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Assessment of electricity excess in an isolated hybrid energy system: A case study of a Dangiwada village in rural Nepal

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Abstract

The increasing demand of power can be fulfilled through different architectures and electricity supply models by utilizing the available local resources. But most of the isolated energy system suffers from high energy cost and unreliable energy supply. This study identifies different electricity supply models to fulfill the dynamic demand of power in a remote area, which is analyzed in terms of cost of energy and causes for the high cost of energy. Among different factors, the presence of unusable energy (Electricity Excess) produced by the energy system during fulfillment of the demand is found to be major one cause for the high cost of energy. Further, the importance of energy storage system in isolated energy system is discussed. In this case, up to 83.4 % of electricity excess is observed, which can be utilized in different manners to reduce the total energy cost. Electricity excess profile for different energy model, their impacts and possible techniques of the solution with open views are discussed.

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1. Introduction

In Nepal, most of the people live in rural area, where the energy access percentage is 84.9% (97.7 % Urban and 81.7% rural) [1]. In a report [2], before 2011 more than 550,000 people living in remote areas had been electrified with more than 307 micro hydro plants and 3,099 solar home systems all over the country. Similarly, 4.536 MW of isolated small hydro projects were operating under Nepal Electricity Authority (NEA) [3]. With reference to these cases, the off-grid hybrid system is found to be the single solution to provide the electricity to a remote area [4-6]. A number of researchers have presented the optimum design of the isolated hybrid system (IHS), to provide the energy access at the isolated area [7-10]. However, there are numerous challenges in IHS such as high cost of the system, poor reliability and power quality, low load factor, and problems in maintenance and monitoring activities [11]. Similarly, nature of the renewable energy sources (RES) generally used in IHS such as solar, wind, the water stream is of periodic type.

Different energy storage systems (ESS) are used to address the problems occurred in IHS, and the interest toward the ESS can be attributed to multiple factors such as; the capital cost of managing peak demands, the investment needed for grid reliability, and the integration of RES [12,13]. In addition, conventional generators, battery bank or implementation of distributed generation is generally used in the isolated system to improve the reliability and the power quality [7,14,15]. In different researches, pump storage-type hydropower, compressed air storage, flywheels, hydrogen tank are considered as potential ESS [16-19].

One of the major challenges of the isolated system is to match the energy supply with the dynamic power demand. This problem is solved by integration of ESS which stores the energy excess of electricity (EE) and subsequently meets the electricity demand during peak period [20]. A number of researchers are explaining the importance of ESS such as; for load frequency control, for reliability, and for system quality in the isolated system [21-23]. But, some of the studies related to high-penetration RES assumed that generation should never exceed load [24,25]. According to them, there should not be EE at any instant of time and storage should be used to transfer the energy from the time of excess to time of deficit. Similarly, some of the researchers had recognized the idea that can use the EE to reduce the requirement for energy storage capacity [25,26], resulting the payback period to decrease as well. Also the system will be cost-effective because of the absence of loss due to the ESS [26]. Heide et al. identified an optimal fig. to manage the seasonal nature of the RES (solar and wind) in Europe and presented an amount of EES that need to balance the EE [18]. Similarly Budischak et al. performed a simulation to identify the optimized combination of RES and ESS, which showed that the COE can be reduced by utilizing the EE [27].

In this study, the authors aim to investigate the existence of EE in IHS in Nepal by conducting a case study. The impacts of EE on system's cost and performance are discussed. An energy optimization software is used to simulate the system and identify the potential hybrid models. Based on the results provided by the simulation, the data are analyzed and discussed. After that, some of the possible solutions are recommended to resolve the problems that occur due to the EE. The main objective of this study is to investigate the status of the EE in IHS and identify the opportunities to reduce the energy cost by applying different possible approaches.

2. Description of the case study area

2.1. Background

AEPC [28] conducted an assessment in 2014 for a detailed feasibility study on the implementation of the Wind-Solar hybrid project in Tatopani, Jumla, Nepal, with the cooperation of Alternative Energy Promotion Center (AEPC), Ministry of Environment, Government of Nepal. The report by AEPC presented the technical design of off-grid hybrid system along with financial, environmental and socio-economic analysis. There were around 136 households with a primary school, and the team proposed a wind-solar hybrid system of total capacity 45 kW to meet the demand of base year. The same area was taken for the case study to analyze the system's status in case of EE. The case study area (Dangi wada Village) is one of the remotest area in Nepal located in the mid-western region at 29°16'33.41"N and 81°11'0.12"E with an altitude of 2306 meters above sea level.

Looking at the load profile of the case area, the electricity demand analysis based on the demand assessment survey was performed on each household at 2014 AD [28]. Taking 2014 AD as the base year, the demand pattern of the area was identified. The daily load profile of that area is given in Fig 1. After assuming the day-to-day variability of 15%

and time-step-to-time-step variability of 20%, the scaled annual average load is found to be 162 kWh/d with a load factor of 0.171. Similarly, the average demand and peak demand are measured to be 6.77 kW and 39.4 kW.

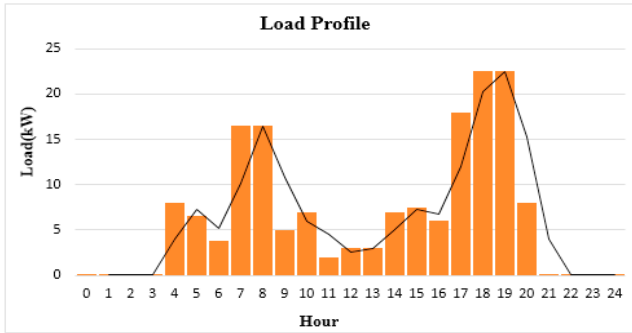


Fig 1: Daily Load profile of case study area

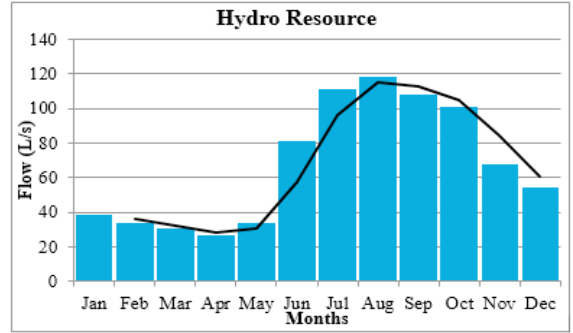


Fig 2: Seasonal pattern of water resource

2.2. Assumption and model inputs

2.2.1. Hydro

As per the report [28], Tila river separates the two portions of the village in the east and the west. So, Installation of micro-hydro and electricity generation can be achieved for this area. Generally, micro-hydropower plants are installed in such areas where the flow of water runs for the whole year. There is no any secondary data of flow discharge to calculate the potentiality of the micro-hydro system. So, to analyze the system’s characteristics, data of similar place is considered. The assumed micro hydro has an annual flow rate of 67.3 L/s in Q50 design, and a net head of 65 meters, with an electrical power output of 38.6 kW. The monthly discharge for the proposed micro hydropower plant is given in Fig. 2. There is no residual flow with 50% minimum flow ratio and 150% maximum flow ratio. Similarly, the efficiency of micro-hydro and pipe head loss are assumed to be 90% and 5%.

2.2.2. Solar PV

Nepal is located in a favorable location for a solar resource with about 300 days a year of sunshine and average solar radiation varying from 3.5- 6.2 kWh/m²/day [29]. This context is also true for the case study area. HOMER imports the solar radiation of the case area from the online data of NASA Surface Meteorology and Solar Energy website. The annual average for daily solar radiation for this region is found to be 5.230 kWh/m²/d with average clearness index of 0.594.

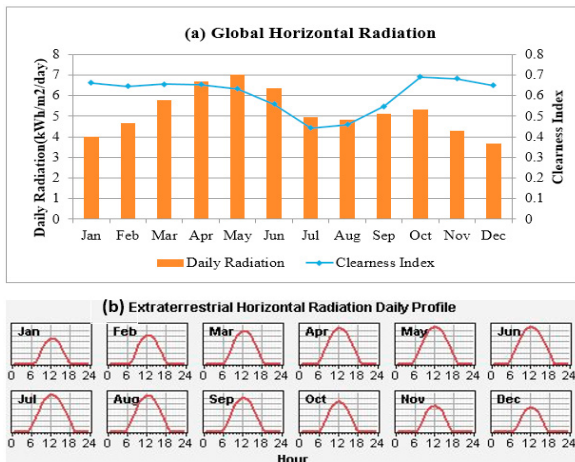


Fig. 3: Solar radiation

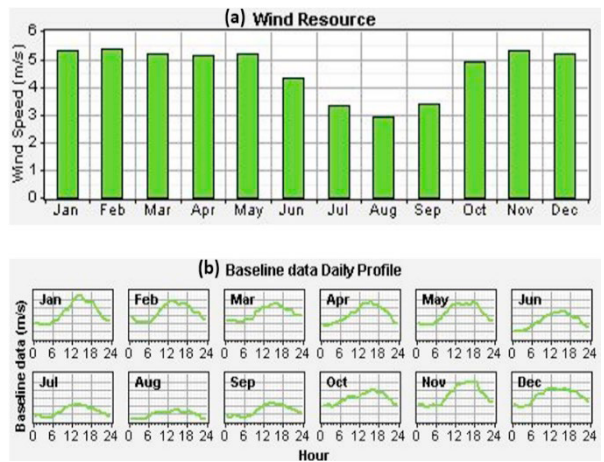


Fig. 4: Wind resource

Fig. 3(a& b) show the Global Horizontal Radiation and Extraterrestrial Horizontal Radiation Daily Profile of the case area. Generic flat-plate PV module is used for the production of electricity as given in Table 1. Table 1 list the assumptions, rating, costs and detailed information of the system.

2.2.3. Wind

The power density of wind less than or equal to 100 W/m² is not useful and greater than 200 W/m² is normally used for isolated conditions, whereas it was found to be 30 W/m² for Jumla district [29]. For the wind speed profile of case study area, secondary data is used and given in Fig. 4 below [28]. The scaled annual average speed of the case area is 4.62 m/s. Fig. 4 (a &b) shows the monthly average wind speed and baseline data daily profile over a year at a hub height of 10 m. Table 1 list the assumptions, rating, costs and other information regarding the Generic-1kW wind turbine.

Table 1: Input values of cost estimation

Component	Rating	Capital Cost (\$)	Replacement Cost(\$)	O & M cost(\$/year)	Sizes (kW) Considered	Quantity Considered	Minimum Life (year)	Additional Information
Solar PV	1kW	1000	1000	0	0-75	multiple	25	Derating factor: 80% Slope: 30 degree Azimuth: 0 degree Ground reflectance: 20% No Tracking Hub height: 10m
Wind	1 kW	1300	1300	50	0-75	multiple	15	Weibull k: 2 Autocorrelation factor: 0.85
Hydro	38.6 kW	80000	80000	1500	0 or 38.6	single	25	Efficiency: 90% Pipe head loss: 5%
DG	1 kW	375	375	0.05/ hour	0- 45	single	15000 hours	Minimum load ratio: 30%
Battery	1kWh	300	300	10	0-848	multiple	5	4V, 1900Ah, 7.6 kWh
Converter	1kW	145	145	0	0-40	single	5	Inverter efficiency: 90% Rectifier Efficiency: 85 %

2.2.4. Diesel generator set and others

To analyze the performance of different possible energy model, DG set is also considered. Availability of diesel depends on the transportation. Therefore, DG set becomes a popular solution to generate the electricity in isolated conditions. In this study, the different option of DG sets was given so that optimum model will be obtained. Further, diesel prices of 0.80\$/L are evaluated, with an emission density of 820 kg/m, the carbon content of 88%, sulfur content of 0.33% and lower heating value of 43.2 MJ/kg. Similarly, a hybrid charge controller is used in between the AC and DC bus bars to exchange the power. The hybrid energy model has an option of multiple strings having 6 batteries (Surrette 4KS25P) of nominal voltage 4V and nominal capacity 1,900 Ah (7.6 kWh). Annual real interest rate and project period are assumed 6 % and 25 years.

To fulfill the dynamic demand of the case area, a hybrid model is proposed. This study is completed in different stages. Different energy sources and their components are already explained in section 2.2. Here, the model is considered so that maximum use of the available resource can be utilized and the required load demand will be fulfilled. It consists of an AC bus of voltage level 220 V and is fed from micro hydropower plant of 38.6 kW and a DG Set. Similarly, the DC bus of voltage level 24V DC is fed from solar PV system, wind turbine and battery bank. A converter is used between the DC and AC bus bar to exchange the power. The loads are connected to the AC bus as load nature.

3. Method

The main objective of this study is to analyze the status and impact of EE in an IHS, and draw some suggestions to address the impacts. In order to analyze the system, a popular energy optimization software (HOMER) is used to identify the possible hybrid system that fulfills the dynamic demand of the case area. Hybrid Optimization Model

for Electric Renewable (HOMER) is an energy optimization software which optimizes the available energy resources based on the bottom-up approach [30]. This software is used to optimize the energy system based on available resources in an area to fulfill the energy demand by providing different inputs like resources data, technical and economic information. It has different energy generating components in its user-friendly library, which is very powerful to analyze the provided data from unit minute to several hours. One of the main advantages of this software is that it includes the technology specific information. All of the inputs and assumptions, and their technical aspects are already explained in section 2.2. After simulation, the results were analyzed and are presented in result and discussion sections.

4. Result and Discussion

Isolated Hybrid System with different sources is used to supply electricity for the dynamic load demand for the case study area. In this case, the annual peak demand and energy demand are calculated to be 39 kW and 162 kWh/d. Table 2 lists the 10 possible hybrid models that can be implemented to meet the demand by utilizing the available resources. The possible models are listed based on least cost of energy. Models for wind with battery and wind-hydro hybrid with battery are found incapable to meet the demand. The rating of different components, Initial Investment Cost (IIC), Operating and Maintenance cost (O & M), Total Net Present Value (TNPV), Cost of Energy (COE), Renewable Fraction and Electricity Excess (EE) for each model are given in Table 2. The model containing solar battery is found to be optimized with COE of 0.199 \$/kWh. This model is eco-friendly and has 100% of the renewable fraction. On the other hand, DG set without battery is the worst model in COE and for the environmental concern. All of the data for each model are given in Table 2, but the authors' aim is to focus toward the EE placed in the last column. Most of the models have huge EE except for a few models: DG with battery and DG-Solar hybrid with battery. Among the different possible models tested, maximum of 83.4 % of EE is calculated in Hydro-Solar with battery. EE profile for all of the models are presented in Fig. 5. Fig. 5 (a) and (b) shows the annual EE profile for solar with battery and solar-wind hybrid system with battery respectively. Since solar radiation takes place at daytime, in both of the cases, the EE occurs during day period. In Fig. 5 (b) the penetration of solar (65 kW) over wind (15 kW) is high. Although the peak of the profile is less in the second case than the first one, the amount of EE is found to be high due to the comparative flat nature of the profile shown in Figure 5 (a) and (b). Similarly, Figure 5 (c) and (d) shows the annual EE profile for DG system without battery and with battery respectively. Since the generation is constant for the generator, the EE occurs all the time except the peak period in DG system without a battery. In this case, 48.2 % of EE is calculated whereas in DG with the battery there is negligible EE.

Table 2: Optimized result for different potential models

Hybrid Model	Solar kW	Wind kW	Hydro kW	DG kW	Batter y No.	Convert er kW	IIC \$	O/M cost \$/year	TNPV \$	COE \$/kWh	Ren. Frac . %	Excess Electricity %
Solar/ Battery	69	-	-	-	114	-	103,200	3,699	150,485	0.199	100	43.7
Hydro/ DG/ Battery	-	-	38.6	25	30	8	99,535	7,101	190,312	0.252	96	79.4
Solar/ Wind/ Hydro/ DG/ Battery	4	1	38.6	25	30	8	116,535	7466	211972	0.281	97	80
Hydro/ Solar/ Battery	52	-	38.6	-	78	36	160,620	4862	222769	0.295	100	83.4
Solar/ Wind/ Hydro/ DG	15	3	38.6	35	-	8	113,185	11,099	255,066	0.337	96	81.9
DG/ Solar/ Battery	13	-	-	25	60	16	42,695	18,163	274,883	0.364	34	0.03
DG/ Battery	-	-	-	30	30	8	21,410	27,244	369,677	0.489	0	0
Solar/ Wind/ Battery	65	15	-	-	114	-	294,200	16379	503582	0.667	100	46
DG/ Solar	15	-	-	40	-	8	31,160	61,219	813,744	1.077	20	52.6
DG	-	-	-	38	-	-	14,250	68,657	891,912	1.18	0	48.2

Similarly, in Figure 5 (e) and (f), the EE frequently occurs in DG- Solar hybrid system without battery, whereas there is negligible EE in the same type of sources with battery. In case of Hydro-DG hybrid and Hydro-solar hybrid system, the EE is found to be very less in March and April months as shown in Figure 5 (g) and (h). This is due to the periodic nature of the hydro resource that has minimum flow at respective months. Similarly, the EE is found to be occurring during the day in a Hydro-solar hybrid system with battery because of the solar radiation at day period. Finally, Figure 5 (i) and (j) shows the annual EE profile for the hybrid system containing all of the sources without battery and with battery. The profile nature is fluctuating as previous models, since it contains all types of the resources. In case of the hybrid system with battery, there is less EE in comparison to the model without battery.

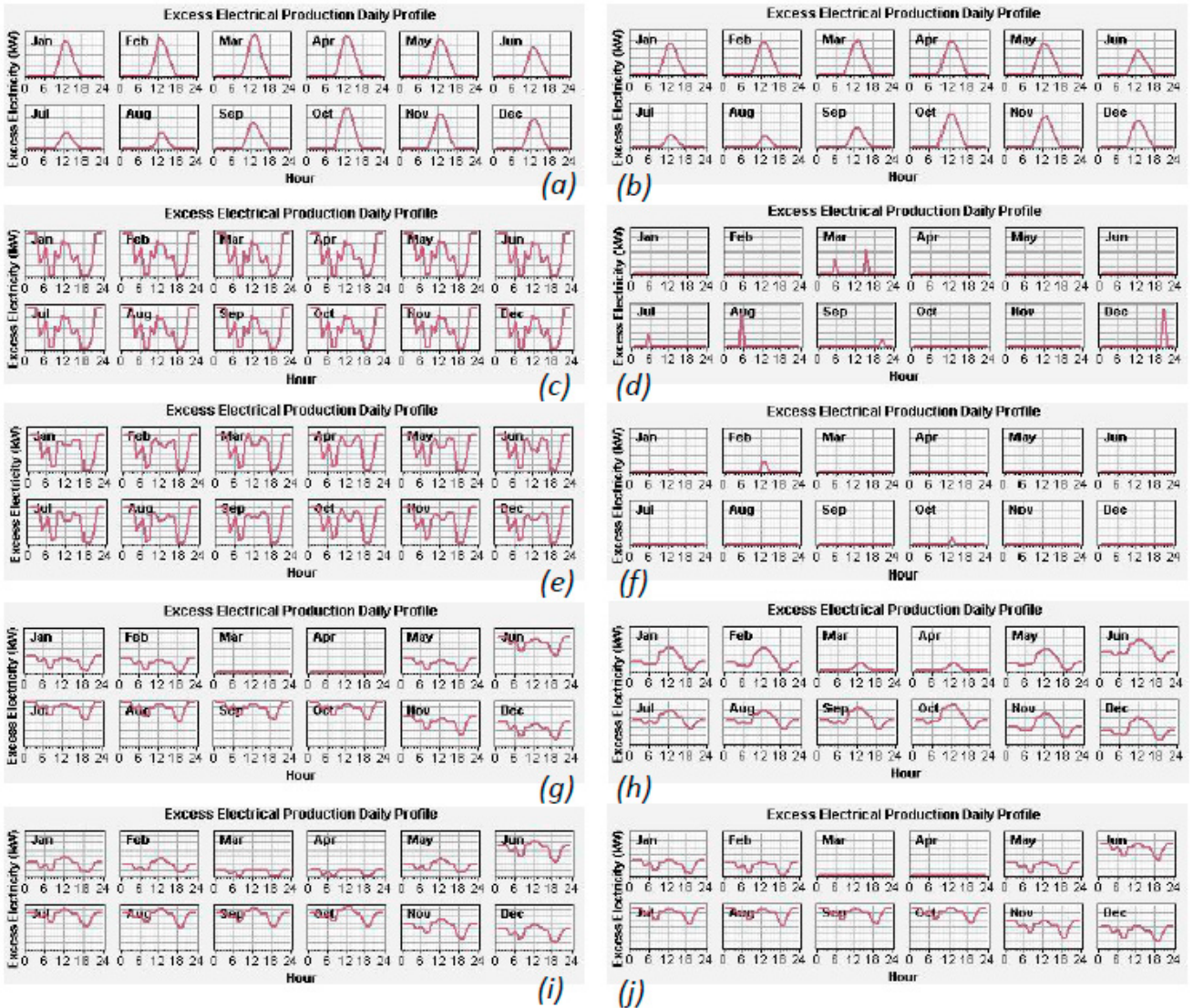


Fig. 5: (a) Solar with Battery, (b) Solar-Wind Hybrid with Battery, (c) DG without Battery, (d) DG with Battery, (e) DG-Solar Hybrid without Battery, (f) DG-Solar Hybrid with Battery, (g) Hydro-DG Hybrid with Battery, and (h) Hydro-Solar with Battery.

For a comparative study, three pairs of energy model having same nature are analyzed. Fig. 6 presents the comparisons of the model with Battery and without Battery. Here the model pairs; all energy sources, DG-Solar Sources and Solar energy sources are considered for both conditions. From Fig. 6, it can be shown that with the Battery, EE is found to be low. Except for the first case (having all sources) in Fig. 6, other two models have negligible EE when battery system is connected. This shows the importance of the storage device which can contribute to

minimizing the EE. However, in case of first model (having all energy sources), there is no sharp drop of the EE. It indicates that having storage device does not mean utilization of all energy within the system. Although, there is probability to drop the COE by utilizing the EE, it could not minimize the EE in all situation by using storage device. Similarly, when a relation between change in electricity excess and change in COE is drawn, a linear correlation was found, as shown in Fig. 7. It indicates the probability of reduction of COE by reducing the EE. Reducing fewer EE results in a reduction of less COE and vice versa. In this way, it can be shown that, if a big difference can be made in EE, there will be a chance to reduce a big amount of COE.

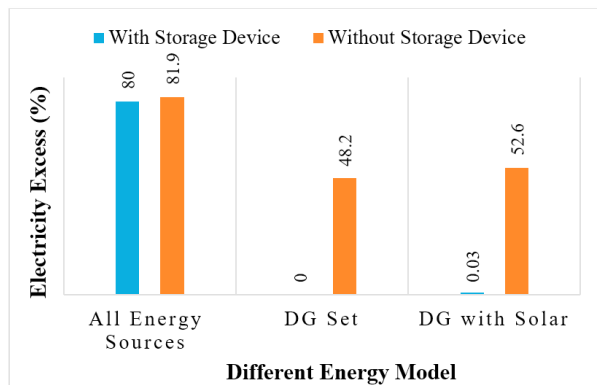


Fig. 6: Electricity Excess at different energy model

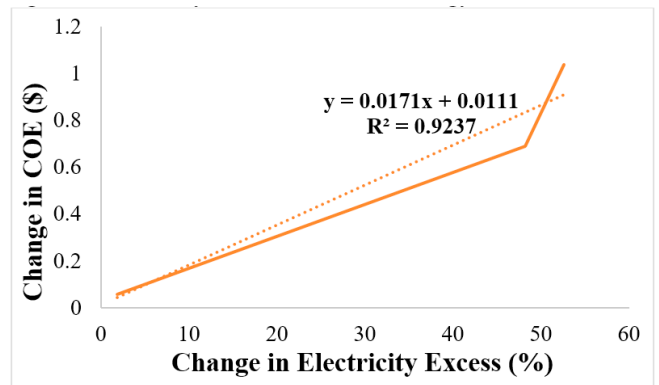


Fig.7: Relation between Δ EE (%) and Δ COE (\$)

1. Conclusion

The off-grid energy system is the one and the only solution to provide the electricity at a remote area. There may be the availability of different RES depending on their geographical location but each RES have different periodic natures. They vary on daily basis as well as a seasonal basis. Similarly, the generation via different RES varies with their periodic nature. Thus, none of the RES can supply continuous and reliable power. To provide a continuous electrical supply, interconnection of a number of sources called Hybrid system becomes an alternative. Hybrid systems are normally used to provide continuous supply and control the load frequency. In addition, it increases the reliability and quality of the system. Nevertheless, the energy cost from off-grid energy system is found to be comparatively high than the grid-connected system. One of the reason of high-energy cost in the off-grid network is high installed capacity requirement to meet the peak demand. Because of periodic nature of RES, the high rated system is required for the continuous supply. Similarly, in a remote area, the load factor is very low and the load pattern is irregular. Hence, ESS is useful to minimize the installation rating by storing the energy generated during off-peak time and utilized in the peak period. Practically, it is not easy as theoretical explanations. There are numerous technical and financial parameters, which contribute to the EE. EE is that amount of electricity/energy, which is being wasted or cannot be utilized by ESS as well. System with ESS has a comparatively low EE. Similarly, the addition of multiple energy sources helps to reduce the EE. Some of the hybrid system such as; solar with battery and Hydro-DG hybrid system with battery have least COE. Further cost may be reduced by well-planned utilization of EE. The main reasons of EE are low load factor, irregular load pattern, and periodic nature of RES. The nature of RES as well as the generation from respective energy sources cannot be changed but can be managed to reduce the EE. There is some experience in which different activities are conducted to utilize the wasted energy that contributes to reducing the energy cost. To reduce the EE as well the energy cost, and to reduce the requirement for energy storage capacity some of the job can be computed such as: increasing load factor by developing a policy, demand-side management or simply by connecting with grid system if possible, otherwise develop mini grid concept.

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