

Techno-Economical Planning of an Off-Grid Integrated Renewable Energy System

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Abstract

This paper focuses on reducing the LCOE (Levelized Cost of Energy), the unmet load, Net Present Cost (NPC) and the greenhouse gas emissions by the utilization of an optimized off-grid integrated renewable energy system. The LCOE has been reduced by 14.8% of that of DG and by 28.6 % of Diesel Generator (DG) with Battery System, whereas the NPC has been reduced by 14.7% of DG only system and by 28.7% of DG with Battery System. A comparison analysis has also been presented based on the performance of the proposed system and most recently published similar studies. To achieve these objectives, an optimization algorithm has been developed and simulated in Hybrid Optimization Model for Multiple Energy Resources (HOMER) software with different combinations of IRES, DG and battery systems. Similarly, intending to analyze the feasibility and performance in terms of the technical and economic aspects of the proposed system, HOMER is used. Based on the obtained results, broadly, it is examined that the proposed system decreases diesel consumption by around 8113 liters/year and the total emissions of greenhouse gas by about 21545 kg/year in the study area; thereby, it can be foreseen as a viable and sustainable option(s) for the development of more such systems in remote locations.

Author Keywords. Feasibility. Off-grid. Solar Photovoltaic. Wind Energy System. Integrated Renewable Energy System. Levelized Cost of Energy. Energy Storage.

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1. Introduction

Obtaining an inexpensive and dependable electricity supply is currently essential for the economic growth and stability of a nation. Due to technical and economic issues, the electrification of the grid of hilly, remote and scarcely populated regions is very difficult ([Uwineza, Kim, and Kim 2021](#)). A DG is often used as a source of energy for such situations. However, it leads to global warming as well as climate change by producing greenhouse gases ([Shan et al. 2017](#)). To address these problems, it is crucial to utilize a renewable energy source that does not create greenhouse gases. Fortunately, the majority of hilly communities are located in regions with tremendously improved development of renewable energy sources, both of which are cost-free and environmentally preferable to fossil fuels ([Gioutsos et al. 2018](#)). Thus, distributed power generation based on renewable energy is a viable alternative to fossil fuels and lowers their detrimental impact on human existence. Because of these pragmatic considerations, the production of energy from locally accessible

Renewable Energy Sources (RES), such as solar photovoltaic, is gaining increasing attention (SPV) (Kumar et al. 2019). The main problem associated with RES is its stochastic nature. This can be mitigated by integrating a Battery Energy Storage (BES) with a RES-based electricity generation unit (Mamaghani et al. 2016). The Integrated Renewable Energy System (IRES) not just improves dependability but also significantly reduces greenhouse gas emissions (Budes, Ochoa, and Escorcía 2017). In sparsely inhabited, isolated, hilly places, RES-based power generation is the ideal alternative to DG due to its cheap maintenance and nearly nil operating costs. Where the demand for power is extremely low as well as the grid is inaccessible for economic and technical reasons. To enhance the effectiveness of IRES, the appropriate size of resource elements is necessary. In constructing IRES, techno-economic effectiveness, which may be significantly enhanced by resource optimization, is the most important factor (Sharma et al. 2021a). In the last decade or so, unique software for optimizing renewable energy systems to satisfy load demand has been developed. According to the scholarly literature, the HOMER system (Mendes, Ioakimidis, and Ferrão 2011; Chauhan and Saini 2016) is the most effective and commonly regarded instrument for technical-economic optimization. It simulates all possible resource configurations and ranks them based on the least NPC of energy (Halabi et al. 2017; Nelem et al. 2021; Shezan et al. 2016; Luerssen et al. 2020). Similarly, economic models are used in HOMER to calculate the average NPC and LCOE values (Bahramara, Moghaddam, and Haghifam 2016).

The NPC and modified LCOE are the two primary economic indicators used by HOMER to rank the different energy systems. Most studies published in the literature emphasized optimal IRES sizing for achieving an economically viable power solution in regions wherein grid electrification is both technically and financially impractical (Murugaperumal, Srinivasn, and Prasad 2020; Ramesh and Saini 2020; Aziz et al. 2019; Sharma et al. 2021b; Das and Zaman 2019; Arévalo et al. 2020; Toopshekan, Yousefi, and Astaraei 2020; Yilmaz and Dincer 2017; Halabi and Mekhilef 2018; Mandal et al. 2018; Halabi et al. 2017).

Therefore, in this paper, an attempt has been made to assess the economic, technical feasibility, and sensitivity assessment of a solar PV/BES off-grid IRES for supplying power to the residential load of a low-load profile, isolated and hilly area. An isolated village, Dewal, in the Mori block of Uttarkashi district, Uttarakhand, India, was selected as the study area. As Dewal is not connected to the grid, the majority of its electricity is generated by diesel-powered generators. Therefore, this consumes 14800 liters/year of diesel with very high emissions of carbon monoxide (244.22 kilograms/year), unburned hydrocarbons (10.66 kilograms/year), particulates (1.48 kilograms/year), and nitrogen oxides (229.42 kilograms/year) as detailed in Table 1. Because of the high price of the per-unit cost of power production and the greenhouse gas emissions connected with the diesel generator set, it is both economically and environmentally unfavorable. This region's electricity needs can be met by locally accessible RES-based electricity production units. The appropriate design of resource elements is essential in order to deliver a cost-effective eco - friendly alternative for the study region. In this study, the HOMER Software programme was used for this purpose.

Fuel used (kiloliters/year) and corresponding emission component (kilograms/year)	DG only	DG/battery
Diesel	14.8	8.11
Carbon Monoxide	244.22	133.86
Unburned Hydrocarbons	10.66	5.84
Particulates	1.48	0.81
Nitrogen Oxides	229.42	125.75

Table 1: Details of the fuel used and corresponding emission components

2. Methodology

This section explains the methodology employed for this investigation. It also provides a comprehensive explanation of the study area's location, load estimation, meteorological parameters, and resource estimation. As shown in Figure 1, the complete methodology may be separated into three major phases: pre-Homer process, Homer analysis, and post-Homer analysis.

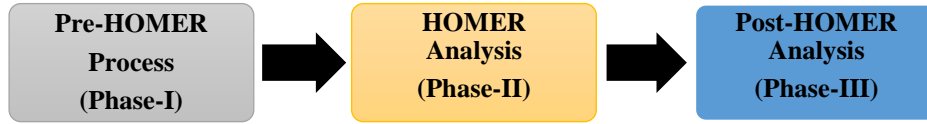


Figure 1: Methodology used in the study

In Homer analysis, the HOMER Pro software is applied with input factors such as solar irradiation, etc., to determine the ideal size of a resource component. In the post-HOMER study, produced findings are compared technically, economically, and environmentally with basic instances (DG and DG/Battery) in order to identify the IRES's major benefits. Figure 2 is a flowchart that explains the entire optimization approach employed in this investigation.

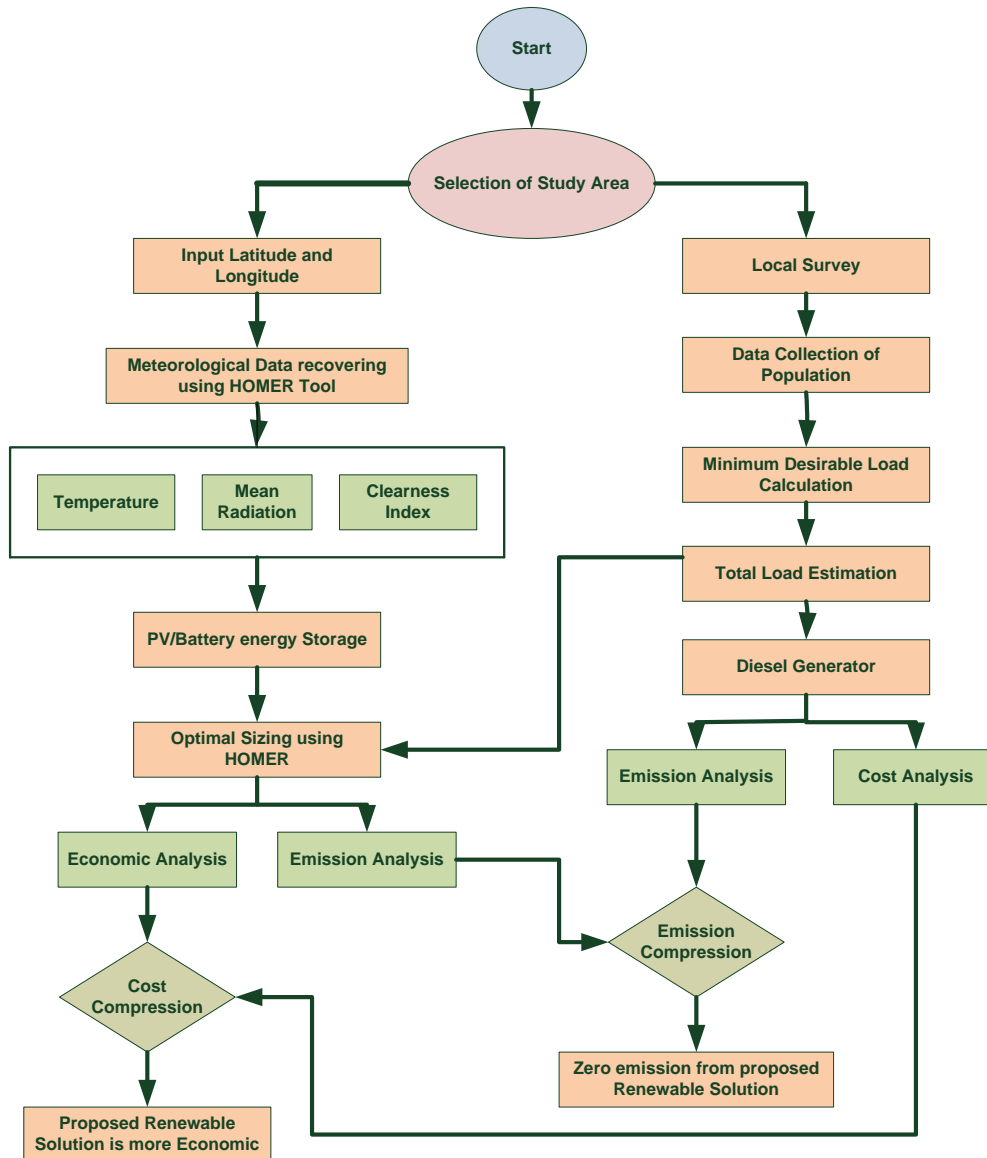


Figure 2: Flow chart of the optimization procedure

2.1. Location of study area

The study area, i.e., Dewal, is a small village located at $[78.439903]^{\circ}$ N latitude and $[30.733299]^{\circ}$ E longitude in the Mori block, Uttarkashi district, Uttarakhand in India. Dewal’s total area is 36.88 hectares (0.37 km²). There are 19 families and 108 inhabitants in the village of Dewal, among which 60% constitute males and 40% constitute females. The literacy level of Dewal is 66.7%, whereas the labour force participation rate is approximately 44.4%. They are mostly involved in the production of woollens, blankets and shawls (Directorate of Census Operations 2014a, 2014b).

2.2. Load estimation of study area

Dewal is a village in the Mori Block of the Uttarkashi district in the Indian state of Uttarakhand. The overall population of the Dewal is 108, composed of 60 men and 48 women. The primary data for calculating the minimum essential load comes from a study of the local region, from which the daily household energy demand has been assessed. To estimate a household's daily power demand, the devices and their corresponding daily working hours are evaluated in Table 2.

It is projected that the village's total land area energy consumption, average demand, and peak power are 64.6 kWh/day, 2.69 kW, & 13.72 kW, respectively. Figure 3 depicts the peak load of a normal day in the research area during the month of January.

S. No.	Appliances	Rating (W)	Quantity (No.)	Working hours/day	Total load (Wh)
1	CFL	10	3	10	300
2	TV	120	1	4	480
3	Fan	75	2	4	600
4	Radio	5	1	4	20
5	Water pump	500	1	1	500
6	Room heater	500	1	3	1500
Load/house/day					3.400 kWh
Total load/day					64.6 kWh

Table 2: Load Demand of a Household (Directorate of Census Operations 2014a)

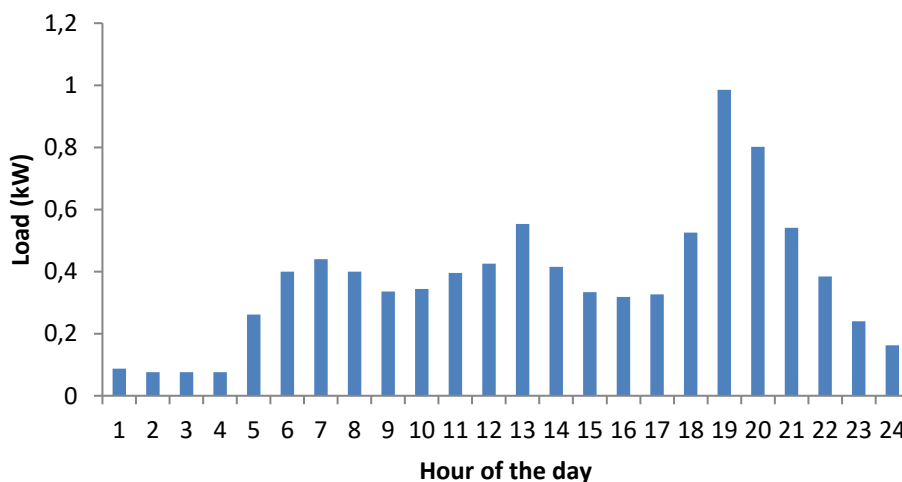


Figure 3: Load profile of a typical day of the study area

2.3. Weather characteristics study area

The meteorological data of the research area is a crucial factor in determining the location of IRES. The average annual temperature of the research area ranges from -10 to 11 degrees Celsius, with a mean temperature of 1.25 degrees Celsius. The National Aeronautics and Space Administration (NASA) provides the monthly average temperature variation of the research area using the HOMER software, as depicted in Figure 4 (NASA, n.d.).

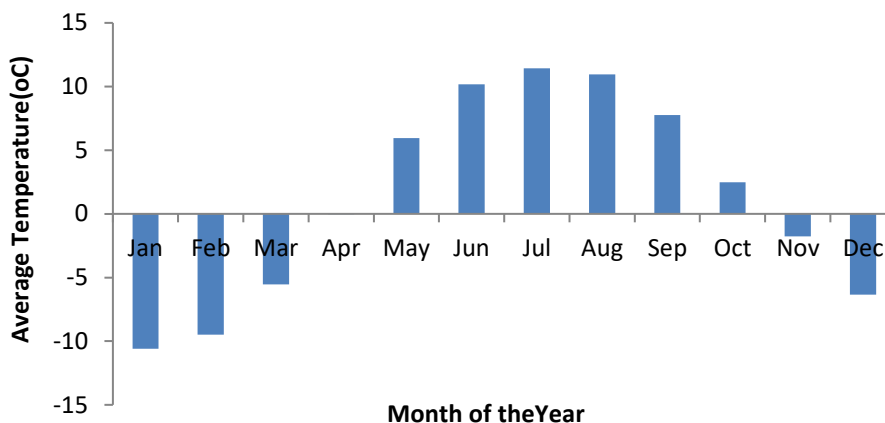


Figure 4: Monthly Average Temperature Variation of Study Area

2.4. Study area's resource estimation

The focus of this research is on exploiting the resources of solar energy in the study region. The sum of the beam combined with diffusion irradiance is referred to as daily sun irradiance. NASA data gathered by using HOMER software suggest that the study area receives an average of 4.63 kWh/m²/day of solar radiation on a horizontal plane. The daily solar irradiance with clearness index for the study area is given in Figure 5. The greatest value of solar irradiation for a region of study is 6.10 kWh/m²/day in June, while the minimum value is 2.85 kWh/m²/day in January. In both February and October, the greatest and minimum clearness index values are 0.658 and 0.479, respectively (NASA, n.d.).

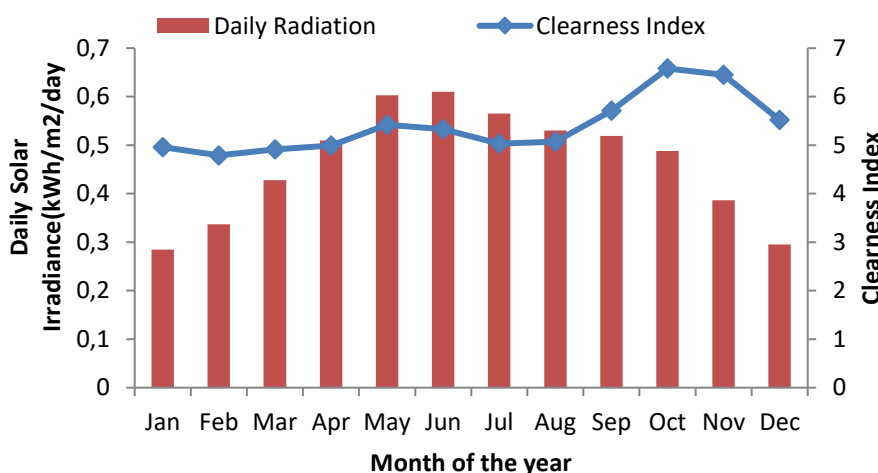


Figure 5: Solar irradiance and clearness index of the study area

2.5. HOMER software as IRES optimization tool

The HOMER is regarded as the international benchmark for simulating and improving renewable energy systems. It is utilised to design and evaluate the economic and technical viability of a hybrid renewable energy system. Economic feasibility, as well as sensitivity analysis, are used to assess the effectiveness of the renewable system. HOMER takes as input

data regarding renewable resources, energy needs, and the technical and economic aspects of the components and runs thousands of simulations to determine the ideal match between energy consumption and energy supply.

2.6. Composition of IRES

As illustrated in Figure 6, the planned IRES for the research region is designed with SPV, BES, and converters. Throughout this IRES, the SPV's DC output is connected to the DC bus. The load demand is deemed AC and is fed directly through the AC bus. AC and DC buses are coupled via a bidirectional converter operating in inverter mode. A BES is also implemented into the IRES to mitigate the random nature of SPV output.

2.6.1. Solar PV

In the current review, a generic photovoltaic panel with a derating factor of 80% and a 25-year lifetime was investigated. The derating ratio is the adjustment factor used to scale the loss in SPV production under real-world conditions, such as the existence of dirt, snow, and shade, as well as the heating of solar panels. The SPV power output is based on the incident solar irradiation and solar panel area, as defined by Equation (1) (Rajanna and Saini 2016).

$$P_{SPV}(t) = \eta_{SPV} \times I \times A \tag{1}$$

Where η_{SPV} , I and A are the efficiency (%), solar irradiance (kW/m²) and area (m²) for solar panels, respectively.

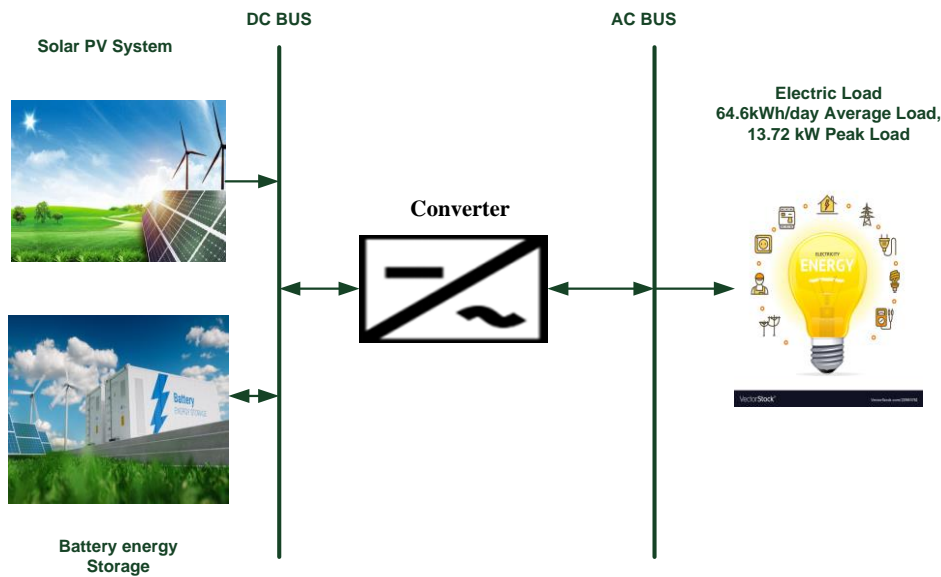


Figure 6: Schematic Diagram of the Proposed IRES

2.6.2. Battery energy storage

To mitigate for the stochastic nature of SPV output, an energy storage system must be incorporated. A BES is also incorporated into the IRES created for the study area due to the numerous advantages afforded by batteries, like strong operating conditions, simplicity of operation, and low maintenance needs, etc.

For the BES, the maximum value of stored energy can be assessed as given in Equation (2).

$$E_{b_MAX} = \left(\frac{\text{Min}(E_{b_MAX_MCR} \ E_{b_MAX_MCC})}{\eta_{b_C}} \right) \tag{2}$$

Where, η_{b_C} is the charge-storage efficiency of the battery.

$$E_{b_MAX_KBM} = \frac{mE_1 e^{-m\Delta t} + Emc(1 - e^{-m\Delta t})}{1 - e^{-m\Delta t} + c(m\Delta t - 1 + e^{-m\Delta t})} \tag{3}$$

$$E_{b_MAX_MCR} = \frac{(1 - e^{-\beta_C \Delta t})(E_{MAX} - E)}{\frac{\Delta t}{M_b \times I_m \times V_m}} \tag{4}$$

$$E_{b_MAX_MCC} = \frac{M_b \times I_m \times V_m}{1000} \tag{5}$$

Where m , E_1 , Δt , E , c , β_C , E_{MAX} , b , I_m and V_m are the storage rate constant (h-1), available energy in the starting time step (kWh), duration of the time step (h), the energy available in the first-time step (kWh), capacity ratio, maximum charge rate (A/Ah), the total capacity of storage (kWh), number of batteries, maximum charge current (A) and the nominal voltage of the battery respectively.

2.6.3. Converter

Several AC and DC buses in this investigation were powered by a system converter with a 1kW capacity. The effectiveness and lifespan of a converter operating in inverter mode are estimated to be 95% and 15 years, respectively. Table 3 outlines several additional economic and technical characteristics applied in this research for converter sizing (Kumar et al. 2019).

S. No.	Component	Parameter (Unit)	Value/Type	Reference
1.	SPV	Type of panel	Flat-plate	
		Rated-Power (kW)	1	Kumar et al. (2019)
		Capital-Cost (\$/kW)	949.28	Kumar et al. (2019)
		Replacement-Cost (\$/kW)	949.28	Kumar et al. (2019)
		O & M Cost (\$/kW)	9.49	Kumar et al. (2019)
		Derating Factor (%)	80	Kumar et al. (2019)
		Lifetime (Years)	25	Kumar et al. (2019)
2.	BES	Type of battery	Lead acid	Kumar et al. (2019)
		Maximum Capacity (Ah/Unit)	513	Kumar et al. (2019)
		Capital-Cost (\$/Unit)	62.73	Kumar et al. (2019)
		Replacement-Cost (\$/Unit)	54.24	Kumar et al. (2019)
		O & M Cost (\$/Year)	1.36	Kumar et al. (2019)
		Nominal-voltage (Volts)	12	
		Round Trip Efficiency (%)	85	
3.	Converter (as Inverter)	Type of converter	Inverter	
		Rated-Power (kW)	1	
		Capital-Cost (\$/kW)	135.61	Kumar et al. (2019)
		Replacement-Cost (\$/kW)	108.49	Kumar et al. (2019)
		O & M Cost (\$/Year)	2.71	Kumar et al. (2019)
		Efficiency (%)	95	
		Life (Years)	15	
5.	Other key parameters	Discount-Rate (%)	8	
		Project-Life (Years)	25	
		Inflation rate (%)	2	

Table 3: Technical and economic parameters of the components of the IRES

2.7. Financial metrics

Using the suggested IRES, the primary goals of this research are to minimize LCOE, NPC, unfulfilled load percentage, as well as greenhouse gas emissions. To evaluate the economic viability of the suggested IRES, the LCOE is a crucial criterion. Therefore, the LCOE is estimated using the HOMER software tool, as well as the minimal LCOE is used as an objective function throughout this research to assess the IRES's technical and economic viability. The levelized cost of energy (LCOE) is the ratio of the overall cost incurred throughout the lifetime of an IRES project to the entire amount of electricity generated over the lifespan of that IRES project. In this analysis, a discount rate of 8%, an inflation rate of 2%, and a project duration of 25 years were assumed accordingly. The LCOE can indeed be determined mathematically using Equation (6).

$$\text{Minimum LCOE} = \frac{NPC \times CRF(d, l)}{\sum_{t=0}^{l-1} E_{GEN}(t)} \quad (6)$$

Where, d , l , $E_{GEN}(t)$ and NPC the discount rate is assumed to be 8% per year, the project's duration is assumed to be in years, while IRES produces energy output in hours while total actual cost is measured in dollars (\$) accordingly. The total NPC consists of the installation cost, operations cost, and total revenue generated by IRES over its lifetime. It is calculated using equation by the HOMER programme (7) (Shan et al. 2017).

$$NPC = \frac{AC_t}{CRF(d, l)} \quad (7)$$

Where, AC_t is the total annualized cost and CRF is the Capital Recovery Factor for IRES. It can be calculated with Equation (8):

$$CRF(d, l) = \frac{d(1 + d)^l}{(1 + d)^l - 1} \quad (8)$$

In the HOMER programme, it is assumed that all prices increase at the same rate; hence, it uses a real annual rate of interest rather than a nominal one. The equation for calculating the recovery cost of an IRES component is included in HOMER (9) (Agyekum and Nutakor 2020; Shan et al. 2017).

$$S = \frac{RC \times l_R}{l_t} \quad (9)$$

Where RC represents the replacement cost of IRES system components in dollars (\$), l_R represents the residual lifetime of IRES parts of the system, and l_t represents the total lifespan of IRES system components in years.

2.8. Constraints

IRES design is subject to various physical and functional restrictions. Such constraints must be met for the entirety of the optimization programme. Listed below are the restrictions examined in this study.

2.8.1. Power Balance Constraint

The total hourly power dissipated by all operating units must meet the energy requirement of the scheduled load, as given by Equation (10) (Agyekum and Nutakor 2020).

$$P_{SPV}(t) + P_{BES}(t) + P_{NS}(t) = \frac{Load}{\eta_{INV}} \quad (10)$$

Where, $P_{SPV}(t)$, $P_{BES}(t)$, $P_{NS}(t)$ and η_{INV} represent the total SPV output power, total BES output power, total power that is not being supplied, and efficiency of the inverter, respectively.

2.8.2.SPV Power Output Limit

Equation (11) describes the relationship between SPV output power and incident solar irradiation (Shan et al. 2017).

$$P_{SPV}(t) = \begin{cases} P_{SN} \frac{(G(t))^2}{G_{STD} R_C} & 0 < G(t) < R_C \\ P_{SN} \frac{G(t)}{G_{STD}} & G(t) > R_C \end{cases} \quad t = 1, 2, 3 \dots \dots T \quad (11)$$

Where $G(t)$, P_{SPV} , G_{STD} , R_C and P_{SN} represents solar irradiance given time (W/m²), the overall power output of SPV, overall typical solar irradiance assumed to be 1000 (W/m²), cut in irradiance value assumed to be 150 (W/m²), as well as SPV rated electrical output under standard conditions. Similarly, several BES design limitations are defined as follows.

2.8.3.BES Power and State of Charge Limit

The BES must never be over-discharged or over-charged. Therefore, for the battery bank's safety procedures, the energy limit and state of charge limitations indicated by Equations (12) and (13) are imposed.

$$P_{BES,min} \leq P_{BES} \leq P_{BES,max} \quad (12)$$

$$SOC_{min} \leq SOC(t) \leq SOC_{max} \quad (13)$$

Where $P_{BES,min}$, $P_{BES,max}$ and SOC_{min} , SOC_{max} represents the minimum as well as the maximum power capacity range and state of charge, respectively.

3. Simulation Results and Discussions

In this section, simulated results from the HOMER software are presented, along with a discussion of their interpretation. The HOMER software optimizes to lower LCOE as well as total NPC while taking capacity shortage limits into account. A capacity deficiency is the difference between the IRES's specified operating capacity and its actual operating capacity. HOMER maintains track of these shortages and computes their annual total. The IRES is optimized to meet the study area's overall load requirement. In addition, the inflation rate, as well as the discount rate, are considered in the sensitivity analysis to establish their tradeoff with the economic and technical feasibility of the IRES. The daily load demand of the study area, as estimated by the HOMER software, is around 64.6 kWh/day and the average load and peak load demand are assessed as 2.69 and 13.72 kW, respectively.

3.1. Technical and economic analysis

The current study simulated a total of 504 options, of which just 360 were feasible and 144 were impossible due to capacity deficit restrictions. Table 4 presents the optimization findings for the SPV/BES resources combination.

To achieve the optimum solution, the SPV of 21 kW rating, 2718 numbers of BES, and a 12kW rating of converter (inverter) are utilized. It can be noticed from the results shown in Table 2 that the optimum values of total NPC and LCOE for SPV/BES-based IRES are 43738.53 \$ and 0.143515 \$/kWh, respectively. The running cost and initial investment cost of the complete SPV/BES IRES are estimated to be 860,0656 \$ and 32,620.02 \$, respectively. The initial cost of a single SPV is \$1,934,91, and its annual energy output is 3,1522.08 kWh. The annual output of BES is 14904.53 kWh per year. BES's normal capacity is 2788.229 kWh/year, while its normal useable capacity is 1672.937 kWh/year. The converter is used as a 2.6912 kW average inverter. The net present value and the yearly value of SPV/BES IRES are 43738.537 \$ and \$ 3383.37 dollars, respectively, according to Table 5, cost overview of IRES components.

SPV (kW)	BES (No.)	Converter (Inverter) (kW)	NPC (\$)	LCOE (\$/kWh)	Operating Cost (\$/year)	Initial Capital Cost (\$)	Energy Production from SPV (kWh/year)	Annual Throughput BES (kWh/year)	Nominal Capacity BES (kWh)	Usable Nominal Capacity BES (kWh)	Converter (Inverter) Mean Output (kW)
21	2718	12	43738.53	0.143515	860.0656	32620.02	31522.08	14904.53	2788.229	1672.937	2.6912
21	2724	12	43779.88	0.143651	861.3758	32644.43	31522.08	14904.52	2794.384	1676.63	2.6912
21	2730	12	43821.22	0.143786	862.6859	32668.84	31522.08	14904.51	2800.539	1680.323	2.6912
21	2718	12.5	43842.55	0.143845	862.867	32687.82	31522.08	14906.8	2788.229	1672.937	2.691427
21	2736	12	43862.57	0.143922	863.9961	32693.25	31522.08	14904.5	2806.694	1684.016	2.6912
21	2724	12.5	43883.9	0.14398	864.1771	32712.23	31522.08	14906.79	2794.384	1676.63	2.691427
21	2742	12	43903.92	0.144057	865.3062	32717.66	31522.08	14904.5	2812.849	1687.709	2.6912
21	2730	12.5	43925.25	0.144116	865.4873	32736.64	31522.08	14906.78	2800.539	1680.323	2.691427
21	2748	12	43945.27	0.144193	866.6164	32742.07	31522.08	14904.49	2819.004	1691.402	2.6912
21	2718	13	43946.57	0.14418	865.6683	32755.63	31522.08	14907.94	2788.229	1672.937	2.691541

Table 4: Optimization results for SPV/BES resource combination

Component of IRES	Capital Cost (\$)	Replacement cost (\$)	O & M Cost (\$)	Salvage Cost (\$)	Total Cost (\$)
Generic 1kWh lead acid Battery (BES)	855.37	328.62	368.59	-103.73	1448.85
Generic flat plate SPV	1542.05	0	199.35	0	1741.40
System Converter	125.88	42.73	32.55	-8.04	193.11
IRES	2523.30	371.35	600.49	-111.77	3383.37

Table 5: Cost summary of the IRES components

In addition, 61.11 percent of such capital cost is borne by SPV, 33.89 percent by BES, and 5 percent by both the converter system. The BES replacement cost is the largest due to its shorter life span of five years, whereas the SPV replacement cost is null due to the SPV's enormous life span, which really is relatively similar to the IRES life of the project of 25 years.

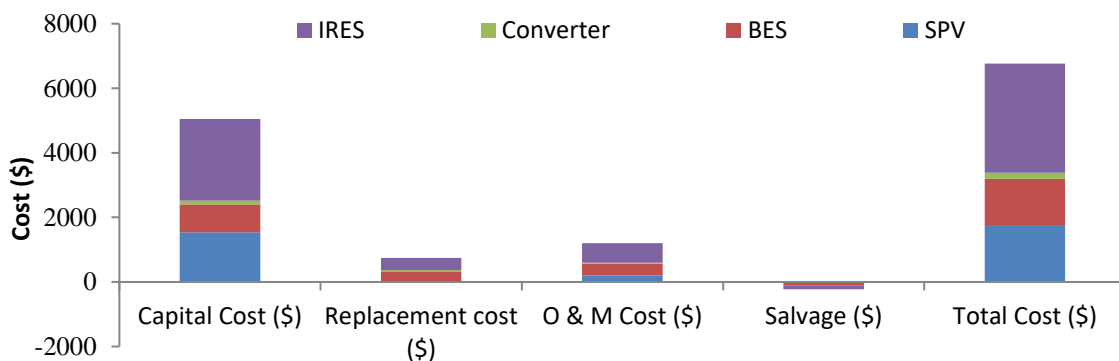


Figure 7: Cost summary of the IRES components

The contract price of the converter is moderately priced and equal to 34% of the capital cost of the converter. The negative character of the BES and converter salvage costs implies that these represent expenditures rather than profits. There is no requirement to replace SPV over the IRES project's 25-year lifespan. Therefore, it has no salvage value. Figure 7 reveals that perhaps the SPV system, BES, as well as converter contributed to 51.47 percent, 42.82 percent, and 5.71 percent of annualized capital cost, respectively. Table 6 details the summary electric results of the planned IRES.

Quantity	kWh/year	%
AC load served	23575	100
Excess electricity produced	4393	13.9
Unmet load	4.08	0.02
Renewable fraction	-	100

Table 6: Electrical results of proposed IRES

The production of energy by IRES is contingent on incident sun irradiation. Annually, the SPV/BES power system generates 31,522 kWh of energy. The annual demand for service load is 23,575 kWh. This value is important enough even to define the SPV/BES system to be self-sufficient for powering the study region. The system capacity deficit is also negligible, with a value of 0.0596%. In October and February, the minimum and maximum power outputs are 3,254.09 kW and 2,034.423 kW, respectively, according to the quarterly power output curve in Figure 8.

The quantity of extra electrical energy produced is a function of the entire area generation and load profile. The surplus power is generated mostly during periods of low load curves and high solar irradiation. The excess electrical energy output for the SPV/BES electric power system is 4,393 kWh/year, or 13.9% of the overall electrical energy generated. This could be

sold or used for commercial purposes. The annually generated excess power is shown in Figure 9.

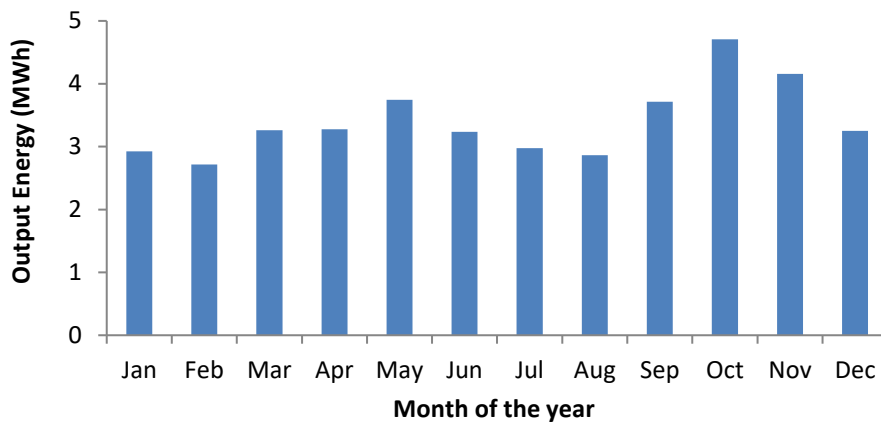


Figure 8: Monthly output energy profile of the SPV/BES

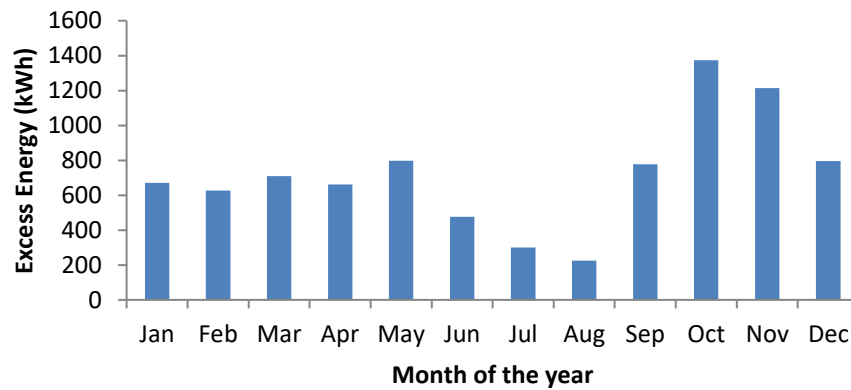


Figure 9: Monthly generated excess energy by the SPV/BES

Further, the accessibility of surplus power and 0.02% unmet load demonstrated that the proposed IRES power system is not just self-sufficient in meeting current energy needs but is also capable of meeting future energy needs in a cost-effective and environmentally beneficial manner.

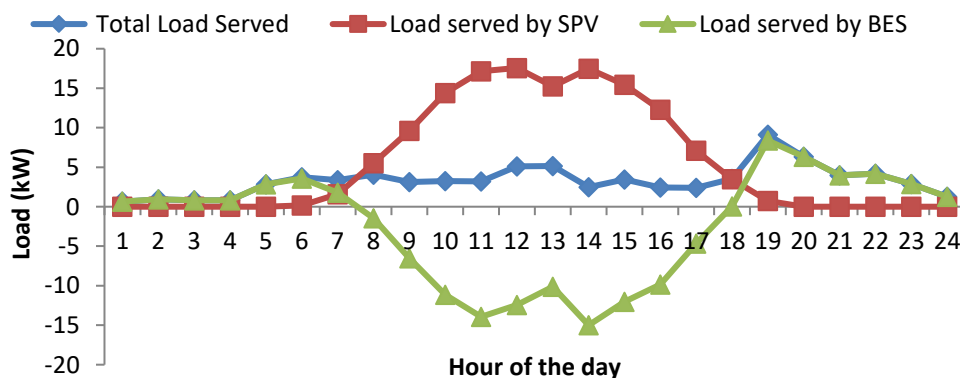


Figure 10: Load shared by the SPV and the BES on a typical day of the month of the June

Figure 10 illustrates the proposed IRES's 24-hour functioning on a normal day during the month of June so that its energy management can be comprehended. SPV serves the load during the day, whereas BES is utilised whenever solar irradiance is unavailable. As depicted in Figure 11, 24-hour demand profile on a typical June day, the BES alone serves the load from

1h to 6h when solar output is unavailable. 7 h to 18 h, when solar irradiance is sufficient, the load is handled by SPV alone and extra energy is used to charge the BES, as seen by the negative load supplied by the BES during this time. Between 18h to 19h, the solar radiation intensity is available but insufficient; therefore, the load is serviced by SPV and BES jointly. From 19h to 24h, there is no sun irradiation; consequently, the entire load is supplied by BES alone.

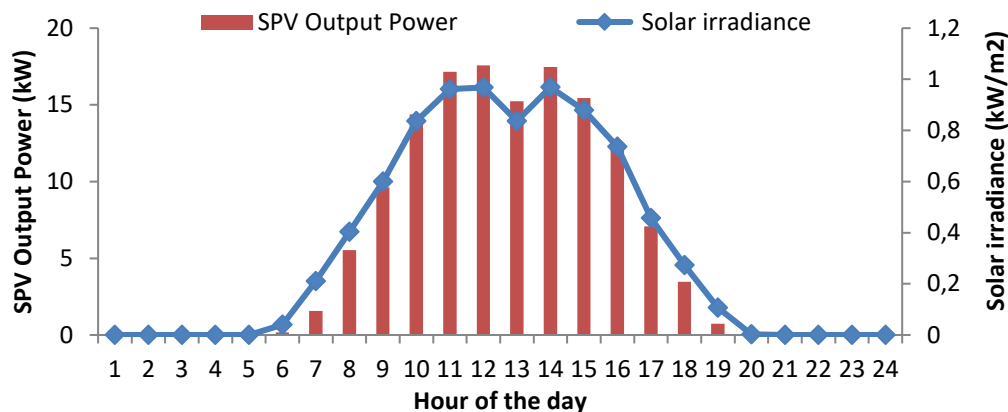


Figure 11: Solar irradiance and the SPV output profile on a typical day of the month of the June

Figure 11 depicts the incident solar irradiation and matching output curve of SPV for a typical June day. According to the results collected, the SPV-rated capacity is 21.0 kW, the average power output is 3.60 kW, the capacity factor is 17.1%, and the total power produced is 31,522 kWh/year. In addition, it is determined that the levelized cost for SPV is 0.143515 \$/kWh with 4,379 operational hours per year.

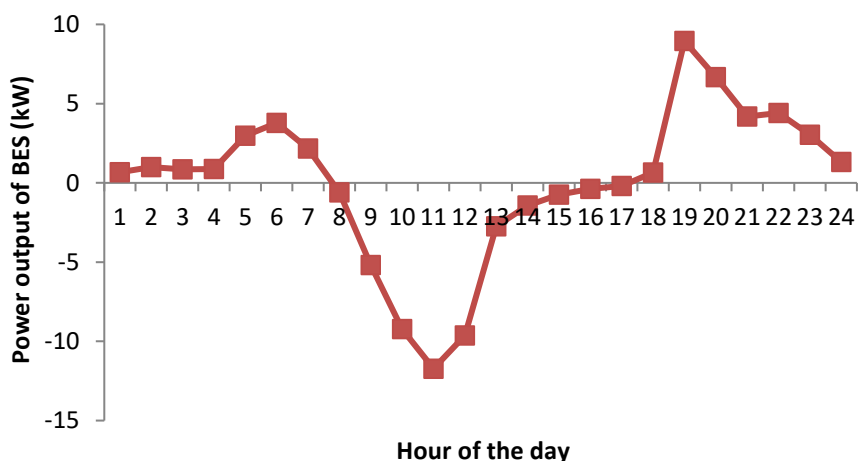


Figure 12: Charging/discharging of the BES on a typical day of the month of the July

Figure 12 depicts the 24-hour charging/discharging cycle of the BES on a typical July day in order to explain the role of the BES in the energy management of the planned IRES. In the lack of sufficient solar irradiation, a very slow discharge between 1h and 4h and a moderate discharge between 4h and 8h are seen. The BES is charged between 8h and 18h, as indicated by the BES's negative output power throughout this time frame. It is discharged gradually between 18h and 24h if the load need is large and cannot be met by SPV production alone.

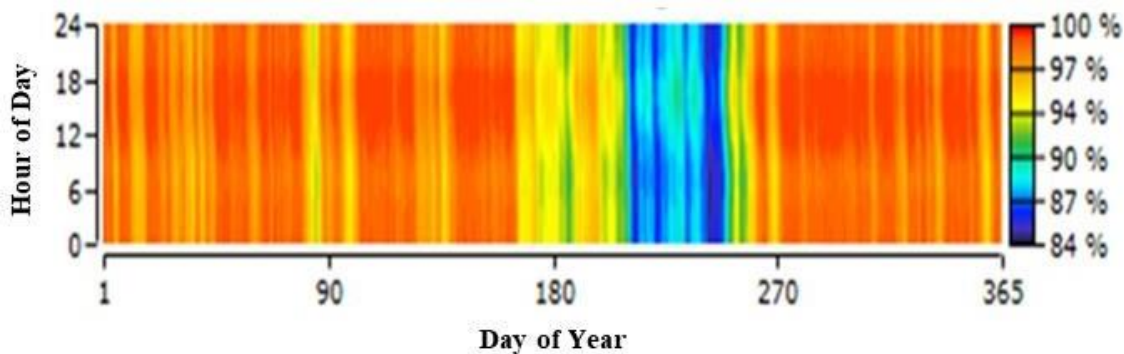


Figure 13: Annually state of charge profile of the BES

Figure 13 depicts the yearly state of charge (SOC) for BES for such SPV/BES IRES system. Input and output energy amounts for BES are 16,051 kWh/year & 13,738 kWh/year, respectively. In contrast, the BES offers a throughput of 14,905 kWh/year with losses arising of 2,426 kWh/year. The overall energy production of the system converter operating in inverter mode during 8760 hours per year is 23,575 kWh per year. It requires a total input energy of 24,816 kWh/year, with losses totaling 1,241 kWh/year. The mean output of the converter and its capacity factor is 2.69 kW and 22.4%, respectively. Presently, the one and only source of electrical power in the community of Dewal is a diesel generator set. Throughout this research, the diesel generator serves as a baseline for comparing the relative performance of designed IRES. According to the simulation results, the payback method of the designed IRES is 8.91 years. In the architecture of IRES, inflation rate increases result in a quick increase in the total cost of the system. Throughout this research, inflation rates ranging from 1% to 6% were employed to determine their impact on system cost characteristics like total NPC as well as LCOE. The data also indicate that an increase in inflation rates resulted in a decrease in the price of energy.

3.2. Comparative analysis with recent renewable study

Due to its fortunate location within the solar belt (40°S to 40°N), India is one of the world's leading recipients of solar energy. India has tremendous potential for solar-powered energy systems. There are numerous remote highland regions in India wherein grid extension is not economically viable. Multiple researches on the economic and technical viability of renewable energy systems for low-load profile areas have been conducted and published in the literature. Efforts have been undertaken to evaluate some of these investigations with the current one, as presented in Table 7.

By implementing the suggested SPV/BES system under the different climatic circumstances of the study area, significantly lower LCOE and NPC values are attained in the current study, as shown by the comparison analysis. These findings are highly relevant for determining investment policies for generating power to the home load in the study region or any other low-load profile location with comparable climatic circumstances.

Reference	System Configuration	Location	Peak Load (kW)	NPC (\$)	LCOE (\$/kWh)
Present study	SPV/BES	Uttarakhand, India	13.72	43738.527	0.1435
Halabi et al. (2017)	PV/WT/BM/DG/BT	Barwani, India	7.8	-	0.1951
Adaramola, Paul, and Oyewola (2014)	SPV/WTG/BGG/BMG/FC/Battery	Karnataka, India	-	8,90,013	0.214
Nag and Sarkar (2018)	PV/WIND/Bio Generator	Korkadu, India	-	16273.393	0.18592
Rajbongshi, Borgohain, and Mahapatra (2017)	PV-BG-PHES-Battery	Silchar city, India	25.54	813,319	0.4864
Shezan et al. (2016)	Solar-Wind-Hydrokinetic-Bioenergy	Jharkhand, India	42.71	605539	0.241
Upadhyay and Sharma (2016)	Photovoltaic/Wind/Biogas/Pumped-Hydro	Sub-Saharan Africa	57.88	448,640.44	0.3100

Table 7: Comparative analysis with similar relevant studies of the recent times

3.3. Comparative analysis with base case 1 and 2

Oil prices in the country are highly volatile due to global factors, including international crude oil prices, currency exchange, as well as inflation rates. As of July 12, 2020, diesel costs 1.02 dollars per litre in the research region. For the purpose of validating the effectiveness of the proposed IRES, its efficiency is also compared to that of two base cases. For base case-1, a diesel generator is examined for electricity supply to the study region. For base case-2, a diesel generator and a battery energy storage system are evaluated. Table 8 contains the technical details of the diesel generator under evaluation.

In addition, as indicated in Table 9, a comparative cost study between base cases-1 and 2 and the proposed IRES has been conducted.

Component	Capacity (kW)	Fuel	Fuel curve intercept (liter/hour)	Fuel curve slope (liter/hour/kW)	Initial capital cost (\$/kW)	O&M cost (\$/hour)	Fuel price (\$/liter)
Diesel Generator	14	Diesel	0.783	0.236	500	0.03	1.002

Table 8: Technical specification of the diesel generator

Case	NPC (\$)	LCOE (\$/kWh)	Operating cost (\$)	Initial capital cost (\$)	O&M Cost (\$/Year)
SPV/BES	43738.53	0.143	860.0666	32620.02	6008.49
Diesel Generator	296014.8	0.97112	22356.56	7000	3679.2
Diesel Generator/BES	152406	0.4999	10252.56	19865.84	834.12

Table 9: Comparative cost analysis between the base cases and the proposed IRES

In the obtained results for base case-1 of Damien electricity production, the LCOE, total NPC, as well as operating costs are predicted to be \$0.97112/kWh, \$29,6014.80, and \$22356.56 year, respectively. For base case-2 of DG/BES, the LCOE, overall NPC, as well as operating costs

are estimated to be 0.49 cents per kWh, \$1,524.06 per megawatt-hour, and \$10,252.56 per year, respectively. Initial capital expenditures for base scenario 1 and 2 are determined to be \$7000 and \$1,865.84, respectively. Table 10 provides a comparative analysis of emissions for base cases 1 and 2 as well as the proposed IRES.

Cases	Diesel (liter/yr.)	Carbon Dioxide (kg/yr.)	Carbon Monoxide (gm./yr.)	Unburned Hydrocarbons (gm./yr.)	Particulates (gm./yr.)	Nitrogen Oxides (gm./yr.)	Total harmful gas emission (kg/yr.)
Proposed IRES	0	0	0	0	0	0	0
Base case-1(DG)	14800.98	38820.86	244216.2	10656.706	1480.098	229415.2	39306.63
Base case-2 (DG/BES)	8112.673	21278.38	133859.1	5841.1245	811.2673	125746.4	21544.64

Table 10: Comparative Emission Analysis

Case-1 requires a total of 14800.98 litres of diesel per year and emits 38820.86 kg/year of carbon dioxide, 244216.2 grams/year of carbon monoxide, 10656.7056 grams/year of unburned hydrocarbons, 1480.098 grams/year of particulates, and 229415.2 grams/year of nitrogen oxides. For running base case-2, the total diesel consumption is 8112.673 liters/year, and so it generates 21278.38kg/year of carbon dioxide, 133859.1 grams/year of carbon monoxide, 5841.1245 grams/year of hydrocarbon emissions, 811.2673 grams/year of particulates, plus 125746.4 grams/year of nitrogen oxides. The comparative emission analysis demonstrates that within base case-1 and base case-2, the releases of dangerous greenhouse gases such as CO₂ monoxide, hydrocarbons, nitrogen oxides, etc., are extremely high, but in the case of the proposed IRES, there are no greenhouse gas emissions. The comparative study of Table 5 and Table 6 reveals that the proposed IRES generates electricity at a significantly lower value of LCOE, NPC, and operating cost to zero greenhouse gas emissions but also guarantees the saving of at least 14,800 litres of diesel fuel and reduction of approximately 21545kg/year of overall harmful greenhouse gases in the climate of the region of the study region in comparison to base case-1 and base case-2.

4. Conclusions

The objective of this study was to evaluate the technical and economic viability of a solar photovoltaic/battery energy storage off-grid integrated renewable energy system for low load profile hilly isolated areas, such as the village of Dewal, Mori block in Uttarkashi district, Uttarakhand, India. Using HOMER Pro software was utilized to size resource components optimally in order to create a cost-effective power supply for the research area. The LCOE and total NPC for SPV/BES-based IRES are 0.143 dollars per kWh and 43738.53 dollars, respectively. Using the suggested SPV/BES-based IRES reduces the LCOE to 14.8% of the DG-only system and 28.8% of the DG-plus-batteries system. NPC is reduced to 14.7% of the DG-only system and 28.7% of the DG-plus-battery system. In the SPV/BES function, 4,393 kWh/year of extra energy is generated at 0.02 percent of the unmet load. This surplus electricity could be sold or used for commercial purposes. By implementing the suggested SPV/BES operations, diesel fuel consumption and GHG emissions can be decreased from a minimum of 8113 liters/year and 21545 kg, respectively. In conclusion, an SPV/BES-based IRES is proposed for powering the study region or other hilly, isolated areas. Not only is it capable of powering the study area alone, but it can also partially meet future energy demands in an inexpensive and environmentally responsible manner. In conclusion, an SPV/BES-based IRES is proposed for powering the study region or other hilly, isolated areas. Not only is it capable of powering the study area alone, but it can also partially meet future energy demands in an inexpensive and environmentally responsible manner. This research does not cover the

concept of required financial subsidies and land costs for siting IRES, which may be incorporated in future studies.

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Nomenclature			
S	Salvage cost (residual value)	AC_t	Total annualized cost
I	Solar irradiance (kW/m ²)	$P_{BES,min}$	Minimum power capacity
A	Solar panel area (m ²)	$P_{BES,max}$	Maximum power capacity
D	Discount rate (%)	SOC_{min}	Minimum state of charge
l	Life of project (years)	SOC_{max}	Maximum state of charge
CO_2	Carbon dioxide	RES	Renewable Energy Sources
AC	Total annualized cost of IRES	GHG	Greenhouse gas
$E_{NS}(t)$	Total energy not supplied in t th time hour	RC	Replacement cost of IRES components
$P_{SPV}(t)$	Total power output of SPV	HRES	Hybrid Renewable Energy System
$P_{BES}(t)$	Total output power of battery energy storage	DG	Diesel generator
$P_{NS}(t)$	Power not supplied	E_{MAX}	capacity of storage (kWh)
$G(t)$	Solar irradiance at t th time hour	NASA	National Aeronautics and Space Administration
$P_{NS}(t)$	SPV rated output power in standard condition	IRES	Integrated Renewable Energy System
G_{STD}	Total standard solar irradiance	O&M	Operational and maintenance
R_C	Cut in value of irradiance point	CRF	Capital recovery factor
η_{SPV}	Efficiency of solar panel (%)	SPV	Solar Photovoltaic
η_{INV}	Inverter efficiency	BES	Battery Energy system
l_R	Remaining life time	LCOE	Levelized Cost of Energy
l_t	Total life time	NPC	Net Present Cost
β_C	Maximum charge rate (A/Ah)	m	storage rate constant (h ⁻¹)
C	Capacity ratio	I_m	maximum charge current (A)
		V_m	nominal voltage of the battery