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REVIEW ARTICLE

Social, environmental, and economic consequences of integrating renewable energies in the electricity sector: a review

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Abstract

The global shift from a fossil fuel-based to an electrical-based society is commonly viewed as an ecological improvement. However, the electrical power industry is a major source of carbon dioxide emissions, and incorporating renewable energy can still negatively impact the environment. Despite rising research in renewable energy, the impact of renewable energy consumption on the environment is poorly known. Here, we review the integration of renewable energies into the electricity sector from social, environmental, and economic perspectives. We found that implementing solar photovoltaic, battery storage, wind, hydropower, and bioenergy can provide 504,000 jobs in 2030 and 4.18 million jobs in 2050. For desalinization, photovoltaic/wind/battery storage systems supported by a diesel generator can reduce the cost of water production by 69% and adverse environmental effects by 90%, compared to full fossil fuel systems. The potential of carbon emission reduction increases with the percentage of renewable energy sources utilized. The photovoltaic/wind/hydroelectric system is the most effective in addressing climate change, producing a 2.11–5.46% increase in power generation and a 3.74–71.61% guarantee in share ratios. Compared to single energy systems, hybrid energy systems are more reliable and better equipped to withstand the impacts of climate change on the power supply.

Keywords Climate change · Hybrid · Renewable energy · Economic analysis · Environmental and social impact · Water desalination

Introduction

Hydrocarbons, specifically petroleum, coal, and natural gas, have been humanity's primary energy source for the past century. However, the ongoing threat of climate change and its effects on human health and well-being has dramatically increased the need for alternative energy sources. Hydrocarbons still account for over 80% of the world's energy supply. Furthermore, the production and use of fossil fuels are responsible for a significant portion (89%) of global greenhouse gas emissions, including carbon dioxide (Farghali et al. 2022). Additionally, reliance on imported fossil fuels risks energy security (Chen et al. 2022; Garba et al. 2021).

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To address these concerns, technologies based on renewable energy are crucial for achieving a sustainable energy future. As illustrated in Fig. 1, various forms of renewable energy have the potential to contribute to the global energy mix significantly. In line with this, there is a growing trend toward increasing the utilization of renewable energy sources, with projections suggesting that the share of renewable energy in global energy production will expand from 14 in 2018 to a projected 74% by 2050 (Osman et al. 2022). Globally, the power capacity of hybrid renewable energy increased from 700 to 3100 gigawatts between 2000 and 2021 (Rathod and Subramanian 2022).

Recent technological advancements in renewable energy systems have led to a reduction in both economic costs and environmental impacts. However, the intermittent nature of these resources remains a significant challenge in creating a reliable and long-lasting clean energy infrastructure. Integration between various sources is feasible and can increase system efficiency and supply balance, avoid limitations, and decrease carbon emissions. It is essential to evaluate the integration of renewable energy from both sustainability and technical perspectives, energy efficiency, and running costs. In addition, challenges to implementing a hybrid energy system must be addressed. This study explores the potential of combining various renewable energy sources and the associated environmental and social impacts. We examine the utilization of hybrid systems in water desalination and compare these systems' effects concerning their individual sources. Additionally, we consider the potential impact of climate change on the complementary operation of integrated systems and evaluate their flexibility in adapting to such changes. Furthermore, we examine the economic feasibility of renewable energy hybrid systems, including the estimation of costs and the potential for expansion in different countries.

Renewable energies hybridization and global production

Renewable energy systems can be based on a single source or a combination of multiple sources. A single-source system utilizes only one power generation option, such as wind, solar thermal, solar photovoltaic, hydro, biomass, and others, in combination with appropriate energy storage and electrical devices. On the other hand, a hybrid energy system combines energy storage and electrical appliances with two or more power generation options, including both renewable and non-renewable sources, such as diesel generators or small gas turbines (Sinha and Chandel 2014). Different configurations including photovoltaic–wind–diesel hydro–wind–photovoltaic, biomass–wind–photovoltaic, wind–photovoltaic, and photovoltaic–wind–hydrogen/fuel cell systems can be used in a hybrid energy system to generate electricity. Hybrid energy systems offer several advantages over single-source methods, such as increased reliability, decreased need for energy storage, and improved efficiency. However, a hybrid system can be oversized or improperly designed, leading to higher installation costs. Therefore, conducting thorough technical and financial analyses is essential when designing and implementing a hybrid energy system to utilize renewable energy sources effectively. Due to their complexity, hybrid systems require careful evaluation (Sinha and Chandel 2014).

As of the end of 2020, there was a global total of 2799 gigawatts of renewable energy capacity available worldwide. The majority of this capacity, 43%, was from hydropower, with a capacity of 1211 gigawatts. Wind and solar energy comprised equal portions of the remaining capacity, with 733 gigawatts (26%) and 714 gigawatts (26%), respectively. The remaining 5% of energy came from other renewable energy sources, including 500 megawatts of marine energy, 127 gigawatts of bioenergy, and 14 gigawatts of geothermal

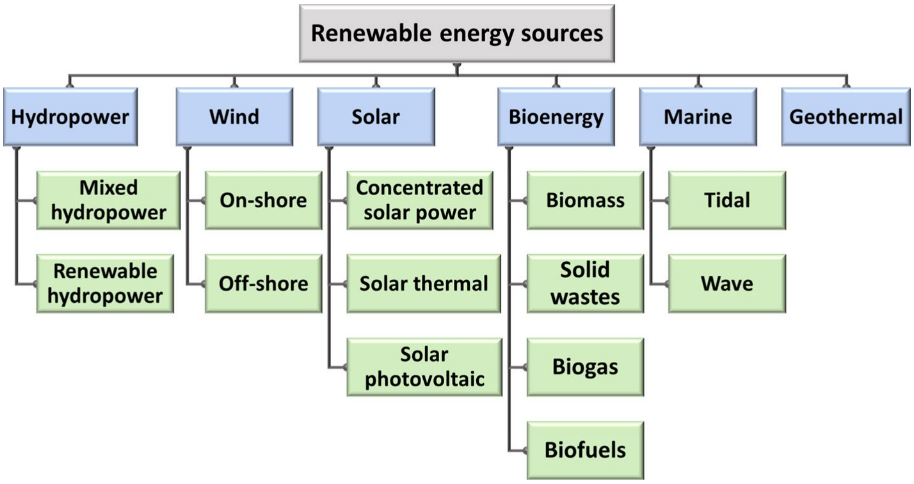

Fig. 1 Different types of renewable energy. The field of renewable energy technology encompasses various methodologies, including solar, wind, geothermal, biomass, and hydropower energy generation. Integrating renewable energy into the electricity grid is crucial to addressing global climate change

energy (Al-Shetwi 2022; IRENA 2021). Figure 2 shows the significant increase in the proportion of renewable energy sources used in electricity generation from 2010 to 2020 (Al-Shetwi 2022; IRENA 2021).

A hybrid renewable energy system is created to overcome this challenge by combining different energy sources. These hybrid systems have the potential to surpass the capabilities of individual energy-producing technologies in terms of energy efficiency, economics, reliability, and flexibility. Globally, the power capacity of hybrid renewable energy systems increased from 700 to 3100 gigawatts between 2000 and 2021 (Rathod and Subramanian 2022).

Various factors influence renewable energy development, including climate change, global warming, energy security, cost reduction, and emission reduction (Osman et al. 2022). A study by Brodny et al. (2021) evaluated the level of renewable energy development in European Union member states and found that the energy revolution in Europe is progressing rapidly. The study found that between 2008 and 2013, the average gross electricity output from renewable energy sources in the European Union increased from 21.18 to 32.11%, and from 2013 to 2018, it reached 38.16%. This rapid shift toward renewable energy is expected to lead to the sustainable development of the economy and reduced emissions, in line with the European Green Deal concept. To achieve sustainable development, Tabrizian (2019) examined the role of technological innovation and the spread of renewable energy technologies in underdeveloped nations. The study found that renewable energy sources are the best and cleanest substitutes for fossil fuels and have a wide range of beneficial environmental consequences, including a significant decrease in greenhouse gas emissions, which is crucial given concerns about climate change. Green buildings may meet the needs of their residents by using renewable energy sources such as solar, wind, and geothermal energy while reducing their energy consumption and carbon footprint to zero (Chen et al. 2023). However, technology diffusion in this sector is slow, and renewable energy technologies are only gradually gaining traction in underdeveloped nations.

Similarly, Hache (2018) also noted that the spread of renewable energies would complicate global energy geopolitics and issues related to energy security. Therefore,

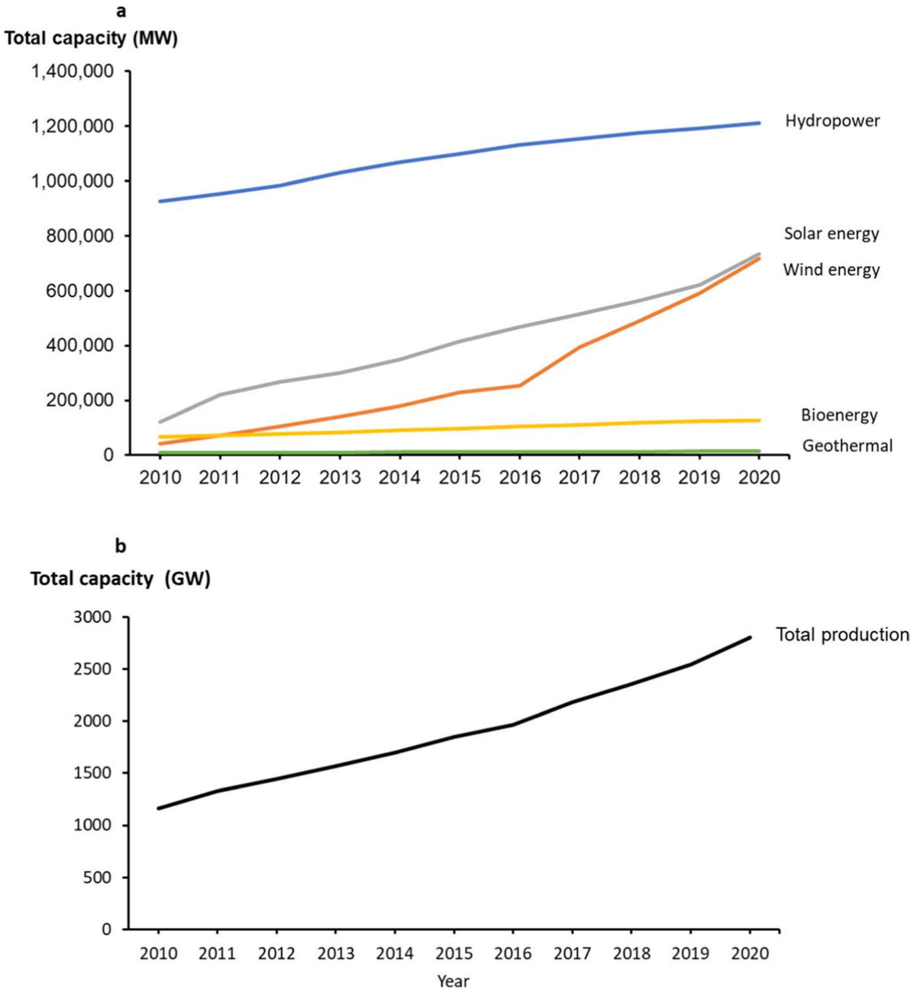

Fig. 2 Worldwide renewable energy sources' generating capacity from 2010 to 2020. The proportion of renewable energy sources (a) used in electricity generation increased steadily from 2010 to 2020. Total production capacities from renewable energy sources reached 2802 gigawatts (GW) (b) in 2020. Hydropower represents the highest share in renewable energy production, followed by wind and solar energies

the current increase in renewable energy installations must be considered alongside energy security and technological advancement for a smooth transition to renewable energy. The trend of renewable energy integration is expected to continue growing, with solar and wind power projected to account for 50% of global power generation by 2050 (Gielen et al. 2019).

Jacobson et al. (2017) found that 139 of the world's 195 nations have plans to transition to 80% and 100% renewable energy by 2030 and 2050, respectively. Additionally, many countries plan to use only renewable energy by 2050. A study by Zappa et al. (2019) shows that a 100% renewable energy power system would still require a significant flexible zero-carbon firm capacity to balance variable wind and photovoltaic generation and cover demand when wind and solar supply is low, even when wind and photovoltaic capacity is spatially optimized and electricity can be transmitted across a fully integrated European grid. Hydropower, concentrated solar power, geothermal, biomass, or seasonal storage are all potential sources of this capacity. Still, none of them are currently being used to the extent required to provide a 100% renewable energy system by 2050. The feasibility of a 100% renewable energy system in Europe by 2050 has been examined from various angles by Child et al. (2019) and Hansen et al. (2019). These studies indicate that renewable energy will continue to develop, and future developments in integration are anticipated.

Integrating renewable energy into the electrical power grid offers several benefits for the power and social, economic, and environmental sectors. From an environmental perspective, the electricity sector is currently a significant producer of carbon dioxide emissions (Bella et al. 2014). By 2040, energy-related emissions are predicted to increase by approximately 16% (Elum and Momodu 2017b). Therefore, electrical grids should be a crucial component of any effort to mitigate the worst effects of climate change and global warming. This is why low-carbon electricity generation that heavily relies on renewable energy sources is essential to a sustainable energy future as we progress toward deep decarbonization of the power industry (Bogdanov et al. 2021b). In this context, renewable energy can significantly support energy security and greenhouse gas reduction in the USA (Khoie et al. 2019). The use of fossil fuels and energy imports, the leading causes of carbon dioxide emissions in the USA, can also be reduced.

Additionally, according to Khan (2006), the increase in the integration of renewable energy into the utility grid has resulted in a reduction of approximately 527 million metric tons of carbon dioxide emissions from the electricity industry, as compared to the 46 million metric tons that were eliminated by renewable energy utilization in 2006. The recent renewable energy trend and its production growth will play a crucial role in the sustainable power sector's response to climate change and global warming. By switching to a 100% renewable energy supply, these sectors will reduce their carbon dioxide equivalent emissions by 90% by 2040, bringing them to zero in 2050 (Bogdanov et al. 2021a).

Environmental, social, and techno-economic impacts of hybrid renewable energy systems

Fossil fuel consumption is increasing dramatically due to excessive anthropogenic activities and industrial expansion to meet energy demands. The increase in fossil fuel consumption has risen by 96% since 1965 (Caglar et al. 2022), leading to adverse environmental impacts. Fossil fuels negatively impact air quality, the environment, health, and water resources. The gaseous emissions that can be released into the air due to fossil fuel consumption include greenhouse gases such as carbon oxides (carbon monoxide and carbon dioxide), sulfur oxides (sulfur dioxide and sulfur trioxide), nitrogen oxides (nitrous oxide and nitrogen dioxide), and volatile organic compounds and aerosols such as particulate matter. It was reported that about 72.5% of the global carbon dioxide equivalent emissions could be released from coal consumption (Sayed et al. 2021), causing the global warming phenomenon. The estimated gaseous emissions for various fossil fuels per megawatt-hour (MWh) of power generated are given in Table 1 (Turconi et al. 2013). One of every five deaths worldwide is induced by pollution from fossil fuel consumption (Azarpour et al. 2022). As a result of pollution, 350,000 people passed away in the USA in 2018. The annual cost of the health effects caused by fossil fuel consumption in the USA was reported to be 886.5 billion dollars (Azarpour et al. 2022). To mitigate the adverse impacts associated with fossil fuel consumption and achieve sustainability, the United Nations organization has established 17 goals for sustainable development (SDGs).

Nevertheless, the growing environmental pollution from fossil fuel consumption influences sustainable development goals, especially goal no. 13 of climate action.

Table 1 Greenhouse gas emissions for various fossil fuels (Turconi et al. 2013). Coal produced the highest gaseous emissions, followed by oil and natural gas. The release of sulfur oxide and nitrogen oxide gases leads to acid rains which can negatively affect crops, forests, and waterways. MWh and kg refer to megawatt-hour and kilogram, respectively

Fuel	Carbon dioxide equivalent, kg/MWh	Nitrogen oxides, kg/MWh	Sulfur oxides, kg/MWh
Natural gas	380–1000	0.2–3.8	0.01–0.23
Oil	530–900	0.5–1.5	0.85–8
Coal	660–1050	0.3–3.9	0.03–6.7

Hence, most countries have become under pressure to reduce fossil fuel consumption after the Paris agreement and the United Nations Conference of Parties (COP-26) (Fawzy et al. 2020). Additionally, around 1.1 billion people are still deprived of electricity in developing countries (Shouman 2017). Energy security is crucial for enhancing the socioeconomic situation of those residing in rural regions. Residents in these areas frequently suffer from power shortages due to their remote locations from the national grid and poverty.

Globally, renewable energy sources such as solar, wind, biomass, and geothermal are considered the most effective solution to minimize the social and environmental problems associated with non-renewable energy sources (Osman et al. 2022). The transition to renewable energy sources creates new jobs and reduces carbon dioxide emissions. By the end of 2018, it is predicted that over 100 cities will be powered by 70% renewable electricity globally, and at least 40 cities will be powered entirely by renewable energy (Liu et al. 2020). Since renewable energy sources produce naturally derived fuel, they can offer a sustainable energy source with minimal operating costs and a regular energy supply. Because so little waste can be produced, renewable energy sources have no detrimental influence on the environment. Moreover, renewable energies such as solar, wind, and tidal power need a minimal amount of water for generating power and thus can participate in saving water resources (Tanaka et al. 2022).

Nevertheless, the unstable availability of renewable energy sources that depend on the weather conditions, such as wind availability and solar irradiation, is a major limitation. Energy storage systems can partially overcome this gap, but the overall cost and energy conversion efficiency is low (Elkadeem et al. 2019a). Hybrid renewable energy systems have been adopted as an alternative and cost-effective technology to address the abovementioned issues. Hybrid renewable energy systems integrate two or more renewable energy sources with or without traditional energy sources (e.g., diesel) and storage. In general, renewable energy sources and hybrid renewable energy systems have gained more attention recently due to their continuously reduced costs and rising social, environmental, and techno-economic benefits. Based on the international renewable energy agency's strategy for renewable energy, it is recommended to increase the utilization of renewable energy sources to 85% by 2050 (Elkadeem 2019a, b; Wang et al. 2019a, b). Since 2010, solar photovoltaics have achieved a remarkable cost reduction of more than 90% (Liu et al. 2020). The cost of wind energy also decreased, with turbine prices falling by 10% to 20% since 2017 (Liu et al 2020). Detailed information about social, environmental, and techno-economic benefits and impacts is discussed herein.

Social impacts

Using renewable energy can lead to several social impacts, including poverty elimination, climate change mitigation, and improving health by reducing pollution associated with gas emissions. Additionally, renewable energy can achieve gender equality by mitigating the harmful health impacts on women's health in South Africa and many developing countries, resulting from the frequent use of firewood as an energy source. Meanwhile, investments in renewable energy projects can help in poverty alleviation by providing job opportunities in rural areas. China, Brazil, and India, the three largest developed nations, strongly encouraged renewable energy investments, where a gradual increase in renewable energy investments from $94.8 million to $197.5 million was observed from 2016 to 2017. The required workforce during the manufacturing, equipment installation, operation, and maintenance processes of the hybrid renewable energy systems was assessed. An annual increase in electricity generation by a 1-gigawatt hour (GWh) from renewable energy sources could offer 3.5 jobs (Arvanitopoulos and Agnolucci 2020). Renewable energy technologies created 9.8 million jobs in 2016 (Elkadeem et al. 2019a). Solar technology provided about 43% of the USA' employment in the electrical sector, compared to 22% from fossil fuels (Cuesta et al. 2020). Solar photovoltaic, battery storage, wind, hydropower, and bioenergy will provide significant job opportunities, with 4.18 million jobs in 2050, 894 thousand jobs in 2050, 504 thousand jobs in 2030, 297 thousand jobs in 2020, and 523 thousand jobs in 2025, respectively (Ram et al. 2020).

Techno-economic and environmental impacts

Life cycle analysis investigations that explore the adverse environmental effects of renewable energy sources such as wind turbines were variable in terms of carbon dioxide emissions. A study revealed that the embodied carbon in wind turbines was between 1844 and 2074 tons of carbon dioxide equivalent per megawatt of capacity (Crawford 2009), while the embodied carbon was 1664 tons of carbon dioxide equivalent per megawatt in another study (Wang et al. 2019b). A techno-economic analysis of hybrid renewable energy systems was conducted in 634 Philippine off-grid islands, and it was found that the required capital costs for renewable energy technologies were greater in the case of larger islands, but the long-term costs were lower (Castro et al. 2022). The study also proved that hybrid renewable energy systems projects are profitable in larger islands at lower electricity rates (Castro et al. 2022). Compared to a diesel-based system, a hybrid renewable energy system offers a more economical option for off-grid energy access (Castro et al. 2022). The techno-economic merit of photovoltaic–wind–battery and photovoltaic–wind systems was also observed compared to sole photovoltaic systems (Liu et al. 2020). The optimized photovoltaic–wind–battery system could cover 81.29% of the yearly load at an economical levelized cost of energy of $0.2230/kWh. In contrast, the sole photovoltaic system could cover 16.02% only of the annual load at a levelized cost of energy of $0.5252/kWh (Liu et al. 2020).

The techno-economic efficiency of a hybrid concentrated solar biomass plant for electricity production in Australia was evaluated. The combination of biomass boilers with concentrated solar power as a hybrid concentrated solar biomass plant showed higher efficiency in terms of techno-economic benefits compared to independent concentrated solar power plants and other renewable technologies in Australia (Middelhoff et al. 2021). The Kingdom of Saudi Arabia intends to reduce annual carbon dioxide emissions by 130 metric tons by 2030 using renewable energy sources, including wind, geothermal, and solar (Barhoumi et al. 2020). Motivated by the plan of the Kingdom of Saudi Arabia, an eco-friendly city that relies on renewable energy sources, "NEOM" city was established to minimize carbon dioxide emissions. Numerous techno-economic investigations have been carried out to improve the effectiveness of the hybrid renewable energy system in the Kingdom of Saudi Arabia, thereby generating the necessary amount of electricity with a low-levelized cost of energy and minimal greenhouse emissions. A techno-economic conducted for the photovoltaic/battery/diesel hybrid renewable energy system demonstrated lower energy costs than diesel (Al-Shamma'a et al. 2020). The photovoltaic/diesel/battery storage hybrid renewable energy system showed the best performance for electricity generation in NEOM city with a levelized cost of energy of $0.4/kWh and 45,912 kg/year of carbon dioxide emission, corresponding to 118,074 gallons of diesel saved (Salameh et al. 2021).

Extensive research has been carried out on optimizing hybrid renewable energy systems. Hybrid renewable energy system optimization studies were conducted to investigate reducing the levelized or net present energy cost, limiting greenhouse gas emissions, and increasing system reliability. An optimized photovoltaic/fuel cell/battery storage hybrid renewable energy system was used to provide energy to the seawater desalination plant with a net present cost of $438,657 and energy cost of $0.117/kWh and to minimize greenhouse gas emissions (Rezk et al. 2020). The techno-economic and environmental analysis of optimized photovoltaic/biomass gasifier/battery hybrid renewable energy system in the western Himalayan territory of India was explored. Based on the techno-economic analysis, the proposed hybrid system has a lower levelized cost of energy ($0.185/kWh) than the traditional diesel system, representing around 92% cost reduction (Malik et al. 2021b).

Meanwhile, the environmental analysis showed that the greenhouse gas emissions are 90.1% lower than the diesel system (Malik et al. 2021b). A comprehensive investigation revealed that biomass-based hybrid renewable energy systems might be a viable economic and environmental solution for rural regions (Malik et al. 2021a). Nevertheless, a techno-economic study exhibited that the most cost-effective solution for Punjab's rural areas is a photovoltaic/biogas generator-based microgrid hybrid renewable energy system, which has a levelized cost of energy of $0.0735/kWh (Kaur et al. 2020). The techno-economic feasibility results showed that the biomass/photovoltaic/battery storage hybrid renewable energy system is the most economically viable system to meet electricity needs with a levelized cost of $0.1498/kWh (Ji et al. 2022). Generally, photovoltaic, wind, hydropower, and diesel generators are the most frequently applied hybrid renewable energy systems. Additionally, using biomass, such as agricultural, animal, and organic waste, is an alternative energy source to traditional fossil fuels in rural regions, particularly in developing nations (Peng et al. 2023). For instance, a biomass–biogas hybrid renewable energy system was optimized with energy costs ranging from $1.204/kWh to $1.630/kWh (Goel and Sharma 2019). The techno-economic analysis of Pakistan's wind/hydro/biomass hybrid renewable energy systems showed the best energy cost, which is $0.0470 to $0.0968/kWh (Ali et al. 2021b). The proposed hybrid system can reduce carbon dioxide emissions by 36,742 tons annually, which will positively influence the environment (Ali et al. 2021b).

Although using renewable energy sources has low environmental impacts and can significantly reduce greenhouse gas emissions, various obstacles limit their widespread application. For instance, some environmental effects of geothermal projects involve those related to land usage, atmospheric emissions, water supply, solid waste, and risks to ecosystems (Soltani et al. 2021). On the other hand, power transmission lines and project construction are examples of related project activities that can cause indirect environmental effects (Bayer et al. 2013). Concerns regarding the impact of the construction and operation of renewable energy power plants on biodiversity have been highlighted. During the operation stage, wind, hydro, biomass, ocean, and geothermal energy can alter ecosystems' behavioral patterns, causing the extinction of some species and the development of other species (Gasparatos et al. 2017). For example, a concern could be raised by striking birds with wind turbine blades during wind energy production. Furthermore, solar photovoltaic panels pose a socioenvironmental problem arising from recycling and management after their end of life. Life cycle assessment exhibited some environmental impacts associated with the management of solar photovoltaic panels, including human toxicity, acidification, terrestrial eutrophication, freshwater ecotoxicity, and the decline of mineral, fossil, and renewable resources (Daniela-Abigail et al. 2022).

Another study investigated the environmental effects of various renewable energy sources in terms of air, soil, water, and people impacts (Rahman et al. 2022). Among various renewable energy sources, the authors revealed that hydroelectric power plants could cause major air impacts on temperature and precipitation fluctuations due to greenhouse gas emissions. Concentrated solar power and solar photovoltaic can also contribute to ozone depletion and greenhouse gas emissions. On the other hand, all renewable energy sources, except biomass energy, affect aquatic ecosystems. Furthermore, hydropower can cause soil erosion, eutrophication, an increase of suspended sediments, and a change in lagoons and deltas, water temperature, and oxygen levels. Almost all power plants cause noise during installation, operation, and maintenance processes except for solar photovoltaic. Wind turbines and concentrating solar power can restrict the movement of planes and sea freight.

In conclusion, hydropower and geothermal power significantly affect human health. Based on the impacts on aquatic ecosystems, hydroelectric power plants have the highest effect, whereas geothermal plants and biomass have the lowest effect. Generally, the environmental impact of biomass power plants and wind turbines is minor, while hydroelectric power plants are the most harmful to the environment.

Renewable energy for water desalination

Around the world, fresh water is crucial for people's lives. Nevertheless, population increase, water contamination, and poor management of water resources all contribute to a decrease in the availability of fresh water. In particular, people in the Middle East and North Africa region suffer from freshwater scarcity due to the rapid growth of the population. Seawater desalination could address this gap because of the availability of saline water resources in most Middle East and North African countries. However, the operation of water desalination plants requires high energy, primarily provided by fossil fuels. Hence, using renewable energy sources instead of fossil fuels could be a sustainable, eco-friendly, and cost-effective solution. It is anticipated that 130 million tons of oil are needed annually to produce 13 million m^3/day of freshwater (Eltawil et al. 2008), leading to increased emissions of greenhouse gases.

The most frequently used renewable energy sources in water desalination plants include wind, thermal, photovoltaic, and geothermal energy. Figure 3 shows the possible integration of renewable energy sources in various desalination technologies. Among various renewable energy sources, geothermal energy has recently attracted worldwide attention due to its reliability and continuous energy generation. Geothermal energy can reduce the cost of water production by around 59% and save 95% of the required power (Sarbatly and Chiam 2013). However, the dependence of geothermal energy on local geology is the main limitation of its utilization (Mohammadi et al. 2021). Various wind energy configurations could be applied in water desalination plants, such as wind energy electrodialysis, mechanical vapor compression, and reverse osmosis techniques (Gude 2018). Solar stills and concentrated solar power are common methods for using solar thermal energy (Ghazi et al. 2022). Geothermal and solar photovoltaic energy can be used in various ways to generate the necessary electricity for desalination procedures (Ghazi et al. 2022). A hybrid renewable energy system was reported to be the most effective option for water desalination, especially in areas where solar light was available. High production of 9000 m^3/day is provided by hybrid renewable energy systems, such as solar and geothermal energy systems in the Arabian Gulf (Ghazi et al. 2022). About 1% of reverse osmosis desalination plants can be powered by renewable energy sources based on solar and wind energy in small-scale desalination facilities in arid and coastal regions (Energy 2012).

In comparison with a diesel system, a photovoltaic/wind/diesel/battery/convertor hybrid renewable energy system showed reduced rates of 60.7, 73.7, 62, and 81.5% in terms of the overall cost, renewable percentage, energy cost, and carbon dioxide emissions, respectively (Elmaadawy et al. 2020). A study showed that the photovoltaic/wind/battery storage hybrid renewable energy system supported by a diesel generator system is the most viable system for providing energy to the desalination unit in terms of economic and environmental benefits. It can reduce the cost of water production and adverse environmental effects by 69 and 90%, respectively, compared to other desalination units that rely on fossil fuels (Das et al. 2022b). To minimize the impacts of the water-energy nexus in India's coastal regions, the research examined an efficient desalination unit powered by renewable energy for the coastal villages of Tamil Nadu in India. The best option was a reverse osmosis desalination unit with a photovoltaic/wind/battery/diesel generator hybrid renewable energy system. The techno-economic and environmental analysis results showed that the lowest water cost is \$4.57/m^3, and the carbon dioxide generation is 2887 kg/year (Das et al. 2022b). The effectiveness of renewable options for water desalination, such as solar and wind, was examined. The study revealed that renewable energy sources could produce more energy at a lower cost, reducing the overall water desalination cost (Koroneos et al. 2007). Although using renewable energies in desalination plants is the most efficient approach for reducing carbon emissions, brine waste management must be considered to protect the environment and aquatic habitats.

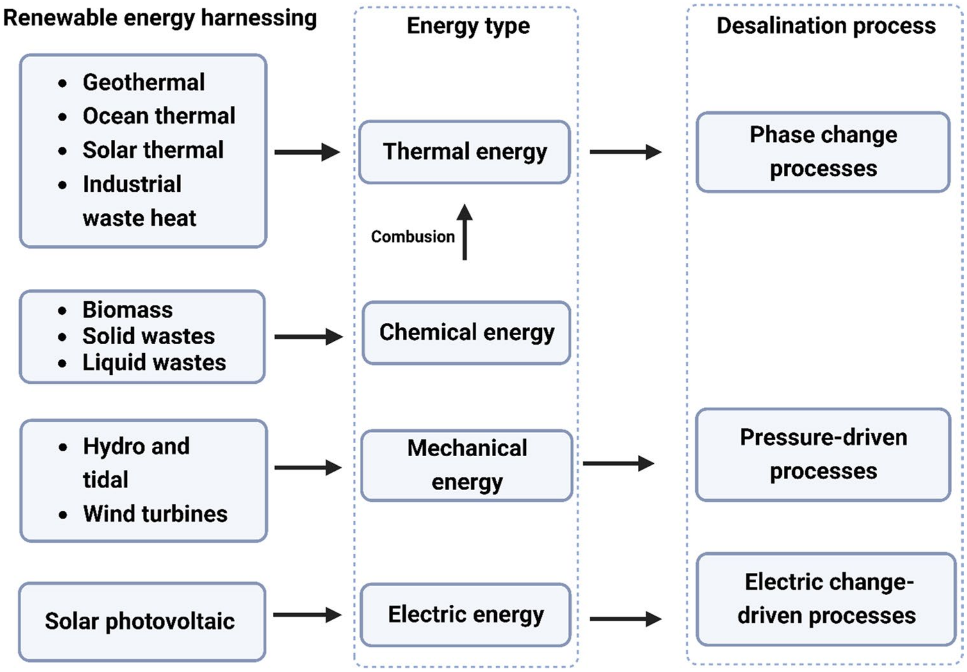

Fig. 3 Possible integration of renewable energy sources in various desalination technologies. Renewable energy harnessing could use geothermal, ocean thermal, solar thermal, or industrial waste heat into thermal energy; this is used in the desalination process in phase change processes. But biomass, solid waste, or liquid waste could use chemical energy that is by combustion to produce thermal energy, which is used in the desalination process and again in phase change processes. In the case of wind turbines and hydro and tidal, mechanical energy is used as an energy type to produce electricity for pressure-driven processes in the desalination process. Finally, solar photovoltaics uses electrical energy to electric change-driven processes in the water desalination process (adopted with modifications from Ahmed et al. 2019 and Bundschuh et al. 2015)

Climate change and hybrid renewable energy

The majority of methods used to alter the climate of this planet involve entirely burning fossil fuels and cutting down trees. These methods include the human impact on the environment and temperature change. Global warming is mainly caused by climate change (Yoro and Daramola 2020). Burning fossil fuels releases many greenhouse gases into the atmosphere, significantly inducing global warming (Bhattacharjee et al. 2020). Global warming frequently causes natural disasters such as rising sea levels, hurricanes, severe droughts, increased flooding, heavy rainfall, and changes in the monsoon season (Bhattacharjee and Nandi 2020). As a result of changes in climatic parameters, such as river flow based on rainfall and photovoltaic power generation based on solar radiation, hybrid energy systems' resource sequences are also subject to change. Therefore, climate change makes these resources less stable (Milly et al. 2015), a significant obstacle for hybrid energy systems.

Impact of climate change on hybrid energy systems

Climate conditions vary depending on location (Mahesh and Sandhu 2015); hence, climate conditions are essential because the entire electricity generation system relies on them (Freitas et al. 2019). Moreover, energy flux is correlated with climate conditions and renewable energy endowment (Viviescas et al. 2019). For instance, solar energy is affected by daylight hours, unavailability at night, and rainy weather diminishes the intensity of light (Chwieduk 2018). In addition, changes in wind speed directly impact the electricity produced by hydroelectric systems, and seasonal droughts and excessive rainfall can also have an impact (Bhattacharjee and Nandi 2020; Ibrahim et al. 2022; Xiong et al. 2019).

As a result, the development of hybrid energy systems enables it to reduce the adverse effects of climate change on the electricity system while ensuring supply stability, high power quality, and reliability, as well as decreased system efficiency unpredictability. The threat posed by climate change to renewable energy generation is significant, but renewable energy contributes significantly to the electricity grids of many countries (Elum and Momodu 2017a). Extreme climate conditions frequently occur, necessitating more flexible electrical systems to identify and isolate electrical faults and save maintenance costs (Kang et al. 2020). The impact of hybrid energy systems on climate change is demonstrated in Fig. 4 and Table 2.

This table illustrates how various climate change considerations affect the different energy types in a hybrid energy system. Hybrid energy systems can increase energy efficiency and respond to extreme climate change more than single energy systems. For example, François et al. (2018) used an atmospheric circulation model to explore the impact of a hybrid photovoltaic/hydroelectric system on future temperature and precipitation changes. Warming indicates more rain than snow as precipitation, which boosts runoff electricity production efficiency and raises the threshold for electricity production in the autumn and winter. Temperature influences local evapotranspiration effects, making them more critical in lowlands than at altitudes, leading to lower discharge at higher temperatures, thus reducing the amount of electricity generated by runoff (Gunawardena et al. 2017). As the altitude decreases, the extent to which the hybrid energy system is affected by precipitation becomes more pronounced. Precipitation has a countering influence on the effectiveness of the energy system at higher altitudes. Senthil et al. (2018) demonstrated how the multi-energy hybrid system's ability to provide power throughout the summer and winter is affected by climate change. The high wind speed in winter increases the effectiveness of the wind energy system, and the prolonged daylight hours in summer aid in the energy supply of the photovoltaic system, ensuring that the system has a steady supply of electricity throughout the day to meet the system load demand and enhance system performance.

Further, hybrid energy systems can also adapt quickly to sudden climate changes. For instance, photovoltaic hybrid battery systems have been shown to reduce the dynamic stress on batteries during rapid transient or abrupt climate change conditions (Javed et al. 2019). However, the efficiency of photovoltaic energy is altered by changes in solar intensity. Thus, this seasonal change can determine an ideal system design for a photovoltaic and wind hybrid system (Abobakr et al. 2022). When adopting a hybrid energy system in Turkey, the grid and wind system are preferable for weather conditions with wind speeds greater than 4.13 m/second.

In contrast, a rise in solar radiation of up to 6 kWh/m^2/day is required to operate the photovoltaic/grid system (Kalinci 2015). Additionally, Tazay et al. (2020) discovered that while variations in wind speed and solar radiation intensity have an impact on the power generated, they have no impact on the voltage of the busbar to the grid at the primary common coupling point of the standard coupling between the photovoltaic plant and the wind farm. This finding adds to the stability of the hybrid energy system and guarantees that it continues to produce more power than the conventional single energy system.

Nasser et al. (2022) investigated the effectiveness of a hybrid system of photovoltaic panels and wind turbines for generating electricity in five climate- and terrain-dependent cities, demonstrating variations in solar radiation intensity and wind speeds due to various geographic locations at different peak power generation times. Higher solar energy does not necessarily translate into higher photovoltaic power

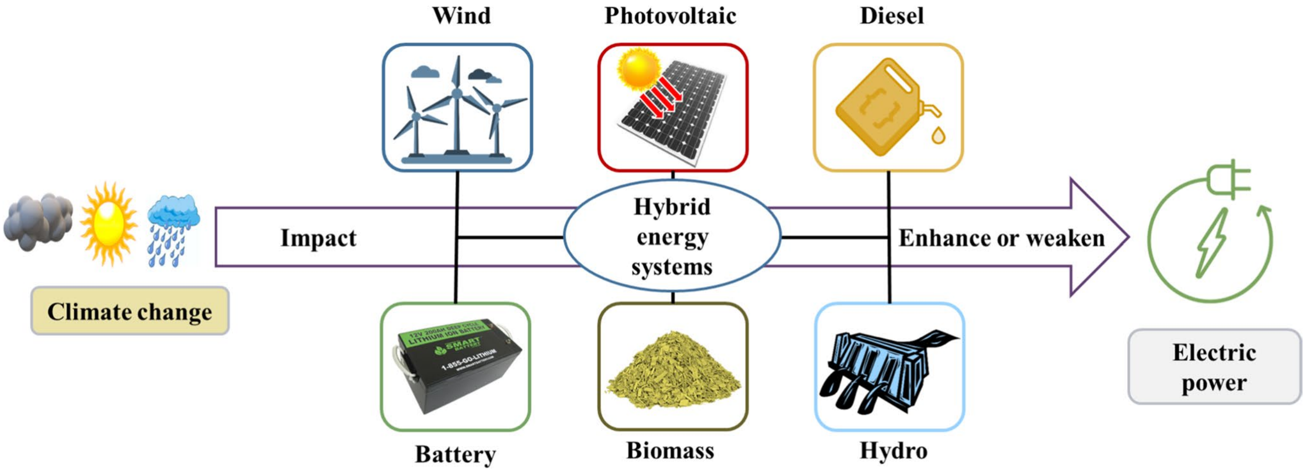

Fig. 4 Impact of climate change on electricity production in a hybrid energy system. Climate change can affect multiple energy system parameters. Solar energy is mainly affected by daylight hours, unavailable at night, and rainy weather diminishes light intensity. In addition, hydroelectric systems are affected by changes in wind speed, seasonal droughts, and excessive rainfall. The hybrid energy system includes wind, photovoltaic, diesel, battery, biomass, and hydroelectric energy sources with solid climate regulations that can withstand severe climate change

Table 2 Quantitative values of climate change impacts on hybrid energy systems. A comparison of the impact of hybrid energy sources and single energy systems on climate change is determined. Energy combination types, climatic conditions, and system impacts are briefly described. The difference in energy efficiency reflects the effect of the hybrid energy system. KVA is kilo volt-amperes

Hybrid energy systems/single energy systems	Climatic conditions	Hybrid energy system impact	Reference
25% photovoltaic/75% hydroelectric	Low altitude, temperature: +5 ℃	Electrical energy rate: − 36.67% (maximum)	François et al. (2018)
	Low altitude, precipitation: +50%	Electrical load rate: +36.67% (maximum)	
	High altitude, temperature: +5 ℃	Electrical energy load rate: − 56.25% (maximum)	
	High altitude, precipitation: +50%	Electrical load rate: +55.56% (maximum)	
Photovoltaic	Temperature: +8 °C	Electrical energy load rate: − 5% (maximum)	
Photovoltaic/fuel cell	Summer	Power: 257.980 kVA (daytime); 339.815 kVA (night-time)	Senthil et al. (2018)
	Winter	Power: 282.276 kVA (daytime); 337.394 kVA (night-time)	
Wind/fuel cell	Summer	Power: 308.264 kVA (daytime); 292.297 kVA (night-time)	
	Winter	Power: 249.851 kVA (daytime); 198.677 kVA (night-time)	
Photovoltaic/wind/fuel cell	Summer	Power: 307.900 kVA (daytime); 362.471 kVA (night-time)	
	Winter	Power: 275.865 kVA (daytime); 261.913 kVA (night-time)	
7.83% photovoltaic/92.17% wind	Solar radiation: 182.8 watts/m^2 Wind speed: 13.18 m/second	Power: 136.5 megawatts	Tazay et al. (2020)
	Solar radiation: 359.7 watts/m^2 Wind speed: 15.62 m/second	Power: 217.9 megawatts	
Photovoltaic	Solar radiation: 182.8 watts/m^2	Power: 8.9 megawatts	
	Solar radiation: 359.7 watts/m^2	Power: 17.9 megawatts	
Wind	Wind speed: 13.18 m/second	Power: 127.6 megawatts	
	Wind speed: 15.62 m/second	Power: 200 megawatts	
Photovoltaic/water	Extremely wet year	Power generation: 8.42×10^9 kilowatts-hour	Li and Qiu (2016)
	Extremely dry	Power generation: 5.89×10^9 kilowatts-hour	
	Normal year	Power generation: 7.29×10^9 kilowatts-hour	

because higher photovoltaic panel temperatures reduce the efficiency of the panels and the amount of energy produced (Bayrak et al. 2019). In the Longyangxia photovoltaic/hydroelectric power system, hydropower plays a dominant role, and inflow conditions determine annual power generation (Yang et al. 2021).

Hydro-meteorological variables may alter how much water is used in power generation, but there may also be indirect effects due to increased water supply competition (Teotónio et al. 2017). Hybrid energy systems embody higher power supply stability against natural disaster disruptions. Galvan et al. (2020) found that connected microgrid operation of photovoltaic/battery systems has stronger resilience to natural disasters, reducing the likelihood of power outages by 38–58% on sunny days and 8–9% on rainy days and enhancing the stability of maintaining power supply.

Due to the uncertainty surrounding climate change values, optimization techniques that quantify the possible effects of extreme weather events on energy systems enable a better evaluation of the resilience of energy systems under various climates (Perera et al. 2020). Modeling climatic uncertainty and occurrence probabilities allow for an efficient assessment of the output effects of hybrid energy systems (Zakaria et al. 2020). The microgrid combined energy approach is a novel way to combine different energy sources to fulfill the best local demands with the flexibility to connect or disconnect from the utility grid (Tummuru et al. 2019). Microgrid electrical systems' control functions will help generate more energy independent of the grid, provide backup to the utility grid, and secure energy supply in emergencies caused by major storms or natural disasters (Ghenai et al. 2020).

In summary, hybrid energy systems can increase efficiency under favorable climate changes and maintain high output levels under adverse conditions. Hybrid energy systems are more resilient to adverse weather conditions than a single energy source. They can adjust how much energy is distributed throughout the system to achieve significant energy efficiency. The combination of microgrids is also helpful for energy security under extreme climate conditions, although climate change is uncertain and needs to be studied as best as possible.

Hybrid energy system's impact on climate change

The leading cause of global warming is energy-related greenhouse gas emissions (Change 2018; Kang et al. 2020). Conventional fossil fuels generate vast volumes of greenhouse gases and possibly toxic substances, which have observable long-term consequences and will contribute to future climate change (Karmaker et al. 2020). Hence, rapid energy system evolution and a high share of renewable energy are required to reduce greenhouse gas emissions (Pastore et al. 2022; Rabiee et al. 2021). A carbon tax would also be an appropriate policy to create incentives for large-scale renewable energy projects (Baneshi and Hadianfard 2016).

The primary approach to reducing greenhouse gas emissions and environmental pollution is utilizing renewable energy sources' sustainability. By this concept, clean and reliable renewable energy sources replace the traditional, highly polluting fossil energy sources and prevent the adverse effects of global warming (Razmjoo et al. 2021). As given in Table 3, the quantified climate change values are well presented for different energy combinations.

This table identifies that hybrid energy systems in different combinations have higher carbon emission reduction benefits. Moreover, there is a positive relationship between carbon emission reduction capacity and the percentage of renewables.

Ajlan et al. (2017) compared the carbon emissions from multiple renewable energy systems and non-renewable diesel resources, which is the primary contributing energy source for carbon dioxide. Solar and wind energy systems demonstrated the best carbon emission reduction performance, which reduced carbon emissions by 100%. Thus, abundant solar energy and wind conditions can influence environmental performance measures and reduce greenhouse gas pollution (Meng et al. 2022). Merida et al. (2021) reported that hybrid pump-turbine/photovoltaic systems show a 30-fold reduction in climate change burden relative to diesel-only systems, with significant potential for further reductions in farm-level pollutant emissions.

Lead-acid batteries that extract and process lead for energy (Yu et al. 2018) have a greater climate change impact compared to lithium batteries. For instance, Aberilla et al. (2020) compared several energy combinations of diesel and photovoltaic/wind with lead-acid and lithium batteries. They found that hybrid solar photovoltaics/wind systems with battery storage have 17–40% lower impacts per kilowatt-hour produced than identical stand-alone installations. However, a home photovoltaic system using lead-acid batteries produces 131 g of carbon dioxide equivalent per kilowatt-hour throughout its lifetime instead of 105 g for a design using lithium-ion batteries. If a lead-acid battery is used, the wind stand-alone systems' greenhouse gas emissions are 470 g carbon dioxide equivalent/kilowatt-hour and 440 g carbon dioxide equivalent/kilowatt-hour when a lithium-ion battery is used. Thus, a lithium battery is a preferred option for the energy battery combination.

Burning fossil fuels in traditional power plants results in significant carbon dioxide emissions and other greenhouse gases. Replacing fossil fuels with a renewable hybrid energy system consisting of a 50% photovoltaic/21% wind/29% diesel achieves a 66.3% renewable component. It reduces carbon dioxide and other greenhouse gas emissions by about 16 tons, representing approximately a 25% yearly reduction (Shezan et al. 2016). In addition, Haghighat et al. (2016) demonstrated that a system of diesel combined with photovoltaic and wind power generation reduced carbon dioxide emissions by 74% (1,578,800 kg of carbon dioxide/year) compared with a single diesel power generation. Diemuodeke et al. (2016) added different combinations of photovoltaic and wind to diesel electricity production systems. Both varieties reduce greenhouse gas pollution. The photovoltaic/wind/diesel system saves 13,156,807 kg of carbon dioxide/year compared to conventional generation, significantly changing the local from the severe greenhouse effect. Therefore, combined diesel and renewable configurations have a shallow carbon footprint because renewable hybrid energy systems reduce the amount of fuel burned.

Diesel-free renewable hybrid energy sources have a higher carbon reduction effect and exceptionally ensure climate stability (Mandal et al. 2018). Figure 5 shows the comparison of hybrid and single energy systems in terms of climate change, which can visually illustrate that hybrid energy systems have a lower climate change potential.

Distributed generation systems integration improves the carbon emissions of traditional centralized generation networks; for instance, Liu et al. (2018) simulated a 42% enhanced carbon reduction capacity of off-grid distributed

Table 3 Climate change potential of different hybrid energy systems. Details about climate change, hybrid energy systems set up optimally, and renewable fractions are briefly described. The renewable fraction reflects the energy system's degree of renewability. Climate change data refer to the release of carbon emissions. "–" indicates that not mentioned

Hybrid energy systems/single energy systems	Optimal combination	Renewable proportion	Climate change data (carbon emissions)	Reference
Photovoltaic/wind/diesel	110 kilowatts photovoltaic array, 80 kilowatts wind turbine, No.18 12 V battery, 40 kilowatts diesel generator, 80 kilowatts converter	64%	84,007 kg/year (70% reduction)	Ajlan et al. (2017)
Photovoltaic/wind	250 kilowatts photovoltaic array, 80 kilowatts wind turbine, No. 260 12 V battery, 100 kilowatts converter	100%	0 kg/year (100% reduction)	
Wind/diesel	120 kilowatts wind turbine, No. 20 12 V battery, two 40 kilowatts and 90 kilowatts diesel generators, and a 30 kilowatts converter	38%	152,212 kg/year (44% reduction)	
Photovoltaic/diesel	180 kilowatts photovoltaic array, No. 20 12 V batteries, 40 kilowatts diesel generators, 90 kilowatts converter	54%	108,161 kg/year (60% reduction)	
Single diesel	Two 40 kilowatts and 90 kilowatts diesel generators	0%	271,206 kg/year	
Hybrid pump-turbine/photovoltaic	–	–	2,600 g carbon dioxide equivalent/kilowatt-hour	Merida et al. (2021)
Diesel	–	0%	73,000 g carbon dioxide equivalent/kilowatt-hour	
Photovoltaic/wind/lithium battery	1.29-kilowatt peak photovoltaic panel, 5 kilowatts wind turbine, 6 kilowatts-hour lithium battery, 1.4 kilowatts converter	–	244 g carbon dioxide equivalent/kilowatt-hour	Aberilla et al. (2020)
Photovoltaic/wind/lead-acid batteries	1.29 kilowatts peak photovoltaic panels, 5 kilowatts wind, 10 kilowatt-hour lead-acid battery, 0.9 kilowatts converter	–	262 g carbon dioxide equivalent/kilowatt-hour	
Wind/lithium battery	10 kilowatts wind turbine, 22 kilowatt-hour lithium battery, 2.2 kilowatts converter	–	437 g carbon dioxide equivalent/kilowatt-hour	
Wind/lead-acid batteries	10 kilowatts wind turbine, 37-kilowatt-hour lead-acid battery, 2.4 kilowatts converter	–	471 g carbon dioxide equivalent/kilowatt-hour	
Photovoltaic/lithium battery	3.45-kilowatt peak photovoltaic panels, 10-kilowatt-hour lithium battery, 1.4-kilowatt converter	–	105 g carbon dioxide equivalent/kilowatt-hour	
Photovoltaic/lead-acid batteries	2.89-kilowatt peak photovoltaic panels, 21-kilowatt-hour lead-acid battery, 1.8 kilowatts converter	–	131 g carbon dioxide equivalent/kilowatt-hour	
50% photovoltaic/21% wind/29% diesel	18 kilowatts photovoltaic panels, two 10 kilowatts wind turbines, 15 kilowatts diesel generator, 25 batteries with 3 kilowatts converter	66.3%	198,347.984 kilotons/year	Shezan et al. (2016)
Conventional power	–	–	198,348 kilotons/year	

Table 3 (continued)

Hybrid energy systems/single energy systems	Optimal combination	Renewable proportion	Climate change data (carbon emissions)	Reference
96% photovoltaic/3% wind/1% diesel	160 kilowatts photovoltaic, 10 kilowatts wind turbine, 25 kilowatts diesel generator, 80 kilowatts converter	99%	4262 kg/year	Haghighat et al. (2016)
24% wind/76% battery	10 kilowatts wind turbine, 25 kilowatts generator, 80 kilowatts converter	24%	131,026 kg/year	
98% photovoltaic/2% diesel	170 kilowatts photovoltaic, 25 kilowatts diesel generator, 80 kilowatts converter	98%	5,548 kg/year	
97% photovoltaic/3% wind	200 kilowatts photovoltaic, 10 kilowatts wind turbine, 40 kilowatts converter	100%	0	
Wind	10 kilowatts wind turbine, 40 kilowatts converter	100%	0	
Photovoltaic	200 kilowatts photovoltaic, 40 kilowatts converter	100%	0	
Diesel	25 kilowatts diesel generator, 40 kilowatts converter	0%	162,142 kg of carbon dioxide/year	
Photovoltaic/wind/diesel	25,000 kilowatts photovoltaic, 25,000 wind turbines, 40,000 kilowatts/hour battery, 25,000 diesel generators, 15,000-kilowatt converters	38%	13,967,743 kg/year	Diemuodeke et al. (2016)
Wind/diesel	25,000 wind turbines, 20,000 kilowatt-hour battery, 25,000 diesel generators, 4,000-kilowatt converters	18%	18,887,588 kg/year	
Photovoltaic/diesel	20,000 kilowatts photovoltaic array, 30,000 kilowatts/hour battery, 25,000 diesel generator, 10,000 kilowatts converter	14%	19,454,924 kg/year	
Diesel/battery	25,000 diesel generator, 15,000 kilowatts/hour battery, 3,000 kilowatts converter	0%	27,121,554 kg/year	
Photovoltaic/diesel/battery	73 kilowatts photovoltaic array, 56 batteries, 57 kilowatts diesel generator, 28 kilowatts inverter	89%	13,720 kg/year	Mandal et al. (2018)
Power grid	–	89%	41,085 kg/year	
Diesel	–	0%	89,338 kg/year	
Kerosene	–	0%	36,135 kg/year	

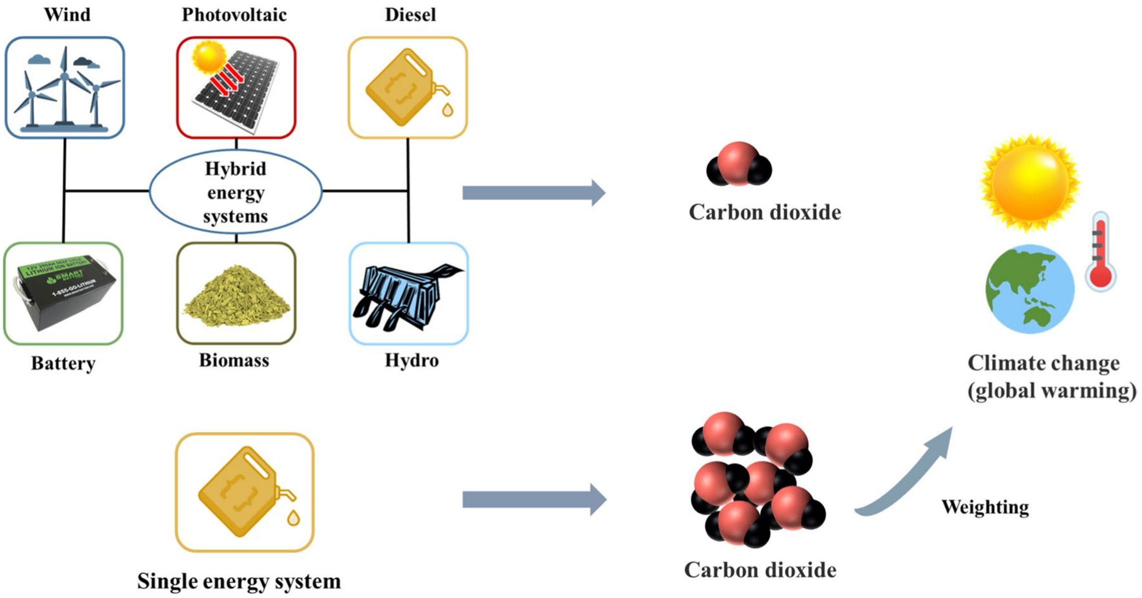

Fig. 5 Comparison of the hybrid and single energy systems' effects on climate change. The impact of the energy system on climate change is mainly in carbon dioxide emissions. The hybrid energy system has a lower climate impact potential because adding renewable energy sources reduces carbon dioxide emissions, and the global warming trend can be attenuated. In contrast, single energy systems have a greater potential to pollute the environment and contribute to climate change. Therefore, hybrid energy systems are less climate-altering and more climate-stable than single energy systems

photovoltaic/wind/diesel systems. However, such hybridization increases the average daily energy cost by 10%. Roy et al. (2020) found that innovative distributed hybrid systems applied to biomass/combustion batteries could reduce 1510 tons of carbon dioxide annually. The distributed generation approach markedly saves carbon dioxide emissions and reduces the potential for climate change from the generation system.

In conclusion, the hybrid energy system reduces the possibility of climate change impact and the proportion of greenhouse gases in the output by-product gases due to increasing renewables proportion. Therefore, the hybrid energy system contributes to lowering the carbon emission output of conventional energy sources and, therefore, is more sustainable. In contrast, distributed generation system is a novel power generation type that effectively improves the hybrid energy system's carbon footprint.

Climate change effects on the complementarity of hybrid energy systems

Hybrid energy systems' capacity to generate electricity is severely impacted by the unpredictability of the climate and weather, making hybridization more challenging to offer a secure and consistent power supply (Guezgouz et al. 2022; Lian et al. 2019). Climate variations in runoff rate, solar intensity, and wind speed can lead to uncertainty in complementary operations (Yan et al. 2020; Zhang et al. 2020). Climate-dependent renewables such as wind, solar, and hydropower are mainly subject to uncertain natural conditions, which means there are challenges in providing a reliable and stable electricity supply (Wang et al. 2019a). The energy system's size, sensitivity, and adaptability all impact these uncertainties (Viviescas et al. 2019). Extreme weather events will become more frequent, severe, and prolonged due to climate change, and future climatic scenarios show how this may affect the stability of the world's electrical systems (Panteli and Mancarella 2015; Yang et al. 2022). However, this issue can be partially eased by merging complementary sources into a hybrid system and using the suggested dependable and economic dispatch approach. Hybrid renewable energy systems are more reliable than single energy systems (Abbes et al. 2014; Sawle et al. 2018), which is more advantageous in integrating multiple energy resources (Tezer et al. 2017). Jurasz et al. (2018) studied the complementarity of solar and wind energy, the impact on battery power, the need to reduce the potential for required energy storage, the impact on netload, or the change in complementarity due to climate change. The complementarity of resources can change the storage and system reliability of electricity. Wang et al. (2021) verified that the complementary photovoltaic/wind/hydroelectric energy model could obtain more stable and reliable power output than the single energy model.

Few studies have considered how hybrid energy systems will be impacted by climate change and evaluated how hybrid energy systems might work in tandem to adapt to climate change (Yang et al. 2022). However, this section outlines the parameters that have changed in relation to how the hybrid energy system's complementarity has changed due to climate change. Table 4 and Fig. 6 indicate that the hybrid energy system maintains a higher complementarity under strong climate change, and its complementarity meets the generation load demand.

The complementarity of numerous hybrid energy systems listed in Table 4 varies in response to climate change. The higher energy complementarity is observed compared to individual energy systems.

Rapid weather changes will somewhat impact the reliability of the power supply to the distribution network because renewable energy production is closely attached to meteorological conditions (Su et al. 2020). Jiang et al. (2021) measured the robustness of several hybrid photovoltaic/wind/hydroelectric energy types under different climatic conditions (water flow, photovoltaic power, and wind speed). The photovoltaic/wind/hydroelectric system was the most robust energy system to address climate change, resulting in a 4.90% increase in system power generation and a 37% guarantee. Moreover, the authors found that water flow is the largest factor affecting its performance efficiency. The likelihood of successfully satisfying stakeholder criteria through complementary manipulation is significantly higher than in a single operation. The complementary nature of photovoltaic and wind energy can be considered to increase the efficiency of power generation because the complementary manipulation reduces the impact of the penalty function setting in the system power output on the best choice. Yang et al. (2022) simulated and compared the energy complementarity of a photovoltaic/hydroelectric system under 961 different climate conditions data. The hybrid energy scenario adds 410 million kWh of annual electricity generation and a 63.14% guarantee rate, illustrating that hydropower and photovoltaic diminish the sensitivity to climate change impacts under complementary energy operating rules. On the other hand, the single energy system appears vulnerable (guarantee rate: 8.47%).

Hybrid photovoltaic/wind/hydroelectric power systems exhibit higher seasonal complementary energy benefits than separate operations from a single energy source (Tang et al. 2020). In particular, in autumn, the complementarity between energy sources was substantially improved (21.8% increase in the mutual coefficient) and proved that the interconnection of multiple energy sources guarantees year-round electricity and power quality throughout the day. Cheng et al. (2022) also studied complementary energy operations. They used remote sensing to predict energy operations under changing future climate scenarios. They found that complementary processes have higher power generation (5.46% increase) and higher reliability (5.13% increase) than single energy operations. Modern power systems now greatly emphasize the complementing process of hybrid power plants (Ming et al. 2018). In photovoltaic/wind/diesel systems, diesel fuel is only used as a backup energy source when solar and wind energy cannot satisfy load demand (Mandal et al. 2018). Diesel generator sets ensure the system's reliability under extreme climate conditions and enhance the system's economy (Liu et al. 2022). Li et al. (2019) investigated water/photovoltaic complementarity operations. Energy systems operating in a complementary manner can adapt to variable climates when runoff is constrained while being supplemented by generation at the photovoltaic output and increasing the guarantee of meeting urban load requirements by 10.39%. In addition, Puspitarini et al. (2020) found that the increase in flux caused by the accelerated rate of ice melting prompted by rising temperatures was 25% photovoltaic and 75% hydroelectric. Climate change has a significantly less impact on the complementarity of water and solar energy because of the increased sensitivity to changes in temperature and precipitation. Furthermore, elevation, glacier cover, and basin structure have uncertain effects. Higher energy complementarity is well demonstrated compared to individual energy systems.

However, the complementarity results depend on different methods, metrics, spatial and temporal resolutions, and data sample sizes (Canales et al. 2020; Kapica et al. 2021). Thus, complementarity analysis lacks a standard parameter and prevents researchers from comparing findings consistently (Yang et al. 2021). Additionally, there are more complex, multi-objective problems with complementary linked energy economics (Tang et al. 2020). As a result, it will be easier to plan, manage, and evaluate energy systems if diverse unpredictable inputs related to climate change are clearly defined. This will also help to inform sound decisions for planning and operating energy systems in a changing environment (Jiang et al. 2021). To reach the ideal system configuration, climatic modeling projections are used to assess the complementary energy efficiency of the area. Zhang et al. (2019) measured the weather forecast data to derive the optimal solution for the configuration of the photovoltaic/wind/hydrogen energy system, thus improving the system power reliability and selecting the optimal system configuration helps to avoid wasteful capital expenditures.

This section provides an overview of how a hybrid energy system performs in terms of energy efficiency under various climatic situations, which helps to identify the best energy configuration and provides greater climate stability than a single energy system. Hybrid energy systems are more advantageous in mitigating climate change, reducing the system's carbon emissions output. Moreover, complementary regulation between energy sources to adapt to climate change is more flexible and ensures efficient power production between energy sources.

Table 4 Complementarity of hybrid energy systems under different climate changes. The changes in the type of energy complementarity, climate change, system power generation, complementarity coefficient, and guarantee rate are briefly described. The difference in system generation response to the efficiency of energy interactions due to climate change is also mentioned. The complementary system and guarantee rate are vital elements to evaluate the complementarity of energy systems. The "–'" refers to not mentioned

Types of energy complementation	Climate change	System power generation	Complementary coefficient	Guarantee rate	Reference
Photovoltaic/wind/hydroelectric	Change water flow, light intensity, and wind speed in the range of − 10% to + 10%	4.90% increase	–	38% increase	Jiang et al. (2021)
Wind/hydroelectric		4.66% increase	–	38% increase	
Photovoltaic/wind		3.43% increase	–	34.40% increase	
Hydroelectric		2.70% increase	–	23.36% increase	
Photovoltaic/hydroelectric	961 different precipitation and solar radiation climatic conditions	7.21 billion kilowatt-hours/year	–	71.61%	Yang et al. (2022)
Single-energy power generation		6.8 billion kilowatt-hours/year	–	8.47%	
Photovoltaic/wind/complementary hydroelectric operation	Summer	–	0.9935	–	Tang et al. (2020)
	Autumn	–	0.9902	–	
	Winter	–	0.5947	–	
Photovoltaic/wind/single hydro operation	Summer	–	0.9394	–	
	Autumn	–	0.8130	–	
	Winter	–	0.5763	–	
Photovoltaic/wind/hydroelectric	Flow rate: + 7.70% Solar radiation: − 0.72% Wind speed: − 2.76%	2.11% increase	–	3.74% increase	Cheng et al. (2022)
	Flow rate: + 21.19% Solar radiation: + 0.45% Wind speed:− 4.17%	5.46% increase	–	5.13% increase	
Photovoltaic/hydroelectric complementary operation	Average photovoltaic output: 173.07-megawatt Average runoff: 553.50 m^3/second	2.65% increase	–	10.39% increase	Li et al. (2019)
Photovoltaic/single hydroelectric operation		2.12% increase	–	6.25% decline	
25% photovoltaic/75% hydroelectric	Precipitation: + 40% Temperature: + 8 °C Upper basin	Penetration rate: 32% increase (glacier 10%); 27% (glacier 50%); 17% (glacier 100%)	33.3% decline (glacier 10%); 90% (glacier 50%); − 135% (glacier 100%)	–	Puspitarini et al. (2020)
	Precipitation: + 0% Temperature: + 8 °C Upper Basin	Penetration rate: 30% increase (glacier 10%); 27% (glacier 50%); 17% (glacier 100%)	35% decline (glacier 10%); 70% (glacier 50%); − 125% (glacier 100%)	–	
	Precipitation: − 40% Temperature: + 8 °C Upper Basin	Penetration rate: 28% increase (glacier 10%); 28% (glacier 50%); 17% (glacier 100%)	25% decline (glacier 10%); 65% (glacier 50%); − 115% (glacier 100%)	–	

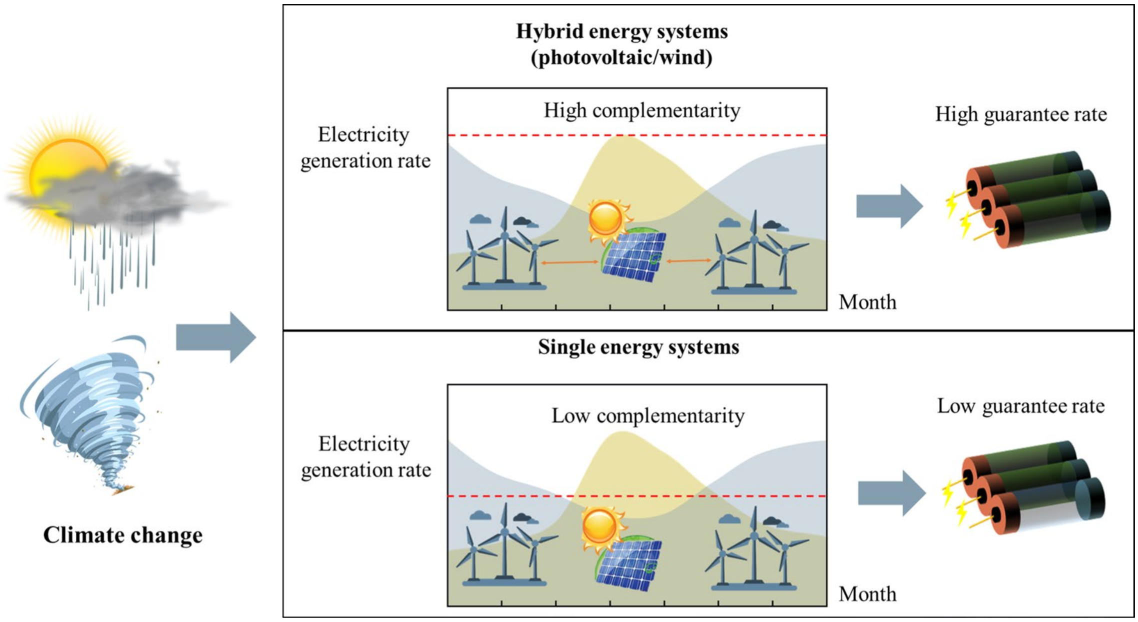

Fig. 6 Impact of climate change on the complementarity of hybrid energy systems. The top graph shows that hybrid energy systems can help supplement electricity generation with climate-independent energy sources under severe climate change, ensuring a higher probability of power generation. The bottom graph shows the inability of a single energy system to maintain higher complementarity that occurs under climate change, causing a higher chance of power failure and not guaranteeing power generation. Thus, hybrid energy systems have higher system guarantee rates to withstand climate change, while the power supply of single energy systems is more affected by climate change

Cost analysis

Economic parameters of the hybrid energy system

Increasing socioeconomic activity due to population growth necessitates a steady energy supply to keep up with demand (Olatomiwa et al. 2015). Satisfying everyday power needs through expensive conventional fuels is a huge challenge for the industry (Boamah 2020). For example, Nigeria's high cost of electricity and lack of reliability has crippled industrialization and national businesses (Adesanya and Pearce 2019; Osakwe 2018). Grid connection technology has made it possible to create electricity from renewable resources, and any surplus energy may be sold to the national grid (Ali et al. 2021a). Hybrid energy systems have the potential to address energy security, energy equity, and environmental sustainability (Pascasio et al. 2021). There is an urgent need for economically viable hybrid energy systems that meet the electrical load requirements of individual households and reduce local reliance on imported fossil fuels (Al-Turjman et al. 2020). Table 5 lists the essential indicators for the economic analysis of the energy system.

This table describes three important parameter metrics in assessing the economic viability of hybrid energy systems. It facilitates further analysis of hybrid energy systems that reduce the burden of urban electric load consumption and provide economically viable rubrics for producing electricity.

The net present value of an asset is the value of all current costs minus the present value of all revenues during its lifespan (Abdelhady 2021), which is checked by the optimal combination of system components based on the life cycle cost (Haratian et al. 2018). The total net present cost includes the initial capital cost, replacement cost, operation and maintenance cost, and cost of energy (fuel cost + any related expenditures) throughout the whole project life. Changes in discount rates and fuel costs significantly affect the cost of energy and net present value costs (Ramesh and Saini 2020). The cost of recovering the components' residual value at the end of the project's life cycle must be included when calculating the system's net present cost (Fazelpour et al. 2016). The net present cost is a more reliable and less deviant indicator, thus being prioritized as an economic parameter in optimizing the economic feasibility of the system. In addition, the variation in equipment replacement costs needs to be minimized, which will help to reduce the impact on the final results. Movahediyan and Askarzadeh (2018) evaluated the net present value of photovoltaic/diesel generators for isolated community design, provided defined parameters for selecting the best system configuration, and developed a crow search algorithm to

Table 5 Economic assessment indicators for hybrid energy systems. The parameters for assessing the economic feasibility of the hybrid energy system are identified. The calculation method and definition of each parameter are also indicated, which facilitates the exploration of the cost of energy profiles. "i" means the real annual rate; "N" shows the project period.

Economic parameters	Formulas	Definition	Reference
Net present cost	Net present cost = initial costs + operating costs + replacement costs + fuel costs = C_{annual}/(i(i + 1)^N/(1 + i)^N-1)	The present value of all costs minus the current value of all revenues, including system start-up costs, replacement costs, and maintenance costs	Buenfil et al. (2022); Das et al. (2017); Gbadamosi et al. (2022); Karmaker et al. (2018); Peddeti et al. (2022); Razmjoo et al. (2019)
Annualized cost	$Cost_{annual}$ = annualized initial costs + annualized operating costs + annualized replacement costs = net present cost × (i(i + 1)^N/(1 + i)^N-1)	The annualized cost of the system is assessed by adding annualized capital cost, annualized replacement cost, and annualized maintenance cost to the average annual cost of the system	Alturki et al. (2020); Adeyemo and Amusan 2022); Basu et al. (2021); Isa et al. (2016); Mandal et al. (2018); Nawaz et al. (2018); Restrepo et al. (2018); Singh et al. (2020); Turkdogan (2021)
Cost of energy	Cost of energy = $cost_{annual}$/electricity provided = net present cost/total energy consumed time	Average cost per kilowatt-hour (dollars/kilowatt-hour) of usable electricity, annualized total system cost as a percentage of the annual electricity provided by the system	Bhakta and Mukherjee (2017); Campana et al. (2019); Mohammed et al. (2019)

find the minimum net present cost. Nesamalar et al. (2021) used the net present cost of on-grid and off-grid systems to enhance customer decision-making by comparing the economic advantages of on-grid and off-grid systems. Genetic algorithms and HOMER Pro software are often used to optimize energy system economic parameters to determine the best solution for achieving the minimum net present cost (Suresh et al. 2020).

Total annualized costs include the entire system's capital, operating, maintenance, and replacement costs (Gökçek and Kale 2018). The actual discount rate and discount factor are used in the HOMER software to calculate the hybrid energy system, which is converted into an annualized total cost through the net present cost (Jahangir and Cheraghi 2020). Cost of energy information is obtained by calculating the ratio of annualized cost to total annualized electricity consumption served by the system. Aziz et al. (2019) optimizes energy costs by reducing the annual cost of unmet load and/or reducing excess yearly energy. The capital recovery factor of annualized cash flows affects the final annualized cost and thus changes the project life cycle decision (Abba et al. 2021).

The energy cost is the fundamental economic criterion for optimizing the size of a hybrid system and is defined as the average cost per kilowatt-hour (dollars/kilowatt-hour) of valuable electricity (Mandal et al. 2018). This is one of the most critical parameters in finding the cost of energy effectiveness of hybrid system services (Das et al. 2019). The minor energy cost differences may be partly due to the relatively different mix configurations of the various studies (Awopone 2021). For calculating its value analysis, it is necessary to consider the initial cost, installation cost, maintenance cost, operation cost, and replacement cost of the various components used to build the hybrid energy system (Ismail et al. 2015). The value of money, economic data (inflation and interest rates), and the residual value of parts to be also replaced impact. Oladigbolu et al. (2021) performed a sensitivity analysis of the energy cost to evaluate the hybrid system's optimum economic performance for rural health institutions in Nigeria. They found that the cost of energy lowers as load demand rises. As a result, the policies required to support the system should focus on offering low discount rates to investors to encourage the system's adoption and produce profitable energy costs for consumers.

Cost analysis of hybrid energy system case

The most significant feature of hybrid renewables is using many non-conventional energy sources to increase system effectiveness and economic constraints (Khan et al. 2018). Solar and wind resources are unlimited; their conversion into power is pollution-free and easily accessible (Vinod et al. 2018). Hybrid renewable energy systems provide a more reliable output throughout the year and can be planned to meet the desired quality at a lower cost (Al Busaidi et al. 2016). Hybrid energy systems that generate electricity from two or more complementary sources are more efficient, reliable, and cost-effective than single energy systems (Lee et al. 2019). Adefarati et al. (2021) found that altering the operational cost, return on investment, and internal rate of return parameters enhanced the standard of living and economic activity in the area where the energy system is located. They also examined the concepts of net present cost, cost of energy, and the annualized cost of the system. Table 6 shows the economic variability of a hybrid energy system versus a single energy system.

This table shows the net present cost and energy cost for the optimal configuration of hybrid energy systems applied in different country regions and power loads. Hybrid energy systems are more economically viable and have lower net present cost and energy cost than single energy systems. A higher percentage of renewables in a hybrid energy system means lower energy costs and economic efficiency in most cases.

Renewable energy hybrid systems are considered highly efficient for traditional energy sources and significantly reduce the cost of energy use (Zhang et al. 2018). Li et al. (2018) compared the economic feasibility of three systems: grid-only, photovoltaic/grid, and photovoltaic/battery/grid, where using a hybrid photovoltaic/battery/grid system emitted the lowest amount of pollutants (9% reduction), but it also had the highest cost (65.74% increase). Therefore, compared to a modest photovoltaic/grid system with lower costs and fewer pollutant emissions, hybrid energy systems' cost and environmental benefits need to be considered. On-grid hybrid photovoltaic, fuel battery and battery cogeneration systems are used in Malaysian hospitals to achieve 30% cost savings in electricity generation (Isa et al. 2016). Despite having a high upfront cost, this sophisticated hybrid energy system dramatically lowers energy costs (by 49.2% compared to a single diesel engine). In addition, the battery stores excess power due to the large proportion of renewable energy components used, which reduces energy waste and meets standards for economic viability (Al-Ghussain et al. 2021). Hydrogen is an attractive way to establish zero-pollutant emission storage technology from various energy sources (Kalinci et al. 2017). Hydrogen can enhance energy efficiency and consequently result in savings because it can be incorporated into a hybrid energy system.

By comparing various hybrid energy systems to find the best photovoltaic/biomass/battery energy combination, Malik et al. (2021b) verified the economic viability of off-grid biomass hybrid systems, yielding significant electricity cost savings of 92% produced from conventional diesel systems. Photovoltaics and biomass are the most prominent components providing power generation, but both biomass gasifier units and photovoltaic arrays have high purchase, operation, and replacement maintenance costs (Tiwary et al. 2019). Therefore, improving biomass production and battery life technology is beneficial further to reduce the overall cost of hybrid energy systems and achieve higher economic efficiency. As a non-renewable energy source, diesel also has a higher production and utilization cost, which should be avoided as much as possible. In Yemen's Shafail, where solar energy resources are more plentiful, a combination of photovoltaic, wind, and diesel energy systems saves 45% of the energy cost compared to a single diesel system (Ajlan et al. 2017). The system uses less diesel due to the high renewable share attained.

Additionally, different energy combinations yield additional economic benefits. For example, Ibrahim et al. (2020) compared eleven off-grid energy combinations' cost and power production performance to apply to an economic seawater treatment system without a grid. They found that the photovoltaic/wind/diesel and photovoltaic/hydrokinetic turbine/diesel systems were economically viable solutions with energy costs of 0.2252 dollars and 0.1216 dollars/kilowatt-hour, respectively. This suggests that the hydrokinetic turbine system is a renewable energy source that entirely depends on fluid-generated power to drive the electricity generated. It is possible to drastically lower the energy cost by utilizing blends of biofuels with other resources due to the large regional waste production and the potential for local biogas production (Khan et al. 2022; Rad et al. 2020).

Hybrid energy systems may increase energy costs while improving system reliability. Fuel batteries were employed by Rad et al. (2020) to create a hybrid energy system that might help maintain energy balance and boost dependability during times of high power demand (Al-Othman et al. 2022). They would nevertheless raise energy prices by 33–37%. System costs with photovoltaic and wind energy are highly correlated to fluctuations in solar radiation, wind speed and changes in interest rates (Elkadeem et al. 2019b). Xu et al. (2020) introduced the economic parameter consideration of the abandonment rate, which, when calculated as a 5% abandonment rate, can reduce the energy cost of the hybrid photovoltaic/wind/hydroelectric pumped storage energy system to 0.091 dollars/kilowatt-hour. This ensures supply reliability to the local load and reduces the initial capital cost. The amount of load influences the hybrid energy system cost and the percentage of renewable and off-grid/on-the-grid are shown in **Fig. 7**.

Unlike individual systems, load demand is a significant factor in developing hybrid renewable energy systems, which offer more dependable electricity for off-grid and standalone applications (Al-falahi et al. 2017). The load factor changes with energy demand and fixed costs are inversely correlated with peak load. Rajbongshi et al. (2017) examined the peak fixed load of the photovoltaic/biomass/diesel

Table 6 Economic analysis of hybrid energy systems. Energy type and optimal allocation, country, load, renewable proportion, net present value, and energy cost are briefly described. The net present and energy costs refer to the system's cost at the configuration size. Key information refers to the information that needs to be noted in the application of this system. "–" refers to not mentioned

Hybrid energy systems/single energy systems	Optimum system scenario	Country/region	Load	Off-grid/on-grid	Renewable proportion	Net present cost (dollars)	Cost of energy (dollars/kilowatt-hour)	Key information	Reference
Photovoltaic/biomass/diesel	63 kilowatts photovoltaic, 10 kilowatts biogas, and 10 kilowatts and 15 kilowatts diesel generators	Golshan area, Iran	431 kilowatts-hour/day	On-grid	50.65%	398,151	19.3	The cost of electricity may be greatly decreased by using backup small-capacity generators with high-capacity photovoltaic panels	Kasaeian et al. (2019)
Photovoltaic/battery/grid	–	Kunming, China	90.8 kilowatt-hour/day		10%	179,876	0.116	Increased inverter ratings increase net present costs and cost of energy	Li et al. (2018)
Photovoltaic/grid	5 kilowatts photovoltaic array and 5 kilowatts inverter				10%	113,382	0.073		
Grid	–				0	108,530	0.070		
Photovoltaic/battery/fuel battery/grid	100 kilowatts grid power, 140 kilowatts photovoltaic, 50 kilowatts fuel battery, 150 Surrete 4KS25P battery storage, 80 kilowatts power converter, and 5 kg/hour reconditioner	Malaysia	250 kilowatt-hour/day		82%	106,551	0.091	Batteries can be used to store excess power from energy systems, improving system efficiency	Isa et al. (2016)
Photovoltaic/fuel battery/grid	100 kilowatts grid power, 140 kilowatts photovoltaic, 50 kilowatts fuel battery, 80 kilowatts power converter, and 5 kg/hour reconditioner				82%	99,094	0.085		

Table 6 (continued)

Hybrid energy systems/single energy systems	Optimum system scenario	Country/region	Load	Off-grid/on-grid	Renewable proportion	Net present cost (dollars)	Cost of energy (dollars/kilowatt-hour)	Key information	Reference
Photovoltaic/battery	100 kilowatts grid power, 3 kilowatts photovoltaic panels, 15 kilowatts inverter, and 15 kilowatts rectifier				5%	154,955	0.133		
Photovoltaic/grid	3 kilowatts photovoltaic panel, 15kw inverter				5%	148,764	0.128		
Diesel	–			–	0	206,710	0.179		
Photovoltaic/wind/fuel battery	300 kilowatts photovoltaic array, 150 kilowatts converter, 2 wind turbines, 100 kilowatts fuel battery, 200 kilowatts electrolysis tank, and 500 kg hydrogen tank	Bozcaada Island, Turkey	684,374 kilowatt-hour/year	–	90%	12,025,188	0.836	The development of hydrogen storage to convert excess energy into hydrogen provides a new direction for hybrid energy systems	Kalinci (2015)
Wind/fuel battery	3 wind turbines, 100 kilowatts fuel battery, 400 kilowatts electrolyzer, and 2250 kg hydrogen tank			–	100%	14,624,343	1.016		
Photovoltaic/wind/grid	20 kilowatts grid, 50 kilowatts photovoltaic, 50 kilowatts converter, and 1 wind turbine			On-grid	72%	2,631,285	0.112		
Photovoltaic/grid	135 kilowatts, 50 kilowatts photovoltaic array, and 50 kilowatts converter				9%	2,709,003	0.186		

Table 6 (continued)

Hybrid energy systems/single energy systems	Optimum system scenario	Country/region	Load	Off-grid/on-grid	Renewable proportion	Net present cost (dollars)	Cost of energy (dollars/kilowatt-hour)	Key information	Reference
Wind/grid	One wind turbine and 120 kilowatts grid				68%	2,343,611	0.103		
Grid	–				0	2,469,688	0.17		
Photovoltaic/biomass/wind	12 kilowatts photovoltaic array, 13 kilowatts biomass gasification system, 5 kilowatts wind turbine, No. 20. 12 V battery and 14 kilowatts converter	Western Himalayas, India	87.6 kilowatt-hour/day	Off-grid	100%	87,610	0.213	Devices with battery storage reduce the cost of energy and can provide power or feed excess power back into the grid	Malik et al. (2021b)
Photovoltaic/biomass	13 kilowatts photovoltaic array, 13 kW biomass gasification system, No. 20. 12 V battery and 14 kilowatts converter				100%	76,080	0.185		
Photovoltaic/wind	58 kilowatts photovoltaic array, 5 kilowatts wind turbine, No. 220. 12 V battery and 30 kilowatts converter			Off-grid or on-grid	100%	197,162	0.48		
Photovoltaic/diesel	42 kilowatts photovoltaic array, 13 kilowatts diesel generator, No. 30 12 V battery, and 24 kilowatts converter			Off-grid	86%	129,081	0.314		
Diesel	15 kilowatts diesel generator, No. 30. 12 V battery and 11 kilowatts converter			Off-grid	0	205,615	0.501		

Table 6 (continued)

Hybrid energy systems/single energy systems	Optimum system scenario	Country/region	Load	Off-grid/on-grid	Renewable proportion	Net present cost (dollars)	Cost of energy (dollars/kilowatt-hour)	Key information	Reference
Biomass/wind	14 kilowatts biomass gasification system, No. 30 12 V battery, and 12 kilowatts converter			On-grid	100%	91,143	0.222		
Biomass	16 kilowatts biomass gasification system, No.20. 12 V battery and 16 kilowatts converter			–	100%	78,964	0.192		
Photovoltaic/wind/diesel	40 kilowatts diesel generator, 110 kilowatts photovoltaic array, 80 kilowatts wind turbine, No.18 12 V battery, 80 kilowatts converter	Shafal Town, Yemen	886 kilowatt-hour/day	Off-grid	64%	722,356	0.137	Combined photovoltaic and wind turbine systems save 30% of energy costs, and photovoltaic/wind/diesel energy systems save 45% of the cost of energy	Ajlan et al. (2017)
Photovoltaic/wind	250 kilowatts photovoltaic array, 80 kilowatts wind turbine, No.260 12 V battery, 100 kilowatts converter				100%	924,792	0.172		
Wind/diesel	Two 40 kilowatts and 90 kilowatts diesel generators, 120 kilowatts wind turbine, No.20 12 V battery, and 30 kilowatts converter				38%	990,143	0.188		

Table 6 (continued)

Hybrid energy systems/single energy systems	Optimum system scenario	Country/region	Load	Off-grid/on-grid	Renewable proportion	Net present cost (dollars)	Cost of energy (dollars/kilowatt-hour)	Key information	Reference
Photovoltaic/diesel	40 kilowatts diesel generator, 180 kilowatts photovoltaic array, No.20 12 V batteries, and 90 kilowatts converter				54%	793,232	0.150		
Diesel	Two 40-kilowatt-hour and 90-kilowatt-hour diesel generators				0%	1,315,262	0.249		
Photovoltaic/hydrokinetic turbine/diesel	2.82 kilowatts photovoltaic panels, 3 hydrokinetic turbines, 4.9 kilowatts diesel generator, 0.984 kilowatts converter, and 15 kilowatt-hour lithium battery	The city of Ras El Bar in northern Egypt	–		98.2%	60,333	0.1216	Single energy system generates more excess power to charge battery packs	Ibrahim et al. (2020)
Hydrokinetic turbine/diesel	3 hydrokinetic turbines, 4.9 kilowatts diesel generator, 2.24 kilowatts converter, and 15 kilowatt-hour lithium battery				85.8%	750,000	0.1479		
Photovoltaic/hydrokinetic turbine	0.138 kilowatts photovoltaic panels, 4 hydrokinetic turbines, 0.00273 kilowatts converter, and 15 kilowatt-hour lithium battery				100%	60,000	0.1245		

Table 6 (continued)

Hybrid energy systems/single energy systems	Optimum system scenario	Country/region	Load	Off-grid/on-grid	Renewable proportion	Net present cost (dollars)	Cost of energy (dollars/kilowatt-hour)	Key information	Reference
Hydrokinetic turbine	Four hydrokinetic turbines, 0.00547 kilowatts converter, and 20-kilowatt-hour lithium battery				100%	66,000	0.1271		
Photovoltaic/wind/diesel	8.3 kilowatts photovoltaic panels, 10 kilowatts wind turbine, 4.9 kilowatts diesel generator, 5.29 kilowatts converter, and 15 kilowatt-hour lithium battery				52%	119,260	0.2252		
Wind/diesel	10 kilowatts wind turbine, 4.9 kilowatts diesel generator, 1.93 kilowatts converter, and 15 kilowatt-hour lithium battery				23.1%	130,000	0.2546		
Photovoltaic/diesel	0.919 kilowatts photovoltaic panels, 4.9 kilowatts diesel generator, 0.476 kilowatts converter, and 7 × 1 kilowatt-hour lithium batteries				3.7%	114,000	0.2294		
Photovoltaic/wind	26.4 kilowatts photovoltaic panels, 2 × 10 kilowatts wind turbines, 5.04 kilowatts converter, and 290 kilowatt-hour lithium battery				100%	210,000	0.4102		

Table 6 (continued)

Hybrid energy systems/single energy systems	Optimum system scenario	Country/region	Load	Off-grid/on-grid	Renewable proportion	Net present cost (dollars)	Cost of energy (dollars/kilowatt-hour)	Key information	Reference
Photovoltaic	2.2 kilowatts photovoltaic panels, 7.49 kW converter, and 421-kilowatt-hour lithium battery				100%	234,000	0.465		
Wind	9 × 10 kilowatts wind turbines, 17.1 kW converter, and 940 kWh lithium battery				100%	550,000	1.090		
Diesel	4.9 kilowatts diesel generator, 0.0365 kilowatts converter, 1 kilowatt-hour lithium battery				0%	114,000	0.2297		
Photovoltaic/biogas	100 kilowatts photovoltaic panel, 15 kilowatts biogas generator, 30 batteries, 45 kilowatts converter	Zavieh Sofla Village, Iran	361 kilowatt-hour/day		–	396,269	0.164	Fuel batteries can reduce system dependability but raise energy prices by 33–37%	Rad et al. (2020)
Photovoltaic/biogas/wind	90 kilowatts photovoltaic panels, 15 kilowatts biogas generator, 2 wind turbines, 30 batteries, 45 kilowatts converter					401,813	0.168		

Table 6 (continued)

Hybrid energy systems/single energy systems	Optimum system scenario	Country/region	Load	Off-grid/on-grid	Renewable proportion	Net present cost (dollars)	Cost of energy (dollars/kilowatt-hour)	Key information	Reference
Photovoltaic/biogas/fuel battery	75 kilowatts photovoltaic panel, 15 kilowatts biogas generator, 10 kilowatts fuel battery, 10 kilowatts electrolyzer, 15 kg hydrogen tank, 60 batteries, 30 kilowatts converter					464,597	0.240		
Photovoltaic/biogas/wind/fuel battery	75 kilowatts photovoltaic panel, 15 kilowatts biogas generator, 2 wind turbines, 10 kilowatts fuel battery, 10 kilowatts electrolyzer, 15 kg hydrogen tank, 60 batteries, 30 kilowatts converter					482,019	0.246		
Photovoltaic/wind/battery	120 kilowatts photovoltaic panels, 9 wind turbines, 120 batteries, 45 kilowatts converter					632,878	0.253		
Photovoltaic/wind/fuel battery/battery	120 kilowatts photovoltaic panels, 9 wind turbines, 30 kilowatts fuel battery, 15 kilowatts electrolyzer, 30 kg hydrogen tank, 90 batteries, 45 kilowatts converter					708,230	0.293		

Table 6 (continued)

Hybrid energy systems/single energy systems	Optimum system scenario	Country/region	Load	Off-grid/on-grid	Renewable proportion	Net present cost (dollars)	Cost of energy (dollars/kilowatt-hour)	Key information	Reference
Photovoltaic/wind/hydro	18 sets of 250 kilowatts wind turbines, 13,786 kilowatts photovoltaic, 1,726.6-kilowatt variable speed pumps, 5,376.7 kilowatts water turbines	Sichuan, China	–		–	–	0.2345	The photovoltaic/wind/hydro system had the lowest cost of energy of $0.091/kWh when the abandonment rate was 5%	Xu et al. (2020)
Photovoltaic/hydro	21,106.4 kilowatts photovoltaic, 3681.3 kilowatts variable speed pump, 5376.7 kilowatts water turbine					–	0.3493		
Wind/hydro	82 sets of 250 kilowatts wind turbines, 13,786 kilowatts photovoltaic, 4810 kilowatts variable speed pumps, 6341.6 kilowatts water turbines					–	0.4268		
Photovoltaic/wind/diesel	–	Damghan City, Semnan Province, Iran	22 kilowatt-hour/day	–	76.5%	34,741	0.338	Systems with the highest proportion of renewables also have the highest costs and require long-term planning to advance economic viability	Razmjoo and Davarpanah (2019)
Photovoltaic/wind	–				100%	84,781	0.826		
Wind/diesel	–				75.2%	70,375	0.686		
Photovoltaic/diesel	–				72.5%	48,471	0.472		

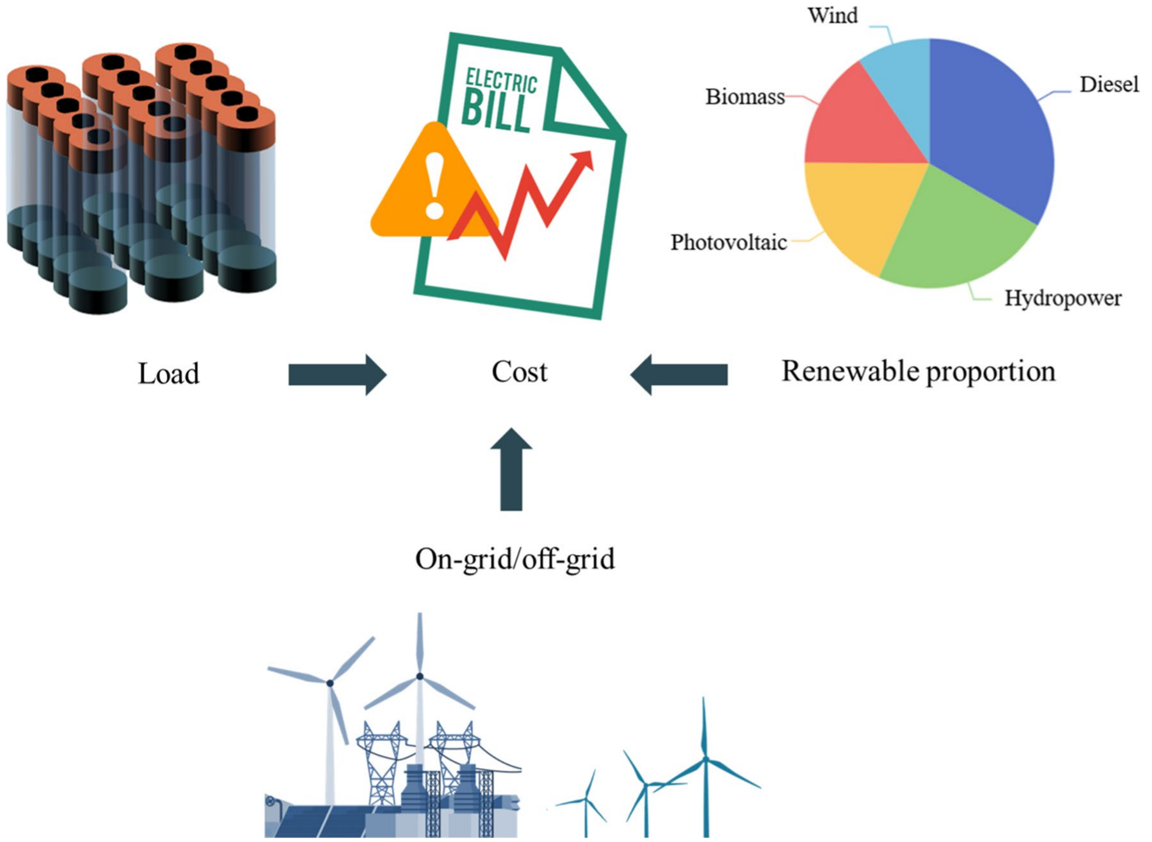

Fig. 7 Factors affecting the cost of the energy system. This figure shows that the system load factor, renewable proportion, and grid connection/off-grid degree affect the energy system cost. An increase in load factor reduces the cost of energy. Increasing the renewable proportion minimizes the application of traditional expensive energy sources. The off-grid energy system can sell excess power to the grid, thereby reducing energy costs

system. The authors found that the energy cost decreased from \$0.145 to \$0.119 as the load factor increased from 25 to 40%, so a higher load factor is needed to reduce the cost of electricity generation. Similarly, a solar/diesel/battery hybrid system was implemented in a rural Saharan community where load demand rose from 49.4 kWh/day to 89.4 kWh/day, causing a 33.35% decrease in photovoltaic penetration and a 31.6% reduction in energy cost (Fodhil et al. 2019).

The renewable proportion is the percentage of the system's overall energy production that comes from renewable energy sources and meets the load (Yuan et al. 2022). A high renewable energy percentage indicates a higher fraction of renewable energy in the load. To lessen the effects of environmental issues and to keep costs as low as possible, it is strongly advised to maintain a high share of renewable energy sources (Aziz et al. 2022). Increasing the renewable energy percentage reduces the net present value costs sustained by the system operator (He et al. 2023). However, it is necessary to comply with the government's energy policy by increasing the proportion of renewable energy sources with an appropriate renewable energy ratio and energy costs, reducing fuel and environmental pollution (Tsai et al. 2020). In this context, Pan et al. (2020) used a two-tier model to effectively lower the price of hydrogen supply at the planning stage by modifying the system's share of renewable energy equipment and sourcing power from an up-gradient site. However, large-scale use of renewable energy could threaten the power grid's security (Beyza and Yusta 2021), forcing the traditional distribution grid to move from employing a single power source to various renewable sources. This results in a tidal current reversal on the distribution grid, which changes the grid's power supply mode.

However, voltage distribution brings hidden risks to the distribution grid's safe operation (Gong et al. 2021; Topić et al. 2015). Even with greater reserve capacity, consuming significant renewable energy is difficult due to transmission congestion and transmission section caps (Tan et al. 2021). As a result, integrating renewable energy into the power system is fraught with volatility and stochasticity, and the share of renewable energy increases stochasticity (Chen et al. 2021). Additionally, the proportion of renewable energy cannot be precisely controlled due to fuel uncertainty. However, by imposing a maximum proportion limit on each technology to keep fuel diversity within reasonable limits and maximum proportion constraint, the proportion of high-cost energy can be controlled to the maximum extent possible (Ioannou et al. 2019).

Costly renewable energy technologies necessitate expenditure (Toopshekan et al. 2020). Depending on the operation mode, adopting hybrid systems can boost overall dependability, lower power costs, or even raise the value of electricity (Esmaeilion 2020; Jurasz et al. 2020). In off-grid mode, capital, operation, maintenance costs, and grid tariff are the inputs for the economic comparison of off-grid systems and grid extensions. In an on-grid way, grid tariff and sell-back rate are the input data (Li et al. 2022). The advantage of being on-grid is that it sells excess clean energy to the grid and supports grid power, while the only source of revenue for being off-grid is salvage (Jahangir et al. 2022). Off-grid systems have higher net present costs and energy costs than grid-connected systems, whereas on-grid systems have fewer components because the primary power consumption is from the grid (Majdi et al. 2021; Nesamalar et al. 2021). On-grid hybrid is beneficial for reducing the cost of energy, but it takes time to set up and can lead to higher installation costs (Chowdhury et al. 2020). Das et al. (2021) conducted an economic feasibility analysis of a hybrid photovoltaic/wind/diesel/battery energy system. They found that the energy cost for an on-grid system (0.072 dollars/kilowatt-hour) was much lower than an off-grid hybrid energy system ($0.28/kWh). Additionally, Ali et al. (2021a) examined the economics of diesel and biogas generators, photovoltaic panels, and wind turbines in off-grid and on-grid scenarios. They found that on-grid systems with lower energy costs (0.072–0.078 dollars/kilowatt-hour) were more suitable for practical applications, with a 44–49% reduction over off-grid systems (0.145–0.167 dollars/kilowatt-hour).

In Guiyang, Li et al. (2021) studied green buildings, grid-connected systems were more cost-effective than off-grid systems for supplying electricity to residential buildings via hybrid intermittent generation systems. In off-grid systems, the battery capacity grows after the peak energy capacity surpasses the maximum electricity demand to prevent overproduction and avoid dumping extra power (Campana et al. 2019). Furthermore, Li et al. (2022) mentioned that increasing the capacity of photovoltaic panels, wind turbines, and converters allows flexibility and cost-effectiveness by shifting from off-grid to on-grid mode.

Most populations cannot afford high energy costs compared to traditional grid purchases. Hybrid energy systems pay much investment upfront due to the high renewable proportion, and the power transmission system still has higher costs. Therefore, it is essential to have a good electricity infrastructure to handle the transmission of these renewables (Das et al. 2020). Facing complex energy installation procedures also requires additional training costs (Ellabban et al. 2014). Photovoltaic prices can change significantly over time, and there is uncertainty in the prices of other energy sources, which good design decisions need to consider. Therefore, various decision variables between energy sources need to be considered in the optimization process to evaluate the optimal size of the hybrid system at the lowest annual cost (Sawle et al. 2018). Energy scheduling is based on previous-day simulations using predicted energy prices, weather data, and load consumption curves. Energy savings by scheduling energy use in houses connected to hybrid energy systems, energy scheduling strategy reduces daily operating costs by 45% (Bouakkaz et al. 2021). The developed procedure considers various constraints, such as the weight penalty cost of carbon emissions, the elemental cost of carbon dioxide, and the annual system component power consumption, to obtain the optimal configuration of the hybrid system (Clarke et al. 2015).

Similarly, inflation or nominal interest rates may vary over time (Das et al. 2022a; Shafiullah et al. 2021). Therefore, some economic policies have been implemented in favor of recommending hybrid energy applications (Xin-gang et al. 2020), for example, incentives in the form of tax exemptions and sales taxes on renewable energy imports of equipment in the UK (Ali et al. 2021b). The renewable energy policy in Bangladesh provides several fiscal incentives, such as a 15% value-added tax exemption on purchasing equipment and raw materials and a 10% increase in the purchase price for the private sector (Mandal et al. 2018). The availability of incentives or support programs through grants or subsidies can further address the high overall energy system costs by reducing investment costs (Odou et al. 2020). The current limitations of determining the economic viability of energy are summarized as shown in Fig. 8**.**

This section summarizes the economic parameters for evaluating hybrid energy systems, assessing net present cost, annualized cost, and cost of energy to provide a comprehensive analysis of the economic viability of hybrid energy systems. In addition, the hybrid energy system represents better economic viability than a single energy system. However, there is also the impact of renewable proportion and off-grid/on-grid operation mode; the system needs to address the challenges of high upfront investment cost, interest rate, and inflation rate resulting in price changes.

Conclusion

Estimating renewable energy hybrid impacts is essential to verify the future expansion of the hybridization concept compared to the individual used source. In addition, the economic estimation potential of such systems in different countries is essential. Here, we discuss the theory of renewable energy combinations, approaches, suggested combinations, models, and economic, environmental, and social impacts. The role of hybrid systems in water desalination

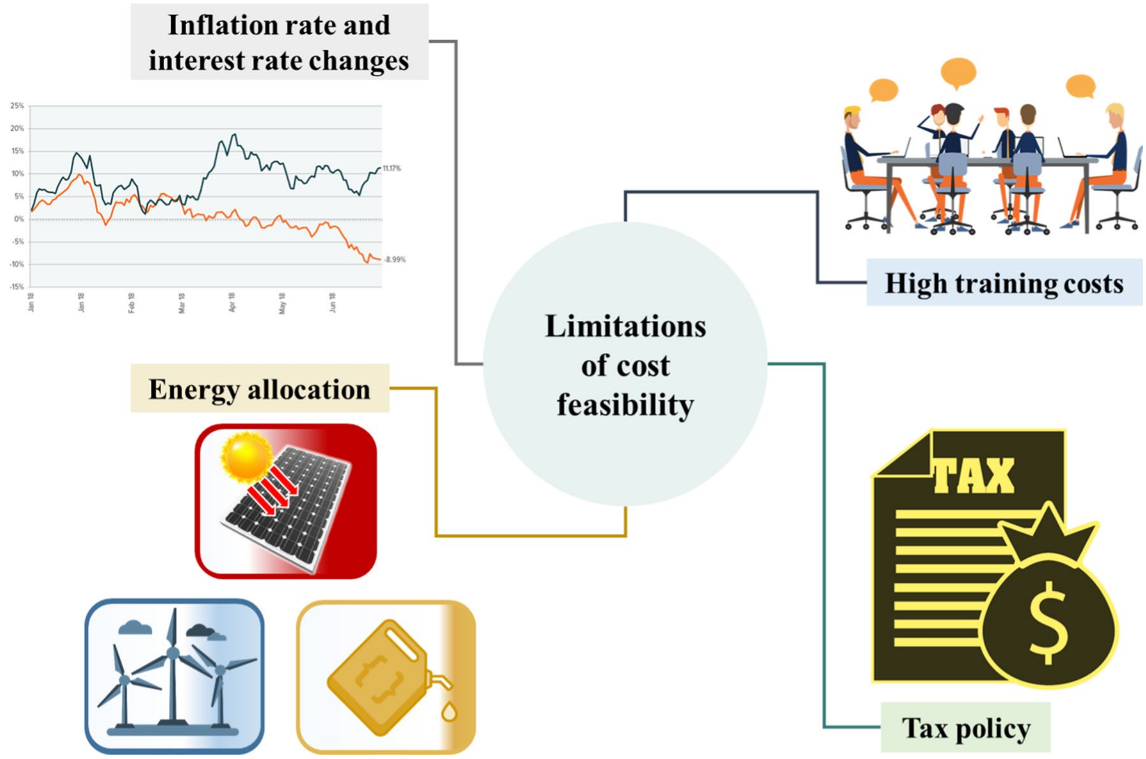

Fig. 8 Limitations of the economic viability of hybrid energy systems. Optimal allocation of energy can improve energy efficiency and thus reduce costs. Inflation and interest rates can affect cost changes. The application of hybrid energy systems requires additional personnel training. The taxation system of the policy can affect the investment in hybrid energy

was also included. Besides, a comparison between the effect of hybrid energy systems and their respective source was fully discussed to determine the best scenario for climate change mitigation. How the complementary operation of this integrated system could be affected by climate change and its flexibility to climate change was also discussed.

Complementarity between energy sources is improved when adapted to changing climate conditions, maximizing the ability to counteract its effects, and increasing power generation and guarantees. However, a standardized approach for evaluating energy complementarity is lacking, making it necessary to simulate complex climate data with more optimal estimation methods for accuracy.

Reducing the amount of non-renewable energy and increasing the proportion of renewable sources not only reduce net present value costs for system operators but also align with government energy policies and reduces fuel and environmental pollution. Yet, large or poorly designed systems can result in high installation costs, emphasizing the need for thorough technical and financial evaluations before implementing a hybrid energy system. Selecting the most valuable renewable source is vital for decision-makers in ensuring optimal utilization and successful implementation of such complex systems.

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Declarations

Conflict of interest The authors have not disclosed any competing interests.

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