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OFF-GRID HYDROKINETIC, PHOTOVOLTAIC AND WIND BASED POWER GENERATION FOR ELECTRICITY SUPPLY

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ABSTRACT: Pakistan needs to expand its power generation capacity owing to significant increase in load demand and electricity shortfall. Moreover, government is working to add more sustainable resources to mitigate the dependency on fossil fuels and reduces greenhouse gases. Wind / Photovoltaic energies are intermittent and volatile in nature which makes the system impractical. In this article, optimization sizing strategy are developed and analyze, based on various cost factors and longterm energy production. Finally, HOMER tool is utilized for feasibility and techno-economic evaluations. The simulations results indicate that the Hydrokinetic, Photovoltaic and Wind based hybrid energy system is economically and technically feasible. Moreover, this hybrid system is suitable to achieve 100% energy autonomy in remote communities or standalone applications.

Keywords: Off-grid, Hydrokinetic, Photovoltaic, Wind, Standalone, Power generation, Economic

INTRODUCTION

World population is growing rapidly and therefore the energy demand which is estimated at 2.6% per annum, as an increasingly greater number of peoples are adopting modern lifestyles. Moreover, urbanization has also had an effect on electricity consumption. Many countries like Pakistan are facing energy shortage and price fluctuations. There is not regularly grid connected to the rural areas and number of these areas still remain without electricity (Kamran *et al.,* 2018). Furthermore, grid extension requires huge capital investment, have significant transmission and distribution losses and time-consuming process because these areas located far away from urban life in remote regions. To empower economic developments in these areas, some type of electricity production is needed. While considering this rural system, it is important to design an electricity model which is reliable and requires minimum maintenance as in these areas repairs and replacements would not be simple easy.

With respect to the above demanding and challenging problems, Renewable energy resources (RES) are capturing attention due to its numerous advantages such as environment benefits, free from dependency on oil and omnipresence. But on the other hand, RESs are volatile and depends on nature. So, utilization of single source is not possible to compete the energy demand as photovoltaic energy is available in daytime, but no electricity is generated in night. Similarly, wind energy is not considerable largely available in summer seasons. Therefore, neither wind turbines, nor photovoltaic can supply un-interrupted electricity due to above stated issues. Consequently, for decentralized / standalone system, more than one renewable energy sources are utilized for electricity generation which splits this demand in various energy sources and decreases dependence on intermittent nature source and reduces overall system size. Moreover, storage devices are utilized to store excess amount of energy which makes the system more stable and reliable.

In the literature (Giday, 2014), techno-economic evaluation of hybrid system for rural educational institute is conducted and compares the PV / diesel system with diesel system. But in this study authors considers hypothetical data and only 24 hours simulations were utilized for the analysis. Similarly, In Kenya off-grid system (Wind / diesel generator/Batteries) was analyzed by authors in (Lau *et al.*, 2010) for rural electrification by using HOMER software. Photovoltaic / Wind / diesel-generator / Batteries based system for rural areas are compared with standalone diesel-based system in (Rohani and Nour, 2014). In (Diaz *et al.,* 2010), off-grid configurations (hydro / diesel or diesel alone or PV / diesel) are analyzed for the electrification of remote villages. Hydro / Wind / PV / diesel generator / battery based numerous configurations are analyzed in Cameroon using HOMER software in (Muh and Tabet, 2019; Saheli *et al.*, 2019).

But in this study, authors did not discuss about system reliability and load growth. In (Hafez and Bhattacharya, 2012), authors analyzed the hybrid system (PV / Wind / hydro) but they used hypothetical load demand and they utilized diesel generators which caused environmental issues. For rural electrification in Ethiopia, authors try hybrid model based on PV / Wind / Battery in (Bajracharya, 2015). Similar study was performed for islands in china in (Ma *et al.,* 2014). Technical and economic study of PV / Wind / Hydro / Battery for rural areas in India are performed by authors in (Amutha and Rajini, 2016). In (Hafez and Bhattacharya, 2012), sizing strategy was considered for the renewable hybrid system. Similarly, PV / Wind / Hydro based system is analyzed for rural areas in Ethiopia by the authors of (Bekele and Tadesse, 2012). Various researchers conducted similar studies like case of Bangladesh, Cameroon and Algerian are presented in (Nandi and Ghosh, 2010); (Nfah *et al.*, 2008) and (Fodhil *et al.*, 2019) respectively; case of Ethiopian village is discussed in (and Tadesse, 2010).

It is obvious that different research is conducted on various types of hybrid system, but least attention is given to the hydrokinetic system. Data related to RES and load demand are very important to design an optimized system, but it was observed that, majority of researchers considered an estimated data for their research work. Here, an off-grid or decentralized hybrid system based on hydrokinetic along other renewable energy resources is discussed with carefully collection of real time data from various concern departments. An optimal combination of renewable energy sources based decentralized/off-grid electrification for the objective function that is to increase reliability, minimize the cost of energy, environmental impact and electricity availability is considered. Therefore, a model based on renewable energy is developed, and economical/technical feasibility is considered and analyzed.

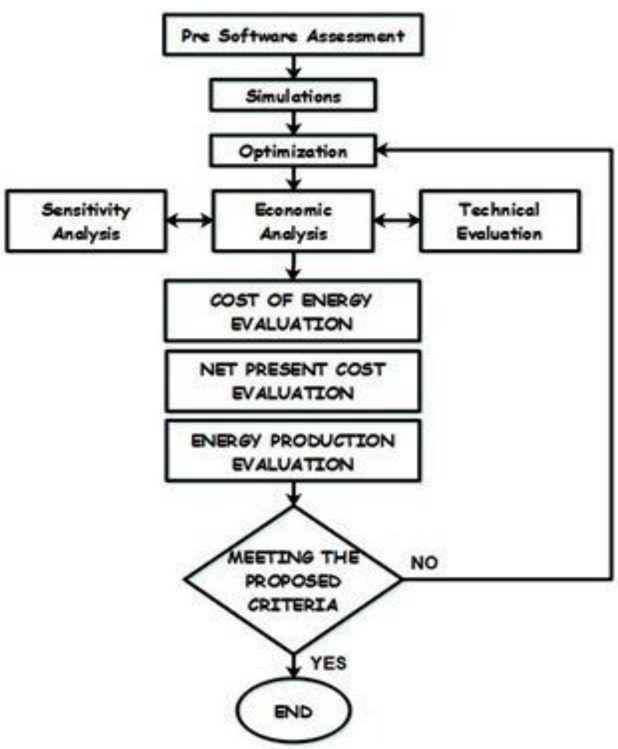

Figure 1: Simplified block picture of proposed energy system.

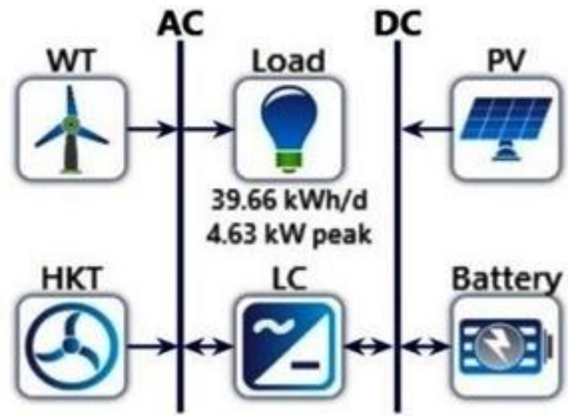

Figure 2: Flow diagram of the system for analysis.

MATERIALS AND METHODS

In this analysis, hydrokinetic, photovoltaic and wind based renewable hybrid system is considered for electricity supply. This system is based on sources that are easily available in these regions. Fig. 1 illustrates the simplified block diagram of proposed typical hybrid system. It has two types of AC and DC buses in which hydrokinetic and wind turbine along electrical load are attached to the AC bus. similarly, solar-panels and batteries are attached to the DC-bus. After that by utilizing bi-directional-converters both buses are attached to each other. This analysis or study is investigated on Homer software for optimal sizing and optimization. Fig. 2, presents the detail steps taken for entire analysis.

Study Site: Urban areas utilized more electricity than rural areas because load demand is directly proportional to the population density. For this research purpose as a case study, Punjab has been selected; as in these areas renewable energy resources are mostly available and have extensive canal system. This project targeted to the residential, irrigation and small industrial users.

This section reveals the various input variables, that are required for the software or simulation of standalone/decentralized hybrid system. The potential of each generation unit is considered with precise to the island's energy demands.

Wind speed time series assessment: Wind energy potentials are assessed from the wind resources. In this article, "Energy Sector Management Assistance Program" (ESMAP) administrated by "The World Bank" is utilized for the assessment of wind resources that is wind speed, located at longitude 71.819° E, latitude 29.325° N. This data was measured since May-2016 to April-2017 with the interim of 10 minutes. The average monthly wind-speed at study location is given in Table. 1 and 6.24 m/s annually average was calculated.

Table 1: Monthly average of available renewable energy resources

Renewable Energy sources	January	February	March	April	May	June	July	August	September	October	November	December
Wind-speed m/s	5.23	5.662	7.115	7.560	7.537	7.411	6.760	6.099	6.346	5.996	4.518	4.601
Solar irradiations kWh/ m^2/day	2.96	4.664	5.632	6.724	6.927	6.819	6.391	5.545	6.193	5.100	3.819	3.172
Clearness index	0.29	0.449	0.536	0.659	0.717	0.733	0.678	0.559	0.599	0.492	0.380	0.320

Solar irradiation time series assessment: It is essential for sizing an effective photovoltaic system to assess a reliable solar irra diation. At study site, these irradiations were recorded with the interim of 10 minutes since May 2016 to April 2017 from ESMAP located at longitude 71.819° E, latitude 29.325° N. The monthly average variations of solar irradiations are presented in Table. 1 and 5.33 $kWh/m^2/day$ annually average was calculated. Clearness index indicated the solar irradiation fraction that reaches to the earth surface. This various from 0.29 to 0.73 as mention in Table. 1.

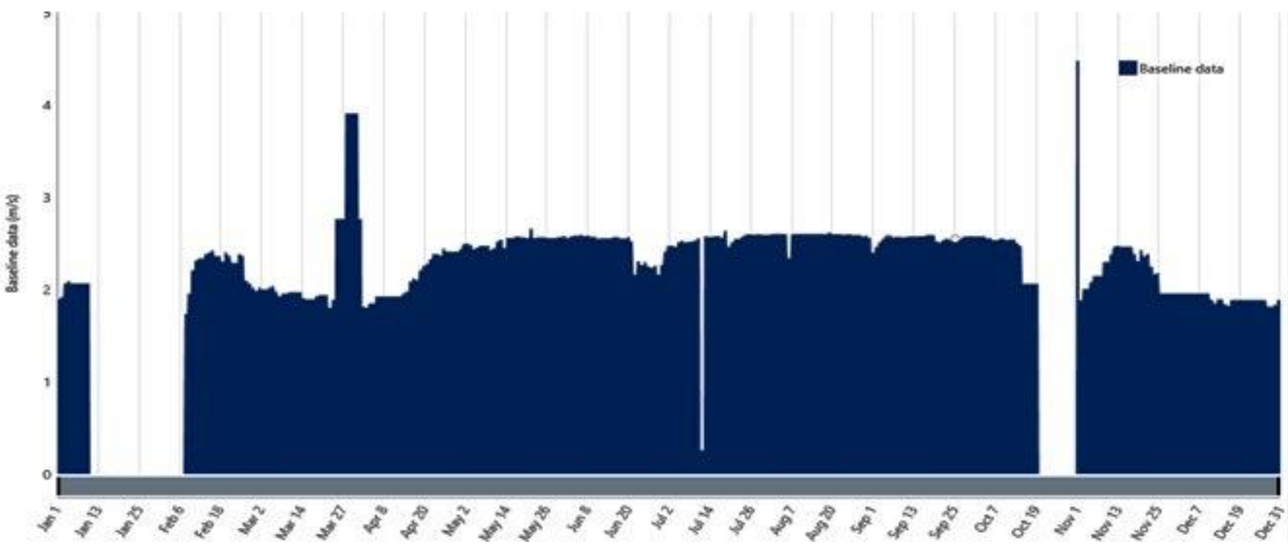

Figure 3: Annually water flow rate through SMB. Time (Days) VS Velocity (m/s)

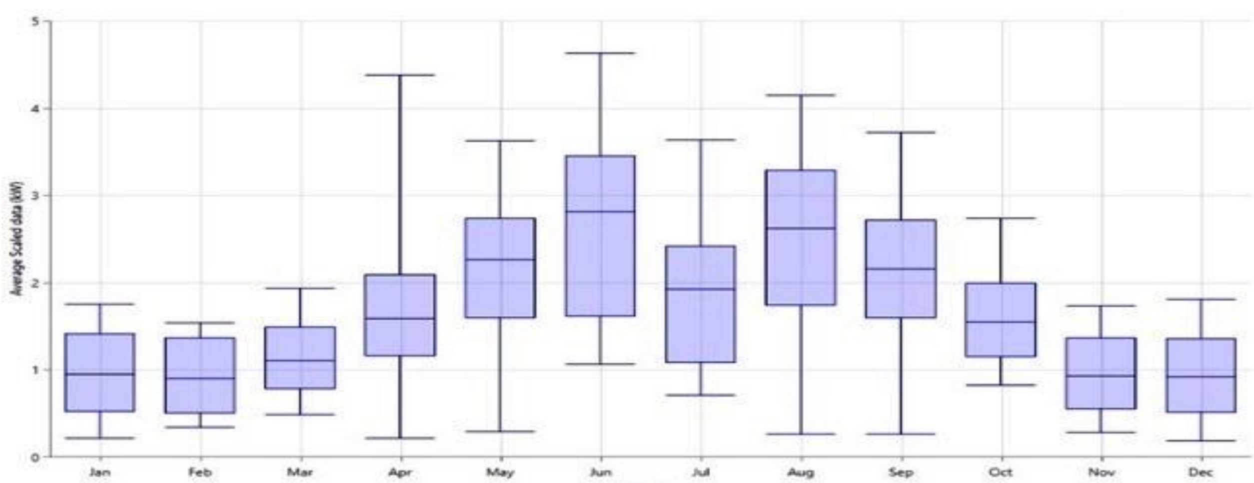

Figure 4: Monthly electric load demand.

Hydro-metric data time series assessment: "Sidhnai Mailsi-Bhawal (SMB) link canal", off-taking from a Ravi River and irrigates around twenty million acres of agricultural land. An hourly discharge through SMB is gotten from Irrigation department over a period of one year. Then, this discharge is converted into current by

Load demand time series assessment: "Multan electric power company (MEPCO)" Ltd. was set up in 1998 which is a electrical distribution company that distributed electricity up to 13 districts of Province and to approximately 34 million peoples. To make this study more precise, real time rural feeder's data with quarter-hour interim is obtained and scaled it down to the level of village electric load demand. Fig. 4, presents the monthly average electric load demand and the daily average of 39.7 kWh with peak of 4.63 kWh is obtained in June.

Mathematical modeling and selected components characteristics of proposed system are exhibits in this section.

Wind turbines modeling: A wind turbine from the manufacturer named "Australian wind and solar Ltd. (model: AWS-HC 1.5kW)" is employed in this study. Table. 2, presents technical characteristics of turbine. Capital cost of the wind turbine is taken as $3600. The overall performance and availability losses are taken as 5.86% with lifespan of twenty years are considered. Following equation demonstrate the total power generated from wind turbines:

$$P_{WT} = \frac{1}{2}\,.A.\eta.\rho_a.C_p \int_{t_0}^{t} f(t).v^3(t)dt \qquad (3)$$

where: ρ, A represents efficiency and swept area, ρ_a, C_p represents air density and performance coefficient, f(t), v represents the density function and wind velocity respectively.

Photovoltaic panels modeling: The photovoltaic panels from the manufacturer named "Canadian Solar Ltd. (model: CS6U-330P)" is employed in this analysis. These panels are set to be confronting at fixed direction toward south. Moreover, effect of temperature on these photovoltaic panels are considered. The derating and reflectance are set to be 88% and 20% respectively. Table. 2, illustrates the technical specifications of photovoltaic panels and output electrical power from these panels are determined from this mathematical relation:

$$P_{PV} = P_{rated} f_{PV}\left(\frac{I_T}{I_S}\right)\left[\,1+\alpha_p(T_C - T_s)\right] \qquad (4)$$

Here: I_T, α_p represents the cell temperature and temperature coefficient. I is the solar incident, f_{PV}, P_{rated} represents derating factor and rated capacity of photovoltaic panels respectively.

Hydrokinetic system modeling: The hydrokinetic turbine from the manufacturer named "SMART Hydro Power GmbH Ltd. (model: SMART-Monofloat kinetic

utilizing the below stated relations and this velocity is given in Fig 3.

$$V = \frac{Q}{A} \qquad (1) \qquad A = Z.D^2 + B.D \qquad (2)$$

where: Q, B are the discharge and bed-width, D, Z represents the water depth and side slop of canal.

5KW)" is employed in this study. This turbine particularly design for the production through canals or rivers. Its required minimal breadth of canal or water depth to be a 2m. Capital / Replacement cost of this turbine is estimated to be $11039 with a lifespan of twenty Years is taken into consideration and following equation is utilized for power generation:

$$E_{HKS} = \frac{1}{2}\,.A.v^3.\eta.\rho_w.C_p.t \qquad (5)$$

where: ρ_w, A, η represents velocity, area and efficiency of the turbine respectively. t, C_p, v represents operation time, performance coefficient of turbine and water density (1000kg/m^3) respectively.

Table 2: System Components Specification.

Hydrokinetic Turbine			
Lifetime	20	Cut In speed	1
Rated Capacity	5	Cut Out speed	4
Wind Turbine			
Rated capacity	5.1	Curt in speed	2.7
Peak power	5.7	Cut Out speed	12
Output Voltage	48LV	Lifetime	20
Batteries			
Nominal voltage	2.0	Min-SOC	30 %
Nominal capacity	7.15 kWh	Lifetime throughput	10,196 kWh
Float lifetime	20		
Photovoltaic Panels			
Type	Poly-crystalline	Operating temperature	45±2°C
SC current	9.45	Open circuit Voltage	45.6
OO-temperature	37.2	OO-current	8.88
Max-Power at STC	0.33		

where: speed mention in "m/s", lifetime in "years", power in "kW", current in "A" and voltage in "V". SC represents the short circuit and OO represents the optimal operating.

Converters and inverters modeling: Power converters are utilized to keep power flow between various busses. The optimum capacity is taken so that it allows power supplies, even though in peak demand. 48V DC having 5kW capacity of converters is employed in this study, which has Capital/Replacement price of $560 per kW, 96% efficiency and fifteen years lifespan are taken into consideration as per company warranty.

Battery bank modeling: Battery banks are used to compete the energy demand whenever limited electricity generation is available due to various factors such as non-availability of renewable resources. Along with this, these battery banks are incorporates to store surplus electricity and supply during increase in the load demand. Here, "Hoppecke OPzS 3000" battery model is employed, it has the capacity to supply 3000A and 2V cell voltage. Capital/Replacement cost of $1644/kWh is considered with twenty Years of lifespan. Table. 2, represents the technical specifications of this battery. Total Energy supply and state-of-charge of batteries can be calculated from these relations:

$$B_{SOC} = \frac{Q_{bat}}{Q_{bat,max}} \quad (6)$$

$$E_{bat} = Q_{bat,o} + \int_0^t V_{bat}\, I_{bat} dt \quad (7)$$

where: Q, V, I represents the charging, voltages and current that is drawn from the batteries respectively

Sensitivity of inputs: The main problem with renewable hybrid energy systems is that it might be normally unsure. Here in this study, the uncertainties of RES (Wind, Solar, hydro) are considered. The sensitivity of 25 and 26°C for temperature, 5.33 and 5.13 $kWh/m^2/day$ for solar irradiations, 2.09 and 2m/s of water flowrate are taken into account for simulations.

Economical aspects: The lifespan of this research project is taken as Thirty Years, with the inflation rate of 1.9% and discount rate of 10%.

Systems Performance metric and Definitions: The main findings discussed in this study are based on life cycle or Levelized cost-of-energy (LCOE) and Net-present-cost (NPC). NPC is the cost that is experience for project's lifespan, minus all revenue earns over its lifespan. Following equations are used for these calculations:

$$C_{NPC} = C_{ann} \Big/ \left(\frac{i(1+i)^n}{(1+i)^n - 1}\right) \quad (8)$$

where: C_{ann}, i, n are the annual cost, interest rate and project lifetime respectively. Cost-of-energy (COE) per kWh can be calculated from following relation:

$$COE = \frac{C_{cap} + C_{rep} + C_{OM}}{E_s} \quad (9)$$

where: Q, V, I represents the served energy and various types of cost associated with the project receptively.

RESULTS AND DISCUSSION

In his section, simulations result of research and investigations are presented in detail. Firstly, the optimum results, followed by electricity output is described. Then, financial or economical, sensitivity and environmental characteristics are presented in detail.

Optimization results: Multiple combinations of renewable hybrid electric power system are attempts with hydrokinetic turbines, photovoltaic panels, wind turbine, battery banks and converters. Various feasible and conceivable combinations were procured in this analysis. These optimization results are categorized and illustrated in Table. 3. Ranked # 1 system is the predominantly considered as most optimized hybrid energy system that can supply electricity with least cost. This system consists of photovoltaic panels, wind turbine and hydrokinetic turbines with battery reinforcement. It has $38,393 NPC, $0.234/kWh COE and composed of 100 % renewable resources and have no greenhouse-gases emissions. It consists of one unit of hydrokinetic turbine, one-unit wind turbine, four units of batteries, 9kW photovoltaic panels and 5kW converter. Components based cash flow details of most optimized system is presented in Fig. 5. The considerably greater portion of capital cost accounted for hydrokinetic system i.e. 36.9% which can produce 51.7% energy needs of total serve energy. Adversely, photovoltaic panels have 19.6% of capital cost.

Electrical results: This study reveals that 51.7% (17,392 kWh/year) energy is produces from hydrokinetic system, 41.1% (13,840 kWh/year) energy is produce from photovoltaic panels and 7.17% (2.413 kWh/year) energy is produces from wind turbines. Monthly average production of each individual generation unit is presented in Fig. 6. It can be noticed that largest portion of energy production corresponding to hydrokinetic system. Meanwhile, least production is corresponding to the wind energy system. This least fraction owing to the highest capital cost associated to wind turbine and limited wind energy resources. Fig. 7, presents the daily electricity production of each energy source. However, the most optimized hybrid system generates 42.2 % excess-electricity. Along with this, very less amount of 0.012% (4.13 kW/year) electricity is unmet throughout the year. This capability of system reveals that it has capacity to supply electricity to nearby villages, which will decrease the overall cost-of-energy.

Table 3: Hybrid System optimization results.

Rank	Architecture					Cost			System	
	PV (kW)	WT (Unit)	Battery (Unit)	HKT (Unit)	LC (kW)	COE ($)	NPC ($)	Initial capital ($)	EE (kWh/yr)	UL (kWh/yr)
1	9	1	4	1	5	0.234	38,393.98	29,691.87	16,729.76	4.14
2	9.33	1	4	1	5	0.236	38,726.49	29,899.22	16,748.53	4.18
3	15	0	5	1	5	0.257	42,046.00	31,506.00	23,394.00	10.90
4	15.6	0	5	1	5	0.260	37,076.00	31,789.00	25,648.00	11.00
5	20	1	13	0	5	0.332	54,370.00	40,361.00	17,099.00	6.38
6	21	0	14	0	5	0.333	54,494.00	39,063.00	15,973.00	7.53
7	21.2	0	14	0	5	0.334	54,661.00	39,168.00	16,040.00	7.35
8	21.3	2	11	0	5	0.337	55,110.00	41,084.000	21,570.000	5.65
9	19.9	2	12	0	5	0.338	55,413.00	41,825.00	18,530.00	5.79
10	22	0	14	0	5	0.339	55,459.00	39,670.00	16,117.00	7.20
11	20	2	12	0	5	0.339	55,561.00	41,917.000	18,555.000	5.75
12	0	6	8	1	5	0.340	55,629.00	46,591.00	15,056.000	9.04
13	0	14	18	0	5	0.560	91,669.000	77,592.00	18,440.00	3.54
14	0	10	90	0	5	1.310	214,781.00	183,160.00	8,601.00	0.00

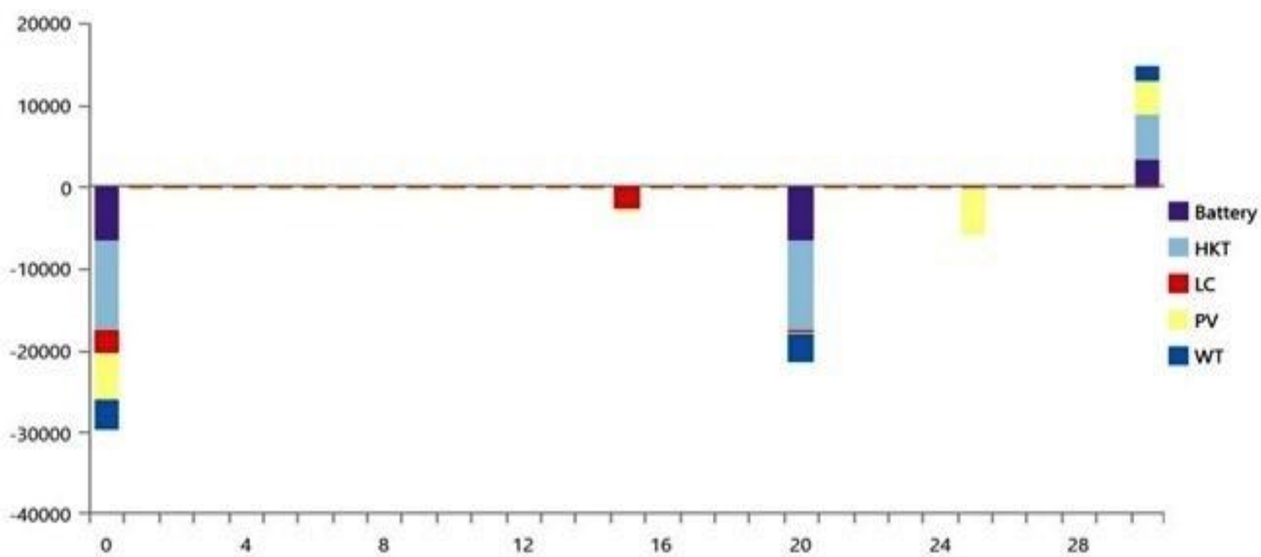

Figure 5: Annual cash flow by components.

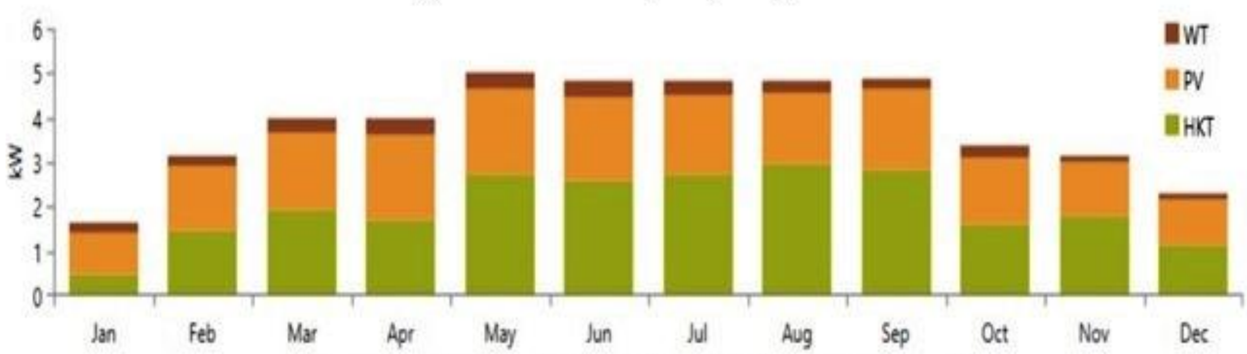

Figure 6: Average power generation of various generation units

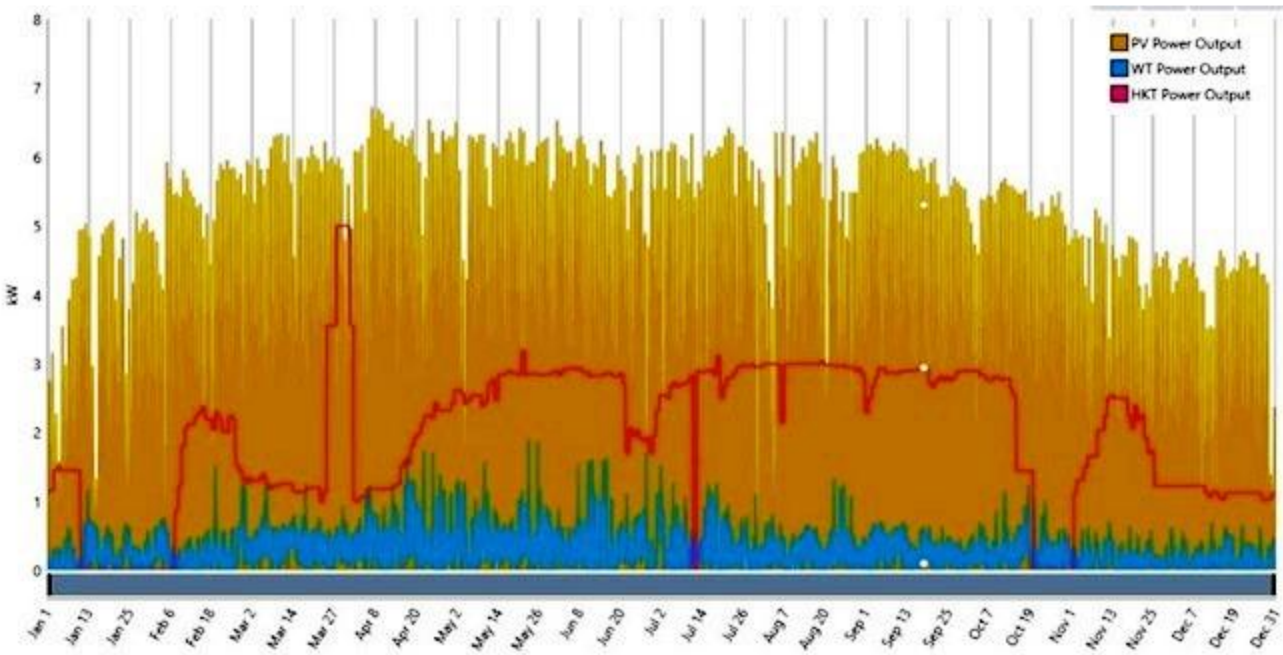

Figure 7: Electrical profile of the system in term of generation

Sensitivity results: Sensitivity analysis can remove each unfeasible combination of hybrid system and sorts all found systems by considering the parameters vulnerability and ranked them based upon NPC. Moreover, the effect of variations in wind speed, solar irradiation, water flowrate and temperature on COE is considered and analyzed. For all these variations, renewable hybrid energy system evaluated to find and investigate the most appropriate hybrid combination that compete the electrical load demand in reliable means.

Conclusion: Hydrokinetic systems are gaining attentions as a cost-effective power generation source. However, the seasonal/environmental aspects prevent these systems from being entirely independent or reliable. Thus, hydrokinetic system with other renewable energy resources are analyzed to meet the load demands. A hybrid energy model consists of Hydrokinetic/Photovoltaic/Wind systems is suggested and investigated based on lowest COE and NPC. Simulation results disclose that greater part of energy is generated from hydrokinetic system with makes this system much cheaper. Wind and photovoltaic panels contribute 7.17% and 41.1% respectively. The LCOE for optimized HRES is calculated as \$0.234/kWh with NPC of \$38,393. Moreover, this system produces 42.2% excess electricity with very least 0.012% unmet electricity. These optimization results reveal that this proposed HRES is reliable, environment friendly and cost-effective solution to achieve 100% energy autonomy in remote location/communities or for remote applications. In future, different energy storage devices like pumped storage system can be utilized to attain more effective results.

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