Designing and Optimization of Stand-alone Hybrid Renewable Energy System for Rural Areas of Punjab, Pakistan

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Abstract- Increasing energy demand accompanied by diminishing of natural resources is the prime reason behind the growing popularity of renewable energy resources. Hence to develop a power system model for sustainable and efficient power deliverance is inevitable. To serve the purpose, we proposed in this paper a hybrid renewable energy system (HRES) that consists of run-off canal micro hydro/PV/wind integrated with a diesel generator. Main purpose is the electrification of remote areas of province Punjab, Pakistan. The authors selected the BS link canal-I located at 300 52' N and 730 55' E in Punjab, Pakistan, for the proposed HRES. Beforehand, load and resource profile of selected site was evaluated to present an economically optimized model of the proposed energy system. Moreover, Hybrid Optimization Model for Electric Renewables (HOMER) was used as an optimization tool to perform techno-economic feasibility of the micro hydro/PV/wind energy system to entertain the evaluated load of the location. Mainly three strategies are employed due to scarcity of hydro resources and based on the availability of the energy resources. First strategy suggests to use diesel generator integrated with solar and wind power systems, HOMER declares this strategy most expensive with total Net Present Cost (NPC) of $ 670,121 and Cost of Energy (COE) of $ 0.0936/kWh. The recovery period of the hybrid energy system under this strategy is 13 years. The second strategy focuses on the water management strategy using 100 % renewable energy. NPC diminishes to $ 479,835 and the COE reduces to $ 0.0670/kWh. The system recovers all the incurred cost in 5.5 years. The last one enacts renewable energy systems with capacity shortage scheme. NPC and the COE reduces to $ 284,877 and $ 0.0437/kWh respectively from the previously discussed strategy. The system recovers all the incurred cost in 1.7 years. Based on the NPC, the COE and the minimum payback period, HOMER executes the optimization analysis on all the proposed strategies and found 1st strategy to be the least feasible and 3rd strategy the most feasible respectively.

Keywords Hybrid energy; micro hydro; HOMER; run-off canal; solar; wind.

1. Introduction

Lack of diversification in energy resources has led Pakistan's current energy mix to be dictated by the imported fossil fuel energy resources, causing a high burden on the national economy in the form of import bills. IPPs (Independent Power Producers) hold the thermal power plants operated on imported oil taking the electricity costs far beyond the consumers. When the circular debts to the IPPs accrue to a huge amount they shut the power plants and the load shedding becomes worse. Energy mix and the annual shortfall of electricity in Pakistan is shown in Table 1. On the average, a shortfall of 5 GW has been consistently there since 2008. A huge shortfall of electricity has brought on the average 8-10 hours of electricity blackout in urban areas and 14-18 hours in urban areas [1]. In Pakistan, 70 % of the population is the resident of the rural areas and 45 % people are still off-grid [2]. A complete blackout in rural areas has brought the irrigation and domestic activities to a standstill. Though the single sourced renewable energy systems like solar, wind, biomass and micro hydro are in focus; many such grid-connected projects are in different stages of project development. Hybrid renewable energy systems are more sustainable than single sourced electricity in off-grid rural areas because of the intermittency of these renewable energy resources [3]-[4]. Renewable energy resources like solar, wind, biomass and micro hydro can be integrated with and without energy storage system [5]. Hybrid off-grid energy systems with best energy management techniques are more reliable, sustainable and green smart microgrids [6]. Energy engineers and researchers use various tools and software like HOMER, Hybrid2, TRNSYS, eQUEST, E Huga, Energy

Plus, etc. to model the energy systems and implement the energy management technique. These tools optimally size the components and perform optimization and sensitivity analysis based on load demand, availability of resources and their cost. HOMER (Hybrid Optimization Model for Electric Renewables) is the latest simulation model that chooses the viable hybrid energy system among various components you select. HOMER performs optimization analysis on all possible combinations of the equipment used and sorts out the feasible one based on optimization variable. It provides thousands of combinations and after comparing understands the variability of the system with change in variables that are beyond the control such as wind speed, solar irradiance, hydro flow and fuel cost. This tool can simulate latest technologies such as solar PV, the wind, hydro, biomass, hydrogen, advanced grid, advanced load and combined heat & power.

Previously several authors conducted a feasibility study either on single sourced system or hybrid energy systems. Olatomiva et al. [7] performed a feasibility study on hybrid energy system consisting of the solar array, wind and diesel generator for remote rural electrification. Six locations were selected from six geopolitical zones in Nigeria to implement the results in other locations of these six geopolitical zones. They used HOMER as optimization tool and found the hybrid of solar PV/diesel/battery optimum architecture with diesel price as a sensitive variable. Lau et al. [8] proposed a PV/diesel hybrid energy system for Malaysia to overtake the conventional diesel generators extensively used in remote areas. Swarnkar et al. [9] conducted a study on hybrid renewable energy system (PV/wind/diesel generator) for the technical institute with grid connected and off the grid; he concluded the grid connected hybrid energy system to be cheaper than off grid system. He excluded the wind turbine from the hybrid system because of the high cost and low wind speed. Bhatt et al. [10] studied the techno-economic feasibility of an off-grid hybrid energy system with multiple energy sources such as micro hydro–photovoltaic–biomass and biogas–diesel–battery for remote areas of India. They simulated the hybrid model in HOMER and selected the most feasible combination with feasible net present cost, the minimum cost of energy, maximum renewable fraction, and lowest carbon emissions. Shahzad et al. [11] proposed a hybrid energy system of PV/biomass for electrification of off-grid rural areas of Punjab, Pakistan for irrigation purposes. They concluded that a combination of 10kW PV, 8kW biogas generator, 32 storage batteries and 12kW converter as a feasible solution for the proposed hybrid energy system. The proposed system saved PKR 4.84/kWh proving the economic feasibility of the hybrid proposed system. Refs. [12], [13] conducted a study on the renewable hybrid energy systems with different load management strategies using battery storage. Ref. [14] used the Particle Swarm Optimization (PSO) and optimized the power flow from hybrid energy sources by reducing the levelized cost of energy (LCOE). Ref. [15] conducted a review of the hybrid energy system using HOMER. Refs. [16]–[19] studied hybrid energy systems using HOMER.

Table 1. Pakistan energy mix in GW (2008-15)

	2008	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Thermal	13.539	14.576	15.047	16.363	16.069	16.041	16.366	16.814
Hydro-electricity	6.555	6.555	6.555	6.645	6.730	6.947	7.116	7.116
Nuclear	0.462	0.462	0.462	0.787	0.787	0.787	0.787	0.787
Wind	0	0	0	0	0.001	0.50	0.106	0.106
Total installed capacity	20.232	20.556	22.064	23.795	23.587	23.825	24.375	24.823
Peak demand	16.838	17.852	18.467	18.521	18.940	18.827	20.576	21.701
Peak supply	12.442	13.637	12.751	13.193	12.320	14.600	16.170	16.500
Deficit	(4.396)	(4.215)	(5.716)	(5.328)	(6.620)	(4.227)	(4.406)	(5.201)

This paper proposed a micro hydro/PV/wind/ diesel generator hybrid energy system for off-grid remote areas of Punjab, Pakistan. We proposed this hybrid energy system on BS link canal-1 originated from balloki barrage on river Ravi and sulaimanki barrage on river Sutlej. Simulation of the proposed hybrid system was conducted on HOMER. Based on the available energy resources, we proposed and evaluated three strategies. The 1st strategy was simulated for the actual available resources: 2nd was simulated by using a diesel generator replacing the hydro to meet the load in the month of January: 3rd strategy introduced a capacity shortage and load demand management. We calculated the recovery period of all the strategies and compared the results to choose the most feasible and economic scenario.

The paper is organized as: Section 1 presents introduction and literature review. Section 2 gives the methodology adopted to evaluate the load profile and resources of the hybrid energy system. Section 3 presents the designing of the proposed hybrid energy system. Results and the discussion have been presented in section 4. Section 5 concludes the study.

2. Methodology

We used HOMER (Hybrid Optimization Model for Electric Renewables) developed by NREL (National Renewable Energy Laboratory) for the feasibility study of the proposed hybrid energy system. HOMER requires some preliminary data to perform the optimization analysis. First, it needs coordinates and load of the proposed location to be served by the hybrid energy system. The other inputs to the HOMER are the resources potential such as solar, wind, and micro-hydro [20], [21]. After taking all the inputs of load and resources, HOMER performs the optimization analysis and generates results. Fig. 1 shows the flow chart of the methodology adopted to design the proposed hybrid energy system.

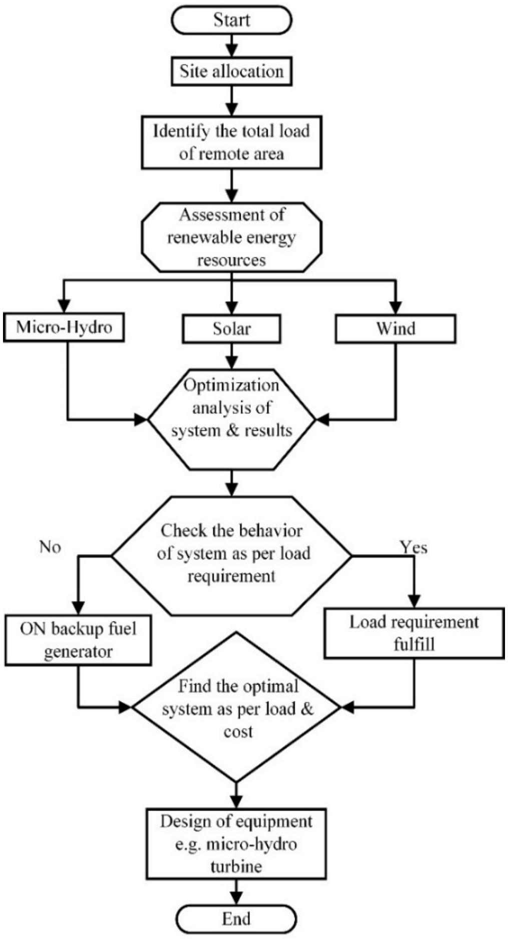

Fig. 1. Methodology of the analysis of the proposed hybrid energy system

HOMER makes different arrangements of the system by taking diverse combinations of the components used and perform an energy balance for each of these configurations. For each of these configurations, HOMER determines feasibility by knowing whether the load demand is met under specified conditions. It also determines the installation and operation & maintenance cost for the lifetime of the project.

For the optimization of the simulated system, HOMER Pro contains two optimization algorithms. (1) The original grid search algorithm that simulates all the possible configurations (2) proprietary "derivative-free algorithm" that searches only least cost system configurations and presents a list of feasible configurations organized by net present cost.

HOMER asks for sensitivity variables that are prone to variations such as wind speed, solar irradiance, and diesel prices. It performs optimization for each of these sensitivity variables with a specified range of variation.

2.1. Site allocation

Choosing a suitable location is key to the accomplishment of any renewable-energy based power project, economically and technically. Availability of resources such as solar, wind, biomass, and hydro in the proposed location must be evaluated along with the load to be met. Selecting a site and designing appropriate system components are the first milestone of any successful project. The site selected for this micro hydro based hybrid energy project is at the BS link canal-I located at the coordinates 30^o 52' N and 73^o 55'E in the province of Punjab, Pakistan. The site consists of eight villages: (1) kot faizi, (2) kandu wala, (3) kot bukanke, (4) kot mian waryam, (5) dakku, (6) new dakku, (7) kot khan badar, and (8) Kitan kalan. The project proposed location is shown in Fig. 2.

2.2. Load assessment

The hybrid renewable energy system was proposed to electrify the off-grid community consisting of eight villages located at coordinates 30.87° N and 73.93° E in Punjab, Pakistan. For proper evaluation of load, we surveyed and collected the relevant information about no. of houses, no. of electric devices with type and rated power and their operating hours. The locality was divided into 4 different categories: small/medium houses, large houses, departmental stores, and schools. No commercial and industrial load was there in the locality. Table 2 shows the load evaluation of the whole locality for a day. Primary load calculated was 1906 kWh/day.

HOMER has the facility to add thermal, electrical and hydrogen load within the system. It dispatches all the energy sources used to meet the specified load. HOMER uses the scaled load data in the simulation. It multiplies the baseline load to a factor to find scaled load. This factor is determined by the fraction of scaled annual average and baseline annual average. Daily load profile for the whole year is shown in Fig. 3 indicating how the load demand varies throughout the day. Maximum load demand is at 6 PM while from 12 AM to 6 AM is the off-peak duration. April to August is the peak demand months.

2.3. Resources assessment

2.3.1. Solar irradiance

Solar radiation data was obtained by HOMER built in function of getting solar data from NASA Surface Meteorology and Solar Energy database by putting the coordinates of the location. For solar PV outputs, HOMER uses Global Horizontal Irradiance (GHI) which is the sum of Direct Normal Irradiance (DNI), diffused light and reflected light. The maximum solar radiation 6.6 kWh/m^2/day was in the month of June with scaled annual average solar radiation of 5.01 kWh/m^2/day. Fig. 4 shows the monthly solar radiation with clearness index confirming the efficient solar PV potential for electricity generation at the proposed location.

2.3.2. Wind resources

HOMER gets the wind speed data in m/s monthly averaged values over 10 years period from NASA Surface Meteorology and Solar Energy Database measured at 50 m anemometer height. Fig. 5 shows the monthly wind speed record on the proposed location. Maximum speed is 5.03 m/s in June with the annual average speed of 3.67 m/s. In the proposed hybrid system hub height was adjusted at 30 m by the HOMER. The hub height tends to increase with increase in wind speed. HOMER uses the power law profile of Eq. (1) to evaluate the wind speed at the hub height. In the present study HOMER reads the wind potential shown in Fig. 5 and adjusts the hub height according to the wind potential.

$$V_{hub} = V_{anem}\left(\frac{Z_{hub}}{Z_{anem}}\right)^{\alpha} \qquad (1)$$

where

$V_{hub,}$ wind speed at hub height.

V_{anem}, wind speed at anemometer height.

Z_{hub}, the hub height.

Z_{anem} , the anemometer height.

α, the power law exponent.

Fig. 2. Project proposed location

Table 2. Load evaluation of the proposed location

	Load type	Rated Power (Watt)	Quantity	Hours	Energy (Wh/day)	Total energy (kWh/day)	No. of houses	Total (kWh/day)
Small/medium houses	Refrigerator	50	1	12	600	3.32	306	1015.92
	TV	80	1	8	640			
	Light	20	3	8	480			
	Fan	80	1	14	1120			
	Miscellaneous	20	1	24	480			
Large houses	Electric motor	820	1	1	820	7.40	104	769.6
	TV	80	1	8	640			
	Light	20	5	8	800			
	Fan	80	3	14	3360			
	Refrigerator	100	1	13	1300			
	Miscellaneous	20	1	24	480			
Stores	Refrigerator	100	1	12	1200	3.36	25	84
	Light	20	4	5	400			
	Fan	80	1	16	1280			
	Miscellaneous	20	1	24	480			
Schools	Light	20	10	7	1400	7.48	5	37.4
	Fan	80	10	7	5600			
	Miscellaneous	20	1	24	480			
Total (kWh/day)								**1906.92**

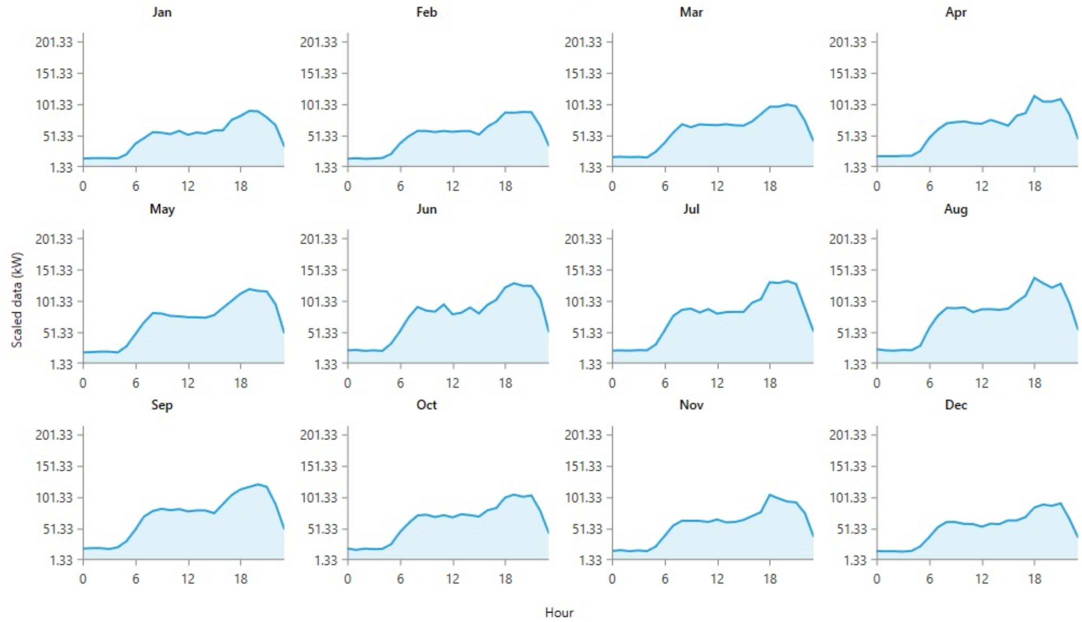

Fig. 3. Annual load profile

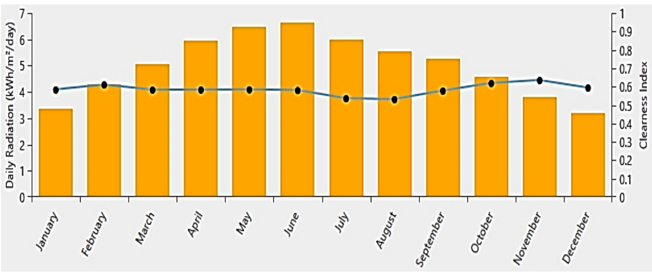

Fig. 4. Solar radiation profile

Fig. 5. Wind profile

2.3.3. Micro hydro

Hydropower is the potential energy available in water at the high head which is converted into mechanical energy of the turbine couple electrical generator and hence the electrical energy. Hydropower is categorized based on the available head. The proposed location in this paper is the run of the canal on BS link canal-1. As the canal is a linkage between river Ravi and river Sutlej, water resources are abundantly available throughout the year except in January when the limited water is given to the BS link canal-2. The water flow is maximum in the month of June, July, and August when rivers are flooded because of the melting of glaciers. Monthly streamflow for the whole year is shown in Fig. 6.

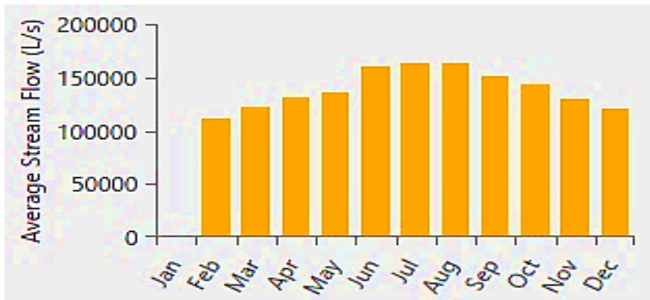

Fig. 6. Hydro resources

3. System Designing

The proposed hybrid energy system consists of four energy sources: micro hydro, solar PV module, wind turbine and conventional fuel-based diesel generator. Battery storage backups the system in peak hours and store surplus energy in off-peak hours. A converter converts the electricity from AC to DC and DC to AC. The schematic of the proposed hybrid energy system along with load is shown in Fig. 7.

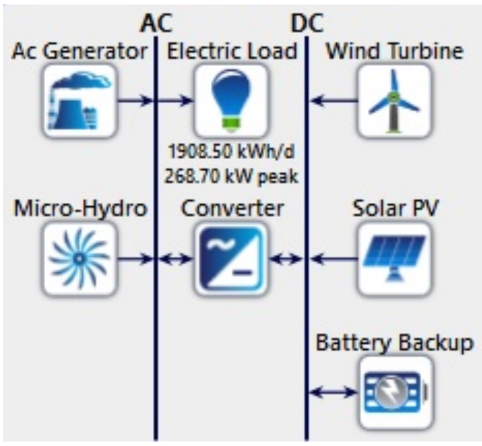

Fig. 7. Configuration of the hybrid energy system

3.1. Micro hydro

A micro hydro uses the potential energy of falling water that is used to rotate the turbine coupled to the electrical generator. Micro hydro does not require any major civil construction thus having no environmental effects. Water from the running flow of river/canal or natural fall is diverted and after electricity generation sent back to the stream. The power capacity in water mainly depends upon flow rate and head of the falling water that can be calculated by the following equation.

$$P_t = \rho \, g \, Q \, H \tag{2}$$

where

P_t, Theoretically available power (Watts)
ρ, Water density (1000 kg/m^3)
g, Gravitational acceleration (9.8 m/s)
Q, Flow rate (1.406 m^3/s)
H, Head (9 m)

By using Eq. (2), nominal hydropower comes out to be 108 kW. The available electrical power can be calculated by multiplying the theoretical power with the efficiency of the system. The system efficiency of the turbine and generator is 75 % and the nominal electrical power available comes out to be 81 kW.

3.1.1. Penstock losses

In calculating the theoretical power, head or penstock losses cannot be ignored. These are the losses occurring due to the water friction with the penstock and can be calculated by Eq. (3).

$$h_f = f \times \left(L/_D\right) \times \frac{v}{2g} \tag{3}$$

where

f, Multiplying friction factor (0.1)
L, Length of the penstock (10 m)
D, diameter of the penstock (0.300 m)
v, average velocity (m/s)
g, Gravitational accelration (9.8 m/s^2)

Eq. (3) gives the head losses 0.968 that results in net available head 8 m.

3.1.2. Electric power

After bringing the head losses into account, actual power available at the generator output can be calculated by using Eq. (4)

$$P_{act.} = \rho \, g \, Q \, H_n \, \eta \tag{4}$$

where

H_n, Net head (8m)
η, system efficiency (75 %)
The actual electric power of the system comes out to be 74 kW.

3.2. Solar PV System

In the proposed hybrid energy system, polycrystalline type solar PV has been used to charge the battery and provide electricity during the peak hours. Solar PV modules of 1 kW, 30 kW, and 50 kW have been used in integration with the wind turbine and micro hydro turbine. HOMER makes different combinations of the sensitivity variables and chooses the best optimum one. Details of the solar PV modules is given in Table 3. As the performance of the solar PV system is vulnerable to the varying temperature and the irradiance, to compensate the degraded performance of the solar PV module a Maximum Power Point Tracker (MPPT) was also employed in the proposed system as shown in Fig. 8. MPPT tracks the maximum power point on the P-V curve of the solar module and let it work always on that MPP. Till now, incremental conductance [22] and the P&O [23]-[24] MPPT algorithms are widely used because of the better efficiency and the less complexity involved. HOMER includes MPPT in the system by adding its efficiency in the MPPT section of the system.

Table 3. Solar module's parameters and cost

Parameters	**Value**	**Units**
Capital cost	1600	$/kW
Replacement cost	1600	$/kW
O&M cost	10	$/kW
Lifetime	25	Year
slope	25	Degree
Derating factor	80	%
Rated Power	250	W
Short circuit current, Isc	8.76	A
Open circuit voltage, Voc	37.5	V
Voltage at maximum power, VMPP	30.3	V
Current at maximum power, IMPP	8.24	A

3.3. Wind turbine

The wind turbine of 10 kW was used in the proposed hybrid energy system. The output power of the wind turbine is a function of the wind speed. The hub height of the wind turbine is 30 m. HOMER converts the wind speed from 50m anemometer height to the 30m hub height. Costs and the technical parameters of the wind turbine are shown in Table 4.

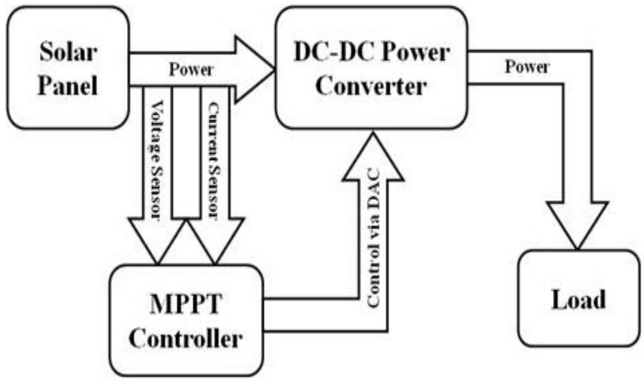

Fig. 8: Block diagram of the solar PV system

3.4. Converter

The converter in HOMER's simulation consists of inverter and rectifier. The inverter converts the DC electricity from the solar module and the battery backup to AC voltage to feed the AC line. The lifetime of the inverter is 15 years with 90 % efficiency. The rectifier converts the AC electricity into DC electricity that is used to charge the battery backup only as there is no DC load in this system. The efficiency of the rectifier is 85 % while the capacity relative to the inverter is 100 %.

Table 4. Wind turbine's parameters and cost

Parameters	Value	units
Capital cost	33,640	$
Replacement cost	23,640	$
O&M cost	360.20	$/year
Hub height	30	meter
Lifetime	20	year
Model	BWC-Excel-R	
Rotor diameter	7	meter
No. of blades	3	
Cut-in wind speed	3.4	m/s
Cut-off wind speed	60	m/s
Rated power	10	kW
Generator voltage	220	volts

3.5. Batteries

Because of the intermittency of the renewable energy resources and the variation in the load profile, batteries are used to store the spare electricity and share the load during peak hours. Trojan IND9-6V batteries with 602 Ah were used in the proposed hybrid renewable energy system. According to HOMER, the battery has the round trip efficiency of 81 % with 20 years of lifetime. The nominal capacity of the battery is 4 kWh. To simulate the optimization, HOMER needs to know the kWh capacity and does not need to know how much batteries are in series or in parallel. In the optimized case of the 3rd strategy HOMER optimized 96 batteries to meet the kWh capacity. While designing a system, the bus voltages are determined by the size of the string i.e. no of batteries in parallel. Eq. (5) gives the no. of batteries required for a solar PV system by considering the 50 % depth of discharge.

$$No.of\ Batteries = \frac{E\ D}{V_b R_b} \qquad (5)$$

where,
E, Energy per day (kWh/day)
D, Autonomy day
V_b, Battery voltages (V)
B_R, Battery Rating (Ah)

4. Results and Discussion

Based on resources management, we presented three strategies to allocate the energy resources in an efficient manner with least net present cost and the cost of energy.

4.1. First strategy

This strategy is based on the actual available resources. The total load demand will be served by the available energy resources. As the hydro sources are not available in the month of January, electricity is produced by using a standalone diesel generator that takes part to meet the load in integration with solar and wind. Diesel fuel price has been used as a sensitive variable as shown in Table 5. Optimization case of this sensitive case is shown in Table 6. On the optimization of the sensitive case, HOMER excluded the wind turbine from the hybrid system and resulted in the hybrid energy system consisting of 40 kW solar PV module, 74 kW hydro, 247 strings of storage batteries, 125 kW system converter and 240 kW diesel generator. The best sensitivity case is with fuel price $0.74/L. The net present cost of the system was $670,121 and the cost of energy was $0.0936 which was the highest cost among presented system strategies. This strategy is the least preferable as the costs are highest and the renewable fraction is 94 %. The use of diesel enhances the environmental concerns. The emissions generated in this strategy using diesel generator are given in Table 7. The operating cost of the system is also high because of the use of diesel. Because of the huge battery backup system, initial capital cost also went too high.

Fig. 9 and Table 8 show the annual electricity production by source. Because of the absence of hydro resources in January, electricity was produced from solar PV and the diesel generator. The remaining demand was fulfilled by the huge battery backup storage. In the remaining year, electricity was produced by hydro and solar PV. Owing to the absence of DC load, all the produced electricity was consumed by the AC primary load. 27 % excess electricity was stored in the battery backup.

Table 5. Sensitivity cases of the 1st strategy

Sr. No.	Diesel fuel price ($/L)	PV (kW)	WT	DG (kW)	Battery backup	Micro Hydro (kW)	Converter (kW)	COE ($/kWh)	NPC ($)	Operating Cost ($/yr)	Initial Capital $	RF %
1	0.74	40.3		240	247	73.6	125	0.0936	670,121	18,774	430,129	94
2	0.84	31.3		240	262	73.6	133	0.0958	685,848	20,020	429,923	93

Table 6. Optimization cases of the least cost sensitivity case

Sr. No.	PV (kW)	WT	DG (kW)	Battery backup	Micro Hydro (kW)	Converter (kW)	COE ($/kWh)	NPC ($)	Operating Cost ($/yr)	Initial Capital ($)	RF (%)
1	40.3		240	247	73.6	125	0.0936	670,121	18,774	430,129	94
2	40.3	1	240	254	73.6	124	0.0996	713,351	19,133	468,766	94
3			240	387	73.6	131	0.104	743,838	21,233	472,407	92
4		1	240	372	73.6	148	0.108	776,195	21,593	500,164	92

Table 7: Emissions from diesel generator in first strategy

Quantity	Value	Unit
Carbon dioxide	31,333	kg/yr
Carbon monoxide	77.34	kg/yr
Unburned hydrocarbons	8.57	kg/yr
Particulate matter	5.83	kg/yr
Sulphur dioxides	62.92	kg/yr
Nitrogen oxides	690.11	kg/yr

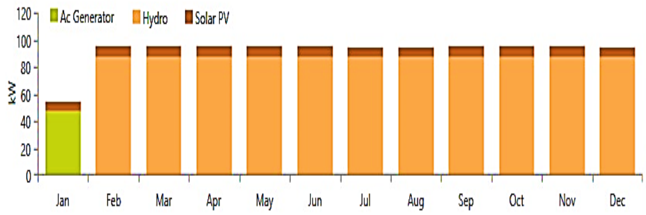

Fig. 9. Electricity production from hybrid energy system in 1st strategy

Table 8. Annual electricity production and consumption by the hybrid energy system in 1st strategy

Production			Consumption			Quantity		
Source	**kWh/yr**	**%**	**Sink**	**kWh/yr**	**%**	**Quantity**	**kWh/yr**	**%**
Solar PV	65,880	8.22	AC primary load	560,058	100	Excess electricity	212,927	26.6
Micro hydro	700,890	87.40	DC primary load	0	0	Unmet load	327.6	0.1
Diesel generator	35,148	4.38				Capacity shortage	559	0.1
Total	801,918	100	Total	560,058	100			

If the energy (kWh) is sold to the community at a price PKR 12, the annual average cost of energy amounts to PKR 82,37,808 while the cost of energy under this strategy is PKR 9. Profit per unit of electricity is PKR 3. Calculation of the recovery period revealed that the cost of the project will be recovered in 13 years

4.2. Second strategy

As stated earlier in hydro resources that in the month of January, hydro resources are not available in the BS link canal-1 because the limited available water is supplied to the BS link canal-2. Water management strategy can be negotiated with the irrigation department to divert water from BS link canal-2 to BS link canal-1 in the month of January to run the hybrid energy project consistently. This strategy will lead to 100 % renewable fraction leading to a reduction in annual emissions as compared to the 1st strategy. The cost of energy, operating cost and the net present cost has been reduced as compared to the 1st strategy because of the removal of a diesel generator. However, the initial capital cost of the system is still high due to the huge battery backup storage system as shown in the Table 9.

Fig. 10 and Table 10 show the electricity production by each renewable source. The share of micro hydro has been increased from the 1st strategy. All the electricity is generated from the solar and micro hydro resources. 29 % surplus electricity was used to charge the battery backup which spared no unmet load.

The sale price of the unit (kWh) was set at PKR 12 that amounted to the annual revenue PKR 82,37,808. The cost of energy under this strategy was PKR 6.7. The system cost recovery period was found to be 5.5 years which is 7.5 years earlier than the 1st strategy.

4.3. Third strategy

The 3rd and the least expensive system configuration is the total renewable energy system with some capacity shortage. Capacity shortage strategy provides you the option to keep some load unmet to allow a less expensive system with the available energy resources. If the load management strategy makes sure the 5 % load be unmet, it means the system will meet the 95 % of the annual electric load and the operating reserves. Operating reserves is the spare working capacity of the system that immediately responds to an abrupt and random increase in load demand or the sudden decrease in renewable output. Operating reserves comes in action at sudden variations in electric load or renewable output power guaranteeing the consistent electric supply to the load. At the end of the year, HOMER calculates the capacity shortage fraction y using Eq. (6). If it is equal to or lower than the maximum annual capacity shortage, HOMER declares the system feasible.

$$f_{cs} = {E_{cs}}/{E_{demand}} \quad (6)$$

where
f_{cs}, Capacity shortage fraction
E_{cs}, Total capacity shortage (kWh/yr)
E_{demand}, Total electrical demand

This strategy of the proposed hybrid energy system is the most preferable. Capacity shortage management and the load demand management makes the system feasible as the net present cost and the cost of the energy are the least one. Rejection of the diesel generator has eliminated the fuel price in the operating cost of the system. Capacity shortage management has reduced the battery backup reducing the initial capital cost of the system. The renewable fraction of the system is 100 % thus this strategy is environment-friendly hybrid energy system as shown in the Table 11.

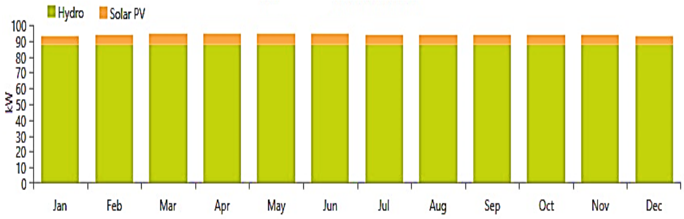

Fig. 10. Electricity production from hybrid energy system in 2nd strategy

Table 9. Optimization cases of the 2nd strategy

Sr. No.	PV (kW)	WT	DG (kW)	Battery backup	Micro Hydro (kW)	Converter (kW)	COE ($/kWh)	NPC ($)	Operating Cost ($/yr)	Initial Capital ($)	RF (%)
1	34.6			253	73.6	134	0.0670	479,835	7,685	381,599	100
2	34.6		240	253	73.6	134	0.0722	516,633	6,881	428,671	100
3				387	73.6	131	0.0778	556,679	10,275	425,335	100
4	18.4	1		300	73.6	200	0.0794	568,683	9,706	444,604	100

Table 10. Annual electricity production and consumption by the hybrid energy system in 2nd strategy

Production			Consumption			Quantity		
Source	kWh/yr	%	Sink	kWh/yr	%	Quantity	kWh/yr	%
Solar PV	56,507	6.87	AC primary load	560,031	100	Excess electricity	235,846	28.7
Micro hydro	765,944	93.13	DC primary load	0	0	Unmet load	354.7	0.1
Total	822,450	100	Total	560,031	100	Capacity shortage	559	0.1

In this strategy, the capacity shortage was set to be 10 %, so the hybrid system will meet the 90 % of the annual electric load and the operating reserves. Fig. 11 indicates no electricity production in the month of January. A load management strategy was adopted to meet the load with the capacity shortage. Table 12 shows the dominance of the micro hydro over the solar PV throughout the year. Solar power, being intermittent, produced electricity from 6 AM to 6 PM that in peak hours entertained the load and in off-peak hours batteries are charged. 99.11 % electricity was produced by the micro hydro while solar PV produced only 0.89 %. There was no DC load in the system and all the energy produced was consumed by the AC load. 174,547 kWh/yr is the excess electricity that was used to charge the battery backup. 8.9 % of the load was unmet that was managed by the capacity shortage management.

As already stated that the sale price was set at PKR 12/kWh. The annual revenue generated in this strategy was PKR 82,37,808. The cost of energy under this strategy was PKR 4.3. Calculations estimated the recovery period to be 1.7 years much earlier than the 1st and 2nd strategy.

Table 11. Optimization cases of the 3rd strategy

Sr. No.	PV (kW)	WT	DG (kW)	Battery backup	Micro Hydro (kW)	Converter (kW)	COE ($/kWh)	NPC ($)	Operating Cost ($/yr)	Initial Capital ($)	RF (%)
1	3.87			96	73.6	61.1	0.0437	284,877	6,588	200,660	100
2				125	73.6	61.4	0.0448	293,168	6,526	209,742	100
3		1		102	73.6	51.9	0.0492	321,350	7,149	229,964	100
4			240	15	73.6	19.2	0.0597	397,115	17,657	171,400	91

Table 12. Annual electricity production and consumption by the hybrid energy system in 3rd strategy

Production			Consumption			Quantity		
Source	**kWh/yr**	**%**	**Sink**	**kWh/yr**	**%**	**Quantity**	**kWh/yr**	**%**
Solar PV	6,328	0.89	AC primary load	510,340	100	Excess electricity	174,547	24.7
Micro hydro	700,890	99.11	DC primary load	0	0	Unmet load	50,045	8.9
Total	707,218	100	Total	510,340	100	Capacity shortage	60,388	10.8

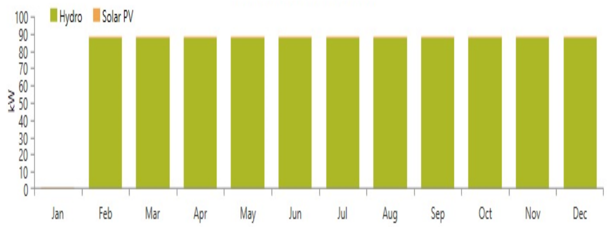

Fig. 11. Electricity production from hybrid energy system in 3rd strategy

A cost summary of the least-cost configuration of the hybrid energy system is shown in Fig. 12. The major capital cost was incurred for hydro system and the battery storage system. Hydro resources and the solar irradiance are freely and abundantly available that's why there was zero cost sustained on fuel. Most of the replacement cost was experienced by the storage backup.

Cost comparison of the proposed three strategies of the hybrid energy system is shown in Table 13. A comparison between the proposed strategies indicates that the COE and the total NPC diminished as we moved from 1st to 3rd strategy. Switching from 1st strategy to 2nd, COE and total NPC decreased by 28.42 % and 28 % respectively. Swapping from 1st to 3rd strategy, COE and the total NPC decreased by 53 % and 58 % respectively. Similarly, if we move from 2nd to 3rd strategy, the reduction in COE and total NPC is 35 % and 41 % respectively. Another important factor is the recovery period. In 3rd strategy, the system recovers its costs in 1.7 years only that makes this strategy more attractive.

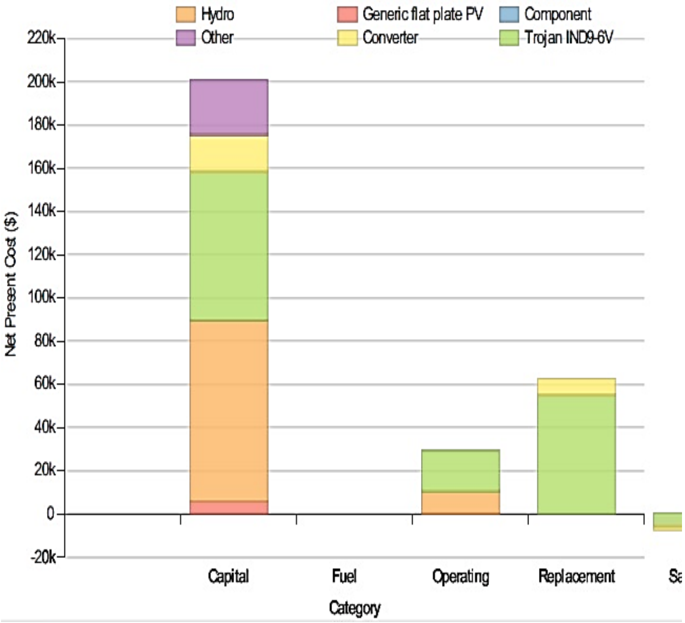

Fig. 12. Cost summary of the hybrid energy system

Table 13. Cost comparison of the three strategies

	COE ($/kWh)	NPC ($)	Operating Cost ($/yr)	Initial Capital ($)	RF (%)	Recovery Period (Year)
Strategy 1	0.0936	670,121	18,774	430,129	94	13
Strategy 2	0.0670	479,835	7,685	381.599	100	5.5
Strategy 3	0.0437	284,877	6,588	200,660	100	1.7

5. Conclusion

This paper presents a hybrid energy system based on run-off canal hydropower system integrated with the wind turbine and solar PV. The hybrid energy system is proposed on BS link canal-1. The system is designed and optimized using HOMER software. Based on available renewable energy resources, three strategies are presented. HOMER simulates all the strategies and performs optimization analysis on different configurations of each presented strategy. In 1st stategy, a diesel generator is used in the month of January as the hydro resources are not available in that month. HOMER declares this strategy most expensive with total NPC of $ 670,121 and cost of energy of $ 0.0936/kWh. The recovery period of the hybrid energy system under this strategy is 13 years. The 2nd strategy assumes the hydro resources management under which negotiation could be conducted with the irrigation department to receive hydro resources in the month of January. This strategy gives 100 % renewable energy fraction in the hybrid energy system. Net present cost and the cost of energy of the system in this strategy is less than the 1st strategy. NPC diminishes to $ 479,835 and the COE reduces to $ 0.0670/kWh. The system recovers all the incurred cost in 5.5 years. In the 3rd and the least expensive strategy, capacity shortage and the demand side management is introduced. The optimum configuration of the hybrid system is micro hydro and solar. Demand side management is organized in a way that the specific load is shut down in peak hours according to the 10 % capacity shortage throughout the year. This conservation and efficient use of electricity avoid the extra construction of power plants to meet the loads. This strategy is more economical as the load management reduces the net present cost and the cost of energy of the system. NPC is $ 284,877 and the COE is $ 0.0437 much less than the previous two strategies. Switching from 1st strategy to 2nd, COE and total NPC decreases by 28.42 % and 28 % respectively. Swapping from 1st to 3rd strategy, COE and the total NPC decreases by 53 % and 58 % respectively. Similarly, if we move from 2nd to 3rd strategy, the reduction in COE and total NPC is 35 % and 41 % respectively.

Pakistan, affluent in renewable energy resources, is the best place for such hybrid renewable energy systems that are more reliable and effective as compared to the stand-alone conventional power plants. The technical problem in one conventional power plant causes the blackout in the whole locality while in the hybrid energy system, various sources are present. The shutdown of one energy source does not affect the functioning of other hybrid sources of electricity. The government of Pakistan can introduce a power policy promoting such hybrid renewable energy system to electrify the off-grid remote rural areas.

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