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TREND EDITORIAL

A review of Yemen's current energy situation, challenges, strategies, and prospects for using renewable energy systems

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Introduction

Yemen's Republic is located in the Middle East, between 13 N–16 N latitude and 43.2–53.2 longitude in southwest Asia. Its south and west are covered by mountains and coastal plains. It borders Saudi Arabia in the north, the Red Sea in the west, the Gulf of Aden and the Arabian Sea in the south, and Oman in the east. Sana'a is the capital and largest city of Yemen. The territory of Yemen includes more than 200 islands, the largest of which is Socotra Island, about 354 km^2 south of the Yemeni mainland. Yemen is the second-largest country on the peninsula, covering an area of 527,970 km^2 as seen in Fig. 1. Yemen is divided into three regions: mountainous, desert, and coastal. Yemen's Republic has one of the highest levels of sunshine in the world, and the weather is divided into two seasons in almost every part of the country: spring and summer (McSweeney 2010). Yemen, in addition to being located in a sunny belt with long sunshine hours and high isolation levels, offers many solar energy and solar technology benefits (Bank 2014).

On May 22, 1990, the Yemen Arab Republic (YAR) and the People's Democratic Republic of Yemen (PDRY) were united to the Republic of Yemen (ROY). This unification led to dramatic political and economic reforms in Yemen. However, since 1990, it has repeatedly led to serious retrogression of the national economy up to now. The Yemeni government is committed to economic reform, hoping that it will lead to further economic stability and recovery in the upcoming future. The energy sector is one of the key elements of these improvements (The Republic of Yemen 2013). Besides, Yemen's power industry is currently witnessing the worst crisis in the nation's history. It is burdened with overloaded infrastructure and a considerable capacity gap and is affected by unprecedented load reduction, excessive transmission and distribution losses, and huge revolving debt. According to the statistics of the Yemeni public power company (YPEC), in 2020, the national power generation gap exceeds 2444 MW, the demand was 3102 MW, and the supply was 658 MW. It was reported that so far, some rural areas have experienced load-shedding and blackouts, while the blackout time in cities has increased to 20 h a day, and some cities have experienced complete blackouts (Economic Consulting Associates Limited 2009; Arab Union of Electricity 2016).

One of the most serious developments in Yemen is the increase in power shortages. It has become a major political issue, undermining the government's credibility and legitimacy. Some observers believe that the power crisis in the country has the potential to further aggravate the country's social structure and may eventually overshadow the threat of terrorism (OCHA 2017). The lack of electricity has caused severe damage to Yemen's economy and constituted a binding and powerful constraint on the country's growth. This situation has limited the growth of the nation's GDP in the past and has had an adverse impact on employment, international competitiveness, and exports, and has aided in promoting poverty. For ordinary citizens, the load-shedding is causing serious interference to their daily life and for industrial, commercial, and agricultural users, the price of the surge in power shortages is huge. In Yemen, the power industry has been weakened because of the rash and reckless energy policies over the past three decades, hindering the development of cheap and abundant domestic energy sources like solar and wind. The task of restructuring Yemen's power sector and designing

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Fig. 1 Location of the Republic of Yemen

an appropriate policy framework to attract large-scale private investors and improve its performance is complex and arduous. There are, of course, several important factors in other countries' sector reforms that can provide useful benchmarks. However, the unique disadvantage confronted by Yemen is to improve government performance which has been a major obstacle to the restructuring efforts and this has led to Yemen's energy bankruptcy which is caused by massive institutional and governance failures (JIC 2010).

Renewable energy is the alternative method for achieving clean energy production in many countries. Due to environmental problems, restrictions on fossil fuel supply, changes in prices, and technologies, many developing countries, including Yemen, are considering using renewable energy sources like solar and wind to address power shortages and distribution while reducing greenhouse gas emissions. Renewable energy in the form of solar or wind energy has proved to be cost-effective and profitable for a long time (Timmons et al. 2018; Alkipsy et al. 2020). It is estimated that by 2050, renewable energy will account for 63% of the total global energy supply, and combining renewable energy with high energy efficiency can reduce greenhouse gas emissions by 94% (Gielen et al. 2019). The International Energy Agency (IEG) sustainable development scenario (SDS) in 2018 points out that to achieve the long-term climate goals, the average capacity of renewable energy needs to increase by more than 300 GW per year up to 2030. The total installed capacity of renewable energy power generation reached 181GW by 2018 and 200 GW by 2019. By the end of 2019, the proportion of renewable energy in global power generation has increased to 27.3%, which is expected to increase to 85% by 2050, and the carbon dioxide emissions of the whole power generation industry will decrease by 85% (Alganahi et al. 2009; IEA 2018; IRENA 2018; Gielen et al. 2019; REN21. 2020).

Under the influence of global warming and climate change, a large number of renewable energy potential assessment studies have been carried out all over the world (El-katiri 2014; Nematollahi et al. 2016; Akuru et al. 2017; Nugroho et al. 2017; Singh et al. 2017; Kaya et al. 2017; Bulut and Muratoglu 2018; Islam et al. 2018; Aguirre-Mendoza et al. 2019; Ocon and Bertheau 2019; Fodhil et al. 2019; Kougias et al. 2019; Mubaarak et al. 2021). These studies can be used in a variety of applications that can electrify remote areas (Mandal et al. 2018; Al-Dousari et al. 2019), islands (Mekonnen and Sarwat 2017; Surroop and Raghoo 2018), telecommunications (Weir 2018), and water desalination (Khan et al. 2017). The USA (Padrón et al. 2019) studied the potential of renewable energy while taking socioeconomic factors into account. This study found that by 2050, greenhouse gas emissions will be reduced by 40% and 17%, respectively, as the proportion of renewable energy increases. China is the country with the largest energy consumption and carbon dioxide emissions in the world, and its renewable energy potential has been reassessed in Kelly et al. (2019). Research shows that wind power and hydropower technology is relatively mature and low cost, which makes them the priority of development in present and near future. With the support of the national strategy, solar energy will develop rapidly, while biomass energy and geothermal energy are expected to develop rapidly with a good resource guarantee.

Kumar et al. (2022) discussed the accomplishments, policies, efforts, and future potential of the agricultural industry based on solar technology. In addition, the article elaborately elucidated each solar-based agricultural system with its challenges and opportunities in the current scenario, while Afrane et al. (2022) conducted a bibliometric analysis on research documents collected from the Web of Science Core Collection to discover trends and characteristics of the renewable energy knowledge area in Africa from 1999 to

2021. However, the study in Solaymani (2021) examined trends in energy consumption, policies, and development of renewable energies, as well as the causal link between renewable and non-renewable energies and economic growth utilizing two techniques. In addition, the study in Shahzad et al. (2022) aimed to identify and prioritize the obstacles that entrepreneurs face in developing RE projects in Pakistan. Finally, the review in Yoro et al. (2021) critically assessed current achievements in energy modeling and simulation, with limited insights into its methodologies, problems, and opportunities in a few renewable and sustainable energy systems (RSES). In addition, the idea of model validation in RSES is thoroughly examined using both in-sample and out-of-sample techniques, with prospective data sources for model validation in RSES being emphasized.

This research contributes to previous knowledge in four distinctive ways as follows:

1. This study reviews Yemen's electricity and energy sector before and after the onset of the conflict that began in 2015 and presents the current state of power generation, transmission, and distribution systems in the country by assessing the negative impact in the electricity sector caused by the ongoing conflict.
2. This study investigates the factors that promote the expansion of renewable energy technologies at the rural and national levels in Yemen, as well as the challenges that impede the development of renewable energy techniques and recommends modern tools to meet Yemen's current and future needs.
3. This study provides detailed discussion of the various strategic scenarios appropriate for achieving adequate electrification for the Yemeni population, with a particular focus on the proposed strategy to electrify the entire urban and rural Yemeni population by 2050.
4. Finally, this study connects renewable energy to sustainable rural expansion by examining whether current renewable energy resources can meet the future energy needs.

The remainder of the paper is organized as follows: "The energy in Yemen" represents the energy in Yemen. "The development prospect of potential renewable energy in Yemen, Middle East, and Africa region" addresses the development prospect of potential renewable energy in Yemen, Middle East, and Africa region. "Challenges of energy and renewable energy development in Yemen" addresses the challenges encountered in the energy and renewable energy development in Yemen. "Proposed strategy and solutions to electrify the population of Yemen using RES by 2050" introduces the proposed strategy and solutions to electrify the entire Yemeni population using RES (renewable energy system) by 2050, while "Configuration and design of proposed hybrid renewable energy systems" covered the various configurations of renewable micro-grid energy systems including PV and wind turbine (WT) for electrifying a diverse range of consumers. "Conclusions and recommendations" summarizes the conclusions and recommendations.

The energy in Yemen

According to the literature, the development of renewable energy at the national level involves at least the four key categories listed as follows: (A) energy consumption; (B) the current situation of power plants, transmission, and distribution networks; (C) the current energy types and proportion of power supply in Yemen; (D) heavy fossil fuel costs; every category comprises some aspects, which are discussed in detail below.

Energy consumption

Yemen has recently experienced a severe power shortage, unable to meet the power needs of its population and infrastructure. In 2009, the installed power capacity was about 1.6 GW, while, in fact, the power supply gap was about 0.25 GW. The power development plan (PDP) forecasts and estimates the capacity demand of 3.5 GW in 2020. In 2011, electricity capacity fell to less than 70% of total capacity due to anti-government demonstrations, oil pipeline strikes, and the evacuation of foreign workers. This was the worst in 2015 when the situation in Yemen turned into internal and external conflict (Al-Shetwi 2021). Now, it is speculated that the situation in Yemen will not improve, so the country needs to plan alternative energy infrastructure (Al Asbahi et al. 2020). The sustainable transition from fossil fuels can be achieved by installing clean energy projects in the State Grid, such as wind power, hydropower, solar photovoltaic, and biomass systems. Yemen is facing serious energy problems, such as circulation obligations, line losses, obsolete transmission lines, and electricity theft among the rural population (71%), resulting in 8–10 h of power shortage. If we set aside wars and conflicts, which we hope will end soon, and focus on the real obstacles to Yemen's power generation, we will encounter how to find the best solution to this problem (Xiaohui 2016). One of the great challenges and hallows of Yemen's electricity is its total dependence on fossil fuels, including diesel, heavy crude oil (mazot), and liquefied natural gas (LNG). Due to environmental and economic considerations, these resources have attracted much attention (Energy and Renewable Profile 2004; Ministry of Electricity 2012; Jahangiri et al. 2016). Besides, Yemen's geographical composition of rural areas poses other challenges to power distribution. The rural population makes up about 75% of the total population, but only 23% of the population has access

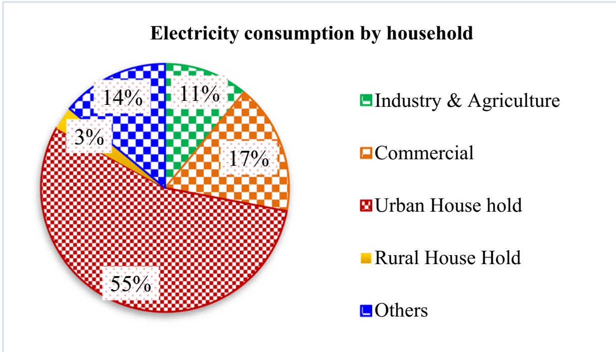


Fig. 2 The main electricity consumption is household

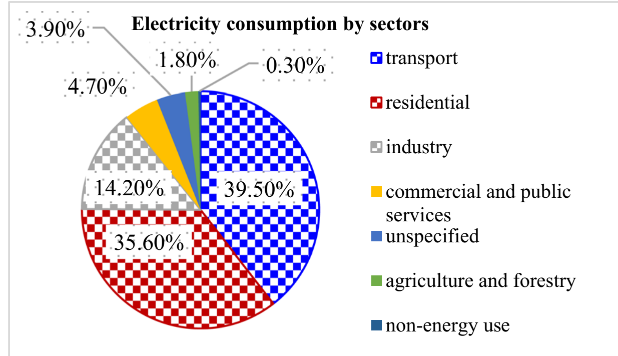


Fig. 3 The main electricity consumption by sectors

to electricity. Due to the lack of continuous power supply, industrial activities are very weak, and the main electricity consumption is household, as shown in Fig. 2.

The sustainability of the energy system can be assessed using macroeconomic energy indicators, such as average annual energy consumption and energy intensity. According to the International Energy Agency, in 2000, oil made up 98.4% of the total primary energy supply in Yemen with the remainder comprising biofuels and waste (International Energy Agency). Natural gas and coal were introduced into the energy mix around 2008, and wind and solar energies were added around 2015. In 2017, oil made up about 76% of the total primary energy supply, natural gas about 16%, biofuels and waste about 3.7%, wind and solar energies etc. about 1.9%, and coal about 2.4%. According to the International Energy Agency report, the final consumption of electricity in Yemen in 2017 was 4.14 TWh. This figure was also broken down by sectors, with transport consuming 891 kiloton of oil equivalent (ktoe) (39.5%), residential 804 ktoe (35.6%), industry 320 ktoe (14.2%), commercial and public services 105 ktoe (4.7%), agriculture and forestry 41 ktoe (1.8%), and non-energy use 7 ktoe (0.3%), and 88 ktoe (3.9%) unspecified. Electricity consumption was 0.15 MWh/capita in 2017 (Sufian 2019). Figure 3 depicts the major electricity consumption by sectors. This demonstrates Yemen's significant challenges in optimizing the use of oil and gas resources, raising concerns about unbalanced and unsustainable energy systems that could lead to unsustainable development. As a result, it has an impact on a wide range of social, economic, and environmental development, such as livelihoods, water use, agricultural productivity, health, population levels, education, and gender-related issues (Afsharzade et al. 2016).

Current situation of the power system in Yemen

As mentioned earlier, according to the International Energy Agency, in 2000, oil made up 98.4% of the total primary energy supply in Yemen, while in 2017, oil made up about 76% of the total primary energy supply, and natural gas about 16%. Oil and gas are the largest suppliers of fuel for power plants (Sufian 2019). However, given the recent lack of oil due to the situation in Yemen, as well as the scarcity of natural gas during the cold season, the primary difficulty of power generation during these seasons is to provide fuel for power plants. The power generation industry has been severely harmed by this reliance on oil and natural gas, and the development of the power grid has been stifled. As a result, these issues are the primary motivations for shifting energy production to renewable sources.

The main generating power plants of electricity

Currently, the power plant and transmission lines in Yemen have suffered from severe losses, and the power supply has become a national power grid constantly threatened by a total collapse due to the destruction of factories and transmission lines. Some of the power plants are prone to collapse completely due to continuous attacks, and the other reason is lack of maintenance (Al-Shabi Mohammed 2014). Yemen is experiencing a severe shortage of several gigawatts of electricity, according to the Yemen Public Electricity Corporation (YPEC), which is a semi-independent arm of the Yemen Ministry of Electricity and Energy (YMEE) (World Bank 2009). As shown in Fig. 4, Yemen also has four major energy production stations, according to the same source: (1) Ma'rib gas station in Marib being the largest with a power generation capacity of 350–400 MW, (2) Alhuso gas station in Aden, (3) Mokha gas station in Taiz, and (4) Alkaseb gas station in Hodeida, as well as Yemen has a 132 kV main grid, as shown in Fig. 4. In Ma'rib, east of Sana'a, a new gas-fired power plant was completed in 2010 and connected to the main grid via Bani Hoshish's 400 kV double circuit transmission line, and a second 400 kV transmission line from Ma'rib to the 132 kV substation at Damar, south of Sana'a, is proposed and there is also a smaller grid in the

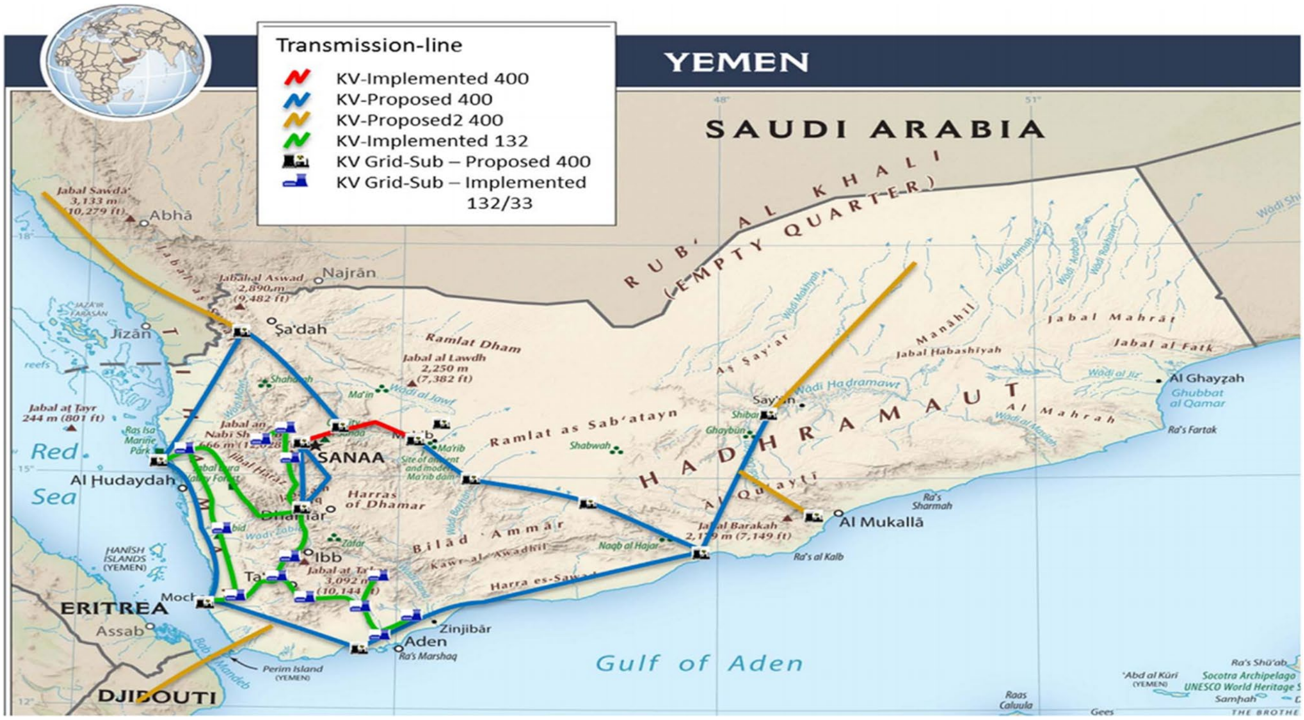


Fig. 4 Yemen's electrical transmission network system

Middle East of the country, with an isolated grid around Sada city (Arab Union of Electricity 2015).

Yemen's electricity mainly depends on oil-fired power plants: 684 MW of diesel power, 495 MW of steam power, and 340 MW of natural gas power. In 2015, the total installed capacity of the state grid was 1519 MW. The power plant generates power at different voltages of 10.5 kV, 11kv, 13.8 kV, and 15 kV, and then improves the voltage level to 33 kV, 132 kV, and 400 kV. The medium voltage level of 33 kV is used to transfer power from the substation to the demand site. The distribution network uses 11 kV power transmission to the distribution transformer. The nominal frequency of the grid is 50 Hz. Figure 4 shows Yemen's transmission network with all power stations and substations (Sufian 2010). In August 2013, Yemen began construction of a new 400 MW (Ma'rib II) gas-fired power generation facility, which is scheduled to start operation at the end of 2014, but was delayed to the recent years due to the recent security turmoil (Economic Consulting Associates Limited 2009; Arab Union of Electricity 2015; U.S. 2017; Rawea and Urooj 2018). Table 1 shows the capacity of Yemen's main power plants.

Power supply and demand balance forecast

Yemen has the lowest electricity access rate (40% of the population), compared with about 85% in the region. Rural and urban households have unequal access to electricity. Although the rural population accounts for about 75% of the total population, only about 23% of the population has access to electricity, while the urban population accounts for about 85%. Although the electricity supply rate is low, only about half of these people are connected to the public grid, and the other half are supplied from other private sources, including diesel generators (which usually operate for several hours for lighting) and low-intensity appliances. Non-grid electrified rural households are using alternative lighting, including kerosene lamps (about 67%) and liquefied petroleum gas (LPG) lamps (about 5%), which have a serious impact on the environment (NECRA. Lmt. 2010).

Figure 5 depicts the power supply and demand balance, and the balance of the reserve fund is 20%. The goal of system reliability is to assume that 48 h of the load is lost per hour. The gap between supply and demand was estimated to be about 500 MW in 2013. The latest power development plan (2009–2020) predicted that the total capacity demand will reach 3102 MW in the next decade, with an annual growth rate of 10%. Yemen relies on fossil fuels for most of its electricity supply, including mazot, diesel, and most recently LPG, 79.91% of electricity from oil fuels of installed capacity, 20% of electricity from natural gas fuel, and 0.09% of electricity from renewable energy (Sufian et al. 2017).

Table 1 Electrical power generation capacity existing in Yemen (2018)

Station	No. of units	No. of available units	Type of generation	Fuel used	Fuel's transport	Total installed capacity (MW)	Total available capacity (MW)	Manufacturer	Date of installation
Marib 1	3	3	GT	Gas	Pipeline	340.5	340.5	SIEMENS	2010
Ras Katnib	5	5	ST	RFO + LFO	Ship and truck	150	0	ANSANDO	1981
Al Mukah	4	3	ST	RFO + LFO	Ship and truck	160	0	ANSALDO	1987
Hiswah 1	5	3	ST	RFO + LFO	Pipeline	125	50	RUSSIA	1986
	1	1	ST			60	30	CHINA	2008
Hiswah 2	2	2	GT	Diesel Gas	Pipeline	60	50	CHINA	2016
Almansorah 1	8	2	DG	RFO Diesel LFO	Pipeline and truck	64	5	MITSUBISI MAN B&W	1982
Almansorah 2	7	7	DG	RFO + LFO	Pipe line and truck	70	45	WARTSILA	2007
Khormaksar	5	1	DG	Diesel	Truck	15	3	CEMTPIESTIC	1970
	2	2	DG			10	10	WARTSILA	2003
Twahi	5	0	DG	Diesel	Truck	7.5	0	CATERPILLAR	2016
	3	0	DG			6.6	0	SKL	2004
Shenaz	8	4	DG	Diesel	Truck	10	30	CATERPILLAR	2016
	26	13	DG			30		CATERPILLAR	2016
Hedjuff 2	6	0	DG	Diesel	Truck	6	0	CATERPILLAR	2016
	5	0	DG			5	0		
	8	6	DG			9.6	8		
Stadium	52	26	DG	Diesel	Truck	40	25	CUMMINS	2016
Dahban 1	4	2	DG	Diesel	Truck	21	10.5	GMT	1980
Dahban 2	5	1	DG	Diesel	Truck	25.5	5	WARTSILA	2000
Hiziaz 1	6	6	DG	Diesel	Truck	30	30	WARTSILA	2003
Hiziaz 2	7	5	DG	RFO + LFO	Truck	70	50	WARTSILA	2004
Hiziaz 3	6	3	DG	RFO + LFO	Truck	30	30	WARTSILA	2007
Taiz	4	1	DG	Diesel	Truck	16	13	2 DEUTZ 2 WARTSILA	1979 2003
Al Hali	5	5	DG	Diesel	Truck	27.75	20	3 GMT 2 WARTSILA	1980 2003
AlKormish	3	2	DG	Diesel	Truck	7.5	5	DEUTZ	1979
Sana'a	6	3	DG	Diesel	Truck	19.7	12.5	3 DEUTZ 3 WARTSILA	1972 2004
Jaar	5	3	DG	Diesel	Truck	10.2	2.1	1 DEUTZ 2 NIGATA	1985 2006
Ryan	7	7	DG	RFO + LFO	Truck	70	54	WARTSILA	1998–2007
Khulf	4	4	DG	Diesel	Truck	13	3.4	DEUTZ	1980–1984
Monsawrah	9	9	DG	Diesel	Truck	16 1982	4.9	5DIHATSU 2GM 2 WARTSI LA	1995 1999

Table 1 (continued)

Station	No. of units	No. of available units	Type of generation	Fuel used	Fuel's transport	Total installed capacity (MW)	Total available capacity (MW)	Manufacturer	Date of installation
Shehr	5	5	DG	Diesel	Truck	13	2	3 MAK 2 GMT	1987 1996
Sayoon	7 4	4 3	DG DG	Diesel Diesel	Truck Truck	31.92 24.93	10.5 15.5	4 NIGATA 4 DEUTZ 2 GMT 1 MAN	1982 1990–1996–2006
Petro-Masselah	3	3	GT	Diesel	Pipeline	75	33.5	GE	2018
Total generated power in (MW)						**1670. 7**	**898.4**		

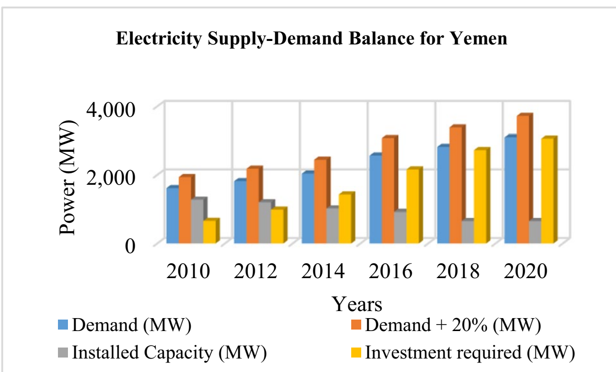


Fig. 5 Electricity supply–demand balance for Yemen

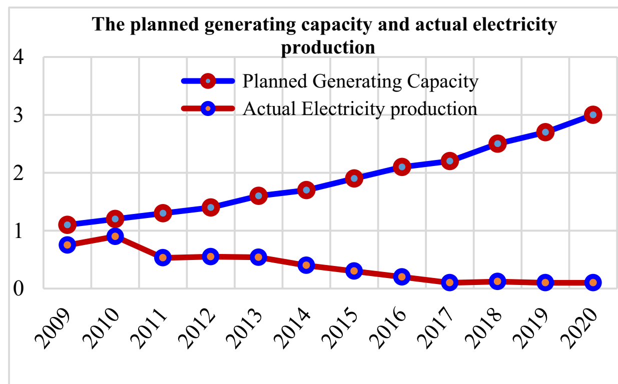


Fig. 6 Peak demand forecast for main interconnected grid GW

Status of energy type and proportion of power supply in Yemen from 2009 to 2021

Yemen had a strategy to develop and improve its electrical potential before the events of 2011. The Public Electricity Corporation is responsible for developing this strategy, which is overseen by a group of power engineers. It seeks to treble the capacity of power generation from 2009. It is the equivalent of 3 GW, and it includes services for new locations and residences that are not connected to the public grid, as well as providing access to factories and service providers. It was created between 2009 and 2020. The impact of the events of 2011 on power output, however, was so enormous that the power plant was shut down in 2015. Figure 6 depicts the planned generating capacity and actual electricity production. In 2011, the decline of electric energy production began to appear obviously. Power generation was about 0.75GW in 2009, compared with 1GW in 2010. The incident continued to take place in the country, thereby undermining the behavior of the power sector. Transportation lines and power plants were completely shut down in 2015 (Bank. 2005).

Extensive military operations began in Yemen in mid-2015 and continued until the time of writing this article. The power business has been severely impacted, with public energy availability plummeting from 60% in 2014 to 10% at the end of 2017. The consequences are disastrous. Some power plants have been completely destroyed, while others have been partially wrecked, resulting in a significant reduction in power generation capacity and even making fuel delivery problematic for power plants (Al-ashwal 2005). Currently, the average electricity supply is between 200 and 250 MW. Sana'a, the capital, for example, has a power requirement of roughly 500 MW but only receives 40 MW of power for a few hours each day. Aden province was likewise experiencing a power crisis, with 390 MW required but just 190 MW was available. Alburaydah and IBB provinces both have a total demand of 280 MW, which they do not meet. Taiz, Yemen's most populous province, requires 111 MW of electricity, but the public infrastructure appears to be unable to provide it (Sufian 2019).

Transmission lines will be attacked on a regular basis if the conflict continues, negating the need to operate power plants. The World Bank (World Bank 2013) has

Table 2 Generation investment plan, Yemen

Plant	Type	Capacity (MW)	Year
Ma'rib II	OCGT to CCGT	352 to 528	2013 to 2019
Ma'rib III	OCGT to CCGT	264 to 396	2014 to 2020
Wind	Wind turbines	180	2012 to 2014

recommended a viable solution: moving the electrical sector away from centralization and toward decentralization. First, technically and institutionally, the power system is rebuilt from the ground (solar energy). Then, the solution is extended from a small off-grid system to an urban power grid, and municipal power grid (sub-national), and continues gradually to the national power grid. The proposed solution will take a long time; in parallel the conflict is expected to come to an end. Table 2 summarizes recent proposals for modernization and the building of new power plants. Some power plants using the Open Cycle Gas Turbine (OCGT) technology have been installed and will be converted to power plants using the Combined Cycle Gas Turbine (CCGT) system (Al-Shabi Mohammed 2014). This adjustment occurred as a result of a revised gas valuation at a higher price. It is, however, contingent on the supply of natural gas.

Yemen also struck an agreement with China's National Corporation for Overseas Economic Cooperation in September 2012 to build three natural gas–fueled power facilities. Each will have a generating capacity of more than 400 MW. Furthermore, in late 2012, the Turkish government committed to assist Yemen in the construction of a 263-MW electric plant capable of burning both petroleum and natural gas. Unfortunately, due to the onset of the 2015 war (Sufian 2019), none of the above ideas came to fruition.

Heavy fossil fuel costs

According to the latest report of the World Energy Statistics Review 2020, 84% of the world's energy is still supplied by fossil fuels, while renewable energy accounts for only 11% of global primary energy consumption. Burning fossil fuels to produce energy leads to a large number of greenhouse gas emissions, which is harmful to the environment and leads to global warming, while the greenhouse gas emissions of renewable energy are less (Al-Shetwi 2021; Ansari et al. 2019; Energy 2020). The wide pollution is one of the by-products of the country's uncontrolled energy consumption. Yemen's CO_2 emissions were at the level of 10.9 million tons in 2019, up from 10.5 million tons the previous year; this is a change of 3.25% which ranked the country as 97th in the world in 2019 as shown in Fig. 7 (REN21. 2019). It is worth noting that the power plant is the largest centralized emission source, accounting for about 69.3% of the total national emissions.

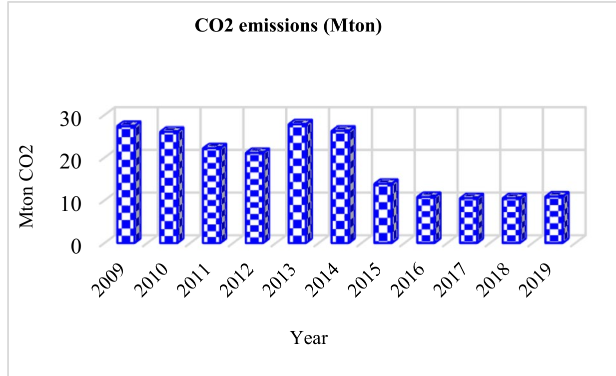


Fig. 7 The total CO_2 emissions in Yemen up to 2019

Yemen is not an industrialized country. As a result, industrial activities do not produce a lot of greenhouse gases. Energy-related greenhouse gas emissions made up 69.3% of all greenhouse gas emissions. Non-energy sectors such as agricultural activities, waste recovery, and industrial processing accounted for the remaining 30.7%, accounting for 23.1%, 3.7%, and 2.9%, respectively. Although the energy sector produces greenhouse gas emissions, fossil fuel combustion in power generation, transportation, and other sectors accounts for the majority of emissions (19.3%, 19.2%, and 16.6%, respectively). The rest is due to domestic, agricultural, and commercial use of kerosene and diesel. The total amount of greenhouse gas emissions has not had a significant impact on the global climate. In 2019, CO_2 emissions per capita for Yemen were 0.37 tons of CO_2 per capita. Though Yemen CO_2 emissions per capita fluctuated substantially in recent years, they tended to increase through the 1970–2019 period ending at 0.37 tons of CO_2 per capita in 2019, ranking 151st among 181 countries with per capita greenhouse gas emissions as shown in Fig. 8 (Emission Database for Global Atmospheric Research 2021).

The wide pollution recently in Yemen from the random use of the energy sectors as well as the pollution from the conflict leads to a lot of the extensive economic, social, and environmental consequences which include the costs of environmental degradation of the GDP and death toll caused by air pollution. It is also predicted that in 2025, the cost of CO_2 emission and environmental degradation will increase if the country lasts using random energy as well as the continuous conflict. In its efforts to alleviate GHG emissions, Yemen is implementing several mitigation interventions such as the promotion of LPG in replacement of biomass energy in rural areas, shifting towards natural gas in transportation and energy production, promotion of solar energy for household use, among others (Emission Database for Global Atmospheric Research 2021).

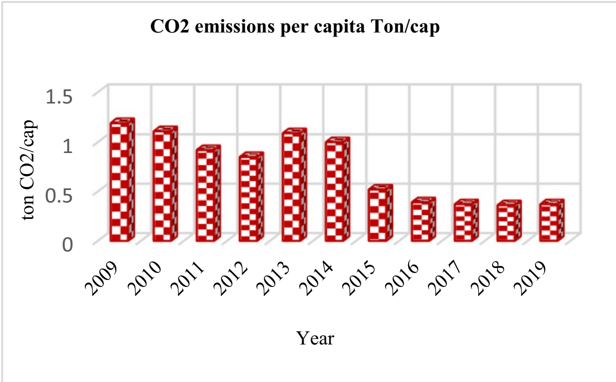


Fig. 8 The greenhouse gas emissions per capita in Yemen

Environmental performance index (EPI)

The EPI 2016 ranks countries on more than 20 performance indicators covering both environmental public health and ecosystem vitality. The main environmental indicators include health impact, climate and energy, water resources, air pollution, and biodiversity. According to Yale University (Yale Center for Environmental Law and Policy and Environmental 2020), based on the EPI, Yemen was ranked 150th among 180 countries in 2016. According to data, Yemen is dealing with a growing environmental crisis; one of them is a water scarcity, since natural freshwater resources are limited and drinking water supplies are insufficient. Yemen has long been experiencing water-shortage because of atmospheric conditions, years of poor water management, and population growth. Sana'a, the country's capital, has been experiencing a water crisis since 2017, and 84% of the population in the southern province is attempting to find or purchase enough clean water to drink, cook, and produce food on a daily basis (ACTED 2016). On an average, each Yemeni can only access about 140 m^3 of water a year for all purposes. Apart from coastal waters, Yemen has no permanent open waters.

Energy architecture performance index (EAPI)

The EAPI is a global process for creating a set of indicators that help to highlight the efficiency of energy systems of various countries. According to the World Economic Forum 2017 (Crisis in the Arabian Peninsula), EAPI measures the specific contribution of the energy system in three components of the energy output: security supply, environmental sustainability, and economic growth and development. It consists of 18 indicators collected into three baskets related to these three imperatives; in the EAPI ranking in 2017, Yemen was ranked 126th among 127 countries followed only by one country which is Bahrain.

Yemen is dealing with the dilemma of energy networks that are unstable and indefensible. Due to the fighting, certain energy systems have been completely damaged, while others have been partially devastated, resulting in a drop in generation capacity and even fuel delivery challenges from power generation plants. As a result, new energy structure design is required for a secure, cheap, and sustainable environment (Al-Shetwi 2021).

The development prospect of potential renewable energy in Yemen, Middle East, and Africa region

Many small renewable energy projects have been carried out by some companies or individuals to generate and sell electricity instead of the electrical governmental sectors, some of which have already ceased to operate. According to the Yemen Public Electrical Corporation (YPEC), there have been too many visions for introducing renewable energy to help Yemen's electricity sector, but nothing has been done so far. This paper promises to present solutions based on a study of Yemen's renewable energy potentials, as well as a knowledge of the most common renewable energy exploitation sites based on location, as well as a proposed strategy for using and optimizing renewable energy and energy efficiency (REN and EE), which is pending the availability of funds to begin implementation; Yemen has a high potential of renewable energy sources, which are solar, wind, geothermal, and biomass resources that have a brief description as follows (IEA 2016; ESMAP. 2020).

Renewable energy generation in the Middle East and Africa region was set to reach a percentage of total generation capacity in the coming years. Djibouti, on the other hand, has set a target of obtaining100% of its energy from renewable sources by 2035. The Middle East and Africa region's renewable energy business has been growing as a result of measures taken by countries in the region to accelerate the implementation of renewable energy solutions. Figure 9 depicts renewable energy capacity targets for the Middle East and Africa region from 2020 to 2050. Furthermore, Fig. 10 depicts Yemen's primary renewable energy supply in 2018 when compared to some other Middle Eastern countries that use renewable energy.

Overview of Yemen's renewable energy potential

There are four main renewable energy sources available in Yemen. A recent "renewable energy strategy" study conducted by the Ministry of Electric Power and the PEC for Yemen shows that Yemen has a great potential for renewable energy. The average solar radiation is between 18 and 26 MJ/m^2 per day over 3000 h of clear blue sky each year, and

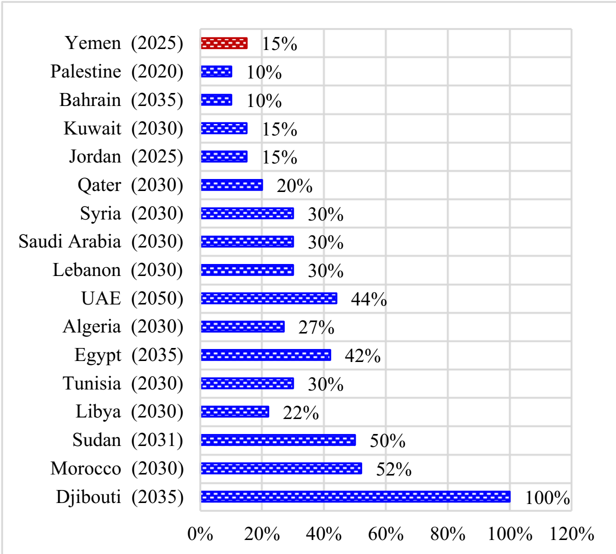


Fig. 9 Renewable energy capacity targets for the Middle East and Africa region from 2020 to 2050

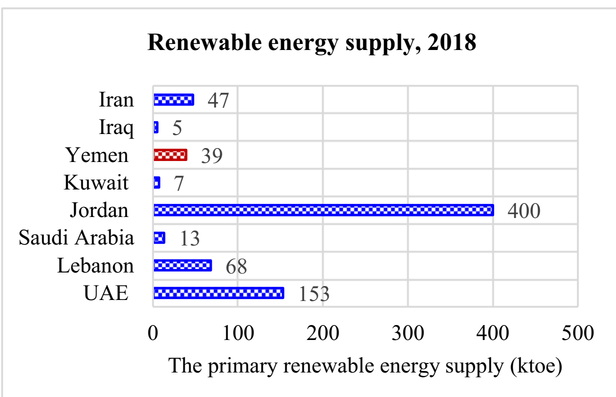


Fig. 10 The primary renewable energy supply in the Middle East 2018. (Source: IEA World Energy Balances)

the theoretical solar electricity potential using concentrated solar power (CSP) is at 2,446,000 MW. Wind energy has a capacity of 308,722 MW, whereas geothermal energy has a potential of around 304,000 MW. The following is a summary of Yemen's renewable energy potential (LAHMEYER and International GmbH 2008; NECRA. Lmt. 2010; Alkholidi 2013).

Theoretical potential

The theoretical potential describes the amount of physical, climatic, or biological energy accessible in each location at a certain time or period. It refers to energy derived from renewable sources that can be converted from their natural state into a form that is beneficial to humans. It is dependent on the earth's inherent energy flow. These energy flows are connected to naturally occurring physical phenomena that have always been in our physical world and come in a variety of forms, including wind, solar energy, geothermal energy, and ocean energy. Table 3 depicts the Republic of Yemen's renewable energy flows (Al-Shabi Mohammed 2014; Sufian 2019).

Technical potentials

This is a potential (geographic potential) to extract energy from nature using specific technologies, depending on the type of energy extracted, such as solar energy, but not limited to photovoltaic systems—solar hot water, passive solar heating, and solar lighting, etc., and wind power, considering the amount of power lost during the transformation from natural to useful form. The technical potential is divided into gross technical potential and practical technical potential as shown in Table 3. The gross technical potential refers to the potential that can be realized by using known technologies, taking into account various technological factors (such as resource recovery, the efficiency of technologies used in resource development, and land use). The accessibility of the grid is considered in the practicable potential. The actual technological potential takes into account the accessibility of the electricity grid (Sufian 2010).

Table 3 Yemen's renewable energy resource

Renewable energy resources	The theoretical potential (MW)	The technical potential	
		Gross technical potentials (MW)	Practical technical potentials (MW)
Wind energy	308,722	123,429	34,286
Solar electricity (CSP)	2,446,000	1,426,000	18,600
Geothermal	304,000	29,000	2900
Biomass-landfills	10	8	6

Ministry of Electricity and Energy "Renewable Energy Strategy and Action Plan Study Report," 2008

Yemen's future renewable energy mix up to 2025

Even before the conflict in 2015, most of Yemen's population was deprived of basic electricity services. Yemen has the lowest electricity access rate in the Middle East and North Africa. The power obtained from the grid or off-grid sources is estimated to be 40 to 60% (MOEE). In 2014, Yemen's per capita electricity consumption was 217 kWh, less than one-sixth of the regional average. The power supply is estimated to be 1520 MW in 2015. The demand is seriously unbalanced and the supply capacity is 20% lower than the peak demand. Most grid-connected users suffer from frequent load-shedding every day. Despite substantial direct and indirect subsidies, the sector is unable to produce the affordable, reliable, and adequate electricity needed to sustain economic growth and to sustainably increase the coverage of electricity services in rural areas (Sufian and Barra 2016).

As previously stated, solar energy has the highest total technical potential of the four renewable energy sources in Yemen, but it is only second to wind energy in terms of total practical potential. For over 3000 h of clear blue sky per year, average solar radiation is around 18–26 MJ/m^2/day, and the theoretical potential of concentrated solar power (CSP) generation is about 2.5 million MW. Wind energy has a potential of 308,000 MW, while geothermal energy has a potential of around 304,000 MW. However, Yemen's current energy mix is dominated by fossil fuels (about 99.91%), with renewable energy accounting for only about 0.009%. The national renewable energy and energy efficiency strategy, on the other hand, sets goals, including a 15% increase in renewable energy contribution to the power sector by 2025 (Fig. 11).

Solar energy resources

Yemen belongs to the global sun-belt with average sunshine 9–11 h/day throughout the year, that is, equal to more than 4000 h yearly, and the peak sun hour (PSH) reaches 5–6 h, that is, equal to 2000–2200 h yearly, which makes the less cost of power than any other country with less PSH, with also average solar radiation being between 450 and 550 cal/cm^2/day. That equals 5.2–6.8 kW/m^2/day or 18.9–23.1 MJ/m^2/day. According to a study of the solar energy potential in several cities in the Republic of Yemen (Sana'a, Hodeidah, Bayhan, and Lahaj) (Alganahi et al. 2009; Alkholidi 2013) and the maximum and minimum temperatures measured in Yemen shown in Figs. 12 and 13, the findings suggested that Yemen's favorable geographic location could encourage Yemenis to use solar energy applications. On the other hand, the compatibility of potentials and demands, such as solar energy, is the most encouraging factor for implementing

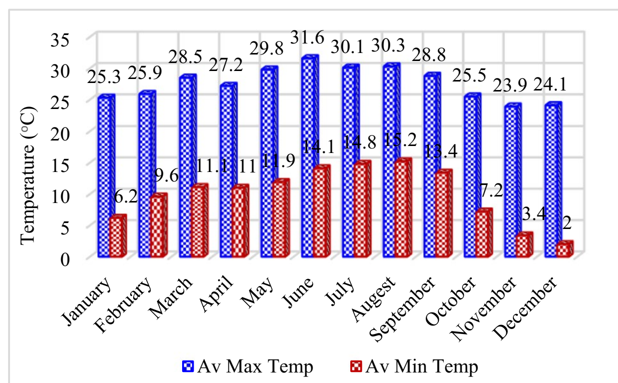


Fig. 12 The average temperature of mountainous areas

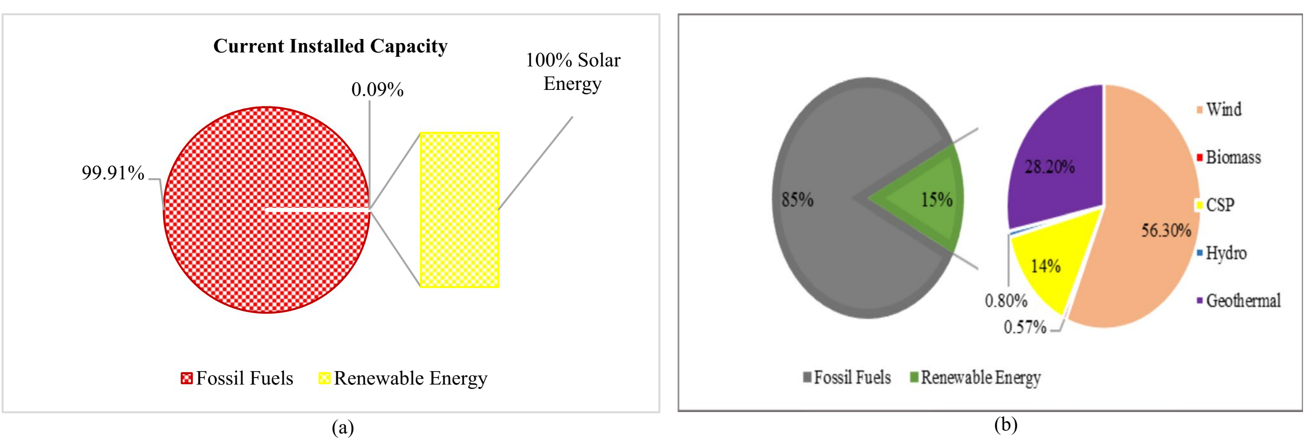


Fig. 11 Share of renewable energy in energy mix in Yemen. **a** Current installed capacity in Yemen 2021. **b** Renewable energy strategy target for Yemen 2025

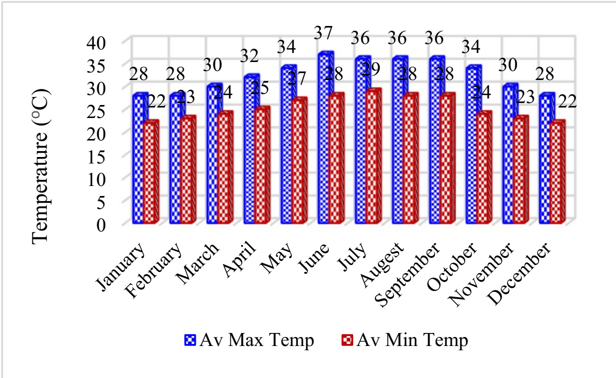


Fig. 13 The average temperature of coastal areas

projects in the field of renewable energy in Yemen to supplement the electricity sector (Tummuru et al. 2015).

It is possible for Yemen to use one of two types of solar power supply: centralized (on-grid) for larger farms or decentralized (off-grid) for small-scale power generation. The latter application can be used for rural electrification, which affects three-quarters of Yemen's population but receives only a quarter of the country's total power. Connecting rural areas to the main grid is difficult due to high transmission costs and increased power loss due to transmission. All of these obstacles motivate us to show that decentralized power demand has a lot of potential for rural electrification (A-TK. 2014). The map in Fig. 14 shows the distribution of solar energy resources in the Republic of Yemen (Annual sunshine hours map of the world 2016; Al-Shetwi 2016), whereas the installed capacity and the electricity generation by the solar system from 2010 to 2019 are shown in Fig. 15 (Saleh Qasem 2018).

Wind energy resources

Under the Yemeni Ministry of Electricity's Renewable Energy Strategy and Action Plan, renewable energy sources were studied, including wind. In that respect, a wind resource map was developed based on data from the Civil Aviation and Meteorological Service, the Global Upper-Air Climatic Atlas, and an ongoing wind measurement campaign. Yemen has a long coastal zone with a length of more than 2500 km and an average width of 45 km along the Red Sea and the Arabian Sea. The average annual wind speed in these coastal areas is more than 8 m/s. There is a great potential to build wind farms in coastal and offshore areas. These studies show that the most promising areas of this kind of energy are mountains and valleys (Sana'a, Damar, and Sayan) and the coastal areas (Aden, Hodeida, and Mokha). Al Mokha

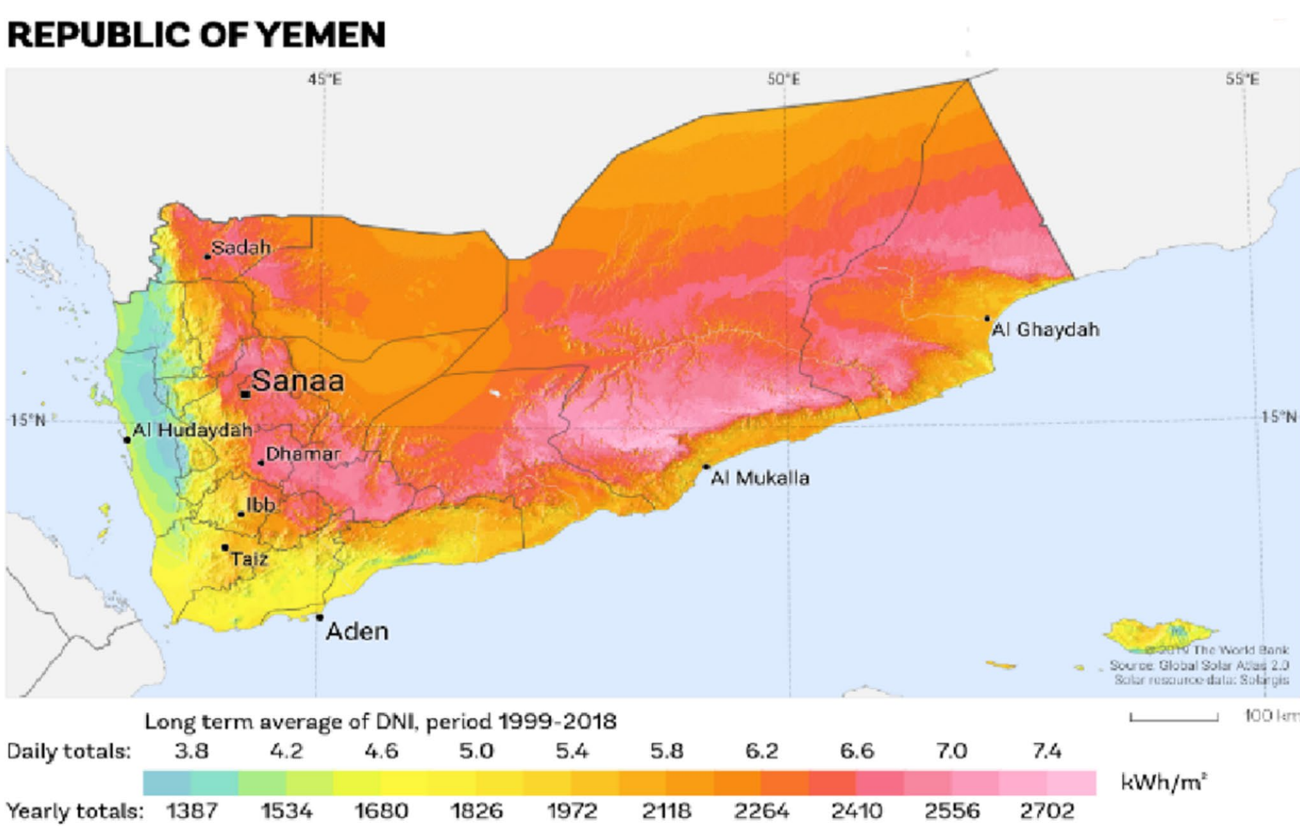


Fig. 14 The distribution of solar energy resources in Yemen

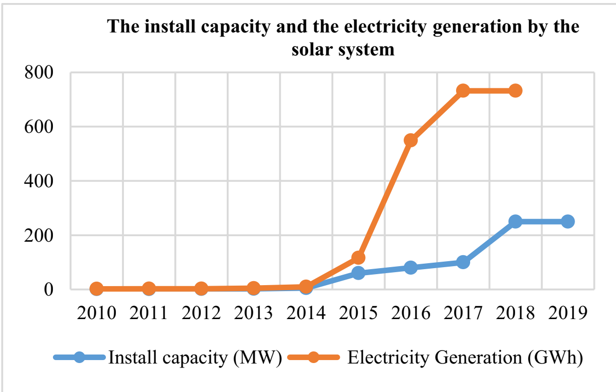


Fig. 15 The installed capacity and the electricity generation by the solar system from 2010 to 2019 in Yemen

area in Taiz has good wind conditions in Yemen. According to Egyptian experts, it is estimated that 1.8 GW of electricity can be generated within 300 km^2 of Al Mokha alone, 14,200 MW providing about 42,300 GWh of electricity per year (Al-ashwal 2005; Sufian et al. 2017).

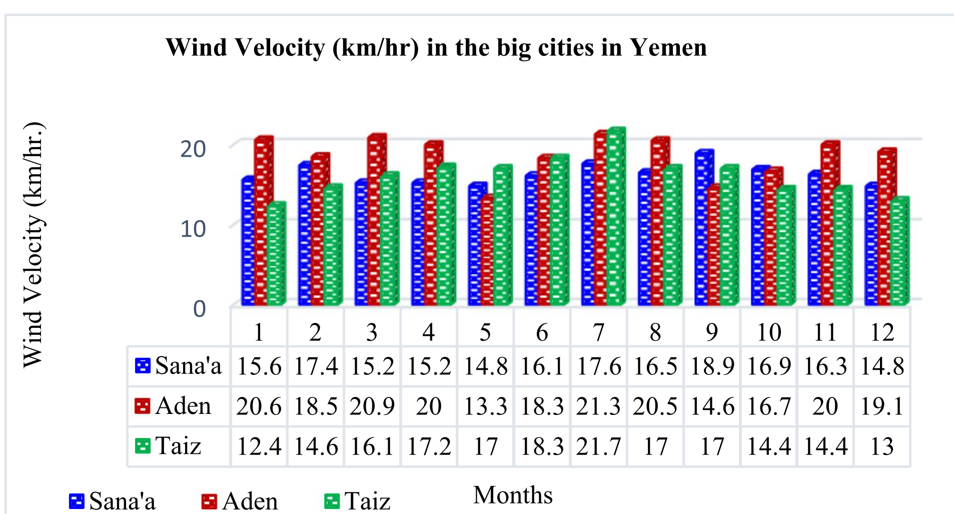
Besides, based on the wind resource map, the technical potential for wind power at technically attractive sites in Yemen (i.e., where more than 3000 full load hours (FLH) could be generated or with a more than 35% capacity factor) could generate 14,214 MW. And economically attractive sights in Yemen (i.e., where more than 3500 FLH could be generated or with a more than 40% CF) could generate about 2507 MW, which is about 8293 GWh of electricity per year. The total wind power potential is estimated to be 34GW. The technical potential was estimated at 14,200 MW providing about 42,300 GWh of electricity per year (ESMAP. 2020).

Figure 16 shows the annual wind speed km/h in three big cities of Yemen during all year's months. It can be observed that the maximum wind speed in Sana'a, the capital of Yemen, exceeded 18.9 km/h in September, and the minimum wind speed in the same city reached 14.8 km/h in May and December. In Aden, the maximum wind speed recorded is 21.3 km/h in July and 21 km/h in March. In May, the lowest wind speed in the city reached 13.3 km/h. The city of Taiz is one of the windiest areas in Yemen, namely the coastal area of Mocha and the Arrows Mountains surrounding the city of Taiz. The maximum wind speed in July can reach 21.7 km/h, and the minimum wind speed is in December (The International Renewable Energy Agency (IRENA)).

Geothermal energy resources

An investigation assessed that 2900 MW of force may be accessible from geothermal sources. A fundamental overview in 1984 by the World Bank distinguished that there is some geothermal potential toward the south of Sana'a; the most encouraging of which is situated at Dhamar district (100 km south of Sana'a). This asset is believed to be adequate to help a 50-MW plant and a definitive asset could be between 250 and 500 MW. An understanding was endorsed with an Icelandic organization to build up a 10-MW plant on the site; however, the organization failed during the monetary emergency. Exploratory boring is currently being financed by the United Nations Environment Programme (UNEP). Likewise, Yemen is indicated as one of the nation's having high heat flow. The heat flow mirrors the capability of geothermal energy. The world guide of heat flow shows that Yemen and Italy have the equivalent capability of heat flow (60 mW/cm^2). The complete limit of geothermal force introduced in Italy is more than 500 MW, which shows the high capability of geothermal energy in Yemen. Furthermore, an additional examination might be done in two ways to facilitate the execution of the GeothermEx study and appraisal of geothermal energy in different territories in the country (Al-ashwal 2005).

Fig. 16 The annual wind velocity (km/h) in the three big cities in Yemen



Biomass energy resources

Yemen has been known for centuries as an agrarian state, with agriculture serving as the backbone of the country's economy. The over-centralization of action in this area will bring about the great misuse of the asset. Also, the waste related to modern creation can influence the climate if not maneuvered carefully. The over-simplification of these waste kinds could be placed into utilization conceivably to produce biomass energy to be utilized for some reasons like gasification for the power age or cooking purposes. This innovation can be utilized to make biogas plants in significant urban areas like Sana'a, Aden, and Taiz, to create power from biomass rather than diesel or substantial fuel (mazot) utilized essentially in the diesel power plants in Yemen. For instance, on the off chance that we take the trash to squander that is gotten by the waste vehicles consistently in Sana'a city that possesses more than 2,000,000 occupants, this will be approximated by 1000 tons of refuse. This garbage bin is conveying to disasters to deliver biogas, which is made from 60% methane (CH4) and 40% carbon dioxide (CO_2). We estimate getting 50 m^3 of biogas for each massive load of waste. Thus, 1000 tons of garbage will be fit for delivering almost 5000 m^3 of biogas each day around the Sana'a area; this is equivalent to 30,000 KWh. This creation limit is assessed to have furnished almost 5000 family units with 6 KWh normal power need (U.S. 2017).

Challenges of energy and renewable energy development in Yemen

Electricity is the main driving force of the national economy because it provides the necessary conditions for the full operation of economic, industrial, commercial, agricultural, and service activities. On the other hand, per capita, electricity consumption is considered the main indicator to evaluate the living standard of the people in the country. The per capita electricity consumption of Yemen's population is very low, so the living standard of Yemen is also considered to be very low, far lower than that of any neighboring Arab countries, as well as the per capita electricity consumption can be compared with other Arab countries such as Jordan, Egypt, and Tunisia.

Yemen has a variety of potential to improve its power generation, transmission, and distribution capacity, exemplified by the availability of various fuels (fossil and renewable) to enable the construction of different power plants and the opportunity to invest in the power generation and distribution sectors.

However, first and foremost, the current problems and challenges confronting Yemen's power sector are as follows:

- Financial and administrative corruption,
- Aging of generator sets in different power plants,
- The transmission and distribution network is aging,
- The security situation endangered by attacks on the transmission network and its components,
- Because many users did not pay the electricity bills, the distribution network was attacked, and without the knowledge of the relevant authorities, the distribution network was connected to steal electricity, thus endangering the security situation,
- Lack of the ability to collect electricity charges from all users, especially from government departments,
- Financial constraints have hindered the implementation of many reform plans in the power generation, transmission, and distribution sectors,
- Supporting or subsidizing the idea behind the unit price, which leads to different types of consumers' lack of understanding of electricity consumption.

Secondly, the problems and challenges of renewable energy development in Yemen are shown in Fig. 17.

Therefore, it is necessary to upgrade Yemen's power industry and work hard to solve the problem of power shortage according to a well-thought-out plan, to ensure that the Yemeni people have sufficient and sustainable power. According to the negative impact of the above obstacles and challenges, Yemen must also take measures and policies to promote and develop renewable energy projects, including making up for part of the power shortage and keeping up with the world's plans to move to environmentally friendly energy, and also ensure investment opportunities for domestic and foreign investors in Yemen.

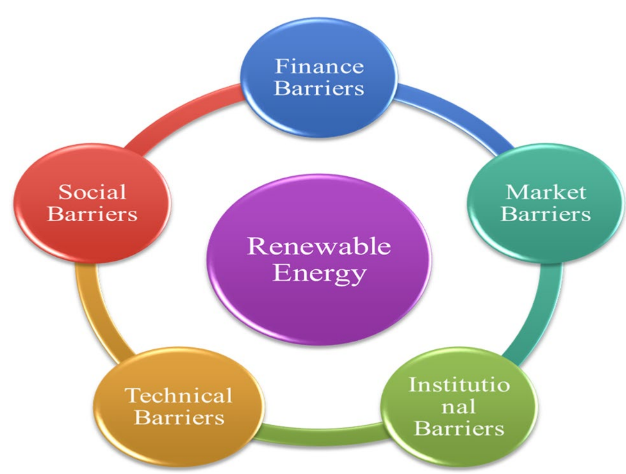


Fig. 17 Challenges and barriers of Yemen's renewable energy

Proposed strategy and solutions to electrify the population of Yemen using RES by 2050

In this section, we will examine the various strategies for meeting Yemen's power needs. This demand is calculated on the basis of per capita consumption, which includes household, industrial, agricultural, and commercial requirements. The required power, as well as its growth, will be forecasted and mapped out until 2050.

Population map of the Republic of Yemen by 2050

According to the population census for the year 2014 (Ministry of Planning & International Cooperation and (CSO) 2004), annual statistical books of the Ministry of Planning and Statistics (Ministry of Planning & International Cooperation and (CSO) 2011), and Towfick and Abdulraqib (2012), the population forecast of the Republic of Yemen in 2050 is shown in Table 4. The migration of people from rural to urban areas is a problem that must be addressed. This is illustrated more clearly in Fig. 18 which shows the expected population growth in Yemen by 2050. Yemeni households consist of an average of 7 individuals; the population map for Yemen's households and the projected growth until 2050 is calculated and presented in Table 5 and Fig. 19.

The expected electricity demand of Yemen's population by 2050

Yemen's people are among the poorest in the world without access to electricity. This poverty is the result of policies and decisions to electronically map Yemen, and implement and manage Yemen projects. According to the 2011 Annual Report (PEC) issued by the Ministry of Electricity and Energy, the best year for electricity production from 2007 to 2011 is 2010. Table 6 shows the production of electricity and energy according to the results of the 2011 Annual Report.

From the above data, the per capita electricity (PEC + private purchase) is about 335 kWh/person/year, that is, 918 Wh/person/day, which is very low, so the Yemeni population is once again classified as a low-income electricity user. If the above electric energy (918Wh) is consumed within 10 h/day, it means that the electric

Table 4 Expected population growth of Republic of Yemen up to the year 2050 (millions)

Year	Rural population (millions)	Urban population (millions)	Total population (millions)
2015	19.84	8.99	28.83
2020	22.86	11.37	34.23
2025	26.32	14.3	40.62
2030	31.02	17.22	48.24
2035	35.93	21.38	57.31
2040	41.62	26.5	68.12
2045	48.21	32.68	80.89
2050	55.84	40.27	96.11

Table 5 Expected growth of the Yemeni household population by 2050

Year	Rural household population (M)	Urban household population (M)	Total household population (M)
2015	2.84	1.28	4.12
2020	3.27	1.62	4.89
2025	3.76	2.04	5.8
2030	4.43	2.46	6.89
2035	5.14	3.05	8.19
2040	5.95	3.78	9.72
2045	6.9	4.66	11.56
2050	7.98	5.75	13.73

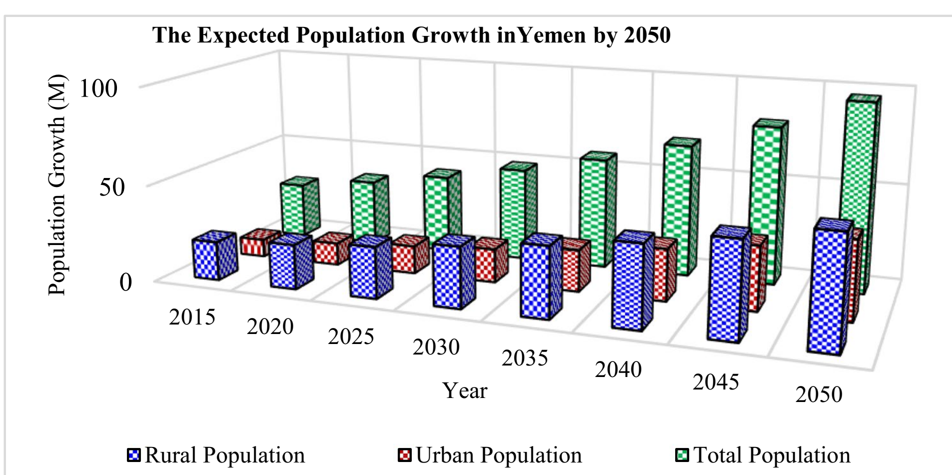


Fig. 18 Expected population growth in Yemen up by 2050

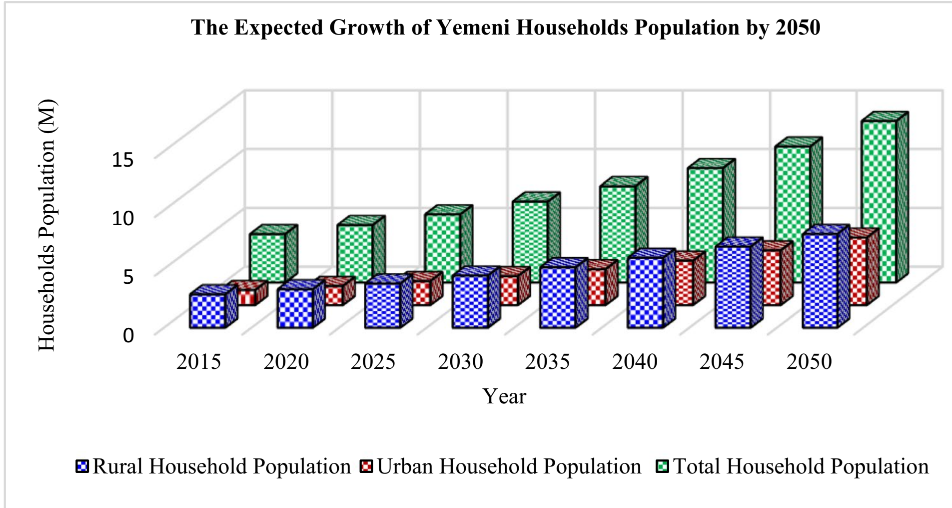


Fig. 19 Expected growth of Yemeni household population by 2050

Table 6 The 2011 Annual Report of the production of electricity and energy in Yemen

The production of electricity and energy in 2011	Value
Electrical energy generated by PEC	6400.6 GWh
Electrical energy purchased from the private sector	1357.0 GWh
Total electrical energy generated	7757.6 GWh
Electrical energy transmitted to the distribution network	7091.7 GWh
Combined power generated by PEC	1526 MW
Combined power of purchased energy	280 MW
Total electrical energy sold	5036 GWh
Total population (Central Statistical Organization CSO)	23.154 M

energy obtained by a person is about 92 W, highlighting the low level of electric energy per capita. If the power generated by PEC is considered as well, the per capita power is only 276.44 kWh/person/year, corresponding to 757.4 Wh/person/day. That means the power is 76 W per capita, which is also very low. If the total electric energy sold is considered at the same time, the electric energy per capita is 217.50 kWh/person/year (the World Bank data in 2014 is 216 kWh/person/year), which is corresponding to 595.89 Wh/person/day and 60 W per capita power (Sufian 2019).

Proposed strategies based on electrical energy demand

Based on the electricity map for the Yemeni population as projected to 2050 and based on the least requirement, the strategy of the three cases (minimum, medium, and relatively high demands) leads to the following projections in Table 7. The strategy of case two is almost about 50% of the share of Tunisian/capita in the year 2014 and is almost about 2.0 kWh/day/capita with a power of 200 W/capita.

Predicted electrical energy consumption for cases 1, 2, and 3 by 2050

According to the above three strategic assumptions, it is expected that the electricity map by 2050 will be based on the following assumptions: the economic growth will be quite small, and the growth of per capita GDP will also be very small. Based on these assumptions, the following Tables 8, 9, and 10 show the projected total power and electricity requirements of the Yemeni population

Table 7 The strategy cases with the minimum, medium, and relatively high demand predictions

Cases	Average expected electrical energy (kWh/year/per capita)	Average expected electrical energy (kWh/day/per capita)	Average expected electrical energy (Wh/10 h/per capita)
Expected, electrical, energy			
Strategy of case one (minimum demand)	402kWh/year	1.10kWh/day/capita	110 W/capita
Strategy of case two (medium demand)	730kWh/year	2.0kWh/day/capita	200 W/capita
Strategy of case three (high requirement)	1460kWh/year	4.0KWh/day/capita	400 W/capita

https://www.energycharter.org/fileadmin/DocumentsMedia/Occasional/2019-Yemen_paper_final.pdf

Table 8 Predicted electrical energy consumption for case one

Year	Total population (millions)	Total energy consumption/day (GWh)	Total energy consumption/year (TWh)	Total power required (GW)
2015	28.83	31.75	11.59	3.171
2020	34.23	37.69	13.76	3.766
2025	40.62	44.73	16.33	4.469
2030	48.24	53.12	19.9	5.307
2035	57.31	63.10	23.04	6.305
2040	68.12	75.00	27.38	7.494
2045	80.89	89.1	32.53	8.898
2050	96.11	105.82	38.63	10.573

Table 9 Expected electrical energy consumption for case two

Year	Total population (millions)	Total energy consumption/day (GWh)	Total energy consumption/year (TWh)	Total power required (GW)
2015	28.83	57.66	21.05	5.766
2020	34.23	68.46	24.99	6.846
2025	40.62	81.24	29.66	8.124
2030	48.24	99.48	35.22	9.648
2035	57.31	114.62	41.84	11.462
2040	68.12	136.24	49.73	13.624
2045	80.89	161.78	59.05	16.178
2050	96.11	192.23	70.16	19.223

Table 10 Expected electrical energy consumption for case three

Year	Total population (millions)	Total energy consumption/day (GWh)	Total energy consumption/year (TWh)	Total power required (GW)
2015	28.83	115.32	42.10	11.532
2020	34.23	136.92	49.98	13.692
2025	40.62	162.48	59.31	16.248
2030	48.24	99.48	70.43	19.296
2035	57.31	229.24	83.68	22.924
2040	68.12	272.48	99.46	27.248
2045	80.89	323.56	118.1	32.356
2050	96.11	384.45	140.32	38.445

by 2050. Figures 20, 21, and 22 graphically illustrate the expected increase in power consumption. Table 11 and Fig. 23 show the total power required for the three strategic cases by 2050.

The minimum strategy shows that Yemen needs about 3.766GW of power generation by 2020 and about 10.573GW by 2050 to maintain the minimum demand per capita. As of 2014, Yemen's total installed power capacity is about 1.50 MW. If it can recover after the conflict, Yemen will need to immediately install another 2.266 MW to meet the first strategic case, 5.346 MW to meet the second strategic case, or about 12.20 MW to meet the third strategic case.

Electrical power generation in Yemen from renewable energy resources wind and solar by 2050

Electrical power is generated either from fossil fuels, which are classified as unsustainable fuels, or from non-fossil fuels, which are classified as sustainable or renewable fuels. Using non-renewable fuels to generate electricity has a number of drawbacks, including the following:

a. Using these fuels to generate electricity requires a lot of money for exploration activities or purchase, refining, refining, transportation, and storage;

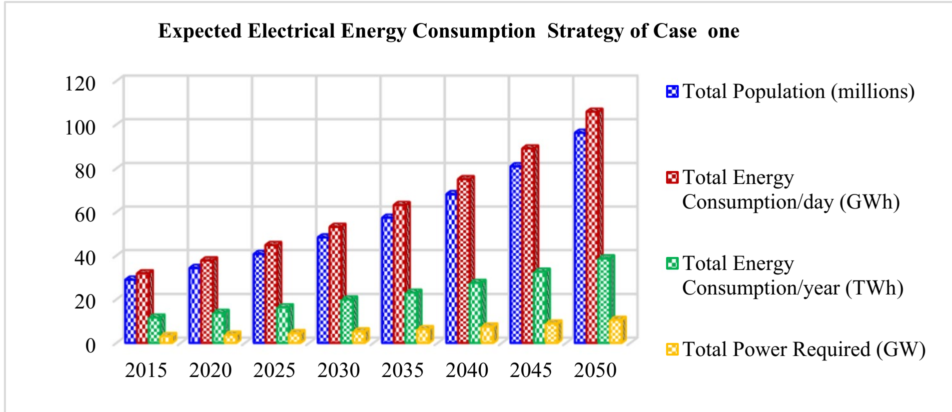


Fig. 20 Expected electrical energy consumption for case one

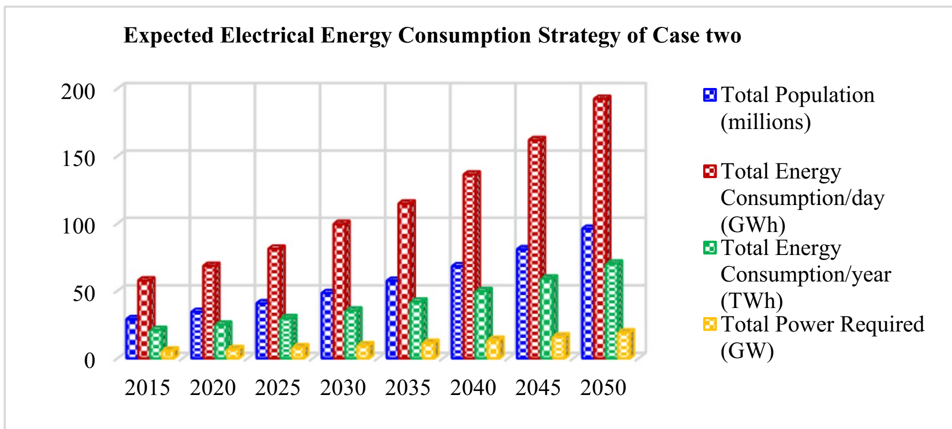


Fig. 21 Expected electrical energy consumption for case two

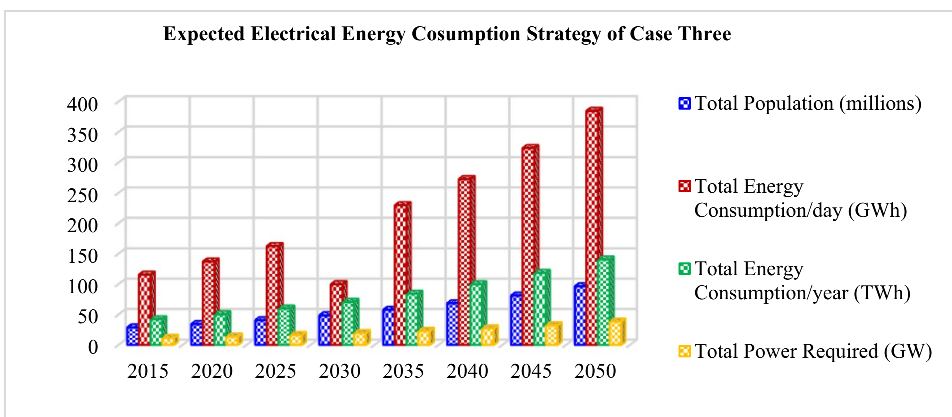


Fig. 22 Expected electrical energy consumption for case three

b. Converting these fuels into electricity will produce greenhouse gases and other environmental pollutants;
c. These fuel resources have a specific service life and then are exhausted. The extracted fuel cannot be replenished in a year, a decade, or even a hundred years.

Unsustainable fossil fuel power generation should be resumed only when there are no sustainable or insufficient fuel resources at all. However, Yemen is fortunate to have a large number of sustainable fuel resources, such as wind and solar energy. These resources are sufficient to generate enough electricity to meet the Yemeni people's needs for centuries. As shown in Table 12, the available potential energy of wind and solar power generation is about 52886 MW (52.886GW). Using sustainable energy to generate electricity produces much fewer greenhouse gases

Table 11 Expected electrical power requirement for strategy cases 1, 2, and 3

Year	Total power required strategy case one (GW)	Total power required strategy case two (GW)	Total power required strategy case three (GW)
2015	3.175	5.766	11.532
2020	3.766	6.846	13.692
2025	4.469	8.124	16.248
2030	5.307	9.648	19.296
2035	6.305	11.462	22.924
2040	7.494	13.624	27.248
2045	8.898	16.178	32.356
2050	10.573	19.223	38.445

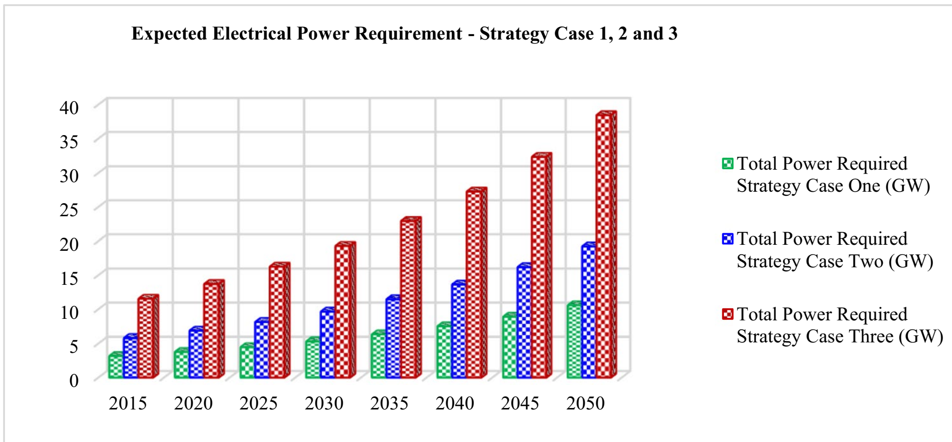


Fig. 23 Expected electrical power requirement for cases 1, 2, and 3

and environmental pollution than fossil fuels. Unproductive greenhouse gases (GHGs) can provide economic benefits for Yemen through carbon trading. Yemen will generate annual revenue from carbon trading and the sale of unused fossil fuels (such as oil and its by-products) and natural gas by relying on renewable energy to generate electricity.

The total generating capacity of wind and solar energy is 18600 + 34,286 = 52886 MW (52.886GW). If this amount is extrapolated to the above three strategic cases, Table 12 and Fig. 24 can be created, showing the percentage (%) of total wind and solar power expected to be required by Yemen according to strategic cases 1, 2, and 3.

Table 12 shows that according to strategy case three the electrical power required in 2030 is 19.296GW (Table 11) and the amount of wind and solar energy available is 52.886GW, which means only about 36% will be used to provide electricity for the whole Yemeni population. Therefore, the remaining power of wind and solar energy is about 33.59GW and according to case two, the total power required which is 9.648GW needed by the Yemeni population in 2030 only accounted for about 18% of the total available power of 52.886GW of wind and solar power, and the remaining power is 43.238GW. As well as the strategy of case one, the total power required by Yemen's population in 2030 is (5.307GW) and will only account for about 10% of the total available power of 52.886GW of wind and solar power, with the remaining power of 47.579GW. In each of the three strategy scenarios in 2050, Table 12 shows the amount of power required for the Yemeni population that can be connected to the national grid as a percentage (%) of the power estimated to be obtainable from wind and solar energies.

Table 12 The percentage (%) of total generating capacity from the wind and solar resources expected to 2050

Year	Strategy case one	Strategy case two	Strategy case three
2015	6%	10.90%	21.81%
2020	7.12%	12.94%	25.89%
2025	8.45%	15.36%	30.72%
2030	10.03%	18.24%	36.49%
2035	11.92%	21.67%	43.35%
2040	14.17%	25.76%	51.52%
2045	16.82%	30.59%	61.18%
2050	20%	36.35%	72.69%

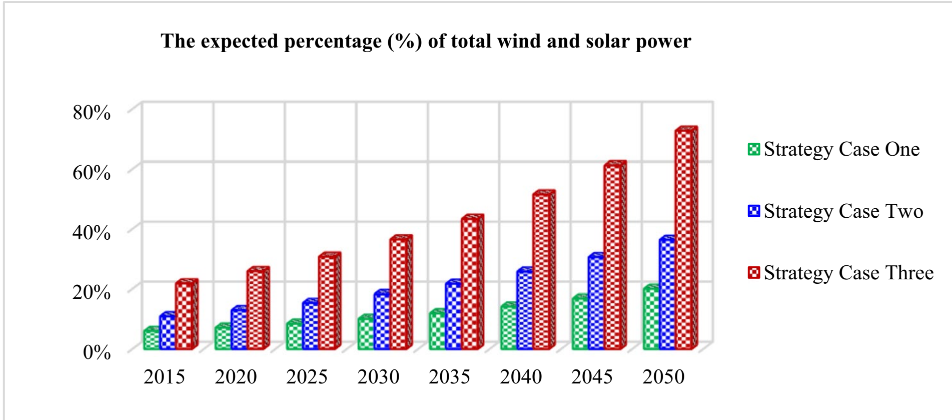


Fig. 24 The percentage (%) of total generating capacity from the wind and solar resources expected to 2050

The advantages of using renewable electricity include reduced emissions, reduced energy loss, reduced power lines and equipment, and lower capital costs due to the use of lower capacity equipment (such as a transformer capacity reduction of 50 kW per MW installed). Renewable energy sources such as wind, solar, and geothermal are abundant in Yemen. This means that the country can develop large power generation projects as well as decentralized systems to meet the energy needs of rural and remote communities. Renewable energy is a rapidly evolving technology today.

In fact, we will focus on solar and wind energy as a solution for Yemen's power sector in this work for several reasons:

- It is a source of energy that is both renewable and limitless.
- Only 23% of Yemenis living in rural areas where the national grid system is unavailable in most villages have access to electricity; about 10–14% are connected to the national grid system, and the rest are estimated to have access from other sources, such as a diesel generator or a few solar panels.
- Yemen has one of the highest levels of solar radiation in the world, increased solar irradiation availability throughout the year.
- Yemen has a long coastline and high altitudes of 3677 m above sea level, making it an ideal location for wind energy generation, with an estimated 4.1 h of full-load wind per day. The wind energy can be converted into mechanical and electrical energy, and it could be a viable option for bolstering the electricity power sector. It is important to note that this energy is a volatile source of energy.

Configuration and design of proposed hybrid renewable energy systems

As mentioned in Table 7, 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. Strategy (1) is to supply 1.10 kWh/day/capita. Strategy (2) is to supply 2 kWh/day/ capita, which is 50% of the average electrical energy/capita of other Arab countries. 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. Yemen has low electricity access, which about 85% urban and 23% rural population can access. The government classified those people who live in the rural area into four types based on the ability to access the national electricity grid. The first type has easy access to the grid, the second can access the grid with a slightly higher cost, the third can access the grid with a high cost, and the fourth has a high cost and is difficult to access the grid. The study is being developed to design various configurations of microgrid energy systems including PV and wind turbine (WT) for electrifying a diverse range of consumers in Yemen as shown in Fig. 25. The simulation results and discussions of the two different configurations of the hybrid renewable energy systems are introduced below.

PV/BES on grid system

Figure 26 depicts the first configuration of the considered grid-connected hybrid PV/BES systems. The system consists of a PV array (PV gen.) interfaced to the DC bus through a boost DC/DC converter with a maximum power point tracking (MPPT) controller. The MPPT maximum was implemented via the boost converter by means of a Simulink model using the "Incremental Conductance + Integral Regulator" technique (Al-Wesabi et al. 2022a) (Ibrahim et al. 2020) (Farh et al. 2018). The voltage source converter (VSC) facilitates the MPPT operation through regulation of the DC bus voltage as well as transfer of power from the DC bus to the utility grid. In addition, the VSC provides synchronization of the PV system with the grid during startup or reconnection after system islanding (Alturki et al. 2021) (Farh et al. 2020) (Al-Shamma'a et al. 2020).

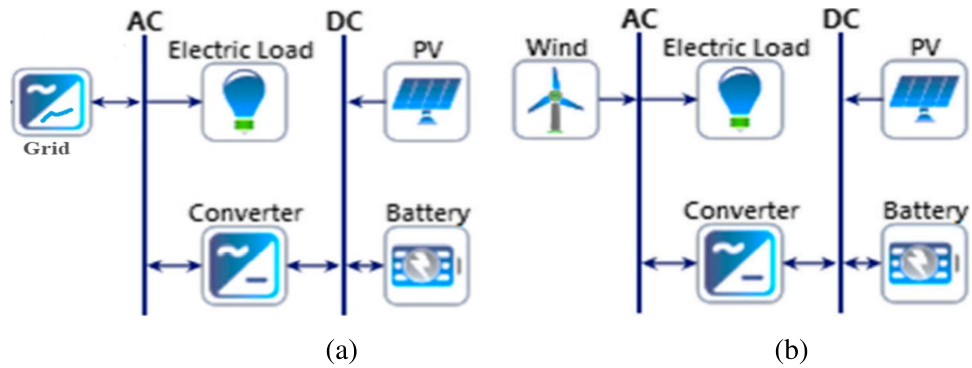


Fig. 25 Schematic diagram of different off and on grid renewable energy systems. **a** PV/BES on grid system. **b** PV/WT and BES off grid system

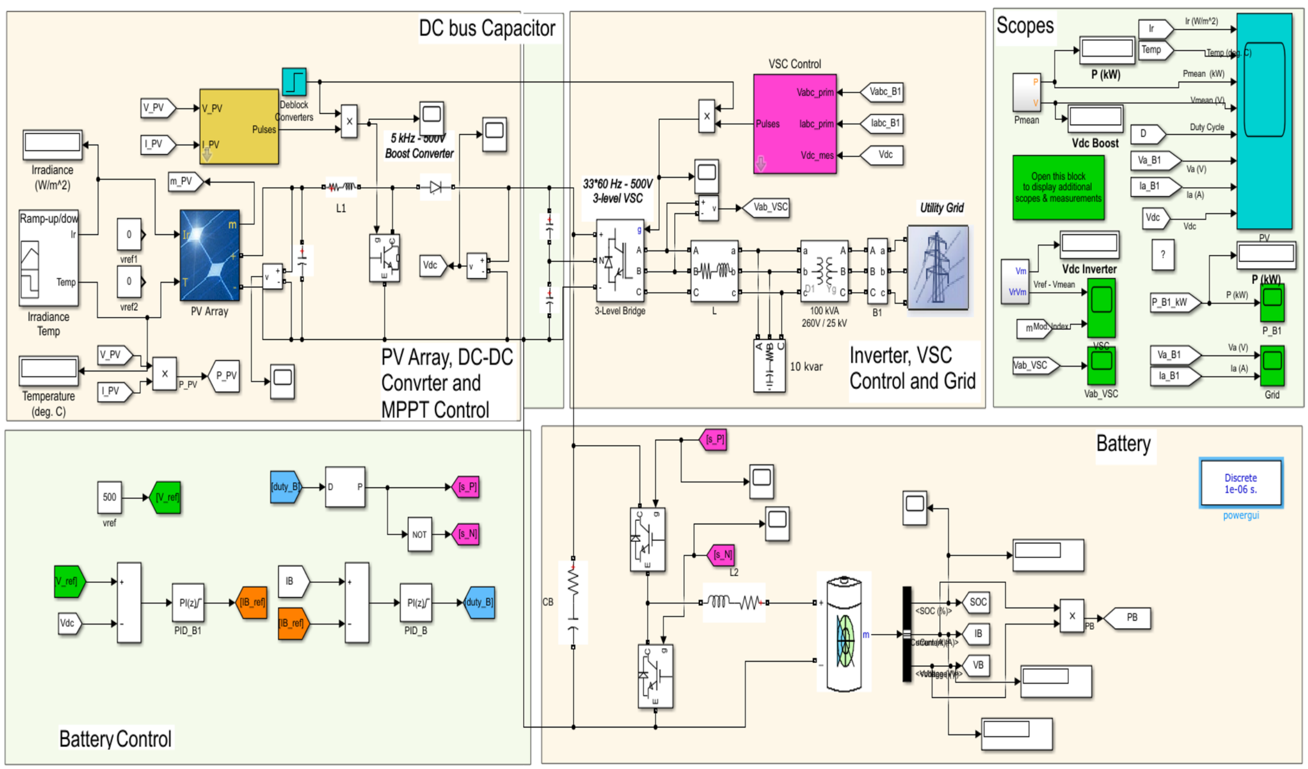


Fig. 26 Schematic diagram of on grid renewable energy systems

As shown in Fig. 26, BES is used to enhance DC bus voltage regulation where it is interfaced via a bidirectional buck-boost converter (BES conv.) that controls the charge/discharge processes during severe operating conditions such as abrupt changes in solar irradiation level and fault occurrences. From the VSC AC output terminals, the hybrid subsystem is connected to the utility grid at the PCC through a low-pass filter and an interconnection transformer that is represented by an inductor. These components are responsible for filtering harmonics and isolating the entire system from the utility grid. The transformer steps up the voltage level of the PV system from low level voltage to high level and vice versa. The PV/BES system injects total power, *PG*, to the utility grid in which in this case the utility grid network is based on a standard medium voltage distribution system (Al-Wesabi et al. 2022b) (Farh and Eltamaly 2020).

Three cases are considered for analyzing the system performance under different test conditions and Standard Test Condition (STC). First, it is assumed that the 100 kW PV solar system operates with 1000 W/m^2 radiations and 25 °C temperatures. Second the system is also tested under 250 W/m^2 radiations and 25 °C temperatures which generates 24.4 kW, and the system is also tested under 1000 W/m^2 radiations and 50 °C temperature as the third case to generate 92.9 kW. The model parameters are adjustable to work with various solar radiations. The simulation results of all cases are shown in Fig. 27. If $P_{PV} < P_{load}$, in this case, the battery is discharged to provide the additional needed power to load, and the DC current output of the BES is indeed positive. The main grid also works normally to feed the load deficit. But if $P_{PV} > P_{load}$, then, the PV DC current output is higher, and the battery is in charging mode. Thus, the BESS current is negative with excess power to the utility grid. As the consequence of power feeding to the grid network, the current amplitude of both the inverter and external grid is higher in comparison to the case of $P_{PV} < P_{load}$.

PV/WT and BES off grid system

The PV/WT and BES off grid system shown in Fig. 28 comprises of PV system, permanent magnet synchronous machine–based wind systems, and battery storage. The PV and wind systems have their own DC-DC buck converter equipped with PID controller. The battery system has its CCCV battery charger. The battery is charged or discharged depending on the availability of excess or shortage of power. The maximum power ratings of PV and wind systems considered here are 400 W and 400 W respectively and battery rating taken here is 373 W. The various components of the PV/WT and BES off grid system with the proposed controller are simulated in MATLAB/Simulink as shown in Fig. 29.

The PV power generation is maximum, that is, 400 W, as seen from Fig. 29, and wind power is maximum, that is, 400 W. Different powers—PV power, wind power, load power and battery power changing with time (s) as obtained from simulation—are shown in Fig. 29. It is analyzed from the simulation results that power generation from PV and wind system always meets the load demand.

Conclusions and recommendations

This paper provides detailed insight on the Yemeni national energy profile, energy use, and energy services in rural areas. Furthermore, it shows the energy consumption through transportation, electricity, and other different sectors. It also provides basic information on electricity production, consumption, and consumer categories. In addition, this paper examines various renewable energy sources such as solar energy, wind energy, biomass, and geothermal in the sampled nation. Furthermore, the study shows that Yemen is rich in solar radiation and wind speeds, where all the regions in the country are characterized by the availability of these two resources. Additionally, this paper proposed three case strategies to electrify the entire Yemeni population (rural and urban) by 2050. Finally, the study is developed to design

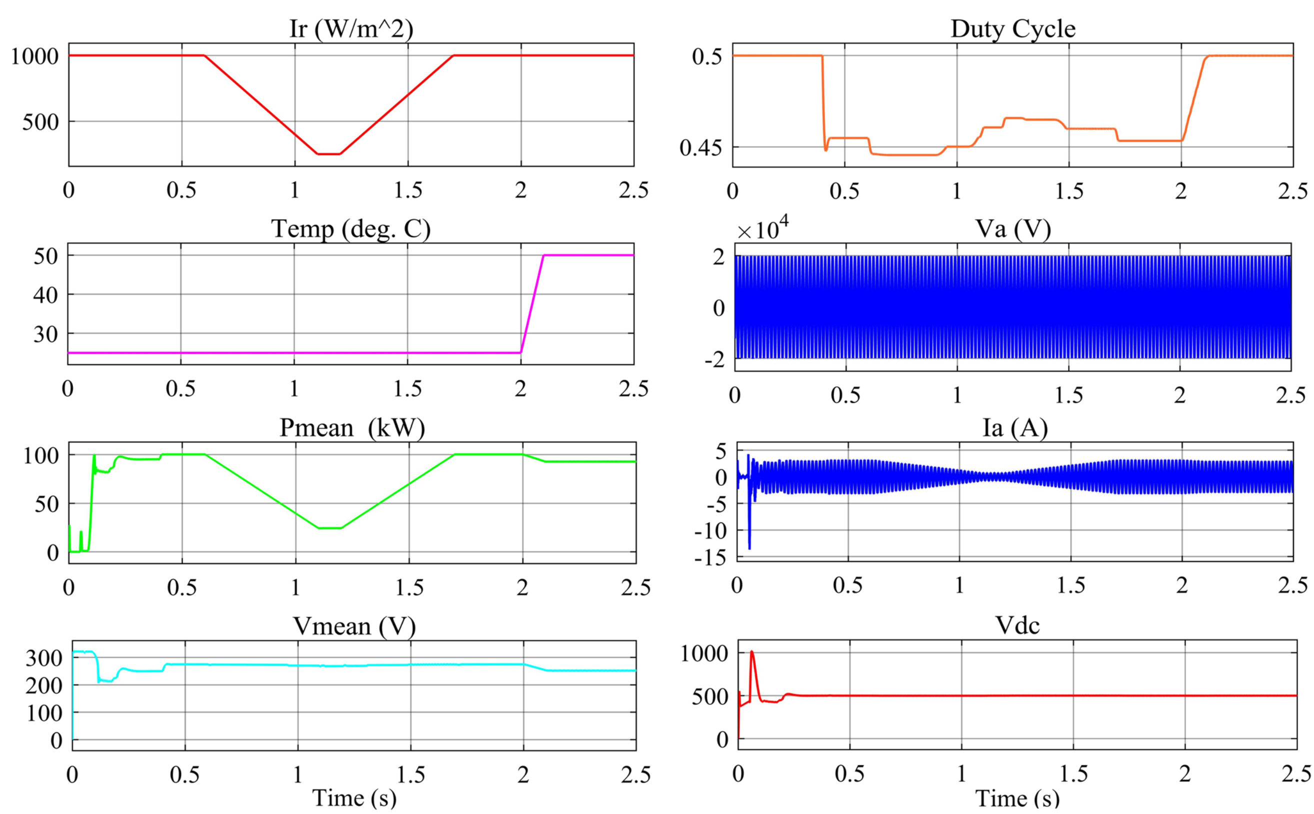


Fig. 27 The simulation output results of on grid renewable energy systems

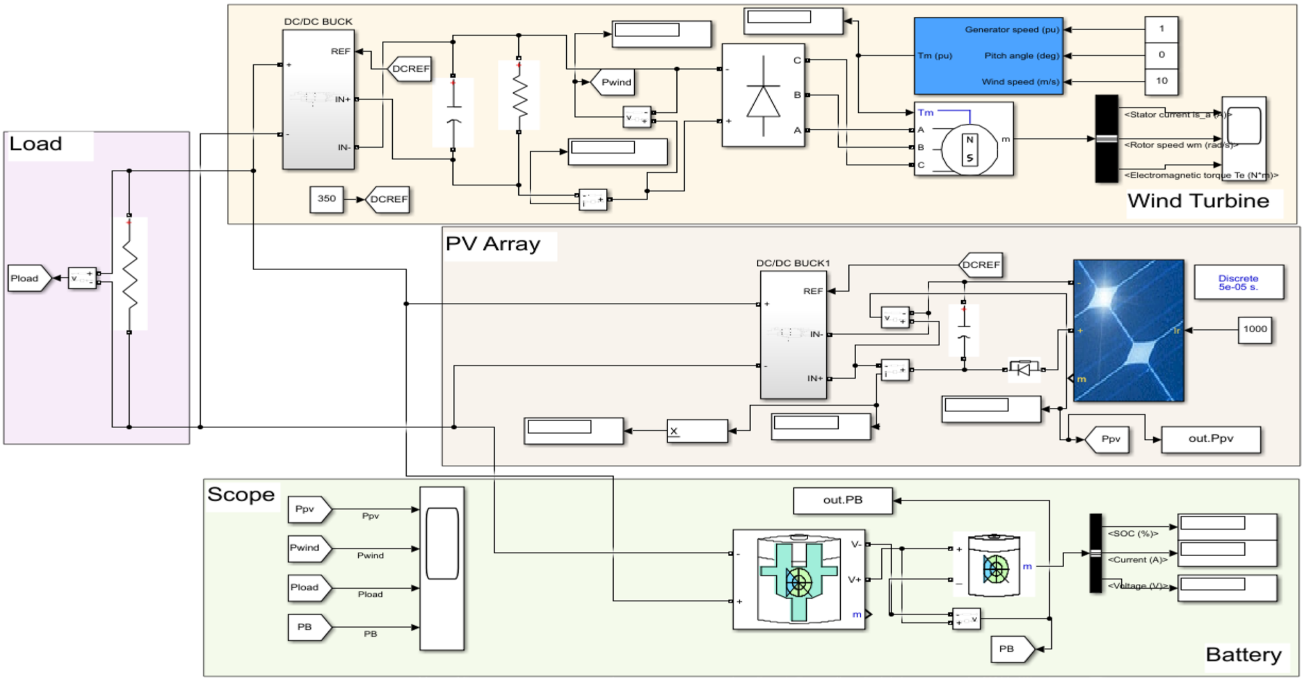


Fig. 28 Schematic diagram of off grid renewable energy systems

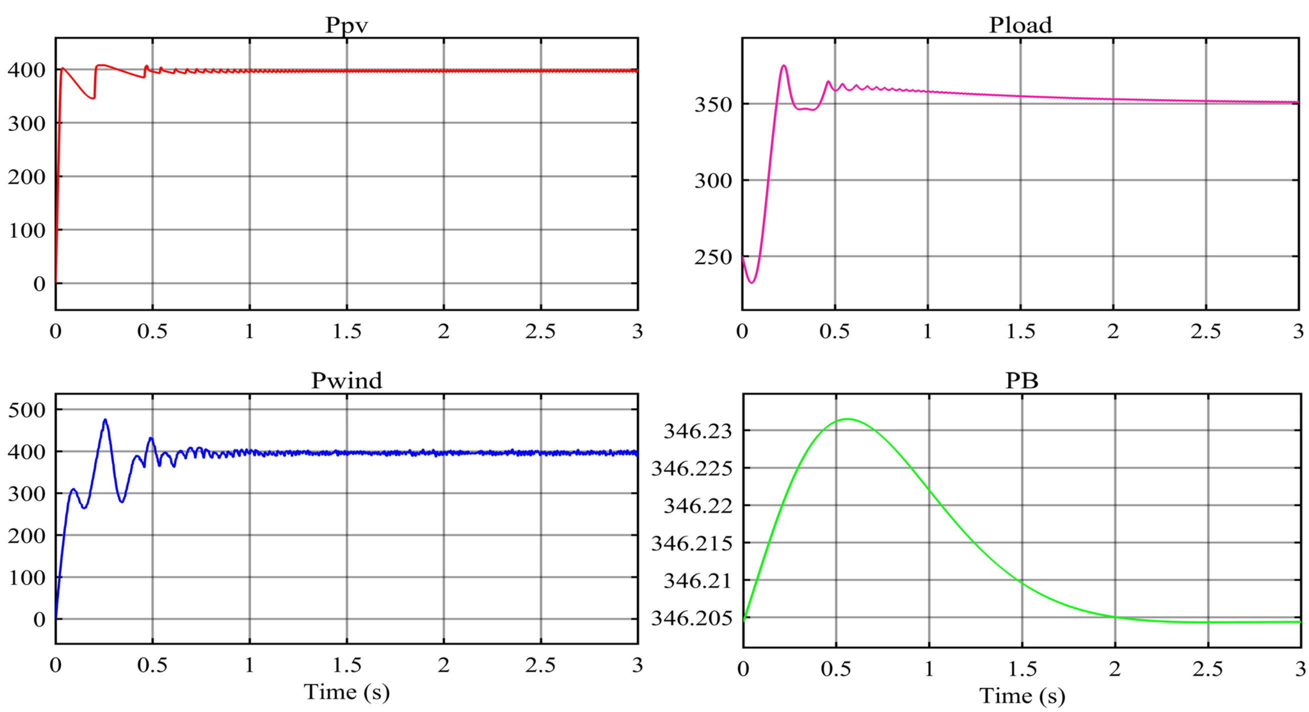


Fig. 29 The simulation output results of off grid renewable energy systems

different configurations of off/on hybrid energy systems including PV, WT, and battery for supply power to various consumer categories in Yemen under three scenarios of energy strategies.

This study showed that Yemen could access sustainable, clean, and renewable energy sources. It is logical that fossil fuels have better and more valuable applications than heating and lighting. Yemen, despite remaining a key supplier of crude oil and discovering and developing new oil reserves, has adequate and strong incentives to explore renewable and sustainable solutions. High gasoline costs are now having a significant impact on food prices and other macroeconomic indices because of the conflict, and the government should look for better ways to alleviate public discontent. Although the government should strive to be a part of international agreements and environmental regulations, such as the Kyoto and Paris agreements, to focus CO_2 emissions reduction, there is still a commitment to reduce CO_2 emissions and preparing Yemen's infrastructure for clean energy use. The future of renewable energies appears to be unclear in general, at least in terms of the efficiency of government policies. Although certain policies appear to assist some individuals more than others (for example, the usage of solar panels in remote rural regions), the overall prospects of these policies have been minimal. Now, renewable energy technologies do not play a significant or suitable part in Yemen's energy supply. This has also happened in another nation with abundant energy resources, i.e., Saudi Arabia (Amran et al. 2020). The key obstacles to renewable energy development in Yemen include the absence of appropriate and effective government policies, international sanctions, and low public awareness.

When the energy mix is examined more closely, the decision to use more fossil fuels, particularly natural gas, even if they are less ecologically friendly, appears to contradict the goal of lowering greenhouse gas emissions and undermining energy security. The current Yemeni policy for the development of renewable energy sources can be considered a step in the right direction, but a more active approach to developing potential renewable energies, such as biomass, is required. Under the current framework, the implementation of solar, biomass, wind, and thermal exploitation techniques can be facilitated in key government entities. Yemen, a country with abundant fossil fuel resources, requires proper regulations and guidelines for the future development of renewable energy, as well as reduced international barriers to the use of sophisticated technology and knowledge of other countries' renewable energy experiences. At the local level, it is necessary to invest a significant portion of crude oil export profits in a variety of high potential renewable energy sources to prepare for a future without fossil energy resources. To attract private investors, it is necessary to reduce energy subsidies, raise public awareness, and provide meaningful and appropriate incentives. Salam and Khan (2018) also demonstrated that raising public awareness through the media is critical for Saudi Arabia's renewable energy development. The usage of a wind–solar hybrid plant to generate both energy more effectively than single power plants is also recommended. Mohammed (2018) and Marchenko and Solomin (2018) both proposed a hybrid renewable energy system for Iraq and Russia, respectively.

The Public Electricity Cooperation (PEC) and the Ministry of electricity and Energy (MOEE) are advised to pay attention to the following recommendations and ensure that they are implemented to enable vision 2050 become a reality.

- Improve the efficiency of the electric energy industry by carrying out routine and periodical maintenance of the electricity sub-sectors (generation, transmission, and distribution)
- Providing necessary training and employing technical engineers, especially those with knowledge about generating electricity from renewable or sustainable primary energies
- Strive to achieve high reliability of the three sub-sectors in all cases, especially the grid transmission network, so that Yemen can connect with the transmission network of neighboring countries
- Increase power generation by building new power plants using natural gas, wind, geothermal, and solar energy
- Encourage investment in the electric power generation and power distribution sectors
- Develop enabling investment policies for the Yemeni power industry to encourage internal and external investors
- Formulate policies to regulate electricity power generation and power supply
- Prepare technical research to achieve future electrical interconnection with neighboring countries and realize sustainable power supply for consumers
- Implementing strict control for household and industry appliances to achieve efficient and economic power consumption.

The proposed energy efficiency strategy is advised to be adhered to before investing into this sector. While implementing the use of renewable energy, the main policy objectives are as follows:

- Optimize the utilization of domestic energy resources, prevent the increased dependence on fossil fuel energy imports in the future, and improve the security of energy supply (energy security),
- Increase the share of renewable energy in power generation (from the interconnected national power grid, to isolated power grid, and to household level) by diversifying the national energy structure.
- Improving the national environmental situation through greenhouse gas (GHG) emissions reduction
- Ensuring sustainable rural development, and economic growth by promoting access to decentralized renewable energy conversion technologies that will be integrated

into government development plans in all relevant sectors,

- Promoting energy efficiency and conservation initiatives which will aid in mitigating the impact of future surge in fossil fuel and electricity prices on the populace.
- Enhancing the sustainable development of the power sector by establishing renewable energy power generation and distribution companies in the rural areas of Yemen.
- Providing renewable energy technology to foreign and private investors (independent target power producers) and various non-governmental organizations, and allotting services in rural areas (rural energy service providers).

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Author contribution Each of the authors made an equal contribution. Conceptualization: I.A.-W., Z.F; methodology: I.A.-W; software: I.A.-W.; validation: Z.F. and C.P.B.; formal analysis, investigation: H.L.D; resources: Z.F.; data curation: I.A.-W.; writing—original draft preparation: I.A.-W., Z.F. and C.P.B.; writing—review and editing: I.A.-W., H.L.D.; visualization: H.L.D.; supervision: Z.F.; funding acquisition: Z.F. C.P.B was in charge of the overall formatting of the paper. The paper has been read and approved by all authors.

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Data availability On request, data will be made available.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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