IOP Conference Series: Materials Science and Engineering

PAPER • **OPEN ACCESS**

Techno-Economic Analysis of Energy Systems in Thakle Namuna Basti - A Case Study

To cite this article: Malesh Shah *et al* 2023 *IOP Conf. Ser.: Mater. Sci. Eng.* **1279** 012007

Techno-Economic Analysis of Energy Systems in Thakle Namuna Basti - A Case Study

Malesh Shah[1*], Kshitiz Koirala[1], Saugat Upreti[1] and Nawaraj Sanjel[1]
[1]Kathmandu University, Dhulikhel, Nepal
*Corresponding author: malesh.shah@ku.edu.np

Abstract. The electrical supply system in most underdeveloped nations is incredibly undependable. The country's existing distribution system has experienced regular power outages due to population growth, industrial expansion, rough terrain, and a long-distance transmission network. The conventional approach to centralized generation and transmission is failing to address this challenge and as a response, the utilization of renewable energy sources is expanding day by day to alleviate the energy crisis. The purpose of this study is to perform a techno-economic analysis of a 100% renewable off-grid and on-grid hybrid energy system for the electrification of Thakle Namuna Basti, a small communal village in Melamchi, Sindhupalchwok. The HOMER Pro 3.14 program is used to analyze the feasibility of the suggested hybrid power system. The available resources are provided as an input parameter along with load data and HOMER Pro optimizes the list of system architecture for that specific site. In addition, sensitivity analysis is performed for the proposed HES (Hybrid Energy System). The main outcome of the project is to find out the best system architecture based on various economic parameters such as NPC (Net Present Cost), LCOE (Levelized cost of electricity) and Operating and Maintenance Cost. The system having lowest NPC and LCOE makes the best system architecture.

Keywords: Net Present Cost, Levelized Cost of Electricity, Department of Urban Development and Building Construction, HOMER Pro, Internal Rate of Return

1. Introduction

Energy is a critical component of a developing country's rural socio-economic development. To achieve economic growth, poverty eradication, employment creation, and village livelihood improvement, rural electrification is crucial [1]. At present, developing countries lack grid-connected electricity. Grid extension is impractical due to dispersed populations and rugged terrain. Thus, as a result, small off-grid standalone renewable energy systems are a viable option for ending the electricity gap in rural areas of developing countries, where grid extension is lagging behind population growth. Even though these small-scale energy systems generate relatively little electricity, they can make a significant contribution to life quality and human sustainability by improving net energy production, public health and education for rural households in developing countries [2].

Due to advancements in technology, enabling regulatory frameworks in solar home systems and successful off-grid electrification projects have been established in numerous nations utilizing technologies such as mini-grids and solar household systems. Additionally, the growing need to reduce carbon emissions from fossil fuel-based networks, the rising cost of grid expansion, the declining cost of renewable energy alternatives while improving performance and the inaccessibility of various settlements all favored the distributed generation approach [3]. Hence the solution for this situation could be to promote alternative forms of clean and eco-friendly energy generation, such as solar, wind, hydro, biogas, biomass, tidal, wave, ocean thermal energy, etc. [4].

In the developed world, mini-grids are used to increase energy security, power quality and stability as well as to avoid blackouts during natural disasters. Reduce the loss of energy during transmission and distribution. However, in developing countries, mini- grids are used to increase energy access for isolated rural and island populations. Island settlements, whether developed or developing also use the concept of mini-grids [3].

The most common approaches to decentralized electrification are stand-alone with local generation, a pure extension of the central grid and hybrid solutions. Depending on the technical and financial feasibility, one of the models can be used; however, until now, in most of the cases solutions have been limited to either a pure extension of the central power grid or a stand-alone micro grid. The primary advantage of hybrid systems is that when a variety of energy sources are combined, the system's reliability improves. Additionally, there are cost reductions associated with renewable energy technologies as a result of R&D, and increased deployment makes them more appealing to investors [5].

Global gross electricity production increased by 3.9 percent in 2018 over 2017. Since 1974, except in 2008 and 2009, global electricity production has increased at an annual rate of 3% [6]. Similarly, in Nepal's fiscal year 2019/20, a total of 3021 GWh of electricity is generated, an increase of 18.57 percent over the 2548 GWh generated in FY 2018/19. However, insufficient production means that 1,729 GWh of electricity is imported from India in 2019/20. The majority of electricity is generated by hydropower plants while 53.41 MW is generated by thermal power plants and 1.350 MW is generated by solar power plants [7]. Enhancements to the industrial and service sectors electricity supply can contribute to increased economic growth. Growth in the electricity sector is expected to continue, owing to rapid urbanization and an increase in the number of energy-intensive industries. Electricity demand is expected to increase from 10,138 GWh in 2019 – 2020 to 31,196 GWh in 2029 – 2030 [8].

Exploring renewable energy sources eliminates the need for electricity transmission to remote rural areas, raises living standards and promotes a clean environment. These non-traditional or renewable energy sources can meet demand and, in some cases, exceed it without posing environmental risks. As a result, this option is more suitable for addressing the issue of rural energy requirements, as these sources are abundant in rural areas. This decentralized energy generation will contribute to resolving the rural electrification crisis. The combustion of wood and agricultural waste for heating and cooking is inefficient and contributes to pollution through the production of gases such as CO2 [9]. To devise an effective solution to this problem, a thorough assessment of the current state of affairs must be made. The plan that will be developed will depend on how the village's existing resources are utilized and how they can be converted into useful and clean forms of energy for village households.

The disadvantages of wind and solar energy are their unpredictability and reliance on weather and climate change. Additionally, wind and solar energy variations may not correspond to the time distribution of electricity demand. In such cases, decentralized renewable hybrid power can provide viable alternatives, wind/photovoltaic/battery, wind/battery photovoltaic/battery, and other solutions without a battery backup option [10]. Each renewable energy system must undergo a techno-economic analysis to determine its efficiency and economic viability. The analysis is complicated by the fact that it involves a large number of generating systems. Additionally, the optimal design capacity of energy facilities is highly dependent on electric demand and the extent to which renewable energy is consumed, both of which are difficult to forecast in advance. To avoid excessive energy consumption, design capacity must be calculated in conjunction with operation planning, which is based on anticipated energy demand and production. Any additional energy generated as a result of inefficient capacity planning and operation is almost certainly wasted [11]. The HOMER Pro program could easily be used to simulate and determine the optimal component arrangement for the case study. We investigated off-grid and grid-connected systems with and without battery storage. The financial and environmental implications of several cases are then discussed, including the COE (Cost of Electricity), NPV (Net Present Value), IRR (Internal Rate of Return), renewable fraction, CO_2 emissions, etc.

2. Study Area

The study area is Thakle Namuna Basti which lies around 5 to 6 km away from Bahunepati, Melamchi and is located in Melamchi Municipality of Sindhupalchwok District with longitude and latitude of 27 48’14” N 85 32’49” E. There are around 130 people in that community and the total number of houses is 32. Each house is identical as it was, built by the DUDBC (Department of Urban Development and Building Construction) under the National Reconstruction Authority and supported by Oxfam Nepal. The primary source of income and livelihood is agriculture whereas youth work as drivers, technicians and so on. The majority of people belong to Tamang tribes. The village makes use of both traditional and modern energy sources. The traditional energy sources are fuelwood and crop residue etc. for cooking. Electricity is used for lighting and few people use LPG for cooking purposes. Most of the family members especially women spend a considerable amount of time collecting fuelwood. Most of the electricity is consumed for lighting though some people even use television, induction stove, water boiler, etc. The figure 1 shows the google view of Thakle Namuna Basti [12].

Figure 1. Thakle Namuna Basti from google maps

3. Load Profile of the Study Area

A survey was conducted to find the load of the study area. Customer’s electricity bills were used to find the monthly load which was compared with load demand to get an idea of exact load demand of that place [13]. Studies have revealed that a large proportion of the variability in electricity demand is dependent on weather variables such as air temperature, humidity, wind speed, cloud cover, and luminosity [14]. So, to find the variability on the load profile the result of the survey, considering the appliances that are used and their operating hours and even the load profile of the country were taken in reference. Figure 2 shows the monthly load profile of Thakle Namuna Basti given by Homer Pro.

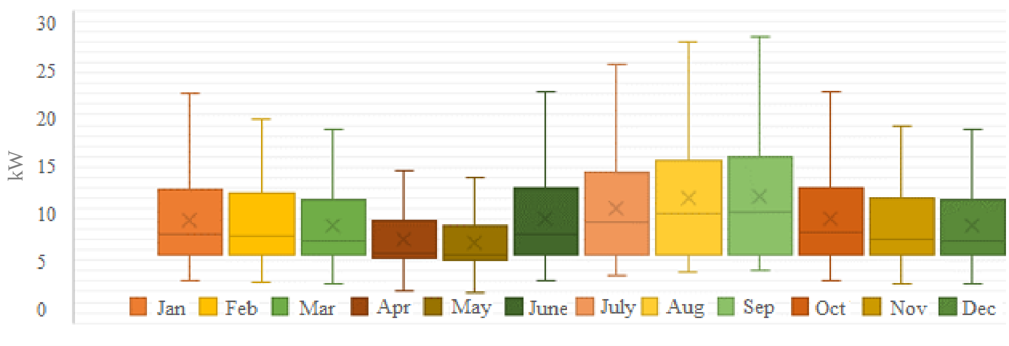


Figure 2. Monthly load profile of Thakle Namuna Basti

4. Resources Available

After the field visit, data is collected from different sources and studied. The potential of available renewable energy resources such as solar energy, wind energy, and hydropower were considered.

4.1. Solar Potential

For solar radiation, National Renewable Energy Lab Database [15] is used. It was found out that the average solar radiation in the selected area is 4.97 kWh/m^2/day similar data from the Meteonorm. Data from Meteonorm is also taken and after comparative study, National Renewable Energy Lab data is used as there is not much difference in average monthly irradiance. The curve in figure 3 shows the monthly average solar global horizontal irradiance and the bar graph in figure 3 shows daily radiation of the study area of every month.

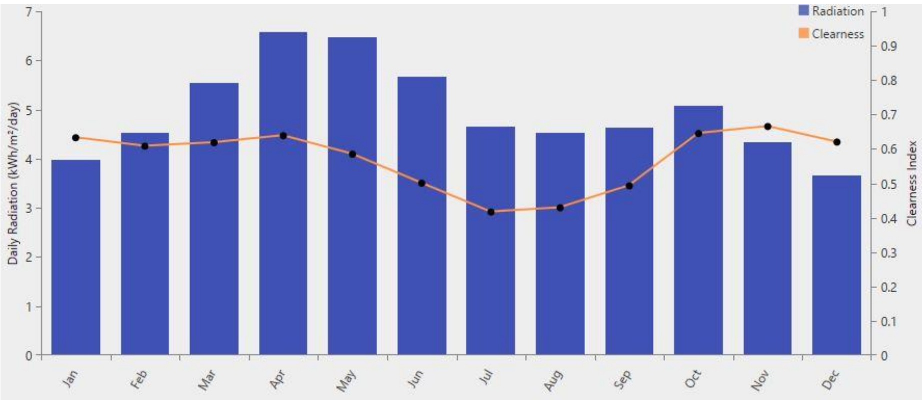


Figure 3. Daily Radiation along with Monthly average solar data

4.2. Wind Potential

For wind resources, HOMER Pro estimate data from NASA Surface meteorology and solar energy database [15] is used which gave the monthly average wind speed at 50 meters above the surface of the earth over 10 years' time period (July 1983 – June 1993). The figure 4 shows the average monthly wind speed of every month for 10 years from the HOMER Pro Database.

Figure 4. Monthly average wind speed data

4.3. Temperature Variation

The temperature data file from the Meteonorm is imported into HOMER Pro. The below figure shows the temperature of Thakle Namuna Basti in each month for a year. The lowest average monthly temperature is 9.9 °C in January and the highest average monthly temperature is 23.8 °C in June, July, and Aug and the average annual temperature is 18 °C.

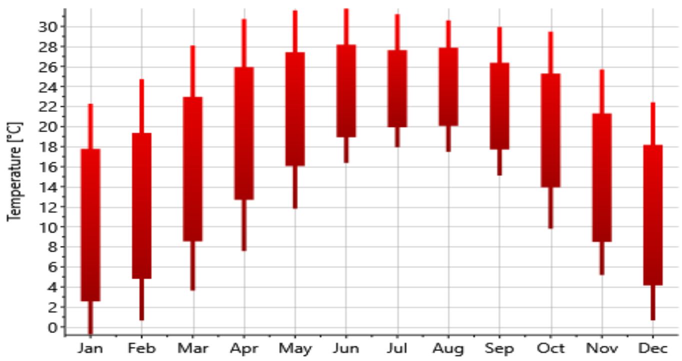


Figure 5. Monthly average temperature variation data

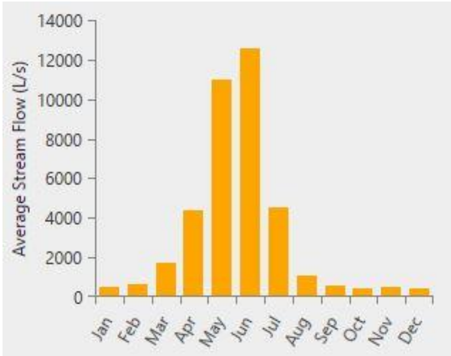


Figure 6. Monthly average flow rate of Sindhu River

4.4. Nearby Hydro Resource

The hydro resource that is available in the study area is the Sindhu River. For calculating the power, the flow rate and head of the river is required.

$$P = \rho \, Q \, g \, H$$

Where,

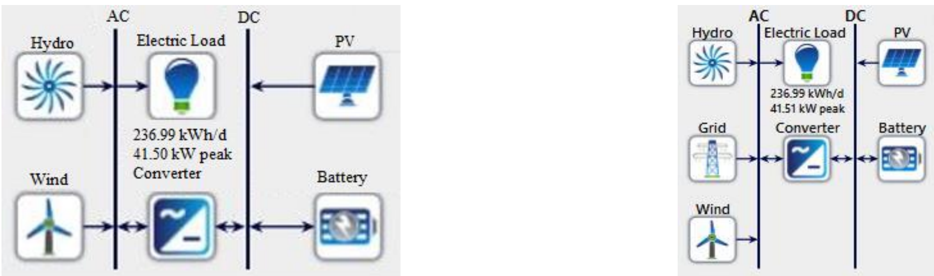
ρ = Density of water
Q = Flow rate of water
g = Acceleration due to gravity
H = Head from turbine to reservoir

To find the flow rate Stream- flow Prediction Tool which is provided by ICIMOD [16] is used which gave an estimated flow rate of the river in time series.

5. System Components

5.1. Proposed system architecture in HOMER Pro

Two system architecture were used for analysis. One with grid and another without grid. Figure 7 (a) shows the system architecture for off grid system and figure 7 (b) shows system architecture for an on-grid system.



(a) (b)

Figure 7.(a) System architecture (Off grid system) Figure **7.**(b) System architecture (On-grid system)

5.2. Wind Turbine

A generic wind turbine model is considered for this study. Its nominal power is 10 kW at 13 m/s. The technical specifications of the turbine are presented in the table 1, while its power curve is also shown in the figure 6 which shows the variation of the output power to the wind speed where the output is maximum at a rated speed of 13m/s [17].

Table 1. Specification of Wind Turbine

Items	Specification
Model	Generic 10 kW
Manufacture	Generic
Rated Capacity	10 KW @13 m/s
Hub Height	24 m
Output type	AC
Life Time	20 Years
Cut-in Wind Speed	3 m/s
Max. Design Wind Speed	60 m/s

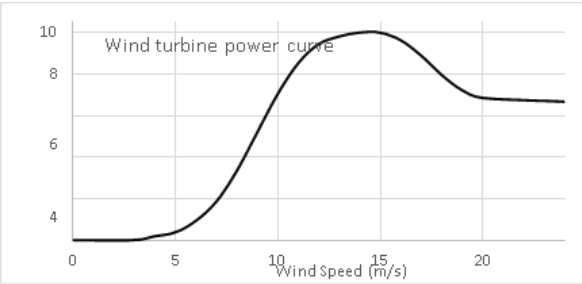


Figure 8. Wind turbine power curve

5.3. Photovoltaic Arrays

1 kW Generic flat-plate PV is selected for this project. A dedicated inverter technical specification for this type of PV array is presented in Table 2. Considering the market for renewable energy sources in Nepal, the installation, replacement, and maintenance costs for a 1 kW solar energy system are estimated to be $1100, $1100, and $10 per year respectively [18].

Table 2. Specifications of PV Arrays

Parameter	Value
Rated Capacity	1 KW
Derating Factor	80%
Nominal operating cell temperature	47.5 C
Ground reflectance	20%
Lifetime	25 years

5.4. Battery

EnerSys PowerSafe SBS 1200 is selected for the study. The cost for the battery is considered $646.10 and the replacement cost is $646.10. The operation and maintenance cost of the battery is considered as $5 per year with a life span of 15 years [19].

Table 3. Specification of Battery

Items	Specification
Model Name	EnerSys PowerSafe SBS 1200
Manufacturer	EnerSys
Type	Lead Acid Battery
Model	Kinetic
Capacity(kWh)	16.68
Duration (hours)	0.6
Max charge current (A)	1.20E+03
Max discharge current(A)	2.30E+03
Capacity Ratio	0.297
Roundtrip efficiency (%)	97

5.5. Converter
A power electronic converter is required for maintaining the energy flow between the AC and DC buses. Installation and replacement costs for a 1 kW converter system were estimated to be $300 in both cases. The lifetime of a unit was estimated to be 15 years with an efficiency of 95 % [19].

6. Results for On-Grid System

6.1. Sensitivity Analysis
Table 4 shows the list of sensitivity variables that are used during this simulation. Total four sensitivity variables were taken which were Power price, Sellback rate, Hydropower cost and Hydro flow rate.

Table 4. List of sensitivity variables for on-grid system

Power Price($/kWh)	Sellback Rate($/kWh)	Hydropower Cost($/kWh)	Hydro flow rate(L/s)
0.14	0.04	15000	50
0.15	0.05	18000	75
0.16	0.06	20000	100
	0.07	22000	
		25000	

Initial condition:
Power Price - 0.14 $ Hydro Capital Cost – 15000 $
Hydro Flow rate – 75 L/s Sellback Rate - 0.04 $
The table 5 shows the results of the base case and lowest case system while changing the power price at the initial condition.

Table 5. Sensitivity analysis when power price is varied in on-grid system

Power Price($/kWh)	Parameters	Base Case System	Lowest Case System
0.14	NPC	$76,591	$70,507
	Operating Cost	$4764/yr	$2,909/yr
	LCOE	$0.0623/kWh	$0.0588/kWh
0.15	NPC	$80,384	$71,829
	Operating Cost	$5,058/yr	$2,981/yr
	LCOE	$0.0654/kWh	$0.598/kWh
0.16	NPC	$84,176	$72,922
	Operating Cost	$5,351/yr	$2,419/yr
	LCOE	$0.0685/kWh	$0.0588/kWh

Table 6. Sensitivity analysis when sellback rate is varied in on-grid system

Sellback Rate($/kWh)	Parameters	Base Case System	Lowest Case System
0.04	NPC	$76,591	$70,507
	Operating Cost	$4,764/yr	$2,909/yr
	LCOE	$0.0623/kWh	$0.588/kWh
0.05	NPC	$75,482	$71,269
	Operating Cost	$4,679/yr	$3,066/yr
	LCOE	$0.0614/kWh	$0.598/kWh
0.06	NPC	$74,373	$72,072
	Operating Cost	$4,593/yr	$3,244/yr
	LCOE	$0.0605/kWh	$0.0591/kWh
0.07	NPC	$73,264	$66,205
	Operating Cost	$4,507/yr	$-14,849/yr
	LCOE	$0.0596/kWh	$0.0142/kWh

From table 5, we can conclude that when power price is increased then NPC, operating cost and LCOE increase, but LCOE decreases at power price of $0.16 at lowest case system. The table 6 shows the results of the base case and lowest case system while changing the sellback rate at the initial condition. From table 6, we can conclude that when sellback rate is increased then NPC, Operating cost and LCOE decreases. Table 7 shows the results of the base case and lowest case system while changing the Hydropower cost at the initial condition. From table 7, we can conclude that when hydropower cost is increased then NPC and LCOE increases but operating cost remains constant. The table 8 shows the results of the base case and lowest case system while changing the Hydro flow rate at the initial condition.

Table 7. Sensitivity analysis when hydropower cost is varied in on-grid system

Hydropower Cost($/kWh)	Parameters	Base Case System	Lowest Case System
15000	NPC	$76,591	$70,507
	Operating Cost	$4,764/yr	$2,909/yr
	LCOE	$0.0623/kWh	$0.0588/kWh
18000	NPC	$79,591	$73,455
	Operating Cost	$4,764/yr	$2,906/yr
	LCOE	$0.0648/kWh	$0.0614/kWh
20000	NPC	$81,591	$75,455
	Operating Cost	$4,764/yr	$2,906/yr
	LCOE	$0.0664/kWh	$0.0631/kWh
22000	NPC	$83,591	$77,455
	Operating Cost	$4,764/yr	$2,906/yr
	LCOE	$0.0680/kWh	$0.0648/kWh
25000	NPC	$86,591	$80,455
	Operating Cost	$4,764/yr	$2,906/yr
	LCOE	$0.0704/kWh	$0.0673/kWh

Table 8. Sensitivity analysis when flow rate is varied in on-grid system

Hydro flow rate(L/s)	Parameters	Base Case System	Lowest Case System
100	NPC	$52,345	$47,411
	Operating Cost	$2,889/yr	$2,236/yr
	LCOE	$0.0378/kWh	$0.0393/kWh
75	NPC	$76,591	$70,507
	Operating Cost	$4,764/yr	$2,909/yr
	LCOE	$0.0623/kWh	$0.0588/kWh
50	NPC	$106,435	
	Operating Cost	$6,054/yr	
	LCOE	$0.08421/kWh	

From table 8, we can conclude that when the hydro flow rate is decreased then NPC, LCOE and operating cost increases. At 50 L/s the base system wins so there is no separate base case and lowest case system.

6.2. List of all the system architecture

A total of 14 system architectures was proposed by Homer Pro. Based on the cost of electricity, the system architecture having hydro and grid comes out at the lowest price and similarly for lowest NPC the system having 4 batteries, 7.64 kW of converter along with grid and hydro is proposed. Also, for the lowest operating cost, the system having 1.82 kW of Photovoltaic, 3 batteries, 509 kW of converter along with hydro and grid is proposed.

The figure 7 also shows that the system with turbines has the highest LCOE, NPC and operating cost and the system with grid and hydro has the lowest LCOE, NPC and operating cost.

Architecture							Cost			
PV (kW)	Wind	Battery	Grid (kW)	Hydro (kW)	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)
10.9		5	999,999	5.89	8.00	CC	$70,507	$0.0588	$2,909	$32,895
		2	999,999	5.89	2.36	CC	$74,652	$0.0652	$4,492	$16,578
			999,999	5.89		CC	$76,591	$0.0623	$4,764	$15,000
0.316			999,999	5.89	0.322	CC	$76,693	$0.0622	$4,740	$15,414
12.2	1	6	999,999	5.89	10.4	CC	$146,870	$0.118	$3,667	$99,467
	1	2	999,999	5.89	2.96	CC	$149,338	$0.129	$5,313	$80,649
	1		999,999	5.89		CC	$151,770	$0.120	$5,629	$79,000
2.47	1		999,999	5.89	1.31	CC	$152,211	$0.118	$5,412	$82,248
59.0			999,999		44.7	LF	$157,195	$0.0813	$5,992	$79,738
59.9		1	999,999		45.5	CC	$158,542	$0.0813	$5,952	$81,593
55.5	1		999,999		46.9	LF	$230,940	$0.121	$7,062	$139,640
54.8	1	1	999,999		47.0	CC	$231,647	$0.122	$7,133	$139,429
	18	20	999,999		23.0	CC	$1.52M	$1.03	$27,098	$1.17M
	22		999,999			CC	$1.82M	$0.955	$31,764	$1.41M

Figure 9. List of all system architecture proposed by HOMER Pro for on-grid system

6.3. System architecture at the initial condition

Two types of system architecture were proposed by HOMER Pro. One is the winning system architecture which is the system architecture with the lowest NPC. At initial condition, the winning system architecture has hydro of 5.89 kW, converter of 8 kW and PV of 10.9 kW along with the grid. But when the sensitivity variables are changed then the winning system architecture also changes and if there are no sensitivity variables then this section will appear blank.

Another one is base case architecture which is the system with the lowest initial capital cost. At initial condition, base case architecture has only hydro of 5.89 kW and remaining energy demand is supplied from the grid. The base case system in the summary tab can be changed also there could be scenarios where the base case system is also the winning system.

Winning System Architecture

- HOMER Cycle Charging
- Grid
- PV - 10.9 kW
- Battery - 5.00
- Converter - 8.00 kW
- Hydro - 5.89 kW

Base Case Architecture

- HOMER Cycle Charging
- Grid
- Hydro - 5.89 kW

Figure 10. Winning and base case architecture in initial condition

6.4. Winning system architecture

6.4.1. Cost Summary
The Cost Summary tab in the Simulation Results window displays cash flows as either a present value or annualized cost, categorized by component or cost type. Table 9 shows the cash flow based on NPC and categorization is done by the component.

Table 9. Cost Summary of winning system architecture in on-grid system

Component	Capital ($)	Replace ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Battery	$3,230.50	$6,569.53	$323.19	$0.00	($77.11)	$10,046.11
Generic flat plate PV	$13,703.33	$0.00	$129.28	$0.00	$0.00	$13,832.60
Grid	$0.00	$0.00	$17,408.02	$0.00	$0.00	$17,408.02
Hydro Turbine System	$15,000.00	$0.00	$12,927.52	$0.00	$0.00	$27,927.52
Converter	$961.58	$407.97	$0.00	$0.00	($76.78)	$1,292.76
System	$32,895.41	$6,977.50	$30,788.00	$0.00	($153.89)	$70,507.02

The total capital cost of the system is $32,895 whereas the capital cost of the grid is $0 because the grid supply has been already provided to that community so the cost of extension of the grid is not included. The replacement cost of the hydro turbine and generic flat PV is also $0 because the total lifetime of the project is modeled for 25 years and the lifetime of hydro turbine and PV is also 25 years. Since no diesel generator is added to the system so the total cost of fuel is also $0. The total salvage value at the end of 25 years is $153.59 and the overall cost of the system is $70,507.02.

6.4.2. Cash Flow
There are two ways of displaying the cash flow which is graphical and tabular form. The cash flow in the figure 11 displays the cash flow in graphical form. There are also two options for the cash flow graph which is by cost type and by component type and the figure 11 shows the total inflow or total outflow of cash for a single year based on cost type.

The green bar in 1st year shows the total capital which is $32,895.41. After that $2381.59 is spent every year as an operating cost. Every five years $3230.5 is spent as a replacement cost for the battery and at the end of 25 years, the figure shows a salvage value of $642.41.

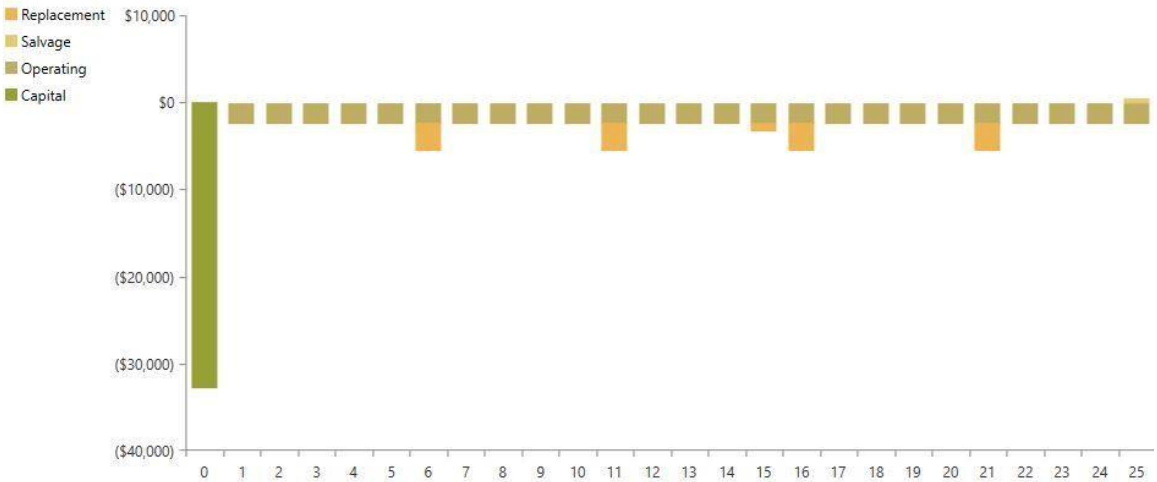


Figure 11. Cash Flow of on-grid system

Based on the components at first year $961.58 is spent for converter, $15,000 for hydro turbine, $13,703.33 for generic flat PV, and 3230.50 for the battery. After that $1346.59 is spent on-grid and $1000 in hydro turbine every year as an operating cost. Every five years, an extra $3255.5 is spent on battery along with other operating costs. At the end of a fifteen-year new converter is also required whose cost is $961.5. If discounted cash flow is kept under consideration, then the operating cost in the first year is $2249.28 and $570.33 on the 25th year at a discount rate of 8%.

6.4.3 Electrical %

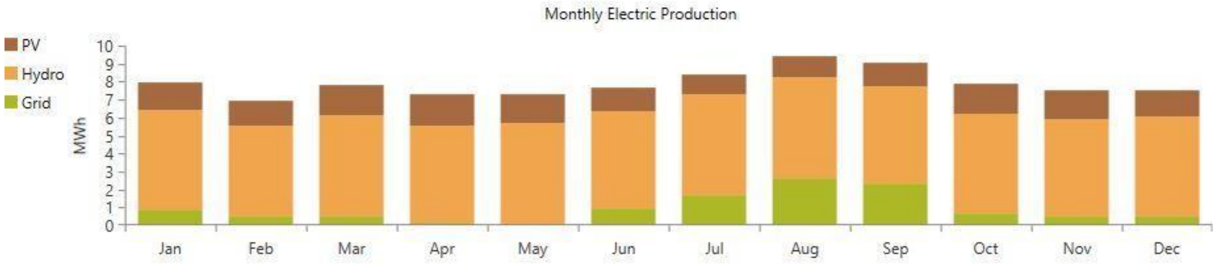


Figure 12. Monthly electric production percentage in on-grid system

The figure 12 shows that out of 100% electric production, Generic flat PV consists of around 18.6% which is 17,609 kWh/yr. Hydro consists of 69.4% which is 65,741 kWh/yr and the rest 12% which is 11,390 kWh/yr is supplied from the grid. Total electricity consumption is 94,740 kWh/yr.

On the consumption part, about 93.3% which is 86,502 kWh/yr is being supplied to AC primary load and the remaining 6.69% is being sold to the grid. This electric percentage is the result of the initial condition. The main factor to vary electric percentage is flow rate. As the flow rate is increased the percentage of hydro in production increases rapidly causing the LCOE of hydro to be very less compared to other sources of energy.

6.4.4. Battery

Figure 13 shows the SOC of the battery for 24 hours. It shows that during the daytime when the sunlight is at its peak the state of charge reaches up to 100% and during morning and night time the state of charge drops down up to 30%.

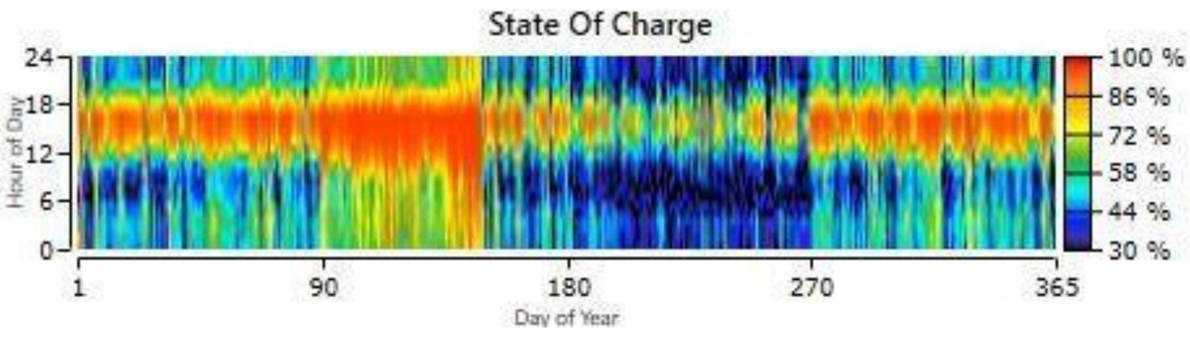


Figure 13. SOC of battery in on-grid system

For this system total number of batteries required is 5. Those batteries will be running at a bus voltage of 12 volts. The autonomy of those batteries is around 5.91 hours which cost around 0.0368 $/kWh. The nominal capacity of the battery is 8.34 kWh whereas the usable nominal capacity is 58.4kWh. The lifetime amount of energy supplied from this storage battery is 89,056 kWh and its expected life is around 5.1 year due to which in every 5-year battery need to be replaced which is clearly explained in the cash flow section.

The total amount of energy into the storage is 17,672 kWh/yr and the total energy out is 17,193 kWh/yr. The total amount of energy depleted in storage is 51.5 kWh/yr and the losses are around 531 kWh/yr. After considering all those parameters, the average energy cost that goes into the storage is around 0.0129 $/kWh.

6.4.5. System converter

Two system converters are used in the system. Inverter for converting DC to AC and rectifier for converting AC to DC. Figure 14 shows power output from the inverter and rectifier for 24 hours throughout the year. The maximum capacity of both inverter and rectifier is 8 kW where the mean output of the inverter is 2.59 kW and rectifier are 0.77 kW with a capacity factor of 32.4% for inverter and 9.63% for the rectifier. The hours of operation of the inverter are 5,499 hrs/yr and the rectifier is 3256 hrs/yr. Total energy out from the inverter is 22,699 kWh/yr and from the rectifier is 6,742 kWh/yr. Total energy into the inverter is 23,862 kWh/yr and into the rectifier is 7,097 kWh/yr. Total losses from the inverter are 1,193 kWh/yr and from the rectifier is 355 kWh/yr.

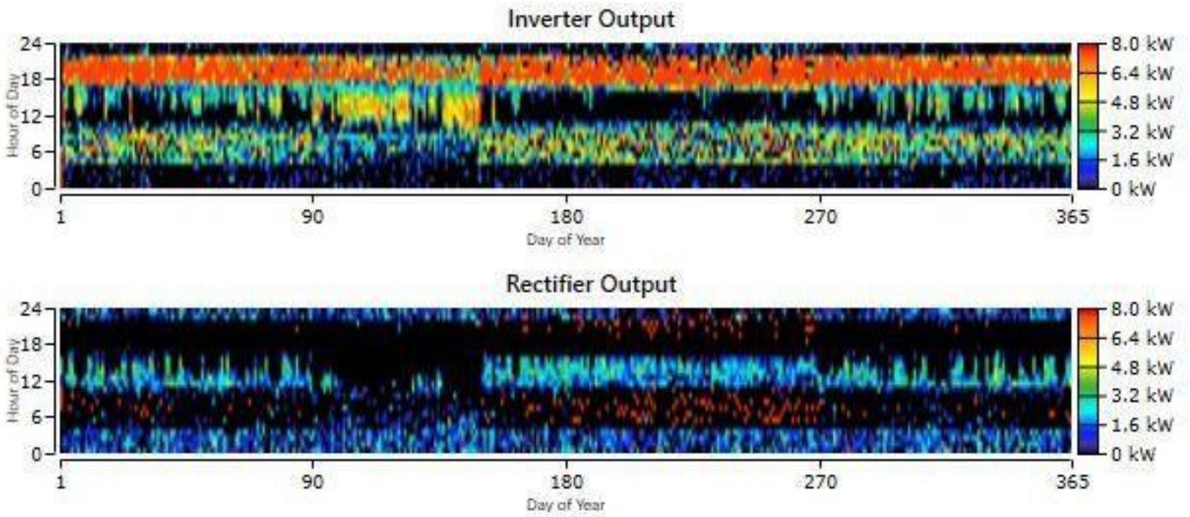


Figure 14. Inverter and rectifier output in on-grid system

6.4.6. PV output

The figure 15 shows PV output for 24 hours throughout a year. From the graph, we can see the output power ranging from 0 kW to 12 kW and output power is at its peak from 12 pm to 2 pm. The total rated capacity of the PV array is 10.9 kW where the mean output is 2.01 kW which is 48.2 kWh/day. The capacity factor is 18.5% and PV penetration is 20.4%. Total production throughout a year is 17,609 kWh/yr in which the hours of operation is 4,381 hrs/yr with an LCOE of 0.0608 $/kWh.

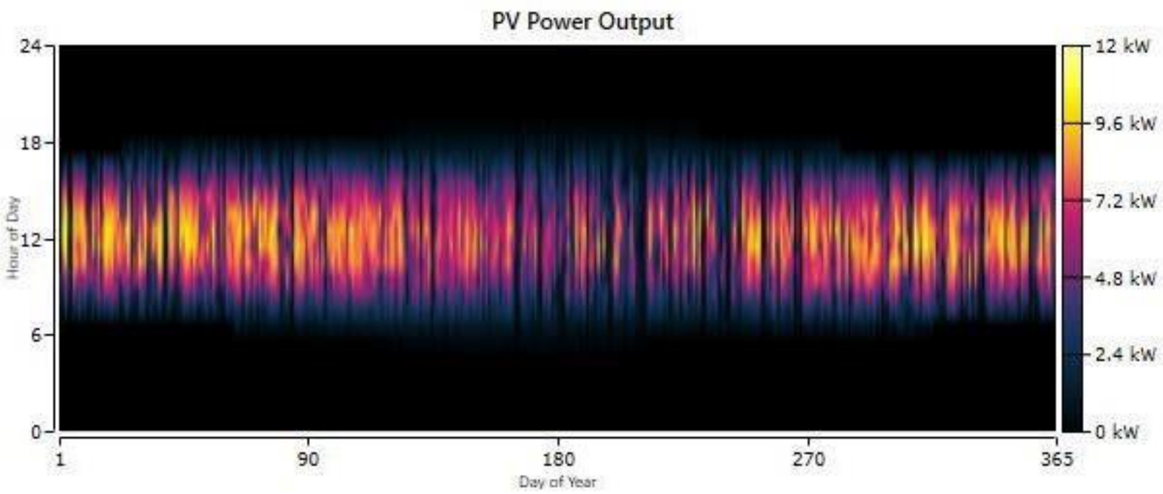


Figure 15. PV output of on-grid system

IOP Conf. Series: Materials Science and Engineering 1279 (2023) 012007 doi:10.1088/1757-899X/1279/1/012007

6.4.7. Grid (Energy Purchased and sold)

The table 10 shows the net energy purchased from the grid along with its peak power. The maximum amount of energy which is 2643 kWh is purchased in August due to the festive season of Nepalese people where there is the highest peak load of 37 kW and the minimum amount of energy which is 47 kWh is sold in May due to the rainy season because the maximum percentage of energy output comes from hydropower.

Table 10. Amount of energy purchased and sold on every month

Month	Energy Purchased (kWh)	Energy Sold(kWh)	Net Energy Purchased (kWh)	Peak Load(kW)	Energy Charge ($)
January	858	499	359	19	$100.13
February	502	432	70	15	$53.03
March	540	556	-15	18	$53.40
April	168	1,368	-1,199	11	($31.12)
May	97	1,544	-1,447	8	($48.23)
June	929	247	682	25	$120.24
July	1,693	47	1,647	26	$235.19
August	2,643	50	2,594	37	$368.09
September	2,353	40	2,313	37	$327.84
October	632	378	254	17	$73.39
November	497	608	-110	20	$45.29
December	476	433	43	17	$49.34
Annual	11,390	6,200	5,190	37	$1,346.59

7. Results for Off-Grid System

7.1. Sensitivity Variables

Table 11 shows the lists of sensitivity variables that are used during this simulation. Two sensitivity variables were taken which were Hydro capital cost and Hydro flow rate.

Initial condition:
Hydro Capital Cost – 15000 $ Hydro Flow rate – 75 L/S

Table 11. List of sensitivity variables in an off-grid system

Hydropower Cost($/kWh)	Hydro flow rate(L/s)
15000	50
18000	75
20000	100
22000	
25000	

The table 12 shows the results of the base case and lowest case system while changing the Hydropower cost at the initial condition. From the table 12, we can conclude that when hydropower cost is increased then NPC and LCOE increase but operating cost remains constant.

The table 13 shows the results of the base case and lowest case system while changing the Hydro flow rate at the initial condition. From the table 13, we can conclude that when the hydro flow rate is decreased then NPC, LCOE and operating cost increase.

Table 12. Sensitivity analysis when hydropower cost is varied in off-grid system

Hydropower cost(L/s)	Parameters	System
15000	NPC	$108,210
	Operating Cost	$1749/yr
	LCOE	$0.09683/kWh
18000	NPC	$111,210
	Operating Cost	$1,749/yr
	LCOE	$0.09951/kWh
20000	NPC	$113,210
	Operating Cost	$1749/yr
	LCOE	$0.1013/kWh
22000	NPC	$115,210
	Operating Cost	$1,749/yr
	LCOE	$0.1031/kWh
25000	NPC	$118,210
	Operating Cost	$1749/yr
	LCOE	$0.1058/kWh

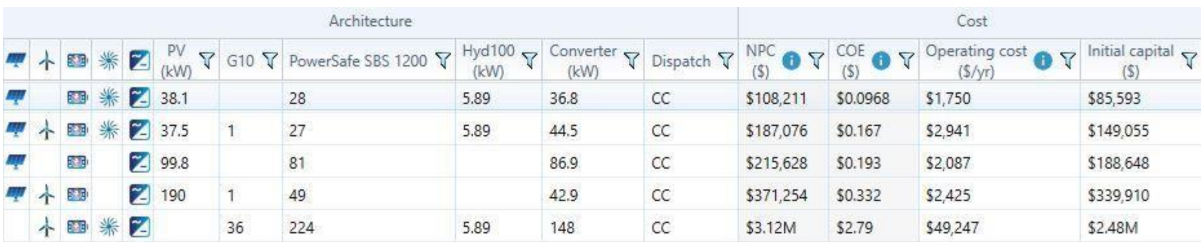
The table 13 shows the results of the base case and lowest case system while changing the Hydro flow rate at the initial condition. From the table 13, we can conclude that when the hydro flow rate is decreased then NPC, LCOE and operating cost increase.

Table 13. Sensitivity analysis when hydro flow rate is varied in an off-grid system

Hydro flow rate(L/s)	Parameters	System
100	NPC	$72,520
	Operating Cost	$1,483/yr
	LCOE	$0.06489/kWh
75	NPC	$108,210
	Operating Cost	$1749.57/yr
	LCOE	$0.09683/kWh
50	NPC	$149,885
	Operating Cost	$2,247/yr
	LCOE	$0.1341/kWh

7.2. List of all the system architecture

The results of HOMER Pro simulation and optimization processes showed that among the 78,260 system solutions, only 28,900 were feasible. 49,360 solutions were infeasible due to capacity shortage constraints. 19,850 were omitted and among them, 10,550 were lacking convertor, 3,810 were having unnecessary converter and 5,070 were for no sources of power generation.



Architecture						Cost			
PV (kW)	G10	PowerSafe SBS 1200	Hyd100 (kW)	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)
38.1		28	5.89	36.8	CC	$108,211	$0.0968	$1,750	$85,593
37.5	1	27	5.89	44.5	CC	$187,076	$0.167	$2,941	$149,055
99.8		81		86.9	CC	$215,628	$0.193	$2,087	$188,648
190	1	49		42.9	CC	$371,254	$0.332	$2,425	$339,910
	36	224	5.89	148	CC	$3.12M	$2.79	$49,247	$2.48M

Figure 16. List of all system architecture in off-grid system

A total of 5 system architectures were proposed by HOMER Pro. Based on the cost of electricity and operating cost, the system architecture for the lowest NPC which is $0.0649 is the system having 16 batteries, 36.8 kW of the converter, 18.7 kW of PV and 7.85 kW of Hydro. The figure above also shows that the system with turbines has the highest LCOE, NPC and operating cost.

7.3. Winning system and base system architecture

In this system architecture, only one architecture is shown because the base case architecture system wins so winning system architecture is also the same in this case. At initial condition, the system architecture has hydro of 3.92 kW, converter of 39.5 kW and PV of 54.6 kW along with the grid. Whenever any sensitivity variables are changed then system architecture also changes as it was with the grid system.

Figure 17. System architecture in initial condition

7.4. Winning system architecture

7.4.1. Cost Summary

The table 14 shows the cash flow on a basis of NPC and categorization is done by the component.

Table 14. Cost summary in off-grid system

Component	Capital ($)	Replace ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
Battery	$18,090.80	$7,675.75	$1,809.85	$0.00	($1,444.60)	$26,131.51
Generic flat plate PV	$48,089.06	$0.00	$129.28	$0.00	$0.00	$48,218.34
Hydro Turbine	$15,000.00	$0.00	$12,927.52	$0.00	$0.00	$27,927.52
System Converter	$4,413.37	$1,872.48	$0.00	$0.00	($352.42)	$5,933.43
System	$85,593.23	$9,547.93	$14,866.64	$0.00	($1,797.02)	$108,210.79

The total capital cost of the system is $85,593. The total replacement cost of the system is $9,547.93 whereas hydro turbine and generic flat PV is $0 because the total life time of the project is modeled for 25 years and the lifetime of hydro turbine and PV is also 25 years. The total Operating and Maintenance cost is $14,866.64. Since no diesel generator is added to the system so the total cost of fuel is also $0. The total salvage value at the end of 25 years is $1797.02 and the overall cost of the system is $108,210.79.

7.4.2. Cash Flow

Figure 18 displays the cash flow in graphical form based on component type.

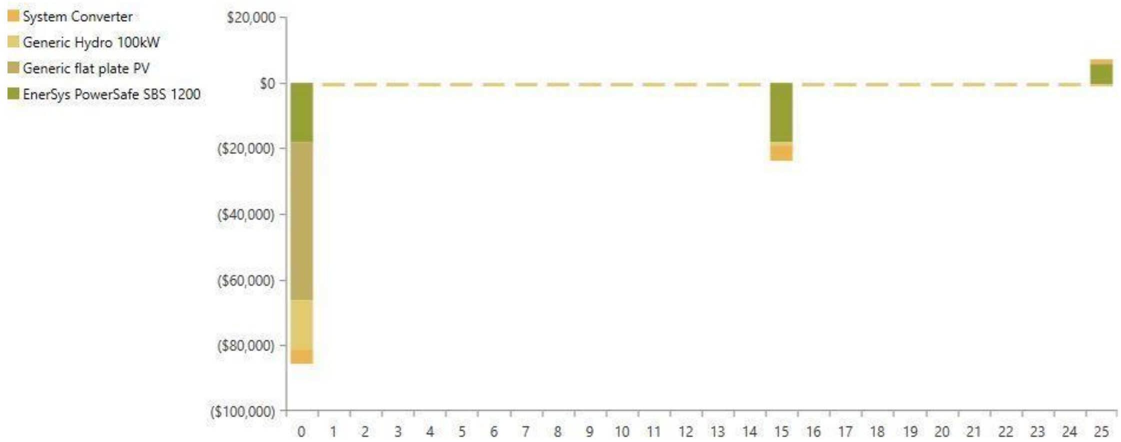


Figure 18. Cash flow in off-grid system

The bar in 1st year shows the total capital which is $85,593.23. Every year $1000 is spent for the operation of hydropower nominally. If operation cost is also discounted, then its value decreases year by year. After 15 years $18230.80 is spent on replacing the battery and $4413.47 is spent on the converter. These two prices are the nominal cash flow but their total discounted cash flow will be $9547.93.

Based on a cost type, the total capital spending in the first year is the same. After that $2381.59 is spent every year as an operating cost. On every fifteen years, $22,504.17 is spent as a replacement cost and at the end of 25 years, the graph shows a salvage value of $7,501.39.

7.4.3. Electrical %

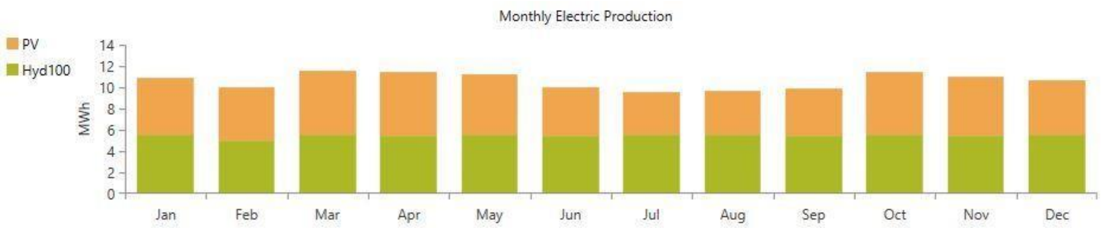


Figure 19. Monthly electric production percentage in an off-grid system

Figure 19 shows that out of 100% electric production, Generic flat PV consists of 48.4% which is 61,703 kWh/yr and Hydro consists of 51.6% which is 65,741 kWh/yr. Total electricity production is 127,444 kWh/yr and consumption is 86,447 kWh/yr. On the consumption part, about 100% energy is being supplied to AC primary load. Since the rate of energy production is higher than the rate of energy consumption in this system about 30.3% which is 38,586 kWh/yr amount of energy will be wasted. The unmet electric load is 53.9 kWh/yr which is nearly negligible.

7.4.4. Battery

Figure 20 shows the SOC of the battery for 24 hours. It shows that from January to July the SOC is above 72% and during day time it's around 100 %. But in August and September SOC is in the range of 30 % to 50% and also during day time it's not reaching to 100%. But after September SOC is the same as its initial months.

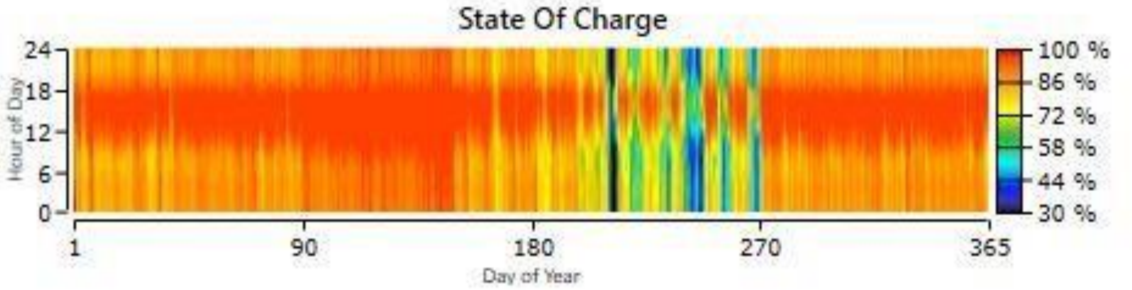


Figure 20. SOC of battery in off-grid system

For this system total number of batteries required is 28. Those batteries will be running at a bus voltage of 12 volts. The autonomy of those batteries is around 33.1 hours which cost around 0.0368 $/kWh. The nominal capacity of the battery is 467 kWh whereas the usable nominal capacity is 327 kWh. The lifetime amount of energy supplied from this storage battery is 368,516 kWh and its expected life is around 15 years due to which in every 5-year battery needs to be replaced which is clearly explained in the cash flow section.

The total amount of energy into the storage is 24,890 kWh/yr and the total energy out is 24,19 kWh/yr. The total amount of energy depleted in storage is 54.2 kWh/yr and the losses are around 748 kWh/yr.

7.4.5. Inverter and rectifier output

Figure 21 shows power output from the inverter and rectifier for 24 hours throughout the year. The maximum capacity of both inverter and rectifier is 36.8 kW where the mean output of the inverter is 3.34 kW and the rectifier is 0.389 kW with a capacity factor of 34% for inverter and 9.09% for the rectifier. The hours of operation of the inverter are 4,852 hrs/yr and the rectifier is 2,217 hrs/yr. Total energy out from the inverter is 29,264 kWh/yr and from the rectifier is 3,408 kWh/yr. Total energy into the inverter is 30,804 kWh/yr and into the rectifier is 3,587 kWh/yr. Total losses from the inverter are 1,540 kWh/yr and from the rectifier is 179 kWh/yr.

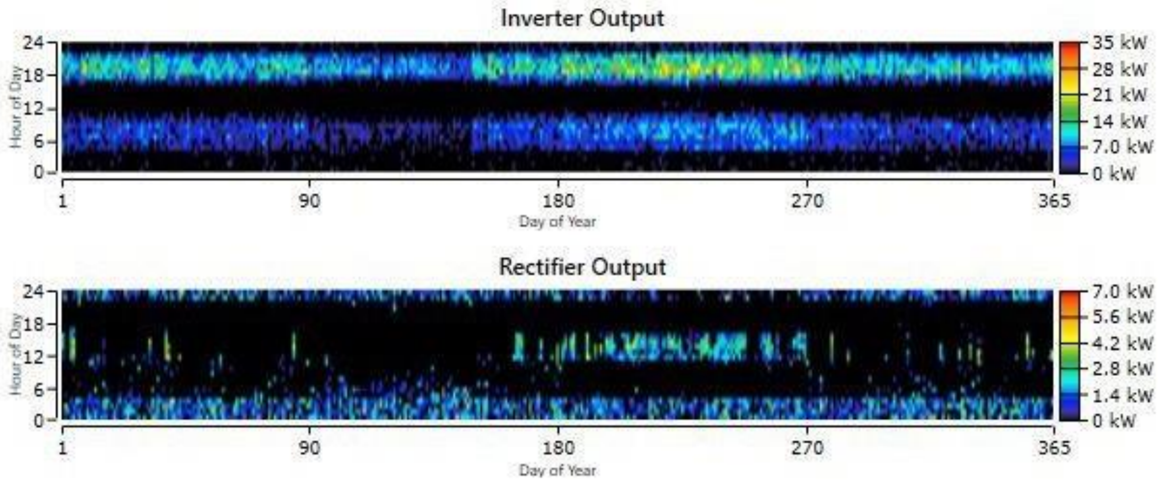


Figure 21. Inverter and rectifier output in off-grid system

7.4.6. PV output

Figure 22 shows PV output for 24 hours throughout a year. The total rated capacity of the PV array is 38.1 kW where the mean output is 7.04 kW and the maximum output is 37.7 kW which is 169 kWh/day. The capacity factor is 18.5% and PV penetration is 71.3%. Total production throughout a year is 61,8703 kWh/yr in which the hours of operation is 4,381 hrs/yr with an LCOE of 0.0604.

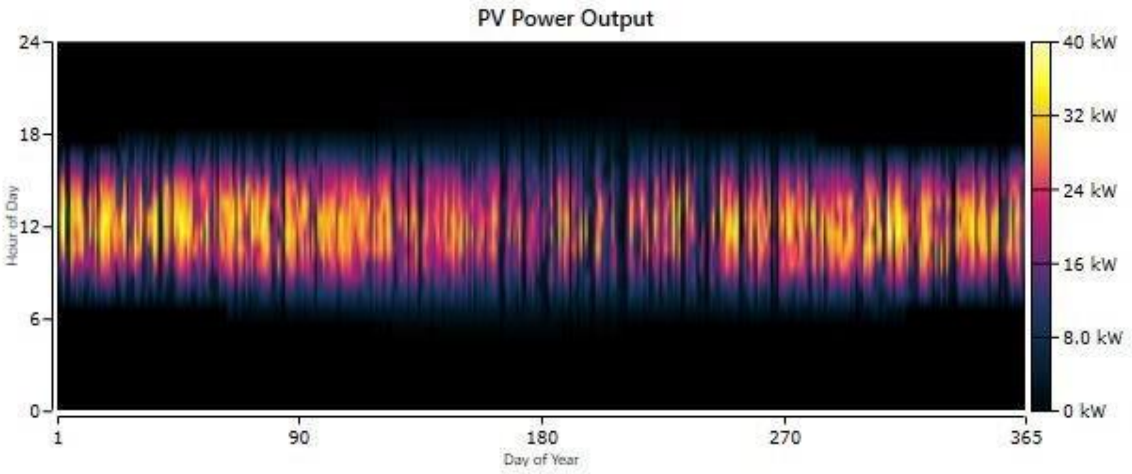


Figure 22. PV output in off-grid system

8. Conclusion

This paper presents a comparative analysis between an off-grid and a grid-connected hybrid power system. The site selected for this project is Thakle Namuna Basti a community village built after the earthquake of 2015. The resources required for this project were provided by NREL and Meteonorm. Two types of results are presented in this paper. Sensitivity analysis was carried out with hydropower cost, the flow rate of the river, sellback and the purchase price of electricity which showed that for the lowest NPC and LCOE the sellback rate of electricity and the flow rate of the river should be high and purchased power price and hydropower cost should be as low as possible. Optimization results showed that for the on-grid system, the system with hydro and grid is the most feasible for the community based on NPC and LCOE. For off-grid systems, the system with PV, Hydro, and Battery is the most feasible to meet the demand of the community village. The price of electricity is higher for an off-grid system compared to an on-grid system but the simulation of an off-grid system was also done because there is a continuous increase in consumption demand which is exerting extra pressure on the central grid. Besides this, any issue in the system may result in a complete shutdown when the whole system is dependent on only the central grid. But again, in an off-grid system, extra battery banks are required for energy storage but in an on-grid system, an extra amount of electricity can be sold to the grid which will also work as a source of revenue.

9. Acknowledgement

The funding for the research was provided jointly through University Grant Commission (UGC) Nepal and Energize Nepal Program, Kathmandu University. Also, we are eternally grateful to Mr. Khil Bahadur Tamang for his assistance during the survey and field visits.

10. References

[1] Rajbongshi R, Borgohain D, Mahapatra S. Optimization of PV-biomass-diesel and grid base hybrid energy systems for rural electrification by using homer. Energy. 2017;126:461–74.
[2] Saheb-Koussa D, Haddadi M, Belhamel M. Economic and Technical Study of a hybrid system (wind– photovoltaic–diesel) for Rural Electrification in Algeria. Applied Energy. 2009;86(7-8):1024–30.
[3] Azimoh CL, Klintenberg P, Mbohwa C, Wallin F. Replicability and scalability of mini-grid solution to rural electrification programs in sub-saharan africa. Renewable Energy. 2017;106:222–31.
[4] Murugaperumal K, Ajay D Vimal Raj P. Feasibility design and techno-economic analysis of hybrid renewable energy system for rural electrification. Solar Energy. 2019;188:1068–83.

[5] Baneshi M, Hadianfard F. Techno-economic feasibility of hybrid diesel/PV/wind/battery electricity generation systems for non-residential large electricity consumers under southern Iran climate conditions. Energy Conversion and Management. 2016;127:233–44.
[6] Iea. Electricity Information - Data product [Internet]. IEA. [cited 2022Nov3]. Available from: https://www.iea.org/data-and-statistics/data-product/electricity-information
[7] Nepal Electricity Authority. A year in review-fiscal year 2019/2020 p. 8–13.
[8] Gunatilake H, Wijayatunga P, Holst DR-. HYDROPOWER DEVELOPMENT AND ECONOMIC GROWTH IN NEPAL. ASIAN DEVELOPMENT BANK; 2020.
[9] Kanase-Patil AB, Saini RP, Sharma MP. Integrated Renewable Energy Systems for off grid rural electrification of remote area. Renewable Energy. 2010;35(6):1342–9.
[10] Li C, Ge X, Zheng Y, Xu C, Ren Y, Song C, et al. Techno-economic feasibility study of autonomous hybrid wind/PV/battery power system for a household in Urumqi, China. Energy. 2013;55:263–72.
[11] Abnavi MD, Mohammadshafie N, Rosen MA, Dabbaghian A, Fazelpour F. Techno-economic feasibility analysis of stand-alone hybrid wind/photovoltaic/diesel/battery system for the electrification of remote rural areas: Case study Persian Gulf coast-iran. Environmental Progress & Sustainable Energy. 2019;38(5):13172.
[12] Google maps. Google; [cited 2022 Nov3]. Available from: https://www.google.com/maps/@27.805681,85.547194,173m/data=!3m1!1e3
[13] Bunnoon P, Chalermyanont K, Limsakul C. Mid-term load forecasting: Level suitably of wavelet and neural network based on factor selection. Energy Procedia. 2012;14:438–44.
[14] Wang C-hsiang, Grozev G, Seo S. Decomposition and statistical analysis for regional electricity demand forecasting. Energy. 2012;41(1):313–25.
[15] NASA Power [Internet]. NASA. NASA; [cited 2022Nov3]. Available from: https://power.larc.nasa.gov/
[16] Streamflow prediction tool - nepal. [cited 2022Nov3]. Available from: http://tethys.icimod.org/apps/streamflownepal/
[17] Homer pro 3.15 [Internet]. Welcome to HOMER. [cited 2022Nov3]. Available from: https://www.homerenergy.com/products/pro/docs/latest/index.html
[18] NewsTeam. Solar Panel Price in Nepal [Internet]. ktm2day.com. 2022 [cited 2022Nov3]. Available from: https://www.ktm2day.com/solar-panel-price-nepal/
[19] Chung I-Y, Liu W, Cartes DA, Schoder K. Control parameter optimization for a microgrid system using particle swarm optimization. 2008 IEEE International Conference on Sustainable Energy Technologies. 2008;