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Design and Operation of Isolated Hybrid Energy System for Sensitive Loads with Consideration of Uncertainties in Resources and Demand

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ABSTRACT

This paper focuses on the optimal design and operation of isolated hybrid energy system supplying sensitive loads, considering uncertainties in renewable resources and demand. The study uses Homer software to determine the optimal combinations of system components and their operation conditions. Renewable resources and load uncertainties are investigated in the form of multiple possible scenarios. The cost equilibrium index (CEI), as a decision making index, is proposed to compare the isolated hybrid energy system with grid development. It could facilitate deciding either develop the grid or create an isolated system based on local energy resources for remote loads. As a case study, design and operation of an isolated hybrid energy system are accomplished for a gas pressure-boosting station in Hamadan, Iran. The results show that the proposed system could supply sensitive loads with adequate reliability and reduce carbon dioxide emissions. According to CEI, the isolated system could be economical for loads 100km far from the grid. This study implies isolated hybrid energy system could improve passive defence considerations for sensitive load in contrast to cost of system. Also advancement of renewable technologies and restructuring the energy system would lead to promotion of hybrid isolated energy system in future.

1) Introduction

In recent years, renewable energy technology has advanced and the cost of producing electricity from these resources has decreased. But for many countries with fossil fuel resources, switching to renewable resources for electricity production is not economical. Of course, grid developing for remote loads is costly too. Additionally, connecting sensitive loads to the network poses a security risk in case of natural disasters or attacks. An isolated hybrid energy system is a microgrid using renewable resources alongside other distributed generations and storage technologies, which does not have access to the grid. It can be an effective solution to meet the demand of sensitive loads while achieving passive defense, economic, and environmental protection goals.

Several studies have proposed hybrid energy system to supply local loads as an alternative to grid development [1-8]. This solution has been submitted and investigated as an alternative to grid development to supply local loads such as remote villages [9], islands [2,5], water supply stations [10] and telecommunication stations [11,12].

HOMER (Hybrid Optimization Model for Electric Renewable) is a popular software tool to evaluate economic and technical models for hybrid systems and was developed by the US National Renewable Energy

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Laboratory (NREL)[13]. Many literatures reviewed in this paper is evaluated based on HOMER [1-11].

Although developing isolated hybrid energy systems has several advantages, but it also may be challenging due to uncertainties in system parameters. The rise in renewable energy resources share, further exacerbates this issue by increasing the tension in the system's reliability. The uncertainty issue is not solely limited to renewable sources; the hourly energy demand also faces by uncertainty. Coinciding uncertainties in energy production and demand might result in energy imbalance during operation. Consequently, addressing uncertainty in isolated systems and its impact on economic performance and reliability, has become a vital research topic in this field [14]. The optimal operation of a microgrid is investigated by factoring in uncertainty and considering both the robustness and economic aspects of the system [14]. In [15], a study on transmission network development planning was conducted, which involved the creation of mathematical models and solution techniques. The models were designed to consider uncertainty in demand and genetic algorithm is used for optimization. The impact of wind energy on the connection between the electricity and natural gas grid, particularly in the presence of wind power plants and gas turbines, was studied in [16]. Several studies have also considered the influence of variable renewable resources in grid development planning, as seen in [17]. Furthermore, researchers have taken an interest in optimization strategies that involve renewable resources and methods to mitigate the effects of uncertainty in the system, as discussed in [18].

Conventional methods considering uncertainty in renewable energy resources, often result in over investment due to excessive reliance on these resources. Typically, two approaches are used to determine the size of renewable resources. The first approach involves selecting the worst-case scenario to determine the system parameters and ensure system reliability. The second approach involves calculating system parameters for a typical design and then adding a safety factor (greater than one) for uncertainty parameters based on the designer’s expert opinion [19]. Energy management is a supplementary approach for covering uncertainty when system id operating. The grid can efficiently schedule power resources and energy storage through system energy management to balance supply and demand. Also, accurate models and precise prediction could attenuate the effect of uncertainties. Recently machine learning algorithms are commonly used to enhance accuracy and optimize system operation [18].

Designing multiple scenarios based on fluctuating probabilities of renewable energies is another approach when the parameters of a system cannot be predicted certainly. This approach deviates from a deterministic process that assumes complete knowledge of parameters such as wind speed, solar radiation, and load demand. Instead, probability distribution-based methods have been incorporated to model potential system characteristics [20].

In conclusion, neglecting uncertainties in renewable resources and energy demand can significantly reduce the system's reliability, which is crucial for sensitive loads. In connected cases, the grid acts as a backup in condition of production and consumption imbalances. Still, this conflicts with the principle of dispersion in passive defence and can compromise the security of sensitive loads. An isolated hybrid energy system is a viable solution for securing sensitive loads. However, designing such a system requires strengthening to compensate its uncertainty. Despite extensive studies on the design of hybrid renewable systems, it needs more attention to the simultaneous uncertainties of resources and demand for sensitive loads in isolated systems. Also it seems lack of overview for decision makers to make an initial decision, either develop the grid or create an isolated system in the case of remote loads. This study aims to address these research gaps.

This paper proposes a decision and design framework for developing a cost-effective hybrid energy system isolated from the grid to supply sensitive loads while considering the uncertainty of resources and demand. For this purpose, Homer software was utilized to develop a plan for optimal design and operation of an isolated microgrid, incorporating climatic conditions, demand situations, and all investment and operation costs throughout the project's lifespan. Then, the overall cost of the system is compared with grid development to find out if the proposed system is more economical or grid development. Due to Homer outputs, cost equilibrium index (CEI), is utilized as a decision making index, to promote decision makers overview to find the best choice between isolated system and grid development. CEI is based on finding distance of the load from the grid which the grid development and hybrid system were economically equivalent. Considering uncertainties, multiple scenarios were defined, each with a different fluctuation coefficient for resources and demand.

A case study was conducted at the Faminin gas pressure boosting station in Hamadan province as a sensitive remote load. Combination of safety factor and scenario building was used to consider the uncertainty of renewable resources and demand. Results were compared to network development using CEI.

Briefly, the contributions of this study are a) running a real case for optimal design and operation of a hybrid energy system, considering comprehensive parameters, b) presenting a decision making framework based on CEI, and c) studying the uncertainties of input parameters by scenario planning based on optimal design and operation plans composed by Homer.

The subsequent section focuses on creating a model for the hybrid energy system, followed by a case study in the third section. The fourth section presents the results and discussions, and the fifth concludes the study.

2) Design of hybrid energy system

An isolated hybrid energy system is a microgrid using renewable resources alongside other distributed generations and storage technologies which does not have access to the grid. Energy storage systems are used as backup of generation and a converter is also employed to link the DC and AC components of the system. Solar and wind energy sources are commonly used for renewables, while diesel generators and gas engines are the most common fossil fuels resources. Chemical batteries are currently the primary method of energy storage. Due to the high cost of renewable technologies and the necessity of meeting energy demand, along with technical and environmental considerations, it is crucial to design an optimal plan for hybrid energy systems. The goal of the optimal design is to determine the type and capacity of components that meet the system's objectives without violating constraints. The primary objective is typically economic. Technical and environmental objectives usually modelled in terms of cost or as system constraints. This paper investigates design a hybrid energy system based on local energy resources to supply sensitive loads. HOMER software was used to design the system considering variety of economic, environmental, technical and geographical parameters. To model uncertainties of renewable resources and demand, 9 scenarios are defined and analysed by assuming the different maximum fluctuation levels of inputs. Finally, the results are compared to grid development by CEI. For design the optimal plan, Homer uses the following technical, economic, and environmental models.

2.1) Economic modelling

Various economic indicators could be used to evaluate energy projects. The most important indicators which are used in this study are the net present value and total energy costs.

2.1.1. Net present cost

The net present cost (NPC) of a system is determined by adding up all its expenses and subtracting its revenues considering the time value of money. The prices of the energy system consist of the initial investment, fuel, maintenance, purchase of electricity from the grid, and pollution fines. Incomes include the sale of electricity and the salvage value of the equipment. Equation 1 calculates the present value of the project according to cash flow. The real interest rate is calculated due to nominal interest rate, using equation 4 [13].

$$NPC = \frac{C_{A-ann}}{CRF(i,n)} \tag{1}$$

$$C_{A-ann} = C_{A\_cap} + C_{A\_rep} + C_{A\_o\&m} \tag{2}$$

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3}$$

$$i = \frac{i' - f}{1+f} \tag{4}$$

where C_{A-ann} is the total annual cost, C_{A_cap} is the annual investment cost, C_{A_rep} is the annual replacement cost, $C_{A\_o\&m}$ is the annual operation and maintenance cost, i' is the nominal interest rate, f is the inflation rate, and n is the project lifespan.

2.1.2. Total energy cost

Total cost of energy (COE) represents the average cost of each kwh of useful energy produced during the life of the project, which can be calculated using Equation 5 [21].

$$COE = \frac{C_{A-ann}}{E_{prim}} \tag{5}$$

where E_{prim} represent total annual energy production.

2.2) Environmental modelling

The production of electricity from fossil resources leads to the emission of environmental pollutants which is calculated based on the equation 6 [13].

$$annual\ plant\ emission = afc * ef_p \tag{6}$$

In this equation, ef_p is emission factor of the fossil fuel power plant and afc is the annual fuel consumption. To make a comparison between the proposed system and grid development, it is necessary to calculate the carbon dioxide emissions that would result if the grid met the demand. Most large power plants in the national grid utilize fossil fuels, and the emissions from these fuels can be calculated using Equation 7.

$$annual\ grid\ emission = ngp * ef_g \tag{7}$$

where ef_g is the emission released per kWh and ngp is the annual energy production from grid.

2.3) Technical modelling

2.3.1. Solar system modelling

Eq.8 has been considered to model the output power of the solar system (P_{pv}) [20].

$$P_{pv} = Y_{pv} \cdot f_{pv}\left(\frac{G_T}{G_{T.STC}}\right)[1 + \propto_p (T_c - T_{c.STC})] \tag{8}$$

The given parameters are used to calculate the output power of a solar panel in the simulation. Y_{pv} represents the nominal capacity of the solar arrays in kilowatts (*kw*). The reduction factor, f_{pv}, considers the effect of heat, dust, and other factors on the panel's efficiency and is expressed as a percentage. The intensity of incoming radiation on the panel's surface in each simulation time step is represented by G_T in kilowatts per square meter (*kw/m*^{2}). In contrast, $G_{T.STC}$ represents the radiation intensity in standard test conditions (*kw/m*^{2}). The temperature coefficient on output power is defined by $\propto_p$ in degrees Celsius per percentage (*C°/%*), and T_c represents the cell temperature in each simulation time step in degrees Celsius (*C°*). $T_{c.STC}$ indicates the cell's temperature in standard test conditions in *C°*.

2.3.2. Wind turbine modelling

Figure 1 illustrates the harnessed power from wind by wind turbine in four regions, which are categorized based on the wind speed: below the cut-in speed, up to the nominal speed, up to the cut-out speed, and over the cut-out speed. Equation 9 [22-25] is used to determine the turbine power within each region.

$$P_{WG} = \begin{cases} 0 & ;\ V_w \le V_{cutin}, V_w \ge V_{cutout} \\ P_{WG,max} \times \left(\frac{V_w - V_{cutin}}{V_{rated} - V_{cutin}}\right)^3; & V_{cutin} \le V_w \le V_{rated} \\ P_{WG,max} + \frac{P_{furl} - P_{WG,max}}{V_{cutout} - V_{rated}} \times (V_w - V_{rated}); & V_{rated} \le V_w \le V_{furl} \end{cases} \tag{9}$$

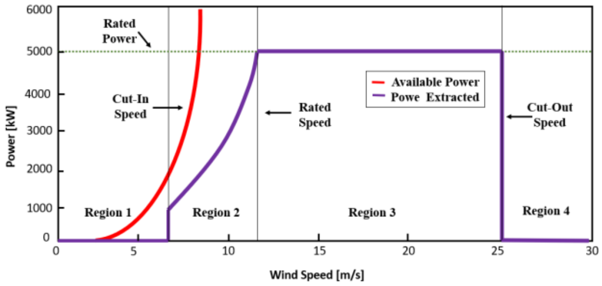

Fig. 1. Wind turbine power [26]

Variables used to determine the output power of a wind turbine include output power of the wind turbine (P_{WG}), wind speed (V_w), the minimum wind speed required to start the turbine (V_{cutin}), the maximum wind speed at which the turbine can operate (V_{cutout}), the maximum output power of the turbine ($P_{WG,max}$), and the output power during periods of high wind speed (P_{furl}). Furthermore, Equation 10 calculates wind speed:

$$V_w^h = V_w^{ref} * (\frac{h}{h_{ref}})^{\propto} \quad (10)$$

where V_w^h indicates wind speed at height h, V_w^{ref} represents the wind speed at the measuring height h_{ref} and $\propto$ is a constant coefficient of the relationship.

2.3.3. Diesel generator

The relationship between the energy produced by the diesel generator and its fuel consumption has been defined in equation 11 [13].

$$F = F_0 \,.Y_{gen} + F_1 \,.P_{gen} \quad (11)$$

where, F_0 indicates y-intercept of the fuel curve, F_1 is the fuel curve slope, Y_{gen} is the rated power of the diesel generator and P_{gen} is the generated power of the diesel generator.

2.3.4. Converter

Power electronic converters are required to integrate storage devices and some renewable resources, such as photovoltaic systems, into the AC network. However, converters result in energy loss depending on their efficiency ratio when converting DC to AC and vice versa. Equation 12 formulates the calculation of converters' efficiency ratio [27].

$$\eta_{inv} = \frac{\rho}{\rho + \rho_0 + k\rho^2} \quad (12)$$

Where k and ρ_0 are constant values of the converter. ρ represents reduced power and is calculated using following equation. $P_{out,inv}$ and $P_{rated,inv}$ indicates the converter's output power and rated power, respectively.

$$\rho = \frac{P_{out,inv}}{P_{rated,inv}} \quad (13)$$

2.3.5. Battery

Equations 14 and 15 provide the battery model for charge and discharge conditions. Equation 14 calculates the maximum power the battery can absorb, while Equation 15 determines the total power discharged from the battery [13].

$$P_{batt,cmax,kbm} = \frac{kQ_1.e^{-k\Delta t} + Qkc(1-e^{-k\Delta t})}{(1-e^{-k\Delta}) + c(k\Delta t - 1 + e^{-k\Delta t})} \quad (14)$$

$$P_{batt,dmax,kbm} = \frac{-kcQ_{max} + kQ_1 e^{-k\Delta t} + Qkc(1-e^{-k\Delta t})}{(1-e^{-k\Delta}) + c(k\Delta t - 1 + e^{-k\Delta t})} \quad (15)$$

After calculating the actual charging and discharging power, it calculated the amount of available energy at the end of each simulation with the following equations.

$$Q_{1,end} = Q_1.e^{-k\Delta t} + \frac{(Qkc - P)(1-e^{-k\Delta t})}{K} + \frac{Pc(k\Delta t - 1 + e^{-k\Delta t})}{K} \quad (16)$$

$$Q_{2,end} = Q_2.e^{-k\Delta t} + Q(1-c)(1-e^{-k\Delta t}) + \frac{P(1-c)(k\Delta t - 1 + e^{-k\Delta t})}{K} \quad (17)$$

Where Q_1 is the battery accessible energy at the beginning of each time step *(kWh)*, Q_2 is the battery energy at the beginning of each time step, Q is the total amount of energy in the battery at the beginning of each time step, k is the constant rate, c is the battery capacity ratio, Δt is the simulation time step, Q_{max} is the total capacity of the battery bank, and P is the input or output power to the battery bank.

2.4) Cost equilibrium index (CEI)

The distance between the load and the main grid is a key factor that impact on economic feasibility of the hybrid system. To consider this factor, cost equilibrium index (CEI) has been proposed in Homer as is described in equation 18. It evaluates the economic aspect of the plan in comparison to grid development. CEI is the distance between the load and grid where the total cost of the grid development equal to the total cost of the hybrid isolated system during the lifespan of project. So if the distance between the load and the network exceeds CEI, construction the hybrid system is economical. If not, extending the grid would result in lower costs.

$$CEI = \frac{C_{NPC} \,.\, CRF(i, R_{pro\,j}) - C_{power} \,.E_{demand}}{C_{cap} \,.\, CRF(i, R_{pro\,j}) - C_{om}} \quad (18)$$

In this Equation, C_{NPC} represents net present cost of the hybrid system, $R_{Pro\ j}$ is the project lifespan, C_{power}, is the tariff of electricity selling by grid, E_{demand} is the annual energy demand, C_{cap} shows the investment of grid, and C_{om} is the maintenance cost of grid.

3) Case study

This section investigates the feasibility of an isolated hybrid energy system to supply sensitive loads in a real case. The proposed method is implemented to design the system for the Faminin gas pressure boosting station in Hamedan province. Various scenarios are presented and analyzed, considering the parameters' uncertainty. The main objective of this study is to create a hybrid energy system that can effectively meet the station's energy demand in different circumstances. The study is based on a project with a 20-year lifespan and is conducted with an interest rate of 24% and an inflation rate of 30%, reflecting the current economic conditions in Iran.

3.1) Faminin pressure boosting station

Gas pressure boosting stations are crucial locations where gas passes through to be pressurized and prepared for transmission. The compressing process is achieved periodically through compressor units. Faminin station is a gas pressure boosting station responsible for gas transmission. It boosts three pressure-boosting units, one of which is reserved, and the activated units depends on the gas pressure of the transmission pipeline. A compression turbine (compressor) is employed to increase pressure, which is powered by natural gas.

3.2) Description of the proposed hybrid energy system

Figure2 illustrates the proposed hybrid energy system, including electric loads, energy resources, production and storage units in the station. The system relies on solar panels, wind turbines, and diesel generators as its power sources, with a battery bank serving as backup and energy storage. DC/AC converters have been utilized as charge controllers to regulate and convert power. The following sections will provide detailed information regarding each component of the system.

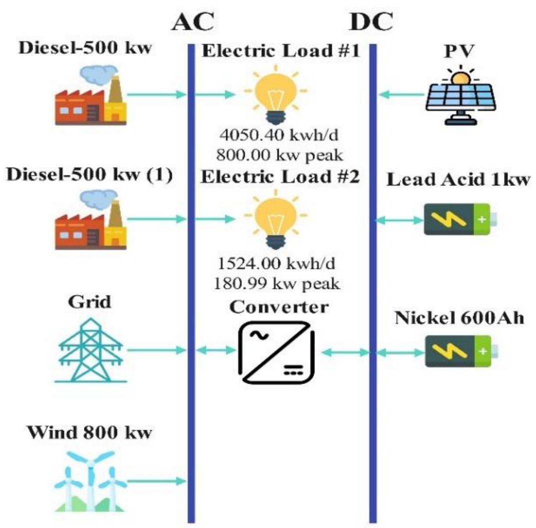

Fig. 2. Structure of the proposed system

3.3) Load of the pressure boosting station

The gas transfer station has two categories of loads: base load and unit load. The base load is a regular consumption of the station to basic functions. In contrast, unit loads are additional consumers that only operate during gas transmission operations to either increase gas pressure or decrease its temperature. The base loads of the station include lighting, cooling, ventilation, administrative tasks, a 90kW air compressor, and instrumentation equipment. For about 70% (8 months) of the year, no units are active in the station, and only the base load is connected. The daily consumption of the base load is logged and illustrated as daily load curve for both warm and cold seasons in Fig 3.

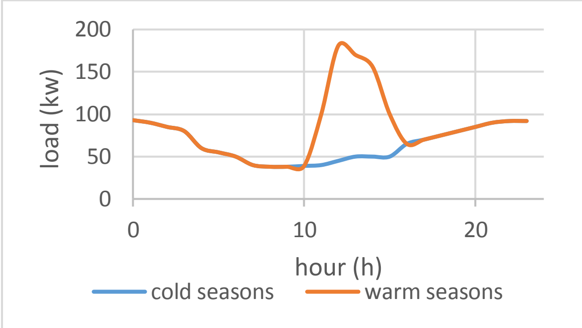

Fig. 3. Daily load curve for base load

The electrical equipment of the unit comprises two sets of 37kW cooling fans, two sets of 45kW starting motors, one set of 10kW oil cooler, two sets of 2.2kW turbine and lubrication pumps, a set of 0.75kW lubrication pump for turbine, and one set of 11kW lubrication pump for compressor. When turbine operates, the gas pressure and temperature increase and 4 to 5 units of 37kW gas cooling fans may be required or 8 to 10 units if both sets are active simultaneously. Under the operating conditions of the Faminin station, only one unit is active for about 25% of the year (3 months) due to the activity of the upstream gas pressure boosting station in the gas transmission network. The peak load during this time is approximately 500kW. Also two units are activated only about a month of year with 1000kW peak load. The load profile for one and two operational units is illustrated in Figure 4.

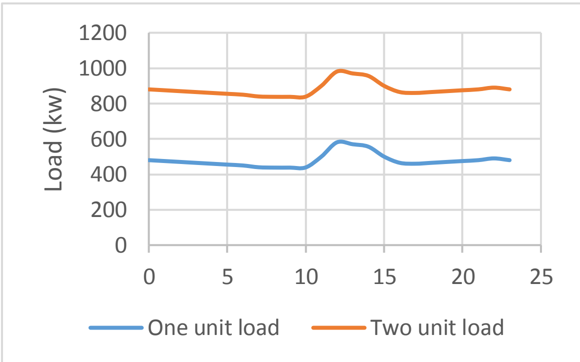

Fig. 4. Daily load curve in the condition of one and two units being active.

3.4) Energy resources

In Homer software, required data of energy resources, such as long-term average solar radiation and wind intensity, have been extracted from the NASA meteorological database based on the geographical location of the Faminin station. Figure 5 displays the radiation data for each month, including the average daily radiation and transparency index. The transparency index is a ratio that ranges from zero to one and represents the ratio of solar radiation received by the Earth's surface to the solar radiation received by the atmosphere. Figure 6 shows the monthly average wind speed for different months of the year in Hamadan province.

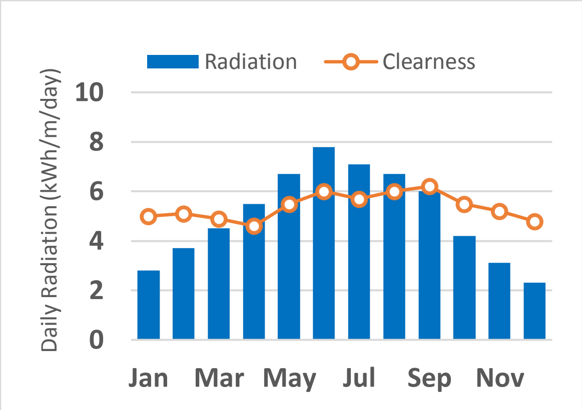

Fig. 5. Solar radiation in Faminin station.

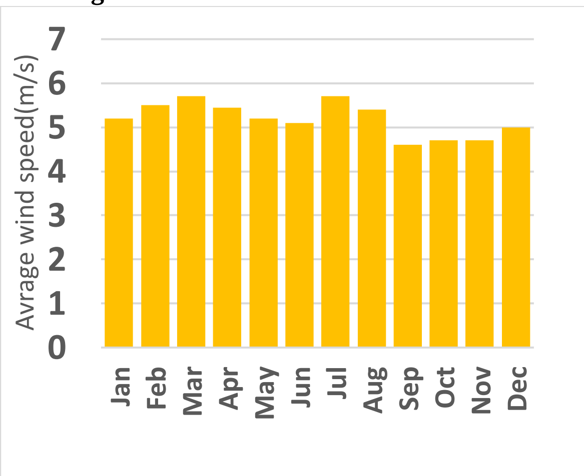

Fig. 6. Monthly average wind speed in Faminin station

3.5) Energy system components

3.5.1. Photovoltaic panel

The study employs photovoltaic systems as one of the prevalent sources of renewable energies. Specifically, it utilizes 330-watt AE SOLAR polycrystalline panels with an 18% efficiency and 20-year lifespan, experiencing an annual production decline of 4%. In the Iranian market, small-scale panels cost 400 dollars, and large-scale panels cost 330 dollars per kilowatt. Moreover, an annual maintenance cost of one dollar per kilowatt is considered. The software will calculate the optimal solar system capacity based on its technical and economic data.

3.5.2. Wind turbine

Wind turbines are a renewable energy source that can generate medium to high-capacity power depending on wind conditions. For this study, a wind turbine unit has a capacity of 80kW and a height of 30m, with a nominal speed of 13m/s and a useful lifespan of 20 years. This study also investigates the optimal number of turbines required. The initial capital cost of a turbine is 80,000 dollars. The software calculates the optimal number of turbines needed to achieve the desired output.

3.5.3. Diesel generator

In order to compensate variations of renewable resources, the proposed system includes a generator fuelled by diesel. Initially, the optimal capacity of the diesel generator was determined through software simulation, resulting in a capacity almost equal to peak consumption. To further enhance the system's performance and reduce costs while increasing manoeuvrability, two units with 50% peak capacity were utilized instead of a single unit with equivalent peak capacity. The software also determined the ideal operating conditions for these generators.

This study considers Volvo diesel generators with a lifespan of 80,000 hours and a capacity of 500 kVA, with an initial capital cost of $59,000 based on price inquiry. After 1000 hours of operation, periodic repairs are needed, costing $200, and overhaul is required every 30,000 hours at $10,000. The cost of diesel fuel is 1.0 cent per litter.

3.5.4. Battery

Employing a storage device is a viable approach to ensure the efficient utilization of renewable resources. This research evaluated two types of batteries (lead-acid and nickel-cadmium) based on their technical and economic characteristics to determine the optimal number of each battery. each lead-acid battery have a 1kWh capacity, $150 cost, and negligible maintenance. Its useful lifespan is five years. Nickel-cadmium batteries have a capacity of 0.72kWh per unit and cost $900. Their lifespan is 20 years.

3.5.5. Converter

The converter in the suggested system regulates battery charging and facilitates the exchange of energy between AC and DC buses. GROWATT converter is considered in this study which boosts a capacity of 1kW, a 20-year lifespan, and a maximum efficiency of 97.1%. The software will calculate the optimal number of converters needed for meeting the desired output. Each converter incurs capital cost of $250 and does not require significant maintenance expenses.

Table 1 provides a summary of the technical and economic features of the system components. To compare isolated system with grid development, a 20kV feeder is considered for grid development with the cost of $24,000 per kilometre.

Table 1: Technical and economic features of the system

Component	Size (kW)	Investment cost ($)	Replacement cost ($)	Maintenance cost ($/year)	Lifetime (year)
PV	1	400	400	1	20
Wind turbine	80	80000	80000	5	20
Diesel generator	500	59000	59000	200 ($/1000 hours)	20
Battery (lead-acid)	1	130	130	0	5
Battery (Ni-Cd)	0.72	900	900	0.2	20
Converter	1	250	250	0	20
Grid	1	24000	-	40	-

3.6) Defining scenarios including uncertainties

Planning and operation of hybrid energy systems contain inherent uncertainty of resources and load. In this paper, uncertainty of resources and load are defined by maximum fluctuations of renewable resources and peak of demand. As the base case, it is assumed a medium level of uncertainty for resources and load. To investigate the impact of uncertainty on system design, three scenarios are defined: no uncertainty, medium uncertainty, and high uncertainty. Fluctuations of resources are assumed to be 0%, 15%, and 30% for solar and 0%, 30% and 60% for wind sources in the three scenarios respectively. Also, load uncertainty levels in the scenarios are defined by the possibility of demand peak changes in three fluctuation states respectively: 0%, 5%, and 10%. Combination of uncertainties of resources and demand composes nine different scenarios as investigated in this study.

3.7) Simulating proposed hybrid energy system

Optimal design and operation of the hybrid system is simulated using Homer software, which uses energy balance equations and simulate various modes of operation over the project's lifetime. Homer also determines the best start-up times for systems that consist of batteries or generators and provides all possible configurations that can meet the user's electrical demand under desired conditions. After simulating thousands of solutions, Homer presents a sorted list of configurations based on their NPC.

4) Results and discussion

4.1) Base scenario results

Using Homer software, an analysis was conducted to identify the most cost-effective solution supportting the system load while adhering to the technical constraints of the system. The simulation created 199 thousand possible solutions. The most technically feasible options are then filtered further, leaving around 30,000 solutions ranked by NPC value of the project. The most cost-effective solution ultimately chose as outlined in Table 2.

Table 2: Components of the optimal hybrid system.

Component	PV	diesel generator	Lead acid battery	converter
Capacity	1161 (kw)	2*500 (kw)	2321 (quantity)	550 (kw)

The project's net present worth is 2.8 million dollars and COE is approximately 4 cents per kilowatt-hour. According to *equation 18*, in this project the CEI is 102km. This means the investment is enough to construct a102km long 20kV line. Therefore, grid development will be cheaper if the load is within 102 km of the nearest grid substation. However, if the distance between load and grid is more than 102 km, building a hybrid energy system would be more cost-effective. It is important to note that this approach is practical only in specific locations, as the access to national network is less expensive in most parts of the country. The high cost of renewable energy and storage devices In addition to low tariff of electricity significantly contributes to this issue. Table 3 provides a breakdown of the expenses by type and system components. During the project's lifetime, the most expensive components are batteries, followed by the relatively high cost of installing solar panels. Although wind turbines have low uncertainty, their high price has rendered them uneconomical for this project. The hybrid energy system has a notably low operating cost. Still, the acid batteries have a short lifespan and require replacement every five years, result to increase cost of the system.

Table 3: Economic features of the base scenario.

Component	Capital 10^3 $	Replacement 10^3 $	O&M 10^3 $	Fuel 10^3 $	Salvage 10^3 $	Total 10^3 $
Diesel (1)	59	116	142	130	69	378
Diesel (2)	59	0	142	15	111	105
PV	364	0	40	0	0	404
Battery	301	1,479	0	0	0	1,780
Converter	137	0	0	0	0	137
System	922	1,595	323	145	180	2,805

Figure 7 illustrates the monthly production schedule, indicating that the second diesel is only utilized during the annual peak in one month. This confirms the effectiveness of using two smaller diesel engines instead of one larger one. The capacity of the photovoltaic system is designed to be nearly equivalent to the base load and is utilized when there is solar radiation. The first diesel engine only operates when the demand is more than the base load, resulting in lower annual fuel consumption.

The results indicate that the base scenario produces 1126 tons of CO_2 emissions per year. However, if the system's demand is met using fossil resources in the network, over 1320 tons of CO_2 would be released annually. This implies that the proposed system would decrease emissions by 15%.

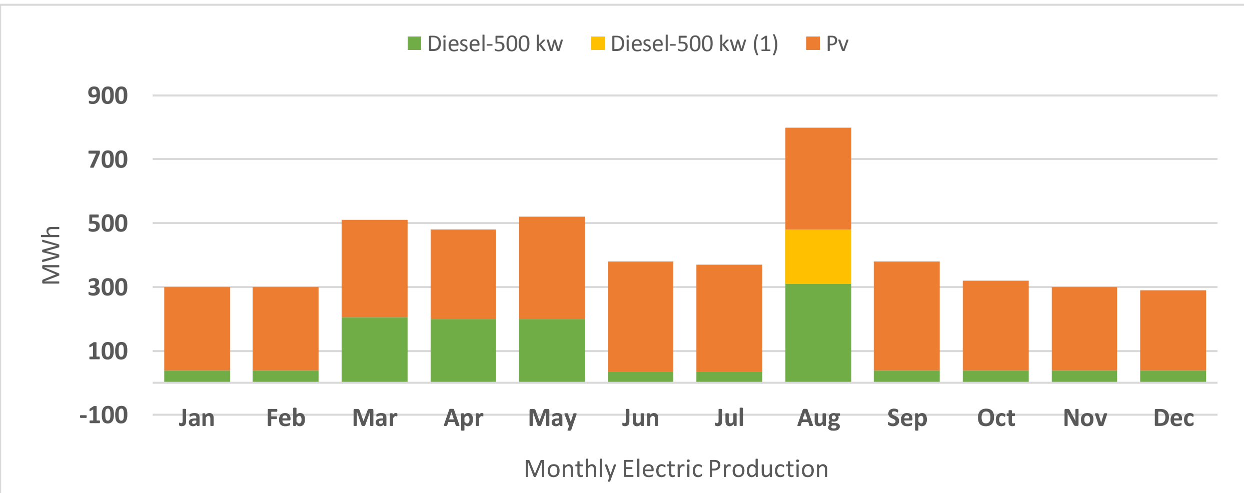

Fig. 7. Monthly load supply by resources.

Table 4: Results of different scenarios of uncertainty

Scenarios \ Components	PV (kw)	diesel generator (kw)	acid battery (quantity)	converter (kw)	NPC (M$)	COE ($)	operation hours of diesel generator 1	operation hours of diesel generator 2	Renewable share	CEI (km)
1-Without uncertainty of load and resources	1477	500*2	1612	637	2.38	0.0343	5400	469	66.6%	85.34
2- medium resource uncertainty, without load uncertainty	1733	500*2	1620	890	2.53	0.0365	5276	451	71.1%	91.2
3- High resource uncertainty, without load uncertainty	1494	500*2	1856	502	2.54	0.0367	5476	466	66.3%	91.81
4- Medium load uncertainty, without resource uncertainty	1324	500*2	2132	561	2.71	0.0392	5545	476	63.5%	98.54
5- High load uncertainty, without resource uncertainty	1727	500*2	2333	611	3.01	0.0435	5406	451	70.2%	110.2
6- Medium resource and load uncertainty	1161	500*2	2321	550	2.8	0.0405	5612	498	59.9%	102.1
7- Medium resource uncertainty, high load uncertainty	2040	500*2	2333	587	3.11	0.0449	5401	431	73.7%	114.2
8- High resource uncertainty, medium load uncertainty	1428	500*2	2317	581	2.89	0.0418	5500	470	65.5%	105.6
9- High resources and load uncertainty	2502	500*2	2323	587	3.26	0.047	5331	412	77.8%	120.0

4.2) Results of uncertainty scenarios

Nine scenarios were created and simulated through scenario analysis to consider uncertainties in resources and demand according to *sec.3.6*. The results of these simulations are presented in Table 4. Assuming uncertainty, increases costs in the hybrid energy system, resources must be expanded to meet demand under all conditions. This problem reduces the feasibility of the proposed energy system compared to grid development and enhances the system's reliability. It is important to note that uncertainty is an inherent characteristic of the system, and neglecting it is impractical.

4.3) Discussion

The research findings suggest that implementing a hybrid energy system for sensitive loads can enhance passive defence and increase the proportion of renewable resources in the national energy mix. By comparing development of nationwide network with isolated hybrid system using the cost equilibrium index, this paper provides a practical approach to deciding how to meet demand in remote areas. However, considering the current condition in Iran, the proposed system may not be economically justified for loads near to grid, and is better suited for remote loads. Therefore, the following discussion can be drawn based on the research results.

- The proposed system has key advantages over the network due to the emphasis on dispersion and separation, as highlighted by the principles of passive defence. For sensitive load this advantage could cover the high cost of hybrid isolated system in comparison to grid development.
- Cheap electricity tariff in Iran has hindered the competitiveness of the hybrid energy system. It is mainly due to the significant energy subsidies provided to consumers, which makes it more cost-effective to meet the energy demand through the grid. However, at free market environment, adopting renewable energy sources would be a more cost-effective option.
- The proposed system offers the additional benefit of enhancing the utilization of renewable resources, resulting in 15% decrease in carbon emissions compared to the network expansion, which should have been considered during the economic evaluation. Reducing carbon emissions is cost-effective if a carbon tax or emission penalty is imposed. In such a scenario, the integration of renewables could become more economically viable, making the proposed hybrid system a more competitive alternative to the conventional grid.

• The energy demand is a key factor that can impact the result, where lower demand may render network development less necessary. Hence, measuring the CEI concerning the demand level is essential. For instance, the hybrid system catering to smaller loads may be deemed feasible even at a proximity closer to the grid compared to the findings reported in this paper.

• Considering the unpredictability of resources and demand, designing system components with larger capacity is essential to ensure reliability in the face of unforeseen fluctuations.

• The considerable rise in system costs caused by uncertainty, highlights the significance of tending to exact forecasting within the system. Utilizing precise assessment, in the event that it gets to be doable to estimate renewable resources and system's demand with more prominent certainty at any given time, then it would be possible to utilize more exact models that are less expensive and don't require overabundance capacity.

• Advancing renewable technologies and particularly storage devices, it is anticipated that the cost of the proposed system will decrease. It is likely to prompt further interest and investment in developing such systems in the future.

• The study did not consider the impact of load management on system design. However, by implementing demand-side management and demand response strategies, the production and consumption of energy can be balanced, especially in uncertain conditions. This approach can be a cost-effective solution, as it eliminates the need to create additional reserve capacity in the system. Instead, it reduces or shifts demand during peak periods, lowering system costs.

5) Conclusion

This paper focuses on passive defence to meet the demand of sensitive loads by designing and comparing an isolated hybrid system with national network development. The study considered climatic conditions, actual costs, and annual load curves to optimize the design and operation of the hybrid system, which was tested on a gas pressure-boosting station. The financial and environmental results are compared with national network development, taking into account the cost equilibrium index (CEI). The study found that although renewable energy power plants connected to the grid may not compete with conventional power plants in countries with fossil resources, they can be integrated to supply sensitive loads far from the grid while reducing carbon emissions and protecting the environment. The study also highlights the importance of considering uncertainty in resources and demand, as neglecting it reduces reliability. By designing different scenarios, the study found that designs with high uncertainty led to a more reliable design with a higher cost.

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