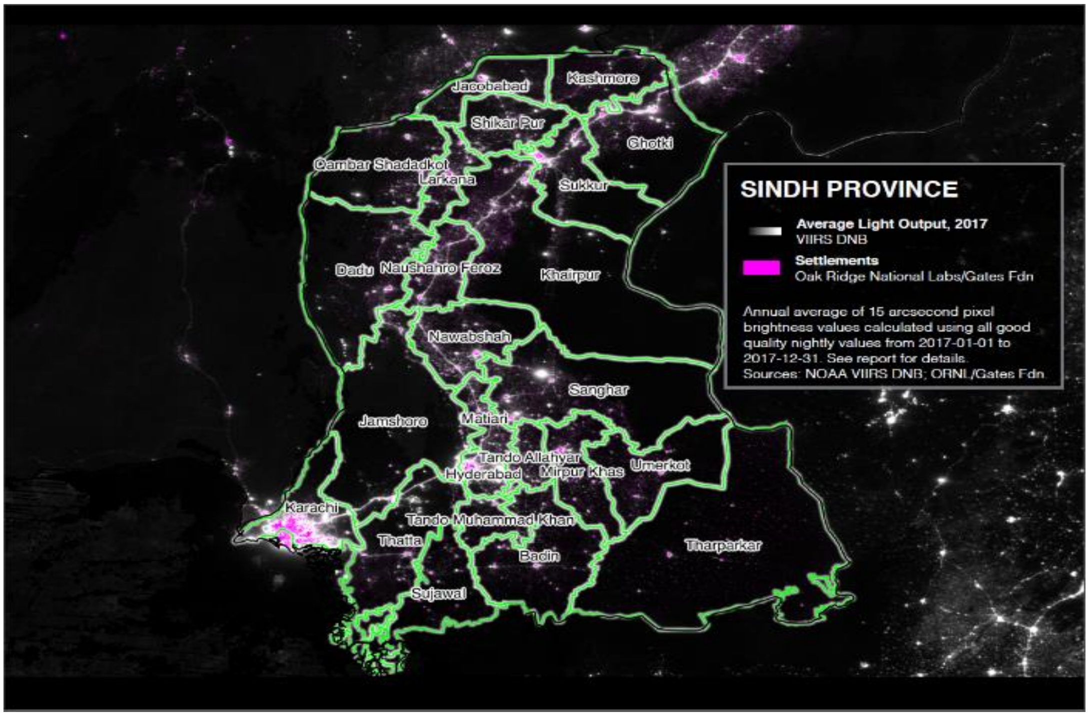

Figure 3.4: Sindh Night-time Satellite Imagery

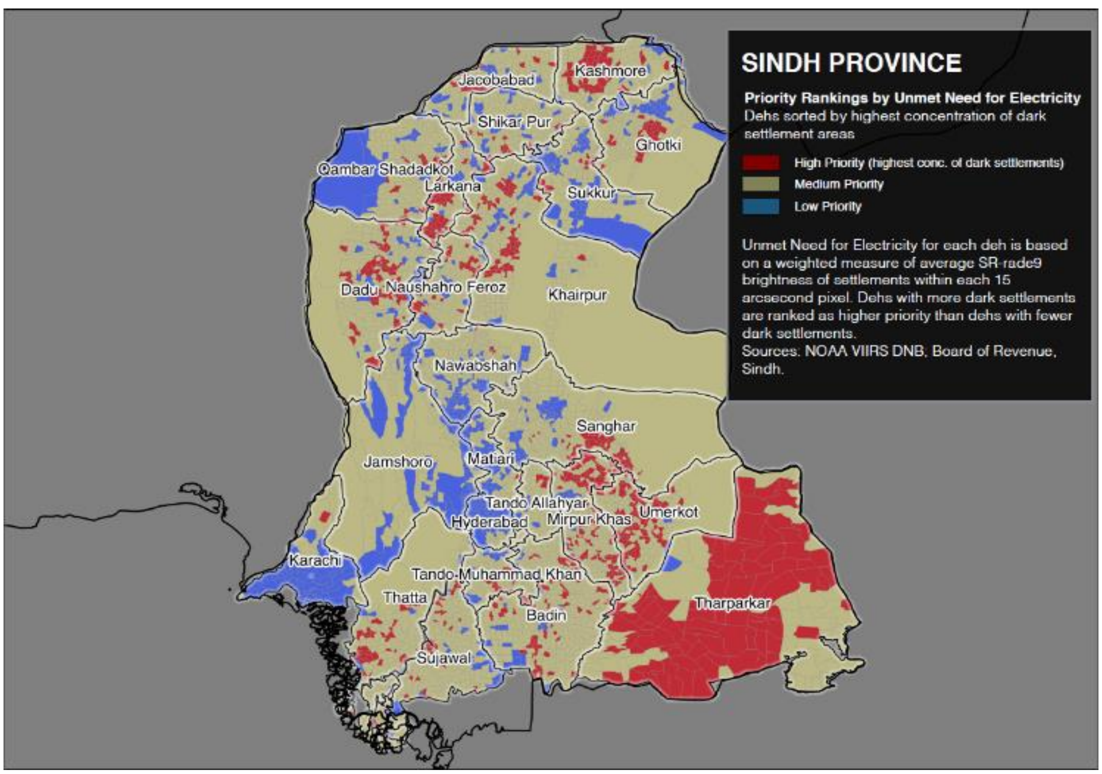

Figure 3.5: Sindh Map of Priority Rank

3.2 Techno-Economic Analysis of Off-grid PV System

The following subsection describes the economic viability of off-grid Photovoltaic System in rural regions:

3.2.1 Evaluating Potential of Solar Energy

Solar radiation 1 kW/m^2 is used to determine the peak sunshine hours; the solar radiation of a particular region can be calculated when the number of sunshine hours in that region is maximum for a certain period of hours. For example, if a 100 Wp solar array is installed and the power from the solar array 5 kWh/m^2/day. Annual energy output can be calculated for PV system performance from Equation 3.1 [2].

$$\text{Annual energy Output} = \text{Global irradiation}((kWh/m^2)/year) \text{ x Performance ratio} \quad \textbf{(3.1)}$$

3.2.2 System Sizing and Storage Unit

A general photovoltaic system comprises Solar Panels, Load, Battery storage, control system, and inverter. The solar irradiation received by the panels further carries it to the control system where transformation to Direct Current (DC) takes place. After that, it is transmitted to the inverter where an alternate current (AC) is received. The energy generated by solar panels depends on the solar energy received by a module in a certain region. However, there are certainly other variables like tilt angle, efficiency, and PV maintenance that affect the overall performance [3]. Moreover, the DC-AC transformation system encounters certain losses which also need to be evaluated. Multiple methods are available to calculate the solar PV yield.

Here the solar power potential to generate electricity is calculated using equation 3.2.

$$P_{Pv} = A_{Pv} \text{ x } E_{Pv} \text{ x } I_a \text{x } PR \quad \textbf{(3.2)}$$

where A_{Pv} is the panel area, E_{Pv} is efficiency, I_a is solar irradiation annually received on PV panel, and PR is performance ratio of PV system. Further, E_{Pv} is calculated as [4],

$$E_{Pv} = E_r \text{ [1- } G_r \text{ [}T_a – T_r + (T_n \text{ - } T_{a.n})]] \text{ x } I_T/I_n \quad \textbf{(3.3)}$$

where E_r is panel efficiency, G_r is the solar panel efficiency, Ta is ambient temperature, T_r is referenced temperature of PV panels, Tn is the nominal operating temperature and $T_{(a.n)}$ is the ambient nominal operating temperature, and I_n is solar irradiation.

Similarly, one of the vital parameters related to the solar PV system design is to account for a load that the system can handle easily. Hence before designing and installation of a solar PV system, the electricity demand pattern must be analyzed [5], i.e., ratings of electric appliances, number of operational hours, and total energy consumption. In Table 3.3, the total operational load is 407 watts in a single household which includes fans, mobile charging slots, and lights.

Table 3.3: Load profile of Rural Household

Appliances	No's operational	Operational Hours	Wattages	Load (Watt-Hour)
Pedestal Fan	1	9	12	108
Ceiling Fan	1	12	12	144
Charging port	2	3	5	30
LED	5	5	5	125
Total Watts per day				407

Whereas the difference between electricity demand and supply is given as:

$$\text{Electricity difference} = \sum_{i=1}^{365} P_{Pv} - P_d \qquad \textbf{(3.4)}$$

During the daytime sunshine hours, a Solar PV system can effectively produce energy to maintain the load requirements of a rural household. However, during the nighttime, a storage unit ensures a required energy supply and can serve the purpose of an uninterrupted energy generation source. Furthermore, the off-grid areas are mostly situated in rural regions and hence have an additional cost associated with maintaining storage battery units. The operation of the storage unit depends on the relation of supply and demand of electricity, for example; if the energy produced from the solar PV system is greater than the demand ($P_{Pv}>P_d$) the excess energy is stored in a battery unit and can operate optimally, whereas if the energy from the solar PV system is less than required demand ($P_{Pv}<P_d$), then the system is badly designed for required load. Therefore, the annual electricity stored in a battery storage unit Ss is:

$$S_s = (\sum E_e - \sum S_e) \text{ x } E_b \tag{3.5}$$

Where E_e is extra energy, S_e is shortfall energy and E_b is battery efficiency. The daily battery storage capacity, S_b, is given as:

$$S_b = K_b/365 \tag{3.6}$$

3.2.3 Economic Analysis

To compare the different electricity generation technologies on cost/unit, the Levelized cost of energy (LCOE) is a principle measuring unit to evaluate technologies. Based on cost-effectiveness it prioritizes different choices. In this study, the comparison is done between Photovoltaic and conventional generation systems to evaluate the best option for off-grid electrification. Therefore, the estimated LCOE per unit kWh for the Solar PV system is compared with rival conventional technologies [6].

$$\text{LCOE} = \sum_{a=1}^{n} \frac{I+M+F}{(1+i)^a} \Big/ \sum_{a=1}^{n} \frac{e}{(1+i)^a} \tag{3.7}$$

where I is the investment cost, M is the operation & maintenance cost, F is the fuel cost, a is the time of the year, e is the energy generated in kWh, i is the discount rate and n is the life cycle duration of the project. The degradation factor is also taken into account while calculating the LCOE [7].

3.2.4 Carbon Emission Mitigation

One of the ways to mitigate the effect of climate change mitigation is to induct renewable energy technologies into the electricity generation sector. The use of Solar PV technology helps in curtailment of Green House Gas emissions worldwide. Therefore, to nullify the effects of diesel generation on the overall environment, the government and private sector must facilitate the induction of renewable technologies in the off-grid electrification sector. However, the only carbon emission associated with the solar PV system is during its production, and it produces little or no carbon dioxide during operation [8]. In addition to that, nowadays the major challenge in front of the world is climate change, which is taking its toll on different countries due to the excessive use of fossil fuel and hence affecting the climate in worse possible ways [9] [10]. Thus, the solar PV system can help in mitigating carbon dioxide emission if it replaces conventional energy resources like diesel-powered generators.

By employing the solar PV system, the total carbon dioxide mitigated, and fuel saved, Fs, is considered as [6].

$$F_s = P_{Pv} \text{ x } F_r \quad \textbf{(3.8)}$$

where Fr is the fuel required to generate unit kWh of electricity. The decrease of Carbon dioxide emission is measured in kilograms(kg) when the Solar PV system is employed, now the total emission saved is [6].

$$\text{EM} = P_{Pv} \text{ x } (E_d - C_{pv}) \quad \textbf{(3.9)}$$

where E_d is the emitted carbon in kilograms when generating unit kWh from diesel generators, and C_{pv} is the emission in kilograms when generating unit kWh from the Solar PV system.

Summary

In this chapter, we have covered different research methodologies that have been followed by the researcher. Parameters, formulae, and criteria for this research have also been presented in detail. In the next chapter, we will look at the results evaluated using the methods described in the previous chapter.

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Chapter 4

Results and Discussion

4.1 Unmet Need Assessment and Verification

To identify the unelectrified districts, the analysis has been done based on the energy deficiency data of the districts. Table 3.1 in the previous chapter shows the light output, brightness values, and average unmet needs based on which these districts are selected. The built-up area which has high unmet need has been prioritized for analysis as shown in Table 4.1. In these multiple districts, almost 40% of the union councils have high energy deficiency. In addition to that, the build-up to non-built-up ratio also gives us an idea about the density of human settlements. As shown in Table 4.1, the Rajanpur and D G Khan districts have the most scattered off-grid population [1][2].

Table 4.1: Build-up area of Punjab Districts.

Regions	Area (km^2)		
	Total	**Built-Up**	**Non-Built Up**
Bhakkar	8160	211.5	7948.2
Chakwal	6633.5	186.9	6446.6
D G Khan	11925.1	187.3	11737.7
Layyah	6273.9	186.3	6087.6
Mianwali	5827.4	181.4	5645.9
Muzaffargarh	8260.7	330.1	7930.6
Rajanpur	12335.5	114.3	12221.2

Similarly, the number of districts selected in Sindh province is shown in Table 4.2. The criteria for selection pointed out nine districts of Sindh which has unmet energy needs. Despite having an overall lower population than Punjab, the energy deficiencies in Sindh is more than that of Punjab. Furthermore, the build-up to non-build-up ratio from Table 4.2 shows that the unelectrified population is more scattered in Sindh than in Punjab. Tharparkar and Jamshoro stand out as having a higher unelectrified rural population.

Table 4.2: Build-up area of Sindh Districts.

Regions	Area (km^2)		
	Total	Built-Up	Non-Built Up
Badin	6647.00	97.29	6549.70
Jamshoro	11076.87	56.96	11019.90
Tando M Khan	1779.93	36.06	1743.86
Thatta	6244.20	65.89	6178.31
Mirpur Khas	3452.3	87.11	3365.22
Sujawal	4752.60	34.02	4718.58
Tando A Yaar	1438.95	37.64	1401.31
Tharparkar	19720.94	151.15	19569.79
Umar Kot	5209.09	77.78	5131.31

4.1.1 Verification from Pakistan Bureau of Statistics

In addition to the data presented before, the Pakistan standard of living measurement report issued by the Pakistan Bureau of statistics contains different socio-economic parameters of the country [3]. One of the parameters is the percentage of sources used by people of the particular region for lightning. So, from the data provided by PBS, the number of off-grid population is evaluated as shown in Table 4.3. Table 4.3 shows that South Punjab as well as regions close to the Balochistan border are suffering the most and more than 2 million people are without electricity, which includes un-electrified areas as well as weak grid areas.

Table 4.3: Off-grid Population of Punjab

Regions	% Source use for Lightning				Off-grid Population
	ELECTRICITY	GAS/OIL	WOOD & Candle	Other	
Bhakkar	92.98	6.54	0.13	0.34	115775
Chakwal	93.38	4.32	1.05	1.25	99035.2
D G Khan	82.2	12.41	4.9	0.49	511216
Layyah	84.26	12.07	0.68	2.99	287097.6
Mianwali	89.65	5.35	0.65	4.35	160011
Muzzafargarh	89.9	8.05	1.19	0.86	484901
Rajanpur	73.96	23.85	0	2.19	519758

Similarly, the status of the off-grid population in Sindh is given in Table 4.4. This table shows that the Tharparkar is the most suffered region in terms of access to electricity with close to a million people without electricity. In addition to that, the overall electricity status of the rest of Sindh from Table 4.4 is not encouraging i.e., more than 3 million people in Sindh do not have a sustainable supply of electricity.

Table 4.4 - Off-grid Population of Sindh

Regions	% Source use for Lighting				Off-grid Population
	Electricity	Gas/Oil	Wood & Candle	Other	
Badin	73.47	2.08	1.26	23.19	478866.5
Jamshoro	91.14	2.93	0.67	5.26	104,274.45
Tando M Khan	83.34	1.98	5.74	8.94	112826.18
Tando A Yaar	94.67	0.24	0.98	4.11	44606.07
Mirpur Khas	79.48	13.76	1.91	4.85	101984.60
Sujawal	44.96	50.87	1.51	2.66	429312
Thatta	56.91	38.85	0.27	3.97	422203.14
Tharparkar	38.55	9.47	13.33	38.65	1013925
Umar Kot	66.91	12.46	4.22	16.4	355055.7

4.2 Solar Profile of Un-electrified Districts

For the induction of the PV system, the first step is to analyze the solar profile of that region [4]. In this study, we have obtained the solar data from the NASA database and average it out over 5 years to accurately reflect the solar energy potential of the required regions [5].

4.2.1 Solar Profile of Punjab

The solar profile data of the seven regions; Bhakkar, Chakwal, DG Khan, Layyah, Mianwali, Muzaffargarh, and Rajanpur has been provided in Table 4.5. In all the concerned regions, there is enough availability of solar energy to generate electricity throughout the year [6]. Moreover, in Figure 4.1 to Figure 4.7, the daily solar irradiance on a flat surface is presented and relative annual solar irradiation is given in Figure 4.8

[7]. The highest Annual Solar Irradiation is in Rajanpur, followed by the Layyah region, the DG Khan region, the Muzaffargarh region, the Mianwali region, the Bhakkar region, and the Chakwal region, respectively.

Table 4.5: Solar Data of Selected Regions of Punjab

Months	**Bhakkar**		**Chakwal**		**DG Khan**		**Layyah**		**Mian-Wali**		**Muzaffargarh**		**Rajanpur**	
	Daily Solar Irradiation kwh/m^2/day	**Earth Temp**	-	-	-	-	-	-	-	-	-	-	-	-
Jan	3.0	11.6	2.9	10	3.4	13	3.4	12	3.0	9	3.1	12.9	3.5	13.9
Feb	4.0	15.8	3.8	13	4.3	17	4.3	16	3.9	13	4.1	17.3	4.5	18.1
Mar	4.7	22.1	4.5	19	5.1	23	5.1	22	4.6	19	5.0	23.8	5.4	24
Apr	6.0	29.8	6.0	26	6.2	31	6.2	30	6.1	24	6.1	31.7	6.5	31.9
May	6.5	36.8	6.6	33	6.6	37	6.6	36	6.7	34	6.4	38.0	6.8	37.8
June	6.1	40.5	6.1	37	6.2	40	6.2	39	6.4	38	6.0	40.3	6.3	40.1
July	5.1	39.5	5.2	34	5.4	39	5.4	39	5.5	36	5.4	40.0	5.7	38.9
Aug	5.3	38.2	5.4	32	5.7	37	5.7	37	5.6	34	5.5	38.4	5.9	37.3
Sep	5.2	34.08	5.2	29	5.5	34	5.5	33	5.3	31	5.4	34.9	5.7	34.6
Oct	4.2	26.93	4.3	24	4.7	27	4.7	27	4.3	25	4.4	28.1	4.9	28.5
Nov	3.1	18.81	3.2	16	3.6	20	3.6	19	3.2	17	3.3	20.0	3.8	20.1
Dec	3.0	13.36	2.9	11	3.3	14	3.3	14	3.0	12	3.0	14.4	3.4	15.4
Avg Annual Values	4.74	27.31	4.7	24.	5.0	28	5.0	27	4.8	24	4.8	28.3	5.2	28.4

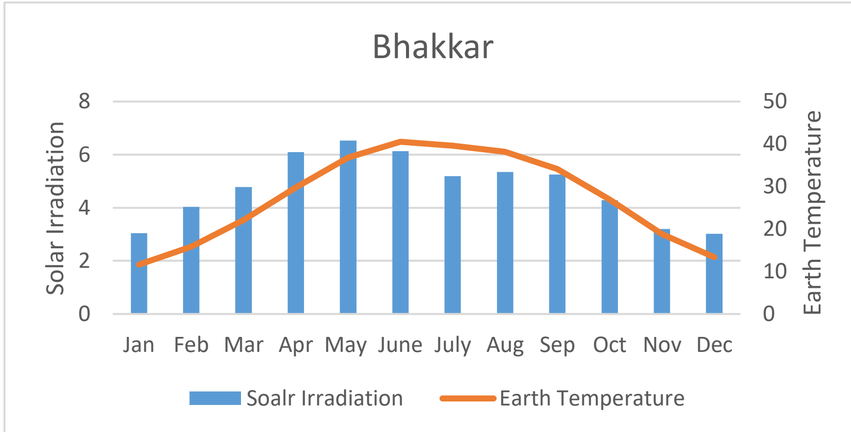

Figure 4.1: The Bhakkar Region daily solar Irradiance received

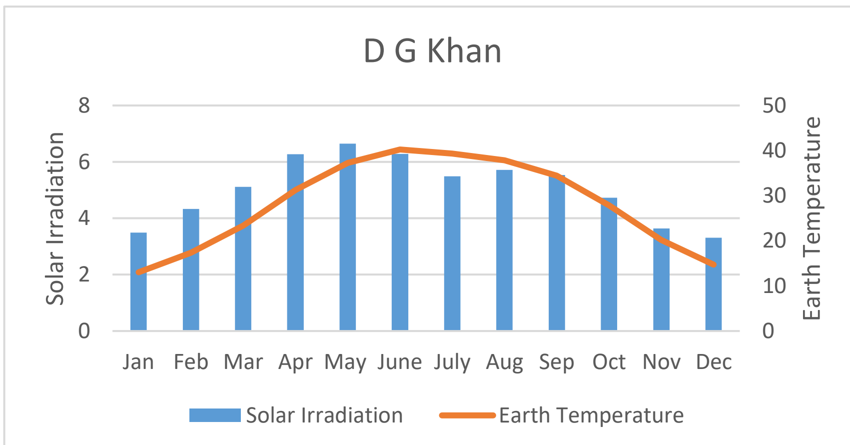

Figure 4.2: The D.G.Khan region daily Solar Irradiance received

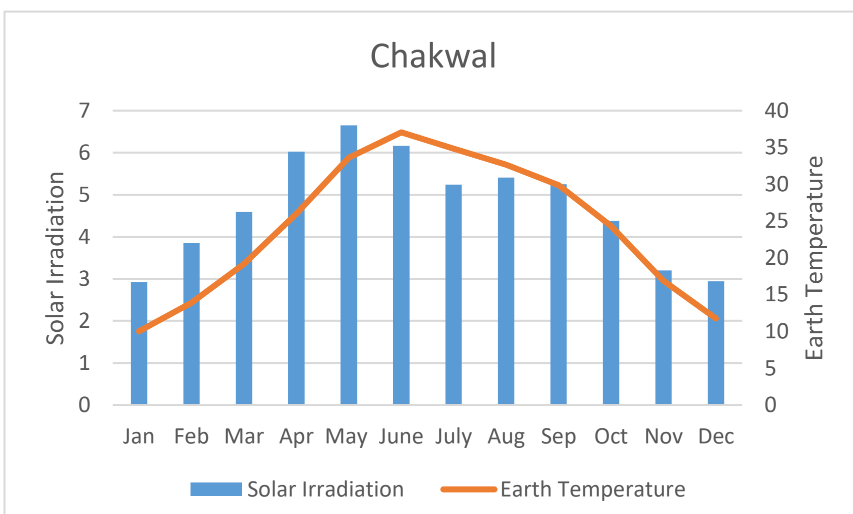

Figure 4.3: The Chakwal region daily solar Irradiance received

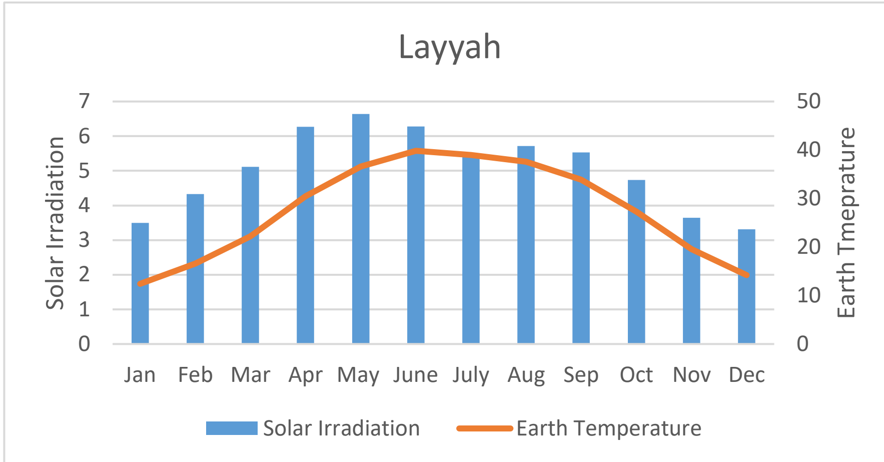

Figure4.4: The Layyah region daily solar Irradiance received

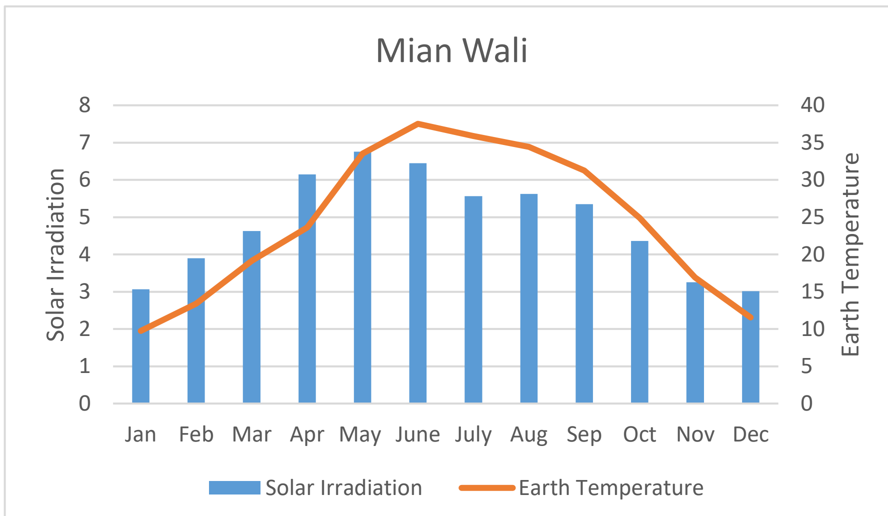

Figure 4.5: The Mianwali region daily solar Irradiance received

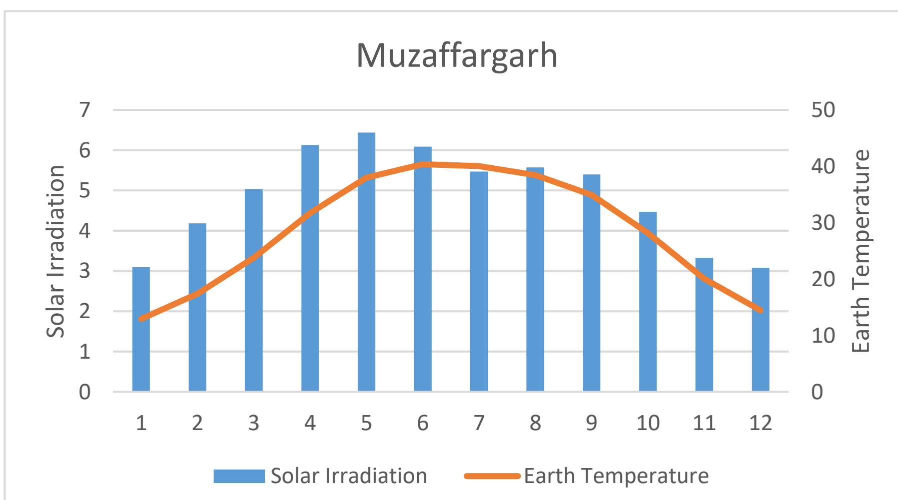

Figure 4.6: The Muzaffargarh region daily solar irradiance received

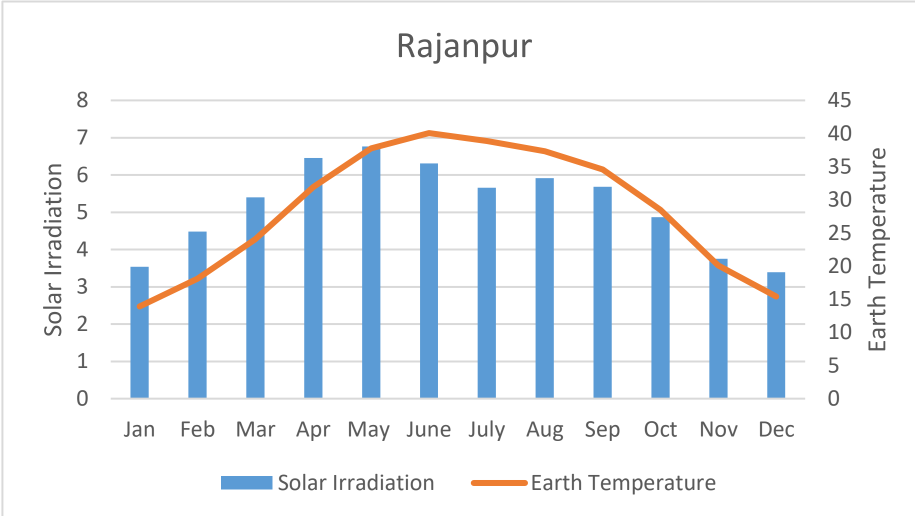

Figure 4.7: The Rajanpur region daily solar irradiance received

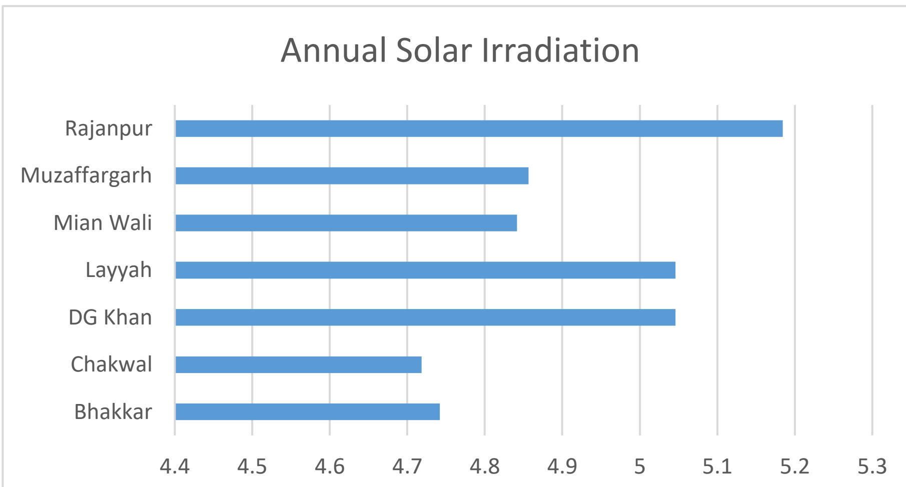

Figure 4.8: Annual Solar Irradiation of seven districts of Punjab

4.2.2 Solar Profile of Sindh

Similarly, the solar profile data of the nine regions; Badin, Jamshoro, Tando Muhammad Khan, Tando Allah Yar, Mirpurkhas, Sujawal, Thatta, Tharparkar, and Umarkot has been provided in Table 4.6 and Table 4.7. In all these concerned regions, there is also enough availability of solar energy to generate electricity throughout the year [8]. Moreover, in Figure 4.9 to Figure 4.17 the daily solar irradiance on a flat surface is presented and relative annual solar irradiation is given in Figure 4.18. The highest Annual Solar Irradiation is in Jamshoro and Tando Allah Yar districts, followed by the Tando

Muhammad Khan region, the Tharparkar region, the Umar Kot region, the Mirpur Khas region, the Sujawal region, the Badin region, and the Thatta region, respectively [9].

Table 4.6: Solar Data of Selected regions of Sindh (I)

Months	Badin		Jamshoro		Tando Muhammad Khan		Tando Allah Yar	
	Daily Solar Irradiation kwh/m²/day	Earth Temp	-	-		-	-	-
Jan	4.34	19.47	4.22	18.07	4.22	18.56	4.22	18.56
Feb	5.19	23.64	5.07	22.23	5.07	22.79	5.07	22.79
Mar	6.12	29.44	6.03	28.42	6.03	29.14	6.03	29.14
Apr	6.72	34.08	6.68	33.37	6.68	34.23	6.68	34.39
May	6.88	37.15	6.87	36.61	6.87	37.81	6.87	37.96
June	5.9	36.93	6.40	36.15	6.40	37.29	6.40	37.29
July	4.45	33.37	5.35	33.85	5.25	34.64	5.35	34.64
Aug	4.68	33.10	5.57	33.40	5.57	34.2	5.57	34.2
Sep	5.49	32.82	5.8	32.74	5.8	33.71	5.8	33.71
Oct	5.26	31.91	5.26	31.16	5.26	31.82	5.26	31.82
Nov	4.38	25.49	4.24	24.46	4.24	24.94	4.24	24.94
Dec	3.95	19.48	3.82	18.09	3.82	18.69	3.82	18.69
Avg Annual Values	5.28	29.74	5.44	29.04	5.43	29.82	5.44	29.84

Table 4.7: Solar Data of Selected Regions of Sindh (II)

Months	Mirpur Khas		Sujawal		Thatta		Tharparkar		Umar Kot	
	Daily Solar Irradiation kwh/m²/day	Earth Temp	-	-	-	-	-	-	-	-
Jan	4.20	18.26	4.3	19.34	4.31	19.45	4.37	19.12	4.21	18.72
Feb	5.13	22.60	5.19	23.80	5.26	23.13	5.16	23.44	5.19	23
Mar	6.02	29.20	6.18	28.84	6	28.04	6.24	29.36	6.04	29.21
Apr	6.67	35.14	6.74	33.26	6.77	32.02	6.86	34.42	6.66	34.70
May	6.89	396	6.86	36.14	6.88	34.89	7.04	38.04	6.85	38.30
June	6.14	38.57	5.92	36.26	5.96	35	6.17	37.53	6.14	37.96
July	5.23	35.92	4.41	32.81	4	32.47	4.43	33.27	5.23	34.47
Aug	5.24	35.54	4.69	32.59	4.78	31.96	4.88	32.69	5.20	34
Sep	5.66	34.76	5.40	32.10	5.58	31.13	5.50	32.64	5.64	33.79
Oct	5.26	31.89	5.27	31.58	5.35	30.83	5.44	31.22	5.26	31.56
Nov	4.21	24.74	4.33	25.47	4.40	25.37	4.49	24.73	4.27	24.74
Dec	3.84	18.44	3.97	19.33	4	19.69	3.91	19.21	3.88	18.93
Avg Annual Values	5.36		5.28		5.27		5.38		5.36	29.96

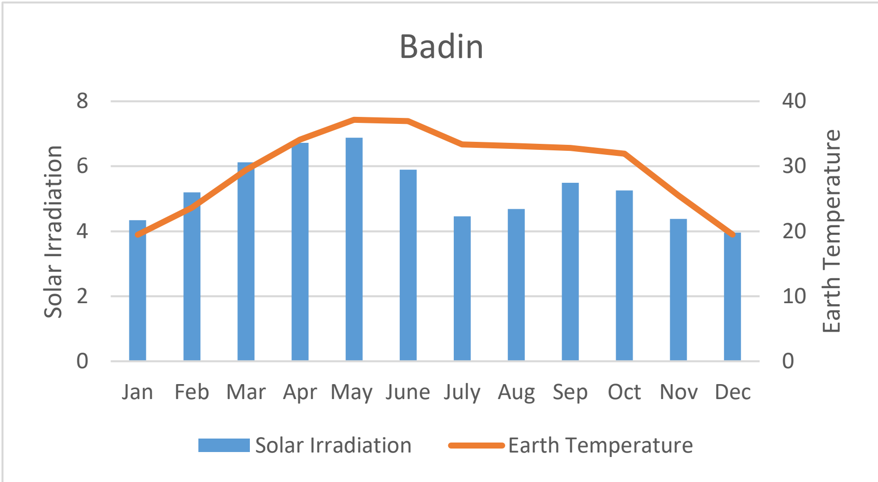

Figure 4.9: The Badin region daily solar irradiance received

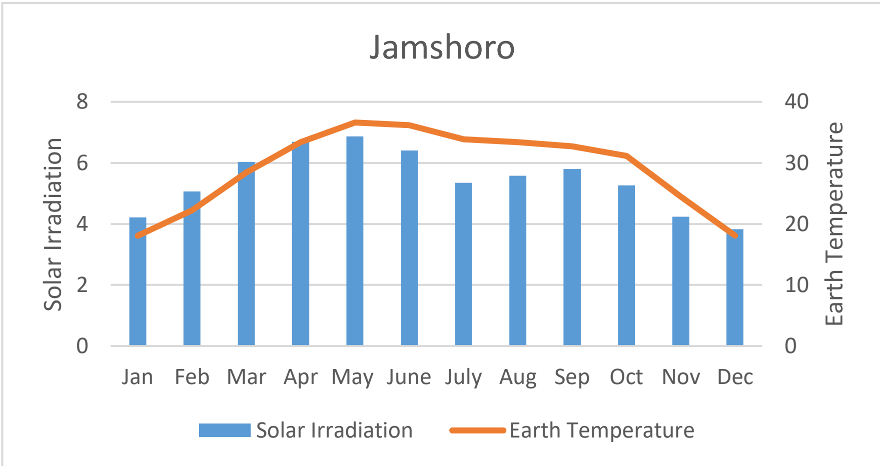

Figure 4.10: The Jamshoro region daily solar irradiance received

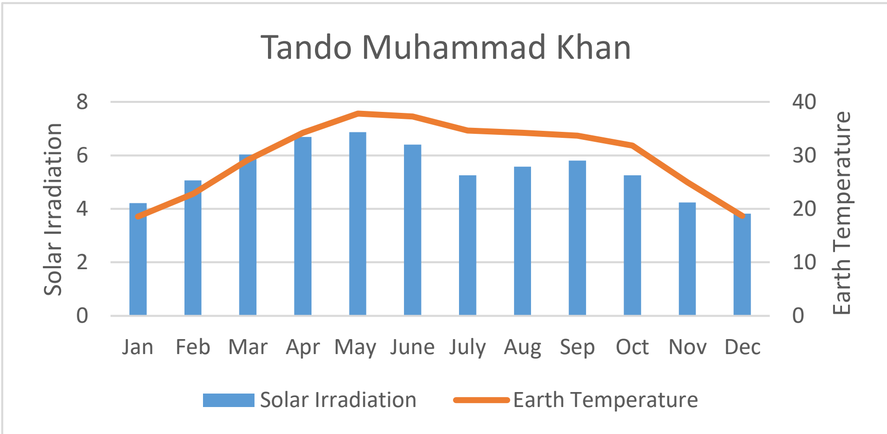

Figure 4.11: The Tando Muhammad Khan region daily solar irradiance received

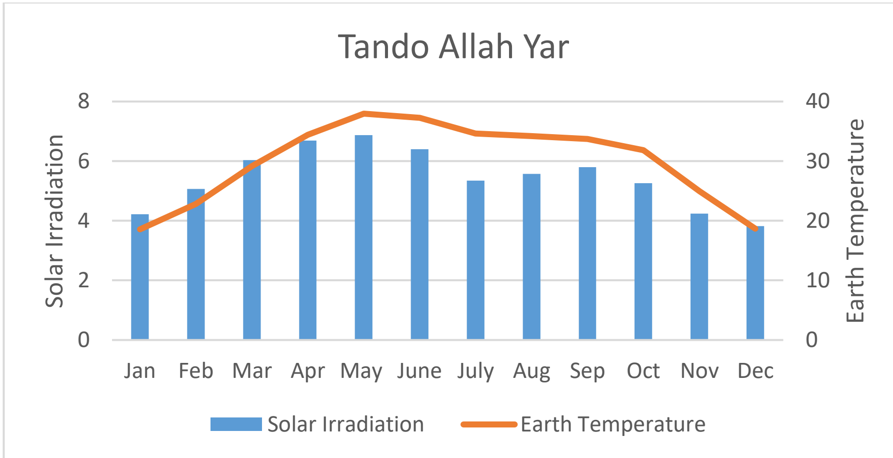

Figure 4.12: The Tando Allah Yar region daily solar irradiance received

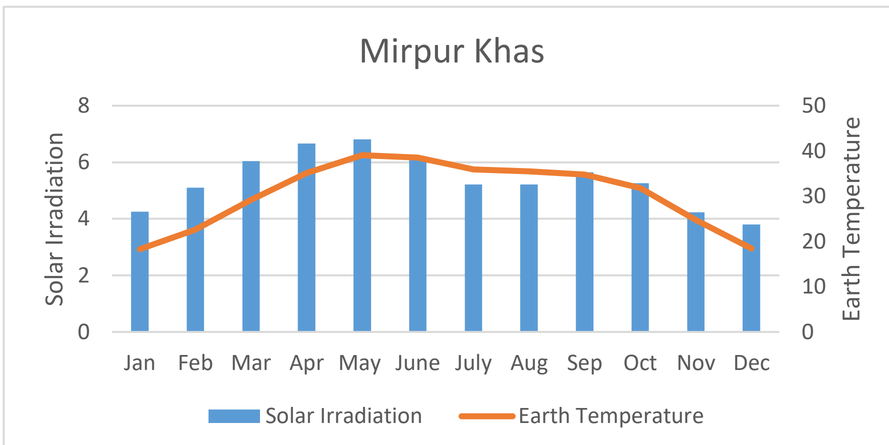

Figure 4.13: The Mirpur Khan region daily solar irradiance received

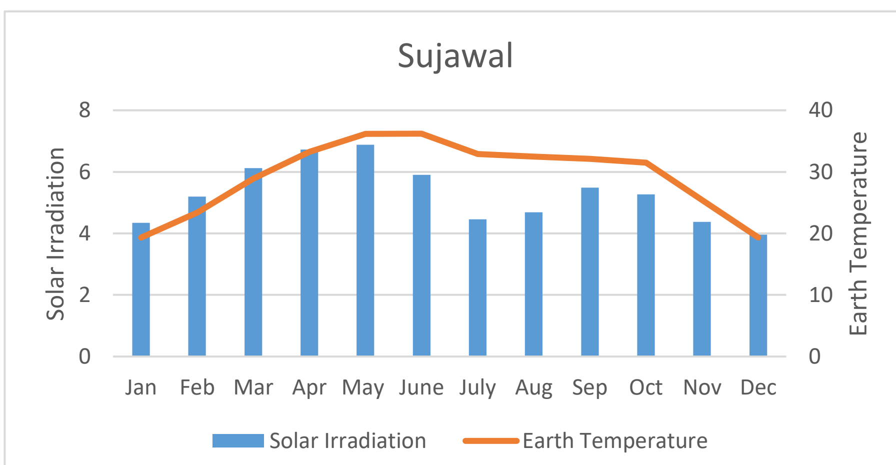

Figure 4.14: The Sujawal region daily solar irradiance received

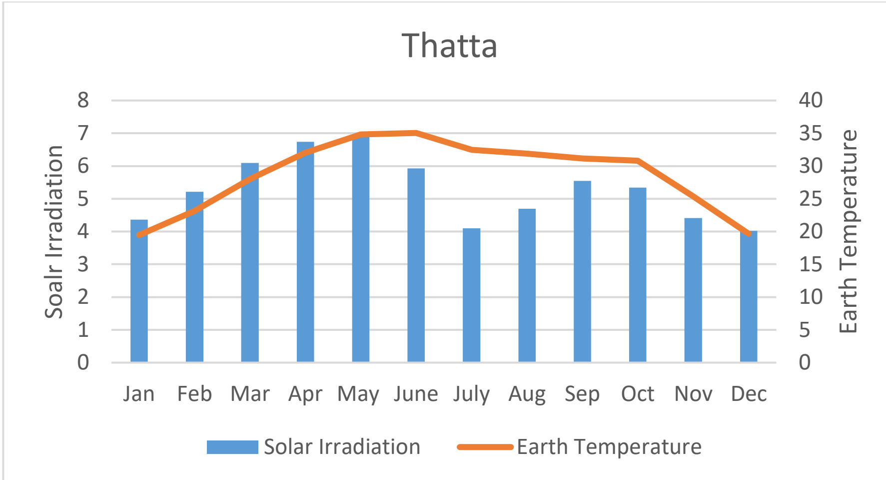

Figure 4.15: The Thatta region daily solar irradiance received

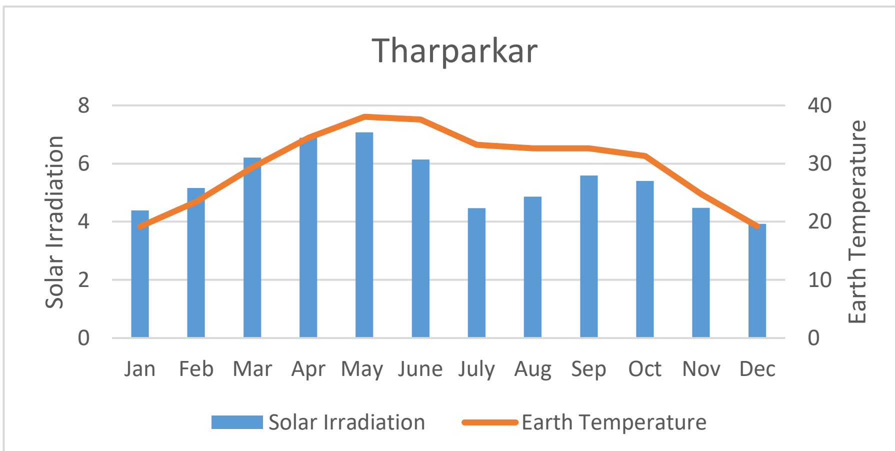

Figure 4.16: The Tharparkar region daily solar irradiance received

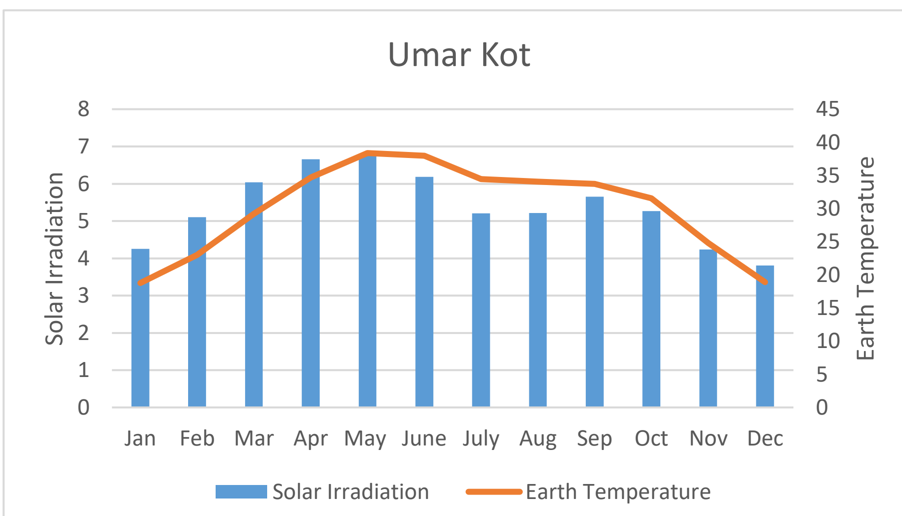

Figure 4.17: The Umar Kot region daily solar irradiance received

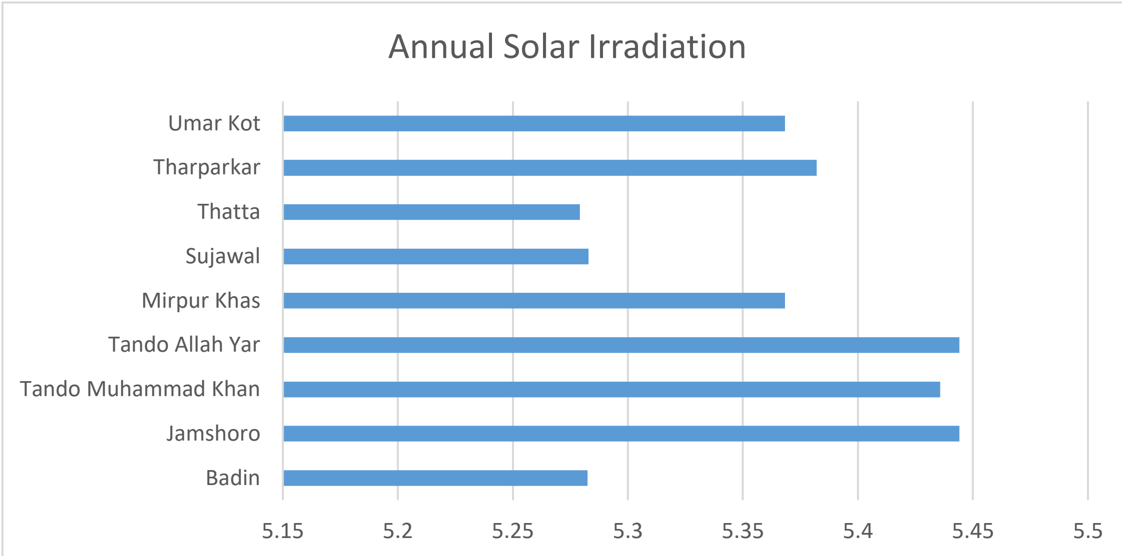

Figure 4.18: Annual Solar Irradiation of nine districts of Sindh

4.3 Feasibility of Photovoltaic Power Generation Systems

4.3.1 Solar Feasibility of Punjab

The above-stated Figure 4.1 to Figure 4.8 give the solar profile of regions of Punjab under consideration. For these selected regions average peak solar hours are presented in Table 4.8 combined with the total potential of solar photovoltaic systems [10]. Further, the solar potential for PV generation is quite significant. For example, The Rajanpur, Layyah, and DG Khan region, with solar irradiation of around 5.18 kWh/m^2/day, 5.046 kWh/m^2/day, and 5.046 kWh/m^2/day annually. Furthermore, the system in these regions can produce energy close to 500 Wh, which can easily cope with the demand for rural households [11].

Table 4.8: Photovoltaic generation potential in Punjab

Regions	Solar Irradiation (kWh/m^2/day)	Avg Peak Hours	Daily energy output (Wh)	Annual Energy Output (kWh/KWp)
Bhakkar	4.74	4.74	474	1298.14
Chakwal	4.71	4.71	471	1291.64
DG Khan	5.04	5.04	504	1381.34
Layyah	5.04	5.04	504	1381.34
Mianwali	4.84	4.84	484	1325.40
Muzaffargarh	4.85	4.85	485	1329.39
Rajanpur	5.18	5.18	518	1419.22

4.3.2 Solar Profile of Sindh

Similarly, for Sindh, the stated Figures 4.9 to Figure 4.18 give the solar profile of regions under consideration. For these selected regions average peak solar hours are presented in Table 4.9 combined with the total potential of solar photovoltaic systems. Further, the solar potential for PV generation is also quite significant. For example, The Jamshoro, Tando Allah Yar, and Mirpur Khas region, with solar irradiation of around 5.44 kWh/m^2/day, 5.44 kWh/m^2/day, and 5.36 kWh/m^2/day annually. Furthermore, the system in these regions can produce energy of more than 500 Wh, which can easily cope with the demand for rural households [12].

Table 4.9: Photovoltaic generation potential in Sindh

Region	Solar Irradiation	Avg Peak Hours	Daily energy output	Annual Energy Output (kwh/Kwp)
Badin	5.28	5.28	528	1446.08
Jamshoro	5.44	5.44	544	1490.34
Tando Muhammad Khan	5.43	5.43	543	1488.05
Tando Allah Yar	5.44	5.44	544	1490.34
Mirpur Khas	5.36	5.36	536	1469.58
Sujawal	5.28	5.28	528	1446.19
Thatta	5.27	5.27	527	1445.17
Tharparkar	5.3	5.38	538	1473.34
Umar Kot	5.36	5.36	536	1469.58

4.3.3 Levelized Cost of Energy of PV Generation Systems in Punjab & Sindh

For the electrification of off-grid areas of Punjab and Sindh, solar PV generation is purposed [13] [14]. In Table 4.10 different system components parameters are given which is provided by [15]. PV module area is identified as 1.3 m^2, using Equations 3.2 and 3.6. Furthermore, maximum current and voltage were found to be 7.61 A and 26.3 V. The production capacity of a single household is taken as 200W or less [16]. Therefore, for a load of a single household 200 W panel and 140Ah/12 V battery is appropriate. Moreover, the solar panel conversion efficiency is taken as 17% [17]. In all the selected regions maximum PV electricity generation is from April to June, however, due to the presence of monsoons season in the following months, a reduction is observed from July to October in these regions. The cost associated with this system is also presented in Table 4.10. The LCOE of the required PV generation system was identified as PKR 10.5/kWh in which a degradation factor of 0.5%/year is included [18] whereas, the cost of electricity from conventional generation sources is Rs 20.79/kWh [15]. Thus, the total savings generated from shifting towards solar is approximately PKR 10.29.

Table 4.10: Assumed Variable

Variables	Unit	Value
Panel Area	m^2	1.30
Max: power current	A	8.13
Max: power voltage	V	24.6
Power Rating	WP	200
Ambient Temperature	°C	20
Referenced Temperature	°C	25
Reference Efficiency	%	17.2
Panel Life	Year	25
Capital Cost	PKR/WP	115
Battery efficiency	%	85
Battery Cost	PKR/Ah	130
O/M cost	% of the Total Cost	4
Discount Rate	%	9
Battery Duration	Year	5

4.3.4 Mitigation of Carbon Emission through Photovoltaic Generation System of Punjab and Sindh

A diesel generator consumes 0.3 Liters per kWh [19]. The annual demand for a given household is 140 kWh, so the conventional generation would require 42 L/year. Therefore, based on equation 3.9, the Solar PV generation system could mitigate CO_2 of about 98.7 kg/year/household. According to Table 4.3, more than 2 million people are living in off-grid areas of Punjab which is about 325,043 households at 6.7 persons per household [20]. Similarly, Table 4.4 represents the off-grid population of Sindh district which is close to 3 million people. Moreover, at an average of 6.7 persons per household, there are 457172 households in Sindh without sustainable excess to electricity. Hence a high level of CO_2 could be mitigated if these regions are electrified using renewable energy resources [21].

Summary

This chapter covers the result and analysis of the off-grid areas of Punjab & Sindh. The identification of off-grid areas, design of distributive generation system based on Solar energy, economic analysis of the proposed system, and carbon emission mitigation are included in this chapter. In the following chapter, we will present the conclusion and future work recommendations related to strategy for off-grid electrification.

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Chapter 5

Conclusion & Policy Recommendations

5.1 Status Quo in off-grid Energy Development

As pointed out in chapter 1, there are 13 to 51 million people in Pakistan who don't have access to the National Grid [1]. Most of these areas are in rural regions. In addition to that, an equal number of people suffer from major supply interruptions (weak grids). Moreover, Figure 5.1 shows the overall off-grid population in Pakistan [2].

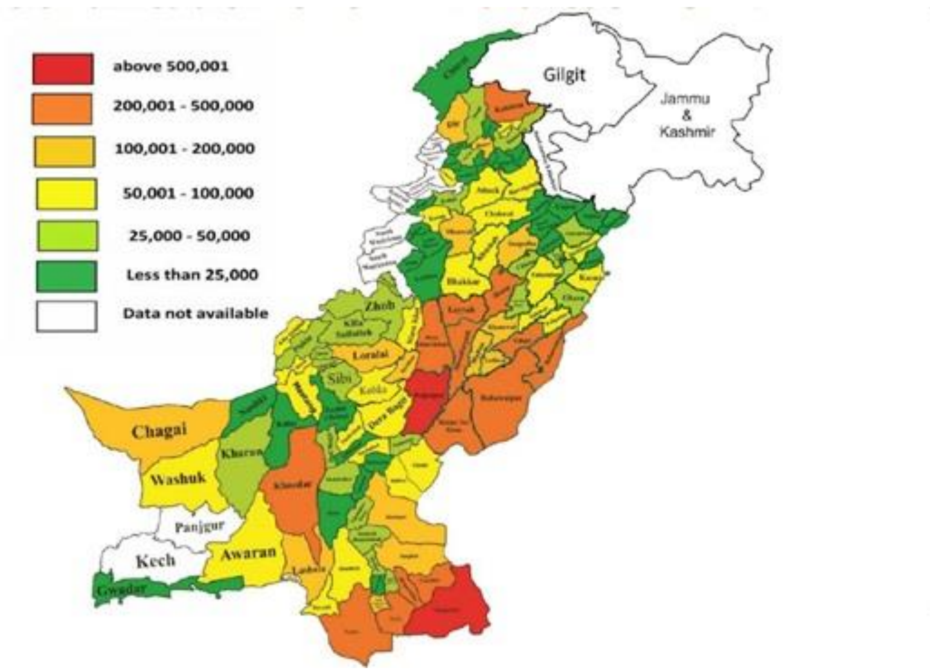

Figure 5.1: Off-grid Areas Based on PSLM report

5.1.1 Pakistan's off-grid Market

Pakistan's off-grid market electric solutions are in the starting phase compared to other countries like Kenya, the Philippines, or Bangladesh [3]. In the past, there have been initiatives to set up mini-hydro and solar home systems through public funding [4]. However, many of these systems have later suffered from failure and lack of repair.

Since 2018, some off-grid companies have started installing quality solar home systems on a commercial basis [5]. These companies are still small compared to the total amount of off-grid areas, and their access to finance is limited.

5.1.2 Market Views

In South Asia, the off-grid market is mostly associated with India and Bangladesh. One being the most populous country in the world and the other is home to an emerging market. However, Pakistan which has been in the energy crisis for the past 15 years, is mostly ignored. The expensive electricity rates have forced the people of Pakistan especially the rural population, to explore alternative means of energy production [6]. Hence, off-grid companies are starting to introduce their products in rural communities [7].

Off-grid companies see the solar grid market in Pakistan as follows:

- Solar appliances and Solar Home Systems (SHS) are currently the most frequent products in use.
- Mini-grids are so far all based on donor grants for CAPEX and community-operated; most of them through the Pakistan Poverty Alleviation Fund (PPAF) [8].
- Distribution in the past of solar systems to end-users for free has harmed the market.
- The monthly installment is the limiting factor for rural households, rather than the total price. Hence, Credit schemes are crucial [8].
- The importance of quality needs to be explained to end-users: Cheap imported products are often 50% of the price but last less than 1 year.
- Outreach cost to remote areas is high – last-mile support needed.
- System prices for end-users are driven up due to excessive duties on energy-efficient DC equipment (fans, TVs, etc. –up to 100%).

5.1.3 Business Models Being Use

The effective business model is an essential factor in promoting the growth of the Solar business. These business models vary depending upon the targeted consumer. Systems design; load Profile; living standard; location of the community is all scaled while developing an effective model. Hence, there are four business models which are being used in Pakistan which are as follows.

1. The first one is the total ownership of the system by an individual. Here the consumer owns the whole system. However, the future maintenance of the systems will be done by the consumer himself.
2. The second one is the partial ownership of the system based on the lease/loan system. Here the consumer is charged monthly based on the capital cost. However, based on the contract time, the maintenance tasks will be taken by the company itself up to the date of the contract.
3. The third model is the rent model, which is based on the number of days the system is operating. Here the maintenance tasks reside only on the company.
4. The last model is based on per unit factor rather than days. The consumer is charged based on the number of units it consumed.

Table 5.1: Business Models of Solar Companies

Retail/Cash: Purchase & Ownership (prevailing case so far)	Retailers & Supply companies
Retail + Credit: Ownership with loan/lease	Supply & credit companies
Rent: Rent (per day)	Service companies
Per-use: Rent (per kWh)	Service companies

5.2 Economic Evaluation

Two factors play a key role in economic evaluation.

- The quality-Price Problem
- Economic Parameter

5.2.1 The Quality-Price Problem

Customers in Pakistan are very price sensitive. That is why sub-standard equipment is easily available in rural areas which are mostly brought illegally and even for regular imports custom standards are not practiced by officials.

The price of sub-standard equipment is typically 30-40% less compared to the established IFC standard but performance and lifetime are very doubtful. As a result, vendors of quality equipment have difficulties entering the market.

5.2.2 Economic Parameter

Levelized cost of energy is the accepted format of comparing the cost of different sources of energy. It is simply expressed as

LCOE = Sum of Cost / Sum of Energy of Lifetime

The LCOE becomes even more feasible if the energy-related equipment is developed indigenously. Moreover, the local production often results in a higher quality product if effective monitoring is done. Apart from those, local costs of energy do not leave the region. They are expenses for the consumer but a stimulus for the local economy resulting in a huge foreign exchange impact.

5.3 Future Policy Recommendation

The proposed strategy has been divided into the following sections given below:

5.3.1 Framework & Market Creation

So far off-grid electrification happens by itself and aside from national rural electrification plans, off-grid electrification solutions need to be integrated into the national electrification plan as a valid option for electrification (apart from grid extension). Activities of different players need to be harmonized. In this regard, a framework for market creation must be developed as shown in Figure 5.2. Furthermore, for effective implementation of this market strategy the following policy framework should be followed:

- Government must give required planning security to off-grid service companies.
- Integrate off-grid and weak-grid supporting solutions into national electrification planning.
- Determine “grid today” “grid tomorrow” and “off-grid” areas and have clear grid extension and grid supporting plans.
- Set national targets for off-grid and weak-grid electrification to send a signal to market players in the sector: 100% electrification in Pakistan by 2030.

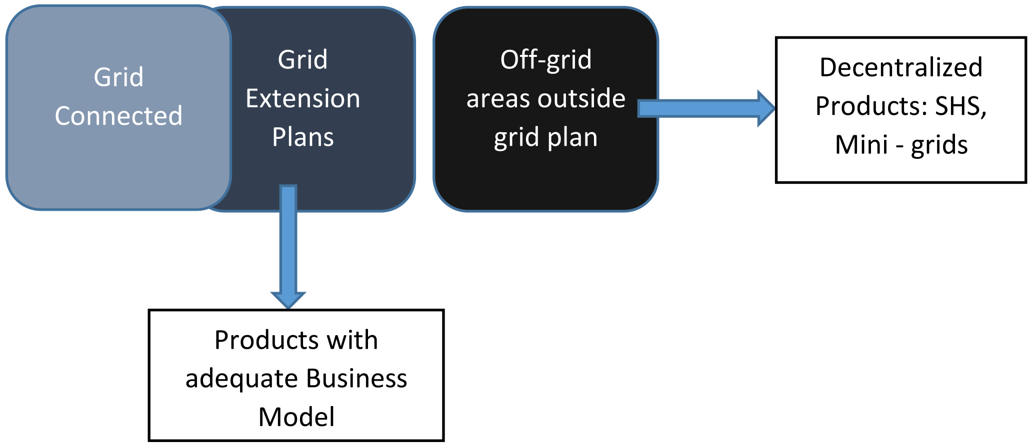

Figure 5.2: Framework of Market Creation

5.3.2 Action Panel for stakeholders

For a directed implementation and progress review of off-grid electrification, a clear framework and coordination between all involved agencies are needed, which the Alternative Energy Development Board (AEDB) should lead. The distribution companies, regulatory authorities, and other stakeholders must be taken on board as shown in Figure 5.3. For effective implementation, a targeted strategy must be placed where the concerned departments review the electrification status of rural communities after every three months.

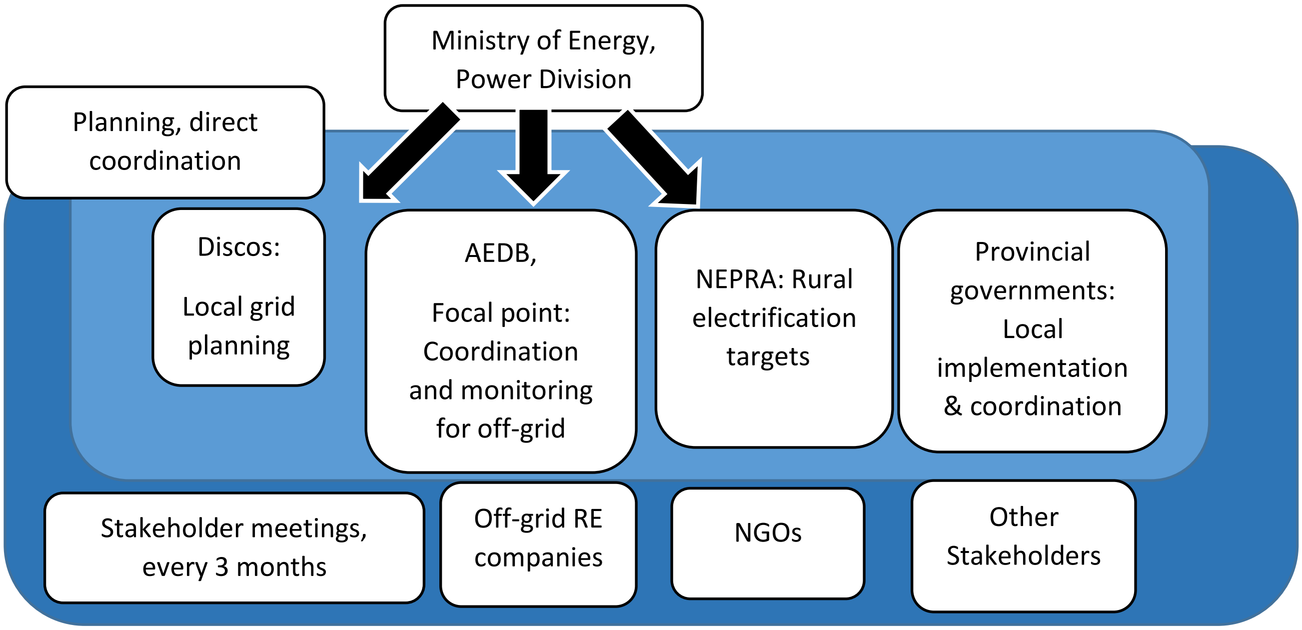

Figure 5.3: Framework and Coordination among Agencies

5.3.3 Financial Guidelines

Financial guidelines for effective implementation are given as follows:

- No grants to end-users. Grants are counterproductive to the market.
- Working capital for startups for the off-grid service companies.
- Inclusion of Micro finance institutes for credit schemes.
- Support from the government to make it viable for companies to service the remote areas (Last mile support).
- Support for low-income households.
- Make use of international climate funds etc.

5.3.4 Import Duties on off-grid equipment

- Custom exemptions are already in place for RE in Pakistan, but they need to be simplified i.e., one-stop window.
- Custom exemption needs to be extended to energy-efficient off-grid appliances: LEDs, table fans, mobile chargers, TVs that are energy-efficient and run on 12V.

5.3.5 Off-grid Companies

- Solar off-grid companies will be providing an essential service to rural households. So, companies that deliver quality products, after-sales service and have an interest in sustainable solutions for their customers must be supported in the future.
- This support should also be extended to companies who focus on lasting solutions through workshops, census information on rural areas, and partnerships with local governments, etc.
- All these activities should be led by AEDB. Eventually, this could be converted into a separate entity for this purpose.

5.3.6 Marketing Campaign

- Start in targeted areas (pilot) and then roll out on national level
- Use close-to-door customer channels like roadshows or promotional events.
- Identify good partners, such as NGOs or rural associations like farmer associations who are in touch with the target group.
- Address the grievances of suppliers and distributors.
- Create instructive leaflets/manuals for end-users to explain about solar.

Summary

This chapter has presented the conclusion of the thesis. It covers the ongoing status of rural electrification as well as economic parameters currently in place in the off-grid electrification market. Furthermore, a future policy recommendation that includes a framework, financial guidelines, and action panel for stakeholders has also been presented related to off-grid electrification.

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Appendix A: Conference Paper

Techno-Economic Framework for Solar Electrification Using Night-time Satellite Imagery in Punjab - Pakistan

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Abstract

The electrification of off-grid areas in rural regions through the Solar PhotoVoltaic system is the most viable and convenient solution. However, for a developing country, the major barriers are locating the load centers of off-grid areas, identification of solar energy potential of those areas, and the relevant economics. Therefore, in this study the off-grid areas of Punjab, Pakistan are located through night-time satellite imagery, and the data is substantiated through the Pakistan Bureau of statistics database. Furthermore, the solar energy potential of selected regions is evaluated and is followed up by economic viability related to those regions. The outcome of this study endorsed that south Punjab regions have acceptable solar irradiation to be harnessed for electricity generation. Moreover, the economic analysis based on the Levelized Cost of energy has been done which revealed that the cost of producing electricity through solar PV system is PKR 10.7/kWh and the electricity generated through conventional energy sources is around 20.79/kWh. Furthermore, by installing the solar PV system in un-electrified rural areas, a high level of CO 2 could be mitigated. Hence, this study will help the concerned authorities to make use of solar PV technology in the remote and off-grid areas of Pakistan.

Keywords: Sustainable development, off-grid Solar PV system, economic Analysis, CO_2 Mitigation.