Techno-Economic Analysis of a Hybrid Grid-Connected/PV/Wind System in Pakistan

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Abstract- In view of the current energy crisis prevailing in Pakistan, renewable energy resources are considered as practical and economical alternatives. In this work, technical as well as economic aspects of hybrid photovoltaic (PV) and wind systems connected to commercial grid are investigated for selected locations of Pakistan. A pre-feasibility study of the renewable resources was done using NREL's Geospatial Toolkit having a broad meteorological database and additionally, a database of various renewable energy system components from different manufacturers. The locations were selected on the basis of favorable environmental criteria based on meteorological data e.g. daily, monthly and annual profiles of solar irradiance, temperatures, wind speeds etc. The suggested hybrid system was simulated in NREL's HOMER software over the system life span as guaranteed by the manufacturers. Performances and economic impacts of various components constituting the system in different locations were then analyzed to draw a conclusion with respect to the least calculated Net Present Cost (NPC). Finally, an optimum hybrid system with most appropriate components was suggested for the location that rendered least NPC. The consumer-end advantages of such systems over grid-alone system were also presented. The system was simulated for four different locations in Pakistan and was shown that it could input an adequate amount of energy into the main grid.

Keywords Hybrid, Technical, Economic, Photovoltaic, Wind, Net Present Cost

1. Introduction:

As the lifestyle of individuals is progressing day by day, energy requirements are increasing proportionally. The economic performance of a country depends on its available energy resources. Many researchers have concluded positive prospects of renewable energy in their respective countries. Diemuodeke et al. for example indicated the utilization of PV-Battery-Diesel generators in Nigeria which would in turn decrease dependency on diesel generators [1]. Similarly Sayedus Salehin et al. showed the benefits of using hybrid PV-diesel energy system in Char Parbotipur,Bangladesh [2]. Abdul et al. specified the role of energy resources in the growth of various sectors of a country [3].

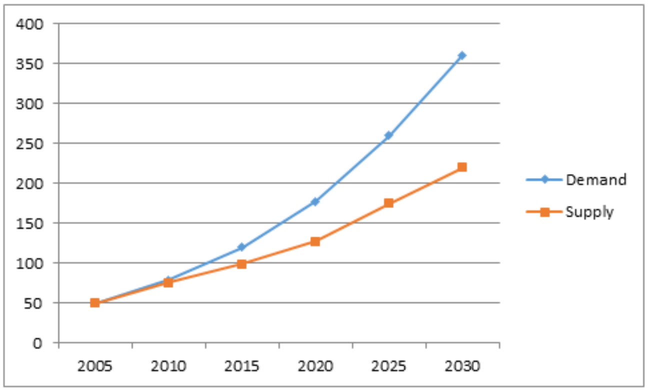


Fig 1: Energy supply and demand in Pakistan [4]

Pakistan has a shortfall of energy and this is expected to increase in future. Alongside, the economic burdens due to import of foreign oil, the country is facing adverse effects in educational, social and agricultural sectors due to shortage of electricity. In such scenarios, renewable energy technologies are a reasonable and pragmatic option. Pakistan is ideally situated in a geographical location that receives high solar radiations i.e. more than 300 clear days and solar radiation of 5.5 kW/m2 are received on an average [5]. Wind energy on the other hand is another attainable option as it compliments solar energy. The 60 km long Gharo-Keti Bunder corridor on the Sindh province coastline can alone generate 60,000 MW of electricity [6],[7]. Hence, solar along with wind energy are the most feasible, cost effective and clean renewable energy resources that exist in the country. Numerous researches have been carried out involving renewable energy technologies in Pakistan. In 1980's, the very first use of wind energy for water pumping was witnessed in Pakistan [8]. Sukhera studied the local condition of Cholistan desert population and proposed suitable solar energy conversion systems [9]. In 1990s, Hasnain and Gibbs presented a detailed study on the importance of renewable energy resources for the modernization and advancement of remote areas in Pakistan [10]. In 1990, the solar radiation in five stations: Karachi, Quetta, Peshawar, Multan and Lahore received on a horizontal surface were recorded. [11]. In 1994, solutions to prevent energy crisis, including use of renewable technologies and energy-conservative applications, were suggested [12]. The progress, development and research in the field of photovoltaic (PVs) along with solar thermal systems were reviewed up to 1996 by many researchers [12]. The wind energy for usage in rural areas remote from the grid could effectively be utilized in Pakistan [13]. In 1998, decision-making strategies for hybrid solar-wind power systems were developed [14].

In 2003, a comparison of Pakistan with various other countries in the same region gave a better status of Pakistan's renewable energy resources development [15]. In 2004, the prospects of solar energy in Pakistan were discussed, cost of solar energy was compared to that from the grid system, and its merits and demerits were highlighted [16]. In 2005, it was recommended that solar energy could be used as a source for rural electrification [17]. In 2009, M. Akhlaque Ahmed studied the wind energy potential for specific coastal areas (Ormara, Pasni, Jivani and Karachi). [18].In 2012, Abdul Waheed Bhutto suggested the measures, which if adopted, would accelerate the use of solar energy technology in Pakistan [19]. In 2013, Romana et al. used satellite images in their research to locate the potential areas that were a good source of solar energy [20]. In a similar perspective, in 2013, Hassan A. Khan and Saad Pervaiz focused on technological aspect as one of the major hurdle towards the advancement of solar energy in Pakistan [21]. In 2014, future prospects of non-conventional sources of energy in Pakistan were given [22]. Renewable energy in Pakistan is still under wide scale research. Coastal areas along Sindh and Baluchistan exhibit wind speeds of around 5-7 m/s. Pakistan receives about 19 MJ/m² of solar energy daily. Solar energy has been recognized as the best of renewable energy resources especially for standalone applications. However, solar data is not available for all sites. This data is required for prediction of performance as well as efficiency of the solar systems. Wind and solar maps as well as resource data have been provided by NREL. These have a high resolution of about 10 km.

Pakistan's energy demand is increasing annually. To meet the energy requirements a mixture of renewable energy resources along with fossil fuels can improve the current situation. The aim of this paper is to find an optimum location for a renewable hybrid energy setup. The different cases are location specific and differentiated on wind speed and solar irradiation. Results indicate the location with optimum wind and solar radiation (PV system with average irradiation greater than 4 kWh/m²/day and wind speeds higher than 6.0 m/s).

1. Methodology:

In this research hybrid system has been selected by combining PV, wind and grid. The word hybrid essentially stands for a system, which is a result of combining two or more different elements. In power generation hybrid system usually combines two or more main sources of energy. Solar and wind energy vary in intensity due to the intermittent nature of renewable resources, so due to this if the system is standalone, a reliable system for backup must be available for continuity of supply.

The research has been carried out using the simulation software HOMER developed by Renewable Energy Laboratories (NREL). The system has been modeled for supplying electricity to a small community which was assumed to have an annual average load demand of 250 kWh/day and for an annual peak load of 30 kW as shown in Fig 2. This load profile has been assumed for simplicity of system and is kept same for all four locations.

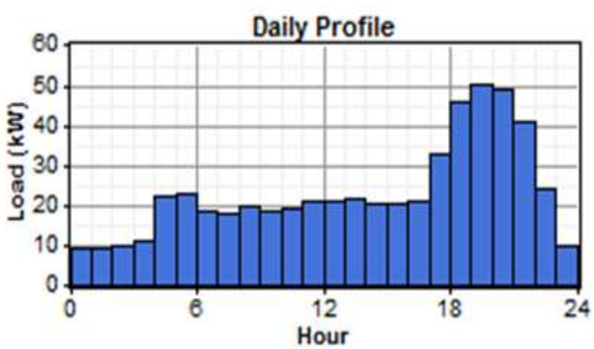


Fig 2: Daily Load profile

Simulations of the hybrid system were carried out for optimum Net Present Cost (NPC). Maximum power of PV was limited to 15 kW. Maximum two wind turbines each having a power of 7.5 kW out of four was selected for optimization. The solar and wind operating reserves were taken to be 15% each as percent of total output.

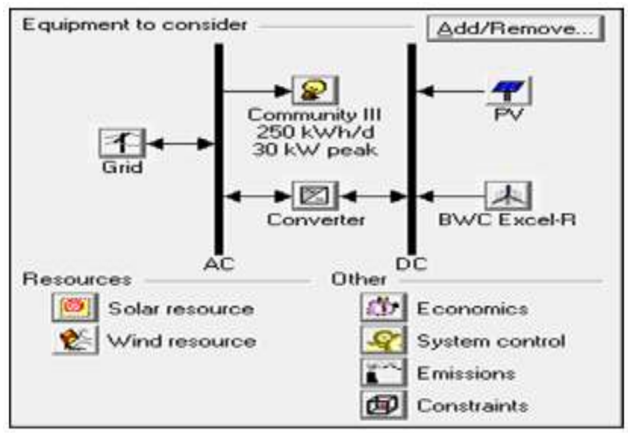


Figure 2: Hybrid system model constructed in Homer

2. Selection of Locations

Four different locations have been selected from the very south to very north of Pakistan on the basis of annual solar radiation and wind speed data. Data for solar and wind has been taken using Geospatial toolkit software [23] and National Aeronautics and Space Administration (NASA) [24].

Table 1 shows the latitudes and longitudes of the locations.

Table 1: Latitude and Longitude of selected locations

Location	Latitude	Longitude
Gilgit	35° 55'N	74°18'E
Juzzak	29°1'N	61°38'E
Gwadar	25°7'N	62°19'E
Multan	30°11'N	71°28'E

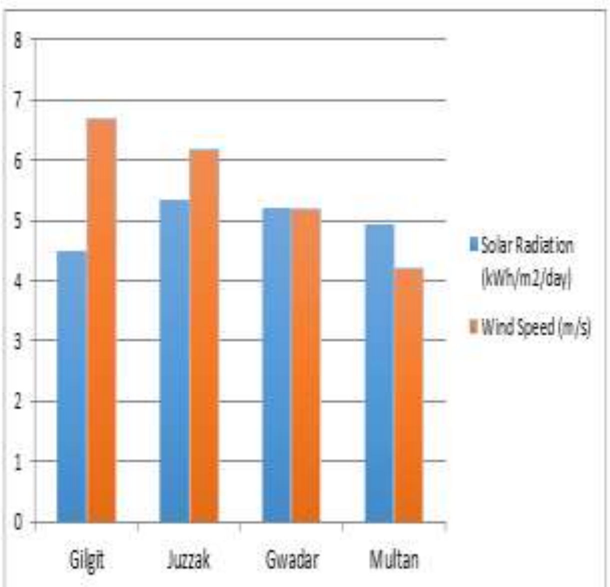


Figure 3: Annual daily radiation and wind speed data [24]

3. Input Parameters of HOMER

There are four input parameters of HOMER in this research:

- Solar Resource
- Wind Resource
- Converter
- Grid

3.1. Solar Resource

The hybrid model was provided with latitude, longitude along with the monthly average solar radiation data [24] for each of the selected locations. Clearness index was calculated using the Eq. (1)

$$K_T = \frac{H}{H_o} \qquad (1)$$

Where H is the average global horizontal radiation on the earth's surface $[kW/m^2]$ and H_O is the average extraterrestrial horizontal radiation $[kW/m^2]$, calculated on basis of geographical location and solar data using Duffie and Beckman method [25].

3.2. Wind Resource

For each location wind speed data at 50m height was obtained from NASA using geospatial toolkit. The autocorrelation factor was taken as 0.85, which is a direct measure of the wind speed in one specific hour to all the wind speeds in previous hours[26].

The Weibull wind speed probability density function (PDF) is given by Eq. (2) [Weibull parameter]:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \qquad (2)$$

Where

v is wind speed (m/s)

k is Weibull shape parameter (unit less)

c is Weibull scale factor (m/s)

Weibull shape parameter k, indicates the breadth of the wind speed probability density distribution. Higher k values correspond to narrower wind speed distributions and vice versa.

In this work the Weibull parameter and diurnal pattern strength were taken to be 2 and 0.25 respectively.

3.3. Converter

The capital, replacement, operation and maintenance (O&M) cost for the AC↔DC converter is $800, $750and $1 respectively with a lifetime of 15 year[27].

3.4. Grid

The grid acts as a backup when renewable energy inputs are unable to meet the load requirements.

Table 2: Technical Specifications of the system

Description	Specification
PV Panels	
Size Considered	1kW-15kW
Capital Cost	$1800/kW or PKR 180,000/kW
Replacement Cost	$1800/kW or PKR 180,000/kW
O & M Cost	$3/kW or PKR 300/ year
Lifetime	25 years
Wind Turbine	
Type	BWC Excel-R
Rated Power	7.5 kW DC
Quantity Considered	1 to 4
Capital Cost	$16,400/kW or PKR 1640,000/kW
Replacement Cost	$ 13,000/kW or PKR 180,000/kW
O & M Cost	$ 15/year
Lifetime	15 years
Converter	
Sizes Considered	1 to 20
Capital Cost	800$/kW or PKR 80,000/kW

Replacement Cost	$ 750/kW or PKR 75,000/kW
O & M Cost	$ 1/year
Lifetime	15 years
Grid	
Price	0.149 $/kWh or PKR 14.9/kWh
Sellback	0.070 $/kW or PKR 7/kWh

4. Economic Parameters:

4.1. Net Present Cost (NPC):

The net present cost of the modeled hybrid system was optimized through simulations in HOMER. NPC is the present worth of all the costs subtracted from all the revenue generated by the system over its lifetime. These costs include the capital costs, replacement costs, fuel costs, emission costs and the cost of purchasing electricity from the grid. It is calculated according to Eq. (3) [28].

$$\mathrm{Cost_{NPC}} = \frac{\mathrm{Cost_{ann,tot}}}{\mathrm{CRF_{(i,Rec_{Proj})}}} \qquad (3)$$

Where,

$\mathrm{Cost_{ann,tot}}$ is total annualized cost ($/year)

CRF is capital recovery factor

i is interest rate (%)

$\mathrm{Rec_{Proj}}$ is project lifetime (years)

4.2. Levelized Cost of Energy (COE):

The levelized cost of energy is defined as the average cost per kWh of useful electrical energy produced by the system. It is calculated by dividing the annualized cost of producing electricity by the total useful electric energy production:

$$COE = \frac{Cost_{ann,tot}}{E_{Prim,AC}+E_{Prim,DC}} \qquad (4)$$

Where
$E_{Prim,AC}$ is the primary AC load served (kWh/year), and
$E_{Prim,DC}$ is the primary DC load served (kWh/year).

4.3. Renewable Fraction (RF):

The renewable fraction is the total energy production initiating from renewable resources. This is calculated by dividing the total yearly renewable power production by the overall energy production.

$$f_{ren} = \frac{E_{ren}}{E_{tot}} \qquad (5)$$

Where
E_{ren} = Renewable electrical production [kWh]
E_{tot}= Total electrical production [kWh]

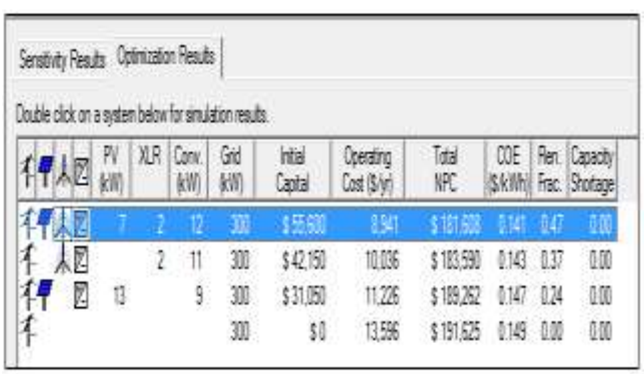
5. Results and Discussion:

The above specified system was run on all four sites with the same sizes of PV panels, wind turbines and converters. The results are as shown in table 3. For Gilgit, the system exhibited least NPC utilizing 47% of energy from renewable sources. A series of simulations indicated that a hybrid PV-wind grid connected system was most suitable for Gilgit and Juzzak whereas for Gwadar and Multan PV-Grid system was considered as optimum with least NPC. In the next section, Gilgit will be discussed as the most appropriate location for the proposed system.

Table 3: Results for each location.

	Number of PV panels	Number of Wind turbines	Converter	Operating Cost($)	Total NPC($)	RF (renewable fraction)
Gilgit	7	2	12	8,941	181,608	47%
Juzzak	11	1	10	10,584	182,576	38%
Gwadar	12	1	10	10,225	190,607	35%
Multan	12	1	9	10,892	199,157	29%

The hybrid system model for Gilgit used 7 kW PV panels, 2 wind turbines (7.5 kW each) and 300 kW from the grid. The hybrid setup used 47% of renewable energy. The optimized results show that the grid only system (NPC=$191,625) is much expensive as compared to the hybrid system (NPC=$181,608) with wind and solar energy inputs. The setup used 2 wind turbines, 7 kW of energy from the sun and utilized 12 kW of converters. The COE for this system was 0.141 $/kWh. The initial capital of the hybrid system is however high ($55,600) but the operating cost per year is the lowest (8,941 $/year). Also, the line graph indicates that a hybrid PV/Wind system connected to the grid shows the least NPC as opposed to the grid system which shows the highest NPC in the four systems discussed.


Sensitivity Results | Optimization Results

Double click on a system below for simulation results.

PV (kW)	XLR	Conv. (kW)	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
7	2	12	300	$ 55,600	8,941	$ 181,608	0.141	0.47	0.00
	2	11	300	$ 42,150	10,036	$ 183,590	0.143	0.37	0.00
13		9	300	$ 31,050	11,226	$ 189,262	0.147	0.24	0.00
			300	$ 0	13,596	$ 191,625	0.149	0.00	0.00

Figure 4: Optimized results for Gilgit

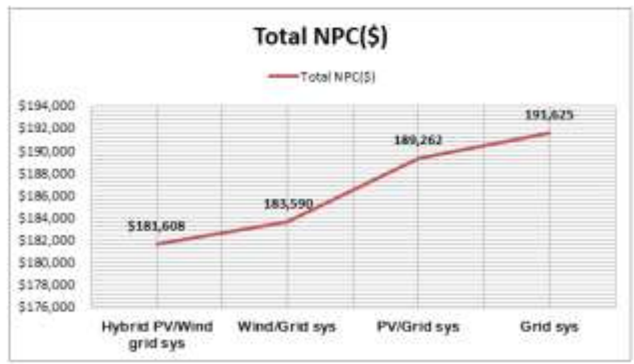


Figure 5: NPC comparison for the four locations

The cash flow summary for Gilgit shown in figure 7 indicates that most of the net present cost (NPC) is due to the grid component whereas the renewable components do not contribute much to the total cost. The grid takes about $110,000 whereas wind turbines take lesser. The cost of PV panels is less than $15000.

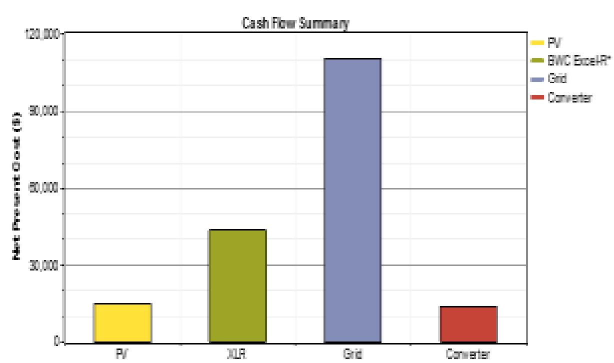


Figure 6: Cash flow summary for Gilgit

The cash flow summary with respect to different costs is shown in figure 8. It indicates that most of the capital and replacement cost is utilized in the wind turbines, converters and PV panels. However the renewable energy components do not have any operating costs. The grid consumes all of the operating cost and no fuel costs are shown by the hybrid renewable system.

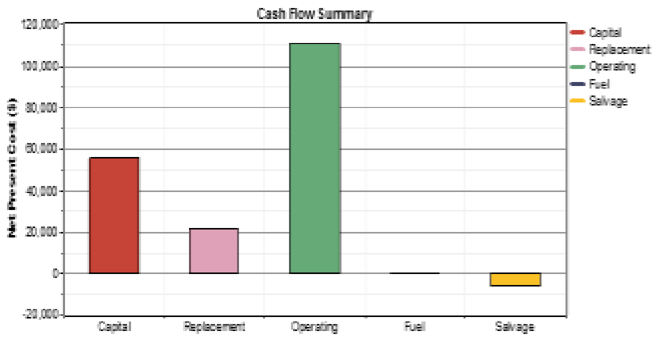


Figure 7: Cash flow summary w.r.t. components

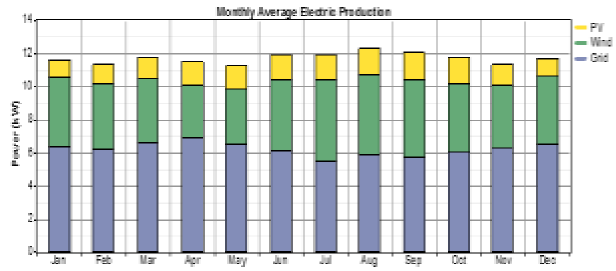


Figure 8: Monthly Average electric production for Gilgit

The percentage production of different sources is given in table 4:

Table 4: Annual energy production and renewable fraction for Gilgit

Source	Production (kWh/year)	Percentage (%)
PV array	12,063	12
Wind turbines	36,069	35
Grid purchases	54,447	53
Total	102,580	100

6. Conclusion:

A model system utilizing wind and solar energy was designed to provide energy to a load of 250 kWh/day. The four selected locations were then categorized according to their annual NPC. Locations with optimum solar irradiation and wind resources showed most favorable results with least NPC. Gilgit and Juzzak showed a hybrid Wind-PV grid connected as the optimum system, whereas a PV-grid connected system was suitable for Gwadar and Multan due to the low wind speeds. As wind and solar energy resource are the model sensitivity parameters, the locations with higher solar radiation and wind speeds depicted a better NPC as compared to a location with poor scaled annual average solar radiation and scaled annual average wind speed. The simulated system for Gilgit was economically and technically feasible and used 2 wind turbines whereas 7kW of PV panels were utilized. Furthermore, Gilgit had the highest renewable energy fraction (47%) followed by Juzzak (38%), Gwadar (35%) and Multan (29 %). Wind energy was seen to have contributed more to the hybrid system as compared to solar energy. Locations that had wind speed of more than 6 m/s were most optimum with respect to NPC. The line graph in figure 10 supports the argument with the wind speeds of the locations under consideration and their variation with NPC where the global solar irradiation was considered constant.

The paper indicates a clear possibility of setting up hybrid renewable systems in Pakistan. Pakistan not only has ample amount of solar energy but has also sufficient wind energy resources in many places.

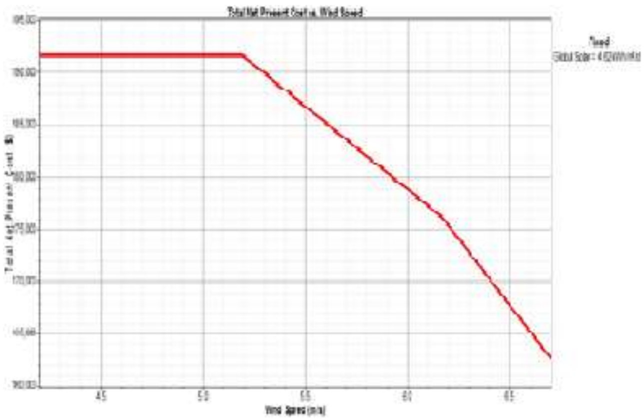


Figure 9: Total NPC vs. Wind speed

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