Khalid, F, et al. 2018. Techno-economic Feasibility of Renewable Energy Based Stand-alone Energy System for a Green House: Case Study. *Future Cities and Environment,* 4(1): 12, 1–9, DOI: https://doi.org/10.5334/fce.41

TECHNICAL ARTICLE

Techno-economic Feasibility of Renewable Energy Based Stand-alone Energy System for a Green House: Case Study

Farrukh Khalid[*,†], Rami S. El-Emam[*,‡], Janette Hogerwaard[*] and Ibrahim Dincer[*]

As the negative impacts of fossil fuel consumption for power generation become increasingly globally evident—particularly the effects of greenhouse gas (GHG) emissions on climate change—so too does the conversely positive potential of renewable energies to reduce the rate of damaging environmental impacts as energy demand grows. In addition to the clear environmental advantage, stand-alone renewable energy power generation options offer energy security and stability in regions where socio-political issues or geographic location might otherwise pose access limitations on fuel and/or electric grid power, particularly in remote communities. This paper discusses the techno-economic considerations for renewable energy power systems in residential community applications. A case study for a residential house in New Cairo in Egypt compares two different renewable energy systems that meet typical electrical demand for this region. Economic assessment—in terms of system net present cost (NPC) and levelized cost of electricity (LCOE)—provide measures for system performance comparison and optimization. The LCOE for system-I and system-II are found to be $0.359/kWh and $0.373/kWh, respectively.

Keywords: Green House; hydrogen; fuel cell; electrolyzer; solar energy; wind energy; battery

Introduction

There are numerous reasons for the implementation of renewable energy systems; environmental and human health implications, power grid and fuel access in remote communities are to name only a few. However, certain prevailing challenges require objective consideration and innovative solutions; intermittent availability, inconsistent energy levels (i.e. daily solar insolation, wind speed), and—perhaps most importantly—initial system cost can make these systems less practical relative to traditional fossil fuel systems. Rather than seeking a one-size-fits-all solution, it is more pragmatic to instead apply these challenges as guidelines. Specifying a system case-by-case using a top-down approach—beginning with the particular application, then tailoring the system for typical load demands via systems integration using regionally abundant renewable resources, practical energy storage options, and economic feasibility—has the best potential to provide sustainable, cost-effective solutions for the shift away from fossil fuels.

Energy consumption to meet demand in residential and/or commercial buildings is a prevalent field of research and discussion in literature. Khalid et al. (2015a) assess three sustainable energy systems integrating conventional (natural gas) and renewable energies (solar, wind, biomass) for HVAC applications. The authors state average energy efficiencies for the systems ranging from 19.9%–27.5%, identifying the natural gas system as exhibiting the highest efficiency, with the caveat of CO_2 emissions as a system drawback, while the system option integrating solar PV-thermal with a vapour refrigeration chiller exhibiting the highest exergetic performance, stating exergy efficiencies ranging from 1.2%–3.9%.

Economic considerations are a key factor for decision makers in selection of the most feasible system option. Khalid (2014) discusses this topic in depth, proposing various sustainable energy systems capable of meeting current and future predictions for building energy consumption. The study assesses multigeneration systems integrating various combinations of solar, biomass, ground source heat, and wind energies using comprehensive energy and exergy analyses, as well as techno-economic assessment using HOMER (Hybrid Optimization of Multiple Energy Resources) software to determine the optimal levelized cost of electricity (LCOE), minimum environmental impact, and renewable energy share of each system for the city of Oshawa, Canada. For this region, Khalid (2014) identifies the system integrating concentrating solar collectors and biomass subsystems as the most sustainable and economic option with net present cost (NPC) and LCOE of $2.7M and $0.117/kWh, respectively, and 100% renewable energy share. Bekele and Tadesse (2012) discuss the feasibility of a renewable energy system integrating hydro,

* Clean Energy Research Laboratory (CERL), University of Ontario Institute of Technology (UOIT), Oshawa, L1L1C8, ON, CA

† Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University (HBKU), Doha, QA

‡ Faculty of Engineering, Mansoura University, Mansoura, 35516, EG

Corresponding author: Farrukh Khalid (Farrukh.Khalid@uoit.net)

PV, and wind energies for electricity production in rural areas of Ethiopia, with case study results from the HOMER assessment indicating a LCOE less than $0.16/kWh.

Storage options for regionally abundant renewable energy resources is an important aspect of system integration in order to provide reliable and constant electricity supply for various residential loads. Battery storage is a common storage method for this purpose, and is convenient in terms of scalability and commercial availability. In their feasibility study for off-grid electricity supply in the remote village of Palari, India, Sen and Bhattacharayya (2014) integrate battery storage with hydro, PV, bio-diesel systems for dependable electricity supply at $0.420/kWh. The authors discuss the importance of resource diversity in maintaining low system costs and reliable energy supply, stating the preference for renewables when available and particularly where there are government subsidies to support their implementation. Khalid et al. (2016) analyze a conceptual integrated renewable-based energy system for providing electricity, hot water, heating and cooling to a green building using HOMER. The levelized cost of energy of the system is reported as $0.181/kWh. Khosravi et al. (2018) consider a system that utilises solar and wind energy. Their system uses a combination of wind turbines, PV, hydrogen tank, electrolyzer and fuel cell. Energy, exergy and economic analyses are carried out on the proposed system. PV system is found to have the maximum exergy destruction, while economic analysis reveals that energy storage system (electrolyzer+hydrogen tank +fuel cell) contributes to the 50% of the total investment.

In regions where there are sufficient sources of either potable or non-potable water there is potential to store renewable energy in a chemical form as hydrogen via electrolysis, which can later be supplied to fuel cells and/or combustion generators for electricity production option. Rezk and Shoyama (2014) utilise HOMER software for techno-economic assessment and optimization of a stand-alone PV-fuel cell system that powers water irrigation systems and stores excess energy as hydrogen using water electrolysis. The authors state that it is more economic to install the stand-alone systems than grid extension for locations further than 3.39 km from grid access. Beccali et al. (2008) compare the energetic, economic, and environmental performance of various renewable energy systems integrating natural gas vs. hydrogen fuel cells, including different methods of obtaining hydrogen fuel for residential applications in Palermo, Italy. From the results of a HOMER assessment comparing systems integrating grid and H_2-fuel cell systems producing hydrogen from wind turbine and PV electricity, the authors report NPC and COE values of $5.04M and $0.725/kWh, and $13.00M and $1.87/kWh, respectively. Environmental impacts of each system are minimal for the 493 MWh/year systems, with only low levels of NO_x—11.1 kg/year and 13.9 kg/year for the wind and PV systems, respectively. Khalid et al. (2015b) analyze a residential power generation system combining wind turbine and PV arrays with PEM-electrolysis integration for storage of excess electricity as hydrogen, reporting energy and exergy efficiencies of 26% and 26.8%, respectively, and a LCOE of $0.862/kWh. Belmonte et al. (2016) present comparative assessment between two powered systems, one uses PV-hydrogen technology (electrolyzer + fuel cell) while the other uses PV-batteries technology. Their results show that PV-hydrogen technology is more costly compared to PV-batteries technology. However, from environmental point of view, PV-hydrogen technology system outperforms the PV-batteries technology. Khalid et al. (2017) report the levelized cost of electricity from a multigeneration geothermal-solar energy system, with hydrogen production and storage, as $0.089/kWh with a net present cost of the optimized electrical power system of $476,000.

Renewable Energy and Power Generation in Egypt

The electric power generation in Egypt is mainly dependent on subsidized fossil fuels, which is utilized for producing about 95% of the total power generation. Since 2008, Egypt became an oil importer which was accompanied with lack of fuel supply to power plants due to the unbalanced period following 2011 revolution. This resulted in massive blackouts due to forced outage of generating units especially during the very hot summer season. Despite the great challenges, the country was able to overcome the shortage of electric power supply by end of 2014 resulting in stable supply during summer 2015. Further development of the power infrastructure is approached including the contract signed with Siemens to implement three combined-cycle power plants with 14,400 MW total capacity of which 6400 MW have been delivered. In addition, an agreement was initiated with Russia to build a nuclear power plant in Egypt to produce 4000 MW of electricity.

Renewable energy sector was growing slowly in Egypt through the last two decades. However, renewable energy is of great interest to the stakeholders and the government as well as the private sector. This is highly reflected in the new energy policy in Egypt with the implementation of renewable energy strategies aiming to generate 20% of energy supply from renewable energy by 2022. In 2014, and modified in 2016, a feed-in-tariff (FIT) policy was implemented in an encouraging step towards renewable power generation. Recently, the government implemented oil and gas based energy subsidy reform accompanied with growing interest in investing in renewables. Currently, hydro power comes as the third power source after oil and natural gas. Hydropower resources in Egypt used to cover the power demand for years. Nowadays, it is utilized to cover the increase in energy demand during evening peaks, forming 9% to 10% of the country installed capacity and energy. The total hydro installed capacity is 2800 MW with annual production of around 1300 GWh.

Wind Energy

Wind energy is the second largest renewable energy resource after the hydropower in Egypt with total installed capacity of 750 MW. Based on the Wind Atlas of Egypt, the Egyptian Suez Gulf area experiences wind speed up to 10.5 m/s, among other excellent wind regimes in Sinai and on the Nile banks in eastern and western deserts (Mortensen et al., 2005). **Figure 1** shows the areas with potential for new wind power plants (Mortensen et al., 2003, 2005; Frank, 2003). It also shows currently operating Zafarana wind farm with capacity of 545 MW from 648 installed wind turbines, this project started in 2001, through governmental collaboration protocols with Germany, Denmark, Spain, and Japan. Another 200 MW wind farm is commissioned in 2015 at Gabal Al-Zeit, Red Sea, with 100 installed wind turbines, with plans for expansion to 240 MW. In addition, several governmental projects with international collaboration are in process, including: 232 MW wind farm in Gabal Al-Zeit 2 with Japan, and 120 MW wind farm in Gabal Al-Zeit 3 with Spain. Several other projects are under consideration with total capacity of 800 MW. Furthermore, 8 projects are considered for BOO system, with total capacity of 970 MW (NREA, 2015).

Solar Energy

Egypt geographical location and nature with its climatic condition makes it very attractive for solar energy market. The annual direct normal solar irradiance in Egypt is 2500 kWh per unit area in average with maximum of 3200 kWh/m^2 in Upper Egypt, with average sunshine time of 9 to 11 hours. In 1980s, there was governmental solar heaters initiative. However, due to lack of maintenance and high-quality manufacturing at this time, solar heaters industry did not flourish as expected. Currently, solar heaters are used in the touristic residences and hotels in Sinai and there is new initiative with high interest in more investment in this sector with plan of solar water heaters of 1.2 million square meter. On the other hand, concentrated solar power (CSP) market has great expectation to expand in the near future. Currently, parabolic trough based integrated system of 140 MW is operating 100 km south of Cairo, at Kuraymat. This plant operates since June 2011 with 20 MW electric power generated from the solar power. Another 100 MW CSP plant is under construction in Kom-Ombo in south of Egypt. The operation of a European Union co-funded demonstration CSP plant for cogeneration of power and water in Borg Al-Arab, Egypt, was launched earlier this year. It uses 10,000 m^2 of linear parabolic mirrors for the production of 1 MW of electric power, and a multi-effect distillation unit replacing the condenser for producing 250 m^3/day of fresh water. The Supreme Council of Energy plans to provide around 2500 MW of CSP by 2022. The third promising market of solar energy in Egypt is photovoltaic (PV) power production. Several projects funded by European Union and other countries have been launched over the last decade to provide electricity to villages in remote areas through PV systems to cover the demand of lighting homes, roads, and provide power to medical centers and other necessary power demands. As part the most recent project, funded by United Arab Emirates, solar PV was utilized to provide 211 villages with electric lighting of 2 MW, and electricity was provided to over 167,000 inhabitants in different governates. It also included the implementation of 8 central PV plants of total capacity of 30 MW in Siwa (10 MW), Farafra (5 MW), Abu Monkar (0.5 MW), Halayeb (1 MW), Shalateen (5 MW), Marsi Alam (6 MW), Abu-Ramad (2 MW), and Darb-Elarbeen (0.5 MW). Several PV plants are considered for the near future including 20 MW plant in Hurghada, and 20 MW plant in Kom-Ombo. Large-scale PV projects are also considered for deployment under Build-Own-Operate (BOO) policy including 10 plants each of 20 MW capacity in Kom-Ombo. In March 2018, the first of 32 PV-stations of the Benban Solar Park in Aswan started operation producing 50 MW of electric power. The plant expected to be finished by mid-2019 is the largest solar power installation in the world, with total capacity of 1465 MW. Last year, 16 other solar projects, with cumulative capacity of 750 MW were identified by the European Bank of Reconstruction and Development to receive partial financing, with additional funding from private sector.

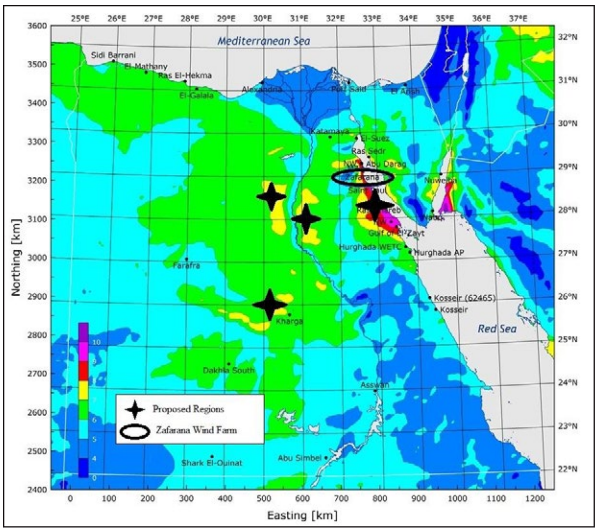

Figure 1: Wind map of Egypt showing regions with wind power plant potential, modified from Mortensen et al. (2005).

Biomass and MSW

Biomass has great potential to be used in Egypt as a source of energy. The agricultural waste and municipal solid waste (MSW) represent good candidate for this purpose. In Egypt, MSW is estimated as 23 million tons with about 2% annual increase, with same amount of agricultural waste. More than 55% of the MSW in Egypt is composed of organic waste, and 80% of the recyclable matter is collected through unorganized sector. Currently and since 1999, Egypt suffers from a seasonal challenging black cloud of think layers of smog that is formed from burning rice straw after the harvesting season. The government put in effect certain laws and restrictions to seize this issue (El-Emam and Dincer, 2014). The main target is setting the required standards and regulations to organize the waste management sector. With the increase in oil prices, cement industry started burning biomass in Egypt and other companies started biogas plants. Different studies were conducted to study the potential of clean combustion and gasification of rice straw and other biomass for energy production and multigeneration (El-Emam et al., 2014, 2015; El-Emam and Dincer, 2015).

Case Study: Green House in New Cairo, Egypt

This study comparatively assesses the techno-economic performance of two renewable energy systems for a house in New Cairo in Egypt. The two proposed systems use the combination of wind turbines and solar PV arrays for the production of electricity. These systems differ only in the storage devices as one of the system uses battery when there is excess electricity so that it can be used in peak hours while the other system uses hydrogen tank and fuel cell to store and utilise excess electricity for peak hours. The considered house is composed of three floors with a floor area of 182 m^2, as shown in **Figure 2**. The details of each floor are shown in the figure and rooms are identified in **Table 1**. The house is for a big family living in two separate floors. The ground level hosts the garage space and a small apartment for hosting the housekeeping staff.

The house average energy demand is estimated based on the considered loads listed in **Table 2**. The energy load on daily basis is calculated over the year considering two periods: (A) Spring and Summer, (B) Fall and Winter as shown in **Figures 3** and **4**. The daily demand is estimated as 406 kWh for period A with peak demand of 36 kW, and 258 kWh for the whole house through period B with peak demand of 28 kW. It is clear from the **Figures 3** and **4** that most of the peak load is from 4: 00 pm to 11: 00 pm.

Figure 2: Floor-plans for the considered house.

Table 1: Number of rooms in each floor of the considered house.

	GL	L1	L2
Bed Room	1	3	3
Living	–	1	1
Kitchen	1	1	1
Bathroom	1	2	2
Garage	2	–	–
Halls	1	1	1

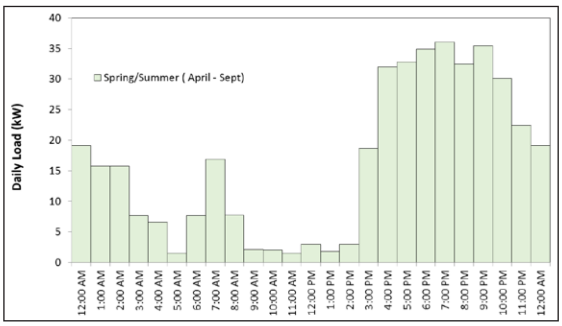

Figure 3: Daily energy load profile for the proposed house from April to September.

Table 2: Load of appliances in the proposed house.

Appliance	Load (W)	Number of units
Main Appliances and Devices		
Low Energy Light	23	66
Air Conditioner	3200	8
Heater	1500	8
Refrigerator & Freezer	1000	3
Dishwasher	1800	2
Laundry Machine	800	1
Dryer	2600	1
Kitchen Appliances		
Broiler	1100	3
Coffee Maker	1200	3
Food Blender	300	3
Microwave Oven	1450	3
Toaster	1150	3
Iron	1200	3
Vacuum Cleaner	1300	2
Multimedia & Video		
56 Plasma TV	470	2
32 LCD TV	100	6
Desktop	320	4
Laptop	45	6
Xbox/PlayStation	190	2

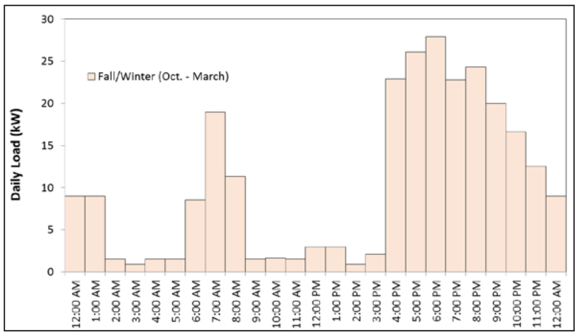

Figure 4: Daily energy load profile for the proposed house from October to March.

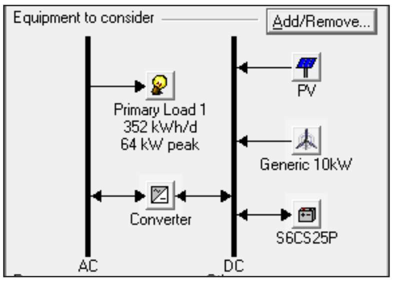

Figure 5: Optimized system-I.

Table 4: Optimized system-I architecture.

PV Array	140 kW
Wind Turbine	30 kW
Battery	180 unit
Rectifier	60 kW
Inverter	60 kW

Table 3: Comparison of two hybrid energy system.

System number	PV (kW)	Wind Turbine (kW)	Battery Quantity	Converter Capacity (kW)	Electrolyzer (kW)	Fuel Cell (kW)	Hydrogen Tank (kg)	Total Net Present Cost ($)	Cost of Electricity ($/kWh)
1	140	30	180	60	–	–	–	581,916	0.359
2	160	50	–	120	180	50	40	603,856	0.373

Results and Discussion

In this study, two hybrid energy systems are studied and compared in terms of their performance. The HOMER (2012) software developed by NREL is used in the assessment. **Table 3** shows the comparison between the two systems considered. From the economic point of view system-I is superior while from environmental point of view system-II is superior. The main reason for the system-I to be not environmental benign is that it has batteries as a storage device to store excess energy while system-II produces hydrogen and store it in storage tank, which is more environmental benign.

Optimized System-I

The schematic diagram for optimized system-I design in HOMER is shown in **Figure 5**. The total connected load is 352 kWh daily. **Table 4** lists that it requires PV arrays of 140 kW, three 10 kW generic wind turbine, 180 batteries (Surrette 6CS25P) and 60 kW converter to meet the energy demand of the house. The total net present cost of the optimized system-I is $581,916 and cost of electricity is estimated to be $0.359/kWh.

The cash flow summary of the optimized power system is shown in **Figure 6**. It is clear from the **Figure 6** that the

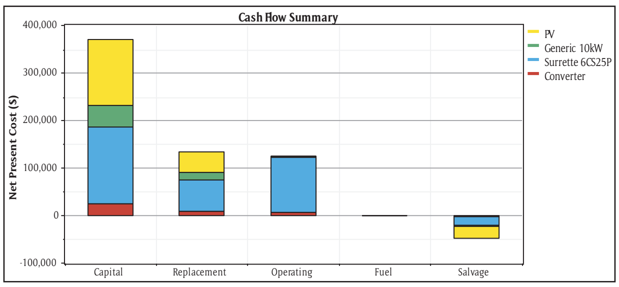

Figure 6: Cash flow summary of optimized system-I.

capital cost of the PV system is more compared to the capital cost of the wind turbine. The capital cost of the batteries is the second most followed by the converter. **Figure 7** shows the monthly production of electricity for optimized system-I and it is evident that the electricity produced by PV is more compared to the wind turbine for most of the year.

Table 5 gives the optimized renewable energy power system electrical configuration for system-I. Around 85% of the electricity is produced by PV arrays. The electricity produced by the wind turbine is 41,686 kWh/yr i.e. 15% of the total electricity produced.

Table 5: Optimized system-I electrical configuration.

Component	Production (kWh/yr)	Fraction (%)
PV array	236,006	85
Wind turbine	41,686	15
Excess electricity	114,995	41.4
Renewable fraction	–	100

Table 6 provides the different renewable energy configuration for optimized system-I. If system only operates on PV, the cost is more compared to the case in which the system operates on a combination of PV and wind. For the case of wind, the cost of the system is maximum (see **Table 6**).

Optimized System-II

Figure 8 shows the schematic diagram of the optimized system-II design in HOMER. The daily total connected load is 352 kWh. **Table 7** lists that it requires PV arrays of 160 kW, five 10 kW generic wind turbine, 180 kW electrolyzer, 50 kW fuel cell, and 120 kW converter to meet the energy demand of the house. The total net present cost of the optimized system-II is $603,856 and cost of electricity is $0.373/kWh.

Figure 9 shows the cash flow summary for the optimized system-II. The operating cost of the fuel cell is more compared to its capital cost. It is evident from **Figure 10** that the electricity produced by the fuel cell is more compared to the electricity produced by the wind turbine and the electricity produced by the optimized system-II is more in the months of March and September while least in the November and December. **Table 8** shows that

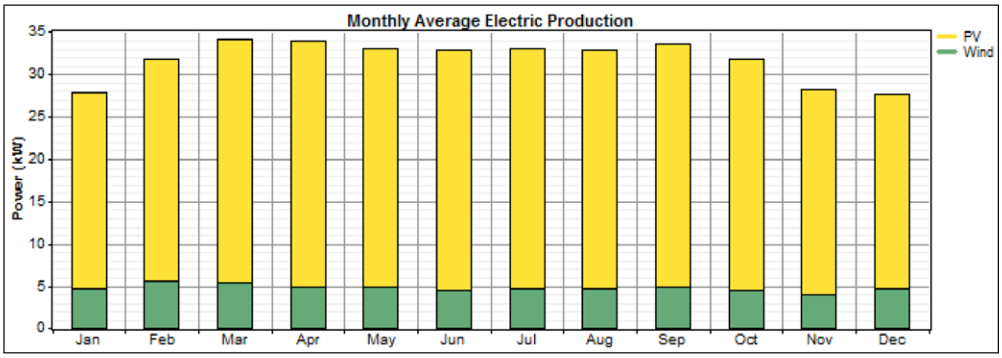

Figure 7: Monthly production of electricity for optimized system-I.

Table 6: Total net present cost for different renewable configuration for optimized system-I.

Power Structure	PV (kW)	Wind Turbine (kW)	Battery Quantity	Converter Capacity (kW)	Total Net Present Cost ($)
1	140	30	180	60	581,916
2	160	–	180	60	590,996
3	–	350	250	80	1,192,826

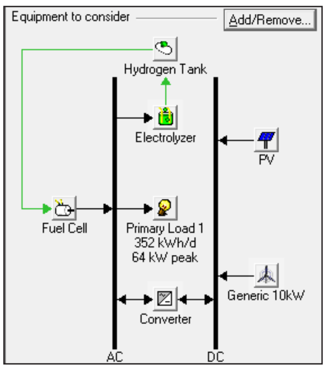

Figure 8: Optimized system-II.

Table 7: Optimized system-II architecture.

PV Array	160 kW
Wind Turbine	50 kW
Electrolyzer	180
Fuel Cell	50 kW
Hydrogen Tank	40 kg
Rectifier	120 kW
Inverter	120 kW

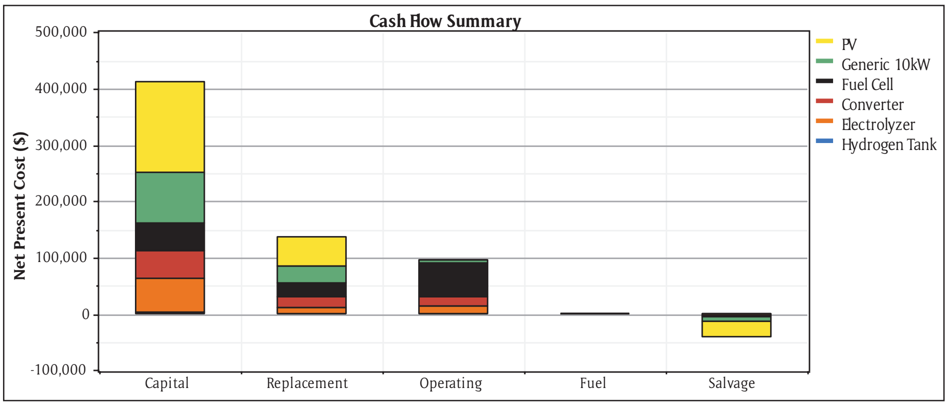

Figure 9: Cash flow summary of optimized system-II.

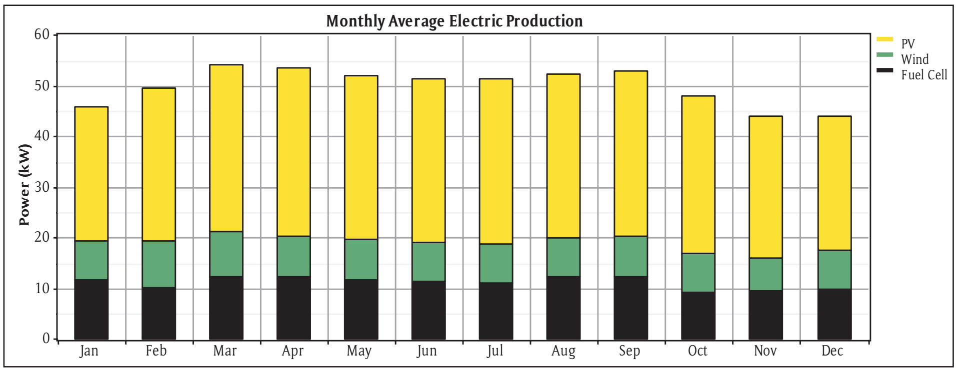

Figure 10: Monthly production of electricity for optimized system-II.

Table 8: Optimized system-II electrical configuration.

Component	Production (kWh/yr)	Fraction (%)
PV array	269,720	62
Wind turbine	69,477	15
Fuel cell	97,633	22
Excess electricity	54,131	12.4
Renewable fraction	–	100

Table 9: Total net present cost for different renewable configuration for optimized system-II.

Power Structure	PV (kW)	Wind Turbine (kW)	Fuel Cell (kW)	Storage Tank (kg)	Electrolyzer (kW)	Converter Capacity (kW)	Total Net Present Cost ($)
1	160	50	50	40	120	120	603,856
2	160	50	50	60	120	120	605,936
3	160	50	50	200	120	100	606,703

the electricity produced by the fuel cell is around 22% of the total electricity produced by optimized system-II i.e. 97,633 kWh/yr with a renewable fraction of 100%.

Table 9 provides the different renewable energy configuration for optimized system-II. For power structure 1, the net present cost is the minimum while for the power structure 3, the net present cost is maximum. The difference in the cost is due to the different number of components required for both the configurations.

Conclusions

In the present study, two renewable energy based hybrid energy systems are techno-economically evaluated by using HOMER. The simulation results show that integration of renewable energy sources and using hydrogen as a storage option for the residential application have promising future. The total net present cost of the optimized system-II is found to be $603,856 with a cost of electricity as $0.373/kWh. From environmental point of view system-II is found to be better. In the coming future with the advancement in the material and technology, the cost of electricity generation from system-II would be reduced significantly making it economically feasible as well.

Abbreviations

CSP Concentrated Solar Power
GHG Greenhouse Gas
LCOE Levelized Cost of Electricity
MSW Municipal Solid Waste
NPC Net Present Cost
PV Photovoltaic

Competing Interests

The authors have no competing interests to declare.

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How to cite this article: Khalid, F, El-Emam, RS, Hogerwaard, J and Dincer, I. 2018. Techno-economic Feasibility of Renewable Energy Based Stand-alone Energy System for a Green House: Case Study. *Future Cities and Environment,* 4(1): 12, 1–9, DOI: https://doi.org/10.5334/fce.41

Submitted: 25 January 2018 **Accepted:** 23 April 2018 **Published:** 25 May 2018

]u[*Future Cities and Environment,* is a peer-reviewed open access journal published by Ubiquity Press.

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