African renewable Energy potentialities review for local weak grids reinforcement study

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***Abstract* -This paper presents a literature review based standalone microgrids including the hybrid renewable energy sources (wind, solar PV, hydroelectricity) with energy storage systems. Some configurations of the hybrid systems based on the DC-bus and AC-bus are proposed. A general overview is given on the renewable energy potentialities in Africa, and in particularly in Guinea where the rural electrification is today major challenges. Several control strategies related to the intermittency of the renewable energy sources are analyzed. The methods are generally focused on energy production optimization, energy conversion performances, microgrid stability, multi-source energy management strategies. Different architectures and topologies of the most common converters and filters used in hybrid renewable energy applications are also discussed. Potential solutions and research trend are identified through the synthesis of recent studies proposed in the literature.**

Keywords-Renewable energy, Standalone, Microgrid, Wind, Solar PV, Hydroelectricity, Energy management.

I. INTRODUCTION

Today energy demand through the world is key challenge, in particularly in Africa, where the rural population increasing and the dependence to fossil energies is expensive. The greenhouse emissions which are responsible today for the climatic disturbance have for consequence the rise of water and the increase of natural disasters, oblige to use other forms of energies, less constraining with regard to nature and whose current consumption does not compromise the future needs. For this, renewable energies such as PV system, wind energy, hydroelectricity, tidal energy, geothermal energy and biomass are essentially. In 2021, the energy consumption through the world is focused on oil (30.95%), natural gas (24.42%), coal (26.90%), nuclear (4.25%), hydroelectricity (6.76%) and renewable energy (6.70%), [1]. According to ODD7 (*Objectif de Development Durable n°7*), by 2030, access to reliable, sustainable and modern energy services at an affordable cost must be guaranteed for all. This goal was slowed due to the COVID19 pandemic and at this rate, 670 million people worldwide will remain without electricity for a global electrification rate of 92%, [2]. World energy production in 2009 depended on fossil fuels for 80.3% against 82.27% in 2021, that is to say a higher global contribution than 10 years ago. This is explained by the fact that the post-COVID19 stimulus plan grants six times more investment to fossil fuels than to renewables [1],[3]. According to the IEA (International Energy Agency), the lifetime of oil reserves is estimated at 54 years, for gas 63 years, coal 112 years and uranium 100 years under current operating conditions. In this situation, it is necessary to anticipate the depletion of reserves of these sources, and for this purpose energy efficiency and development of multi-source systems based renewable energies must to be explored in particular, [4]. Different technologies of the renewable energy sources are summarized in Figure 1. In 2020, Africa people is estimated about 17% of the world's peoples, but Africa is the one of least developed continent in the world and has enormous renewable energy potential that is unevenly distributed across the continent from one area to another. However, it consumes only 3.2% of the world's primary energy, i.e., an average electricity consumption by people/year of 600 kWh against 3200 kWh, the world average [5]. According to IRENA (*International Renewable Energy Agency*) report in 2017, the potential of the renewable energy resources in Africa is distributed as follows [6]: 130 billion tons of biomass stock in 2010; 350 GW of hydroelectricity, where 90% is not exploited; 10 TW in solar energy; 1300 MW in wind energy; and 10 to 15 GW in geothermal energy. In view of these multiple renewable energy potentials, we can identify some solutions that could contribute to the achievement of the sustainable development objectives which is universal access to energy for all African peoples. In Africa, rural areas are the most confronted with this reality given the difficulties of access, their distance from the interconnected networks and the low people density to make investments profitable. However, they benefit from the advantages of nature, notably the relief, hydrology, sunshine and flora that can serve as primary energy sources to satisfy the local need of electrical energy. Among these sources, the major of the works are focused on hydroelectricity, solar PV and wind power which are the most abundant and therefore more accessible. Some works include the diesel generators and energy storage units to optimize the multi-source systems operation. These elements will be the subject of studies in the continuation of this work.

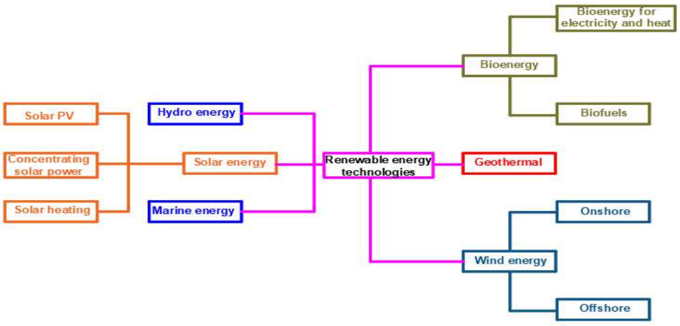


Figure 1: Different technologies of renewable energy sources, [11].

II. POTENTIALITIES OF RENEWABLE ENERGY SOURCES IN AFRICA

A. *Potential of Hydroelectricity in Africa* [7]

Hydroelectricity energy comes from the water energy conversion that flowing in a river or from an artificial developed water storage. This transformation is carried out by a hydraulic turbine placed in the flow of water which transforms the kinetic energy of water into mechanical energy then transmits this energy to the shaft of the generator to be in turn converted into electrical energy. The hydroelectricity represents 16% of world energy production, i.e., an installed capacity of 1230 GW in 2021, [7]. Amount of energy produced depends on the head of the water mass, the flow rate of the water and the efficiency of the turbines [8]. There are

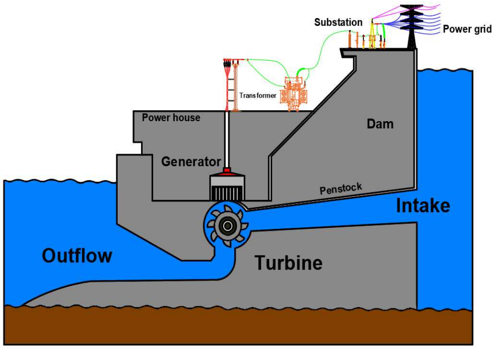


Figure 2: Hydroelectric power plant with water storage, [7]

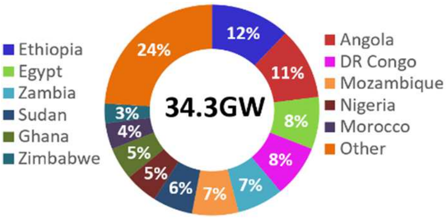


Figure 3: Installed Hydropower Plant Capacity in Africa 2021[7]

three classic types of hydropower plant: -water storage turbines, -run-of-river turbines and the water pumped-storage ones. In the first type, a storage dam is built to store water which is diverted through a pipe to feed the turbine which drive the generator as illustrated in Figure 2. The second type, run-of-river, uses the natural flow of a stream or river, this flow can be maintained at its natural rate by using a weir. This technology is usually proposed for low power applications such as rural energy production. Water pumped-storage type uses two tanks (upstream and downstream of the turbine). The upstream is filled with water by pumping during off-peak hours when demand is low and the price of electricity is low from the downstream tank, and in reverse operation to produce electricity during periods of high demand and or the price of energy is high. This increases the storage capacity of the dam but also ensures the flexibility of the network. Another advantage of hydropower plants is their ability to start up quickly to cope with fluctuations between supply and demand. In [9], the study reveals that the capacitive load over a certain operating range, strongly degrades the power quality delivered by small hydropower plants. The installed hydropower plants in Africa recently and some hydropower plants projects in African countries are presented in following paragraphs. Figure 3 presents the installed hydroelectric capacity in Africa in 2021, which is estimated to 34.3 GW. It is dominated by Ethiopia and Angola, while waiting for investments in the sector for other countries with huge hydraulic potential such as Congo. We also note that this hydroelectric potential is largely under-exploited in the continent in reference to its estimated value. Figure 4 shows the installed pumped storage hydroelectricity (PSH) capacity in Africa. Two countries are currently leaders in this technology: South Africa and Morocco. It is one of the solutions to increase the efficiency of hydroelectric plants. Figure 5 shows the major investments in hydroelectricity projects planned in various African countries by 2037. Ethiopia, Congo and Nigeria are in pole position in this framework of massive investments of the sector in the continent. Other countries such as Guinea also stand out in this area. Figure 6 shows the significant investments in the pumped storage system of the hydroelectricity plants planned in the African continent. Three countries have integrated the development of this technology and its expansion over the horizon in their energy policy: South Africa, Egypt and Morocco. Generally, hydropower production still has significant negative environmental and social impacts that slow down its large-scale deployment. Today, considered solutions to facilitate their expansion are focused on the hydropower plants retrofitting to increase their production capacity, the development of smaller scale projects such as decentralized riverine generation to mitigate environmental and social impacts.

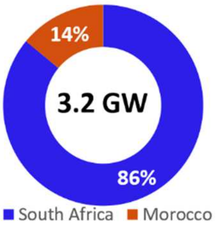


Figure 4: Installed Pumped-Storage Hydropower capacity in Africa 2021 [7]

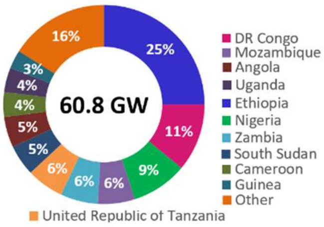


Figure 5: Projection of Hydropower plant projects in Africa 2022-2037 [7]

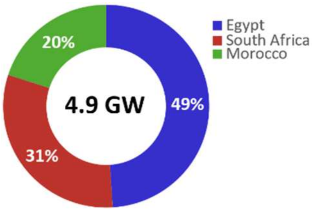


Figure 6: Projection PSH capacity in Africa 2022-2037 [7]

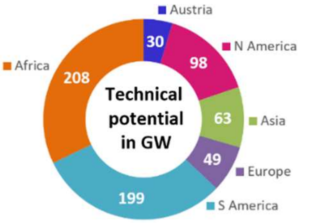


Figure 7: Technical Potential of Salinity Gradient in the world [10]

For offshore applications, the technologies are based today on: Tidal power to harness the potential energy associated with tides ; Tidal currents to exploit the kinetic energy associated with the tides ; Waves to exploit the kinetic and potential energy associated to ocean water waves ; Temperature gradients to harness the energy released by the heat between the sea surface and the deep waters [7], [11] ; and Salinity gradients to exploit the energy provided by the mixing of fresh and salt water at the mouth of rivers. Technical potential of the salinity gradient for different continents extracted in [10] are given in Figure 7, where Africa presents big potential with 208 GW. This figure reveals another source of renewable energy called salinity gradient of which the African continent has the greatest potential in the world. To obtain an optimal operation of the systems, the researchers are doing on the control in case of overload of the hydropower generator when there is excess water in the dam; on the real-time simulations of power oscillation in the hydropower generators in order to mitigate them by modulating the excitation system of the synchronous generator.

Others key actions are doing to reduce the duration of the transient states during the start-up of the pumping turbines in the production unit and/or the network; the monitor the systems in case of circuit breaker malfunction to avoid damage to the windings; and to control the system in case of a long penstock in an isolated system.

B. *Potential of Wind energy in Africa*

Wind energy is one of the most widespread forms of renewable energy after solar energy. The power supplied by a wind turbine is approximately proportional to the surface area of the rotor, the power coefficient of the turbine and the cube of the wind speed. Based on the environment of implementation we have the onshore wind turbines and offshore wind turbines. A distribution of the wind turbines installed in the world in Onshore and Offshore applications are presented in Figure 8. In Africa, the capacity of wind generation amounted to 6.5 GW by the end of 2020 [13].

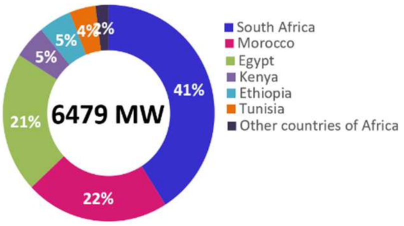


Figure 8: Installed Wind Generation Capacity in Africa in 2020 [13]

Most of this power was supplied in North Africa and Southern Africa, which benefit from an average annual wind speed of about 7m/s. The capacity of the wind turbines installed in Africa in date of 2020 is presented in Figure 8. This potential is clearly under-exploited compared to its estimated value of about 461 GW in the continent [13]. However, its large-scale deployment is confronted with financial and technological constraints, which is why studies are being conducted by researchers to find solutions to the problems related to their cost of manufacture and operation in extreme conditions, especially for offshore types. Some prospective studies are discussed in the next section. The design of high-performance wind turbines and generators with the low cost under extreme operating conditions such as offshore are under development, [14] [15], [16], [17]. The development of large-scale integration solutions to overcome the problems of intermittency imposed by meteorological conditions is proposed in [18].

C. *Potential of Solar PV in Africa*

Energy transported by the sunlight to reach us on earth and transformed into electricity in direct current, is done by photovoltaic cells that are generally composed by the semiconductor-based silicon. The set of cells interconnected between them form a photovoltaic module and the PV module combined with a set (inverter, batteries, electrical components and associating devices), form a PV system. For heating and heat supply on a domestic or industrial scale, concentrated light PV cells with flat collectors or vacuum tubes are also used, which are the most popular in the technologies presented in Figure 9.

For these technologies, the efficiency of energy production is around 40%. Combined with a thermal storage device, they can produce electricity even after sunset to meet peak demand. The greatest potential is identified in semi-arid and hot regions. In terms of cost, although initially higher than electric or gas water heaters, over the life of the system the average annual cost is significantly low about $27 compared to $95 for electric and $82 for gas. These technologies require a sufficient quantity of water for the cooling and condensation processes, about 3700 L/MWh for parabolic trough plants and LFR (Linear Fresnel reflector), moreover they work at optimal efficiency only with the direct component of the sun, in other words when the sky is completely clear. Compared to Concentrating Solar Power (CSP) technology,

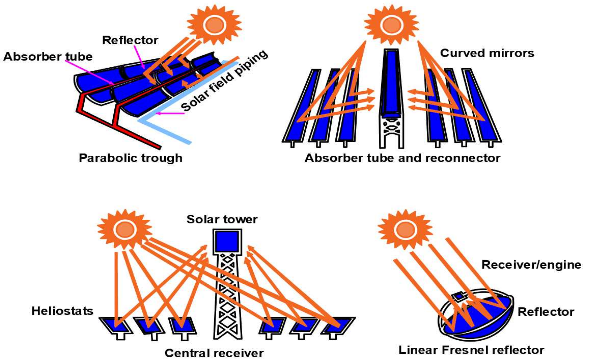


Figure 9. Technologies of the Concentrated light receiving systems [11]

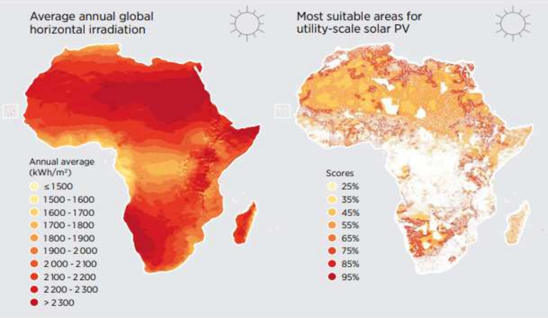


Figure 10. Maps of average annual solar irradiation and areas with high potential for solar photovoltaic energy in Africa [13]

PV has advantages such as the maturity of the PV technologies enables to obtain a significant economy of scale. Its modularity allows a wide range of applications. Its energy production with a partially clear sky, gives it the possibility to use the direct and diffuse components. Because of the ability to predict sunlight with high accuracy, favors the integration of PV in the energy system at the expense of wind turbine whose prediction of wind speed is complex [19]. In Africa, solar energy is the fastest growing energy source, with an average compound annual growth rate of 54% between 2011 and 2020. Its technical potential is estimated at 7,900 GW [13]. The maps of average annual solar irradiation and areas with high potential for solar PV energy in Africa is presented in Figure 10.

D. *Model of the PV system*

In the literature, several models are proposed. These are generally based on single diode models with different numbers of parameters but also empirical models that describe the behavioral aspects of PV modules from a mathematical equation.

In recent literature, single-diode models with a shunt resistor in addition to the series resistor are the most common. In [20], a single-diode model is used for the detection and classification of power loss in series resistance to improve the efficiency of a neuro-fuzzy classifier. However, the robustness of the model to identify other types of faults are not verified. In [21], the same model is used but with a simplified explicit mathematical model to describe the electrical behavior of PV systems based open circuit voltage V_{oc}, short circuit current I_{sc} and factor FF. It has been experimentally validated for predicting the current and voltage characteristics of the PV modules with high accuracy. However, its robustness on the application of large-scale PV systems it not verified. In [22], single-diode PV model is used to translate the temperature dependence of the current-voltage characteristics of the PV modules. Two mathematical models based on current $I_f(I_{sc},T)$ and voltage $V_f(V_{oc},T)$ behavior are established from the temperature. The obtained results based crystalline silicon technology cells voltage range of 0.5V-0.7V, allows a better estimation of the maximum power Pmax and the form factor FF. However, for the types based on high efficiency heterojunction and back contact technologies, the results are not satisfactory. In [23], the same single-diode PV model is used to do the techno-economic comparison of fuel cell-batteries and fuel cell-supercapacitors energy storage systems for a residential building application. In [24], the same one-diode model is used to study the impact of dust accumulation on the surface of PV modules. In [25], a mathematical model of the PV module output power is expressed as a function of the standard PV power, illuminance and temperature. An empirical model adapted to transient weather conditions to predict the short-term power output of solar PV panels is proposed in [26]. This model takes into account the ambient temperature, the irradiance, the wind speed and the relative humidity to predict the temperature of PV modules to the nearest minute. The model has been experimentally tested and the results are interesting with a high accuracy, i.e. an improvement of 46% compared to the basic model. In [27], three-diode model of the PV system is proposed to accurately study the nonlinear behavior of the current-voltage characteristic of commercial PV modules. The model is based on an Equilibrium Optimizer Algorithm (EOA) to extract the parameters with accuracy under different environmental conditions, where the error rate is less than 0.5%. In [28], the control strategy of the Automatic Voltage Control (AVC) system of a photovoltaic power plant based on use of DigSILENT software is done. Three control strategies are tested in the same operation conditions (constant voltage, constant power factor and constant reactive power). In [29], a single-diode model with a new digital control based maximum power point tracking of PV module is proposed through a Single Input Fuzzy-Logic (SIFLC) based on the constant voltage algorithm. The SIFLC generates the control signal for the DC/DC Boost converter. From the experimental study between SIFLC and P&O, it appears that SIFLC is more accurate in the maximum power tracking of the PV with the high-performance compared to P&O. However, its implementation in a real time applications is not proven today.

Based literature review, one of the key challenges for researchers is to find an accurate model that can present a good accuracy of the PV module behavior regardless of the manufacturer. For this purpose, a compromise is necessary between the complexity and the accuracy of the model. Moreover, the development of algorithms for extracting the maximum power and maintaining the constant DC-bus voltage are among the current research. Due to intermittent nature of the PV system (no sun at night), battery energy storage solutions or the use of high efficiency diesel generators are also being developed. The renewable sources taken individually cannot ensure a continuous supply of quality energy to consumers. For example, the hydropower plants present the alternation of the seasons, its production decreases during the dry season or the summer, this leads to a decrease in supply compared to demand. For the solar PV, during the night no sun and therefore no energy production. For wind turbines, the dynamics and the prediction of the wind speed are complex, in more its direction and speed change instantaneously. In view of these shortcomings, the multi-source system including energy storage units is widely encouraged. This issue will be analyzed in the next section.

III. TYPICAL HYBRID SYSTEMS

A multi-source system is the combination of two or more sources including renewable sources or not, used in a complementary way to satisfy an energetic demand [30]. Different configurations of the multi-source are proposed in the literature as following:

-*Wind-Solar PV* configuration presents an efficient and combination to produce more energy than each source individually. An additional advantage is that they do not have peak hours at the same time of the day or year.

-*Wind–Solar PV-Diesel* configuration is a complex combination with addition of a complementary source dependent on non-conventional fuels. However, it has advantages as a backup generator to ensure continuous supply of electricity to isolated microgrids, allows reducing the size of converters associated with the system and its flexibility to work automatically with other sources thanks to modern controllers [31].

-*Wind-Solar PV-batteries* configuration is an alternative solution to diesel which is expensive, cumbersome and polluting. Its operating principle is to charge the batteries when the renewable sources produce in excess, i.e., the supply is greater than the demand and to restore them in the opposite case. This system has an important economic impact [32].

-*Wind-diesel turbine* configuration is an interesting solution for isolated sites with an important wind potential. Determining factor for its dimensioning is the quantity of wind energy produced. In case of underproduction, the diesel generator intervenes in the system to maintain the parameters of the network within the admissible limits, particularly the voltage and frequency [33].

-*Solar PV- Diesel* configuration is a solution that feeds the network from solar energy and the shortcomings of the priority source are automatically filled by diesel. This presents a considerable economic disadvantage, especially during the night when there is no more production. For this reason, it is advisable to associate such a combination with a storage system in order to optimize the solar energy supply [34]. Other combinations are possible such as *Wind – Solar PV – hydropower* plant [35], which can be combined to energy storage system by batteries or by water pumping in hydropower plants with water retention at the dam.

A. Typical implantation site based in "Dialakoro" in Guinea.

For multi-source system implementation site, Niger River at Dialakoro in Guinea illustrated in Figure 11 is considered, where the wind, solar irradiance and hydrometric data are recorded from 2017 to 2022. To make a good choice of multi-source technology for an isolated or non-isolated site, it is imperative to take into account the availability of renewable sources and the cost of realization, which are determining factors for its development. This study evaluates the possibilities to design a multi-source system based on the river hydropower combined to solar PV and onshore wind turbines according to their potentialities in Dialakoro site to satisfy local energy demand. The choice of Dialakoro is based on the analysis of the hydrological potential data of the different hydrometric stations installed on the Niger River in Guinea from 2017 to 2022 as presented in Figure 12. These data not only allowed us to identify the Dialakoro site as the one that records the greatest flow of water at water time during the year, but also to know the periods of drying up of the river during the low water period, which generally takes place between mid-February and the beginning of June of each year. This information allows us to project the installation of a hydroelectricity production source to supply energy to riparian population. However, considering the irregularity of the water on the river during the year and in order to increase the efficiency of the production, a mixed solution with solar and wind power is necessary. Figure 13 shows the sunshine of the Dialakoro area from 2017 to 2022. These data are obtained through the geographical coordinates of the hydrometric station through the geographic information system of NASA, to assess the production of electrical energy based on solar energy in the area. From the analysis of these data, we notice that Dialakoro has an abundant and sufficient solar potentiality, on average 434,18W/m², which allows to project the installation of a solar power plant as one of the alternative solutions within the framework of the energy mix. However, at night, there is no sunshine and therefore no solar production, which brings us back to the same situation as at the beginning, i.e., periods when hydroelectricity and solar production are not able to meet the demand. Figure 14 presents the wind speeds recorded on the NASA geographic information site for the Dialakoro area between 2017 and 2022. We notice through this curve, an average wind speed that oscillates around

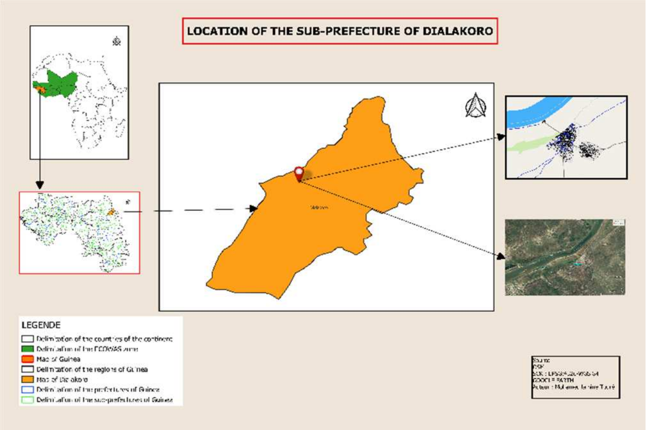


Figure 11. Niger River at Dialakoro in Guinea, with latitude of 11.45 and longitude of -8.9, where watershed area is 71000 km²

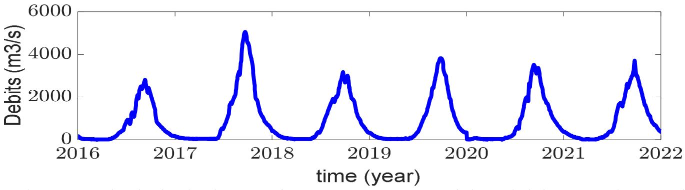


Figure 12. hydrological curve from 2017 to 2022 of the Dialakoro station on the Niger River (http://nigerhycos.abn.ne/portal/spip.php?article118)

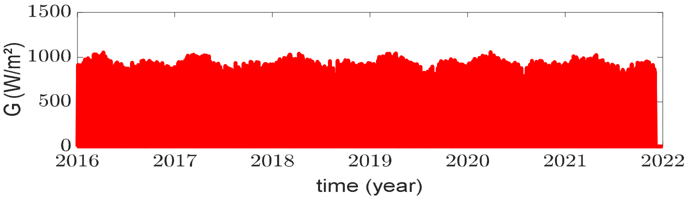


Figure 13. Irradiation of the Dialakoro area from 2017 to 2022 (https://www.earthdata.nasa.gov/news/enhanced-power-dave)

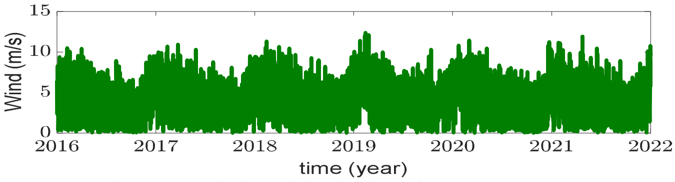


Figure 14. Wind speed in Dialakoro from 2017 to 2022 (https://www.earthdata.nasa.gov/news/enhanced-power-dave)

4,32 m/s each year and given its presence night and day, then it allows to project the installation of a wind production to overcome the shortcomings of solar and hydroelectricity in the framework of the energy mix.

However, its profitability remains to be determined and failing that to think of proposing other tracks of solution to increase the efficiency of the production of the system. Today, several research have been conducted to find an optimal solution of cogeneration of different renewable sources in the same microgrid.

In [36], rural electrification through microgrid is proposed as solution. However, their implementation and control system are challenges. One of the proposed solutions for control is the storage system to overcome the intermittency of renewable sources. Learning-based Power Scheduling Control (PSC) is described in [37] to management a solar-diesel-storage system energy mix. The study reveals that the quadratic model is the most appropriate model for PSC. A hybrid PV-Hydro system is studied in [38], where the hydropower deficit is compensated by the PV system during peak demand and conversely energy storage unit is charged by hydropower when the irradiation is in low level. Energy prediction and converters control based fuzzy-logic from artificial intelligence applied to PV-Wind hybrid system associated to energy storage is proposed in [39]. In [40], the study shows that the wind turbine contributes to 24% against 76% for solar in a low wind region. In [41], the authors show that the increase in demand for electric vehicles, large batteries charges stations and technological development, makes the integration of batteries in hybrid systems competitive. The authors of [42] show that the PSO particle swarm optimization algorithm can handle the variability of electricity price, intermittency of PV-Wind renewable sources with energy storage system, detect the islanding mode of the grid. In [43], the authors show the fast computational of the distributed method in the smart energy management strategy for microgrid applications.

B. Architecture of multi-source systems based Renewable Energies [44]

The architecture of a multi-source depends to the nature of the energy sources , the loads to be supplied, and system operation conditions. Generally, it includes the converters, energy storage units such as the batteries, and the controllers. For a hybrid wind-solar-batteries system to feed an AC load, DC-bus and AC-bus are needed as illustrated in Figure 15. In case, where diesel generator is associated, and the loads are in DC and AC, then a single DC-bus system can be implemented with an automatic starting controller of the diesel generator to limit the battery's discharge condition as illustrated in Figure 16. So, AC-load can be connected to the system through an inverter.

C. Energy storage system

The uncertainties related to the production of hybrid systems of renewable sources, favors the integration of energy storage units in the various configurations to ensure a good functionalities of voltage regulation, harmonic and/or power fluctuations mitigation, load leveling and stability of the frequency and during the transient state. Among the energy storage technologies, batteries and supercapacitors are the most widespread. In the market, there are Several parameters are taken into consideration in the design of batteries, notably voltage and current, charging and discharging rates and duration, operating temperature during charging and discharging, life span in terms of number of charging and discharging cycles, cost, size and weight constraints. The practical realizations are implemented in the Pacific with a capacity of 5 MW Li-ion type, 32 MW Li-ion in West Virginia and 8 MW in California [45]. In the hybrid renewable energy system, batteries and supercapacitors present a complementary role. Indeed, the first one has a slow charge and discharge rate due to its low power density, therefore, they cannot meet peak load demands. On the other hand, they can ensure a great autonomy during long hours thanks to its high energy density while the second one has a fast rate of charge and discharge due to its high-power density, therefore, can respond effectively to the demand during peak load. However, they cannot ensure a long autonomy due to their low energy density. For renewable energy applications, theoretically three configurations (passive, semi-passive and active storage systems) of the batteries-supercapacitors energy storage are possibles. In *passive configuration,* the batteries and supercapacitors share the same DC-bus and therefore the same voltage as illustrated in Figure 17. The advantage of this topology is that it increases peak power by reducing internal losses and eliminates transient currents under pulse load conditions. However, it does not allow the supercapacitors to take full advantage of its charging and discharging capacity because of the small voltage difference across the batteries. In *semi-passive configuration*, two topologies can be distinguished, namely the active control of the supercapacitors power flow through a bidirectional converter, in which case the batteries are directly connected to DC-bus, and the active control of the batteries power flow through a bidirectional converter, in which case the supercapacitors are directly connected to DC-bus as illustrated in Figure 18. In the first scenario, this decoupling of the DC-bus and the batteries with the supercapacitors, increases its volumetric efficiency by operating over a wide voltage range. However, the batteries are exposed to high fluctuating current, which will impact negatively their lifetime. In *active storage configuration*, the batteries and supercapacitors benefit from an active power control through the bidirectional in *active parallel configuration* presented in Figure 19, each converter, this allows to increase their cycle life and flexibility. The most common configurations of this topology are parallel active storage and cascaded active storage. Storage component is decoupled from the DC-bus by a bidirectional power converter. This allows the high-power density property of the supercapacitor and the high-energy density property of the battery, to improve their lifetime and the stability of the DC bus, to operate in a wide range by the frequency management technique as an example. In *active cascade configuration* presented in Figure 20, the converter that separates the batteries is in current-controlled to avoid the batteries rapid charging and discharging in order to increase their life time, and the one that separates the supercapacitors to the DC-bus is voltage-controlled to maintain the variations of the DC-bus voltage within a range that will not affect the efficiency and to allow it to absorb the rapidly varying power exchanges. The quality of the power converters and their control system are the performance indicators of this architecture.

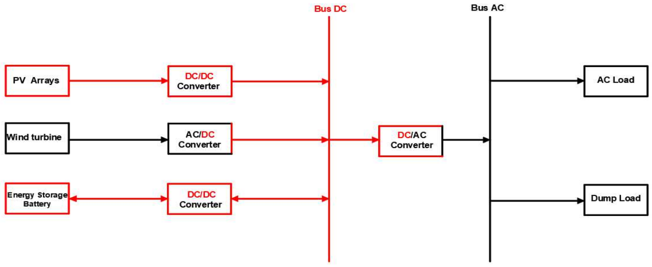


Figure 15 : Structure of the PV-wind-batteries hybrid system

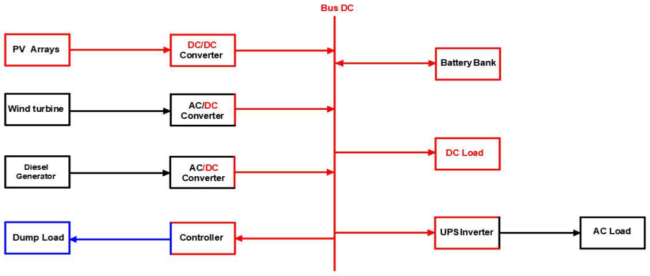


Figure 16 : Structure of the PV-wind-diesel-batteries hybrid system

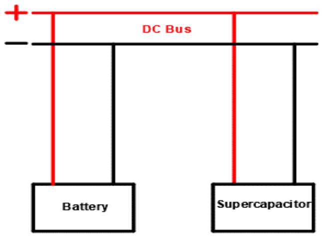


Figure 17: Passive storage for hybrid renewable energy systems [46]

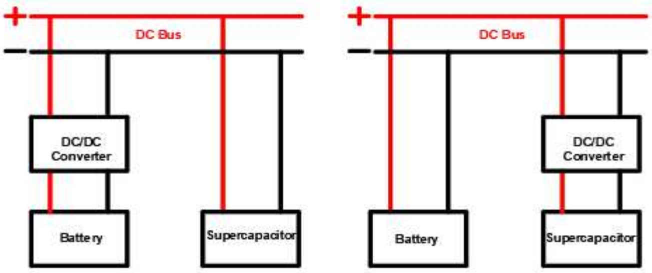


Figure 18: Semi-active storage for hybrid renewable energy systems [47]

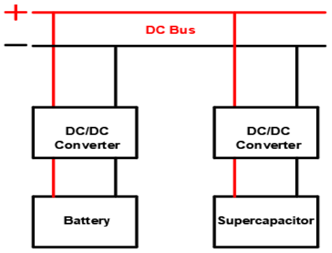


Figure 19: Active parallel storage for hybrid renewable energy systems [48]

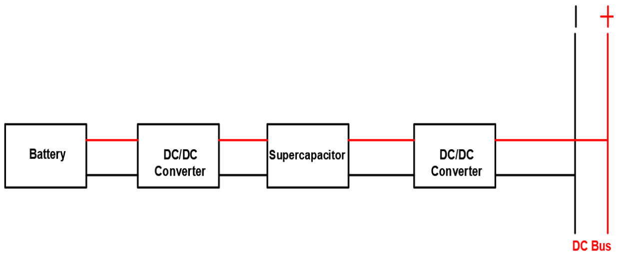


Figure 20: Active cascade storage for hybrid renewable energy systems

Power converters serve as an interface between the renewable energy sources and the load in order to extract the maximum power to be supplied to the load. In practice, back-to-back power converters are used for the integration of wind turbines into the grid, and for PV modules unidirectional DC/DC converters associated to the inverters are usually proposed [49].

D. *Coupling bus type in hybrid renewable energy systems*

With the advent of multi-port power converters, it is possible to use a single converter as an interface between multiple renewable energy sources and the load, this allows a 25% reduction in the total cost of solid-state switches [50]. Today, we have *Grid-connected AC coupling and DC coupling* major applications of the renewable energies. The configuration of the Grid-connected AC coupling is presented in Figure 21. This type of coupling is complex due to the necessity of synchronization of the sources. In configuration with DC-bus presented in Figure 22, all the generation transits through a common DC-bus and electric power are injected in the grid through the inverter. The advantage of this configuration is the reduction of the number of inverters and the achievement of a better efficiency thanks to the DC coupling. However, the drawback is that if the inverter fails, the renewable sources are isolated to grid.

IV. MULTI-LEVEL INVERTERS FOR RENEWABLE ENERGY APPLICATIONS [53]

These are inverters that have a large number of semiconductors switches, and this has the advantage of giving them the ability to withstand higher DC line voltages, provide them with low harmonic distortion, reduce the power variations to obtain sinusoidal step waveform. Another advantage is that their use allows the reduction of the cost and size of filters. Several types of multilevel inverters are presented in literature such as: neutral point clamped (NPC) inverters, cascaded H-bridge inverters, flying capacitor inverters, modular multilevel converters, and their derivatives. The choice of a topology of a multilevel inverter, answers specific application needs in terms of performance, efficiency, cost, power density and reliability. For the NPC inverter, the T-type configuration is the most advanced and the most common topologies in hybrid renewable energy applications are the three-level I-type (3L-INPCI) and the three-level T-type (3L- TNPCI) presented in Figure 23 and Figure 24 respectively. In 3L-INPCI type architecture, the main role of the blocking diode connected to the neutral point is to create a zero potential reference to allow for the three voltage levels at the output. The 3L-TNPCI type excludes blocking diodes in its configuration, it has two groups of internal and external switches, the group of internal switches is connected to the neutral of the DC-bus and blocks half of its voltage, conversely, their cut-off voltage becomes half of the voltage of the external switches. Compared to 3L-INPCI, the 3L- TNPCI has advantages such as a reduced number of switches due to the absence of blocking diodes and a short switching loop. For grid-connected hybrid renewable energy systems, the three most commonly used multilevel inverter topologies are: blocked diode, flying capacitor (FC) and cascaded H-bridge (CHB) as illustrated in Figure 25. They are more used in industries and considered as conventional multilevel inverter topologies due to the following advantages: low harmonic distortion rate of current and voltage at the capacitor output about 75% reduction [54]; high voltage withstand capability; low common mode voltage and low voltage variations for the output waveforms. There is also the modular multilevel converter (MMC) presented in Figure 26, which is a modified PWM topology. This last one has received special attention for the integration of renewable energy sources because of its better performance of modularity, scalability, efficiency and output waveform of the link capacitor charge balance [55]. Considering these different topologies and although challenges remain, cascaded H-bridge (CHB) families seem to be the most appropriate for the application of hybrid systems with energy storage because of the better performance of scalability, reliability, power density in a reasonable range and stability of electric grid.

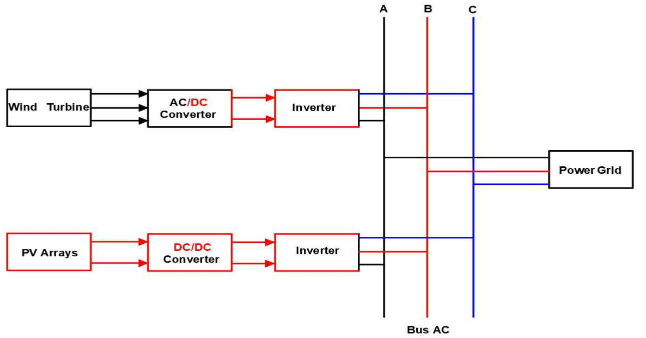


Figure 21 : AC-bus coupling for renewable energy applications

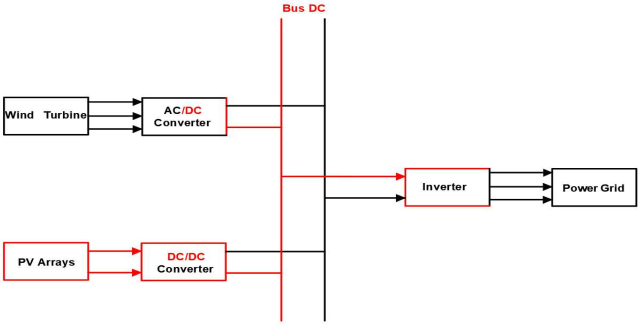


Figure 22 : DC-bus coupling for renewable energy applications [51], [52]

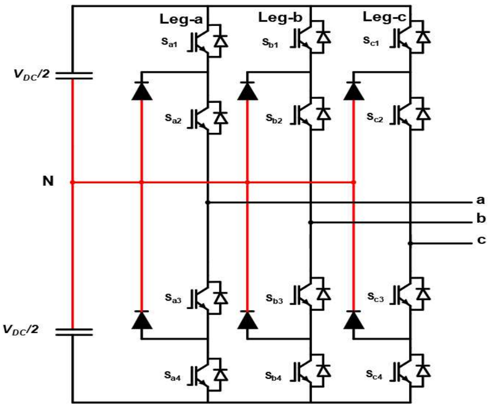


Figure 23: Topology of the multilevel inverter circuit with neutral point clamp (NPC) based three-level I-type.

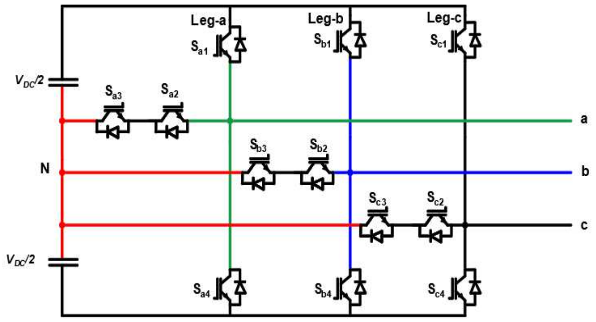
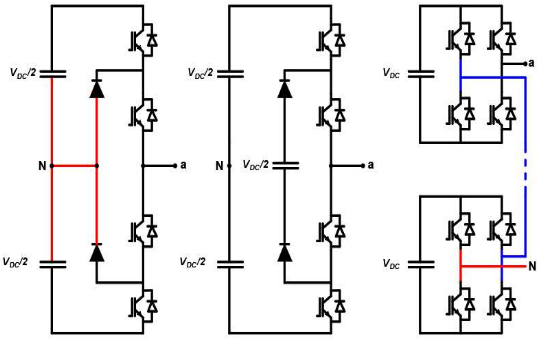


Figure 24: Topology of the three-level T-type multilevel pinch-connect inverter (NPC) circuit.

V. CONTROL OF THE INVERTER COUPLED TO GRID

A grid-coupled inverter typically performs three functions: grid synchronization, grid power flow management and grid pulse width modulation (PWM). Grid-coupled inverter uses generally an inner loop and an outer loop as presented in Figure 27 and Figure 28. The outer loop is based on voltage control that maintains the DC-bus voltage and provides the active power current reference to the inner loop. The inner loop is based on current control through the active and reactive power references that provide decoupled regulation of the active and reactive power components as well as providing the appropriate voltage reference. This voltage references provided by the current loop, also serves as a control signal in the form of PWM pulse for the semiconductor switches of the inverter. Inverters used in hybrid renewable energy systems with energy storage are responsible for supplying active and reactive power to the grid. For this purpose, they are classified into grid-following inverters and grid-forming inverters. The first category is dominated by the phase-locked loop (PLL) used to align with the grid voltage at the point of common coupling with the inverter, therefore, this category does not react to grid frequency variations. The second category with grid formation allows to regulate the grid voltage and frequency. There are several types of PLLs, the most efficient are EPLL and FFSOGIPLL over a frequency range of 1 to 2 Hz [56]. In view of this reality, the inverter control must be structured to allow it to switch from a grid-following control to a grid-forming control in order to avoid the problems associated with low inertia. This will allow the inverter to dampen frequency variations and bring its mode of operation close to that of a synchronous machine.

Since the grid-tie inverter generates its own internal reference voltage angle from its output power, then it is possible to have this dual role in the same inverter. The high frequency switching of power converters, which varies from 2 to 15 kHz in hybrid renewable energy systems, is a source of instability of the network, particularly through harmonics. Therefore, a passive filter is required to attenuate or eliminate the harmonics. In the literature, several passive filter topologies are available such as L, LC and LCL. Due the simplicity of its structure, L filter is easy to implement, however, a high value of Inductance or switching frequency must be selected to reduce harmonics and this causes losses in the semiconductor devices significantly but also slows down the dynamic response of the system. The LC filter (Figure 29, a) has good performance in current-to-voltage conversion. However, the damping of high frequency noise is a challenge in this type of filter [57]. The LCL filter presented in Figure 29, b is a third order filter with an attenuation of -60db/decade which produces a resonance peak. It has many advantages compared to other filters in applications of renewable energies such as: high frequency noise suppression due to its additional inductance, its capacitor is not exposed to line current distortion at the fundamental frequency, low switching frequency for attenuation of a given harmonic, low distortion of the current and the reactive power on the grid [58]. However, the design of an LCL filter is carefully done according to the parameters of the inverter such as: current ripple, filter size, switching ripple attenuation. In general, several aspects must be considered simultaneously when developing a filter, including voltage drop, attenuation ratio, losses, cost, weight and volume.



(a) (b) (c)

Figure 25 : multi-level inverter circuit topology for one phase: (a) Three-level blocked diode, (b) Three-level flying capacitor, (c) Five-level cascaded H-bridge.

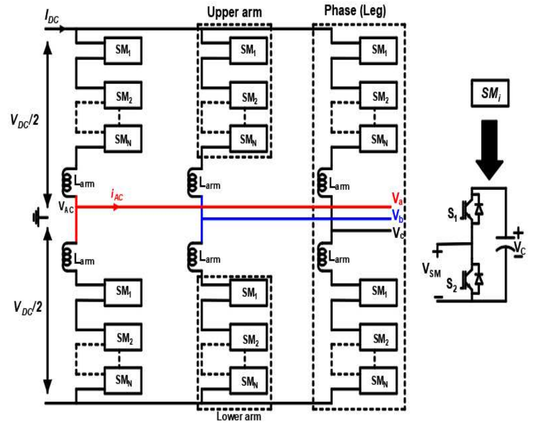


Figure 26 : Modular multilevel converter (MMC) topology

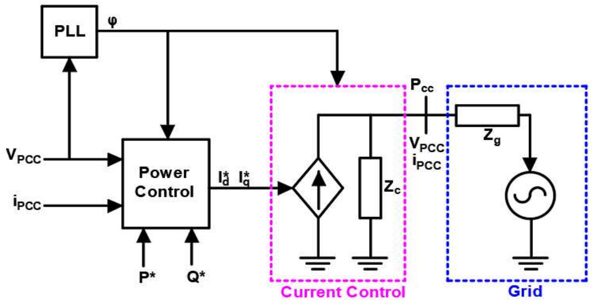


Figure 27: Control of grid monitoring inverter

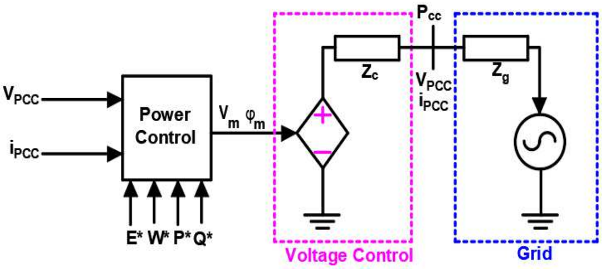
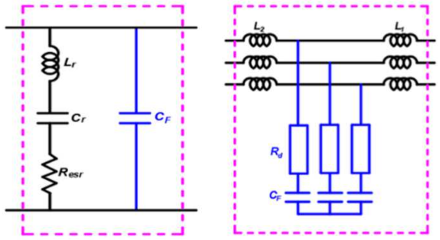


Figure 28: Control of grid-connected inverter



a) b)

Figure 29: Electrical circuit of the LC and LCL filter

VI. CONCLUSIONS

In this paper, the authors have reviewed the different renewable energy sources, their production techniques, their potential in the world, in particularly in west Africa. A critical look has been observed on the production constraints of each source, its operation mode and the techniques for monitoring the maximum power. The role of converters and filters in multi-source based renewable sources has been presented. The topologies and control techniques for the optimal management of the energy mix have been detailed. Several possibilities of multi-source mixing have been seen and the most widespread are the PV-wind types with storage system. This work is part of the development of electrification of landlocked rural areas to meet their minimum vital needs. The economic aspect is not a priority at this stage of the project.

ACKNOWLEDGMENT

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REFERENCES

[1] Sefe-energy, "The *global energy mix in 2022". 25 août 2022.*

[2] The World Bank, "Slowing *progress towards universal energy access due to the COVID-19 pandemic". 1 juin 2022.*

[3] Geo, "the *share of fossil fuels as high as ten years ago". 16 juin 2021.*

[4] Edf, "the *depletion of resources"*.2023.

[5] Cea, "Africa's *energy transition calls for pragmatic measures to maintain the continent's competitiveness "15 juin 2022.*

[6] R Berahab, *Policy Center for the New South, "Energies renouvelables en Afrique : Enjeux, défis et opportunités". PP-19/06 Mai 2019. pp. 12-17.*

[7] Irena, *"the changing role of hydro power, challenges and opportunities" ISBN: 978-92-9260-522-3. pp.12,17,58. 2023.*

[8] J-Bolduc, David; Cote, Emmanuel. *Hydro energy generation and instrumentation & measurement: hydropower plant efficiency testing. IEEE Instru &Measure Magazine, 17(2), 10–14. doi:10.1109/mim.2014.6810039*

[9] Zhongzhu, Y; Zhidong, W; Yanchun, X; Xiaoyuan, L; Can, W; Zian, H ; Shaohua, Z. *(AEEES) - Study on the Impact of Different Load Types on Island Small Hydropower.848–852.* doi:10.1109/AEEES48850.2020.9121456.

[10] Hussain, Akhtar; Arif, Syed Muhammad; Aslam, Muhammad. *Emerging renewable and sustainable energy technologies: State of the art. Renewable and Sustainable Energy Reviews,71,12–28.doi: 10.1016/j.rser.2016.12.033.*

[11] A. Brown, S.Müller, Z.Dobrotkova. Iea. *"Renewable energy markets and prospects by technology". ©OECD/IEA, pp.10,33,44. 2011.November2011.*

[12] Gwec. *"Global wind report 2022". pp.111.*

[13] Irena in collaboration with African development bank group. *ISBN: 978-92-9260-417-2. pp.41,43,44. ©IRENA 2022 "renewable energy market analysis africa and its regions*".

[14] K. Patryniak,M.Collu,A.Corradu. *“Multidisciplinary design analysis and optimisation frameworks for floating offshore wind turbines: State of the art”. 0029-8018/© 2022. Available online 23 March 2022*.

[15] L.Wang,A.Kolios,X.Liu,D.Venesanos,R.Cai. “*Reliability of offshore wind turbine support structures: A state-of-the-art review” 1364-0321/© 2022. Available online 16 March* 2022.

[16] A. Ciuriuc,J.I.Rapha,R.Guanche,J.L.D-Garcia. *“Digital tools for floating offshore wind turbines (FOWT): A state of the art” 2352-4847/© 2021.*

[17] Bensalah, A.; Benhamida, M.A.; Barakat, G.; Amara, Y. *2018 XIII (ICEM) - Large wind turbine generators: State-of-the-art review.2205–2211.* doi:10.1109/icelmach.2018.8507165.

[18] Venkataraman, Aditya; Dutta, Shreya; Li, Yanling; Kayal, Said; Costa, Luis M.; Jiang, Tianxiang; Plana, Robert; Tordjman, Philippe; Tang, Difei; Choo, Fook Hoong; Foo, Chek Fok; Puttgen, Hans B. *(ACEPT) - Development of a power mix management system for REIDS microgrids.1–5.* doi:10.1109/ACEPT.2016.7811510.

[19] V. Prema 1, M. S. Bhaskar 2, D Almakhles 2, N. Gowtham 3 and K.U. Rao 4, *“Critical Review of Data, Models and Performance Metrics for Wind and Solar Power Forecast” Digital Object Identifier10.1109/ACCESS.2021.3137419*.

[20] Belaout, Abdesslam; Krim, Fateh; Mellit, Adel. *2016 8th (ICMIC) - Neuro-fuzzy classifier for fault detection and classification in photovoltaic module. 144–149.* doi:10.1109/ICMIC.2016.7804289.

[21] Boutana, N. Mellit, A. Haddad, S. Rabhi, A. Pavan, A. Massi. *An explicit I-V model for photovoltaic module technologies. Energy Conversion and Management, 138(), 400–412*. doi: 10.1016/j.enconman.2017.02.016.

[22] Hishikawa, Y., Doi, T., Higa, M., Yamagoe, K., Ohshima, H., Takenouchi, T., & Yoshita, M. *Voltage-Dependent Temperature Coefficient of the I–V Curves of Crystalline Silicon Photovoltaic Modules. IEEE(JP), 8(1), 48–53.* doi:10.1109/jphotov.2017.2766529.

[23] Krishan, Om; Suhag, Sathans. *Grid-independent PV system hybridization with fuel cell-battery/supercapacitor: Optimum sizing and comparative techno-economic analysis. Sustainable Energy Technologies and Assessments, 37, 100625–*. doi: 10.1016/j.seta.2019.100625.

[24] Ni, Jian ; Yang, Mei ; Jiang, Yingtao. *2017(ICCSEC) - Virtual Reality Simulation of Dust Accumulation on the Surface of Solar Panel.425–430.* doi:10.1109/iccsec.2017.8446946.

[25] Arcos-Aviles, Diego; Pascual, Julio; Guinjoan, Francesc; Marroyo, Luis; Sanchis, Pablo; Marietta, Martin P. *Low complexity energy management strategy for grid profile smoothing of a residential grid-connected microgrid using generation and demand forecasting. Applied Energy, 205(), 69–84*. doi: 10.1016/j.apenergy.2017.07.123.

[26] Veldhuis, Anton J.; Nobre, Andre M.; Peters, Ian M.; Reindl, Thomas; Ruther, Ricardo; Reinders, Angele H. M. E. *An Empirical Model for Rack-Mounted PV Module Temperatures for Southeast Asian Locations Evaluated for Minute Time Scales. IEEE Journal of Photovoltaics, 5(3), 774–782.* doi:10.1109/jphotov.2015.2405762.

[27] Mahmoud A. Soliman; Ahmed Al-Durra;Hany M. Hasanien. *Electrical Parameters Identification of Three-Diode Photovoltaic Model Based on Equilibrium Optimizer Algorithm. IEEE Access, (), –.* doi:10.1109/access.2021.3065386.

[28] Huang Jingsheng, ; Liu Meiyin, ; Li Yiyan, ; Zhou Rongrong, ; Lin Xiaojin. *(ICRPG 2015) - Research on modelling and verification for PV power plants with AVC system.5.–5.* doi:10.1049/cp.2015.0515.

[29] Farhat, Maissa; Barambones, Oscar; Sbita, Lassaâd. *Efficiency optimization of a DSP-based standalone PV system using a stable single input fuzzy logic controller. Renewable and Sustainable Energy Reviews, 49, 907–920.* doi: 10.1016/j.rser.2015.04.123.

[30] P. Roy 1, J.He 1, T.Zhao 2, and Y.V.Singh 3 . *“Recent Advances of Wind-Solar Hybrid Renewable Energy Systems for Power Generation: A Review”.* DOI 10.1109/OJIES.2022.3144093. volume 3, 2022.

[31] Dong, Van Huong, Nguyen, Xuan Phuong. *2020 6^{th} (ICACCS) - A strategy development for optimal generating power of small wind-diesel-solar hybrid microgrid system.1329–1334.* doi:10.1109/ICACCS48705.2020.9074324.

[32] Xuewei, S., Xuefang, S., Wenqi, D., Peng, Z., Hongyan, J., Jinfang, W., & Yang, W. *Research on Energy Storage Configuration Method Based on Wind and Solar Volatility. 2020 10^{th} (ICPES)*. doi:10.1109/icpes51309.2020.93496.

[33] Mubarok, Husein; Krisna Yoga, Tegar. *2018 (ISATIC)- Economic Studies of the Wind Turbin-Diesel Hybrid Power Generation System (Case Study at: Queen of the South Beach Resort Hotel, Yogyakarta, Indonesia). 591–596.* doi:10.1109/ISEMANTIC.2018.8549747

[34] M.mohamadi., E. Roshandel., S.M.Gheasaryan.(*Dec. 22nd, 2017*) – *A comparison of implementation of solar and diesel power generation for case study in kaloo. . (Case study in kaloo) –. doi:10.1109/KBEI.2017.8324954*.

[35] W. Hu, Y. Wang, Y. Sun, Q. Nie, R.Ding, X.Zhang. *Research on comprehensive complementary characteristics evaluation technologie of wind-solar-hydro combined power generation system - doi:10.1109/POWERCON53785.2021.9697711*.

[36] G.S. Thirunavukkarasu, M. Seyedmahmoudian, E. Jamei, B.Horan.,S. Mekhilef,A.Stojcevski. *A-review on Role of optimization techniques in microgrid energy management systems-doi: 10.1016/j.esr.2022.100899*

[37] Kanwal, Sidra; Khan, Bilal; Muhammad Ali, Sahibzada. *Machine learning based weighted scheduling scheme for active power control of hybrid microgrid. International Journal of Electrical Power & Energy Systems, 125, 106461–*. doi: 10.1016/j.ijepes.2020.106461

[38] Olatunde, Oladepo; Hassan, Mohammad Yusri; Abdullah, Md Pauzi; Rahman, Hasimah Abdul. *Hybrid photovoltaic/small hydropower microgrid in smart distribution network with grid isolated electric vehicle charging system. (JES), 31(), 101673–*. doi: 10.1016/j.est.2020.101673

[39] Amir, M., & Srivastava, S. K. *Analysis of MPPT Based Grid Connected Hybrid Renewable Energy System with Battery Backup. (GUCON).* doi:10.1109/gucon.2018.8674902.

[40] Kumar, Prakash. *2018(PEEIC) - Power Management in Microgrid Integrated Wind- PV-Battery Generation System.746–750.* doi:10.1109/PEEIC.2018.8665648.

[41] Kr. Tiwari, Shailendra; Singh, Bhim; Goel, Puneet K. *Design and Control of Autonomous Wind-Solar Hybrid System with DFIG Feeding a 3-Phase 4-Wire System. (TIA),1–1.* doi:10.1109/TIA.2017.2780168.

[42] Keles, Cemal; Alagoz, Baris Baykant; Kaygusuz, Asim. *2017(IDAP) - Multi-source energy mixing for renewable energy microgrids by particle swarm optimization.1–5*. doi:10.1109/IDAP.2017.8090163.

[43] Du, Wen; Yao, Lisha; Wu, Di; Li, Xinrong; Liu, Guodong; Yang, Tao. *2018 IEEE(PESGM) - Accelerated Distributed Energy Management for Microgrids.1–5.* doi:10.1109/PESGM.2018.8586094.

[44] Sun, Zhuoya; Bae, Sungwoo. *2018 7th (ICRERA) - Multiple-Input Soft-Switching Step-up/down Converter for Renewable Energy Systems.632–636.* doi:10.1109/ICRERA.2018.8567017.

[45] G.He., J. Michalek., S. Kar., Q. Chen., D. Zhang., J.F. Whitacre. *Utility-Scale Portable Energy Storage Systems. Joule 5, 379-392, February 17, 2021,* doi: 10.1016/j.joule.2020.12.005.

[46] Ma, T., Yang, H., & Lu, L. *Development of hybrid battery–supercapacitor energy storage for remote area renewable energy systems. Applied Energy, 153, 56–62*. doi: 10.1016/j.apenergy.2014.12.008.

[47] Alon Kuperman; Ilan Aharon. *Battery–ultracapacitor hybrids for pulsed current loads: A review.15(2), 981–992.* doi: 10.1016/j.rser.2010.11.010.

[48] Shreelekha, K.; Arulmozhi, S. *2016(ICEEOT) - Multiport isolated bidirectional DC-DC converter interfacing battery and supercapacitor for hybrid energy storage application.2763–2768.* doi:10.1109/iceeot.2016.7755198.

[49] Liu, Xiong; Loh, Poh Chiang; Wang, Peng; Blaabjerg, Frede. *A Direct Power Conversion Topology for Grid Integration of Hybrid AC/DC Energy Resources. IEEE Transactions on Industrial Electronics, 60(12), 5696–5707.* doi:10.1109/TIE.2012.2236993.

[50] Ali, Kawsar; Das, Pritam; Panda, Sanjib Kumar. *A Special Application Criterion of the Nine-Switch Converter with Reduced Conduction Loss. IEEE Transactions on Industrial Electronics, 65(4), 2853–2862.* doi:10.1109/tie.2017.2748044

[51] Aurangzeb, Muhammad; Ai, Xin; Hanan, Muhammad; Jan, Mishkat Ullah; Ur Rehman, Haseeb; Iqbal, Sheeraz. *(EI2) - Single Algorithm Mpso Depend Solar and Wind Mppt Control and Integrated with Fuzzy Controller for Grid Integration.583–588*. doi:10.1109/EI247390.2019.9061805.

[52] Kovaltchouk, Thibaut; Multon, Bernard; Ben Ahmed, Hamid; Aubry, Judicael; Venet, Pascal. *Enhanced Aging Model for Supercapacitors Taking into Account Power Cycling: Application to the Sizing of an Energy Storage System in a Direct Wave Energy Converter. IEEE Transactions on Industry Applications, 51(3), 2405–2414*. doi:10.1109/tia.2014.2369817.

[53] Sajitha, M.; Sandeep, J.; Ramchand, Rijil. *TENCON 2019 - 2019 IEEE (TENCON) - Comparative Analysis of Different Modulation Techniques for Three Level Three Phase T-type NPC Inverter.1529–1534.* doi:10.1109/TENCON.2019.8929574.

[54] M.Benson., D. Xiaofeng., M. Guven., K. Lee.,L.Jinyeong.,W.Lee. Neutral-point-less (NPL) multilevel inverter topology with single DC-link capacitor: H-type inverter. doi: 10.1109/ITEC53557.2022.9813762.

[55] Ahmadzadeh, Taher; Sabahi, Mehran; Babaei, Ebrahim. *Modified PWM control method for neutral point clamped multilevel inverters. 2017 14th (ECTI-CON) - 765–768*. doi:10.1109/ECTICon.2017.8096351.

[56] J. Qiu,G.DING,Q.Wu,Z.Qian,T.A.Tsiftsis,Z.Du,ANDY.Sun.Comparative study of single-phase phase-locked loops for grid-connected inverters under non-ideal grid conditions. *CSEE Journal of Power and Energy Systems. https://doi.org/10.17775/cseejpes.2019.02390.*

[57] A. Mukhopadhyay;V.John. *Constraints Based Design of DC side LC Filter for Single-Phase Voltage Source Converter. 2020 IEEE(PEDES) –.* doi:10.1109/pedes49360.2020.9379380.

[58] Popescu, Mihaela; Bitoleanu, Alexandru; Suru, *On the design of LCL filter with passive damping in three-phase shunt active power filters.* Vlad. *2016 (SPEEDAM) - 825–830*. doi:10.1109/SPEED2016.7525899.