Technical Design and Socio-Economic Study of Hybrid Renewable Energy System Based on Solar Energy and Wind Energy for Development of Microgrid in Rural Sindh

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Electricity has remained a critical issue for Pakistan. According to a recent report published in April 2018 and prepared by International Renewable Energy Agency in collaboration with Government of Pakistan, almost half of rural population of the country has no access to electricity. Areas with access to electricity face load-shedding due to power deficit between supply and demand. The shortfall has reached almost 6000 MW while during June 2018, peak power deficit climaxed to 9000 MW (NEPRA).

Inadequate electricity is one of the main causes of poor industrial, economic and social development of the country. Despite the additions in generation capacity, the power deficit persists. This paper is an endeavour to present technical feasibility for prospects of generating electricity from hybrid renewable energy systems (HRES) in rural areas where the national grid is unavailable. Interconnection with the main grid requires extensive study and financial resources. This paper encompasses a study of potential for micro-grids in remote areas for local transmission from the generation unit.

The global shift towards renewable resources owes to the sustainable and environmentally friendly nature of renewable energy. Fossil fuels are not only hazardous for the environment but also drain exorbitant amount of foreign exchange from the country with world oil prices staying volatile throughout. Pakistan is not an oil-rich country and heavily depends on imported fuel to fulfill its increasing demand. In this paper, detailed study of potential areas for hybrid renewable energy systems is conducted. The technical work and simulations are carried out on professional software: WindPRO for wind energy and PVSyst for solar.

Keywords: Renewable Energy Systems, Wind Energy, Solar Energy, Hybrid, Micro-grids, Sustainable, Environment, Electrification, Rural, Economics

INTRODUCTION

Access to electricity has become a necessity in the 21st century and a major parameter in determining the standard of living of any country. However, according to the recent census conducted in 2017, one-third of the population of Pakistan has no access to electricity; 80 % of which lives in rural areas [1]. Constraints of huge investment cost of grid network and its unavailability have been a major cause of non-electrification. Fortunately, the province of Sindh is bestowed with abundant and free natural resources of wind and solar energy. The Gharo-KetiBandar-Jhimpir region of Sindh has wind power potential of approximately 50000MW [2]. Sindh is rich in solar energy resource as well with average GHI ranging from 2100 to 2700 kWh/m^2 [3]. Several wind power projects have started operating in this area and many are in progress; however, the power is evacuated by the national grid.

Owing to the clean and environmentally friendly nature of renewable energy resources, the world is now abandoning the conventional fuels. Hydrocarbons are said to emit greenhouse gases which have led to global warming at an alarming level. The economic catastrophe in shape of hurricanes and floods require several years of rebuilding infrastructure and rehabilitation of dislocated population. Climate change may also indirectly influence the destructiveness of tropical cyclones through an increase in sea levels. With higher average sea levels, the impacts of storm surges will increase, even if there is no change in storm frequency, wind speed, or other characteristics [4]. The economic and environmental benefits of wind and solar energy surpass those of conventional fuels in the long term while the renewable resource remains free of cost.

Although, wind or solar power plants, individually, pose issues of variability and instability for transmission, the battery-backed hybrid system is stable, more reliable and an optimized solution. Hybrid systems have proved to be the best option to deliver “high quality” community energy services to rural areas at the lowest economic cost, and with maximum social and environmental benefits. Indeed, by choosing renewable energy, developing countries can stabilize their CO_2 emissions while increasing consumption through economic growth [5].

Microgrids represent an emerging paradigm of future electric power systems that address the two critical challenges of power reliability and integration with RE due to the increasing penetration of clean energy resources as a result of the growing environmental awareness [6].

Electrification of rural areas through localized microgrids can help alleviate the problems of rural population, improve living standards and enhance the socio-economic development of the region. Rural microgrid improves local income generating activities, communication services, education services and agricultural production [7]. Objectivizing the socio-economic development of rural areas of Sindh through electrification by stand-alone microgrids powered by wind energy, solar energy and battery backup, this paper shall present the technical, environmental and socio-economic aspects of an optimized model design for a specific village which may be viable for implementation in other similar rural areas too.

RESEARCH METHODOLOGY

The research paper covers four aspects of hybrid renewable energy systems:

i. Wind Farm Design
ii. Solar PV Farm Design
iii. Hybrid Optimization of Battery Backed Wind + PV Microgrid
iv. Socio-Economic and Environmental Aspects of Electrification through Renewables in a Rural Area

Location having Combined Wind and Solar Energy Prospects in Sindh

The percentage access to electricity is tabulated based on data acquired from report by Sindh Bureau of Statistics and UNICEF [8]. An unelectrified area is selected in Sindh Rural based on a study of wind resource availability and solar irradiation. The wind speed data over a 18 years' time span is acquired from MERRA-2 and wind speed profile is generated. Similarly, 30 years' data for Global Horizontal (GHI) is acquired from Meteonorm 7.1. The results for average wind speeds and average GHI of six locations of Sindh, based on MERRA-2 and Metornorm data, are shown in the Table 1.

Area	Symbol	Easting	Northing	Wind Speed (m/s) at 50m	GHI ($kWh/m^2/yr$)	Access to Electricity
Badin	**A**	**474671**	**2709608**	**6.20**	**1980.9**	**74.10%**
Badin	**B**	**537993**	**2709637**	**6.12**	**1974.4**	
Badin	**C**	**537841**	**2765000**	**5.95**	**1982.0**	
Badin	**D**	**474773**	**2764971**	**6.11**	**2001.9**	
Sujawal	**E**	**348017**	**2710410**	**6.16**	**1857**	**59.80%**
Sujawal	**F**	**411348**	**2709866**	**6.33**	**1905.6**	
Sujawal	**G**	**411702**	**2765233**	**6.46**	**1890**	
Thatta	**H**	**348624**	**2765785**	**6.19**	**1849.4**	**75.90%**

Table 1. Wind Speed, GHI Data and Access to Electricity

Determination of Load Profile

The sectors considered for electrification are: **domestic, health and education, commercial development, public** and **utility**. The load is calculated on the basis of following assumptions:

- Number of Houses = 50
- Persons per House = 6
- Total No Persons = 300
- Water Consumption = 50 litres/ person/ day
- Total Water required = 15000 litres/ day
- Pump Flow rate = 3750 litres/ hr
- Maximum Load = 20.895 kW
- Average Load = 16.701 kW

Based on the power ratings of appliances and the number of operating hours of each appliance per day, the average hourly load profile for a typical day of a year is generated and shown in Figure 1. The **Average Daily Load** of the entire village is **16.701 kW** while the **Peak Load** during a day is **20.895 kW** while considering all the appliances in use**.** In terms of units of energy, peak monthly load is **12 MWh**.

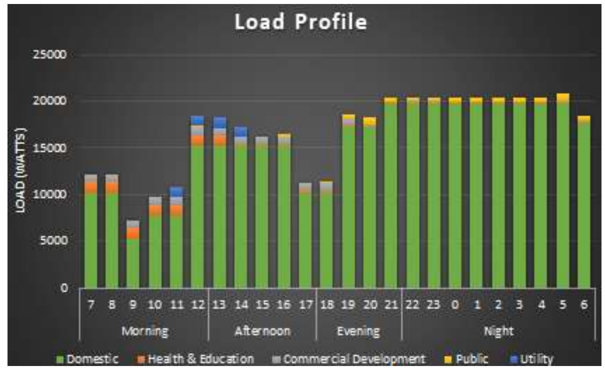

Figure 1. Daily Load Profile (Maximum)

Wind Farm Design

The technical design and simulation of wind farm with installed capacity of **44 kW** is carried out on WindPRO software with WAsP module (Wind Atlas Analysis and Application Program is a Windows program for predicting wind climates, wind resources, and energy yields from wind turbines and wind farms). The location F is selected for the installation of wind turbines. Selection process of wind turbine is conducted by simulating for a number of Wind Turbine Generators (WTG) and finalizing the one with optimized results. Technical specifications of the selected WTG and its Power Curve are shown in Table 2 and Figure 2 respectively as follows:

Turbine Technical Specifications	
Rated power	**22 kW**
Rotor diameter	**15 m**
Tower	**Tubular**
Grid connection	**50 Hz**
Generator type	**One Generator**
Rpm, rated power	**75 rpm**
Hub height	**30 m**

Table 2. Wind Turbine Technical Specifications

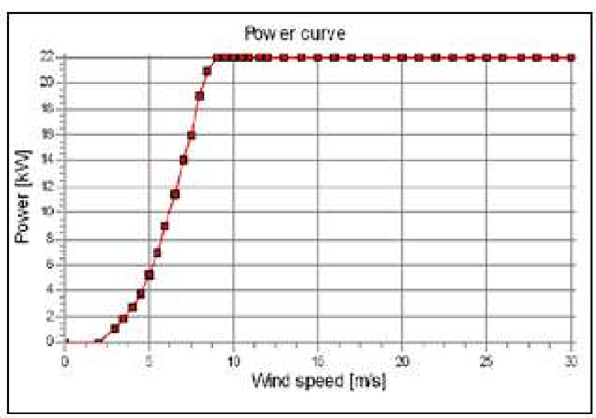

Figure 2. Turbine Power Curve

Specific to the location F, the annual directional orientation of wind is depicted in the Wind Rose (Figure 3) as acquired from WindPRO through an input wind speed data of 18 years.

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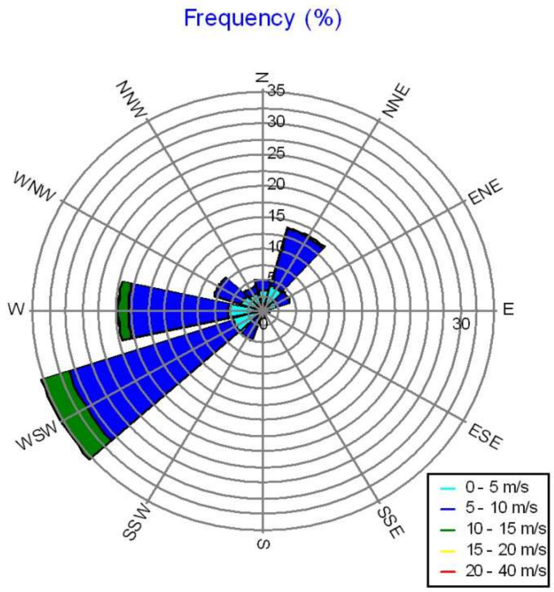

Figure 3. Wind Rose for Site F

The power contained in wind is translated in terms of its probability density function (PDF). The variation in wind speed is represented most accurately by the Weibull Probability Density Distribution Function. The Weibull PDF for the selected site is shown in Figure 4.

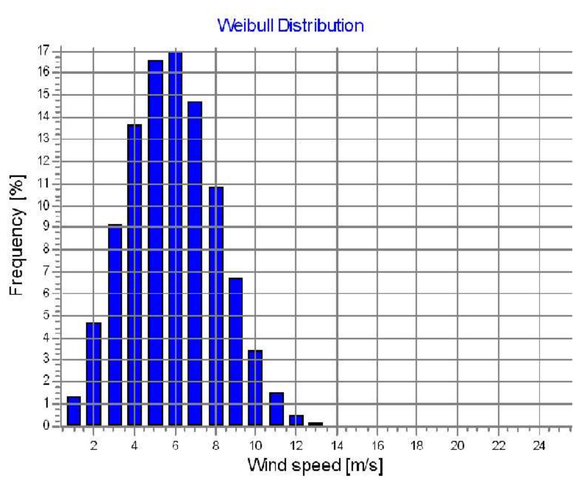

Figure 4. Weibull Distribution

The results of design and simulation of wind farm from MERRA-2 data are tabulated as follows.

WINDPro Results	
PARK Result [MWh/y] at P50	**147.6**
Wake Loss + Other Losses[%[	**10.1**
Capacity Factor [%]	**38.3**
Full Load Hours [Hours/y]	**3354**
Mean Wind Speed at Hub Height [m/s]	**5.9**
Number of WTGs	**2**

Table 3. WINDPro Main Results

Calculating the average monthly generation as 147.6/12=12.3 MWh, the wind farm is designed to be able to meet the demand of 12 MWh per month. However, due to the intermittent nature of wind and variation in diurnal wind profile, it is essential to install solar farm for a stable microgrid.

Solar Photovoltaic Farm Design

The design and simulation of solar farm with installed capacity of **25.2 kWp**, is conducted on PVSyst software. GHI values for the selected site F, are acquired for years 1981-2010 from Meteonorm 7.1. The average monthly GHI profile for a year is shown in Figure 5.

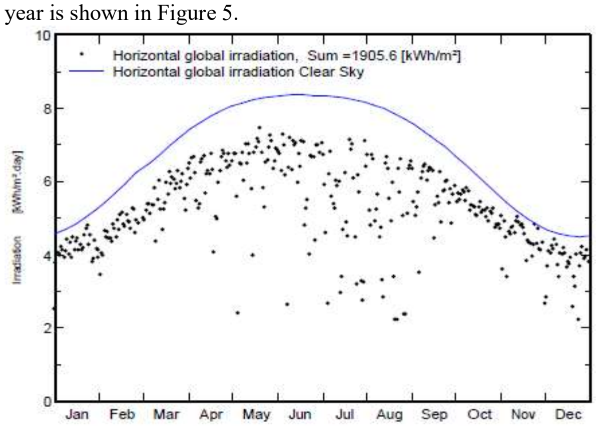

Figure 5. Monthly Average GHI- Sujawal F

Technical specifications of the photovoltaic module and inverter are shown in Table 4.

Technical Specifications of PV Module	
Module Type	**Polycrystalline**
Unit Nominal Power	**350 Wp**
Module Area	**1.95 m2**
Current (mpp)	**8.89 A**
Voltage (mpp)	**39.7 V**
Efficiency	**18.10%**
Fill Factor	**0.785**
Inverter Specifications (Output AC Grid Side)	
Grid Voltage	**230/400 V**
Frequency	**50 Hz**
Phase	**Tri-Phase**
Maximum AC Power	**25 kWac**
Maximum AC Current	**36 A**
Efficiency	**97.00%**

Table 4. Technical Specifications of PV Module and Inverter

The system simulation for the solar PV farm on PVSyst, assuming a module tilt of 25 degrees, accumulates the following results:

PVSyst Results	
System Production [MWh/y]	**43.22**
System Losses [%]	**16.724**
Capacity Factor [%]	**19.58**
Specific Production [kWh/kWp/y]	**1715**
Mean GHI [kWh/m²]	**158.75**
Number of modules	**72**

Table 5. PVSyst Main Results

Battery Energy Storage System

Since, the entire system is designed to provide electricity to 100% of the load through renewables, the reliability of the system is maintained by considering backup for full load up to 3 hours to account for any occurrence of event that may stop generation. The following table provides details of the battery configuration and specifications.

Battery Calculations for Maximum Load	
Maximum Village load (kW)	**21**
Backup time (hours)	**3**
DoD (%)	**70**
Required Capacity (kWh)	**90**
Required Specific Power (kW)	**21**
Battery Technology	**Li-ion**
Battery Voltage	**48V**
Battery Capacity Selected (kWh)	**100**
Battery Specific Power (kW)	**21**
Battery Cost ($/kWh)	**209**
Total Battery Cost ($)	**20,900**

Table 6. Battery Configuration

Hybrid Generation Profile

The energy generation profiles calculated for wind and solar farms individually, are further analysed on a monthly basis to estimate the total combined electrical units generated per month. The **maximum generation is 23,042.43 kWh** in the month of May and **minimum generation is 10,740.51 kWh** in the month of November.

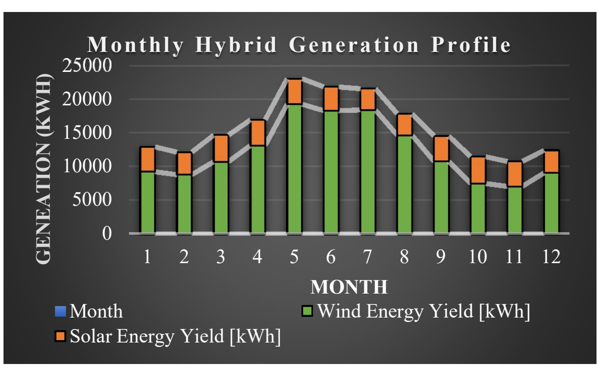

Figure. 6. Combined Monthly Generation Profile Wind+Solar

The microgrid schematic design as shown in the figure 7 comprises of the load (described in detail previously), the wind farm generation, solar PV generation, battery storage for grid stability and converters.

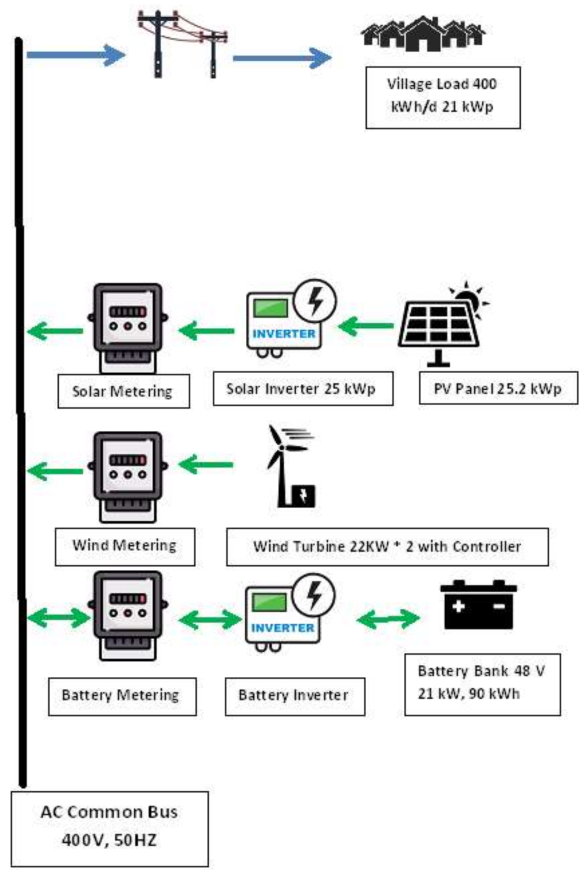

Figure 7. Microgrid Schematic

Financial Details and Calculation of Levelised Cost of Energy (LCOE)

The cost of electricity is an essential parameter in design of any power plant. The basic assumptions for the model in consideration are:

Inflation	4%
Life Period	25 years
Discount Rate	10%
IRR	10%

According to the detailed financial modelling of the system, the LCOE is calculated to be 10.3 cents which is equal to the base tariff currently implementable. However, in comparison with the conventional kerosene or diesel that are imported with a fluctuating cost, the environmental benefits of renewables and the free of cost fuel, are an added advantage.

Moreover, the otherwise exorbitant cost of installing the national grid up to the rural un-electrified villages, adds to the positives of microgrid run on renewable energy. Monetary losses due to transmission and distribution losses over long distances can be avoided by utilizing locally generated electricity transmitted over short distance.

Calculation for Levelized Cost of Energy (LCOE)					
Equipment	**Unit Cost ($)**	**No. of Units**	**Total Capital Cost ($)**	**O&M Cost/Yr ($)**	**Replac e ment Cost ($)**
Inverter Cost	3,200	1.00	3,200	150	
Panels Cost	158	72.00	11,376	1,000	
Wind Turbine Cost	15,000	2.00	30,000	800	
Battery Cost	20,900	1.00	20,900	500	20,900
Battery Inverter Cost	2,900	5.00	14,500	500	
Solar Installation Cost	2,000	1.00	2,000		
Solar Frame Cost	3,000	1.00	3,000		
WTG Installation Cost	5,000	1.00	5,000		
Battery Installation Cost	4,000	1.00	4,000		
Microgrid EBOP Cost	15,000	1.00	15,000	1,000	
Total Cost			108,976	3,950	20,900
LCOE-US Cents/kWh	10.3				

Table 7. Financial Details and LCOE

SOCIO-ECONOMIC IMPACT

In order for Pakistan to meet its sustainable development goals (SDGs) by 2030 access to clean and affordable energy is imperative. The unserved demand not only hinders economic growth but also impedes the efforts to improve health, education, employment, gender equality and other social problems of the region.

Electricity and Human Development Index

Quantitative analysis of the benefits of rural electrification, Human Development Index (HDI) is the most appropriate parameter to gauge the aforementioned indices which collectively indicate the socio-economic development of a society. HDI is a composite index of a country's:

a) Life expectancy at birth;
b) Literacy rate including primary and secondary education;
c) Standard of living measured in terms of GDP per capita

A country with higher HDI has higher mortality rate; better access to education often leading to better employment opportunities; improved standard of living and vice versa [9]. According to a recent study, there exists a strong correlation between electricity consumption and HDI especially for Low-Medium Human Development Economies and transition from low to medium occurs at a threshold value of 500 kWh per capita [10]. Pakistan's electricity consumption and HDI are 471 kWh per capita and 0.548 respectively [11] [12]. Supplying unserved electricity to the rural communities will significantly help us to improve our Human Development score.

Food Preservation

Proper food refrigeration is essential in maintaining the longevity of food, preserving its nutritional value and eliminating the chances of foodborne illnesses. Rural electrification will help in better food preservation as residents will have the option to refrigerate their additional food for later use.

Access to Better Education

Electricity consumption per capita and Education Index reflect a strong correlation of greater than 66% across 120 countries [13]. Access to electricity helps in creating a comfortable environment for pupils - by means of fans and lights - which helps to retain the student for a longer period of time that in turn improves the probability of continued education [14]. Moreover, electricity can be used to introduce to computers and other audio-visual aids in the classroom to improve the teaching and learning process.

Access to clean water and sanitation

Provision of electricity will be used to pump water from tube-well to a central reservoir which will be easily accessible to all the residents of the community. Availability of clean water at the door step will help to improve sanitation and health, as time spent collecting water the significantly reduces the consumption for non-drinking purposes [15].

Increased Working Hours

Generally, activities in the rural communities cease to exist after sunset because of the absence of lighting through electricity. By employing LEDs for residential and public lighting system residents will be able to extend their working hours by 2-3 hours. This additional time can be used for leisure or productive activities such as studying, relaxing, learning new skills and social gatherings.

Improved Gender Equality

Extension in working hours will enable women of the community to attend vocational trainings at night. The skills learned at the centers will create income-generating opportunities for women boosting their economic freedom, ultimately bridging the gender-gap [16].

Limiting Fire Hazards

Using candles and kerosene lamps is one of the major reasons for residential fires in rural homes, which is not only financially burdening but can also be fatal. Using LEDs for artificial lighting will help to eliminate this risk.

Local Employment

Installing a microgrid will help to boost economic activity in the community and create local employment opportunities. Rural electrification shall enhance the day to day commercial activities such as development of general cum medical store, a barber shop and a tailor shop. Moreover, as a direct consequence, local people will be hired and trained to operate and maintain the microgrid and related equipment and installations.

Health Benefits

Improved access to better sanitation, clean drinking water, food preservation has a direct impact on improving health related issues of the general population. Improvement in safe sanitation habits positively impacts health including protection against infectious diseases, nutrition and well-being of the inhabitants [17].

Environmental Benefits

In the wake Conference of Parties (COP21), Paris Climate Agreement 2015, 195 countries have submitted pledges to drastically reduce their GHG emissions. Pakistan in pursuit of sustainable development has pledged to create a low-carbon society based on diversified solution to reduce its carbon footprint. Employing renewable energy microgrid will be a step in the right direction.

Challenges and Barriers

- Scalability
- Tariff Collection
- Project Financing
- Training Staff for O&M

CONCLUSION

It can be concluded henceforth that the un-electrified rural areas of Sindh are rich in renewable resources of wind and solar energy whereby, the capacity factor even at very small scale results in high capacity factor: 38.3% for wind farm and 19.58% for solar farm. It is to be noted that wind turbines at a greater height and installation of solar modules on large scale produce even higher capacity factors due to economies of scale. The solution to absence of national grid due to lack of:

- generated electricity
- transmission and distribution network

lies in microgrids running from locally generated electricity from the locally present natural resources that are:

- renewable
- free of cost
- environmentally friendly

The socio-economic benefits are an added advantage for the local people. Electricity is now a necessity and living without it in 21^{st} century is deprivation of a necessity. The leverage impact on human resource development can be massive as discussed with various aspects previously.

The next stage and future scope of work for this research is to carry out a study on the challenges of:

- population growth with time especially in rural areas
- quantify and predict the increase in electricity demand for future and control mechanism of supply/demand
- calculate the extensions required in the installed power plants
- manage the revenue collection and O&M accordingly
- advantage of transmission and distribution over short distance due to local microgrid as compared to long distance

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