Potential Techno-Economic Feasibility of Hybrid Energy Systems for Electrifying Various Consumers in Yemen

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Abstract: Global warming and climate change are becoming a global concern. In this regard, international agreements and initiatives have been launched to accelerate the use of renewable energy and to mitigate greenhouse gas (GHG) emissions. Yemen is one of the countries signed on these agreements. However, Yemen is facing the problem that the structure of the power grid is fragile and the power shortage is serious. Accordingly, this paper aims to study the potential for renewable energy in Yemen and assess the technical and economic feasibility of hybrid energy systems. Firstly, this paper introduces the status and challenges of Yemen’s electricity sector, the status of renewable energy, and the status of GHG emission. Secondly, this study proposes the method of optimizing different configurations of off-grid hybrid (solar/wind/diesel engine) energy systems for electrifying various consumers in Taiz province, Yemen under three scenarios of energy strategies. The objective function is to seek the most optimal hybrid energy system that achieves the least cost and most advantageous technical performance, while instigating the best economic scenario of energy strategies. Finally, Homer pro software is used for simulation, optimization, and sensitivity analysis of the designed energy systems. The results found the best economically feasible scenario, the hybrid PV/wind/diesel energy system, among the other scenarios. A photovoltaic (PV)/wind energy system achieved the best technical performances of 100% CO₂ reduction, with a 54.82% reduction in the net present cost (NPC) and cost of energy (COE); while the hybrid energy system (PV/wind/diesel engine) achieved the best economic cost of 61.95% reduction in NPC and COE, with a 97.44% reduction of CO₂ emission.

Keywords: techno-economic feasibility; hybrid energy systems; optimized configuration; energy strategy; greenhouse gas emission

1. Introduction

A recent statistics review of world energy 2020 reported that 84% of global energy is still supplied by fossil fuel, while renewable energy merely supplies 11% of global primary energy consumption. Burning fossil fuels for energy production results in a major amount of GHG emission that harms the environment and causes global warming, while renewable energy sources have less GHG emission [1,2]. In this context, accelerating the development of renewable energy has become an essential concern of many countries and organizations around the world. Renewable energy is expected to grow up to 63% of the global total energy supply by the year 2050, and the combination of renewable energy with high-energy efficiency can decline 94% of GHG emission. The International Energy Agency (IEA) Sustainable Development Scenario (SDS) has stated that to attain long-term climate
aims, the renewable energy needs to grow over 300 GW average capacity each year up to 2030. A total of 181 GW renewable power was installed by 2018, which reached 200 GW by 2019. The rate of renewable energy has grown up to 27.3% of the global electricity production by the end of the year 2019, and was expected to grow up to 85% by 2050 and decline 85% of carbon dioxide emission across the electricity generation sector [3–6].

Several international conventions and initiatives have been launched for renewable energy promotion. The Paris agreement on climate change (December, 2015) is a well-known convention that belonged to the Framework Convention on Climate Change organized by the UN and approved by 196 countries. The core outcome of the Paris agreement is to keep the global temperature below 2 degrees Celsius above pre-industrial levels. Countries have responded to reduce more than 80 percent of greenhouse gas emissions [7]. As well, the Kyoto protocol is historically extended to the United Nations Framework Convention on Climate Change (UNFCCC). It was adopted in 1997 and entered as international law in 2005. The protocol committed the developed countries group to reduce 25–40% of greenhouse gas emission compared to the 1990 level by 2020, and for developing countries to reduce it 15–30% by 2020, till a new policy Agreement is started in 2020 [8,9]. The United Nations Environment Program Finance Initiative (UNEP FI) has launched for the 47 countries of sub-Saharan Africa. The initiative is to install 7 GW new power generation per year to meet increasing demand and attain economic stability [10]. The Beijing International Renewable Energy Conference (BIREC) was participated by ministers and government representatives from 78 countries around the world. All attendees declared their commitment to implement the outcomes of the Earth Summit, the World Summit on Sustainable Development (WSSD) [11]. The UN Refugee Agency (UNHCR) has established a global strategy for sustainable energy to promote using clean energy to the refugee camps, hosting sites, and support facilities [12]. Sustainable Energy for All (SE4All) is an international initiative created by the UN in 2011. Now it has become an organization that cooperates with UN agencies, governments, and civil societies. It aims to access global energy, double the share of renewable energy from the current rate to 36%, improve energy efficiency and minimize energy intensity growth rate to $-2.6\%$. These goals have to be attained by 2030 [13]. The China ‘Belt and Road’ initiative has also adopted a vision of green development [14].

In the context of the influences of global warming and climate change, a lot of studies have been carried out to assess renewable energy (RE) potential in different locations in the world. These studies are served for various applications which may achieve the electrification of the remote area [15,16], island [17,18], telecommunication [19], and water desalination [20]. RE’s potential was studied in the U.S [21] which took into account socio-economic factors. The study found that with the increasing ratio of renewable energy the GHG emission reductions could reach 40% and 17% by 2050. China, the world’s largest country in energy consumption and CO$_2$ emission, had its RE potential assessed in [22]. The study indicated that wind and hydropower are on the priority of development at the present time and near future, due to more mature technology and low cost. Solar will rapidly develop with national strategic support, while biomass and geothermal power will hopefully grow fast on the condition of well-guaranteed resources.

In Algeria, solar energy shows great potential with a 93% renewable fraction in the hybrid energy system (photovoltaic (PV)/diesel/battery) for electrifying remote Saharan regions in southern Algeria; the cost of energy (COE) was 0.37 dollars/kWh [23]. The potential of a solar and wind hybrid energy system for electrifying the island Kavaratti in India is found to be the best choice among current existing power systems, the system supplied energy with 0.10995 dollars/kWh [24]. In Indonesia, the study in [25] assessed RE feasibility by considering the current state of the renewable energy market, estimation cost, switching to renewable energy sources and their implantation. The study found that renewable energy is promising. Different configurations of off-grid hybrid energy systems (solar/biomass/diesel) have been projected for none electrified areas of northern Bangladesh. The result exposed that the COE of an off-grid optimum energy system is much higher than the grid-connected tariff. Whereas, it is more economical than the diesel-
based power generation. The analysis also found that the CO\textsubscript{2} emission could be reduced by 75\% comparatively [26).

In Colombia, solar PV energy is found to be a promising solution for electrifying Colombian Caribe island. While, the study confirmed that the wave, tidal energy and wind do not have the potential [27]. The RE potential for powering the Mediterranean islands is represented to be best cost-effective energy provider. Replacing diesel power systems with a renewable energy capacity can not only add environmental protection, but also at the same time save amounts of transport costs [28]. In this context, replacing diesel power plants with renewable energy power generation in the Philippines Island can reduce huge economic expenses and environmental risk prevention [29]. Akuru, U.B. et al. [30] concluded that 100\% RE is possible in Nigeria, due to the absence of government policy to utilize these resources. The study suggested that individuals/communities can drive this 100\% RE transition instead of unexpected government attention.

In terms of the Middle East region, that occupies more than half the world’s crude oil production and more than a third natural gas service [31]—from the perspective of commitment to the regional countries restriction of carbon emission and stopping environmental damage—the RE potential is rapidly being assessed. It has been found that the Middle East has a great potential for solar and wind sources [32]. Many countries have carried out a lot of research on investigating the renewable energy potential in their lands, such as studies conducted in Turkey [33,34], Iran [35,36], Egypt [37], and Morocco [38]. The gulf countries are the major Middle East countries of crude oil and gas production—in the top 25 of the world’s countries CO\textsubscript{2} emissions. The energy consumption growth, with an 8\% rate each year, means that they have doubled energy production [39]. The six gulf cooperation council (GCC) countries have already started considered these issues, by including renewable energy sources as the best alternative option toward sustainable energy that would reduce CO\textsubscript{2} emission. Various studies have been implemented to evaluate RE potential in different Gulf countries, such as studies in [40–42] for the kingdom of Saudi Arabia (KSA), others studies for the United Arab Emirates (UAE) [43,44], Qatar [45,46], and Kuwait [47,48]. The conducted studies in Kuwait have shown that the PV power is not suitable in the states of Kuwait, due to environmental conditions. However, wind energy is the best alternative.

Yemen is one of the Middle East countries. Its regional location is in southwest Asia, the southern Arabian Peninsula, and located at 15.5527° N, 48.5164° E. Yemen shares a border with Saudi Arabia from the north, Oman from the east, the Red Sea from the west, and Aden gulf from the south. It is overlooked on Bab-el-Mandeb Strait, which is one of the most important trade lines in the world. The geographical characteristics of Yemen consist of three major zones: the mainland, highland, and island. The total area is approximately 536,869 km\textsuperscript{2}. In terms of renewable energy sources, Yemen has been invited by several international organizations to investigate renewable energy potential. The results are reported that Yemen has abundant renewable energy and can play a vital role to drive up the energy sector. The annual average solar radiation is in the range of 18–26 MJ/m\textsuperscript{2}/day over 3000 h each year of clear blue sky. The wind speed is in the range of 4–15 m/s and 60 mw/cm\textsuperscript{2} heat flow rate. The theoretical potential of renewable energy is referred to in [49] as 2,446,000 MW solar energy, 3014 MW solar thermal, 308,722 MW wind energy, and 304,000 MW geothermal energy. Some studies have examined the RE potential. For example, studies in [50–52] assessed the challenges in the energy sector, indicators of energy efficiency, and policy of adopting renewable energy. The renewable data is analyzed in [53–55]. Furthermore, influences of the public’s awareness, attitudes, behavior on the accelerated development of renewable energy are also studied in [56,57]. A few related studies have applied renewable energy for power applications [58–61].

According to the current problems of the hybrid energy system, its applications in Yemen, we studied the potential techno-economic feasibility of hybrid energy systems. The significance and contribution of our study are as follows:

(1) The status of the electricity sector, renewable energy, GHG emission, and mitigation strategies in Yemen are reviewed. Based on the status, the study on the potential techno-
economic feasibility of hybrid energy systems is specified. This paper proves that renewable energy has the potential to restore the energy sector in Yemen, and suggests a series of procedures that should be started from a decentralized aspect (sub national grid) to a centralized aspect (official national grid). Then, the paper provides an estimation of GHG emission reduction.

(2) In this study, different configurations of hybrid renewable energy systems (HRES) with conventional power generation systems are considered, and the technical and economic performances of each configuration are assessed. Many previous studies [58–61] have reviewed the feasibility of renewable energy applications. However, those studies have their drawbacks, such as not having dealt with various configurations of renewable energy sources and not considering a wide range of parameters worthy of discussing. Furthermore, other studies have just focused on either studying the obstacles, drawing up strategies [50–52], or data analysis [53–55]. This study offers a wide range of technical and economic choices to enable the making of decisions in which the energy system is the best choice for the region under study.

(3) The studies of the optimal design and techno-economic assessment of stand-alone HRES are very important—particularly in Yemen—while these kinds of studies do not obtain enough research, owing to the reasons of economy and war. As reported in [62,63], most of renewable energy systems are unreliable and inefficient in terms of inappropriate design and sizing. This is due to the lack of consideration of various factors of renewable energy or energy storage, the lack of renewable energy institutes to play a key role of raising the level of trainees, and the lack of conducting studies on related systems. Whereas, this study can answer whether renewable energy is technically feasible and economically competitive or not, and encourage the country and the private sector to switch to alternative renewable energy.

(4) The study could introduce a road map forecasting the potential of renewable energy in Yemen, providing new acknowledgment and answers to achieve the goals of the United Nations Framework Convention and Climate Change (UNFCCC) that is represented by the Paris agreement and Kyoto protocol. In the Paris agreement of climate change, Yemen committed to reducing 14% of GHG emission by 2030, and has shown a positive response in the Kyoto protocol through submitting its own national communications drafts.

The rest of this paper is organized as follows: Sections 2 and 3 introduce the status of the electricity sector, renewable energy, GHG emission and mitigation strategies in Yemen. Section 4 is the configuration and design of HES. Section 5 introduces the data and software. Section 6 is the results and discussion. Section 7 is the conclusions.

2. The Status of Yemen’s Electricity Sector and Renewable Energy

2.1. The Status before 2015

Yemen is the least developed country, but over the last three decades, the electricity demand has rapidly increased due to population increase and economic growth. The electricity is mainly generated by fossil fuel, at the rate of 99.91%, with a 0.09% share from renewable energy. The fossil fuel is constituted of 79.91% heavily fuel oil (HFO) and diesel, and 20% natural gas. The total generation capacity is 1.67 GW. It is one of the lowest among Middle East countries and it is just enough to satisfy 40% of electricity demand with 200 kWh/capita/year. In an attempt to address the gap between electricity generation and demand, the yearly demand growth is 9.6%. By 2012, the Government of Yemen (GOY) and China National Corporation have reached an agreement to construct three natural gas power plants, each one is more than 400 MW. The Turkish government has funded Yemen to construct a 263 MW power plant that can be operated by petroleum and natural gas. Unfortunately, none of the stated projects has materialized due to the 2015-fired conflict. Additionally, Yemen and Ethiopia still negotiate to buy electricity from hydropower south of the country [49,62,63].

On the other side, the Yemen Ministry of Electricity and Energy (YMOEE) has established renewable energy departments by 2002 to encourage environmentally friendly
renewable energy and rely on its sustainable sources [64]. The GOY has launched many strategies to exploit renewable energy sources and share them in the energy sector within the collaboration of international agencies. The GOY representatives of the Environment Protection Authority in cooperation with the United Nation Development Program (UNDP) have created the National Biodiversity Strategy and Action Plan II(NBSAP2) vision called “Productivity and Sustainably Socio-Ecosystem by 2050”. The strategy is promoted for adopting green technology in the industry, manufacturer, and energy sectors [65]. The GOY Ministry of Electricity and Energy (MOEE) has set the national strategy of renewable energy and energy efficiency by 2009, that aims to increase the share of renewable energy up to 15% by the year 2025.

Moreover, Yemen has entered into political instability since 2011. All Yemen’s parties and civil organizations have committed to a national dialogue conference by the year 2013. The purpose is to reset all country affairs—to discuss a process toward putting Yemen on the path of peace. The increasing contribution of renewable energy in the energy sector has been discussed and approved by the sustainable development committee in the conference [66,67]. The GOY adopted reforms on the power sector through the launch of the power sector development strategy of 1997, that was updated in 2006. From this emerged the Rural Electrification and Renewable Energy Development Project (REREDP), which was approved by Cabinet in 2008, that aims to increase access to electricity for over 520,000 new rural households, to increase access from the current rate of 23% to around 46% for rural households, to the benefit of 3.5 million people [68].

2.2. The Status after 2015

In the middle of 2015, Yemen witnessed widely military operations, that are ongoing until the time of writing this paper. The electricity sector is significantly affected, where the percentage of the population’s access to public electricity reduced from 60% in 2014 to 10% by the end of 2017. The impacts were devastating. Some of the power plants have been totally destroyed and others were partially destroyed, causing the reduction of generation capacity, and even difficulties of fuel delivery from the electricity generation plants [49]. Currently, the average power supply is around 200–250 MW. For example, the capital Sana’a’s demand is around 500 MW, but it was only supplied by 40 MW for a few hours each day. Aden governorate has also encountered an electricity shortage, which demands 390 MW but is only covered by 190 MW. The Al buraydah and Ibb governorates, which both required 280 MW total demand, have not been covered at all. The Taiz governorate, which is the largest population in Yemen, requires 111 MW of electricity service, but it seems that the public electricity grid has not provided for it at all.

As long as the conflict continues, the transmission lines are periodically under attack, which means it is useless to maintain power plants. The World Bank [69] proposed a feasible approach that is to shift the electricity sector from centralization to decentralization. First, the electricity system is re-built from the ground (solar), both technically and institutionally. Then, extend the solution from small off-grid systems and increase toward the urban grids, municipal grids (sub-national), and last gradually up to the national grid. This proposed solution takes a long time in parallel with the conflict hopefully reaching the end.

The shortage of electricity supply has extended to have effect on the health services, food supply, water and sanitation, banking facilities, etc., in the absence of the national electricity grid and diesel fuel supply. Therefore, the combined efforts of individuals, private sectors, and a little government contribution are invested in solar PV as an alternative power supply for the public and private sector. The solar PV systems are witnessing a huge penetration in Yemen’s market and approximately 1–2 billion (dollars) has been invested in them. It could be able to supply power to 75% of households in urban areas and 50% in rural areas. Indeed, Yemen’s solar revolution was born by necessity when fuel shortage and public grid damages have become unfeasible. Therefore, stakeholders and households have been unable to find other options. Whatever solar PV energy systems are recently used in Yemeni urban and rural, it is still unreliable and inefficient in terms of
inappropriate design and configuration due to the lack of renewable energy experts and renewable energy institutes to play a key role in raising the level of trainees and conducting studies on related systems [62,63].

3. The Status of GHG Emission and Mitigation Strategies in Yemen

Yemen is not an industrial country. Thereby, industrial activities have not produced a significant amount of GHG emission. Energy-based GHG emission is mainly dominated, occupying about 69.3% of total GHG emission. The remaining 30.7% is contributed from non-energy sectors, such as agricultural activities, waste recycling, and industrial processes at rates corresponding to 23.1%, 3.7%, and 2.9%, respectively. While GHG emissions are generated by the energy sector, the majority of emissions are caused by fossil fuel combustion for electricity generation, transportation, and other sectors contributes to 19.3%, 19.2%, and 16.6%, respectively. The remainder is caused by using kerosene and diesel for residential, agricultural, and commercial sectors [65]. The total amount of GHG emission has not had a major effect on the global climate. It merely contributes to about 0.08% of global emission, at the rank of 130 out of 188 countries of GHG emission per capita [70].

In the background of global efforts to preserve the temperature from rising and to reduce greenhouse gas emissions, Yemen has always conducted positive actions of cooperation with the UNFCCC; it ratified the UN convention of biological diversity. Yemen prepared a National Biodiversity Strategy and Action Plan 1 (NBSAP1) in 2005 for a sustainable and better standard of living through the use of sustainable resources and the stabilizing of consumption [71]. Additionally, Yemen released NBSAP2 in 2017 for achieving a resilient socio-ecosystem, to be productive and sustainable by the year 2050 [65]. In terms of the Paris agreement of climate change, Yemen has signed it in September 2016 without ratifying the agreement. It drafted its Intended Nationally Determined Contribution (INDC) in Nov 2015, committed to reducing 14% of GHG emission by 2030, below a business as usual (BAU) scenario [72]. Furthermore, Yemen worked on adopting a clean development mechanism in 2007 to attain the goals of the Kyoto protocol, that were ratified by September 2004 [73]. Articles 4 and 12 of UNFCCC stated that all countries that have participated in the convention should prepare national communication to describe their inventories of GHG emission and to decrease emission. Accordingly, Yemen drafted its Initial National Communication (INC) in 2002 and submitted the second national communication (SNC) to the UNFCCC by 2013. As well, the 3rd national communication was submitted in 2018. The letters reported the implemented projects, which were already initiated in several different fields: water resources conservation and rational usage, coastal zone management, agricultural reforms, and renewable energy assessment [74,75]. The low emission development strategy emerged in 2008 under the UNFCCC and Yemen prepared its national low emission development strategic (LEDS) in 2003 with the support of the UNDP. The strategy illustrated the emission reduction options and their prospective cost, it presenting a roadmap toward low GHG emission. Additionally, it identified mid-term and long-term mitigation objectives [76].

4. Configuration and Design of Hybrid Energy System

4.1. Energy Strategies and Classification of Electricity Consumers in Yemen

The Government of Yemen (GOY) has established long-term strategies in the energy sector, considering the hypothesis that the economic and the GDP increase slowly [49]. The strategy (1) is to supply 1.10 kWh/day/capita. The strategy (2) is to supply 2 kWh/day/capita, which is 50% of the average electrical energy/capita of other Arab countries. The strategy (3) is to electrify 4 kWh/day/capita, which is about 50% of the world average electrical energy/capita.

A total of 25% of the population in Yemen is in urban areas, and 75% is rural [77]. Yemen has low electricity access, which about 85% urban and 23% rural population can access [62]. The government classifies those people who live in the rural area into four types based on the ability to access the national electricity grid [49]. The first type easily
accesses the grid, the second can access the grid with a slightly increased cost, the third can access the grid with high increased cost, and the fourth is high cost and difficult to access the grid.

4.2. The Topology and Components of the System

The study is developed to design different configurations of micro-grid energy systems including PV, wind turbine (WT) and diesel engine (DE) for electrifying diversity of consumers in the Taiz province, Yemen, under consideration of three scenarios of energy strategies. Five configurations of energy systems are suggested for design, as follows: DE power system (Case I), PV/DE (Case II), WT/DE (Case III), PV/WT/DE (Case IV) and PV/WT (Case V), as presented in Figure 1.

![Figure 1. Schematic diagram of different microgrid energy systems: (a) Case I; (b) Case II; (c) Case III; (d) Case IV; (e) Case V.](image)

The PV, wind and DE are the main power sources. PV and WT are dependent on renewable energy, while DE is dependent on fossil fuel. The battery storage system is used to store excess power in case the generated power is beyond the energy demand, to supply the load when the energy demand exceeds the generated power. The direct current (DC) supplied from PV and battery power systems needs to be changed to alternative current (AC) through a DC-AC converter to accommodate an AC load. The cycle charging energy management strategy is considered for energy dispatching among power sources, energy storage, and demand of power. In this strategy, in case the deficit of supply of the load happens, Homer Pro (hybrid optimization model of electric renewable energy) assesses the best economical energy to switch from either battery storage or DE. The DE operates at full capacity to support the load deficit and charge the batteries.

The allowed maximum annual capacity shortage of the designed system is zero percent and the allowed minimum renewable energy fraction is zero percent too. For creating a more practical and dynamic load, the random variability of the load is considered as 5% a day, 10% sampling time. The minimum load ratio of the diesel engine is 15%. The economic parameters settings are relative to the economic status of Yemen. The nominal interest rate is 27% [78], the inflation rate is 26.7% [79], and accordingly Homer Pro can calculate the real interest rate 0.24%. The diesel fuel price is 1.38 dollars dollars [80]. The
The minimum value of the state of charge (SOC) of the battery is 40% and the maximum is 80%. The project lifetime is considered as 25 years.

Homer Pro is used to simulate, optimize, and assess the economic cost of different scenarios of energy strategies, and examine the technical and economic aspects of different configurations of energy systems. The sensitivity analysis takes into account variation of load scale (population growth) for the upcoming ten years, the variation of real interest rate, and diesel price.

This study seeks for the least cost scenario of energy strategies, and a typical energy system that achieves the least cost and advantageous technical performances. The studies on cloud energy [81] and energy-efficient routing [82] are focused on more efficient energy composition and applications, which are meaningful concerning the utilization of energy and inspiring for the techno-economic feasibility analysis. The technical characteristics and economic costs of system components are collected from manufactory datasheets and explained in detail in the following subsections.

4.3. Components Configuration

This subsection mainly discusses the technical characteristics and economic cost of each energy systems’ components. The components technology is available in the Homer Pro library, the technical and economic specifications are brought from manufactory data sheets related to the technology used. Based on these technical characteristics and the economic cost, the configuration of each component can be obtained.

4.3.1. Solar PV

PV power is based on solar radiation energy. In this study, the PV model capacity is chosen by the Homer optimizer, dependent on solar radiation density, energy demand, and system constraints, such as the allowed maximum capacity shortage and minimum renewable energy fraction. For the configuration of PV, it should be able to supply the load and offer excess energy to be stored in the battery. In Homer, the PV model mathematical expression is presented in Equation (1) [83]:

\[ P_{PV} = \gamma_{PV} f_{PV} \left( \frac{G_T}{G_{T,STC}} \right) \left[ 1 + \alpha_P (T_C - T_{C,STC}) \right] \]  

where, \( P_{PV} \) is the PV array output power in [kW], \( \gamma_{PV} \) is the PV array capacity in [kW], \( f_{PV} \) is the derating factor in [%], \( G_T \) is the time step solar irradiation in [kW/m\(^2\)]. \( G_{T,STC} \) is the standard solar irradiation [1 kW/m\(^2\)]. \( \alpha_P \) is the temperature effect on the power [%/°C]. \( T_C \) is the nominal cell temperature in the current time step [°C], and \( T_{C,STC} \) is the standard cell temperature [25 °C].

The PV that is chosen is the flat plate Sun Power E20–327, manufactured by Sun Power manufactory [84]. The lifecycle of the model is 25 years, the derating factor is 88%, the model efficiency is 20.4% and the ground reflectance is 20%. In our study, the effect of ambient temperature on PV power is taken into account. The operating temperature of the cell is 45 °C, and the temperature effect on the PV model power is \(-0.360%/°C\). The capital cost of PV models is 2180 dollars/kW, the O&M and replacement cost are considered as zero due to the PV model lifecycle is the same project lifetime.

4.3.2. Wind Turbine

In this paper, AC wind turbine technology EnerconE-82E4 is used and the capacity of a single turbine is 3 MW. The Homer optimizer is used to determine the wind farm capacity. The capital cost of a single turbine is 2,895,000 dollars, the replacement cost is 2,695,000 dollars, and O&M cost is 100 dollars [85]. The high O&M cost is due to the lack of trained awareness of wind turbines in Yemen.

The technical specifications of the wind turbine are brought from the manufactory [86]. The lifetime is 20 years, the hub height is 84 m, the number of wind turbine blades is 3, and the rotor diameter is 82 m.
4.3.3. Diesel Engine Generator

The CAT-3500kVA-50Hz-PP diesel engine manufactured by Caterpillar manufacture is used in the proposed systems. The sizing search range is set from 100 to 800 MW and the Homer optimizer is used to seek the optimal configuration within this range. The economic and technical specifications of the diesel engine are brought from the manufactory datasheet [87]. The capacity is 2000 kW, the capital cost is 258,750 dollars, the replacement cost is 240,750 dollars and the O&M cost is 0.2 dollars/h. For the technical performances, the lifetime is 90,000 h and the minimum load ratio is 15%.

4.3.4. Battery

Due to the intermittent output characteristics of renewable power systems, to smooth the intermittent supply and deliver continuous power to the demand load, energy storage is necessary. In the hybrid system, the energy storage unit is the Surrette 6 CS 25P, due to its availability in different scales, appropriate cost, durability recognized in solar applications, and mobility endurance in remote applications [88]. The technical and economic specifications are collected from the manufactory related sheet [89,90]. The single battery is 6 V, 1156 mAh and 6.91 kWh rated capacity. The lifetime is about 10 years, which may be different based on charging cycles. Four batteries are configured in a single string that totals to 24 V DC bus voltage. The Homer optimizer has optimally configured the numbers of strings required to attain the best technical properties of the system. The capital cost of a single battery is 1180 dollars, the replacement cost is 1098 dollars, and O&M cost is 10 dollars. The roundtrip efficiency is 80% and the minimum state of charge (SOC) is 40%.

4.3.5. Converter

In the hybrid energy system, a power converter is an essential part to convert from direct current (DC) to alternative current (AC) or AC to DC. In our model, the converter is used to convert DC power from the PV and batteries to AC and accommodate it to the AC bus bar to be used by the AC load. ABB converter is chosen in this model due to some advantages, such as improved energy efficiency and minimized energy consumption [91]. The configuration is optimally processed by the Homer optimizer. The technical and economic characteristics are obtained from the manufactory data sheet [92]. The capital cost is 210 dollars/kW, the replacement cost is 190 dollars/kW, and the O&M cost is 5 dollars/year. The lifecycle is 20 years and the conversion efficiency is 96%.

4.4. Financial Criteria in Homer Software

This section discusses the economic formulas used to calculate economic indexes such as net present cost (NPC), and the levelized cost of energy (COE). The NPC is defined that the entire system costs (capital costs, replacement costs, and O&M costs) through the system lifecycle minus the salvage costs (revenues earned), which are the remaining costs of the components at the end of system lifecycle [83]. In order to calculate NPC, annualized total system costs needed to be estimated first, which is the annualized costs of the systems’ components minus any miscellaneous costs. By using the formulas in [93], the NPC can be calculated within Equation (2).

\[
NPC = \frac{C_{ANN,TOT}}{CRF(i, N)} \quad (2)
\]

where \(C_{ANN,TOT}\) is the annualized total system cost. \(i\) is the annual real interest rate (the discount rate). \(N\) is the numbers of system lifecycle years. \(CRF(i, N)\) is the recovery factor, that can be calculated by Equation (3):

\[
CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \quad (3)
\]
The real interest rate $i$ can be estimated by the formula written in Equation (4), as follows:

$$i = \frac{i^o - f}{1 - f}$$

(4)

where $i^o$ is the nominal interest rate in [%], which is the profit rate you can gain against the deposit before the effect of inflation. $f$ is the annual inflation rate in [%] through the project’s lifetime.

The levelized cost of energy (COE), which is the average cost of one unit of energy, (kWh) can be calculated in the Homer program by dividing the total entire system cost of one year by the total energy generated by the system within that year. It can be expressed by Equation (5):

$$\text{COE (dollar/kwh)} = \frac{C_{\text{ANN,TOT}}}{E_{\text{load served}}}$$

(5)

where $E_{\text{load served}}$ is the actual load served by the energy system per year.

5. Input Data and Simulation Software

5.1. Location of Study

The Taiz province in Yemen is selected to be studied. Its global location is 13.192° N latitude, 43.148° E longitude. The location is in the south-west of the Republic of Yemen on the border of the Red Sea, as shown in Figure 2. It is located in highlands of Yemen with an approximate elevation of 1400 m and with a total area of 10,462 km². It is the 3rd largest city after the national capital Sana’a and port city Aden. Taiz has been assigned as the cultural capital of Yemen for a long time, it is divided into 23 districts, 3 urban districts, and 20 rural. A total of 19% of the population lives in urban areas and 81% in the mountains, hills, plains and valleys [94,95].

![Figure 2. Allocation of Taiz province in the Republic of Yemen.](image)

5.2. Resources Assessment

The renewable energy sources (solar, wind) are available in nature and the density of renewable is different in different places. By determining the geographical position of the specific region, Homer Pro can access NASA to obtain the meteorological database and download the weather data required to perform a simulation. Solar radiation and ambient temperature are required for PV input to determine the output energy and wind speed is required by the wind turbine to determine the output characteristics. For this study, Homer can use the altitude and longitude of the location and collected solar radiation, ambient temperature, and wind speed. The three weather variables estimations are discussed in the followed parts. The main climate of Yemen is tropical desert climate, hence the problem of water resource shortage is serious. Unlike the Poland [96], it is almost impossible for Yemen to develop hydropower.
5.2.1. Solar Radiation

The downloaded solar radiation for Taiz province is displayed in Homer resource inputs, as shown in Figure 3. The figure shows the monthly average solar radiation, the annual average is estimated at 6.15 kWh/m²/day. From the figure, it can be seen that March, April, May, June, and October show high potential solar radiation above the annual average. The highest value of 6.88 kWh/m²/day is recorded in April. Other months show lower than annual average and the lowest value of 5.65 kWh/m²/day is in December. It is worthy to say that solar radiation shows great potential and can be considered as a promising alternative energy for electricity generation in Taiz province. Additionally, other provinces in Yemen have a similar climate.

5.2.2. Ambient Temperature

Except for the solar radiation, the ambient temperature is taken into account for PV inputs. It has an opposite influence on PV output characteristics. For Taiz province, the ambient temperature displayed at Homer inputs resources is as shown in Figure 4. It is found that the annual average ambient temperature is 25.96 °C, the temperature of April, May, June, July, September, and October are higher than the annual average value. The highest value is 29.77 °C in May and the lowest value is 22.49 °C in January. Taiz province has an appropriate temperature for PV power plants. In the summer, it has not recorded a very high value, which can have a negative impact on PV output.

5.2.3. Wind Speed

For the Taiz province, the wind speed is estimated at 50 m elevation. The monthly average wind speed is illustrated in Figure 5. It is found that the annual average wind speed is 5.22 m/s and the wind speed is showed great potential in January, February, June, July, and August, which are higher than the annual average value. The highest wind speed is 7.49 m/s in July and the lowest value is 3.85 m/s in May.

5.3. Load Energy Estimation

This study’s target is to electrify the Taiz province, which is the third main province in terms of population and occupies 12.15% population of Yemen. The population is estimated as 3,250,084 and about 19% live in urban and 81% in rural areas [94]. Studies show that 38% of the rural population in Yemen cluster in small communities in the mountains [49]. They
can neither access the electricity grid nor obtain the provided electricity grid infrastructure at very high cost.

Figure 4. The monthly average air temperature in Taiz province, Yemen.

Figure 5. The monthly average wind speed in Taiz province, Yemen.

This study tries to rearrange the population of Taiz province into three categories, based on the ability to access the power grid. Urban people are classified in category (1), rural people who easily and at slightly increased cost access the power grid are classified in category (2), and rural people who cannot burden the high cost and have difficulty accessing the electricity grid are classified in category (3).

Furthermore, this study proposed three scenarios of energy strategies for electrifying different consumer categories. Scenario (1) is proposed to electrify consumers of the category (1) by energy strategy (2), and categories (2 and 3) by energy strategy (1). Scenario (2) is proposed to electrify consumers of the category (1) by energy strategy (3), category (2) by energy strategy (2) and category (3) by energy strategy (1). Scenario (3) is proposed to electrify consumers in category (1) by energy strategy (3), and categories (2 and 3) by energy strategy (2), as shown in Figure 6. In the three scenarios, the required energy is 4130.85 MWh/day for scenario (1), 6834.85 MWh/day for scenario (2), and
7735.19 MWh/day for scenario (3). The profile of daily energy required for the three scenarios is shown in Figure 7.

![Figure 6. Schematic diagram of the different scenarios and energy strategies for electrifying various consumers’ categories.](image)

Figure 6. Schematic diagram of the different scenarios and energy strategies for electrifying various consumers’ categories.

![Figure 7. The daily profile of energy required by three scenarios.](image)

Figure 7. The daily profile of energy required by three scenarios.

5.4. Diesel Fuel Price

Diesel fuel is the lifeblood in Yemen. It is the source of electricity generation, agriculture activities, and industries. The diesel price was slight fluctuation from 2000 to 2010 with an average price of 0.155 dollars/L. Since 2010, Yemen began to have internal instability, which led to a war at the beginning of 2015. In this period, the diesel price has significant fluctuation with the average price of 0.54 dollars/L [97]. At present, the diesel price is 1.38 dollars/L [80].

5.5. Homer Software

Homer Pro is an energy modeling software developed by the national renewable energy laboratory in the U.S. It is developed for design hybrid renewable energy systems (HRES) combined with conventional generators, batteries, and hydrogen energy systems, for heating, electric power and hydrogen production. It contains powerful tools for the user for designing, simulation, optimization sizing, as well as sensitivity analysis of different combinations of energy systems [98].

Homer fundamentally optimizes hybrid energy systems through reliable and accurate optimization algorithms. This study simulates optimal configuration for one year, evaluates technical performances and economic costs through a lifetime of the system [99]. For performing optimization and simulation, it has to identify information of climate such as solar radiation, wind speed, ambient temperature, as well as technical specifications and cost of system components.

In the simulation process, Homer can run the model, evaluate the technical performances of different hybrid energy systems, and determine the technical feasibility and entire system cost during the lifecycle. During the simulation process of different hybrid energy systems, Homer can obtain the optimal configurations of systems, which also attains the technical systems constrains at the lowest total net costs. In the sensitivity analysis, Homer implements multiple optimizations under various values of different variables to
see the output related to input change or abnormal condition in the model [100]. Homer has been used by many scholars around the world, carried out lots of studies of optimization and techno-economic analysis of renewable system [101,102], grid-connected system [83,103], and served multi types of load [99,104].

6. Result and Discussion

6.1. Discussing Result

This section discusses the technical and economic performances of each microgrid energy system configuration for different consumers’ categories under three scenarios of energy strategies. The technical and economic indexes, such as the potential of renewable power generation, percent of renewable energy fraction, fuel consumption, GHG mitigation, net present cost and cost of energy have been considered assessment. The microgrid energy system that achieved the lowest cost and advantageous technical performances are highlighted. The result is as follows.

6.1.1. Projected the Five Configurations of PV/Wind/Diesel Engine for Different Consumers’ Categories under Three Scenarios of Different Energy Strategies

For different configurations under the specified three scenarios of energy strategies, the economy is assessed based on net present cost (NPC), which is the summation of individual costs through the lifecycle of the system minus salvage cost that is the remaining cost at the end of the project lifecycle. As shown in Table 1, it is easy to notice that there is one majority cost among various individual costs that has a significant ratio of NPC for each energy system configuration under the different energy scenarios. The costs in the table are expressed in percentage rate as in Figure 8.

| Scenario | Microgrid Configuration | Initial Capital Cost (Dollar) | Replacement Cost (Dollar) | M&O Cost (Dollar) | Fuel Cost (Dollar) | Salvage (Dollar) | NPC (Dollar) |
|----------|-------------------------|-----------------------------|--------------------------|-----------------|------------------|-----------------|--------------|
| 1        | Case I                  | 64,687,500                  | 116,075,258.7            | 10,620,009.25   | 16,232,062,868   | 32,148,174.67   | 16.4B        |
|          | Case II                 | 4,448,705,259              | 2,997,981,232            | 393,621,176.7   | 533,241,401.7    | 737,092,955.5   | 7.64B        |
|          | Case III                | 3,571,200,574              | 3,838,364,386            | 216,609,967.9   | 2,900,875,939    | 2,172,843,469   | 8.35B        |
|          | Case IV                 | 3,840,447,643              | 2,941,326,865            | 313,156,861     | 416,110,538.4    | 1,125,122,696   | 6.39B        |
|          | Case V                  | 4,889,114,330              | 3,165,627,330            | 364,630,791     | 0                | 1,013,651,311   | 7.41B        |
| 2        | Case I                  | 90,562,500                  | 162,505,362.2            | 14,868,012.95   | 25,628,120,519   | 45,007,444.54   | 25.9B        |
|          | Case II                 | 7,222,355,373              | 4,918,537,208            | 638,418,121.1   | 906,061,996.3    | 1,266,845,986   | 12.4B        |
|          | Case III                | 4,308,573,392              | 4,090,663,952            | 121,138,222     | 7,831,385,862    | 2,736,624,628   | 13.6B        |
|          | Case IV                 | 6,335,955,720              | 4,657,547,441            | 482,255,816     | 681,189,244      | 1,809,457,172   | 10.3B        |
|          | Case V                  | 8,090,529,013              | 5,067,381,819            | 574,980,175.1   | 0                | 1,648,482,263   | 12.1B        |
| 3        | Case I                  | 103,500,000                 | 185,720,413.9            | 16,992,014.8    | 29,076,240,403   | 51,437,079.47   | 29.3B        |
|          | Case II                 | 8,258,468,654              | 5,544,745,051            | 720,155,913.4   | 875,139,025.5    | 1,474,947,063   | 13.9B        |
|          | Case III                | 6,253,638,662              | 6,642,433,476            | 339,089,611.3   | 5,886,009,553    | 3,822,561,730   | 15.3B        |
|          | Case IV                 | 6,944,915,613              | 5,157,239,225            | 521,138,670.5   | 1,102,499,236    | 2,049,516,142   | 11.7B        |
|          | Case V                  | 9,535,600,179              | 5,161,567,632            | 595,997,324.2   | 0                | 1,722,210,397   | 13.6B        |

From Figure 8, it can be seen that the fuel cost of the energy system in Case I occupies approximately 98% of NPC for the three scenarios of the energy strategies, due to this kind of energy system consumes diesel fuel every single time of system operation. While the initial capital cost of the energy system in Case II is constituted of a majority cost around 58–59% of NPC, due to this kind of system it requires a lot of expenses at the beginning of investment, represented by the PV section. On the other hand, for the energy system in Case III, the replacement cost is dominated by a large part of NPC with approximately 43–45% in the energy scenarios (1, 3) due to the lifecycle of all components of the energy system being less than the project lifetime. For the same energy system, there is no big difference in fuel cost. Concerning the other two energy systems in case IV and case V, the
initial capital cost occupied large a part of NPC with around 59–60%, 66–70%, respectively. This is due the PV component being included in these configurations and which has a one-time only cost during the project lifecycle.

![Bar chart showing percentage of different individual costs of total net present cost (NPC) for all microgrid configurations under three energy scenarios.](image)

**Figure 8.** Percentage of different individual costs of total net present cost (NPC) for all microgrid configurations under three energy scenarios.

In this context, the NPC is considered an index for the economic assessment of three energy scenarios. As shown in Table 1, it can be noticed that the NPC of all hybrid microgrid energy system in scenario (1) of energy strategies are the lowest cost. The scenario (2) is coming next, and scenario (3) is the highest. Taking the NPC in all hybrid microgrid energy systems in scenario (1) as a reference, the percent of reduction compared to the other two scenarios are illustrated in Figure 9. From the figure, it can be seen that for the energy system in case I, the NPC in scenario (1) reduces 36.6%, 44.12% compared with scenarios (2) and (3), respectively. Regarding hybrid energy systems in other cases, the NPC reduced approximately 38.29–38.72% and 45.16–45.40% compared to scenarios (2) and (3), respectively. It is worthy to say that scenario (1) of the energy strategy is economically feasible and can be considered as an urgent solution to attain the energy demand in urban areas, rural consumers are categorized in the region too. According to the above discussion, this study highlights energy scenario (1) as the best scenario that can achieve the lowest investment cost, the best technical performances, and economic competitiveness for all microgrid energy systems under this scenario.

![Bar chart showing percentage of NPC reduction of energy scenario 1 compared with the other two energy scenarios.](image)

**Figure 9.** Percentage of NPC reduction of energy scenario 1 compared with the other two energy scenarios.

6.1.2. Comparative Analysis of Technical and Economic Feasibility for the Designed Systems in All Cases under Scenario (1) of Different Energy Strategies

The optimal technical performances and economic indexes of the five microgrid systems are discussed in this section. Among the five microgrids, Case I is selected as the
comparative reference. Case I generates 100% power based on fossil fuel, as presented in Table 2. It can additionally be seen from Table 2 that Case II generates 97.5% renewable energy by PV and 2.5% energy by fossil fuel DE. While Case III generates 91.8% renewable energy by wind turbines and 8.2% energy by fossil fuel. Case IV produces 98.3% renewable energy by PV and WT, which 57.5% is from PV and 40.8% is from WT, the other 1.71% is provided by fossil fuel. Case V has 100% renewable energy, of which 79.9% is from PV and 20.1% is from WT.

Table 2. The optimal result of technical performances and economic factors of the five microgrid configurations under scenario (1) of energy strategic.

| Parameters                              | DE (Case I) | PV + DE (Case II) | WT + DE (Case III) | PV + WT + DE (Case IV) | PV+WT (Case V) |
|-----------------------------------------|-------------|------------------|-------------------|------------------------|---------------|
| Production (%)                          | DE (100%)   | 97.5%PV + 2.5%DE | 91.8%WT + 8.2%DE  | 57.5%PV + 40.8%WT + 1.71%DE | 79.9%PV + 20.1%WT |
| Fuel Consumption (L/yr)                 | 485,114,000 | 15,936,540       | 86,696,048        | 12,435,946             | 0             |
| CO₂ emission (Kg/yr)                    | 1,283,022,594 | 42,148,726       | 229,292,444       | 32,890,411             | 0             |
| Reduction of fuel consumption&CO₂ emission compared to Case I (%) | ———         | 96.72            | 82.13             | 97.44                  | 100           |
| Renewable Fraction (%)                  | 0           | 96.1             | 78.60             | 97.1                   | 100           |
| NPC (dollar)                            | 16.4B       | 7.64B            | 8.35B             | 6.39B                  | 7.41B         |
| COE (dollar/kwh)                        | 0.448       | 0.209            | 0.229             | 0.175                  | 0.203         |
| Reduction of NPC&COE compared to case I (%) | ———         | 53.42            | 49.04             | 61.95                  | 54.82         |

In terms of renewable energy fraction, the energy system in Case I does not include renewable energy sources at all, so all the energy is generated by fossil fuel. While Case II includes PV power and the renewable fraction is 96.1%, which reduces 96.72% fuel consumption and CO₂ emission. Replacing the PV power system by WT in Case III, the renewable energy fraction is 78.6%, which reduces 82.13% fuel consumption and CO₂ emission. It is worth concluding that PV is more potential than wind to supply the load, due to abundant solar and limited wind in the area of study. On the other hand, Case IV includes both PV and wind power, the renewable fraction is 97.1%, which reduces 97.44% fuel consumption and CO₂ emission. In Case V, conventional fossil fuel power system is excluded and PV and wind power system are included, which reduces 100% fuel consumption and CO₂ emission. From the discussion above, taking a system in Case I as the reference, it can be summarized that for the highest renewable energy fraction, the fuel consumption and CO₂ emission are the lowest. The system in Case V is ranked the first, the systems in Case IV follows, then Case II, and Case III is ranked at final.

The optimal economic indexes for all designed cases show that the system in Case IV offers the lowest NPC, 61.95% COE reduction compared with Case I. The system in Case V is the second highest with a 54.82% reduction. The lowest reduction of NPC and COE is in Case III with 49.04%, and Case II is 53.42% reduction. This is due to that solar energy is rich and wind energy is poor in the area of study. For future investment, the PV system can be considered as an alternative promising of electricity generation specifically in Taiz province, and generally in Yemen.

According to the comparative analysis of technical and economic aspects of all the designed cases, it is worth noticing that the system in Case V achieves the best technical performances. Case IV achieves the best economic properties. However, it demonstrates relatively poor technical performance. The system in Case IV is selected as the best hybrid microgrid system, which achieves the lowest economic cost and acceptable technical
performances that can effectively help the government so Yemen to achieve its commitment to the Paris agreement on climate change and Kyoto protocol.

6.1.3. The Operation Status of the Best-Selected Optimal Energy System in Case IV under Scenario (1) of Different Energy Strategies

For scenario (1), the energy system in Case IV is selected as the best energy system, which achieves the competitive economic indexes and acceptable technical performances. For the energy system in Case IV, further technical and economic details are discussed and operation status is demonstrated in this section.

The optimal configuration is as follows. The PV generation is 793,931 kW, the wind power generation is 795,000 kW (265 turbines), the diesel engine is 200,000 kW, the battery energy storage is 1,020,540 kW distributed in 255,135 strings, and converter power is 535,152 kW, as shown in Table 3. The PV, WT, and DE are the main power sources that complement each other. The monthly produced energy is illustrated in Figure 10. The annual energy produced by the system is 2,545,226.007 MWh, of which 1,463,783.467 MWh is generated by PV models, 1,037,909.813 MWh is generated by wind turbines, 43,532.729 MWh is generated by diesel engines. The annual net production of batteries is 575,390.9 MWh, as shown in Table 3. The system is effective to supply power to the large-scale load (1,507,685.642 MWh/year), while it has 0.0049% unmet load, 0.092% capacity shortage and 33.6% excess energy.

Table 3. The result of optimal capacity and annual energy production of the system in the Case IV.

| Parameter               | PV        | WT        | DE         | Batteries                          | Converter |
|-------------------------|-----------|-----------|------------|------------------------------------|-----------|
| Rated size (kW)         | 793,931   | 795,000   | 200,000    | 4 Batteries in a single string, 255,135 strings = 1,020,540 Bat | 535,152   |
| Energy production (MWh/year) | 1,463,783.467 | 1,037,909.813 | 43,532.7291 | 575,390.9                          | ———      |

Figure 10. Monthly energy production from different power sources in the Case IV.

The economic aspect is discussed above, in which the NPC of the entire system is 6.39B (dollars) and COE is 0.175 dollars/kWh. The entire system cost is the individual cost of each component in the system lifecycle, as shown in Figure 11. From the figure, it is noticeable that the storage batteries occupied the highest cost of the entire system cost. This is due to renewable energy having great potential, and a huge amount of renewable energy is needed to be stored so that the scale of storage capacity increases and the batteries need to be replaced early. The rest of the system cost is distributed among other components, where the PV system occupies the second highest cost, followed by wind turbines, diesel engines and power converters.
The sensitivity analysis is helpful to assess the abnormal situation of the system, understand the riskiness and the relationship between output and input. For the best selected optimal system in Case IV under scenario (1) of the energy strategy, the sensitivity analysis is investigated based on a prospective variation of unstable variables. The system outcomes are checked based on the prospective change of load scale, real interest rate and fuel price.

The literature predicts a 2.74% population growth rate in Taiz Province [94]. Accordingly, the prospective population growth is estimated for the upcoming ten years up to 2030. It has been discussed previously, under scenario (1) of energy strategy, that the population in the rural area are supplied by energy strategy (1), and the population in the urban area are supplied by strategy (2), taking into account 7% immigration rate from rural to urban [105]. It means some people will leave energy strategy (1) and register in urban area.
energy strategy (2) which will supply 2 kWh/day/capita. Considering these issues, the prospective total energy consumption is estimated for the upcoming ten years. As shown in Table 4, it can be seen the influence of an increase in total energy consumption on the NPC and COE. The NPC rises gradually with the increase of the load, and this is due to the expansion of system capacity to meet increased demand energy led to expenditure more investment. Whereas, the COE stays constant for all years, and this is due to the increase in system capacity that led to a rise in energy production.

Table 4. The economic indexes based on population growth in Taiz province in the upcoming ten years.

| Year   | 2020  | 2022  | 2024  | 2026  | 2028  | 2030  |
|--------|-------|-------|-------|-------|-------|-------|
| Population (million) | 3.25  | 3.43  | 3.62  | 3.82  | 4.03  | 4.26  |
| Total Energy consumption (MWh/day) | 4130.8 | 4698.2 | 5267.7 | 5841.9 | 6423.5 | 7015.0 |
| NPC (billion dollars) | 6.39  | 7.33  | 8.17  | 9.03  | 9.94  | 10.86 |
| COE (dollars/kWh) | 0.175 | 0.176 | 0.175 | 0.175 | 0.175 | 0.175 |

The finance system in Yemen is not stable due to the conflict. The variation of the real interest rate is selected to check the system outcomes. When the actual real interest rate is 0.24%, the result shows that the NPC and COE were 6.39 billion dollars and 0.175 dollars/kWh, respectively. As shown in Table 5, when the real interest rate increases by 5%, the NPC decreases and the COE rises. On the other hand, when the real interest rate decreases by 5%, the NPC increases and the COE declines.

Table 5. The result of economic indexes via variation of a real interest rate for the best-selected optimal energy system under scenario (1) of energy strategies.

| Real Interest Rate (%) | −5 | 0.24 | 5 |
|------------------------|----|------|---|
| NPC (billion dollars)  | 8.23 | 6.39 | 5.30 |
| COE (dollars/kWh)     | 0.105 | 0.175 | 0.249 |

Furthermore, the diesel fuel price is also selected as one of the sensitivity variables to examine its influence on the economic indexes. As shown in Table 6, when the actual diesel price is 1.38 dollars/L, the NPC and COE are 6.39 (billion dollars) and 0.175 dollars/kWh, respectively. When the price increases 50% to 2.07 dollars/L, the NPC and COE accordingly increase. When fuel price decreases 50% to 0.69 dollars/L, the NPC and COE accordingly decline. From the above discussion, it can be deduced that the system demonstrates normal behavior to the sensitive input variables and the outcomes.

Table 6. The result of economic indexes via variation of diesel fuel price for the best-selected optimal energy system in scenario (1) of energy strategies.

| Diesel Fuel Price (Dollar/L) | 0.69 | 1.38 | 2.07 |
|-----------------------------|------|------|------|
| NPC (billion dollars)       | 5.26 | 6.39 | 6.60 |
| COE (dollars/kWh)           | 0.144 | 0.175 | 0.181 |

7. Conclusions

The study is developed to design different configurations of hybrid energy systems including PV, WT, diesel engine for supply power to various consumer categories in Taiz province, Yemen under three scenarios of energy strategies. The purpose of this study is to look for the best scenario to achieve the lowest investment cost. The following conclusions can be obtained from this paper.

(1) The scenario (1) of the energy strategies is economically feasible and is the best choice for urgently restoring electricity services to diverse consumer categories in Taiz
province, Yemen, and scenario 2 and 3 can be considered in the future for economic development.

(2) In terms of technical performances of the designed systems, in all cases scenario (1) is the best of energy strategies. For renewable energy generation, the unique PV system in Case II shows more potential than the unique WT source in Case III.

(3) From the technical aspect, compared with Case I, the energy system in Case V with zero fuel consumption and CO$_2$ emission is a superior energy system.

(4) In terms of the economic aspect, the energy system in Case IV is the best economical system, which its NPC and COE reduce 61.95%.

(5) Case IV is most economically feasible and has advantageous technical performances with 97.44% CO$_2$ reduction. Therefore, the study recommends it as the best choice for Yemen’s investment.

For future work, we will investigate deeply the real situation of the application of renewable energy, the consumers’ ability to access the power grid, and the policy of the electricity sector or government. Furthermore, we will continue to study the techno-economic feasibility of the hybrid energy systems in a more accurate way and take more factors into account. We hope our study can be used in the real application and will study the techno-economic feasibility of the proposed method that extends to all provinces in Yemen.

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Conflicts of Interest: The authors declare no conflict of interest.

Notations

- $P_{PV}$: The PV array output power in [kW]
- $γ_{PV}$: The PV array capacity in [kW]
- $f_{PV}$: The derating factor in [%]
- $G_{STC}$: The standard solar irradiation [1 kW/m$^2$]
- $α_p$: The temperature effect on the power [%/°C]
- $T_{C}$: The nominal cell temperature in the current time step [°C]
- $T_{C,STC}$: The standard cell temperature
- $C_{ANN,TOT}$: The annualized total system costs
- $i$: The annual real interest rate (the discount rate)
- $N$: The numbers of system lifecycle years
- $CRF(i, N)$: The recovery factor
- $i^o$: The nominal interest rate in [%]
- $f$: The annual inflation rate in [%]
- $E_{load\ served}$: The actual load served by the energy system per year
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