Techno-Economic Assessment of Hybrid Renewable Energy Systems for Residential Complexes of Tabriz City, Iran

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Abstract

Tabriz, Iran possesses abundant renewable energy sources like wind and solar energy. Residential complexes in Tabriz consume significant amounts of electrical energy. Most of this electricity is generated by non-renewable energy resources, which results in significant air pollution. This research provides a techno-economic evaluation of hybrid Renewable Energy Systems (RES) for three residential complexes located in Tabriz. Each complex contains three optimum cases (overall nine cases). Proposed hybrid systems require the lowest NPC and COE. First, generators are removed from RES for all nine cases (100 percent RES). The structure of these cases were PV, Wind-PV, and wind with converter and battery. Secondly, due to the affordable price of diesel in this region, diesel generation is added to RES of all cases to explore more feasible and affordable optimized hybrid systems. The structure of these cases were Wind-Diesel-PV, Wind-PV, and Wind-Diesel, and Diesel-PV with converter and battery. Technical and economic assessment of optimized systems is performed by means of HOMER software. The main purpose of optimized systems is to meet the load demand. The electricity load of the study area has been obtained by means of electricity bills. Average load

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demand and peak load of complex one, two, and three were 7972, 3991, and 2960 kWh/d and 1122, 562, and 417 kW respectively. The goal of the current research is to explore the possible usage of the optimized hybrid RES by means of economic and technical parameters. In the optimized configurations with 100% Renewable Energy System, it was interpreted that PV with Wind is fully practicable. In addition, the COE for Battery-Wind-Diesel-PV HES arrangement is minimum for entire complexes. The optimized systems with 100% RESs remarkably reduces harmful emissions.

Keywords: HOMER software, residential complexes, techno-economic assessment, hybrid RES.

Highlights

- This research explores the possible usage of optimized hybrid renewable energy systems by means of economic and technical parameters.
- Residential complexes use significant amounts of non-renewable energy – up to 90 percent of the total generated – in the northwest parts of Iran.
- The recommended hybrid renewable energy systems assessed in this work are practical, both economically and technically, in different areas in the world.

1 Introduction

Renewable energy production in the world was almost 5.9 TWh in 2017. This indicates a 5 to 6-fold enhancement since the 1960s. Although renewable energy adoption of the world considerably improved, nevertheless, as of 2019, total energy generation covers only 5% of this amount. Furthermore, as of 2018, 15 percent of the world's population, or more than one billion individuals, do not have available electricity [1]. In the last eight decades the population in Middle Eastern countries significantly grew. Based upon the US Census Bureau estimates, the population of the Middle East will approximately double in the coming eleven years. From the year 1998–2011, the energy consumption in the Middle East countries grew from 365 TWh to 610 TWh [2].

Generally, Middle Eastern countries are abundant in natural resources. Although diesel fuel prices in most parts of Iran are cheaper than most countries in the world, lately Iran's government, due to environmental concerns, has a new policy to enhance the utilization of wind and solar resources. Although Iran enjoys numerous non-renewable energy resources like gas and oil, the country is the secondary country in the Middle East in terms of enjoying different renewable energy resources. Wind and solar energy are the largest renewable energy sources in Iran, but the country has no specified perspective and policy toward its enormous resources. This brings a main obstacle to policy makers. Iran's energy status needs to be clarified, in order to have an explicit viewpoint, in upcoming years.

Iran has a high percentage of fossil fuel consumption for the generation of electricity among other countries in the Middle East. Accordingly, Iran produces a high amount of emissions in the world. Based on the 2017 population census, Iran's population was nearly 79.9 million, a fourfold increase since 1955 [3]. Therefore, energy consumption will be increased. Owning to population enhancement and remarkable industrialization, energy demand will significantly be increased in the coming years. It is a challenge to cope with this rising demand and simultaneously reduce harmful emissions. Hence, to meet energy demand, sustainable and renewable sources of energy are suitable alternatives. Renewable energy utilization for power generation will reduce emissions and increase Iran's revenues. When overall electricity utilization in Iran is taken into the account, it has been reported that around 18% of the electricity is utilized by industrial areas, nearly 20% by educational and health centers, almost 12% by government-based centers, and more than 50% by residential districts, especially residential complexes. Since residential districts consume more than 50% of the generated electrical load, applying renewable energy sources needs to be the main goal to decrease the utilization of fossil fuel energy resources in the power production process.

The present research represents a technical and economical investigation of three residential complexes located in Tabriz. In this research, the electricity load of the study area has been obtained by means of electricity bills. Based on economic and technical indicators, the simulation outcome of different designs are assessed, and optimized designs are determined using HOMER software.

2 Literature Review

There has been abundant research of the techno-economic assessment of hybrid renewable energy systems. This section reports the most recent studies which are related to research subject. Table 1 shows an overview of recent research in the last few years.

Table 1 An overview of recent research in the last few years

Refs.	Principle Objective	Applied Software	Variables	Electricity Consumption on (kWh/d)	Peak Demand (kW)	Outcome	Hybrid Design	Application	Country
Mojtaba et al. (2018) [4]	To discover suitable resolvent of sand-alone renewable energy in KhshU, Iran	HOMER	Electrical demand, solar radiation, wind speed	3	–	Result illustrated that discount rates raises COE, however NPC would decrease	PV/Wind/Battery	KhshU Site	Iran
Barun et al. (2017) [5]	Environmental and feasibility analysis of a village	HOMER	CO_2 emission, NPC, COE	248	44.41	Results demonstrated that it is impossible to attain electricity price even with government assistance	Wind/Batt/PV/Biogas/Diesel	Remote area	Bangladesh
Abdullah et al. (2017) [6]	To analyse the possibilities of power creation by means of wind and solar for various areas	HOMER	Wind speed and solar radiation	–	–	FC/PV/Wind integration offers lowest COH and COE	Wind/PV/Battery Fuel cell/PV/Wind	Urban areas	Saudi Arabia
Luis et al. (2018) [7]	Economic and technical feasibility of stand-alone BESS-PV for Electric Vehicles	HOMER	power supply, economic, technical, and environmental parameters	–	–	Results illustrate that stand-alone BESS-PV are technically reliable	BESS/PV	Electric vehicles	Spain
Farivar et al. (2016) [8]	To discover the feasibility of electricity supply from hybrid systems for residential sector	HOMER	Heating and cooling load	28.8	4.2	Results demonstrated that the most economical hybrid system is Battery/Diesel/Wind	Wind/Battery/PV/Diesel	Residential building	Iran

Zelalem (2016) [9]	Economic, and technical possibility of hydropower (Grid-connected)	SMART Mini-IDRO, HOMER, RET screen	Greenhouse gas emissions, COE, NPC	2256	222	Small scale hydropower is economically and technically stable	Hydro/Grid-connected	Small Scale Hydropower	Ethiopia
Yildiz et al. (2014) [10]	To study a hybrid RES from economic viewpoint	HOMER	Hydrogen tank capacity, solar radiation, wind speed, COE, and NPC	1875	135	Increasing of RE sources reduces NPC and COE	PV/Wind/Fuel cell/Hydrogen storage	Island areas	Turkey
Ramin et al. (2017) [11]	To analyze the wind use in residential area through data gathering in various parts of country	HOMER	Different regions, economic, and climate conditions	–	10	Results show that FIT is the most energetic item for wind turbines	Wind/Grid-connected	Residential sector	Iran
Taher et al. (2016) [12]	To analyze economic and technical feasibility of Diesel-PV-Wind on stand-alone and grid-connected energy system in Tunisia	HOMER	Excess electricity, CO2 emission	22	4	Hybrid energy system is more beneficial than traditional system	Wind/Diesel/Battery/PV	Urban areas	Africa, Bizerte, Tunisia
Mohammad et al. (2017) [13]	A wide review of power generation on various hybrid systems performed	HOMER	Different systems, various urban areas	–	1.3	Battery/Wind/PV/Diesel provide more power compared with other systems	PV/Wind/Diesel/Battery	Tele-communica-tion applications	India
A. Can et al. (2018) [14]	Electrical demand of stand-alone homes through Fuel cell/PV/Wind is analyzed from technical and economic point of view	HOMER	Climatic and geographic states	165.59	3.31	Economic, and technical investigation demonstrated that battery economically preferred	Battery/Fuel cell/PV/Wind	Occupied Households	Turkey

(*Continued*)

Table 1 Continued

Refs.	Principle Objective	Applied Software	Variables	Electricity Consumption on (kWh/d)	Peak Demand (kW)	Outcome	Hybrid Design	Application	Country
Khalil (2020) [15]	The principal objective of the current study is to evaluate optimized systems of 6 stand-alone remote rural areas in East Azerbaijan province.	HOMER	Emissions, NPC, COE	–	–	Hybrid systems preferred from economical and environmental point of views	Battery/ Wind/ Diesel/PV	Remote rural regions	Iran
Makbul et al. (2015) [16]	To analyze hybrid system with flywheels storage	HOMER	Carbon emission, and fuel consump-tion	32962	2213	The simulation outcomes demonstrated that system offers considerable CO2 emission, COE, NPC	PV/Diesel/ Battery	Urban areas	Saudi Arabia
W. Margaret et al. (2015) [17]	To analyze the technical, economic, and environmental feasibility of different hybrid systems for remote telecom	HOMER	Various supply options	3926	–	Simulation results proposed an appropriate hybrid system which would be feasible for remote telecom	Battery/PV/ Diesel/Wind/ Fuel cell	Rural telecom	India
H. Rezzouk et al. (2015) [18]	To investigate the economic and technical possibility of a Battery/PV/Diesel hybrid system in Algeria	HOMER	Real interest rate, solar radiation, diesel price	640	–	Results illustrated that 25% Battery/PV/Diesel hybrid system is the optimal arrangement	PV/Diesel/ Battery	Urban areas	Algeria
Hazim (2017) [19]	To detect an optimal system to meet the load	HOMER	Solar radiation, average wind speed	556	68	The The results showed that 200 KW PV is economically feasible	Battery/ PV/Wind	Residential sector	Saudi Arabia
Suresh et al. (2019) [20]	To investigate best configuration of a hybrid RES in order to encounter the village load sustainably	HOMER	Various con-figuration and systems	724.83	–	Battery/Biomass/PV/ Biogas/Wind/FC identified as the reliable solution	Diesel/PV/ Fuel cell/Wind	Cluster of villages	India

Farrukh et al. (2016) [21]	To obtain an optimal system based on NPC	HOMER	Exergy and energy efficiencies	410	–	The exergy investigation showed that higher exergy occur in the solar panel and generator	Battery/ Diesel/Wind	Green buildings	Canada
Ephraim et al. (2020) [22]	To assess the economic and technical possibility of Diesel/PV/Wind/Battery for commercial aims in Ghana	HOMER	Inflation rate, cost of fuel, discount rate	2422.06	407.71	Sensitivity analysis demonstrated that cost of energy would diminish when cost of fuel changed	PV/Battery/ Diesel/Wind	Part of Ghana in a town	Ghana
Yahya Z et al. (2018) [23]	In this research a PV/Wind hybrid system designed considering electricity consumption and peak load	HOMER	Highest total energy, NPC, LCOE, CO2 emissions	15000	2395	The simulation outcomes showed that system is environmentally feasible	Wind/PV, Grid-connected	Residential sector	Saudi Arabia
K. Murugaperumal et al. (2019) [24]	Economic-technical possibility and design of HRES for rural area	HOMER	Renewable resources	179.32	19.56	The final result showed that hybrid renewable energy system would be cost effective in remote area	Battery/ Wind/ BIO power/PV	Rural area	India
Mehdi et al. (2019) [25]	This research proposed an energy profile for remote towns in Chad	HOMER	LCOE, NPC	14	2.1	The results showed that in the electricity production case total NPC was $48,165	PV/Diesel/ Wind/Battery	Domestic	Chad
Om et al. (2019) [26]	Optimal design of hybrid renewable energy systems and economic-technical analysis	HOMER, MATLAB	Various hybrid con-figuration	50.15	14	Results showed that Hybrid Battery/Wind/PV is cost effective	PV/Wind/ Battery	Rural community	India

3 Novelty, Work Motivation and Objectives of the Present Study

When overall electricity utilization in Iran is taken into account, it has been reported that around 18% of the electricity is utilized by industrial areas, nearly 20% by educational and health centers, almost 12% by government-based centers, and more than 50% by the residential districts especially residential complexes. It needs to be taken into consideration that residential districts consume more than 50% of the generated electrical load, and that over 90% of this electricity generated by non-renewable energy resources. Hence, there is considerable opportunity to apply this research to optimize energy usage.

As a result of non-renewable energy resource consumption by residential complexes, Tabriz faces significant air pollution. However, implementation of the results of this research – employing optimized hybrid renewable energy systems – can yield significant air pollution and carbon dioxide reduction for most areas in Tabriz to help address this challenge.

This research explores the feasibility of various hybrid renewable energy systems through a techno-economic model to discovery optimized hybrid renewable energy systems for Tabriz. To the best knowledge of the authors, other research has not focused on a similar techno-economic evaluation of residential areas like Tabriz that utilize a high proportion of non-renewable energy. The work in this study offers the first use of this research method for Tabriz. Therefore, this gap needs to be explored, as the recommendations presented here may be economically and technically practical in other areas in the world.

4 Description of the Study Area in the Current Research

This study area contains three residential complexes located in Tabriz. Complex one contains eight buildings, each building has five floors, and each floor is comprised of four apartments, totalling 160 apartments. Each apartment has one kitchen, two bedrooms, one washroom, and one living room. Complex two has seven buildings, each building contains five floors, and each floor comprised of three apartments, with 105 apartments overall. Each apartment has two bedrooms, one living room, one kitchen, and two washrooms. Complex three has six buildings, each building has six floors, and each floor has four apartments, for 144 apartments. Each apartment is comprised of one living room, one kitchen, three bedrooms, and one washroom.

5 Renewable Energy Perspectives & Status in Iran

Achieving sustainable targets in Iran clearly requires development of renewable energy resources [27]. Generally fossil fuels are used for producing electricity in Iran, which is the main contributor to air pollution. The utilization of renewable energies is negligible, while the efficiency of power plants in Iran is sorely little. The present capacity of renewable energy in Iran is almost 200 MW, though government plans call for enhancing this. Based on the Sixth Development Plan (2016–21), Iran should have concentrated more on renewable energy instead of fossil fuels, but this could only be attained by overcoming several obstacles. Renewable energy usage is a key priority for producing of electricity in developing countries, and in Iran solar energy is the most significant resource of renewable energy. Most days are sunny in Iran, with a mean potential efficiency of 4.5 to 5.5 KWh/ m^2/day. Based on the Sixth Development Plan, Iran was seeking to use about 19% of its energy from solar and wind. By February 2016, the share of solar and wind energy was about 240 MW, a small part of the total generation capacity of Iran, which is is approximately 74,000 MW. However, based on the development plan, renewable energy generation capacity should have grown to 5,000 MW. The goal were not even close to being met by 2021.

In spite of substantial potential of renewable energy in Iran, there has not been significant improvement. Although the government has made an effort, and general knowledge toward renewable energy technologies has substantially enhanced, there are economic barriers toward renewable energy development in Iran. Higher expenses of renewable energy technologies, such as wind turbines and PV, are a barrier to their greater usage (apart from less-expensive Chinese products). Transmission costs are also a great challenge for the government of Iran.

6 Explanation of Population and Geographic Location of Tabriz

Tabriz is located in the northwestern of Iran. Tabriz is the fifth largest city in Iran, with a population of almost 1.7 million, according to the 2018 census. It is a capital of East Azerbaijan Province with an area of 324 km^2. The elevation of Tabriz spans from 1355 to 1650 metres [30]. This city is the biggest economic and metropolitan center in the region. Tabriz is an old city and well known for its handiworks. Figure 1 shows the geographical location of study area.

Figure 1 Geographical location of Tabriz.

7 Load Profile

Hybrid renewable energy system layout pertain primarily to the electricity demand. The required electrical load consumption by residential complexes is not similar during the whole year. Based on season variation the day length varies, therefore peak load is not same during the specified time period. Electrical load assessment is a decisive stage in this method of study. In this research, the electricity load of study area has obtained by means of electricity bills. Most significant energy utilization are lighting, entertainment, and domestic electrical appliances. Figure 2 demonstrates average load profiles for one year. Hybrid renewable energy system design mostly pertain to the electrical demand. The required electrical load in the residential complexes is not similar throughout a year. Due to seasonal variation in this region peak load changes during a day. Based on the residential complex's electricity bills, the average load for complex one, two, and three are 7972, 3991, and 2960 kWh/d respectively and peak loads are 1122, 562, and 417 kW respectively. The yearly overall load profile of complex one is obtained and then, as similar electrical load profile behavior, scaled to 2 other complexes. The final overall load profile is demonstrated in Figure 2. Furthermore, the

Figure 2 The yearly overall load profile of residential complexes in 2021.

monthly overall electrical load profile of residential complexes represented in (Figure 1 in supplementary material). Based on Figure 2 and (Figure 1 in supplementary material), it can be perceived that maximum electrical load occurs in peak months, during summer (August and July), due to remarkable energy utilization for air cooling purposes where minimum electrical load occurs in January and December.

8 Available Renewable Energy Resources

The primary target of a hybrid renewable energy system is to transfer the electrical load from the peak hours. In addition, the next aim is to use maximum power output from batteries and PV.

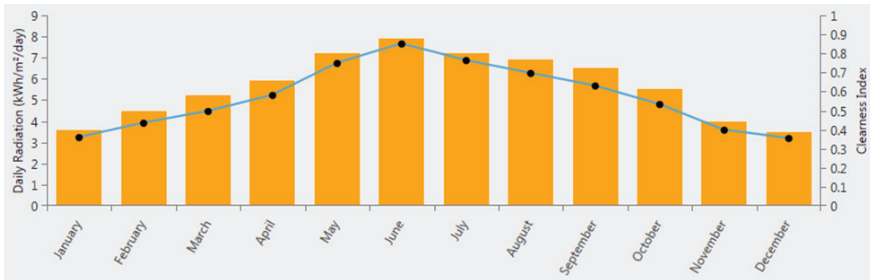


Figure 3 Average monthly quantity of solar radiation in 2021.

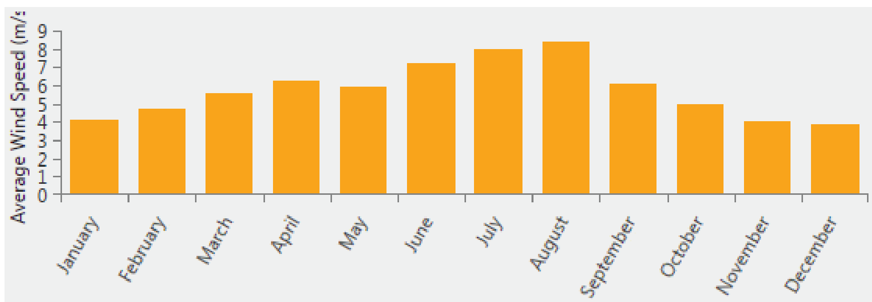


Figure 4 Monthly average wind speed profile for Tabriz, Iran in 2021.

8.1 Solar Radiation

Figure 3 shows the average monthly numerical quantity of solar radiation for Tabriz, which receives extensive amount of solar irradiation during the year. This location can generate energy in an effective way through a PV array. As the figure shows, the maximum value of solar radiation is in June, while the low is in December. The solar irradiation information is taken from NASA's Surface Meteorology and Solar Energy center.

8.2 Wind Speed

Wind speed data for the selected area is also taken from NASA Surface Meteorology and Solar Energy Center. Figure 4 illustrates the monthly wind speed profile for Tabriz in a year. The maximum value of wind speed is in July and August, and the minimum value in December. Tabriz has considerable wind energy sources. (Hourly wind speeds can be observed in Figure 2 in the supplementary material). The maximum wind speed can be found at noon.

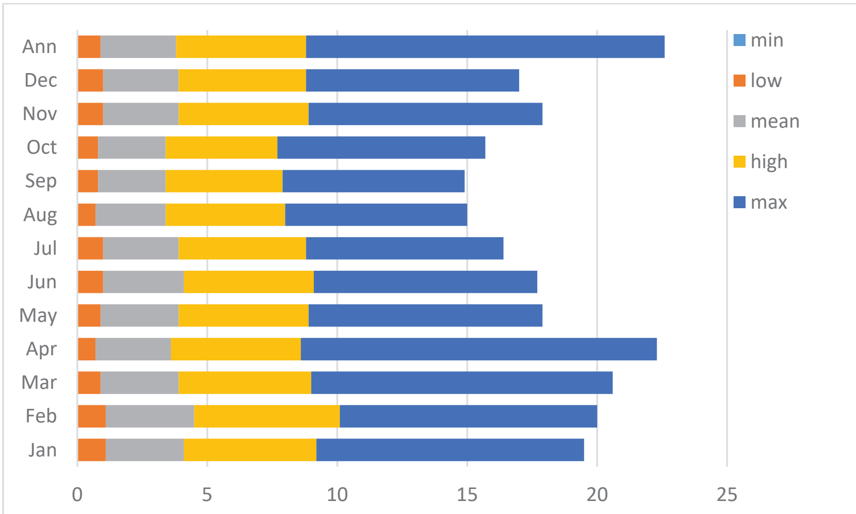


Figure 5 Yearly wind speeds m/s (low, high) for Tabriz in 2021.

Figure 5 shows yearly wind speeds for Tabriz. It can be seen that wind speed (m/s) varies from 0 to 13.7 m/s. Due to seasonal variation, maximum wind speeds can be found in March and April, and lows are in August and September.

9 Methodology

9.1 HOMER Software (Hybrid Energy System Optimization Tool)

HOMER software, developed by the National Renewable Energy Laboratory in the United States, is a software for optimizing and simulating hybrid energy systems combining wind turbines, DG, PV, fuel cells, batteries, and other technolgoies. HOMER is applied here to discover feasible systems that give the lowest CO2 emission and expenses [31]. By using a HOMER software researchers can specify how changeable sources like solar and wind can be unified to hybrid systems. Scholars employ this software to manage various HRE systems, evaluate the outcomes and get pragmatic replacement and capital costs. This programming software builds an improved operating plan for off-grid and grid-connected hybrid renewable energy systems. HOMER provides three main functions including optimization, sensitivity analysis, and simulation. Optimization tests various system arrangements. Sensitivity

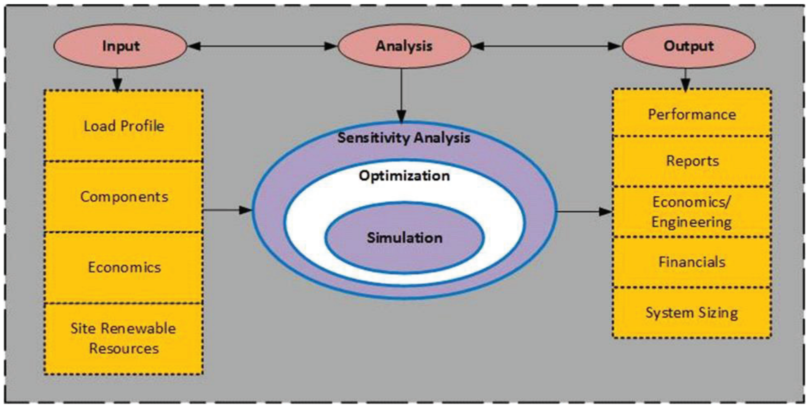


Figure 6 Flow chart of HOMER software.

analysis compares many optimizations under various assumptions. Simulation models the implementation of a specific micro power systems. HOMER assesses the economic and technical possibilities of renewable energy systems. This software is applied to assess renewable energy systems in many different countries [32]. The flow chart of HOMER software illustrated in Figure 6.

9.2 Hybrid Renewable Energy System Components

In the current research, the principal components are a diesel generator (DG), converter, PV, and batteries. Figure 7 shows the architecture of a hybrid RES. This hybrid architecture is formed to power three residential complexes. The AC line consists of the DG and wind turbine. A battery and PV array is placed in the DC line. Since the chosen area has good wind power and solar irradiation over a year, wind turbines and PV arrays can be a practical method to expanding the electrical system for the study area. DG's and batteries are commonly applied in a standalone hybrid RES. Cost investigation is accomplished through operation and maintenance cost, capital cost, lifetime, and replacement cost of renewable energy system elements.

9.2.1 PV array

The PV system lifetime is presumed to be twenty years. It is worth mentioning that the designated region enjoys a plentiful resource of solar radiation, so planning for a PV array installation is an efficient way to respond to energy shortages over a long period of time.

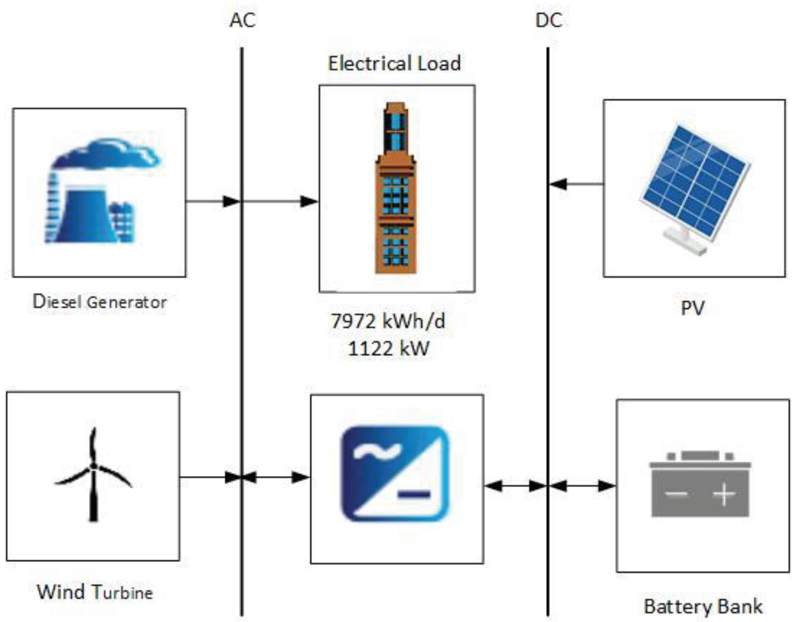


Figure 7 Structure of hybrid renewable energy systems.

The power produced through PV panel can be calculated from

$$P_{PV} = n_{pv}\, V_{PV} i_{PV} \tag{1}$$

where i_{PV} is current, V_{PV} is voltage, n_{pv} is the quantity of PV array. The optimized functioning point and PV array's voltage can be obtained through the following equations [33]:

$$i_{PV} = i_{SC}\left(1 - C_1\left[exp\left(\frac{V_{PV} - \Delta V}{C_2 V_{OC}}\right) - 1\right]\right) + \Delta i \tag{2}$$

And

$$V_{PV} = V_{mp}\left[1 + 0.0539\, log\left(\frac{I_T}{I_{st}}\right)\right] + \beta_0 \Delta T \tag{3}$$

Where

$$C_1 = \left(1 - \frac{i_{mp}}{i_{SC}}\right) exp\left(-\frac{V_{mp}}{C_2 V_{OC}}\right) \tag{4}$$

$$C_2 = \frac{V_{mp}/(V_{OC} - 1)}{ln(1 - i_{mp}/i_{SC})} \tag{5}$$

$$\Delta V = V_{PV} - V_{mp} \tag{6}$$

$$\Delta i = a_o \left(\frac{I_T}{I_{st}}\right) \Delta T + \left(\frac{I_T}{I_{st}} - 1\right) i_{SC} \tag{7}$$

$$\Delta T = T_{cell} - T_{st} \tag{8}$$

$$T_{cell} = T_A + 0.02 I_T \tag{9}$$

Where T_{st} is standard ambient temperature, ambient temperature is T_A, standard solar radiation is I_{st}, total solar radiation is I_T, maximum power is i_{mp}, and maximum voltage is V_{mp}.

It is worth mentioning that various sizes of PV arrays were examined. This study used PV arrays with an output of single panel being 0.253 kW PV. Replacement cost of the PV array is assumed to be $1,750. PV array's lifetime to be considered as 20 years. Operation and Maintenance (O&M) cost and Capital cost of PV were regarded to be $8.5/yr, and $1,750 respectively.

9.2.2 Wind turbine

The role of a wind turbine is to convert mechanical energy to electricity. The wind energy is related to the wind speed in the particular area. The wind turbine output is related to its layout factors. Accordingly, a designated wind turbine with a specified power is correlated with an optimized wind speed. Owing to the optimal energy efficiency, the wind turbine is linked to the AC line. Since generated electricity can provide load demand without deflection from DC line. The power curve of the wind turbine is in Figure 8. Based on the available wind resource, a 10 kW wind turbine is chosen. The hub has a height of 18 m. The lifetime of the wind turbine is twenty years. Replacement

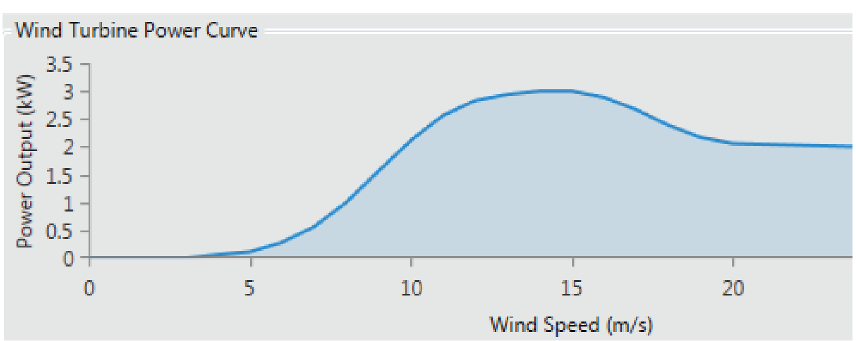


Figure 8 Power curve of wind turbine.

cost, operation and maintenance (O&M) cost, and capital cost assumed to be $28,000, $580/yr, and $28,000 respectively.

9.2.3 Battery

Storage of the PV output is the objective of a battery system. Furthermore, the battery is functioning when solar radiation is not available to supply electricity.

The battery will charge when the power output of hybrid RES is higher than total demand. The battery capacity, as a time factor, is given as [34]

$$C_B(t) = C_B(t-1) \cdot (1-\sigma) + \left(P_T(t) - \frac{P_L(t)}{\eta_{conv}}\right)\eta_{Batt} \tag{10}$$

Where P_L, load demand and P_T is the system's total power.

When total demand is higher than power output of the hybrid RES, the battery capacity, as a time factor, given as

$$C_B(t) = C_B(t-1)(1-\sigma) + \left(\frac{P_L(t)}{\eta_{conv}} - P_T(t)\right) \tag{11}$$

Battery capacity should be retained in the following ranges:

$$C_{B\ min} \leq C_B(t) \leq C_{B\ max} \tag{12}$$

Where

$$C_{B\ max} = C_{Batt} \tag{13}$$

$C_{B\ min}$ is specified through DOD where:

$$C_{B\ min} = (1 - DOD)C_{Batt} \tag{14}$$

The battery's lifetime is assumed to be 20 years. The capital cost of a battery bank is considered to be $1,125. The operation and maintenance (O&M) cost and replacement cost of battery bank are $35/yr and $950 respectively. Table 2 shows the technical characteristics of the battery bank.

9.2.4 Converter

Generally, a converter is employed to transform DC power, received from the PV panel, to AC. In this study, the replacement cost of a converter is considered to be $290/kW. The lifetime of the converter is assumed to be twenty years. The capital cost is the same as replacement cost, $290/kW.

Table 2 Technical specifications of the battery bank

Factors of Specification	
Nominal Voltage (V)	12
Nominal Capacity (kWh)	1
Maximum Capacity (Ah)	83.4
Capacity Ratio	0.403
Rate Constant (1/hr)	0.827
Roundtrip efficiency (%)	80
Maximum Charge Current (A)	16.7
Maximum Discharge Current (A)	24.3
Maximum Charge Rate (A/Ah)	1

9.2.5 Diesel generator

Diesel generators are a stable and reliable resource for power production. A diesel generator has two main functions. First, it can be operated when battery and solar energy cannot meet the required load demand. Second, it can serve as a continuous energy generator to function in the specified time. In this study, the diesel generator has the capacity of 1,600 KW to supply electricity for the selected area when wind and solar energy are not accessible.

Cycle charging and load following are two ways in the DG which can be assessed in HOMER software. In the load following scheme, the DG produces solely the necessary quantity of energy to meet the demand that cannot be met through battery power and the hybrid RES while it is functioning. In the cycle charging scheme, the DG is functioning at its specified capacity so that excess power is utilized for battery charging. Diesel costs, available renewable energy sources, and fuel efficiency are some factors which can be affected. The lifetime of the diesel generator is assumed to be 1.5 years. The replacement cost of this generator is $450. The operation and maintenance (O&M) cost as well as capital cost of the diesel generator is considered to be $0.025/hr and $450 respectively. Table 3 reports technical specifications of the diesel generator.

9.3 Economic Modelling

In the present research NPC and COE are taken into account as costing indicators to assess the possibility of the hybrid energy system. Figure 9 shows an economic model of the most important parameters like Net Present Cost and Cost of Energy. Economic model parameters like descriptions, equations, and components of NPC and COE are shown in Figure 9.

Table 3 Technical specifications of the diesel generator

Factors of Specification		
Emissions	CO (g/L fuel)	16.5
	Unburned HC (g/L fuel)	0.72
	Particulates (g/L fuel)	0.1
	Fuel Sulfur to PM (%)	2.2
	NOx (g/L fuel)	15.5
Fuel Properties	Lower Heating Value (MJ/kg)	43.2
	Density (kg/m^3)	820
	Carbon Content (%)	88
	Sulfur Content (%)	0.4

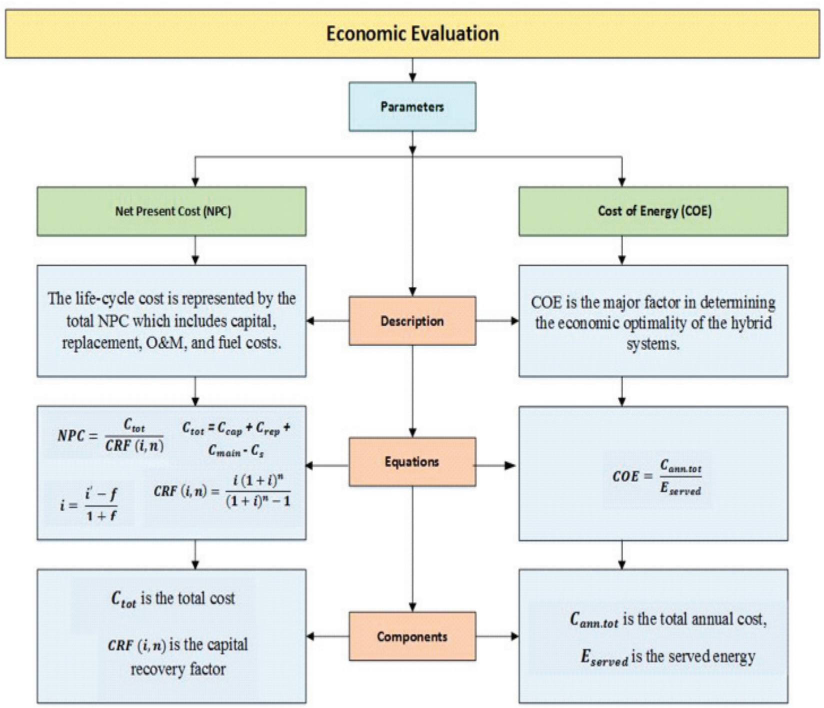


Figure 9 Economic model of the optimized hybrid renewable energy systems.

10 Results and Discussions

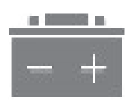
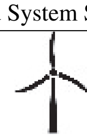
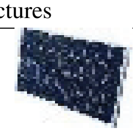
In this research three different sites. along with various electrical loads are considered. In order to discover optimized solutions a HES arrangement including Battery-Wind-Diesel-PV was investigated. Almost fifteen thousand possible solutions were obtained for three complexes. These optimized solutions were organized based upon the lowest NPC and COE. In the current, research, in the first step, nine optimum cases for three residential complexes with hundred percent reneweable energy without a generator are assessed. The three cases for each complex are Wind, PV, and Wind-PV. In addition, in the second step, nine more optimum cases for three residential complexes with a diesel generator are assessed by considering economic and technical parameters. Batteries are also considered in 18 cases.

10.1 Economic and Sizing Discussion of Optimized Configurations with 100% Renewable Energy System

The three optimized hybrid energy system arrangements for each complex chosen were Battery-Wind-PV, Battery-PV, and Battery-Wind.

Table 4 shows the sizing of each component for the optimized configurations with hundred percent RES. In addition, Figure 10 and Table 5 represent graphical and numerical quantities of NPC for all nine cases of system swith 100% RES. Based on Table 5 and Figure 10, the COE for the nine cases spans from $0.29 to 0.62 per kWh. By evaluating Tables 5, 6, Figures 10, and 11, it can be clearly observed that, for all three complexes, Battery-Wind have the greatest NPC, COE, and annualized cost, whereas Battery-Wind-PV have the least. Hence, it can be interpreted that the wind case is not practicable. However, PV with Wind is fully practicable.

Table 4 Sizing summary of hybrid system structures with 100% RES

		Sizing Summary of Hybrid System Structures			
					
N. of Complexes	Optimized Cases	Converter (kW)	Battery	Wind Turbine	PV (kW)
Complex three	Case three	779	2462	79	–
	Case two	321	812	11	638
	Case one	348	1461	–	941
Complex two	Case three	1676	4122	108	–
	Case two	615	996	21	1054
	Case one	611	2153	–	1462
Complex one	Case three	1812	9867	259	–
	Case two	1427	2789	54	2318
	Case one	1709	4505	–	3965

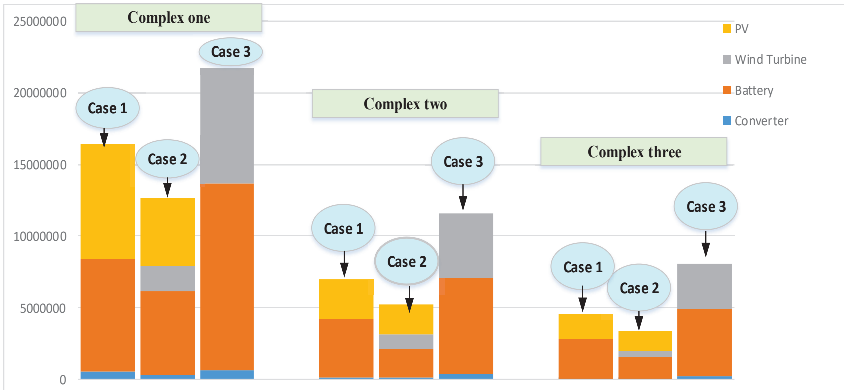


Figure 10 Graphical quantities of NPC for all 9 cases of system components with 100% RES.

Table 5 Numerical quantities of NPC for all 9 cases of system components with 100% RES

N. of Complexes	Optimized Cases	Annualized Cost of System Components (US$)				COE (US$/kWh)
		Converter	Battery	Wind	PV	
Complex three	Case three	161800	4692200	3236000	–	0.60
	Case two	42125	1516500	404400	1406975	0.31
	Case one	56750	2724000	–	1759250	0.40
Complex two	Case three	347100	6710600	4512300	–	0.62
	Case two	78150	2084000	963850	2084000	0.30
	Case one	104400	4071600	–	2784000	0.39
Complex one	Case three	651600	13032000	8036400	–	0.61
	Case two	316750	5828200	1710450	4814600	0.29
	Case one	494100	7905600	–	8070300	0.38

Table 6 Numerical quantities of annualize cost for all 9 cases of system components with 100% RES

N. of Complexes	Optimized Cases	Annualized Cost of System Components (US$)				COE (US$/kWh)
		Converter	Battery	Wind	PV	
Complex three	Case three	12232	342485	256864	–	0.60
	Case two	4090	109072	50446	109072	0.31
	Case one	5012	195468	–	133654	0.40
Complex two	Case three	29088	572055	368442	–	0.62
	Case two	7785	151816	73961	155708	0.30
	Case one	10250	302362	–	199866	0.39
Complex one	Case three	78592	1392204	774694	–	0.61
	Case two	27641	368543	165844	359330	0.29
	Case one	36564	597209	–	585022	0.38

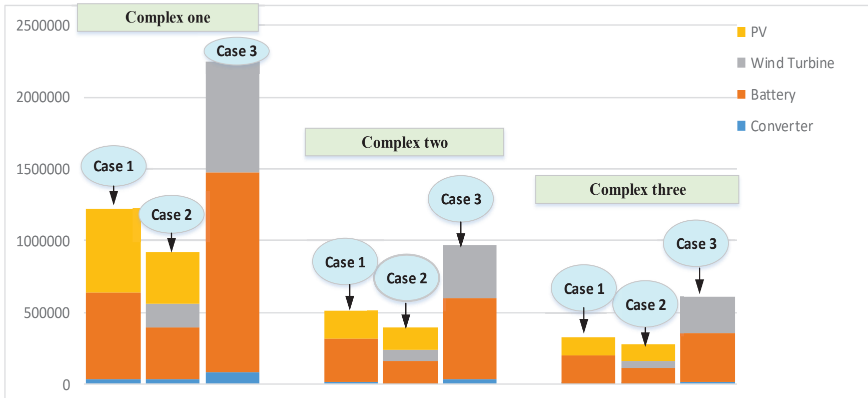


Figure 11 Graphical quantities of annualize cost for all 9 cases of system components with 100% RES.

The unmet electric load is almost 4 percent, which is insignificant. In addition, it is interpreted that excess electricity is produced in almost all cases with 100 percent renewable energy. Tables 5, 6, Figures 10, and 11 demonstrate the annualized cost and NPC for all cases with 100 percent RES in the three complexes. It also appears that almost 60% of the annualized cost and NPC for all complexes is related to batteries. In the Battery-Wind-PV case, 41% of the whole cost is related to batteries and 41% is related to PV panels. Almost 47% of the costs in case 2 are related to PV panels and 47% related to batteries.

10.2 Power Production of Optimized Configurations with 100% Renewable Energy System

Figure 12 shows power generation for each part of the system. It is perceived that case 3 yields significant excess electricity production for all three complexes. This case is not practicable for off-grid systems as the production of electricity is excessively underutilized. For grid-connected hybrid RES this case can be effective. In the Battery-Wind-PV case, PV produces nearly double the power in comparison to wind. In case 1, the excess power production is almost 35% of all electricity production. Accordingly, for a 100% Renewable Energy System, case 2 is evidently the most practicable for all three complexes, by considering excess power production, COE, and NPC.

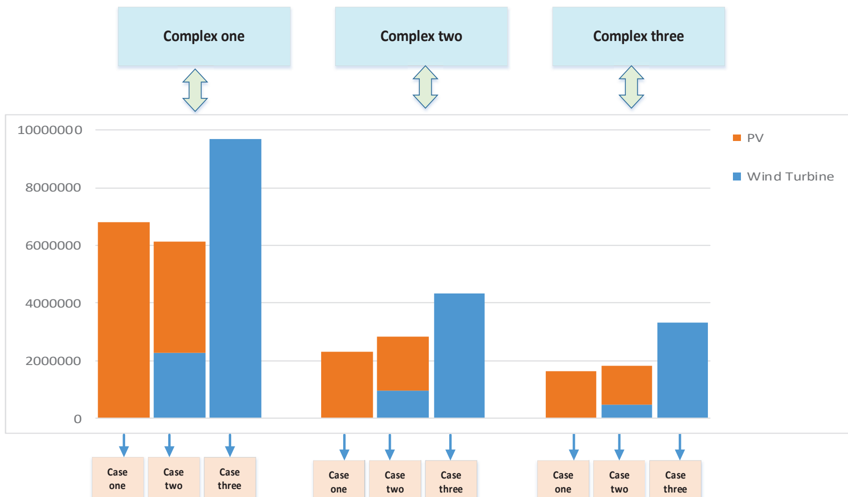


Figure 12 Graphical quantities of power production for all 9 cases of system components with 100% RES.

10.3 Economic and Sizing Discussion of Optimized Configurations with Diesel Generator

Due to cheap fuel price in most parts of Iran, a diesel generator is added to hybrid systems to explore more feasible optimized hybrid systems.

Table 7 demonstrates the sizing of hybrid energy system components for the three optimized configurations of all complexes based upon lowest NPC and COE. Out of nine optimized cases, energy production from wind turbines is feasible in eight cases, a diesel generator in seven, and PV in six. The annualized cost, COE, and NPC for these configurations are interpreted henceforth. Figures 5 and 6 report NPC and annualized cost overview of systems for all nine cases with diesel generators. Additionally, Figures 13, 14, Tables 8, and 9 illustrate graphical and numerical quantities of NPC and annualized costs for all cases cases of systems with a diesel generator.

The COE for a Battery-Wind-Diesel-PV arrangement is lowest for all complexes followed by Battery-Wind-Diesel arrangements for complex one and two. The second best arrangement for complex three is Battery-Wind-PV. Next are Battery-Diesel-PV, Battery-Wind-PV, and Battery-Wind-Diesel for complex one, two, and three. The mean COE for the three optimized cases of complex three is highest at \$0.33 per kWh, followed by \$0.29 and \$0.22 per kWh for complex two and one.

Table 7 Sizing summary of hybrid system structures with diesel generator

		Sizing Summary of Hybrid System Structures				
N. of Complexes	Optimized Cases	Converter (kW)	Battery	Wind Turbine	Diesel G (kW)	PV (kW)
Complex three	Case three	243	279	28	1600	–
	Case two	301	781	10	–	638
	Case one	225	231	13	1600	213
Complex two	Case three	596	1014	21	–	998
	Case two	279	419	39	1600	–
	Case one	347	463	26	1600	356
Complex one	Case three	877	914	–	1600	1053
	Case two	568	487	66	1600	–
	Case one	621	752	49	1600	479

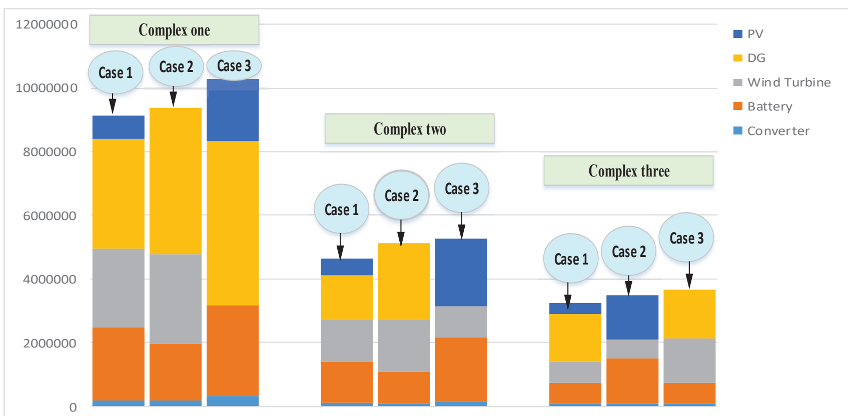


Figure 13 Graphical quantities of NPC for all 9 cases of system components with diesel generator.

Based on Table 8 and Figure 13, it can be interpreted that the mean NPC for the three cases for complex one, two, and three are $9,603298, $5,003,290, and $3,472,314. It can be concluded that the annualized cost and NPC are greatest for case 3 of all three complexes. One lead-acid battery was chosen for all options. As demonstrated in Table 7, wind turbine ranged from 10 to 66 kW for case one of complex three, and case two of complex one. Diesel generators were applied in seven optimized configurations as

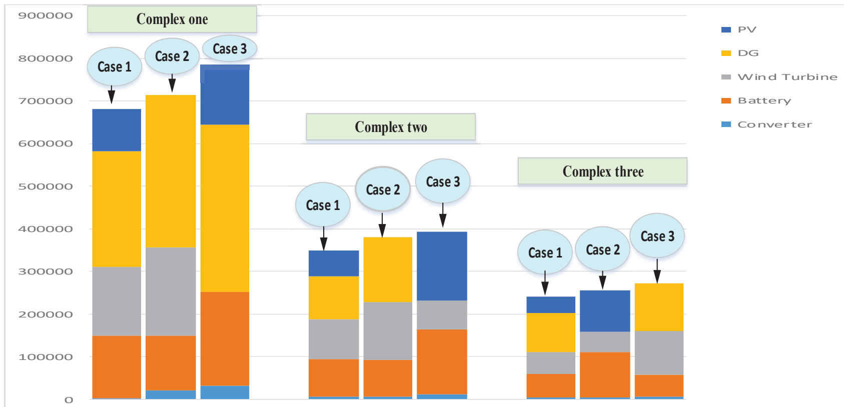


Figure 14 Graphical quantities of annualize cost for all 9 cases of system components with diesel generator.

Table 8 Numerical quantities of NPC for all 9 cases of system components with diesel generator

N. of	Optimized	Net Present Cost of System Components (US$)					COE
Complexes	Cases	Converter	Battery	Wind	Diesel	PV	(US$/kWh)
Complex three	Case three	73600	662400	1398400	1545600	–	0.37
	Case two	69800	1430900	593300	–	1396000	0.34
	Case one	65000	682500	650000	1495000	357500	0.28
Complex two	Case three	157500	1995000	997500	–	2100000	0.32
	Case two	76800	998400	1638400	2406400	–	0.31
	Case one	97440	1299200	1322400	1392000	528960	0.26
Complex one	Case three	308700	2881200	–	5145000	1955100	0.24
	Case two	187400	1780300	2811000	4591300	–	0.23
	Case one	183000	2287500	2470500	3477000	732000	0.21

demonstrated in Table 7. PV capacity changes from 213 to 1053 kW for case one of complex three, and case three of complex one. Generally, wind and solar resources are significant at most of the areas. However, with high efficiency wind turbines, wind energy is feasible in nearly all optimized scenarios. The battery cost in nine cases changes from 16 to 28 percent. The wind turbine cost is almost 21 percent in three Battery-Wind-Diesel arrangements, almost 12 percent in 2 Battery-Wind-PV arrangements, and about 16 percent in 3 Battery-Wind-Diesel-PV arrangements. As illustrated in the numerical and graphical parts of Tables 8, 9, Figures 13, and 14, it can be clearly concluded that the high amount of annualized cost and Net Present

Table 9 Numerical quantities of annualize cost for all 9 cases of system components with diesel generator

N. of Complexes	Optimized Cases	Annualized Cost of System Components (US$)					COE (US$/kWh)
		Converter	Battery	Wind	Diesel	PV	
Complex three	Case three	5450	51779	103559	111734	–	0.37
	Case two	5123	105018	48667	–	97334	0.34
	Case one	4829	54328	50706	91754	39840	0.28
Complex two	Case three	11767	152971	66680	–	160816	0.32
	Case two	6670	84801	137206	152452	–	0.31
	Case one	6971	87140	94111	101082	59255	0.26
Complex one	Case three	31409	219861	–	392608	141339	0.24
	Case two	21402	128415	206891	356708	–	0.23
	Case one	2099	146899	160889	272812	97933	0.21

Cost (almost 50%) for complex one is related to the generator. For complex two and three it is almost 41 percent for options in which a generator was applied. PV cost changes from 19 to 26 percent in three Battery-Wind-Diesel-PV arrangements, and case one of all complexes. In the Battery-Diesel-PV arrangement of complex one as well as the Battery-Wind-PV arrangement of complex two and three, PV cost is about 41 of the entire cost of the system.

10.4 Power Production of Optimized Configurations with Diesel Generator

Generally, based on Figure 15 it can be seen that the electrical generation of wind turbines is significantly high by comparison to diesel generator and PV.

In addition, as Table 10 reports, maximum renewable energy penetration (100%) occurs in case three of complex two, and case two of complex three. Furthermore, minimum renewable energy penetration (25.7%) related to case three of complex one.

Based on Figure 15 it is interpreted that all the optimized configurations completely meet the electricity power demand of the complexes. Among all existing optimized HES arrangements, 50 percent of the all electricity demand in five HES arrangements is generated by wind turbines, diesel generators in one HES arrangement, and PV in one HES arrangement. Accordingly, it can be understood that wind is a feasible case for the study area. Most of the cases have zero unmet load except partial load for case two and three for complex three and two. A minimum 4% of excess electricity is produced for case three of complex one, and a maximum of 35% for

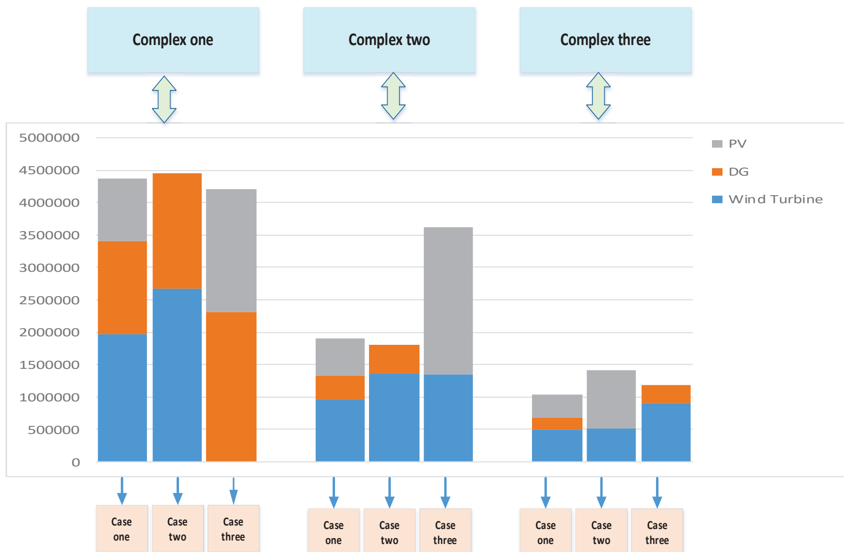


Figure 15 Graphical quantities of power production for all 9 cases of system components with diesel generator.

Table 10 Emissions, RES penetration, and Excess E for all 9 hybrid optimized structure of three complexes

		Emissions, RES Penetration, Excess E of All Complexes		
N. of Complexes	Optimized Cases	Emissions (kg/y)	RES Penetration (%)	Excess E (kWh/yr)
Complex three	Case three	2385	61.7	284212
	Case two	0	100	541190
	Case one	1790	65.8	187295
Complex two	Case three	0	100	1013524
	Case two	396725	59.4	319254
	Case one	198314	73.9	413378
Complex one	Case three	1825291	25.7	100821
	Case two	1311294	41.2	528184
	Case one	1162493	46.1	449112

case three of complex two. As Table 10 shows, RES penetration varies from 25.7% to 100%. Based on Table 10, complex one enjoys significant amount of greenhouse gas emissions reductions. Two HES arrangements out of nine do not contain a diesel generator, accordingly they have zero emissions.

Conclusion and Future Work

Residential complexes contribute significant non-renewable energy utilization in the northwest parts of Iran. It was found that maximum electrical load occurs in peak months, during summer (August and July), due to high energy utilization for air cooling purposes. Minimum electrical load occurs in January and December.

In the first step, the economic, sizing, and power production assessment of optimized configurations with 100% renewable energy were investigated. The COE for the nine cases spans from 0.29 to 0.62 US dollar per KWh. It was found that Battery-Wind-PV have the least NPC, COE, and annualized cost. Indeed, PV with wind is fully practicable.

In the second step, due to cheap fuel prices in most parts of Iran, a diesel generator was added to the hybrid systems to explore more feasible and affordable optimized hybrid systems. It was found that the COE for a Battery-Wind-Diesel-PV arrangement is minimum for all complexes followed by Battery-Wind-Diesel arrangements for complex one and two. A second best arrangement for complex three was Battery-Wind-PV. The third best case was Battery-Diesel-PV, Battery-Wind-PV, and Battery-Wind-Diesel for complexes one, two, and three. The mean NPC for the three cases for complex one, two, and three were almost $9,603,298, $5,003,290, and $3,472,314. The mean COE for the three optimized cases of complex three was the highest, at 0.33 dollar per kWh, followed by 0.29 and 0.22 dollars per kWh for complexes two and one.

The optimized systems with 100 percent RES significantly reduce harmful emissions. For future studies, hybrid renewable energy systems can be used for various areas in the world. However, the weather status would need to be almost the same as the current study area.

Nomenclature

DOD	Depth of Discharge
DG	Diesel Generator
RES	Renewable Energy System
B	Battery Bank
C	Converter
WT	Wind Turbine
Excess E	Excess electricity
HES	Hybrid Energy System
NPC	Net Present Cost
COE	Cost of Energy

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