Technical Analysis Investigating Energy Sustainability Utilizing Reliable Renewable Energy Sources to Reduce CO_2 Emissions in a High Potential Area

A. Razmjoo[a], L. Gakenia Kaigutha[b], M. A. Vaziri Rad[c], M. Marzband[b,d], A. Davarpanah[e], M. Denai[f]

[a]*Escola Técnica Superior dÉnginyeria Industrial de Barcelona (ETSEIB), Universitat Politécnica de Catalunya (UPC), Av. Diagonal, 647, 08028 Barcelona, Spain*

[b]*Northumbria University, Electrical Power and Control Systems Research Group, Ellison Place NE1 8ST, Newcastle upon Tyne, UK*

[c]*Renewable Energies and Environmental Department, Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran*

[d]*Center of research excellence in renewable energy and power systems, King Abdulaziz University, Jeddah, Saudi Arabia*

[e]*Department of Mathematics, Aberystwyth University, Ceredigion SY23 3BZ, UK*

[f]*School of Engineering Technology, University of Hertfordshire, Hatfield AL10 9AB, UK*

Abstract

Reduction of carbon dioxide (CO_2) emissions will have a positive impact on the environment by preventing adverse effects of global warming. To achieve an eco-friendly environment, the primary source of energy needs to shift from utilising fossil fuels to clean renewable energy. Thus, increased utilization of renewable energy overtime reduces air pollution and contributes to securing a sustainable energy supply to satisfy future energy needs. The main objective of this study is to investigate several suitable combinations of hybrid renewable systems for electricity production in Iran. Critical indicators that have the strongest impact on the environment and energy sustainability are presented in this study. After a comprehensive review of the factors affecting the environment, data was collected from the meteorological organization and a techno-economic assessment was performed using HOMER software. It was concluded that the hybrid configuration composed of photovoltaic (PV), wind turbine, diesel generator and battery produced the best results at energy costs of 0.151$/kWh and 15.6% return on investment. In addition, the results

Email address: mousa.marzband@northumbria.ac.uk Corresponding author (M. Marzband)

showed that with a higher renewable fraction exceeding 72%, this hybrid system can reduce more than 2,000 Kg of CO_2 emission per household annually. Although excess electricity generation is a challenge in stand-alone systems, by using a fuel cell, an electrolyzer, and a hydrogen tank unit, the amount of energy loss was reduced to less than one-sixth. These results show that strategically selecting useful indicators such as the appropriate implementation of policies of new enabling green technologies and convincing stakeholders to invest in renewable energy resources, has three potential benefits namely: CO_2 reduction, greater sustainable electricity generation and provides an economic justification for stakeholders to invest in the renewable energy sector.

Keywords: Electric energy, Environmental impact, Renewable energy, Hybrid system, Indicators

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1. Introduction

This section introduces the global approach taken towards the development of renewable energy technologies and reviews similar case studies related to to the importance of sustainable development. Thereafter, the importance of (CO_2) emission reduction is discussed and the purpose of this study is then extensively outlined.

1.1. Global approach: Background and literature

Global concerns about the negative impacts of environmental change, climatic change and increasing oil prices has forced governments across the world to introduce new policies to support a wider adoption of renewable resources [1, 2]. Undoubtedly, the main pillars for sustainable development within a country is the adoption of resilient and reliable energy infrastructure, an abundance of energy resources to ensure continuous economic growth, social development, improved quality of life and security [3, 4]. Due to the continuous depletion of fossil fuel reserves and a significant rise in carbon emissions, developing countries are moving towards a large-scale adoption of renewable sustainable energy sources [5, 6]. Today, the way energy is produced and consumed across the world is constantly

changing. The evidence of this transformation can be seen in the growth and application of new renewable technologies in developing countries [7–12]. Energy analysts and policy makers believe that if appropriate investments are made to utilize renewable energy for electricity generation, the majority of economies currently dependant on fossil fuels will gradually become independent from non-renewable resources in the long run [13, 14]. Various provinces in Iran have a high potential for renewable energy production due to the abundance of wind and solar irradiation levels. Due to the high wind potential in the Persian Gulf islands, an increase in the number of wind turbines can lead to a substantial leap in the country's electricity production [15–17]. Considering theoretical and practical research, F. Mirzapour [18], presented a new prediction model using a lead acid battery in a hybrid power system. S. Rashid et al. [19], also designed a hybrid system to be used in the coastal regions of Bangladesh and reported a significant improvement in the sustainability of electrical energy using a renewable hybrid system. From their results, hybrid systems could respond to 67.3% and 62.3% of the load demand and reduce the CO_2 emissions by 67% and 64%, respectively. S. Faquir at al. [20], presented an energy management strategy based on type-1 fuzzy logic algorithm for a hybrid system composed of photovoltaic panels, a wind turbine, and two batteries to supply a house in Morocco. An economic and environmental analysis of two hybrid systems for energy supply in remote areas was carried out in [21]. R. Sen et al. [22] investigated different hybrid systems to supply villages in India and Tao Ma et al. [23] designed an energy saving microgrid, incorporating a hybrid solar-wind system, formulated as an optimisation problem. This method showed that renewable systems based on umped hydro storage technology can ultimately be used for energy supply in remote areas [23]. A. Razmjoo et al. [24], investigated residential integration of hybrid systems and showed that a PV-wind system compared to other integrated technologies is able to produce more electrical energy at a rate of 18.478KWh/yr. M.A.M. Ramli et al. [25], showed that the expense of wind energy production was calculated to be 0.149$/kWh and for solar energy 0.0637$/kWh. It is evident that the expense of energy production using wind is higher than solar energy [25]. Consequently, critically analyzed literature supports the integration of

PV and Wind systems, which have a high potential to produce the required energy in the aforementioned areas [26].

1.2. Importance of reducing CO_2 emissions

Due to the growing concerns about global climate change, carbon footprint mitigation is currently a critical topic whereby extensive research and in depth investigations are being carried out to find sustainable solutions as it is considered to be one of the main drivers [27]. In this regard, extensive efforts are being undertaken internationally to tackle climate-change by reducing CO_2 emissions and using less fossil fuels as the primary energy resource. Moreover, similar international environmental treaties such as the Paris and Tokyo Protocol emphasize on the importance of reducing greenhouse gas (GHG) emissions to meet the target of a net zero sustainable future [28, 29]. The capture and separation process of CO_2 from fossil fuel-based plants is an effective way to control GHG emissions [30]. It has been reported that 90% of fossil fuel combustion is due to CO_2 emissions which could be avoided through strategic planning and coordinated actions to achieve a sustainable future [4]. The European Union (EU) has successfully lowered GHG emissions by 17% from 1990 to 2012. With proper planning and current strategies in place, they are working towards reducing this figure further by 20% by 2020. The EU aims to continue to implement the Tokyo Protocol to continually reduce GHG emissions [4]. A comprehensive study covering topics on global prospects, progress, and effective policies concerning the environmental impact was presented by E. Hallström et al [31]. This study investigates ways to reduce environmental threats. Furthermore, a practical analysis of the environmental impact has been carried out by H.H. Khoo et al. [32], to evaluate and compare the conventional fossil fuel production and potential of CO_2 sequestration in Norway and Japan. A comprehensive comparison of the environmental impacts of carbon capture, storage, and application of effective technologies was further investigated by R.M. Cuéllar-Franca et al. [33]. Different life cycle assessment studies were examined with concentration on carbon capture and storage (CCS), and carbon capture and utilization. It was found that CCS can decrease the global warming potential by 63% –82%, but it can raise some other

life cycle effects [33]. J. Koornneef et al. [34] investigated new environmental results related to CO_2 capture that is formed by different sectors such as power and transport. They considered projects associated with CCS, underground gas storage, enhanced oil recovery and natural gas production. Important aspects of CO_2 capture, control and storage options, were investigated by D.Y.C. Leung et al in the line with the carbon reduction set targets [35]. Table 1 shows the CO_2 emission (in million tons of CO_2) by region. China is the largest producer of CO_2 emissions in the world.

Table 1: CO_2 emission by region (in million tons of CO_2) [36]

Area	**1995**	**2010**	**2010**
Organisation for economic co-operation and development	10,763	13,427	14,476
Transition economic	3135	3852	4465
China	3051	5322	7081
Rest of the world	4791	8034	11,163
World	22,150	31,189	37,848

In this study, supplementary technologies combined with renewable energy sources such as solar and wind are studied taking into account the technical, economical and environmental aspects, whereby the most suitable system for hybridization using solar panels and wind turbines is introduced. These technologies are selected based on the resources that are available in the identified region for the investors. These include a fuel cell/ electrolyzer/ hydrogen tank unit, battery bank, diesel generator, and also different combination of these technologies. The selection criteria of the optimal system to be considered is the cost of energy, net present cost, excess electricity, reliable power generation profile, renewable fraction and CO_2 emission of the hybrid configuration. The results of this study were generalized to other parts of the world using a sensitivity analysis, and can also be used by other researchers and investors to help develop remote rural areas.

1.3. Influential indicators

Indicators are crucial tools for policy makers and energy experts. They can help policy makers set goals such as socio-political schemes for addressing environmental

and energy issues like global warming and air pollution [37]. Energy indicators are essential measures that help prevent factors affecting the environment (GHG, CO_2, SO_x and NO_x emission) and enhance the population's quality of life. The environment and available energy are two complex issues directly influencing the reduction rate of GHGs and the supply of demanded energy to consumers. The indicators in Table 5 represent a gateway for policy makers and energy experts to come up with a revised practical approach to improve environmental sustainability while meeting energy demand [14, 37]. Table 5 shows the most critical indicators that have the greatest impact on energy and the environment. Several of these indicators have been initially investigated and the best among them was chosen for this study.

Table 2: The most critical indicators for environment and energy

Indicators	**Environment**	**Energy**
Annual freshwater withdrawals	✓	×
Reduction of CO_2 and GHG	✓	×
Energy efficiency	×	✓
Total final consumption	×	✓
Forest area	✓	×
SO_x and NO_x emission intensities	✓	×
Share electricity production by clean energy	✓	✓
Share renewable in transport	✓	✓
New technology	✓	✓
Wastewater treatment connection rates	✓	×
Urban planning	✓	✓
Changing consumption patterns	✓	✓
Energy investment	×	✓
Freshwater quality	✓	×
Green space growth	✓	×
Energy accessibility and equity	×	✓
Instruments used for environmental policy	✓	×
The intensity of use of fish resources	✓	×
Municipal waste generation intensities	✓	×
Policy	✓	✓

2. Methodology

In this section, the initial input data is introduced, thereafter the most important equations of HOMER software are presented.

2.1. Case study and renewable resources

In this research, Rezvan village (Sudaklen, Iran) has been considered as a case study. This village is located $37^{\circ}11^{'}1^{''}$N and $55^{\circ}47^{'}9^{''}$E with an altitude of 1250 m above sea level. The village is located near the city of Miami, northeast of Semnan province, with an area of 1553 Km^2. The distance between Kalposh and Miami is between 110 to 140 km and is 170 to 200 km from Shahrood. The population of the village of Rezvan is just over 2,000 inhabitants. Figure 1 shows the location of Rezvan area in Iran.

Due to its geographic location, Iran has a great potential to increase its generation capacity by exploiting its abundant resources in wind and solar energy. Despite being a major oil producer, the government of Iran is paying serious attention to non-fossil fuel energy resources. Hence, authorities are putting in place a long-term strategic plan to promote the exploitation of these renewable energy resources. Figure 2 shows the daily solar radiation ($kWh/m^2/d$) for Rezvan village. The lowest daily radiation was recorded in the month of December at 2.4 $kWh/m^2/day$, and the highest daily radiation occurred in the month of June at a value of 6.95 $kWh/m^2/d$. Figure 3 shows that this area also has a high potential in wind resources with an average wind speed of 6.21 m/s. The highest recorded wind speed occurred in June at 7.3 m/s, whereas the lowest wind speed occurred in November at 5.4 m/s [3]

2.2. Load profile for Rezvan village

Figure 4 depicts the daily, seasonal and yearly load profile for Rezvan village. The maximum consumption of each household is 13.68 kWh/day by 2.16 kW peak. Due to the tropical climate of the region, energy consumption during the hot months of the year is more than the cold months of the year. The reason for this difference is the use of more cooling appliances in the summer.

Figure 1: Map of Rezvan location in Iran.

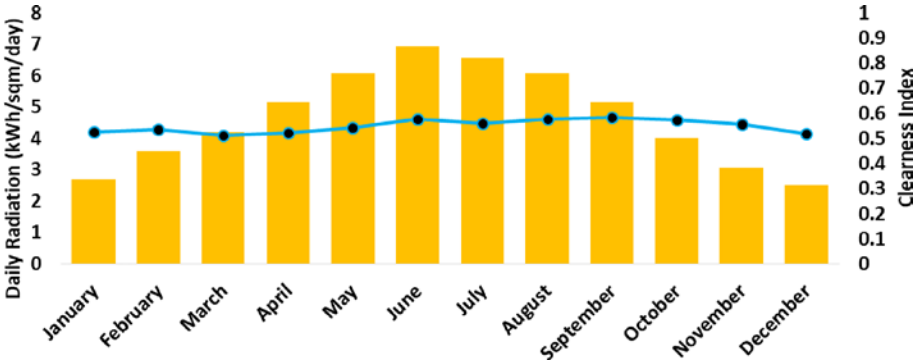


Figure 2: Daily radiation amount for Rezvan village [38]

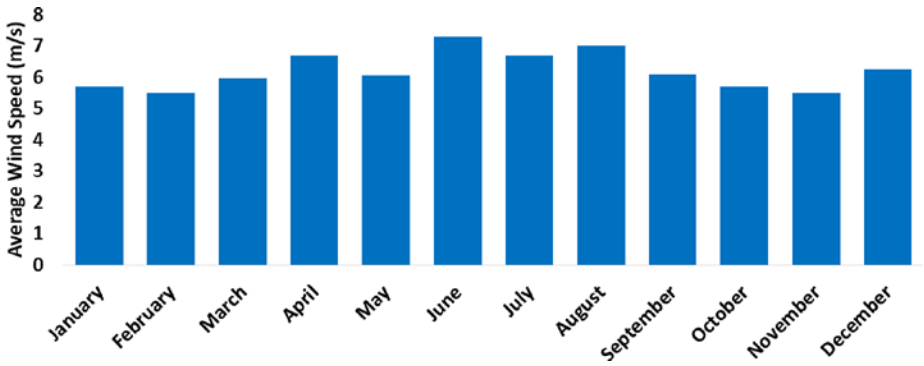


Figure 3: Average wind speed average for Rezvan village [38]

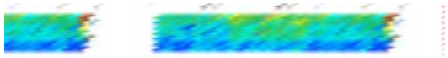


Figure 4: Daily, seasonal and annual load profile for Rezvan area.

2.3. *Modeling of the hybrid energy system*

In this study, HOMER software has been used to calculate the amount of energy production and the environmental impact by the hybrid system, while considering economic issues. After a comprehensive review covering topics on energy security and sustainability problems in Iran, relevant data collected from the Rezvan area was used in the hybrid energy system modeled in HOMER and then analysed using statistical analysis tools. Moreover, for selecting the most appropriate indicators that have the strongest impact on the environment and energy, several indicators have been initially investigated and the best among them were chosen for this study. Finally, several hybrid system configurations were investigated for the selected area and the best among them were proposed in the results section. Three supplementary systems consisting of a fuel cell/ electrolyzer/ hydrogen tank unit, battery bank and diesel generator and various combinations were selected to hybridize with renewable power sources such as a wind turbine and photovoltaic panel. Finally, the optimal configurations were selected considering different technical, economical and environmental aspects. Figure 5 depicts the overall proposed model based on available resources in the area.

2.4. *Economic parameters*

Table 3 shows the equipment used in the overall model. The project life time is considered equal to the life time of the main renewable power generation devices in the hybrid system (20 years) to prohibit the severe salvage effect on the economic outputs of the software tool. The nominal interest rate and expected inflation are considered equal to 15% and 12%, respectively [3]. Also the annual capacity shortage (power shortages) of the designed hybrid system is considered to be 0% to reach a high reliable solution for rural electrification.

2.5. *Problem formulation*

The following formulae are used to calculate the parameters required for an economic assessment of the hybrid systems [42]. The net present cost (NPC) can be calculated as:

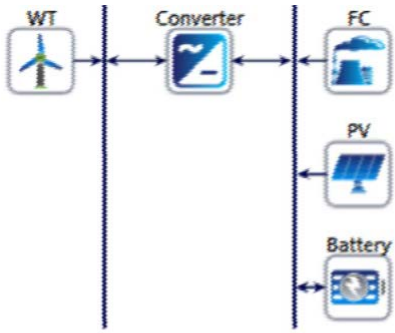


Figure 5: Schematic diagram of the proposed hybrid system.

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

where NPC is the net present cost ($), $C_{t,ann}$ is the total annualized cost, CRF is the capital recovery factor, i represents the real annual interest rate (%) which can be calculated based on the inflation rate and nominal discount rate and n denotes the period of the project (years). The CRF can be calculated using the following formula: CRF is the capital recovery factor, i is the real interest rate that is calculated based on the inflation rate and nominal discount rate. This parameter is calculated based on following equation [45]:

$$CRF(i, n) = \frac{i(1 + i)^n}{(1 + i)^n - 1} \tag{2}$$

The levelized cost of energy (COE) is calculated as follows:

$$COE = \frac{C_{t,ann}}{E_{is} + E_{grid}} \tag{3}$$

where E_{is} is the electrical energy generated by the microgrid system and E_{grid} is the amount of electricity exported from the microgrid to the main grid [13].

Table 3: Characteristics of the equipment used in this study.

Equipment	Model	Rated Capacity	Capital ($)	Maintenance ($)	Life duration	Ref.
PV panel	Sharp-ND	250 W	1300/kW	1% Capital/year	20 years	[39]
Converter	Generic	1 kW	300/kW	1% Capital/year	15 years	[40]
Wind turbine	AWS	1.5 kW	1650/kW	100/year	20 years	[41]
Battery	Li-Ion	1 kWh	500/kW	1% Capital/year	3000 kWh	[42]
Fuel Cell	PEM	1 kW	2000/kW	0.05/hours	50000 h	[43]
Electrolyzer	PEM	1 kW	1500/kW	0.05/hours	15 years	[43]
Hydrogen Tank	Generic	2 kg	600/kg	1% Capital/year	20 years	[43]
Diesel Generator	Generic	1 kW	400/kW	0.02/hour	15000 h	[44]

The return on investment (ROI) is the annual cost savings relative to the initial investment which calculated by following equation [46]:

$$\mathrm{ROI} = \frac{\sum_{i=0}^{n} C_{i,ref} - C_i}{n(C_{cap} - C_{cap,\,ref})} \tag{4}$$

where $C_{i,ref}$ represents the reference nominal cash flow of the system, C_i is the yearly current nominal cash flow of the system , C_{cap} and $C_{cap,\,ref}$ denote the capital cost of the current and reference system respectively.

Another important economic factor is the salvage value which refers to the remaining value in a power generation device of a hybrid system at the end of the project lifetime. HOMER software calculates this value based on the following equation [47].

$$\mathrm{Salvage} = C_{ref}\,\frac{R_{comp} - [n - R_{comp} \times \mathrm{INT}(\frac{n}{R_{comp}})]}{R_{comp}} \tag{5}$$

where C_{ref} is the replacement cost of a component, R_{comp} represents the component lifetime.

Finally, the following equation has been used to estimate the CO_2 emissions.

$$t_{co_2} = 3.667 \cdot M_f \cdot HV_f \cdot CEF_f \cdot X_c \tag{6}$$

where t_{CO_2} is the amount of CO_2 emissions, M_f is fuel quantity (Liters), HV_f is the fuel heating value (MJ/L), CEF_f is carbon emission factor (ton carbon/TJ) and X_c is the oxidized carbon fraction.

3. Result and discussion

In this section, various configurations of hybrid systems are compared with each other in terms of technical, economic and environmental characteristics, then a sensitivity analysis is performed on the most important parameters affecting the optimal system configuration and finally the cost of energy of the optimal system is compared with other studies related to the design of stand-alone microgrids for rural areas.

3.1. Technical analysis

The world today is still heavily reliant on fossil fuels for energy production which is having a huge impact on the environment. Accelerating the deployment of renewables into the existing central electricity systems potentially becomes a viable option to reduce CO_2 emissions. Limiting fossil fuel energy is difficult, but it can be reduced by enforcing appropriate policies and effective planning. Renewable energy resources are projected to supply 70–85% of electricity by 2050 which will considerably reduce CO_2 emissions. In this section, the best supplementary system among the available technologies for Rezvan is analyzed in order to achieve an affordable and highly reliable system. As mentioned previously, these technologies include a battery, fuel cell (along with electrolyzer and hydrogen tank) and diesel generator which are combined with solar panels and wind turbines to supply electricity to households. Table 4 shows the amount of energy produced by each one of the selected configurations. As expected, all the configurations will include a combination of solar panels and wind turbines for these two technologies are both intermittent and can therefore successfully complement each other.

Table 4: Electricity generation with the selected optimal hybrid system configurations for each household in the selected rural area.

Supplementary system	Renewable system	DG (kWh/yr)	FC (kWh/yr)	Battery (kWh/yr)	PV (kWh/yr)	WT (kWh/yr)	Excess power (kWh/yr)
Bat	PV-WT	-	-	1,362	4,336	6,530	5,566
FC	PV-WT	-	874	-	5,493	16,326	8,201
DG	PV-WT	3,581	-	-	753	6,530	5,869
Bat-FC	PV-WT	-	505	640	3,045	9,795	2,793
Bat-DG	PV-WT	1,389	-	577	2,326	3,265	1,842
DG-FC	PV-WT	2,008	249	-	2,065	6,530	3,127
Bat-FC-DG	PV-WT	1,691	66	418	1,165	3,265	263

It is evident in Table 4, when using one type of a supplementary system, the hybrid energy systems generate large amounts of excess electricity. This is due to the energy produced by a PV panel and wind turbine that depend on environmental conditions, whereby the hybrid system has to install a higher capacity of renewable equipment to ensure a continuous supply to the load during peaks periods. Therefore, it ultimately leads to the production of additional electricity during off-peak hours. Also, due to the high initial price and maintenance cost involved, the fuel cell technology has been used less to supply the load which has led to an increase of about 40% in the amount of electricity access, as compared to the use of a battery or diesel generator. On the other hand, with the coupling of supplementary systems, the amount of electricity access is significantly reduced. This is because a combination of several energy sources gives a better flexibility to the system to respond to various load demand conditions. In fact, the use of multiple peripheral devices in the hybrid system has reduced the installed capacity of renewable technologies. Moreover, the coupling of the diesel generator and battery along with renewable power generation systems, has resulted in a reduction of more than 67% of surplus electricity as compared to the use of the battery or diesel generator alone. This is due to transferring the excess electricity to the electrolyser when using the Battery/ FC/ DG combination whereby the lowest amount of excess electricity (equivalent to 263 kWh per year) can be achieved. Therefore, this hybrid system energy configuration can be considered as the most efficient. Figure 6 shows the power generation profile of the hybrid system with different combinations of power sources including: (i) PV/ Wind Turbine, (ii) Diesel Generator/ Fuel Cell, (iii) Diesel Generator/ Battery, (iv) Battery/ Fuel Cell and (v) Diesel Generator/ Fuel Cell/ Battery.

Figure 6(a) shows the output power of the solar panel and wind turbine. In addition, it shows that the auxiliary system was able to supply the total required power demanded especially during night hours. Figure 6(b) shows the performance of the DG/ FC combination. Due to the high cost of the fuel cell, the diesel generator is turned on most of the time in each year, which increases the maintenance costs of the system. In fact, the fuel cell is only turned on during high peak demands or when there is insufficient wind and solar radiation simultaneously. Figure 6(c) shows the

(a) PV and wind turbine

(b) Diesel generator-fuel cell

(c) Diesel generator-battery

(d) Battery-fuel cell

(e) Diesel generator-fuel cell-battery

Figure 6: Power generation profile of the hybrid system.

DG/ Battery combination performance. The reasonable price of the battery significantly reduces the activation times of the diesel generator and also increases the flexibility of the system in response to peak demands. Figure 6(d) shows the performance of the FC/ Battery combination. Due to the limited capacity of the batteries, the fuel cell is more effective in supplying the load during peaks hours than the DG/ FC combination. However, the limited capacity of the hydrogen storage tank also requires the installation of solar panels and wind turbines with higher capacities, and consequently increase the overall system costs. Figure 6(d) shows the performance of three coupled technologies (Battery/FC/DG). Majority of the time, the DG and battery are assisting the solar panel and wind turbine to supply the load, and the FC is turned on when a severe peak demand occurs. In all scenarios considered, the load demand of the remote area is fully and reliably satisfied. However, the ability of the system in managing the excess electricity generation to prevent energy loss (especially in off-grid systems) is also a challenge. According to the results, the Battery/DG and Battery/FC/DG systems were able to successfully manage the excess electricity generated by the solar panel and wind turbine.

3.2. Economic analysis

In this section, an economic evaluation of each hybrid system is presented. According to Table 5, the lowest energy cost in the PV-WT-Bat-DG scenario is obtained as 0.151$/kWh, and then followed by the PV-WT-Bat-FC-DG scenario which is achieved at a cost of 0.231$/kWh. In fact, the choice of these two scenarios as being optimal solutions depends on the investors decision to whether the economic parameters are of more importance or higher efficiency (less power losses) is also to be considered as a goal. The initial investment cost in the PV-WT-Bat-DG scenario is equivalent to 6,930$, which will approximately increase by more than twofold by removing the diesel genertor or adding the fuel cell/electrolyzer/hydrogen tank unit, respectively. Therefore, it can be said that using a 1.58 kW solar panel, a 1.5 kW wind turbine with three batteries and a diesel generator with an annual fuel consumption of less than 500 liters is a cost-effective solution to supply electricity to each household in the remote area. Also, this scenario with more than 70% of

renewable share has a good environmental performance, even though a relatively higher electricity surplus of 1,800 kWh/year is produced. Nonetheless, with about 75% more initial cost, adding 1 kW of fuel cell with 2 kW of electrolyzer and a hydrogen tank (with 3 kg capacity) the excess electricity will decrease to less than one-sixth of the current value.

Table 5: Component sizes and the economic assessment of the optimal scenarios

Hybrid system	DG (Kw)	FC (Kw)	Battery (kWh)	PV (Kw)	Converter (Kw)	WT (unit)	Initial investment ($)	COE ($/kWh)	NPC ($)	RF (%)
Bat-PV-WT	-	-	18	2.94	2.04	2	18,381	0.322	24,662	100
FC-PV-WT	-	2	-	3.72	2.37	5	32,727	0.617	47,233	100
DG-PV-WT	2	-	-	0.51	0.27	2	6,895	0.286	21,913	28.3
Bat-FC-PV-WT	-	1	13	2.06	2.54	3	24,170	0.403	30,854	100
Bat-DG-PV-WT	1	-	3	1.58	1.02	1	6,930	0.151	11,576	72.2
DG-FC-PV-WT	1	1	-	1.4	0.67	2	14,370	0.306	23,388	59.8
Bat-FC-DG-PV-WT	1	1	2	0.79	0.75	1	12,127	0.231	17,648	66.1

Figure 7 shows the breakdown of the project costs in each scenario along with their related rate of return. It is evident that the capital cost has considerably increased when the fuel cell is used, which indicates the need to reduce the price of this technology in order to make it a more economical viable choice to be implemented in hybrid systems. When using the diesel generator, maintenance costs have increased significantly, although with the combination of the diesel generator and battery, the costs have been well distributed among different parts of the project. The salvage means selling the residual value of the equipment to the retail market after the end of the project life, but due to the instability in retail market prices, a higher salvage cannot be considered as a positive factor for the project. In fact, minimal use of the fuel cell useful life during the project lifespan creates the need to sell it at the end of the project and consequently this results in more salvage. The best performance in terms of return on investment with about 15.6% belongs to the PV-WT-Bat-DG hybrid system, however, with the addition of the fuel cell unit to this system the return on investment is further reduced by approximately 2%. Besides the three highlighted scenarios, the DG-FC-PV-WT hybrid system, Bat-PV-WT and DG-PV-WT hybrid system have the rate of return of 9.6%, 4.7% and 3.9%, respectively. In fact, these results show that the fuel cell can functionally complement the diesel generator and battery economically, but it can never substitute them.

Figure 7: Project costs and return on investment of the each optimal scenario.

3.3. Emission Analysis

In this section, the performance of each scenario is examined from an environmental impact point of view. According to Table 6, without using the diesel generator in the stand-alone system, the hybrid system achieved zero pollution, but as mentioned previously, due to the rising final costs, these scenarios cannot be an appropriate solution to supply energy for remote areas. Also, using the diesel generator alone as a supplementary device due to the high annual consumption of fuel can lead to more pollution in comparison with grid electricity. For instance, supplying the selected load from a natural gas-fired power plant in Iran generates 3,299 kg of carbon dioxide emissions per year, whereas in the case of the DG-PV-WT hybrid system the CO_2 emissions are increased only by 12.1%. Therefore, the use of multiple supplementary systems in addition to increasing the technical flexibility of the hybrid system, reduces the system costs and also improves the environmental performance of the design. The PV-WT-Bat-DG system produces approximately 63.2% less CO_2, which is about 76.8% less particulate matter, and approximately amounts to 40.2% less nitrogen oxide annually. Hence, providing an excellent environmental performance for the diesel generator and battery as supplementary equipment to the PV and WT hybrid renewable system.

Table 6: GHGs produced by the different hybrid systems.

Hybrid system	Carbon Dioxide (kg/yr)	Carbon Monoxide (kg/yr)	Unburned Hydrocarbons (kg/yr)	Particulate Matter (kg/yr)	Sulfur Dioxide (kg/yr)	Nitrogen Oxides (kg/yr)	Diesel Consumption (L/yr)
Pure Grid	3299	3.10	0.909	0.599	8.29	11.9	0
Bat-PV-WT	0	0	0	0	0	0	0
FC-PV-WT	0	0	0	0	0	0	0
DG-PV-WT	3,700	23.1	1.02	0.139	9.06	21.7	1,413
Bat-FC-PV-WT	0	0	0	0	0	0	0
Bat-DG-PV-WT	1,212	7.56	0.333	0.0454	2.97	7.11	463
DG-FC-PV-WT	1,988	12.4	0.547	0.0744	4.87	11.7	759
Bat-FC-DG-PV-WT	1,513	9.44	0.416	0.0566	3.70	8.87	578

Figure 8 shows the percentage of participation of each power generation equipment in the required demand, which is either directly used to supply the electrical load or stored in the battery. It is noted that the fuel cell supplies only a small percentage of the demand because this design only works during severe peak loads, which has led to the need for higher capacities to install solar panels and wind turbines. It is important to highlight that the use of the electrolyzer improves the system performance and efficiency by absorbing the excess of energy. By comparing Figure 8(c) and Figure 8(e), it can be concluded that the use of the battery reduces the operating hours of the diesel generator by helping to better satisfy the peak demands. Also, due to the ability to store PV output power during the day and discharging it at night, it has increased the installed capacity of the solar panel. These two factors have significantly reduced economic costs and increased the renewable fraction of the energy system.

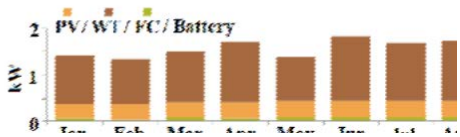
3.4. Sensitivity analysis

In order to assess the ability to generalize the results of the optimal scenario to other parts of the world, a sensitivity analysis has been performed. Figure 9 shows the effect of changes in average solar radiation and average wind speed on the cost of energy and CO_2 emissions. Figure 9(a), in the worse case, by reducing the potential of renewable resources in the region, the cost of energy will reach 0.240\$/kWh and the best case will be about 0.120\$/kWh. In fact, it can be said that the proposed hybrid system for areas with an average annual radiation of above 4.2 kWh/m^2/day, average wind speeds greater than 5.3 m/s and energy costs less than 0.20\$/kWh is achieved, which indicates the potential ability of this hybrid system for implementation in various remote areas. Moreover, Figure 9(b) shows that the

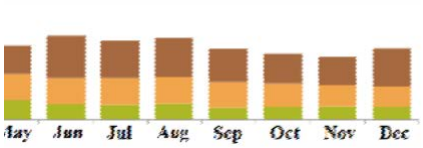
(a) PV (39.9%)- WT (60.1%)

(b) FC (3.9%)- PV (24.2%)- WT (71.9%)

(c) DG (33%)- PV (6.9%)- WT (60.1%)



(d) FC (3.8%)- PV (22.8%)- WT (73.4%)



(e) DG (19.9%)- PV (33.3%)- WT (46.8%)

(f) DG (18.5%)- FC (2.3%)- PV (19%)- WT (60.2%)

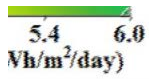
(g) FC (1.1%)- DG (27.3%)- PV (18.8%)- WT (52.8%)

Figure 8: Monthly average contribution of each power generation equipment in the total energy production.

environmental performance of the hybrid system is more dependent on the wind potential in the area because by reducing the average wind speed due to the need of utilising the diesel generator during night hours, the system pollution increases. In fact, in areas with good wind potential, the final system pollution value can be reduced to less than 1,200 kg/year, which when compared to conventional fossil fueled power plants, it prevents the annual emission greater than 2,000 kg of CO_2 emissions per household.

Figure 10 shows the effect of the capital cost of the solar panel and wind turbine on the energy cost and emissions of the hybrid system. According to Figure 10(a), by considering a resonable range of initial price changes of renewable equipments (about 20%), the final energy cost of the hybrid system will be between 0.145$/kWh and 0.160$/kWh. This range indicates the cost-effectiveness of the hybrid system. However, with a 50% increase in the initial cost of the solar panel and wind turbine, the cost of energy is approximately around 0.190$/kWh, therefore, making the initial price of the solar panel and wind turbine a crucial factor for investors. Also CO_2 emissions are more sensitive to the wind turbine capital cost. In fact, by reducing the price of wind turbines by more than 20%, the installed capacity of the solar panel will be very low and the pollution rate will be almost independent of the price of the solar panel. However, with simultaneous capital cost increments of the wind turbines and solar panels, the cost-effectiveness of renewable power generation will be lower than that of the diesel generator, and ultimately increases carbon dioxide emissions.

Figure 11 demonestrates the sensitivity heat map of the NPC based on changes in the economic conditions of the region. In fact, for any given nominal discount rate with a higher inflation rate, higher NPC is achieved which will reduce the investors' willingness to implement such hybrid systems. Therefore, lower inflation rates will make the hybrid system more economical. Also, Figure 11(b), shows that the changes in fuel prices has had a more severe effect on NPC than changes in battery prices. In fact, regarding the minimum international diesel fuel price (1$/liter), the NPC is between 13,000$ and 16,000$ per household power supply, thus, the proposed hybrid system is more attractive in countries with lower diesel

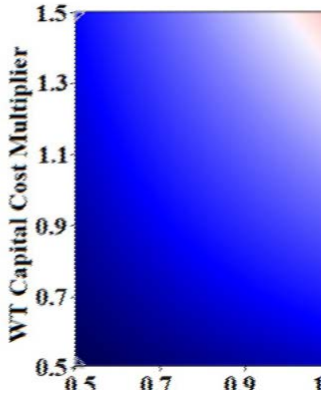


(a) Cost of energy

(b) CO_2 emission

Figure 9: Effect of changes in the average wind speed and average solar radiation on the a) Cost of energy and b) CO_2 emission.

(a) Cost of energy



(b) CO_2 emission

Figure 10: Effect of changes in the PV capital cost and WT capital cost on the a) Cost of energy and b) CO_2 emission.

fuel prices such as fuel exporting countries.

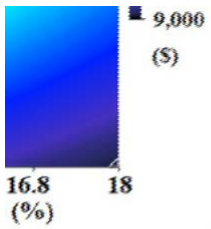
The results of this sensitivity analysis showed that the optimal hybrid system (PV-WT-Bat-DG) with a reasonable cost of energy and high ability to reduce pollution, as well as low impact changes considering economic conditions, will have a good performance for stand-alone power supply in areas with a good potential for renewable energy resources.

3.5. Comparison

In this section, the results of the optimal scenarios in the present study are compared with a number of other papers related to electricity supply in remote areas. According to Table 7, among the different scenarios omitting the use of the fuel cell, it is evident the undertaken study has a good performance with an energy cost of 0.151$/kWh and about 72% renewable fraction. In most other studies, the DG/Bat combination has been introduced as an ideal supplementary design in order to have an economic system, but none of the studies simultaneously compare the technical, economic and environmental characteristics of all possible modes for DG/Bat/FC in order to hybridize with other renewable technologies. Among the scenarios using a fuel cell, the current system with the energy cost of 0.23$/kWh and about 66% renewable fraction has performed relatively well, although the price of the fuel cell, electrolyzer and hydrogen tank can make a significant difference in final costs of the system in the different studies under consideration.

Table 7: A comparative review on the hybrid system cost of energy for rural stand-alone cases

Location	**Year**	**Non-Renewable Systems**	Renewable System	Load (kWh/d)	COE ($/kWh)	RF (%)	Ref.
Algeria	2020	DG	PV /WT	22.5	0.210	63	[48]
India	2020	DG / Bat	FC/ PV/ WT/ Bio	724.8	0.163 to 0.214	—	[49]
Cameroon	2019	DG/ Bat	PV/ WT/ Hydro	100	0.443	91.4	[1]
Iran	2019	DG/ Bat	PV/ WT	242	0.197	67.3	[50]
Nigeria	2019	DG/ Bat	PV/ WT	7.23	0.459 to 0.562	—	[51]
Turkey	2018	DG/ Bat	FC/ PV/ WT	165.6	0.282	95	[52]
India	2017	Bat	FC/ PV	70	0.196	100	[53]
Malaysia	2017	Bat	FC/ PV	140	0.355	100	[54]
Ethiopia	2016	DG/ Bat	FC/ PV/ WT	16000	0.179	99	[55]
Pakistan	2016	DG/ Bat	PV/ WT	205	0.450	84	[3]
Current Study	2020	DG/ Bat	PV/ WT	13.68	0.151	72.2	—
Current Study	2020	DG / Bat	FC/ PV/ WT	13.68	0.231	66.1	—



(a) Nominal discount rate and expected inflation rate

(b) Diesel fuel price and cost of battery unit

Figure 11: Sensitivity analysis of the NPC based on a) Nominal discount rate and expected inflation rate and b) Diesel fuel price and cost of battery unit.

4. Conclusion

The understanding of environmental and energy related issues is of paramount importance. Carbon dioxide footprint is mainly caused by fossil fuel emissions and has become a major concern for policy makers and analysts in many countries across the world. Sustainability and security of electrical energy supply is still a current issue around the globe for many countries for they still depend on the utilization of fossil fuels. In order to achieve the targets of sustainable energy and transition to a low-carbon economy, it is necessary to diversify the central electricity systems by increasing the deployment of clean and renewable energy resources. This will enhance the current electrical systems and make them more reliable, which will ensure energy security in the long run. The main goal of this study was to conduct a comprehensive analysis from an environmental aspect with a techno-economic analysis using HOMER software for several different hybrid systems. The main results of this study are summarised below:

- Technically, the combination of the diesel generator, battery and fuel cell/ electrolyzer/ hydrogen tank unit with only 262 kWh/year of excess electricity produced the best results in terms of reducing the energy loss of the hybrid PV/ WT system by eliminating the hydrogen unit, whereby the amount of excess electricity will increase almost six times over.
- Economically, the battery and diesel generator combined with PV/ WT led to the best hybrid system configuration with energy costs of about 0.151$/kWh. By adding the fuel cell/ electrolyzer/ hydrogen tank unit to this system, the energy costs were increased to 0.231$/kWh, and the return on investment decreased from 15.6% to about 13.5%.
- Environmentally, the PV/ WT/ DG/ Battery system with more than 72% renewable fraction yielded to an annual reduction of more than 2,000 kg of carbon dioxide compared to grid electricity (pure grid). The system also reduced Nox emissions by more than 40% reflecting the ecological performance of the introduced system.
- The sensitivity analysis results showed that the maximum reasonable range

of changes in energy costs will be between 0.120 to 0.240$/kWh, which indicates the proper operation of this system in relation to various economic and environmental conditions. To achieve a more cost-effective solution, the use of this hybrid system is recommended for areas with higher than 4.2 kWh/m^2/day average radiation potential and higher than 5.3 m/s average wind speed.

- The investment approach review showed that selecting useful indicators such as correct policies for the implementation of new technology, and investment on renewable energy has three crucial advantages namely: CO_2 reduction, greater sustainable electrical generation and provides an economic justification for stakeholders to invest in renewable projects.

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