# A comprehensive review of the design and operations of a sustainable hybrid power system☆

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ABSTRACT

The adoption of sustainable hybrid power systems (SHPSs) is witnessing a significant surge among electricity consumers worldwide, which is largely driven by the unexpected geopolitical shock experienced by several European countries during the Russian war in Ukraine and the low electricity coverage in many African nations. The European countries heavily relied on Russian gas for electricity generation, but the sudden outbreak of war disrupted this dependency, leading to severe hardships. In contrast, many African countries face challenges with low rates of electrification and limited progress toward renewables due to a scarcity of technical expertise. To address these issues, sustainable hybrid power systems, which are crucial for achieving a decarbonized energy grid, offer a viable solution. The research delves into the motivation behind adopting sustainable hybrid power systems, reviews key aspects surrounding this topic, explores various renewable resources that can be harnessed for the grid and off-grid applications, and discusses essential considerations related to the planning, operations, and feasibility of implementing the SHPS scheme effectively.

## 1. Introduction

Electricity has become an indispensable aspect of nearly every facet of human life, driving an escalating global demand for energy. This demand stems from factors such as population growth, economic progress, and social advancements. Notably, the interplay of economic and social developments has paved the way for numerous industrial and technological innovations. Consequently, the presence and accessibility of electricity hold a direct correlation with the economic and social development of a country. The influence of electricity is pervasive, permeating every nook and cranny of societal progress. It underpins and empowers a wide array of advancements and initiatives across various sectors, enriching the lives of people and supporting the growth of communities at large. As such, electricity has emerged as a vital catalyst for progress and prosperity in the modern world. In today's world, electricity plays an indispensable role in facilitating essential services and enhancing the overall well-being of communities [1]. From supporting advancements in healthcare and agriculture to ensuring access to clean water and other fundamental necessities [2], electricity stands as

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a pivotal enabler of progress and societal development. The availability of reliable electricity fosters the conditions for a safer, healthier, and more prosperous society. Therefore, Inadequate electricity poses a grave threat to economic and social developments, stifling industrial and technological innovations and negatively impacting the overall quality of life. Recognizing its paramount importance, electricity assumes a central role in the United Nations' sustainable development goals (SDGs), profoundly influencing every aspect of human endeavors. Particularly, SDG 7 explicitly underscores the imperative of granting every individual access to modern, sustainable, reliable, and affordable energy by the year 2030 [3]. This has the possibility of reducing unemployment, hunger, and poverty while fostering economic growth, improved health, education quality, access to clean water, and enhanced livelihoods. Additionally, affordable and sustainable electricity plays a pivotal role in improving the effects of climate change on the environment. Consequently, the absence or insufficiency of electricity renders a thriving and robust economy, as well as productive and healthy households, an unattainable reality. The introduction of various interventions, such as feed-in-tariffs and subsidies, by governments has had a profound impact on the plummeting prices of renewable energy technologies (RETs). As a direct consequence, the economic viability of RETs has substantially improved, leading to a notable surge in their share within the global electricity energy mix [4–8]. Solar photovoltaic and wind turbines are RETs that have received extensive practical implementation and wide research considerations for electricity generation. The efficiency of both RETs has been improved over time, making them suitable for modular and large-scale applications wherever there is a sufficient supply of resources. Out of the two RETs, solar photovoltaic accounts for the largest off-grid household applications because of its modularity. The availability of sunlight is responsible for solar photovoltaic outputs. Weather fluctuations and intermittent supply of sun resources affect the outputs of solar photovoltaics. To make up for the challenges of intermittent supply of RETs resources, a hybrid scheme is typically proposed. The sustainable hybrid power system (SHPS) is the bedrock of smart grids [9–11]. An intermittent supply of RETs resources can also be salvaged using energy storage systems (ESS) [12]. ESS produces reasonably constant and smooth outputs, thereby salvaging energy fluctuations [13]. Economic and technically effective energy systems are possible when the maximum possible output is obtained from the solar panel. Optimal sizing of all components is required to achieve this. Several works of literature have reported the environmental, economic, and technical competitiveness of hybrid systems over fossil-fuel power-generating systems [14,15]. Single-islanded energy sources, such as gasoline/diesel generator, solar, biomass, small hydro, and wind, is typical of off-grid electricity generation. Hybrid power generation is being advocated as a better replacement for single-source generation. The SHPS has a high probability of ensuring a power system with high reliability and efficiency due to the advances in the RETs. An SHPS is a mode of power generation that integrates different resources (conventional and renewable) to achieve an optimal energy output. Often, the output of an SHPS is usually heat, electricity, or both (i.e., co-generation). The intermittent nature of renewable energy resources (RERs) makes their outputs not reliable. The integration of different power resources will make up for the variability of RERs outputs and give an energy output with greater reliability. The SHPS offers the benefits of reduction in the variability problems from RERs and the reduction of emissions problems from purely fossil-fuel generators. Carbon dioxide emissions from electricity generation that is purely fossil fuel account for over 40% of greenhouse gas emissions [16]; hence, the need for SHPS cannot be over-emphasized. SHPS encourages the implementation of RERs and reduces the proliferation and expansion of fossil fuel sources. Adopting SHPS has given rise to the penetration of RERs in the global energy mix, prevalent in off-grid communities where microgrid facilities are made up of SHPS. Fig. 1 shows a typical SHPS diagram. Adopting SHPS is a pathway to a sustainable electricity future. Many international and national entities have proposed frameworks and policies to promote sustainability. The United Nations has also enacted Sustainable Development Goals (SDGs). These SDGs aim to end poverty, promote equality, reduce illiteracy and ill health, develop the economy, ensure the provision of clean energy, and encourage environmental preservation [17]. The SDGs directly affected by SHPS implementations are climate action, affordable and clean energy, decent work and economic growth, and sustainable cities and communities (Fig. 2). The Paris Agreement is another campaign that promotes the reduction of average global temperature below 2°C to save the planet from the climate change crisis [18].

The adoption of Sustainable Hybrid Power Systems (SHPS) encompasses a holistic approach that integrates various perspectives, including environmental, technical, economic, political, and social, and the formulation of essential enabling policies. Achieving sustainability in SHPS involves optimizing the system through expert knowledge, ensuring reliability, and carefully considering techno-economic feasibility. For instance, an expert is crucial for determining the optimal size of an SHPS, which enhances its reliability and cost-effectiveness [19–21]. Care must be taken to avoid oversizing the SHPS, as it can lead to excessive costs and wastage of

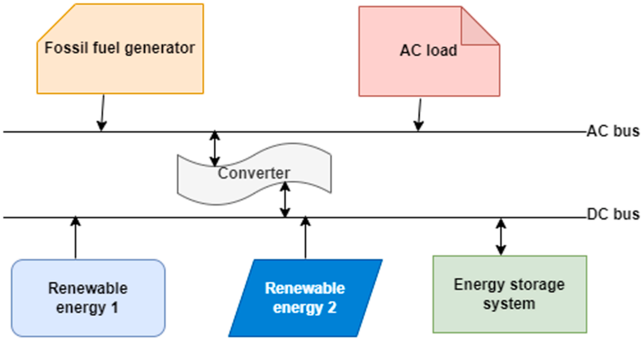


**Fig. 1.** An SHPS Block Diagram.

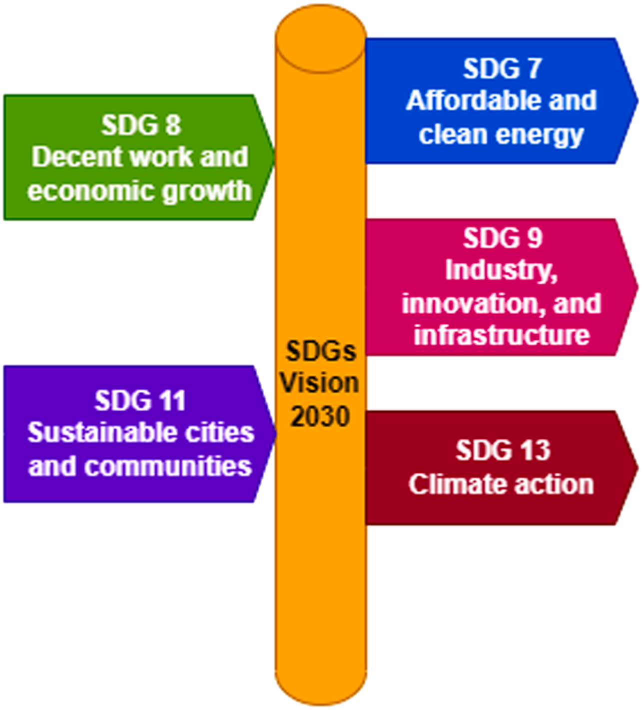


**Fig. 2.** SDGs Directly Affected by SHPS.

energy supply. Conversely, undersizing the system may result in power supply reliability issues and potential outages. Striking the right balance in sizing is essential for maximizing the benefits and minimizing the drawbacks of SHPS.

The rest of the paper is arranged in the following order: Related works are reviewed in Section 2, while Section 3 discusses the various forms of motivations for implementing SHPS. In Section 4, the integration of various forms of RETS with SHPS were enumerated, while Sections 5 and 6 discussed different coupling strategies and control topologies adopted for SHPS. Section 7 highlighted the benefits of implementing SHPS and the conclusions of the research were expressed in Section 8.

## 2. Related works

Numerous studies have been conducted on hybrid power systems, covering various subjects. For instance, Ghenai et al. [22] delved into the design analysis and optimal performance of a hybrid power system for a cruise ship in Sweden. Similarly, Ghenai and Bettayeb [23] presented the design and optimal performance of a hybrid power system tailored for university buildings. In a different context, Gebrehiwot et al. [24] focused on exploring the least-cost alternative for implementing a hybrid power system in a village in Ethiopia, incorporating diesel generators, solar photovoltaic, and wind turbines to achieve an optimal configuration. Rad [25] analyzed and proposed a hybrid energy system suitable for both grid-connected and islanded applications, with the aim of achieving universal electricity access (100%) in Iran. Overall, these pieces of literature contribute valuable insights into the design, optimization, and deployment of hybrid power systems in various settings, demonstrating their versatility and potential for sustainable energy solutions.

The techno-economic characteristics of a hybrid power system in [26] were investigated in the design of an off-grid energy system for rural electrification of a remote community. Different generation sources were optimized in Hybrid Optimization Model for Electric Renewables (HOMER) for a village in China, while the community, agricultural, commercial, and residential demands of the village were considered. A hybrid power system was designed and compared with the diesel-only generation system in a lighthouse in [27]. The hybrid system is made up of a diesel generator, solar energy, tidal current, battery storage, and a converter. The greenhouse emissions from each scenario were compared, and the optimal configuration of the hybrid system was determined. In [28], a hybrid energy system was designed and analyzed. The system comprising solar photovoltaics (PV)/diesel generator (DG)/battery was found to have the least optimal-cost configuration. The hybrid PV/DG/battery system was recommended to replace the current widely implemented PV/battery system in rural communities in Benin. A techno-economic analysis was conducted on a hybrid system consisting of diesel, wind, and solar resources [29] using HOMER software. The analysis revealed that the hybrid configuration would generate more than enough electricity in the study area. A hybrid energy system consisting of a diesel generator, wind turbine, battery, and photovoltaic was proposed in [30] as the configuration with the cheapest energy cost, highest return on investment, and reducing over 2000kg of $CO_2$ per annum per household. A hybrid power system was proposed in [31] to tackle the load requirement of a village in India. The feasibility study of the system was conducted, and optimal power was obtained using diesel, solar, wind, and battery backup. Enviro-techno-economic study of the hybrid power system was done in [32] to investigate sustainable development goal 7.

The load requirement of the residential community was satisfied using the PV/WT/DG/BESS hybrid configuration. The above-mentioned research outputs have treated different subjects on hybrid power systems. But the literature that combines economic, social, technical, policy, and environmental aspects is rare. This knowledge gap is bridged in this research.

### *2.1. This survey*

Table 1 contains the research works of different papers on hybrid power systems. One can see that the subjects of hybrid power system design, motivations, problems, uncertainty assessment, research comparison, multi-criteria method applications, and economic feasibility have not been comprehensively treated as they should be. A state-of-the-art survey is thereby presented comprehensively in this research. A rigorous literature search (method) on science direct, IEEE-Xplore, and Google Scholar were adopted in this survey.

## 3. Motivations for SHPS implementation

### *3.1. Economic motivation*

Economic recession and global economic meltdown have affected different sectors of the economy, such as real estate, construction, manufacturing, retail, leisure, and hospitality [33,34]. The electricity industry is not left out of this. With fossil fuel prices fluctuating regularly, energy costs from coal, oil, and gas sources constantly rise. The global economic crisis and economic slump affected various sectors of the economy of different countries differently, with the resource-rich countries feeling the impact more. But generally, the effects on the economy were felt through a decline in revenue generation, a decline in exports and domestic production, and a decline in investment, which resulted in reduced capital flows [35]. Corruption, unpredictable change in government, and unrest in the fossil fuel-producing areas are some reasons for economic worries affecting fuel prices adversely. Stand-alone fossil fuel generators form the primary source of electricity supply in most developing countries experiencing erratic power supply and low electricity access rates [36–38]. Hence, the effects of fluctuation in fossil fuel prices are obvious among these consumers, and the cumulative cost of maintenance and cost of running these generators is astronomical and unsustainable for most of them [39–44]. The SHPS, due to its improved reliability, also helps safeguard the contingency cost which would have arisen from old and weak grid networks. The logistic costs of transporting fossil fuels coupled with the cost of operating fossil fuel generators are additional motivations to invest in SHPS. Logistics costs related to transporting fossil fuels are those expenses in a fossil fuel-generating plant that constitute a utility's chain of generation and distribution, such as gas or coal acquisition and transportation costs and the cost of operating fossil fuel generators. Since transmission lines are not needed in the implementation of lower SHPS because the energy is generated close to where they are used, the overall cost of production would be reduced, hence, giving access to electricity at a reduced price [45–51].

### *3.2. Technology development*

Implementation of RETs has given rise to diverse innovations in renewable energy, which, in turn, has resulted in the reduction in the costs of RETs and improvement in its efficiencies. For instance, the costs of procurement for both solar and wind technologies have drastically reduced over the years. Government policies designed for wind and solar technologies' stages of development, subsidies, incentives, research, and innovation have contributed to a significant decrease in the cost of acquiring solar and wind technology in recent years [52–55]. This will enable more consumers to be able to afford SHPS. Implementing SHPS also has seen emerging developments and given rise to innovations in energy storage systems. Energy storage systems (ESSs) with improved efficiencies have emerged, leading to improved energy storage at lower prices [56–58], thereby improving affordability by consumers. Some of the new developments in energy storage systems as a result of SHPS implementation include advanced lithium-ion batteries, lithium alternatives, short-term response energy storage devices, battery energy storage systems, advanced thermal energy storage, enhanced redox flow batteries, distributed storage systems, and solid-state batteries [59]. This breakthrough in ESSs will enable the storage of more energy during peak production, which will be released for consumption during peak demand. Breakthrough in ESSs enables the storage

**Table 1**

Comparison of existing literature with this research.

| | [22] | [23] | [24] | [25] | [26] | [27] | [28] | [29] | [30] | [31] | [32] | This review |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SHPS design | √ | √ | | | | √ | | | | √ | √ | √ |
| SHPS motivations and problems | | | | | √ | | | | | | √ | √ |
| Uncertainty assessment | | | | | | | | | | | | √ |
| Research comparison | | | | √ | | √ | | | √ | | | √ |
| Multi-criteria method applications | | | | √ | √ | | | | | | | √ |
| Economic feasibility | | | √ | √ | | √ | √ | √ | √ | √ | √ | √ |
| Mathematical derivations | | | | | √ | | | | | | | √ |
| Optimization techniques | √ | √ | √ | √ | | | √ | √ | | √ | √ | √ |
| Management approaches | | | | | | | | | | | | √ |
| Storage system | √ | √ | √ | √ | | √ | √ | √ | √ | √ | √ | √ |
| Performance indices | √ | √ | √ | √ | √ | | √ | √ | √ | √ | √ | √ |

of more energy for a longer time which is in turn used during non-peak production periods to avert outages, thereby improving the reliability of SHPS.

### 3.3. *Incentives and subsidies*

Governments of different countries have put in place enabling incentives and subsidies to encourage the adoption of RETs at both small and large scales [60–65]. Regional organizations, such as European Union, Southeast Asia, etc., are not left out of such initiatives [66–72]. The initiatives are designed to reap long-term environmental, health, and economic benefits and to encourage the penetration of RETs. Governments implemented incentives and subsidies can be broadly divided into three, vis (1) energy-efficient finance, EEF; (2) market interactions-based incentives, MII; and 3) policies-based incentives, PI. EEF has to do with improvements in the area of storage, distribution, and efficient use of energy. MII is caused by interactions between market participants. While PI is made up of measures proposed by policymakers and implemented after approval by the government, such as accelerated depreciation, tax incentives, and subsidies [73]. Incentives and subsidies are usually targeted at wooing investors to participate in businesses related to RETs. Schemes that regulate climate change and encourage the use of RETs are proposed and executed continuously in Europe. Such incentives include loans for RETs-based enterprises, grants for renewable energy-related research, feed-in tariffs on RETs components, etc. Relevant incentives and subsidies on RETs will encourage the growth of SHPS.

### 3.4. *Environmental factors*

The discovery of the effects of electricity generation (using fossil fuels) on the environment has necessitated caution among utilities and governments worldwide. The effects of climate change have been declared a menace to the globe [74–76]. The consequences of climate change have been categorized as a global threat due to Human rights violations and negative impacts, affecting our right to adequate housing, work, sanitation, water, self-determination, development, food, health, and right to life [77]. Methods to counter the effects of climate change, such as putting a price on carbon (carbon tax), ending fossil fuel subsidies, subsidizing green energy, implementing climate-smart agriculture, using renewable energy, and building low-carbon, resilient cities need to be implemented to avoid the consequent economic waste. Policymakers have come up with different initiatives at various levels of government to conserve the environment. The initiatives are targeted at environmental preservation and greenhouse gas (GHG) emissions reduction. Such initiatives include green infrastructure projects [78–81], atmospheric carbon dioxide removal [82–85], and renewable energy implementation for electricity generation [86–91]. It is imperative to increase the penetration of RETs in global electricity generation since electricity generation using fossil fuels contributes heavily to climate change crises [92,93]. This is why Europe has led the initiatives to promote electricity production using clean and sustainable sources [94,95]. But the hybridization of these clean and sustainable sources is encouraged because of the problems of intermittency of the electricity generated from these sources.

### 3.5. *Availability of RE resources*

Utility companies do not venture into extending the grid to some remote locations and difficult terrains (such as Eleme Creek and Sambisa area in Nigeria) because it does not make economic sense. Islanded forms of energy generation, in the form of fossil fuel generators, are typically used in such locations. But the hybridization of renewable energy resources is a cleaner and cheaper alternative for consumers [96,97]. Remote locations and difficult terrains with an abundance of renewable energy resources should prioritize the adoption of hybrid renewable energy for their electricity generation. Effective strategies to address the obstacles hindering the widespread adoption of renewable energy technologies are the formulation and implementation of relevant policies, increased environmental impact sensitization, provision of incentives, conformity with international standards, awareness creation, and increased supply of renewable technologies [98].

### 3.6. *Political and social considerations*

The influence of the international community in combating the effects of climate change and reducing the emission of GHGs has a bearing on the decisions and policies of those in government. The choice of energy generation, giving priority to RETs, is one such decision. Because of many uncertainties associated, RETs are considered a work in progress [99,100]. As such, the hybrid system is encouraged to be adopted for a more stable and reliable power system.

### 3.7. *Low electricity access*

Access to electricity is very low in many developing nations, particularly African countries [101,102]. Besides, the reliability of the available electric supply, in many cases, is low. As a result, outages are often experienced. Underlying factors contributing to electricity access challenges in numerous developing nations, particularly African countries, are access to finance, education, economic development, infrastructure, and industrialization. Government policies ensuring citizens access to these missing factors (such as finance, education, economic development, infrastructure, and industrialization) are the strategies that could be employed to alleviate these issues [103]. The health of the people and the socio-economic status of the community usually suffer because of electricity access problems [104,105]. Lack of funds, poor government policies, poor planning, poor resource management, corruption, and poor implementation framework are some causes of electricity access problems [106,107]. These problems can be mitigated using islanded hybrid energy systems [108–118].

## 4. SHPS implementation with RETS integration

Remote locations, difficult terrains, and residential households in developing countries with inadequate electricity access can be provided with hybrid power systems with the integration of some established renewable energy technologies such as wind turbines, solar PV, and biomass.

### *4.1. Energy from the wind*

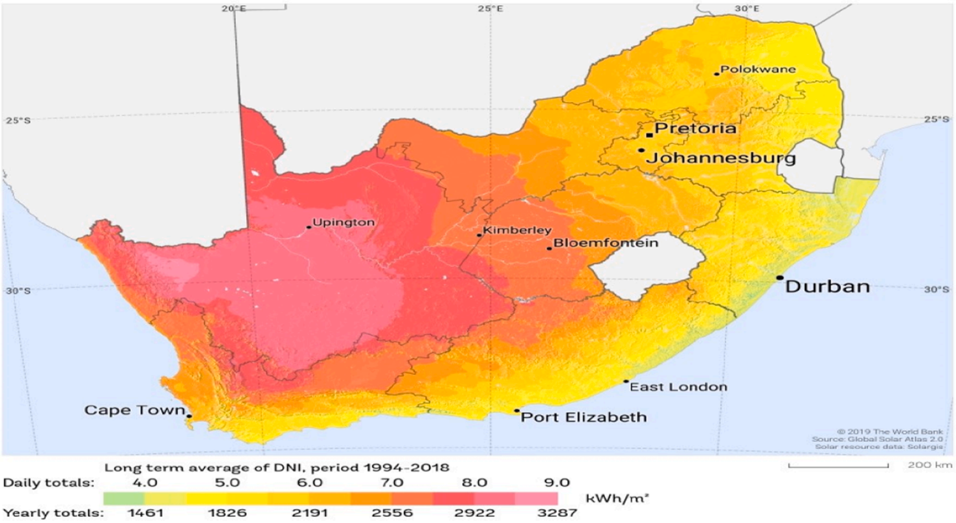
The kinetic energy generated by the speed of the wind is converted to electric energy using the wind turbine. The speed of the wind is efficiently converted to electric energy by a wind turbine using a simple principle like that of a fan. The wind rotates the turbine's propeller blades around a rotor, which leads to the spinning of a generator, thereby generating electricity. The technology of wind turbines is gaining momentum daily and is promising renewable energy. This is because of the availability of wind resources in virtually all parts of the world and the research innovation of wind turbine designs [119,120]. These innovations have resulted in a continuous reduction in the cost of wind turbine technologies [121,122]. Breakthroughs in research have led to the development of standalone off-grid wind turbines, grid-connected on-shore wind technology, and off-shore wind technology. The problem of intermittency in electricity supply from wind energy due to its stochastic nature calls for more research into getting optimal supply from wind turbines. It is not techno-economically feasible for some areas to generate electricity using wind turbines. High altitude and off-shore areas have been confirmed as suitable locations for wind energy generation [123,124]. Although some countries have integrated wind turbines into their national grid, more needs to be done to increase the share of wind energy in the energy mix. This is achievable by applying incentives, such as tax exemption on wind technology components, feed-in-tariffs, and relevant subsidies.

The wind speed, wind density, and the size of the wind turbine blade constitute the wind turbine's power output. A feasibility study should be conducted on a potential wind turbine site to ascertain the maximum energy obtainable and the economic soundness of the investment. A wind map (containing information on the appropriate turbine system) and the wind resource for a particular location is a useful tool for siting a wind farm. The power output, $P_W$, of a wind turbine depends on the rated power, $P_r^W$, the cut-in speed, $V_{ci}$, the cut-out speed, $V_{co}$, the rated speed, $V_r$, and the actual speed, $V_i$ [125]:

$$P_W(v_i) = \begin{cases} 0 & v_i < v_{ci} \\ P_r^W \, x \, \dfrac{v_i - v_{ci}}{v_r - v_{ci}} & v_{ci} \le v_i < v_r \\ P_r^W & v_r \le v_i < v_{co} \\ 0 & v_{co} \le v_i \end{cases} \tag{1}$$

The total energy derivable from a wind turbine is subject to the location/install height. Therefore, considering the effects of the height of the wind turbine [126]:

$$\left(\frac{v}{v_{ref}}\right) = \left(\frac{H}{H_{ref}}\right)^{\beta} \tag{2}$$



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Source: Global Solar Atlas 2.0
Solar resource data: Solargis

**Fig. 3.** Direct normal irradiation (DNI) of South Africa.

Eq. (2) is referred to as Power Law, and β is the power law exponent. H and $H_{ref}$ are the hub height and the reference height, while v and $v_{ref}$ are the wind speed measured at H and $H_{ref}$, respectively. The β depends on the temperature, wind speed, the terrain's nature, time of the day, and elevation.

### 4.2. *Energy from the sun*

Energy derivable from the sun in the form of sunlight and then converted to electric energy is referred to as solar energy. Solar irradiance (measured in $W/m^2$) is the surface power density of the electromagnetic radiation transferred by the sun to the earth. There is vast solar potential in Africa and many parts of the world. Notwithstanding, the period and quantity of the received solar irradiance vary from one part of the globe to the other. Figs. 3–5 show the direct normal irradiation (DNI), global horizontal irradiation (GHI), and photovoltaic power potential (PPP) maps of South Africa [127]. Direct normal irradiation (DNI) is part of the solar irradiance that directly reaches a surface; diffuse irradiance (DIF) is the part that is scattered by the atmosphere; global horizontal irradiation (GHI) is the sum of both diffuse and direct components reaching the same surface. The photovoltaic power potential (PPP) is the projected lifecycle average electricity production (in kWh) generated per kilowatt of installed photovoltaic DC capacity rated at Standard Test Conditions (STC) for grid-connected PV systems without batteries. A photovoltaic solar panel's standard test condition is having $1000W/m^2$ of full irradiance at 1.5 sea level air mass (AM) when the cells and panels are at a standard temperature of 25°C.

$$DHI = DNI + DIF \tag{3}$$

Radiation from the sun can be transformed into active or passive solar energy. In active solar design, solar radiation is converted into heat or electrical energy, while in passive solar design, solar radiation is optimally maximized for building design so that the heat and light from the sun during the day are utilized by the building, thereby, reducing the necessity of artificial heating and lighting [128]. The innovations developed for solar electricity and heating include solar photovoltaic, central tower receivers, parabolic dish collectors, parabolic trough collectors, and linear Fresnel reflectors [129]. The availability of solar energy varies from location to location, and its supply is intermittent. Also, the efficiency of solar to electricity conversion is very low. This is due to a factor known as direct recombination in conversion efficiency, whereby holes and light-generated electrons in the solar panels encounter each other, recombine, and emit photons, thereby reversing the electricity generation process in solar cells and limiting their efficiencies. Therefore, for effective output, integration of solar energy with fossil fuels generators and or energy storage system is recommended. Integration with other renewable energy resources is also encouraged. A PV panel's power output is [126]:

$$P_{pv} = Y_{pv} f_{pv} \left( \frac{\overline{G_T}}{\overline{G_{T,STC}}} \right) \tag{4}$$

If temperature effects are considered, then we have:

$$P_{pv} = Y_{pv} f_{pv} \left( \frac{\overline{G_T}}{\overline{G_{T,STC}}} \right) \left[ 1 + \alpha_{pv} \left( T_c - T_{c,STC} \right) \right] \tag{5}$$

where $Y_{pv}$, $f_{pv}$, and $\overline{G_T}$ are the rated capacity, derating factor, and solar irradiance incident of the PV array, respectively. At standard conditions, the solar irradiance incident and cell temperature are $\overline{G_{T,STC}}$ *GT, STC and Tc; STC,* respectively. The *Tc and* $\alpha_{pv}$ are the cell

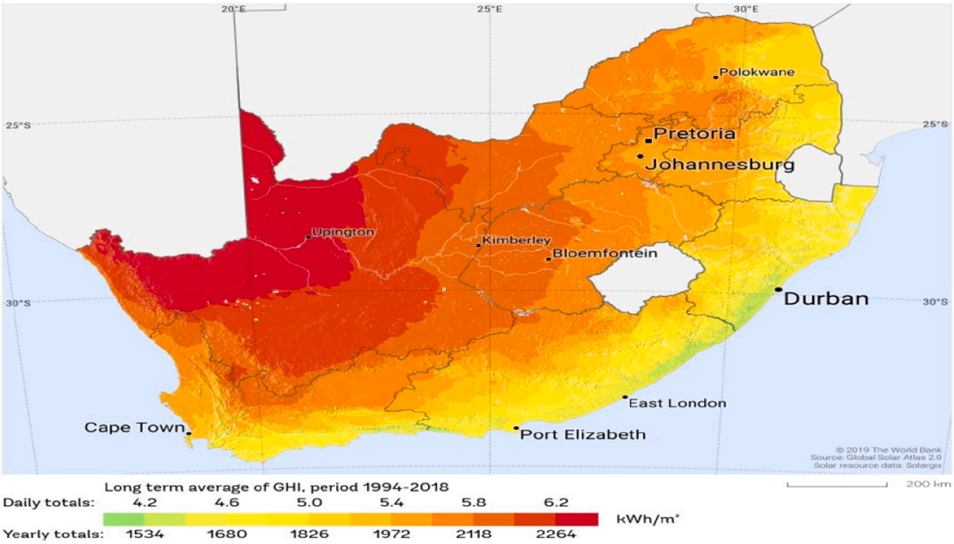

**Fig. 4.** Global horizontal irradiation (GHI) of South Africa.

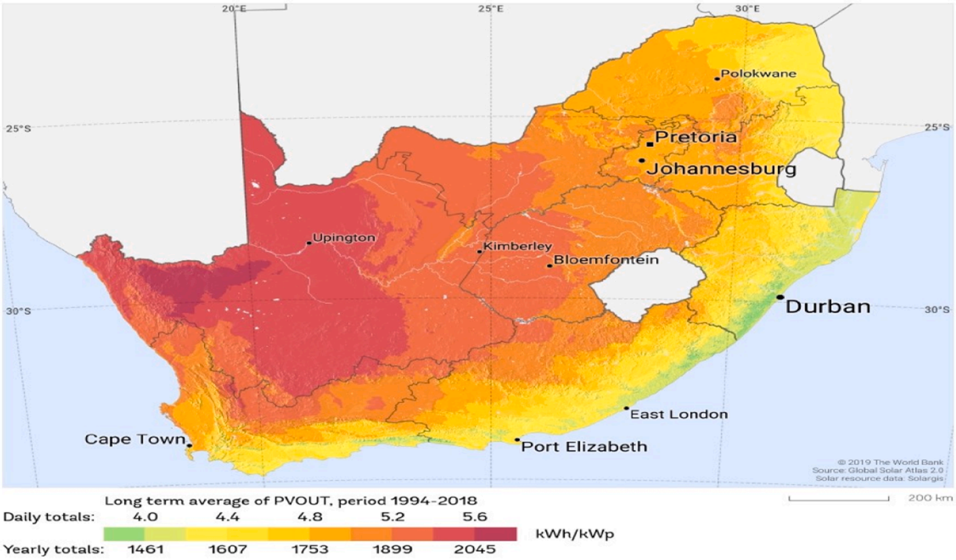

**Fig. 5.** Photovoltaic power potential (PPP) of South Africa.

temperature, temperature co-efficient of power.

### 4.3. *Energy from wastes*

Energy generated from waste is known as biomass. Many rural locations in Africa have an abundance of raw materials for biomass [130]. The raw materials are plants and animal waste. Raw materials are also found in urban centers with vast amounts of food and human waste. This waste can be converted to good use to provide electricity on a large scale for isolated locations, remote terrains, and even urban centers. Biomass, an organic energy source stored from sunlight, can be from forest bioenergy sources, food waste, human waste or dung, industrial sludge or biodegradable waste, crop residues, or agricultural waste [131]. Bio-fuels, such as biomass pellets, bio-diesel, bio-ethanol, bio-methane, etc., can be generated from biomass [132]. Electricity is generated from wastes using different processes such as landfill gas recovery, anaerobic digestion, pyrolysis, gasification, and combustion. Heat or steam generated from biomass can also be used to produce electricity. Biomass, as a source of electrical energy, is grossly under-utilized and under-developed because of factors such as water use policies, land use policies, costs, social acceptance, resource accessibility, technology efficiency, and emission coefficient [133]. The biomass gasification procedure is carried out at very high temperatures, in different stages, such as drying, pyrolysis, combustion, cracking, and reduction [134]. The gasifier's output power, $P_{bmg}$, is [126]:

$$P_{bmg} = \frac{CV_{bmg}\, x\, \eta_{bmg}\, x\, available\ biomass\, x\, 1000}{operating\ hours\, per\, day\, x\, 365} \tag{6}$$

where $\eta_{bmg}$ is the conversion efficiency, and $CV_{bmg}$, is the calorific value of the gasifier.

### 4.4. *Energy storage alternatives*

A piece of backup equipment, in the form of the energy storage system (ESS), is essential for improving the availability and reliability of SHPS services [135]. This will help to overcome the problem created by the intermittent supply of energy by sources such as solar and wind. Problems created by the intermittent supply of energy include power fluctuations, voltage variations, power quality challenges, and the unreliability of supply. ESS has the benefit of storing energy during excess supply and using the energy in times of deficit [136]. Other advantages of ESSs are fast response provision of energy in times of outage, peak shaving, and smoothing fluctuations [137]. There are three states in which ESS operates, and they are the charging state, storage state, and discharging state. Caution is usually taken to disallow the ESS from discharging beyond a threshold level called the maximum depth of discharge.

## 5. SHPS bus interface options

The bus interface alternatives for a PV-Wind-SHPS microgrid are discussed in this section.

### 5.1. *DC bus coupling*

A DC-to-DC converter is used to connect the DC bus to the PV's DC output, while an AC-to-DC converter is used to connect the DC bus to the Wind's AC output. A bi-directional converter is used to connect the DC bus to the ESS for charging and discharging purposes. This is a design for servicing DC loads, but it can be adapted to service an AC load by interfacing with an appropriate (DC-to-AC) converter if desired. A DC-to-AC converter works by toggling the DC input on and off rapidly, producing current pulses alternating between negative and positive. Inductors and capacitors then filter the pulses to produce sinusoidal waves, which is an AC form. The input voltage of the DC-to-AC converter and the toggling speed determines the amplitude and frequency of the AC output. Different types of AC waveforms, such as modified sine waves, triangular, or squares, can be generated by different DC-to-AC converters. While a DC-to-DC converter works by taking the current and passing it through a switch, which turns the signal into a square wave (an AC signal), passing it through a filter, then reverting it back into the appropriate DC signal [138]. The benefits of this configuration are its ability to eliminate synchronization problems and its simplicity [139].

### 5.2. *AC bus coupling*

A DC-to-AC converter is used to connect the AC bus to the PV's DC output, while an AC-to-AC converter is used to connect the AC bus to the Wind's AC output. A bi-directional converter is used to connect the DC bus to the ESS for charging and discharging purposes. Although this is a design for servicing AC loads, it can be adapted to service a DC load by interfacing with an appropriate (AC-to-DC) converter if desired. This topology is widely used for residential, commercial, and industrial purposes. This topology has problems with synchronization [140].

### 5.3. *Dual bus coupling*

The dual bus-coupling configuration uses DC and AC buses. In this configuration, the DC bus is connected to the energy sources producing DC outputs, while the AC bus is connected to the energy sources producing AC outputs. Hence, it discourages using many converters and simultaneously reduces conversion power losses [141], thereby increasing the efficiency of the system and reducing costs relative to a single bus coupling. These benefits account for why the dual bus coupling configuration is the most widely used. The advantage of this configuration is the complexity of managing and controlling the system. Meanwhile, the application determines the best bus coupling configuration to be adopted.

## 6. SHPS control topology

The interconnection of conventional generators, renewable sources, and energy storage systems usually results in problems of frequency, stability, voltage regulation, and power quality [142–148]. A control measure that guarantees a smooth flow of energy is, therefore, required for a reliable, cost-effective, and optimal operation of SHPS. The control measure regulates the voltage and frequency of SHPS at an expected level. The different types of control measures are distributed, centralized, and hybrid control measures [149].

Centralized control measures work by sending each microgrid's measurement signal to a centralized controller, which makes control decisions and acts as an energy supervisor using objective functions and measured signals and communicates the same to the local controllers. Distributed control measures work by sending each microgrid's measurement signal to a corresponding local controller. Distributed control is made up of control elements in the components of each microgrid. The control elements send data from each microgrid to a local controller. The local controllers collaborate and communicate with each other to foster a Pareto (compromise), resulting in collective-microgrid global optimization achievements and operating decisions. Hybrid control measures combine the centralized and distributed control schemes principles. Hybrid control measure groups energy sources having similar features into the same cluster and assign a slave controller to them. These arrangements of different slave controllers are then connected to the master controller. The centralized control measure is used to communicate among similar energy sources, while the distributed control measure is used to communicate between one cluster and the other. Hence, the centralized control measure is used to realize local optimization, while the distributed control measure is used to realize global optimization [150].

Different control measures contribute differently to the regulation of voltage and frequency in hybrid energy systems. For instance, the control design in [151] is a two-level dependent structure. The power regulation and energy management level (first level) produce reference dynamic operating points to individual sub-systems at the second level. When the energy storage is inadequate as a result of intermittent wind conditions, the power regulation and energy management level also controls the operations of load scheduling so as to avoid outages. Based on the points of the individual sub-systems, the local controllers control the battery storage units, electrolyzer, fuel cell, and wind turbine using the operating points of the reference dynamic.

## 7. Importance of implementing SHPS

Having an uninterrupted power supply using a single source of renewable energy is typically impossible because of the intermittent nature of renewable sources and changes in daily weather conditions. But the integration of conventional generation, renewable resources, and energy storage systems will guarantee reliability, reduce life cycle costs, and ensure an uninterrupted power supply. Also, adopting SHPS encourages the reduction of GHG emissions because of the integration of renewable energy resources. Moreover, communities where the national grid could not be reached because of the limited, uneconomical number of consumers, rough and difficult terrain, and isolated locations could be powered using SHPS for cost-effective electrification. Furthermore, the adoption of SHPS has resulted in innovations of power electronic gadgets that are required for effective load management and conversion purposes to achieve high efficiency and cost-effective power supply outputs [152].

### *7.1. SHPS performance assessment and indices*

#### A Performance Assessment

The fossil fuel generators, renewable energy sources, and hybrid systems are assessed using different parameters, as expressed in Table 2.

#### A B. Performance Indices

Indices are used for the performance assessment of SHPS, which help planners in their designs and help policymakers to arrive at sound decisions and formulate laudable policies. For instance, System Average Interruption Frequency Index (SAIFI) is the average number of times, in a year or particular period under study, that the consumers in the system experience an outage. It is measured in units of interruptions per customer. These indices are categorized into technical, economic, environmental, and socio-political indices, as expressed in Table 3. For SHPS to be sustainable, these indicators must strike a balance with one another [126,153,154].

#### A *Multi*-Criteria *Method Application*

Previous assessments of renewable energy projects were based on a single criterion: emission factor, renewable energy fraction, reliability, economic factor, life cycle assessment, etc. Still, for an optimally sustainable system, detailed considerations of the performance indices (technical, economic, environmental, and socio-political) are necessary. The application of the multi-criteria decision analysis (MCDA) technique will give such an optimally sustainable system. Multi-criteria decision analysis (MCDA) is a structured technique used to evaluate criteria with conflicting alternatives and choose the best option. MCDA is like cost-benefit analysis, but rather than being limited to only cost, MCDA evaluates many criteria. MCDA takes a step-by-step process to select the most appropriate options based on diverse conflicting criteria [155–160].

#### A *Uncertainty Assessment*

The probability and procedure of occurrence of events in SHPS modeling cannot be predicted accurately. These events are shrouded in uncertainties that are difficult to enumerate. These events are dependent on climatic, environmental, regulatory, economic, and political factors. For instance, if an SHPS system is designed to have a life cycle of fifteen years and a fossil fuel generator is included in the design, the possibility of fluctuations in fuel prices and availability of the fuel at certain periods would affect the system's life cycle cost, cost of energy, and the system's general performance. The seasonal fluctuations of weather resources can also result in uncertainties regarding the feasibility of an SHPS system [161]. Considering these uncertainty factors in solution algorithms and system modeling usually result in computational complexities. Uncertainty assessment, which ascertains the robustness and flexibility of the proposed model, could be done using sensitivity analysis, portfolio analysis, probabilistic analysis, or scenario analysis [162–165]. Uncertainties in SHPS are usually caused by factors listed in Table 4.

#### A Optimization *of SHPS*

An optimization method is an act of using mathematical models or algorithms to estimate the minimum or maximum values of feasibility factors. Since an SHPS is made up of components of different resources, the optimization of its economic and technical characteristics results in a complex problem because of the diverse constraints and objective functions. The approaches to address the

**Table 2**
Comparison between different energy sources.

| S/N | | Fossil fuel generators | Renewable energy generators | Hybrid generators |
|---|---|---|---|---|
| 1 | Sources | Non-renewable natural source | Renewable natural source | Hybrid |
| 2 | Capital Investment | Low cost | High cost | Moderate cost |
| 3 | Reliability measure | Determined by fossil fuel availability. Usually moderate because of the rate of maintenance of the generator | Determined by resource availability. Usually low because of the intermittent nature | The hybrid nature of the generators results in high reliability. |
| 4 | Effects on the Environment | High adverse effects | Low adverse effects | Moderate adverse effects |
| 5 | Maintenance Investment | High maintenance and operation costs | Low maintenance and operation costs | Moderate maintenance and operation costs |
| 6 | Is fossil fuel needed? | Highly needed | Not needed | Moderately needed |
| 7 | Rate of maintenance | High | Low | Moderate |

**Table 3**
Performance indices of an SHPS.

| Technical indices | Economic indices | Environmental indices | Socio-political indices |
|---|---|---|---|
| System Average Interruption Frequency Index (SAIFI) | Expected Interruption Cost – ECOST (currency or $/year) | Renewable Energy Fraction - REF | National Development Index - NDI |
| System Average Interruption Duration Index – SAIDI (customer hours) | Loss of Load Cost - LOLC (currency or $/year) | Life Cycle Assessment - LCA | Sustainable Development Index – SDI |
| Customer Average Interruption Duration Index - CAIDI (customer hours) | Cost of Energy – COE (currency or $/year) | Embodied Energy - EE | Socio-Demographic Factor - SDF |
| Customer Average Interruption Frequency Index (CAIFI) | Annual Cost of System – ACS (currency or $/year) | Total Emission Avoided - TEA | Social Cost of Carbon - SCOC |
| Average System Interruption Frequency Index – ASIFI (int/kW) | Net Present Cost – NPC (currency or $/year) | | Employment Creation – EC |
| Average System Interruption Duration Index – ASIDI (hr/kW) | Annual Capital Cost – ACC (currency or $/year) | | Human Development Index - HDI |
| Average Service Availability/Unavailability Index - ASAI/ASUI (%) | Annual Emission Cost – AEC (currency or $/year) | | |
| Energy Not Supplied – ENS (kWh) | Annual Fuel Cost – AFC (currency or $/year) | | |
| Expected Energy Not Supplied - EENS (MWh/year) | Annual Maintenance Cost – AMC (currency or $/year) | | |
| Expected Power Not Supplied - EPNS (MW), | Annual Replacement Cost – ARC (currency or $/year) | | |
| Loss of Load Duration - LOLD (hour, day, or week/occurrence) | | | |
| Loss of Load Frequency - LOLF (occurrence/year) | | | |
| Loss of Load Expectation - LOLE (hour, day, or week/year) | | | |
| Loss of Load Probability - LOLP | | | |
| Load Point Reliability Indices: (failure rate ($\lambda$), mean repair (or outage) time (r), and annual unavailability (U) | | | |

**Table 4**
Causes of uncertainties.

| Technical causes | Economic causes | Environmental causes | Socio-political causes |
|---|---|---|---|
| Manufacturing/factory errors. | Changes in tariffs, tax regimes, and interest rates. | Weather fluctuations. | Change in regimes. |
| Equipment maintenance rate. | Changes in maintenance, operation, and replacement costs. | Renewable sources’ environmental impact. | Bureaucratic bottlenecks. |
| Renewable fractions. | Changes in costs of energy. | Natural hazards | Policy changes. |
| System lifespan. | Changes in prices of system components. | Emission reduction policies. | Shift towards international policies on climate change. |
| Changes in demand. | Changes in prices of fuel. | Land use policies | Jump in consumer demand. |
| Relevant codes and standards. | Market structure. | Availability of renewable sources. | Social acceptance. |
| | | | The health risk posed. |
| | | | Availability of fuel. |
| | | | Environmental policies. |

complexity associated with optimizing the economic and technical characteristics of SHPS are Classical (Linear programming model, LPM; dynamic programming, DP; and nonlinear programming, NLP), Metaheuristic (genetic algorithm, GA; particle swarm optimization, PSO; simulated annealing, SA; and ant colony, AC; algorithm), and Hybrid ( Simulated Annealing-Tabu search, SA-TS; Monte Carlo simulation-Particle Swarm Optimization, MCS-PSO; hybrid iterative-genetic algorithm, GA; multi-objective design optimization-genetic algorithm, MODO-GA; artificial neural fuzzy interface system, ANFIS; artificial neural network/GA/MCS; PSO/DE (differential evolution); evolutionary algorithms and simulation optimization-MCS) techniques [166]. Optimal sizing of SHPS is important to obtain a model with optimal management of resources, economic efficiency, technical reliability, and customer satisfaction [167–172]. An oversized SHPS would result in an increase in the cost of energy and cost of investment, and it would be unfeasible economically. Also, an under-sized SHPS would result in a decrease in the reliability of the system. Therefore, to strike a balance, an optimization technique is necessary. Optimization of SHPS may be used to adopt different objective functions, such as maximizing profit, reliability, renewable energy fraction, number of jobs created, or minimizing imported energy, emissions, cost of energy, and life cycle costs [173–178].

## 8. Conclusion

Renewable energy resources are abundant worldwide, presenting a valuable opportunity to fulfill the United Nations’ sustainable development goals, including climate action, affordable and clean energy, and sustainable cities and communities. However, the intermittent nature of these resources poses reliability challenges when utilized for energy generation. As a viable solution, Sustainable Hybrid Power Systems (SHPS) have garnered attention from researchers proposing feasible schemes to address these issues. This study provides a comprehensive review of diverse aspects related to SHPS, covering system configuration, uncertainty evaluation, demand-side management (DSM), emission analysis, reliability, control strategies, consumer types, load demand increase (LDI), application of multi-criteria decision analysis (MCDA) techniques, techno-economic feasibility, energy storage systems (ESS), and optimization techniques. By identifying research gaps and addressing them, this review aims to enhance the design and implementation of SHPS. Despite notable achievements in SHPS optimization and design over the past decade, this review highlights the potential for further improvement. Future studies in this field could consider the following areas:

(1) The impacts of energy efficient (or non-energy efficient) appliances on the techno-economic characteristics of SHPS.
(2) The development of an improved, affordable, and efficient battery energy storage system (BESS) for effective SHPS implementation.
(3) More research on the impacts of temperature and different tracking architectures on PV modules' outputs for residential, commercial, and industrial applications.
(4) Innovative models for obtaining daily electricity demands of consumers isolated from the grid should be developed, implemented, and applied to acquire daily estimates of consumers' load profiles.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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