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Techno-Economic Analysis of Standalone/Grid Connected Renewable Energy (Wind/Solar) System Using Hybrid Energy Modeling Tools Along China Pakistan Economic Corridor (CPEC) Route in Hunza District of Gilgit-Baltistan, Pakistan

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Abstract

Electricity access is crucial in determining a community's socio-economic standing. Energy poverty affects millions of people throughout the world, particularly those living in rural areas of developing countries like Pakistan which are experiencing severe power shortages and frequent load shedding on daily basis. The prime focus of this study is to design a hybrid system (solar/wind) for a microgrid incorporating renewable energy sources for the Hunza district of Gilgit Baltistan lying in the central route of CPEC [1]. Hybrid energy system modelling, and optimization tool Homer Pro [2] has been used to design optimized standalone and grid connected systems. Both the grid connected, and standalone systems have been studied for remote rural areas such as Sost, Gircha and Morkhoon located in Hunza district of Gilgit Baltistan [3]. The important factor in designing a renewable energy (solar/wind) system in an area is to get the most reliable data of solar radiations, wind speed and temperature. The data used in this analysis were obtained from different databases of National Solar Radiation [4], National Renewable Energy Laboratories (NREL) [5], and National Aeronautics and Space Administration (NASA) [6]. The proposed standalone system includes DG set and energy storage devices like batteries to provide power backup in case of low solar intensity or wind potential during a season, while DG sets and energy storage devices are not employed in grid connected system as continuous electrical power could be obtained from grid. The performance of the suggested model has been evaluated by connecting a load with a daily energy consumption [7] of 372.09 kWh/day and a maximum power demand of 188.52 KW. The overall cost of the designed standalone and grid connected systems was optimized based on the decision variables of least cost of energy (LCOE) and net present cost (NPC) [8]. Furthermore, sensitivity analysis, techno-economic analysis and cost analysis are performed and discussed.

Keywords: *CPEC; Homer Pro; Optimization; Standalone; Grid connected; Economical Analysis.*

1. Introduction

The China Pakistan Economic Corridor (CPEC) [1] has been called as the "Game Changer" for Pakistan. By national, regional, and international standards, it is a megaproject that once completed, would have a major and everlasting influence not just on Pakistan's economy but also on the economies of surrounding countries. The economic impact of CPEC is not limited to any single country or a nation but will impact the growth of the whole region. In recent years, infrastructure development along the CPEC routes has been taking place at a rapid pace. Central, Southern, and Eastern route of CPEC has been illustrated in Fig. 1 [9].

Hunza is one of the 14 districts of Gilgit Baltistan located in north. The Hunza valley is surrounded by Kashgar located in China on the north and east, the Nagar District and Shigar District on the south, the Ghizer District on the west, and the Wakhan District of Afghanistan's Badakhshan Province on the north-west as illustrated in Fig. 2. It has a mountainous topography that makes expanding the national grid prohibitively expensive, and electrical supply is reduced in the winter owing to low river flows [3]. As a result, this region remains electrically isolated from the rest of the country, resulting in severe electric power shortages throughout the winter. It is the location of the historic Karakoram Mountain passes and vital route of CPEC. Hunza has enormous economic potential due to its tourist

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attractions, vast renewable energy potential, mineral and precious stone deposits, and geopolitical location, which permits the CPEC's only commercial route between the neighbouring countries of China and Pakistan. The estaiblishment of economic zones in selected regions of Sost, Gicha, and Morkhoon will boost tourism, trade, and provide possibilities for Hunza residents. Overall, enhancing the economic status of region. Thus, Renewable Energy Sources (RES) have gained a lot of attention in recent years due to minimum cost, above average efficiency, and decreased carbon impact. Establishment of Hybrid renewable energy systems are by far the most efficient and cost-effective source of electricity in the mountainous regions with complicated grids.

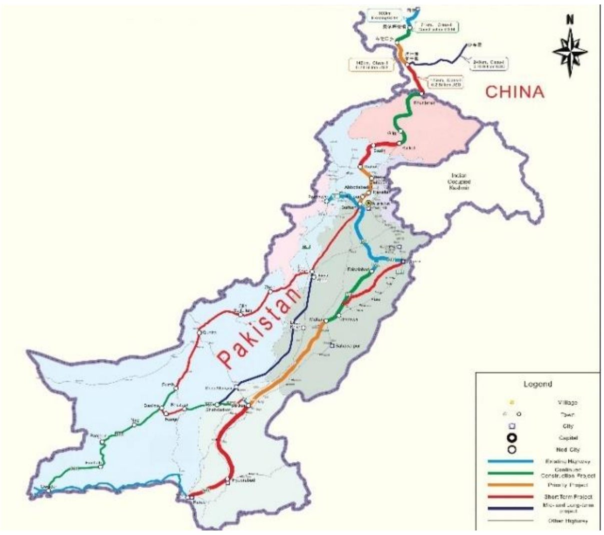


Fig. 1. Central, Southern and Eastern routes of CPEC

Fig. 2. Geographical position of Hunza

2. Research Methodology

The starting point for the problem is individual, community, institution, and industrial load needs, which may be electrical or thermal, or both as needed. After that, the resources available on a certain terrain are evaluated. The selection of components for a hybrid energy system is facilitated by the evaluation of resources. Component size may be optimized using a variety of hybrid energy system modeling tools or an optimization approach. Homer Pro was the optimization tool employed in this study. Homer Pro simulates all conceivable combinations of each configuration and component in the search space. It also considers sensitive elements, making it a useful tool for determining the best-optimized combination. As a result, deciding on the optimal design and components with the lowest net present cost (NPC) is a difficulty. In Homer Pro, the Grahams Algorithm is employed to solve this optimization problem. Therefore, a stand-alone/grid-connected hybrid energy system is developed that considers all aspects of economics, sustainability, and metrological constraints while being restricted by physical and operational constraints. The Net present cost of system is calculated by Eq. (1)

$$C_{NPC} = C_{ann,tot} / CRF\left(i, R_{proj}\right) \tag{1}$$

$C_{ann\ tot}$ = total annualized cost
i = annual interest rate
R_{proj} = project lifetime
CRF$(i\ N)$ = capital recovery factor given by the Eq. (2)

$$CRF(i,N) = i(1+i)^n / [(1+i)^N - 1] \tag{2}$$

N = No. of years
Levelized cost of energy is calculated by below mentioned Eq. (3)

$$COE = C_{ann,tot} / E_{Prim} \tag{3}$$

Where E_{prim} is total amount of primary load

2.1. System Description

The prime focus of this study is creation of economic zones and electrification of rural areas in Hunza district of Gilgit Baltistan along the CPEC route are selected for design and optimisation of hybrid renewable energy systems. Solar and wind energy systems have enormous potential in most parts of Pakistan, therefore they play an important role in supplying loads. Batteries and diesel generators are employed as backups. In this study Homer Pro is used to perform simulation and optimization [10]. The targeted areas, however, are in Pakistan, along the central route of CPEC. Rural regions in the vicinity of Hunza district of Gilgit Baltistan, Sost, Gircha and Morkhoon are among them. Optimization based on NPC is used to test the performance assessment and analysis of the planned system. Sensitivity, emission, and cost analyses are also carried out.

2.2. Location Selection

Hybrid energy systems are designed along the northern passage of the China Pakistan Economic Corridor (CPEC). The rural areas in the vicinity of Hunza district of Gilgit Baltistan, Sost, Gircha and Morkhoon are chosen for the study. The details about the selected locations are indicated in Table 1.

Table 1: Geographical coordinates and time zones of the selected sites

Location	Longitude	Latitude	Time Zone
Sost	36.6577	74.8474	GMT +5
Gircha	36.6489	74.8477	GMT +5
Morkhoon	36.6111	74.8662	GMT +5

2.3. Load Profile

The rural parts of Hunza valley along the northern route of CPEC are considered in this study. Different electrical appliances are discussed, such as lights, fans, TVs, electric irons, and irrigation pumps, which are essential for everyday routine of living. The peak demand load is 188.52 kW, and the daily electrical energy consumption is projected to be around 372.09 kWh/d. An average home size comprises of 8 people in Gilgit Baltistan [3], a per unit household consumption ratio of 18.60 kWh/day was used in this study. The designed grid-connected/On-grid hybrid systems and standalone/Off-grid hybrid systems are depicted in Fig. 3. and 4., respectively.

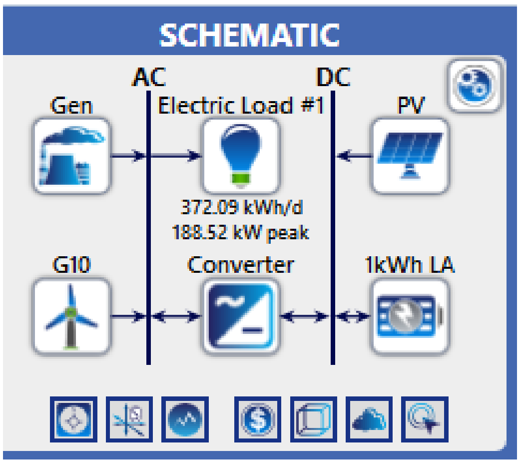


Fig. 3: Grid Connected Hybrid System Model

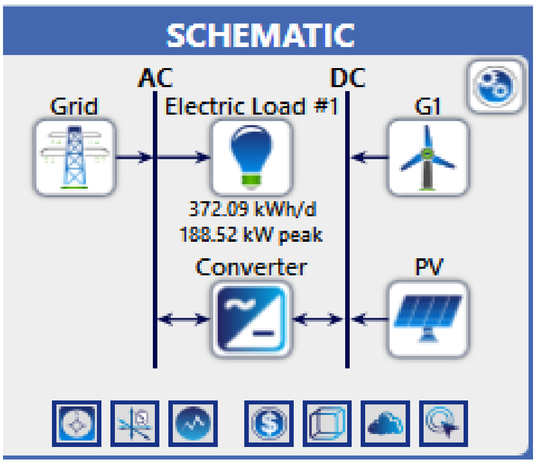


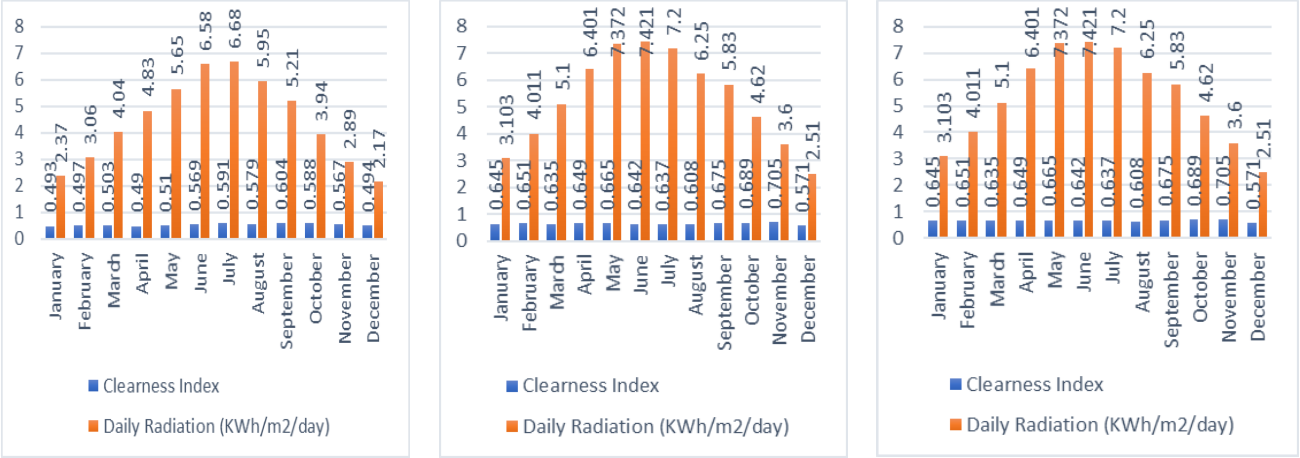
Fig. 4. Standalone Hybrid System Model

2.4. Energy Resource Assessment

Pakistan's solar and wind profiles are greater than the minimum requirements. In this study while developing the proposed hybrid energy systems both solar and wind energy resource potential are considered.

2.4.1. Solar Energy Potential

The degree of solar irradiation at any particular place is determined by the geographical coordinates of longitude and latitude. Monthly solar irradiation statistics and clearness index may be estimated using a number of database sources. The average solar radiation intensity in Pakistan is around 5–7 kWh/m2/day[11], which is more than the required minimum for solar panel installation. The National Sun Radiation Database and NASA Surface Metrology are utilised to estimate monthly solar irradiance (kWh/m2/day) and clearness index data for chosen sites, as shown in Fig. 5.

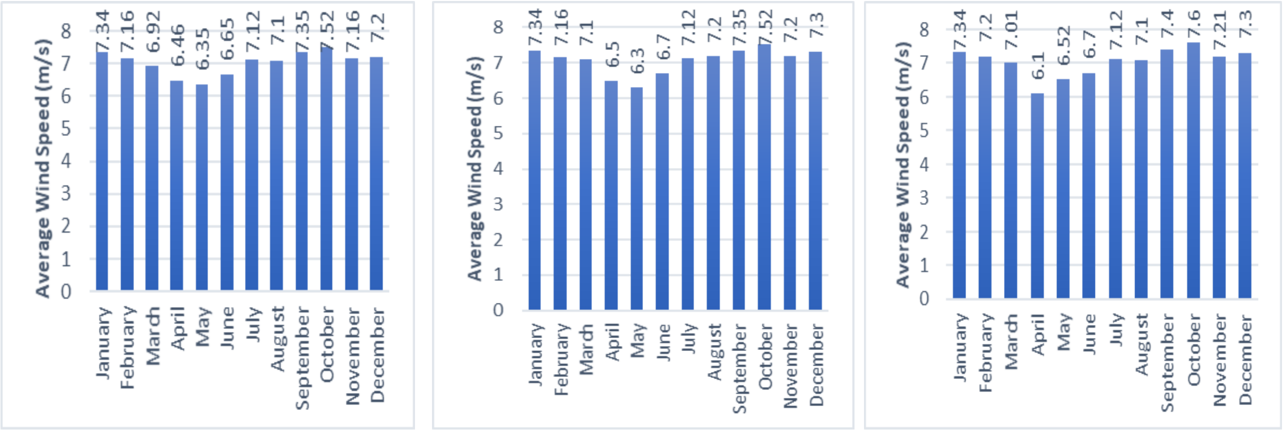


(a) Sost **(b) Gircha** **(c) Morkhoon**

Fig. 5. Daily Solar Irradiance and Clearness Index of Sost, Gircha and Morkhoon

2.4.2. Wind Energy Resource Potential

Multiple online databases can also be used to estimate wind resources. In this study, the wind profile is taken from the National Renewable Energy Laboratories (NREL). NREL's monthly average wind speed (m/s) calculation is based on the use of precise geological coordinates. The average wind speed in the rural areas chosen near Pakistani sites are greater than the requisite 7 m/s. Fig. 6. shows the monthly wind speed data of areas under study.



(a) Sost **(b) Gircha** **(c) Morkhoon**

Fig. 6. Average wind speed data of Sost, Gircha and Morkhoon

2.5. System Components

Table 2 shows the estimated cost of each individual component, which is obtained from market survey and data available from the various areas of Pakistan.

2.5.1. Diesel Generator

The DG (Diesel Generator) set was utilized in this study for off grid system to provide constant power in case of low wind and solar potential. The initial capital cost of DG(Diesel Generator) is minimal and equivalent to the components of renewable energy sources,but the cost of fuel, operation and maintenance costs are significantly greater. The technical characteristics and cost breakdown of the DG set is indicated in Table 2.

$$F_{fuel} = C_o Y_{generator} + C_1 P_{generator} \tag{4}$$

Where,
C_o: *Fuel curve intercept coefficient*
C_1: *Slope of curve*
$Y_{generator}$: Rated Capacity of DG (KW)
$P_{generator}$: Maximum power output (KW)

Table 2: Price per KW and Technical limitations of Diesel generator

Capital Cost ($/kW)	Replacement Cost ($/kW)	Life expectancy (hours)	Efficiency (%)	O&M Charges ($/hour)
500	450	15000	45	0.03

2.5.2. Solar PV Modules

In the proposed hybrid system model, the PV module employed is a standard flat plate with a rated capacity of 1kW. The cost breakdown of the PV employed has been illustrated in Table 3. These figures are based on data gathered from local Pakistani market, PV manufacturers as well as other research papers. On 80 percent derating factor, PV modules have a total lifespan of 25 years [12].The PV array's power output is determined by Eq. (5)

$$P_{PV} = C_{PV} P_{PV} \frac{I_T}{I_s} \tag{5}$$

Where,
C_{PV}: De-rating factor of PV,
P_{PV}: Rated PV array capacity (KW),
I_T: Solar radiation values that strikes on the surface of the PV Array (Kw/m^2)
I_S: Standard radiation value, 1Kw/m^2

Table 3: Solar PV Panels price per kW and technical limitations

Capital cost ($/kW)	Replacement Cost ($/kW)	O&M Charges ($/kW/year)	Life expectancy (year)	Derating factor (%)
700	500	10	25	80

2.5.3. Wind Turbine

In Wind turbines the kinetic energy obtained from the speed of wind is converted into mechanical energy and that mechanical energy is transformed into electrical energy. Wind turbines come in a variety of forms and sizes and may be put at various locations depending on the wind potiential and terrain in which it is employed. The wind blows erratically, causing the wind energy system's power production to be varied and fluctuating. As a result, for reliable electricity supply, the system must be combined with other energy sources. The Homer Pro comes with a built-in library of numerous wind turbines, complete with manufacturer data. Numerous number of wind turbines are available in the Homer Pro database catalogue, but EOCYCLE E020 was chosen for this study because of its low cut-in speed of 2.75m/s and having a cut-out speed of 20 m/s. Cost breakdown along with technical limitations of wind turbine employed is illustrated in Table. 4.

Table 4: Wind Turbine price per kW and technical limitations

Capital cost ($/kW)	Replacement Cost ($/kW)	O&M charges ($/kW/year)	Life expectancy (year)	Cut in speed (m/s)
1500	1250	30	20	2.75

2.5.4. Battery Storage

Solar and wind energy generation is soulely dependent on constantly changing solar irradiance and wind speed. Battery storage is necessary in case of Off-grid systems where energy storage devices like batteries are accommodated to deal with such adversity by supplying stored energy under low solar radiation, high wind speeds, terrible weather, or at night. Lithium-ion batteries are employed in Off-grid system as they are more readily accessible in the local market and perform better than lead–acid batteries. Per kW cost breakdown along with technical limitations of battery storage is illustrated in Table 5.

Table 5: Li-ion Battery Storage price per kW and technical limitations

Capital cost ($/kW)	Replacement Cost ($/kW)	O&M charges ($/kW/year)	Life expectancy (year)	Round-trip efficiency (%)
200	200	10	15	80

2.5.5. Power Converter

Solar panels and energy storing devices like batteries generate direct current (DC) while most of the electrical appliances in a common household utilizes alternating current (AC) for their operation. So, power converter is required for conversion from direct current (DC) to alteranating current (AC) to run domestic electrical appliances of daily use. The technical specifications and prices are listed in Table 6.

Table 6: Power Converter price per kW and technical limitations

Capital cost ($/kW)	Replacement Cost ($/kW)	Life expectancy (year)	Efficiency (%)	Relative capacity (%)
150	150	15	90	100

3. Results & Discussion

The simulation results are discussed in detail and throroughly.

3.1. Sensitivity Analysis

Wind speed and Solar irradiation factors are used as sensitivity variables in the sensitivity analysis. Multiple sensitivity variables are found in the findings, and the decision parameters may be used to make a choice. In this study, the sensitivity analysis is performed using maximum and minimum values of wind speed and solar irradiation data obtained from database.

3.1.1. Sost

The cost of energy (COE) and net present cost (NPC) at different sensitivity variables of Solar irradiance and wind speed for designed On-grid and Off-grid systems at Sost have been illustrated in Table 7 and Table 8 respectively.

Table 7: On-Grid Sensitivity Analysis

SENSITIVITY VARIABLES		COE ($/kWh)	NPC ($)
Solar Radiation (kWh/m^2/day)	Wind Speed (m/s)		
2.17	6.40	0.0388	168,371
2.17	7.52	0.0339	152,337
6.68	6.40	0.00862	61,117
6.68	7.52	0.00622	45,106

Table 8: Off-Grid Sensitivity Analysis

SENSITIVITY VARIABLES		COE ($/kWh)	NPC ($)
Solar Radiation (kWh/m^2/day)	Wind Speed (m/s)		
2.17	6.40	0.452	1.19M
6.68	6.40	0.0339	582,939
6.68	7.52	0.211	558,908

3.1.2. Gricha

The cost of energy (COE) and net present cost (NPC) at different sensitivity variables of Solar irradiance and wind speed for designed On-grid and Off-grid systems at Gircha have been illustrated in Table 8 and Table 9 respectively.

Table 8: On-Grid Sensitivity Analysis

SENSITIVITY VARIABLES		COE ($/kWh)	NPC ($)
Solar Radiation (kWh/m^2/day)	Wind Speed (m/s)		
2.51	6.30	0.0347	158,502
2.51	7.52	0.0296	140,671
7.50	6.30	0.00423	32,306
7.50	7.52	0.00185	14,496

Table 9: Off-Grid Sensitivity Analysis

SENSITIVITY VARIABLES		COE ($/kWh)	NPC ($)
Solar Radiation (kWh/m^2/day)	Wind Speed (m/s)		
2.51	6.30	0.401	1.06M
2.51	7.52	0.311	821,577
7.50	6.30	0.211	557,283
7.50	7.52	0.204	539,751

3.1.3. Morkhoon

The cost of energy (COE) and net present cost (NPC) at different sensitivity variables of Solar irradiance and wind speed for designed On-grid and Off-grid systems at Morkhoon have been illustrated in Table 10 and Table 11 respectively.

TABLE 10: On-Grid Sensitivity Analysis

SENSITIVITY VARIABLES		COE ($/kWh)	NPC ($)
Solar Radiation (kWh/m^2/day)	Wind Speed (m/s)		
2.51	6.10	0.0358	162,115
2.51	7.60	0.0293	139,685
7.42	6.10	0.00459	34,935
7.42	7.60	0.00160	12,532

TABLE 11. Off-Grid Sensitivity Analysis

SENSITIVITY VARIABLES		COE ($/kWh)	NPC ($)
Solar Radiation (kWh/m^2/day)	Wind Speed (m/s)		
2.51	6.10	0.388	1.03M
2.51	7.60	0.317	838,524
7.42	6.10	0.212	560,964
7.42	7.60	0.204	540,484

3.2. Cost Analysis

The cost analysis of the On-grid and Off-grid systems for Sost, Gircha and Morkhoon are depicted. The main concern of the optimization findings is to focus on COE, which is the main issue of rural electrification, the NPC, COE, and operational costs are presented.

3.2.1. Sost

The NPC, COE, and Operating Cost of the designed optimum On-Grid system obtained from Homer Pro analysis at Sost is 168,371, 0.0388 and 2,067 respectively. For Off-Grid/standalone system the NPC, COE, and Operating Cost of the designed optimum system is 1.19M, 0.452 and 40,667 respectively.

Table 12: Cost Analysis of On-Grid and Off-Grid Systems

System Type	NPC ($)	COE ($)	Operating Cost ($/yr)
On-Grid	168,371	0.0388	2,067
Off-Grid	1.19M	0.452	40,667

3.2.2. Gircha

The NPC, COE, and Operating Cost of the designed optimum On-Grid system obtained from Homer Pro analysis at Gircha is 158,505, 0.0347 and 1,520 respectively. For Off-Grid/standalone system the NPC, COE, and Operating Cost of the designed optimum system is 1.06M, 0.401 and 34,942 respectively.

Table 13: Cost Analysis of On-Grid and Off-Grid Systems

System Type	NPC ($)	COE ($)	Operating Cost ($/yr)
On-Grid	158,505	0.0347	1,520
Off-Grid	1.06M	0.401	34,942

3.2.3. Morkhoon

The NPC, COE, and Operating Cost of the designed optimum On-Grid system obtained from Homer Pro analysis at Morkhoon is 162,115, 0.0358 and 1,706 respectively. For Off Grid/standalone system the NPC, COE, and Operating Cost of the designed optimum system is 1.03M, 0.388 and 34,707 respectively.

Table 14: Cost Analysis of On-Grid and Off-Grid Systems

System Type	NPC ($)	COE ($)	Operating Cost ($/yr)
On-Grid	162,115	0.0358	1,706
Off-Grid	1.03M	0.388	34,707

3.3. Optimization

Based on NPC and low cost of energy (LCOE), the optimization has been performed using Homer Pro to discover/find the most optimum system. There may be several viable solutions, and the best system is chosen depending on the decision-making factors. Homer Pro optimizes different combination of systems based on the decision-making factors such as LCOE and NPC[13]. The optimized results obtained through simulation on Homer Pro for different combination of optimized systems in study areas of Sost, Gricha and Morkhoon of Hunza district of Gilgit Baltistan have been indicated in Tables 15, 16 and 17 respectively.

Table 15: Optimization Results of Sost

On Grid System

Solar PV (kW)	Grid (kW)	Wind Turbine (20 kW)	Converter (kW)	COE ($)	NPC ($/kWh)	Initial Capital ($)	Renewable Fraction (%)
132	1	1	28.5	0.0388	168,371	128,104	69.3
132	1	0	28.5	0.0691	229,539	98,104	40.3

Off Grid System

Solar PV (kW)	Generator (kW)	Wind Turbine (20 kW)	No of Battery	Converter (kW)	COE ($)	NPC ($/kWh)	Initial Capital ($)	Renewable Fraction (%)
132	50	1	1,170	141	0.452	1.19M	402,506	86.2

Table 16: Optimization Results of Gircha

On Grid System

Solar PV (kW)	Grid (kW)	Wind Turbine (20 kW)	Converter (kW)	COE ($)	NPC ($/kWh)	Initial Capital ($)	Renewable Fraction (%)
132	1	1	32.4	0.0347	158,502	128,885	71.3
132	1	0	32.4	0.0615	217,792	98,885	45.7

Off Grid System

Solar PV (kW)	Generator (kW)	Wind Turbine (20 kW)	No of Battery	Converter (kW)	COE ($)	NPC ($/kWh)	Initial Capital ($)	Renewable Fraction (%)
132	50	1	1,063	142	0.401	1.06M	381,225	89.7

Table 17: Optimization Results of Morkhoon

On Grid System

Solar PV (kW)	Grid (kW)	Wind Turbine (20 kW)	Converter (kW)	COE ($)	NPC ($/kWh)	Initial Capital ($)	Renewable Fraction (%)
132	1	1	32.4	0.0358	162,115	128,885	70.5
132	1	0	32.4	0.0614	217,551	98,885	45.7

Off Grid System

Solar PV (kW)	Generator (kW)	Wind Turbine (20 kW)	No of Battery	Converter (kW)	COE ($)	NPC ($/kWh)	Initial Capital ($)	Renewable Fraction (%)
132	50	1	905	154	0.388	1.03M	351,532	88.1

4. CONCLUSION

In this study, hybrid standalone and grid-connected systems are designed for Pakistan's rural communities along the China Pakistan Economic Corridor (CPEC) to create economic zones, service areas, to improve the socioeconomic status of locals, and to reduce energy poverty in rural areas of Hunza valley. It includes a comparative analysis for the regions of Sost, Gircha, and Morkhoon in Hunza district, Gilgit Baltistan, involving a standalone and a grid-connected hybrid power system[8]. Grid-connected systems have the lowest optimum cost of energy of 0.0388/kWh, 0.0347/kWh, and 0.0358/kWh for selected areas of Sost, Gircha, and Morkhoon, respectively, according to the optimised results obtained by simulation on Homer Pro, which is suitable if the national grid is already present and reliable. The reduction in grid energy purchases enhances end-consumer savings while also lowering grid power emissions. For the places under consideration, the off-grid hybrid energy system[11] has a cost of energy of 0.452/kWh, 0.401/kWh, and 0.388/kWh, which is expensive but suited for remote and difficult terrains like Hunza district. The cost of the standalone/off grid systems can be decreased even further by raising the yearly electricity shortfall or lowering the capacity of the storage system. Battery wear costs, battery autonomy, and frequent power generation from a diesel generator are all key factors that increases cost in off-grid applications. In underdeveloped parts of the nations with similar resource potential, geography, and unavailability of conventional reliable grid power supply due to rugged terrain and expensive grid extension, standalone/off-grid solutions are found to be more cost-effective and efficient. This study can also help in the reduction of the use of fossil fuels and the burning of woods for heating, cooking and other purposes. Both sources are the major cause of deforestation and glacier melting in the region.

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