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

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## 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-environment, the primary source of energy needs to shift from conventional fossil fuels to clean renewable energy sources. Thus, increased utilization of renewable energy overtime reduces air pollution and contributes to securing sustainable energy supply to satisfy the future energy needs. The main purpose of this study is to investigate several sustainable hybrid renewable systems for electricity production in Iran. In this regard, critical indicators that have the strongest impact on the environment and energy sustainability are presented in this study. After a comprehensive review of environmental issues, 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 outcome with an energy cost of 0.151 $/kWh and 15.6% return on investment. In addition, the results showed that with higher a renewable fraction exceeding 72%, this hybrid system can prevent more than 2000 Kg of $CO_2$ emission per household annually. Although large excess of electricity generation is a challenge in stand-alone systems, by using the fuel cell, electrolyzer, and hydrogen tank unit, the amount of energy loss was reduced to less than one-sixth. These results show that selecting useful indicators such as appropriate implementation policies of new enabling technologies and investment on 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

## 1. INTRODUCTION

This section first introduces the global approach towards the development of renewable energy technologies and reviews some case studies related to sustainable development. Finally, the need to reduce carbon dioxide ($CO_2$) emissions is discussed and the purpose of this study is outlined.

### 1.1 Global approach: Background and literature

Global concerns about the negative impacts of environmental change and rising oil prices, has led governments across the world to introduce new policies to support a wider adoption of renewable resources [1,2]. Undoubtedly, the main pillars for a sustainable development of a country is a resilient and reliable energy infrastructure and an abundance of energy resources to ensure continuous economic growth, social development, improved quality of life and security [3,4]. Due to the continuous decline of fossil fuels reserves and 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, developed, and consumed across the world is ever changing, whereby 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 depending on fossil fuels will become gradually independent of these resources in the long run [13,14]. Various provinces in Iran have a high potential for energy production from renewable sources due to the abundance of winds and solar irradiation levels. Due to the huge wind potential in the Persian Gulf islands, an increase in the number of wind turbines can lead to a substantial leap to the country's electricity production [15–17]. Considering theoretical and practical research, F. Mirzapour [18], presented a new prediction model of utilizing lead acid a 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 substantial 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 et 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 system for energy supply in remote areas was carried out in [21]. The authors R. Sen et al. [22] investigated different hybrid systems to supply villages in India and. Tao Maet 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 Pumped Hydro Storage (PHS) technology can ultimately be used for energy supply in remote areas [23]. A. Razmjoo et al. [24], investigated residential applications of hybrid systems and showed that PV-wind system compared to other integrated technologies is able to produce more electrical energy at a rate of 18.478 kWh/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, the critically analyzed literature supports the integration of PV and wind systems, which have a high potential to produce the required energy in these 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 topic of extensive research and investigation as it is considered to be one of the main drivers [27]. In this regard, extensive effort are being undertaken internationally to tackle climate-change by reducing $CO_2$ emissions and using less of fossil fuels as the primary energy resource. Moreover, similar international environmental treaties such as Paris and Tokyo Protocols 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 fuels-based plants is an effective way to control greenhouse gas emissions [30]. As it has been reported that 90% of fossil fuels 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 gases [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 (CCU). It was found that CCS can decrease the Global Warming Potential (GWP) by 63%–82%, but it can also raise some other life cycle effects [33]. J. Koornneef et al. [30] 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 (UGS), enhanced oil recovery (EOR) and natural gas production. Important aspects of carbon dioxide capture, control and storage options, were investigated by Leung DYC et al. in the line with the carbon reduction set targets [34]. Table 1 shows the $CO_2$ emission (in million tons of $CO_2$) by region. China being the largest producer of $CO_2$ emissions.

Table 1 $CO_2$ emission by region (million tons of $CO_2$) [32].

| **Area** | **1995** | **2010** | **2020** |
|---|---|---|---|
| OECD | 10763 | 13427 | 14476 |
| Tansition Economic | 3135 | 3852 | 4465 |
| China | 3051 | 5322 | 7081 |
| Rest of the World | 4791 | 8034 | 11163 |
| World | 22150 | 31189 | 37848 |

In this study, supplementary technologies combined with renewable sources such as solar and wind are studied taking into account the technical, economical and environmental aspects, and finally the most suitable system for hybridization with solar panel and wind turbine is introduced. These technologies are selected based the resources that are available in the region for investors. These include fuel cell/electrolyzer/hydrogen tank unit, battery bank, diesel generator, and also different combination of these. The selection criteria of the optimal system are 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 sensitivity analysis, and the results can be used by other researchers and investors to develop remote rural areas.

## 2. INFLUENTIAL INDICATORS

Indicators are crucial tools for policymakers and energy experts. They can help policymakers set goals such as socio-political schemes for addressing environmental and energy issues like global warming and air pollution [37]. Environmental and energy indicators are essential measures that help prevent likely problems (GHG, $CO_2$, SOx and NOx emission) and enhance the population's quality of life. The environment and energy are two complex issues, directly influencing the reduction rate of GHGs and the supply of demanded energy to consumers. The indicators in Table 2 represent a gateway for policymakers and energy experts to come up with a revised practical approach to improve environmental sustainability while meeting energy demand [10,37]. Table 2 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 these indicators were then 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 | ✓ | × |
| SOx and NOx emission intensities | ✓ | × |
| SOx and NOx 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 | ✓ | × |

| | | |
|---|---|---|
| Policy | ✓ | ✓ |

## 3. METHODOLOGY

In this section, first the input data are introduced and then the most important equations of HOMER software are presented.

### 3.1 Case study and renewable resources

In this research, Rezvan village (Sudaklen, Iran) has been considered as a case study. This village is located at 37_11_01_N and 55_47_09_E with an altitude of 1250m 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 a little above 2,000 inhabitants. Fig. 1 shows the location of Rezvan area in Iran.

Fig. 1 Map of Rezvan location in Iran.

Due to its geographic location, Iran has the 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. Fig. 2 shows the daily solar radiation (kWh/m$^2$/day) 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 with a value of 6.95 kWh/m$^2$/day. Fig. 3 shows that this area has also 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].

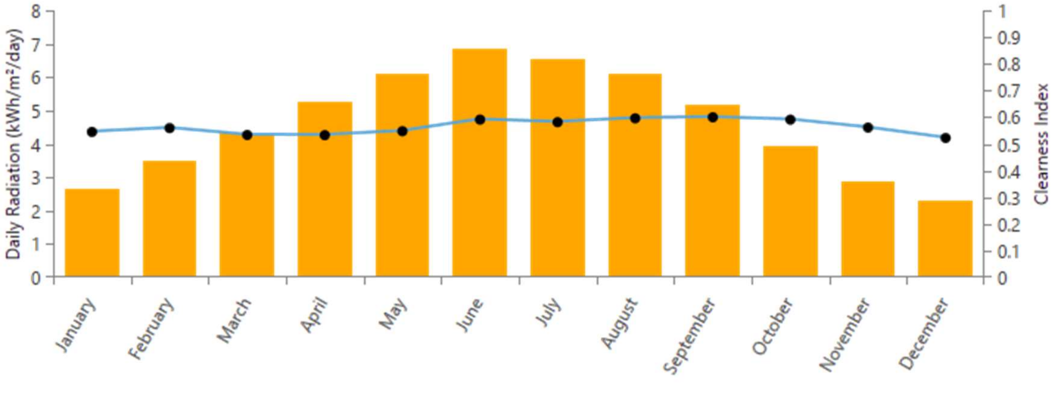


Fig. 2 Daily solar radiation for Rezvan village [38].

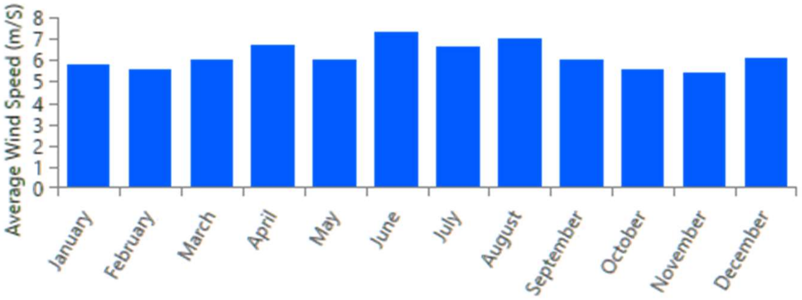


Fig. 3 Average wind speed in Rezvan village [38].

### 3.2 Load profile for Revan village

Fig. 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 in the hot months of the year is more than the cold months of the year. The most important reason for this difference is the use of more cooling appliances in the summer.

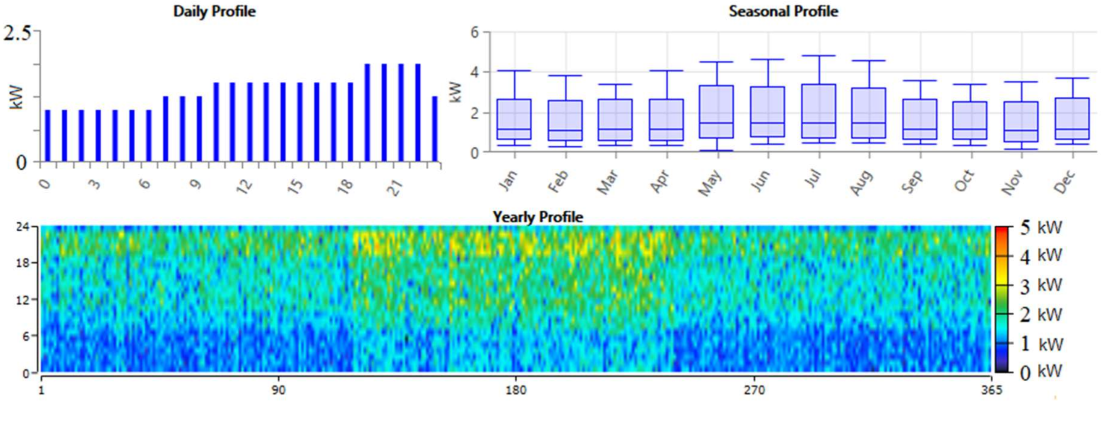


Fig. 4 Daily, seasonal and annual load profile for Rezvan area.

### 3.3 Modeling of the hybrid energy system

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

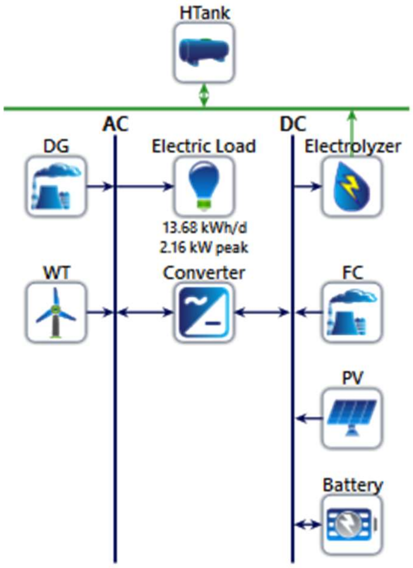


Fig. 5 Schematic diagram of the proposed hybrid system.

### 3.4 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 of 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 % repectively [35]. 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.

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 | [36] |
| Converter | Generic | 1 kW | 300/kW | 1% Capital/year | 15 years | [37] |
| Wind turbine | AWS | 1.5 kW | 1650/kW | 100/year | 20 years | [38] |
| Battery | Li-Ion | 1 kWh | 500/kW | 1% Capital/year | 3000 kWh | [39] |
| Fuel Cell | PEM | 1 kW | 2000/kW | 0.05/hours | 50000 h | [40] |
| Electrolyzer | PEM | 1 kW | 1500/kW | 0.05/hours | 15 years | [40] |
| Hydrogen Tank | Generic | 2 kg | 600/kg | 1% Capital/year | 20 years | [40] |
| Diesel Generator | Generic | 1 kW | 400/kW | 0.02/hour | 15000 h | [41] |

### 3.5 Important formulas

The following formula 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:

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

Where NPC is the net present cost ($), $\mathrm{C_{t,ann}}$ is the total annualized cost, CRF is the capital recovery factor, i represents the real annual interest rate (%) which can be calcutaled based on 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 calcutaled based on inflation rate and nominal discount rate. This parameter calculated based on following equation [45]:

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

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

$$\mathrm{COE} = \frac{\mathrm{C_{t,ann}}}{\mathrm{E_{is} + E_{grid}}} \qquad (3)$$

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

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

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

Where $C_{i,ref}$ represents the reference nominal cash flow of the system, $C_i$ is the current nominal cash flow of the system in each year, $C_{cap}$ 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 the hybrid system at the end of the project lifetime. HOMER software calculates this value based on the following equation [47].

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

Where $C_{rep}$ 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 fuel heating value (MJ/L), $CEF_f$ is carbon emission factor (ton carbon/TJ) and $X_c$ is the oxidized carbon fraction .

## 4. RESULTS AND DISCUSSION

In this section, first 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, 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.

### 4.1 Technical analysis

The world today, is still heavily reliant on fossil fuels for energy production which having a huge impact on the planet. Accelerating the deloployment of renewables into the existing central electricity systems becomes the potentially viable option to reduce $CO_2$ emissions. Of course, limiting this primary source of 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 the studied area of Rezvan is analyzed in order to achieve to an affordable and highly reliable system. As mentioned before, these technologies including battery, fuel cell (along with electrolyzer and hydrogen tank) and diesel generator which are combined with solar panel and wind turbine for supplying 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 panel and wind turbine, because these two technologies are both intermittent and therefore can 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)** | **Bat (kWh/yr)** | **PV (kWh/yr)** | **WT (kWh/yr)** | **Excess (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 |

As can be seen from Table 4, when using one type of supplementary system, the hybrid energy systems generate a large excess of electricity. Because the energy produced by a PV panel and wind turbine depends on environmental conditions, the hybrid system has to install a higher capacity of renewable equipment to ensure a continuous supply to the load during peaks periods, which 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 less used to supply the load, which has led to an increase of about 40 % in the amount of electricity eccess as compared to the use of battery or diesel generator. On the other hand, with the coupling of supplementary systems, the amount of electricity eccess is significanly reduced. This is because a combination of several energy sources gives a better flexibility to the system to respond to various load demands 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 of electricity as compared to the use of battery or diesel generator alone. Because when transfering the excess of electricity to the electrolyser, when using the Battery/FC/DG combination, the lowest amount of excess electricity (equivalent to 263 kWh per year) can be achieved, and hence this hybrid system energy configuration can be considered as the most efficient. Fig. 6 shows the power generation profile of the hybrid system with different combination 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.

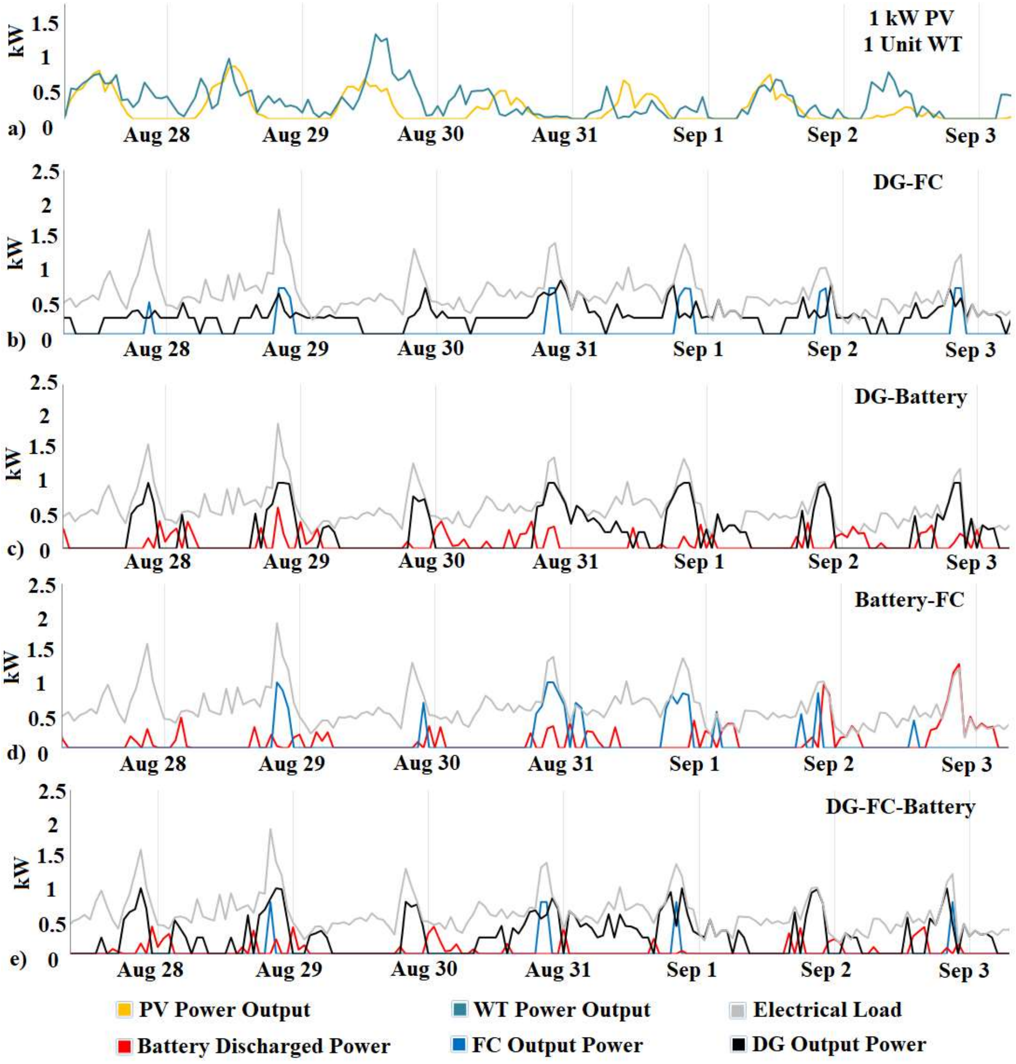


Fig. 6 Power generation profile of the hybrid system: a) PV and wind turbine b) Diesel generator-fuel cell c) Diesel generator-battery d) Battery-fuel cell e) Diesel generator-fuel cell-battery.

Fig. 6 (a) shows the output power of the solar panel and wind turbine. According to this figure, the auxiliary system was able to supply the total required power demand specially at night hours. Fig. 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. Fig. 6 (c) shows the 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. Fig. 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. Finally, Fig. 6 (d) shows the performance of three coupled technologies (Battery/FC/DG). Most of 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. Hwoever, the ability of the system in managing the excess of 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 of electricity generated by the solar panel and wind turbine.

### 4.2 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 by 0.151 \$/kWh, and then followed by the PV-WT-Bat-FC-DG scenario wich achieved a cost of 0.231 \$/kWh. In fact, the choice of these two scenarios as being the optimal solutions depends on the investors decision to whether the economic parameters are more important or higher efficiency (less power losses) is also a goal. The initial investment cost in the PV-WT-Bat-DG scenario is equivalent to \$6930, which will increase almost 3 and 2 times by removing the diesel genertor or adding the fuel cell/electrolyzer/hydrogen tank unit, respectively. Therefore, it can be said that using 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 1800 kWh/year is produced. But with about 75 % more initial cost and 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)** | **Bat (kWh)** | **PV (Kw)** | **Con (Kw)** | **WT (unit)** | **Initial (\$)** | **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 |

Fig. 7 shows the breakdown of the project costs in each scenario along with their related rate of return. As can be seen, the capital cost has increased when fuel cell is used, which indicates the need to reduce the price of this technology in order to make it a more economical choice in hybrid systems. When using a diesel generator, maintenance costs have increased significantly, although with the combination of 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 the retail market prices, a higher salvage cannot be considered as a positive factor for the project. In fact, a little 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, with the addition of the fuel cell unit to this system, the return on investment is further reduced by approximatelly 2%. After these two 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 although the fuel cell can functionally complement diesel generator and battery, economically, it can never substitute them.

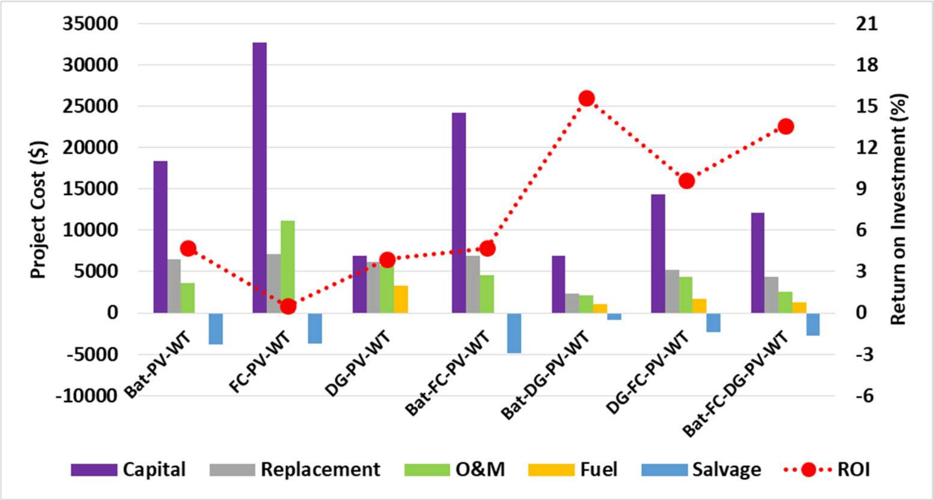


Fig. 7 Project costs and return on investment of the each optimal scenario.

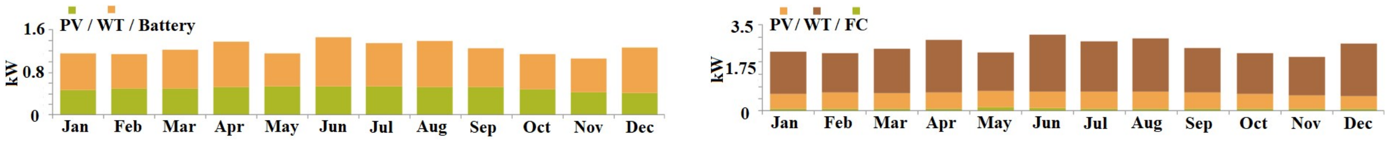
### 4.3 Emission Analysis

In this section, the performance of each scenario is examined from the point of view of environmental impact. According to Table 6, without using the diesel generator in the stand-alone system the hybrid system achieved zero pollution, but as mentioned in the previous section, due to the rising the final costs, these scenarios cannot be an appropriate solution to supply energy for remote areas. Also, using the diesel generator alone as a supplementary equipment due to the high annual consumption of fuel, can lead to more pollution in comparision with grid electricity. For instance, supplying the selected load from a natural gas-fired power plants in Iran leads to 3299 kg of carbon dioxide emissions per year, whereas in the case of the DG-PV-WT hybrid system the $CO_2$ emissions are increased by only 12.1%. Therefore, the use of multiple supplemenrtry systems, in addition to increasing the flexibility of the hybrid system technically, reduce the system costs economically, and also improve the environmental performance of the system. 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, which provides excellent environmental performance for diesel generator and battery as the supplementary equipment to the PV and WT hybrid renewable system.

Table 6. GHGs produced by the different hybrid systems.

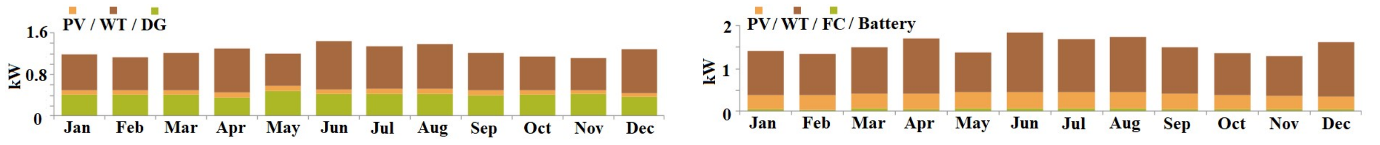
| Hybrid system | Carbon Dioxide (kg/yr) | Carbon Monoxide (kg/yr) | Unburned Hydrocarbons (kg/yr) | Particulate Matter (kg/yr) | Sulfur Dioxide (kg/yr) | Nitrogen Oxides (kg/yr) | Diesel Consumption (L/yr) |
|---|---|---|---|---|---|---|---|
| Pure Grid | 3299 | 3.10 | 0.909 | 0.599 | 8.29 | 11.9 | 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 |

Fig. 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. As it can be seen, the fuel cell supplies only a small percentage of the demand, because of this equipment only works during severe peak loads which led to the need for higher capacities to install solar panels and wind turbines. Although, the use of the electrolyzer improves the system performance and efficiency by absorbing the excess of energy. By comparing Fig. (c) and Fig. (e), it can be concluded that the use of the battery reduces the operating hours of diesel generator by helping to better satisfy the peak demands. Also, due to the ability to store PV output power during the day and use it at night, it has increased the installed capacity of the solar panel. These two factors reduce costs and increase the renewable fraction of the energy system.



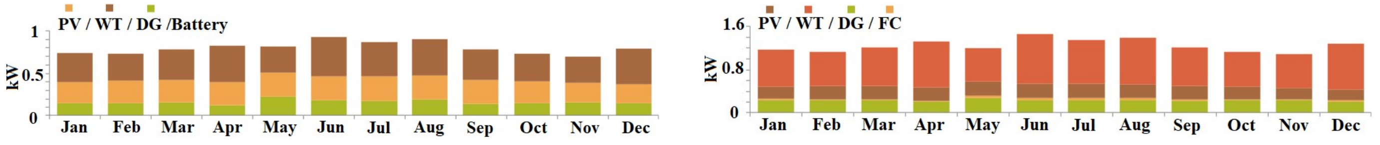
a) PV (39.9%) – WT (60.1%)

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



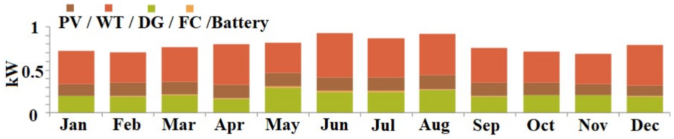
c) DG (33%) – PV (6.9%) – WT (60.1%)

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%)

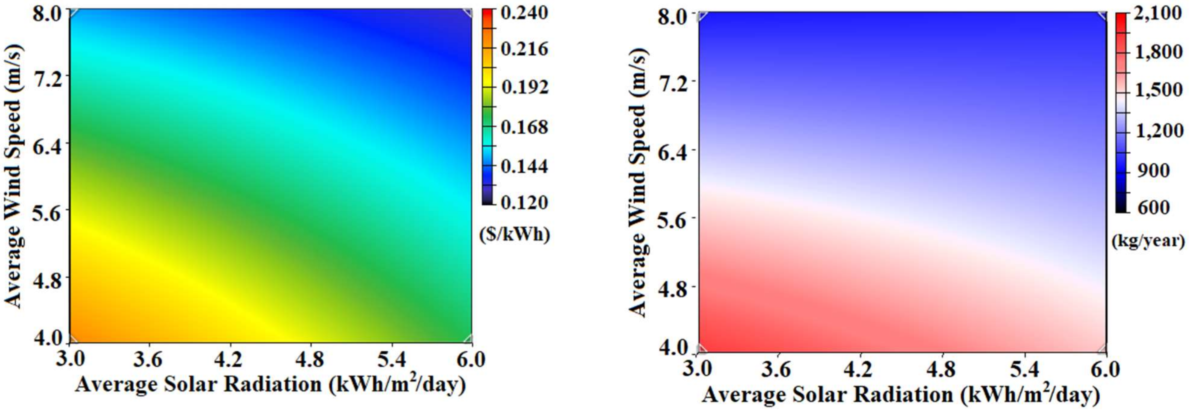


g) FC (1.1%) – DG (27.3%) – PV (18.8%) – WT (52.8%)

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

### 4.4 Sensitivity analysis

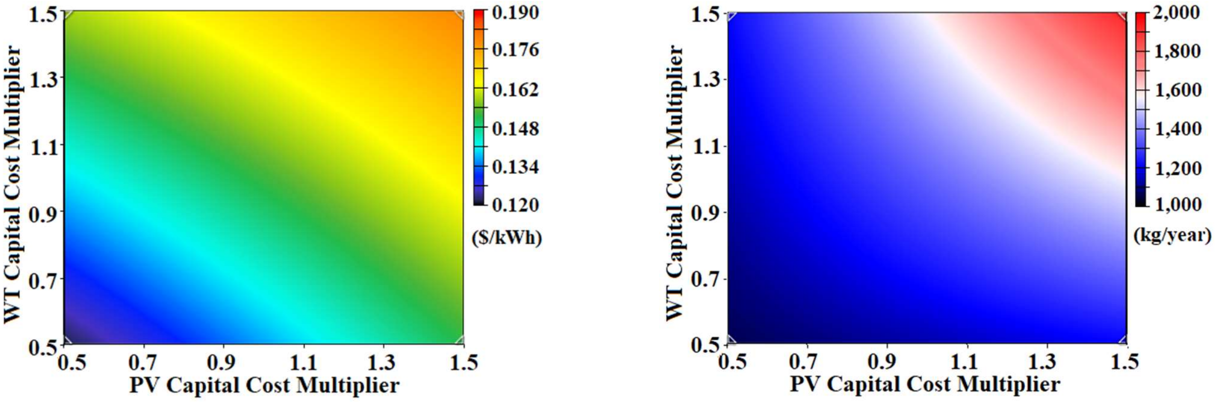
In order to assess the ability to generalize the results of the optimal scenario to other parts of the world, sensitivity analysis has been performed. Fig. 9 shows the effect of changes in average solar radiation and average wind speed on the cost of energy and $CO_2$ emissions. As can be seen from Fig. 9, in the worse case, by reducing the potential of renewable resources in the region, the cost of energy will reach 0.240 \$/kWh and in the best case about 0.120 \$/kWh. In fact, it can be said that the proposed hybrid system, for areas with an average annual radiation above 4.2 kWh/m$^2$/day and average wind speeds greater than 5.3 m/s an energy cost of less than 0.20 \$/kWh is achieved, which indicates the potential ability of this hybrid system for implementation in various remote areas. Also, Fig. 9 (b) shows that the 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 to use more diesel generator at night hours, the system pollution increases. In fact, in areas with good wind potential, the final pollution of the system can be reduced to less than 1200 kg/year, which compared to conventional fossil fueled power plants, prevents the annual emission of more than 2000 kg of $CO_2$ emissions per hoousehold.



a) b)

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

Fig. 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 Fig. 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 solar panel and wind turbine, the cost of energy is around 0.190 \$/kWh, therefore, ensuring initial price of the solar panel and wind turbine will be a crucial factor for investors. Also $CO_2$ emissions is 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, but with simultaneous capital costs increment 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.

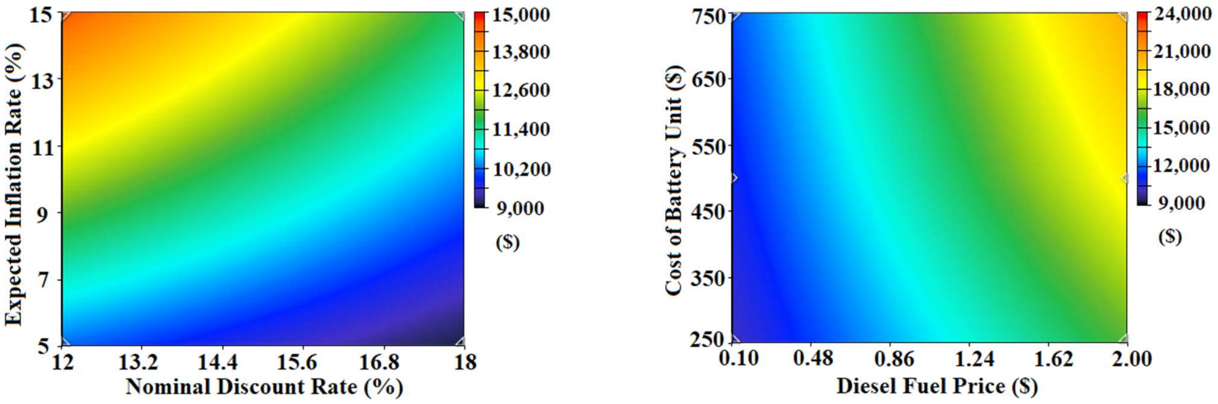


**a)** **b)**

Fig. 10 Effect of changes in the PV capital cost and WT capital cost on the:

a) Cost of energy and b) $CO_2$emission.

Fig. 11 demonestrates the sensitivity heat map of the NPC based on changes in economic conditions of the region. In fact, for any given nominal discount rate, with higher inflation rate, higher NPC is achieved, which will reduce investors' willingness to implement such hybrid systems. Therefore, lower inflation rates will make the hybrid system more economical. Also, Fig. 11 (b), shows that changes in fuel price had a more severe effect on NPC than changes in battery price. 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 fuel prices such as fuel exporting countries.



a) b)

Fig. 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.

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

### 4.5 Comparison

In this section, the results of the optimal scenarios in the present study are compared with the number of other studies related to electricity supply in remote areas. According to Table 7, among the scenarios without using the fuel cell, the present 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 system in order to have an economic system, but none of the studies compares simultaneously 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 fuel cell, electrolyzer and hydrogen tank can make a significant difference in final costs of the system in different studies.

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 | [45] |
| India | 2020 | DG / Bat | FC / PV / WT / Bio | 724.8 | 0.163 to 0.214 | _ | [46] |
| Cameroon | 2019 | DG / Bat | PV / WT / Hydro | 100 | 0.443 | 91.4 | [47] |
| Iran | 2019 | DG / Bat | PV / WT | 242 | 0.197 | 67.3 | [48] |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Nigeria | 2019 | DG / Bat | PV /WT | 7.23 | 0.459 to 0.562 | _ | [49] |
| Turkey | 2018 | DG / Bat | FC / PV / WT | 165.6 | 0.282 | 95 | [50] |
| India | 2017 | Bat | FC / PV | 70 | 0.196 | 100 | [51] |
| Malaysia | 2017 | Bat | FC / PV | 140 | 0.355 | 100 | [52] |
| Ethiopia | 2016 | DG / Bat | FC / PV / WT | 16000 | 0.179 | 99 | [53] |
| Pakistan | 2016 | DG / Bat | PV /WT | 205 | 0.450 | 84 | [54] |
| Current Study | 2020 | DG / Bat | PV /WT | 13.68 | 0.151 | 72.2 | _ |
| | | DG / Bat | FC / PV / WT | 13.68 | 0.231 | 66.1 | |

## 5. CONCLUSION

The understanding of environmental and energy related issues, is of paramount importance. Carbon dioxide footprint is mainly caused by fossil fuels 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 an issue for many countries around the globe, because they currently still depend on the utilization of fossil fuels. In order to achieve the targets of sustainable energy and transition to 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 preformed as below:

- Technically, the combination of diesel generator, battery and fuel cell/electrolyzer/hydrogen tank unit with only 262 kWh/year of excess electricity, produced the best results in terms reducing the energy loss of the hybrid PV/WT system, in fact by eliminating the hydrogen unit, the amount of excess electricity will increase almost six times.
- Economically, the battery and diesel generator combined with PV/WT led to the best hybrid system confiiguration with about 0.151 $/kWh cost of energy. By adding fuel cell/electrolyzer/hydrogen tank unit to this system, the energy costs was increased to 0.231 $/kWh, and the return in investment has 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 2000 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 results of sensitivity analysis 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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