



# A Literature Review on Distributed Generation for Application in the Sudanese Grid

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## ARTICLE INFO

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## ABSTRACT

This study investigates the potential of distributed generation (DG) as a solution to Sudan's electricity challenges. The assessment is based on official national data to ensure accuracy and consistency. Sudan's energy mix is dominated by biomass (56%) and oil (39%), while hydropower contributes only 5%, and renewable electricity remains limited. Although the country possesses significant energy resources, electricity shortages persist due to inefficiencies, as only 76% of generated energy is effectively utilized, while approximately 24% is lost. The residential and industrial sectors account for the highest electricity consumption. The findings highlight distributed generation as a practical approach to reducing system losses, improving grid reliability, and enhancing energy sustainability in Sudan.

## 1. INTRODUCTION

A conventional electrical generation system, such as hydro, nuclear, and thermal, consists of numerous electrical power substations. Substations are typically located far from load centers; therefore, power must be transmitted from generating stations to consumers through transmission and distribution networks. These plants, transmission lines, and "distribution systems" are currently being used to their largest load, but load demand is increasing faster than generation capacity. This rise in load demand needs that new generation electrical plants be constructed and that the transmission and distribution systems be promoted, neither of which is desirable from an environmental perspective., particularly when several regions attempt to face the objectives combination in the Protocol of Kyoto to dominate emissions of greenhouse gas [1]. Accordingly, interest in distribution generation systems has been quickly

growing [2]. "Distributed generation" is roughly known, as tiny-scale generation of electricity supported by green energy sources, such as solar and wind, or by energy from low-emission sources, such as micro-turbines and fuel cells. Networks of distribution generation are commonly connected so that they operate at one time with the distribution grid, and they are mainly joined beside the load. The distribution grid has not been authorized without a utility grid. Nevertheless, the economic feature of "utilizing distribution generation units, connected with the progression in mechanism for mastering these generation units, has driven the prospect of these generation units being engaged in an independent method, or what is famed as "a micro-grid". units' interface of distribution generation to the grid can be classified into two kinds [3]:

- Direct grid-connected DG units.
- Indirect grid-connected DG units.

The distribution generation units of direct-connected networks are accomplished by utilizing either an induction generator or a synchronous generator. Moreover, to drive these generators the prime mover can be operated at a constant speed. The indirect grid-connected interfacing of distribution generation units is utilized when the source output is DC such as fuel and photovoltaic systems, sources of high-frequency AC such as variable frequency such as wind and variable frequency micro-turbines, and. In this case, converters of power electronics are used.

## 2. LITERATURE REVIEW

Based on the literature, there is no single universally accepted definition of "Distributed Generation." However, it generally refers to small-scale generation units installed near or at load centers.. whereby, the qualifier can be variegated based on kind of prime mover, unit connection, and level of voltage, substations generation not being transported, and rating of maximum power [4]. The distribution generation is defined by IEEE [5] as the electricity generation of institutions that are adequately least than central plants of generation to allow linkage at any closely power system point." the size of the distribution generation has been compared by IEEE to that of a traditional plant of generation. A more precise definition has been provided by International Council on Large Electric Systems [6] and distribution generation defined by the International Conference on Electricity Distribution [7], based on location, type, and size. The International Council on Large Electric Systems (CIGRÉ) defines distributed generation as generation units with a maximum capacity typically ranging from 50 MW to 100 MW that are connected to distribution networks and are neither centrally planned nor transmitted over long distances Moreover, International Conference on Electricity Distribution defines distribution generation to be "all units of generation with a maximum rating of 50 MW to 100MW that are commonly linked to the distribution grid." distribution generation also defined by Chambers [8], as "the comparatively tiny generation substations of 30 MW or not more that are placed at or nearby consumer locations to cover particular consumer needs, to back the strategy of economic of the distribution network, or both". in addition, distributed generation also has been defined by Dondiet [9] as "a source of electric power distribution generation or stock typically ranging from minimum than 1.0 kW to 10 of MW that is not a portion of a big power system and is located close to the load." He comprises the stock establishments

on his definition. As well as [10] a distributed grid defined by Ackermann as "a power source of generation jointed straightway to the distribution substations or on the consumer location of the meter." his definition is very inclusive because there is no outlines on the size of distributed grid and rating but he cap the location of the distributed generation.

## 3. HISTORY OF DISTRIBUTED GENERATION

### 3.1 Reciprocating Engines

Engines of Reciprocating display were advanced almost 100 years ago or more and were the first of the fuel fossil-driven technology integration of distributed generation. Both Otto (spark ignition) and Diesel cycle 'ignition of compression' engines have obtained prevalent approval in a common side of the economy and are in implementation capacity from the portion of generation units feeding tiny conventional tools up to 60 MW essential load demand power substations. Engines of reciprocating can be deemed as a subgroup of indoor burning engines that contain rotational engines. Tiny engines are generally prepared for transmission and can be transformed into power distribution with slight modulation. Considerable engines are, in common, intended for electric power distribution generation, marine pushing, or mechanical motors. They are presently obtainable from plenty of suppliers in all distribution grid capacity. Double-fuel engines provide a standby that integrates the reliability and efficiency of an engine of diesel with natural gas emission benefits. The engines generate less NO<sub>2</sub> and higher efficiency and specific emissions than engines of diesel. Moreover, decreasing in emissions can be gained with a pre-ignition room that reduces the quantity of 'diesel fuel' needed for ignition. Modern natural gas units concentrate on complicated -burn mechanisms that utilize a great proportion of air to fuel than conventional units. The engines lean-burn have maximum efficiencies and less NO<sub>2</sub> emissions, but not more output power. This can be reimbursed by promoting turbo -charging to grow power intensity [11].

### 3.2 Micro-turbine

Micro-turbines are a combination of a small generators and a small turbine or can be considered as a group of tiny turbines and generators. The technology of aircraft auxiliary systems of electrical power systems, automotive designs, and diesel engine turbochargers are used to drive micro-turbines. Most groups presented field-testing explanation units for tiny-scale distribution generation in 30-500 kW

capacity. Although several units are available commercially, most are started to enter the market in 2001 and 2002. These kinds of generators are generally fed by natural gas. The size range of the micro-turbines can coordinate from some kilowatts to megawatts.

### 3.3 Industrial Combustion Turbines

Burning turbines used for power generation for several years and coordinate in capacity from natural combination units beginning at about 1 MW to over 100 MW. Units up to 15 MW are commonly indicated as industrial turbines, so as to recognizes them from bigger utility-grade turbines and tinny micro-turbines. Burning turbines have relatively, less emission, heat recovery through steam, and less structured costs, but less electric output power. With these types, burning turbines are generally utilized for distribution generation when an uninterrupted source of hot water, steam, and power is in demand, as in a combined cycle [11].

### 3.4 Fuel Cells

The most used fuel cells are phosphoric acid and proton exchange membrane cells. Sir William Grove promoted the first cell of fuel in '1839'. and until the 1960s practical technology was used by NASA which constructed fuel cells on the Apollo spacecraft and Gemini to generate electricity. There are many kinds of fuel cells presently under process, containing membranes of proton exchange and phosphoric acid, solid oxide, alkaline direct methanol, and molten carbonate, [12].

### 3.5 Photovoltaic Systems

French physicist Edmund Becquerel has discovered some of electrical ideas in 1839 that particular materials product tiny electric currents when bared to light. His previous experiences were low efficiency in transforming light into electricity and accelerated study into these photovoltaic impacts. The following penetration turn up in the 1940s when material science improved and the Czochralski procedure was advanced to product very refined crystalline silicon. Bell Labs used this process in 1954, to promote a silicon photovoltaic cell that grown the light-to-electricity transformation efficiency to 4%. Systems of Photovoltaic, generally recognized as solar panels, or PV-systems are presently openly obtainable, products no emissions, no sound, dependable, and need less repair to work. PV-systems are not utilized openly due to the very costly technologies of distributing generation to buy, only operate while sunlight is obtainable, and have big effects. Distributed generation units of

Photovoltaic relate to the electrical power system by DC/AC converters with ultimate "Power Point Tracking". Several methods are used to let generators of photovoltaic work with "Power Point Tracking", such as feedback of voltage, functional measure process fuzzy logic control, neural network process, approximation of linear line, and balance method [13].

### 3.6 Wind Turbine Systems

Wind energy turns out a considerable subject in the 1970s during the energy crisis in the U.S. and the resulting search for potential renewable energy sources. They were dedicated to producing electricity and deemed the ultimate economically applicable selection by the renewable energy research file. Today, awareness has continued to focus on this technology as an ecologically intact and suitable substitution [14]. Wind turbines can generate energy without needing additional infrastructure development such as new transmission lines, and so on, generally function in remote stations. Many wind presently being used starting from 10 kW up to 10 MW. Wind power is the most commonly utilized distribution generation source in entire countries. Wind power generation is an alternating equipment that transforms the kinetic power of the wind into mechanical power, then into electrical power, utilizing alternating current generators such as synchronous and induction types. These machines are united to the turbine of the wind. It composes wind turbine blades, a gearbox r, a shaft, a rotor a nacelle, and a coupling device. A bunch of wind turbines constructed in a particular place is called a wind farm [15].

## 4. DISTRIBUTED GENERATION APPLICATIONS

There are many different potential applications for DG technologies, they can be used to reduce demand charges imposed by their electric utility, provide premium power or reduce environmental emissions. DG can also be used by electric utilities to enhance their distribution systems [16]. The following are the benefits of application DG technology to electric utilities and their customers:

### 4.1 Continuous Power

The DG units are designed to generate some or all their power on a relatively continuous basis. Important DG characteristics for continuous power include:

High electric efficiency, Low variable maintenance costs, and Low emissions. Currently, DG is being utilized most often in a continuous power capacity for industrial applications such as food manufacturing, plastics, rubber, metals and chemical production.

#### 4.2 Combined Heat and Power

Also indicated to as Heating, Cooling, and Power generation or Cogeneration, the A section of the distribution generation neglected heat is utilized for steam generation, space heating, water heating, or the rest of thermal required. In some instances, this power can also be applied to work on a particular refrigeration apparatus. Essential electrical distribution generator features for composite heat and power involve high utilizable output of thermal energy, costs of changeable maintenance, and emissions are so low. Combined heat power features are the same as those of continuous power, thus the two implementations have almost identical consumer portfolios, though the high demand for thermal essentials here is not a basic for continuous power implementations. As with continuous power, combined heat power is almost generally applied by industrial customers, with a tiny section of aggregate constructions on the commercial side. [17].

#### 4.3 Peaking Power

In peak power demand, distribution generation works between "200 and 3000 hours" per year to decrease the aggregate cost of electricity. Substation units can be applied to minimize the utility's demand charges, to delay buying electricity within the maximum-price duration, or to get permission for lower rates from power suppliers by softening the demand site. Essential distribution generation features for peak power demand comprise minimum constructed cost, speedy startup, and minimum costs of constant repair. Power companies can provide demand peak power implementation to consumers who prefer to minimize the cost of buying electricity through a maximum price duration. Presently, distribution generation peaking units are utilized mostly on the commercial part, as factors of load in the manufacturing sector are comparatively flat. The most general implementation is in the utilities of education.

#### 4.3 Green Power

This distribution generation units are operated by utilities to lower ecological emissions from generating power supply. Important DG characteristics for renewable energy implementation give low emissions, more efficiency, and minimum

repair costs. Companies' energy supply consumers who want to buy generated power with minimum emissions could also use renewable energy.

#### 4.4 Premium Power

Electrical power distribution generation is utilized to offer the service of electricity at a greater stage of accuracy and electrical power feature than commonly obtainable from the network. The increasing prerequisite electrical power market currents facilities with a chance to provide added value and customer services. Customers generally demand continued power for a variety of implementations, and for this reason, outstanding power is divided into three further categories:

**1. Emergency Power System** - the system operates automatically as a backup to offer electricity through a particular duration to substitute the main source if it goes wrong. The system is utilized to power stringent apparatus whose washout would be affect in estate deterioration and overhang health and integrity. Consumers implicate flats, hotels, commercial premises, offices, schools, and a broad area of generic evacuation places.

**2. Standby Power System** - This liberated system offers electrical power to substitute for the main power source if it goes wrong and thus get permission for the consumer's whole utility to carry on working smoothly. a system is stringent for customers such as airports, prisons, distribution and transmission systems, water supply and sewage treatment plants, dairy farms, natural gas, fire and police stations.

#### 3. True Premium Power System

This offers continued energy, and free-for-all-goodness power issues like the diversity of frequency, slope, transient voltage, and twister. Power of this quality is not obtainable straightway from the network – it needs supplementary, conditioning power apparatus and standby power. Instead, the technology of distribution generation can be utilized as the basic source of power and the network can be used as a support. The technology is utilized by important mission systems like nursing homes, banks, hospitals, connecting stations, and insurance companies, essential electrical grid features for outstanding energy comprise speedy startup, construction cost, and fixed repair cost, which is very Low [17].

**4. Transmission and Distribution Deferral** - Generally, putting distribution generation units in strategic locations can assist in deferring the buying of modern distribution or transmission systems and apparatus such as power plants and distribution lines. Essential electrical generation features for distribution and transmission delay comprise low construc-

tion cost and minimum fixed repair costs. Shortly, the Sources Kinds of Distributed Generation shown in Figure 1; set up for this research, and the two main kinds are:

- a. dispatchable and,
- b. non-dispatchable [17].

### 5. ROLE AND INTEGRATION OF DG<sup>S</sup> IN THE POWER SYSTEMS - SUDAN GRID

Sudan's electrical power sector has been subject to poor infrastructure and experiences frequent power outages. About 70% of the electricity is consumed in the Khartoum area. Rural areas do not have access to electricity, except for some large, export-oriented agricultural schemes. So different types of distributed generations can be installed in the west of Sudan are expected to grow in the future years. DG systems employ numerous, but small plants and can provide power onsite with little reliance on the distribution and transmission grid. Utility-scale generation units generate power in capacities that often reach beyond 1,000 MW [18]. So distribution generation can be used when the load demand increases rapidly as in the load demand of Sudan grid, which is totally different when compared through different periods. Figure .2 illustrates the peak of nine years (2013-2021), and load demand variation of Sudan grid which is obtained in Figure 3, the power production and distribution system must respond to the customers' Load demand variation at any time. Therefore, modern electricity distribution utilities need accurate load data for pricing and tariff planning, distribution network planning and operation, power production planning, load management, customer service and billing, and finally also for providing information to customers and public authorities.

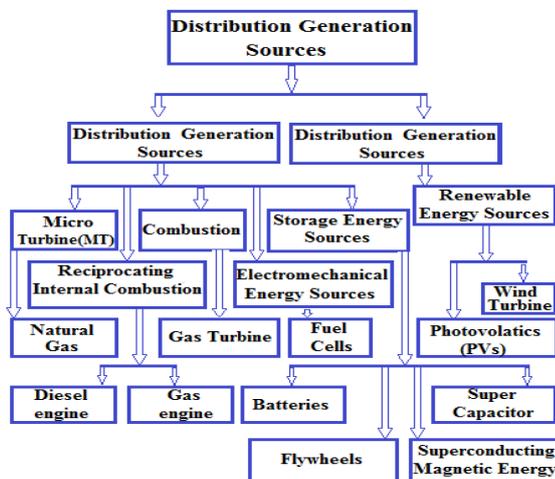


Figure 1: Sources of distribution generation

Renewable energy sources include biomass, geothermal, solar, and wind power. This repair to all power sources that rejuvenate themselves through a stumpy time or are constantly obtainable. Power from hydro energy is only slightly renewable power. This is obviously the state with tidal or river electrical power substations. Moreover, many water dams also produce unsettled combine, like water pumping into heir dams at night and returning power from them through the day when there is demand rising for electrical power. Ever after it is not imaginable to count the amount of output energy, all electrical power from hydro energy are presented partially. In 2018, renewable power, fundamentally hydropower calculated approximately 61.4 % of current total exhaustion in Sudan [22]. In contrast, the fuel price significantly rises in Sudan. As a result of that, some

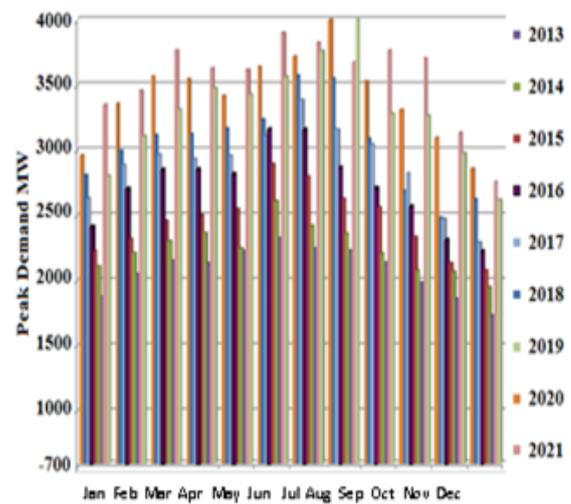


Figure 2. Sudan grid peak demand for 2013-2021

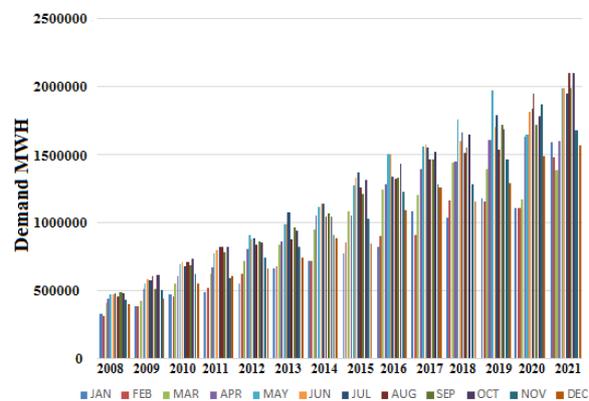
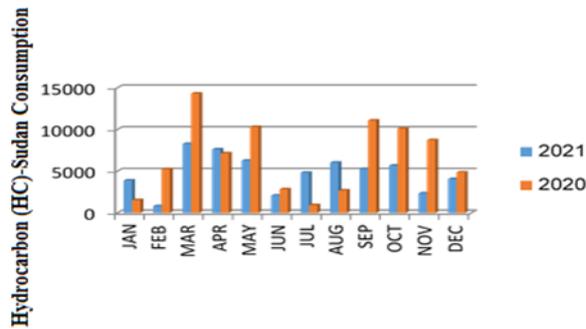
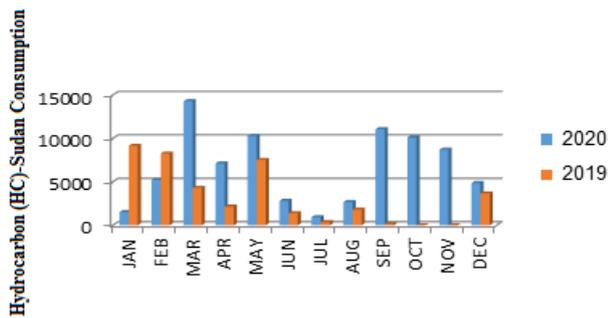


Figure 3: Sudan grid variation of load demand for 2008-2021 for 2008-2021

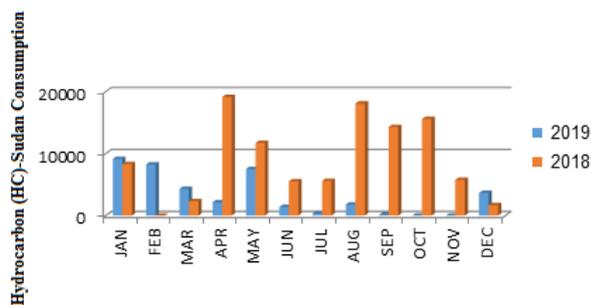
of the utilizing fuel was decreased as compared within the years (2021 & 2020), (2020 & 2019), (2019& 2018), (2018 & 2017), and (2017 &2016). Which illustrated in Figure s 4-8 consecutively.



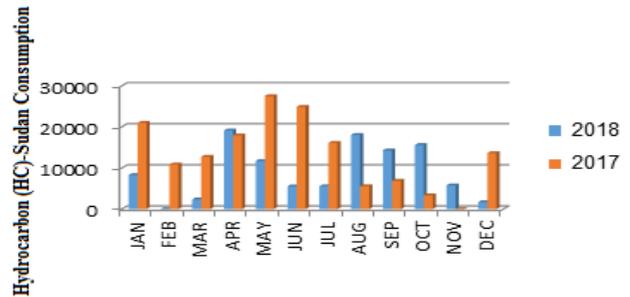
**Figure 4:** Hydrocarbon (HC)-Sudan Consumption in a ton For 2020 & 2021



**Figure 5:** Hydrocarbon (HC)-Sudan Consumption in a ton for 2019 & 2020



**Figure 6:** Hydrocarbon (HC)-Sudan Consumption in a ton For 2018 & 2019

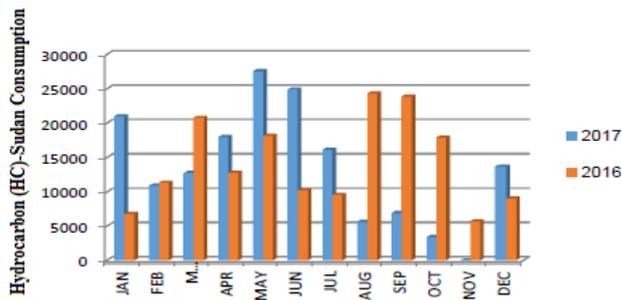


**Figure 7:** Hydrocarbon (HC)-Sudan Consumption in a ton. For 2017 & 2018

## 6. USAGE OF RENEWABLE ENERGIES IN THE SUDAN GRID

Sudan is an agrarian country with prolific ground, several of resources water, cattle, resources forest, and agrarian residues. An overview of the energy situation in Sudan is introduced with reference to the end uses and regional distribution. Energy sources are divided into two main types: conventional energy (biomass, petroleum products and electricity) and non-conventional energy (solar, wind, hydro, etc.). Sudan possesses a relatively high abundance of solar radiation, moderate wind speeds, hydro and biomass energy resources. Implementation of new and renewable sources of energy available in Sudan is now a major issue in strategic planning for alternatives to fossil fuels to provide part of local energy demand [19]. Sudan has a long history of meeting part of its energy needs through renewable resources. Sudan’s portfolio of renewable is wide and various, consequent in section to the state’s broad framework of weather and natural views. As several African commanders in renewable power application, Sudan has a great realized involvement to keep studying, expansion, and application of new processes. Continuous less-carbon power script for the new pairing confirm the unexploited power of renewable energy resources, pastoral areas of Sudan can subserve from this transference. The enhanced facilitate of dependable and effective output energy services catalyze new improvement stand by. Renewable ecologically cordial energy should be supported, advanced, performed, and confirmed, for applying in Sudan [20]. Moreover, supplementing the growth Sudan of a plan to utilize from wind power and solar energy to product more than “5.0 MW” of electrical power in Sudan, which is mainly produced at EL-Fasher state. Meanwhile, the International Renewable Energy Agency (IRENA) has classified Sudan as one of the best African countries with the

largest capacity to produce alternative energies, such as solar and wind [21].



**Figure 8:** Hydrocarbon (HC)-Sudan Consumption For 2016 & 2017

## 7. DEVELOPMENT OF GRID-CONNECTED DISTRIBUTED GENERATION

### 7.1 The distributed hybrid energy system

Major renewable power sources like wind turbines and PV-systems depend on the environmental ambient condition therefore product unstable output power. The other renewable energy sources such as a micro turbine and fuel cell system don't have ambient dependency, but their out-response characteristics are so slow that they can hardly meet the dynamic load conditions. Therefore, renewable energy sourced generation systems are weak in stability and sustainable power supply since the sources are mostly dependent on weather conditions. power system distributed hybrid formed of many new generations power is the future expansion direction in the new power generation of grid connected. Energy system of hybrid distributed, formed of many new generations, is a new integrating energy of distribution and storage technology. The feature system of a hybrid energy are to beat the sensitivity single supply of energy, and realize the integral merit and output power elaboration of various power by using various features of diverse small-scale sources, the intellectual distribution of small-scale sources, and power systems storage; meanwhile, promote thoroughness of electrical power supply and quality of energy at linkage/segregation working case by the leveling of load control strategy and apparatus of energy electronic. In systems of hybrid distributed power, the notional and academic challenges are the structure, layout, and resolve of key elements and strategy of control:

Chosen of the construction and key elements in the system of hybrid-distributed energy; can be achieved by the selection of "a DC-AC double bus", that uses the "DC bus" in the close supply region to decrease

the "AC-DC rectifier" of the energy apparatus and promote the output power of electricity. In the chosen of key elements, the size and construction of the system storage are chosen and pre-apprehension accurately, and the structure feature depends on the converter of connected network, and its achieves the combined tasks of connected network energy generation composed with the organizer of energy characteristic.

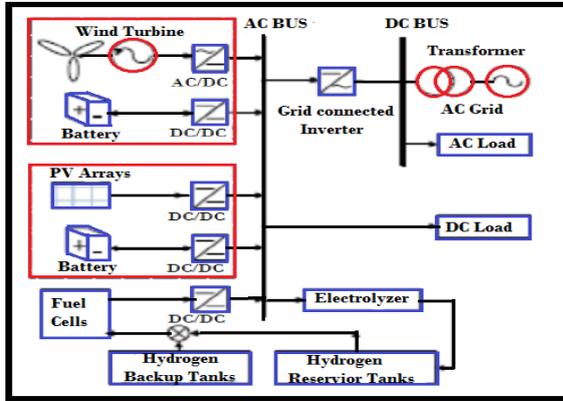
The basic loop layout and different element design in systems of hybrid-distributed energy are researched setup on the characteristics of the small-scale sources and storage power apparatus [23].

The arranged challenges control among diverse small-scale sources in in systems of hybrid-distributed energy have various tiny-Ssources, thus are linked to the "DC bus or AC bus" of the systems of hybrid-distributed energy within developed apparatus of electronic power, almost all of them are resilient and It can be controlled, each of them has a diverse feature of current-voltage and power- frequency, and the various constants time. A greater-arranged control strategy can secure the continuity of operation and quality of power of the advantage network, and afford the whole function to the new generation output power. Figure .9 is an aggregate scheme of a network-linked system of distributed hybrid power. This hybrid distribution system comprises a photovoltaic and wind turbine as electrical power sources, a widespread "DC bus", electronic power converters within convenient electronic power connecting circuits, and a network-linked inverter to the "AC" network. The electrical power system can be easily widened; i.e., the other power sources can be incorporated into the system when they are obtainable. A system of distributed hybrid power is "a DC-AC" double bus construction, which gets hold of the two-track passing and mastering of electrical power among a great generation grid and electrical power system. When surplus wind and solar power are obtainable, the electrolyzer and charging of the battery are turned on. In addition, the electrolyzer generates hydrogen, which is forwarded to the hydrogen tank storage. The strategy of mastering to improve how the supplementary power is applied. When there is a weakness in electrical power generation, the fuel cell accumulates and starts to generate power utilizing hydrogen from the standing-by tanks, or in case, they are vacuous, from the standing-by hydrogen tanks. A battery stack is applied to provide energy to speedy transient load, vibration, and spikes in applications of isolated grids [24].

### 7.2 Smart Micro-Grid

Smart network idea has already appeared. In addition, it is a modern strategy compose of smart grid of distribution. A regular smart network pattern is

display in Figure 10. The key element of a smart network is the combination of four elements into a mainly administrated, power infrastructure of based campus. The main elements are:



**Figure 9:** Example of distributed hybrid energy system

1. **Supply:** the source of renewable, non-renewable and storage.
2. **Demand:** consuming energy apparatus through strategy comprising but not restricted to illumination, heating ventilation air conditioning, and IT apparatus.
3. **IT Management platform:** smart grid to promote sources and load demand depending on administration goals and factors of conditioning.
4. **Environmental factors:** changeable exterior to the system of administration that will affect energy utilization such as comfort, climate, and pricing. Brilliant power and administration-building software of chord system and brains of a smart grid. The shortage of this climacteric element has prevented utility administrators from largely and efficiently realizing smart grids.

The software platform must cover important administration functions as follows:

- i. Collect data,
- ii. Recognize the chance for administrators and managers to take the necessary measures on data, or off-hand carry out procedures, supply strong telecommunication apparatus on goal and advance within actual-time information boards.
- iii. Provide optimization tools and automation management systems to increase personnel and to enhance staff and productivity assets.

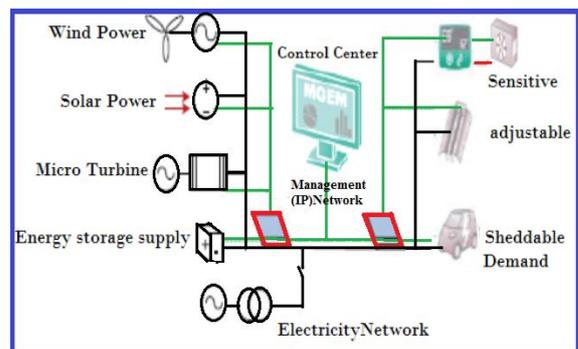
Intelligent networks are comprised of a wide technology range, technology key involves developed technology of power electronics, technology

measurement, and communication, systems of data administration, improved power administration, and improved techniques analysis [25, 26].

Through the scope of the developed networks operation of a sturdy and brilliant distribution grid, the features of distributed systems are integrated to realize healing self-control of intelligent microgrids, distributed generation assortment and conform control, best management of power, and information combination. Intelligent networks will be ultimately brilliant, automation, data, and digitalization. [27].

### 7.3 Microgrids – A part of the Smart grids

Smart grid solutions have supplied electrical power to approximately “90 million” communes all over the world in 2016 [28]. Literature defines smart grids in varied ways. An electrical power distribution system is a generality common up to 10 MW in capacity, including various load demands and distribution resources of power such as distributed generators, storage apparatus, or masterable loads that produce a mastered output power, these power distribution systems work in an organized method even when unconnected, generally known as a ‘microgrid’ [29]. It is recognized from current literature that “15-20” percent of the generated power is wasted in the grids of transmission and distribution, and about “10-20” % of losses power is numbered for stealing towards services, which is also familiar as power manipulating. Generally, about “40 %” of energy is wasted in transmission [30]. Un-centralized grids can actively register the merits of a centralized power generation presented in Sudan’s traditional electrical power system. Moreover, micro-networks can help decrease classic involvement and automate various grid elements, thus settling the complication of electrical power grids’ mechanisms control. Microgrids are considered like nodes in the great grids, and the intelligent grid is elicited across the “peer-to-peer” reaction among these nodes [31].



**Figure 10:** Smart micro-grid model

## 8. OPTIMAL SCENARIO FOR INTEGRATING DISTRIBUTED GENERATION INTO THE SUDANESE NATIONAL GRID

Optimal integration of distributed generation (DG) into distribution networks is a critical component of modern power system planning. DG integration enhances supply reliability, reduces distribution losses, improves voltage profiles, and supports system resilience when properly planned and executed [32].

The key aspects of the optimal integration scenario are summarized as follows:

### a. Criteria for Optimal Integration

The optimal scenario for DG integration into the Sudanese national grid should prioritize strategic siting, sizing, and technology selection based on system characteristics and demand profiles. Analytical and optimization techniques such as metaheuristic algorithms (e.g., genetic algorithms, particle swarm optimization) are widely used to determine these optimal parameters within distribution networks [33].

### b. Multi-objective Planning Approach

A multi-criteria sustainable planning (MCSP) approach provides a robust framework for DG integration. This methodology evaluates DG options by balancing technical performance, economic benefits, environmental impacts, and social considerations [34].

### c. Grid Control and Operational Considerations

For effective deployment, DG units must be integrated with advanced distribution management systems (ADMS) and real-time grid controllers to manage bidirectional power flows. The change from radial to active distribution networks requires updated protection coordination and power quality monitoring [35].

### d. Summary of Best Practices

The optimal integration scenario entails comprehensive siting and sizing optimization, use of multi-criteria decision methods, intelligent control systems, and regulatory frameworks supporting DG interconnection standards [36].

## 9. APPROPRIATE WIND TURBINES FOR DISTRIBUTED GENERATION INTEGRATION

Selecting the appropriate wind turbine technology is critical for the successful integration of wind energy into DG systems. The choice depends on site-specific wind characteristics, grid interconnection requirements, and operational objectives [37].

The key considerations for selecting suitable wind turbines for DG integration are summarized as follows:

### 1. Turbine Technology in DG Context

Wind turbines suitable for DG applications range from small-scale units for rural electrification to larger units providing network support through active and reactive power control [38].

### 2. Horizontal-Axis Wind Turbines (HAWTs)

Horizontal-axis wind turbines (HAWTs) are widely used due to their high efficiency and ability to capture consistent wind energy when wind direction is stable. HAWTs are ideal for grid-connected wind energy systems in moderate to high wind regimes [39].

### 3. Generator Layout: DFIG and PMSG

Among grid-connected turbines, Doubly Fed Induction Generator (DFIG) and Permanent Magnet Synchronous Generator (PMSG) are common. DFIG allows independent control of active and reactive power, while PMSG provides smoother transient responses and improved fault-ride-through performance [40].

### 4. Vertical-Axis Wind Turbines (VAWTs)

Vertical-axis wind turbines (VAWTs), such as Savonius or Turby designs, are suitable for distributed or urban contexts with variable wind directions. They accept wind from all directions and have a simpler mechanical design, making them suitable for smaller DG units near load centers [41].

### 5. Turbine Selection Guidelines

HAWTs are recommended for sites with unidirectional winds and substantial wind resources, while VAWTs are suitable for variable wind directions or space-constrained locations. Selection between DFIG and PMSG should consider grid requirements and operational performance [42].

## CONCLUSIONS

This study reviewed distributed generation technologies and their impact on electrical power systems, with specific focus on the Sudanese grid. Due to rising fuel prices, high distribution losses, and environmental concerns, penetration of renewable-based distributed generation in Sudan is expected to increase in the future. However, integration of distributed generation into existing power systems presents technical and economic challenges. Renewable energy sources such as wind and photovoltaic systems are inherently variable, which may affect grid stability if not properly managed. Therefore, advanced grid integration techniques, hybrid systems, and smart grid technologies are essential to enhance system reliability and economic

performance. Future research should focus on improving integration strategies, grid management techniques, and optimization methods for distributed generation deployment in Sudan.

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