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Research Article

Technological Paradigm Between the Production of Photovoltaic and Thermal Solar Energy in Sahelo-Sahelian Countries

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Abstract

The energy sector in Sahelian countries such as Burkina Faso, Mali and Niger is facing enormous challenges. Indeed, electricity shortages, characterized by recurrent breakdowns of means of production and import dependency due to an unfavorable energy mix, are numerous in these countries. Concerns about the high costs of facilities and operations, as well as environmental pollution, not forgetting to mention the matter of the countries' energy sovereignty, have led to the desire to use reliable, profitable and adapted means of production. The aim of this study is to review the literature on electric power generation systems in the world, in Africa and in Sahelian countries, with an emphasis focus on photovoltaic and thermal solar energy. In addition, it highlights, in views of the problems raised, works that have suggested solutions. To achieve this, scientific articles, theses and other scientific documents dealing with electric power generation systems from 2014 to 2024 have been consulted. This enabled us to get knowledge on the various electric power generation systems, to know their advantages and limitations, and above all the perspectives in terms of electric power generation. Additionally, they provided a source of inspiration for setting up an electric power generation system in line with the realities of the countries of the Alliance of Sahel States (ASS).

Keywords

Diesel Thermal Power Plant, Solar Photovoltaic Power Plant, Electric Power Generation, Sonabel, Sahelian Countries

1. Introduction

Electricity is the main factor of social, economic and industrial development, and it depends on the availability of a sustainable energy supply. It is sometimes considered a crucial element that influences our lives and promotes development [20]. Sources of electrical energy production can be either renewable or non-renewable. The means of renewable power generation are facing financial, political and economic barriers to mobilize sufficient investment in low-carbon technology,

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particularly in low-and middle-income countries [28]. Conventional thermal power plants burn fossil fuels to convert them to electricity, which inevitably leads to excessive CO_2 emissions and which can produce a greenhouse effect [42]. Moreover, demand for energy is growing day by day, and to overcome these challenges, we are relying more and more on the means of transforming the primary source of energy (coal, oil, gas, uranium, etc.) into electricity, such as nuclear power plants, thermal, diesel, etc. However, they release more carbon dioxide and other harmful gases into the environment [28]. It has been empirically demonstrated that the impact of Non-renewable Energy Consumption (NREC) on economic growth in Africa is significantly higher than that of Renewable Energy Consumption (REC). Another study shows that renewable energies are holding back economic growth in West Africa. Whereas in developed countries such as the USA, NREC has had a negative impact, REC has had a positive impact [21]. Burkina Faso, like other Sahelian countries, mainly uses diesel thermal power plants equipped with generators to produce electricity [27]. Today, in a global context marked by environmental challenges and the need to reduce greenhouse gas emissions on the one hand, and the low capacity of national electricity companies in these countries to meet consumer needs on the other hand, the growing adoption of renewable energy sources has become common [14]. In addition, the increase of the specific consumption of the diesel thermal power plants of the National Electricity Company of Burkina Faso (SONABEL) is due to the poor quality of the fuels which are used and to their procurement policy (HFO: Heavy Fuel Oil; LFO: Ligth Fuel Oil), the lack of spare parts for maintenance, poor maintenance practices and, above all, the high temperature of the generator operating environment. While solar photovoltaic energy plays an important role in all scenarios and models of a low-carbon energy system, its implementation requires significant investment. As the operating cost of solar photovoltaic systems is generally low, its life-cycle cost is dominated by the initial investment cost and it is therefore essential that the system provides the expected results, in order to achieve an acceptable return on investment [50]. Indeed, the storage batteries in solar photovoltaic systems are always an obstacle, as they represent the system's most expensive and ageing component. They provide for a large proportion of photovoltaic system costs. Most batteries in this application have a relatively short lifespan of 5 to 10 years and therefore need to be replaced more frequently than photovoltaic panels and other components [54]. Maintenance and analysis of photovoltaic systems failure and installations are becoming increasingly important issues. Then, Data on the long-term operation of 85 photovoltaic power plants in Central Europe show that their actual lifespan is around half of that originally predicted. Indeed, the study shows a reduction in the lifespan of photovoltaic panels from 20 to 30 years, declared in commercial brochures, to an actual lifespan of around 10 to 12 years, which can significantly reduce the profits of photovoltaic power plants [34]. In Burkina Faso, for example, between 2019 and 2021, studies on the largest solar photovoltaic power plant show a direct correlation between solar irradiance and energy production. In fact, during the rainy season (July and August), the photovoltaic plant showed the highest conversion efficiency. Conversely, the hot season (March and April) was associated with the lowest conversion efficiencies, with module temperatures reaching around 47 ℃ [47]. This work consisted to make an extensive literature review of recent energy policies in countries around the world, in Africa and in the Alliance of Sahel States (ASS). It also enabled a cross-analysis of all this literature, in order to identify the models used in each region, their advantages and limitations, and above all the perspectives in terms of electric power generation.

2. Methodology

This study explored power generation systems in countries around the world, in Africa and in the ASS through a review of recent literature. In order to cover a wide range of articles of scientific journals, a search engine namely Google Scholar and three (03) databases (SCOPUS, Web of Science and CASSI) were used. In addition, the following parameters and options were used:

1) research field: energy, engineering, environmental sciences;
2) research years: 2014-2024;
3) parts of articles and theses consulted: abstract, introduction, result, conclusion;
4) research language: English and French. Figure 1 below illustrates the study methodology.

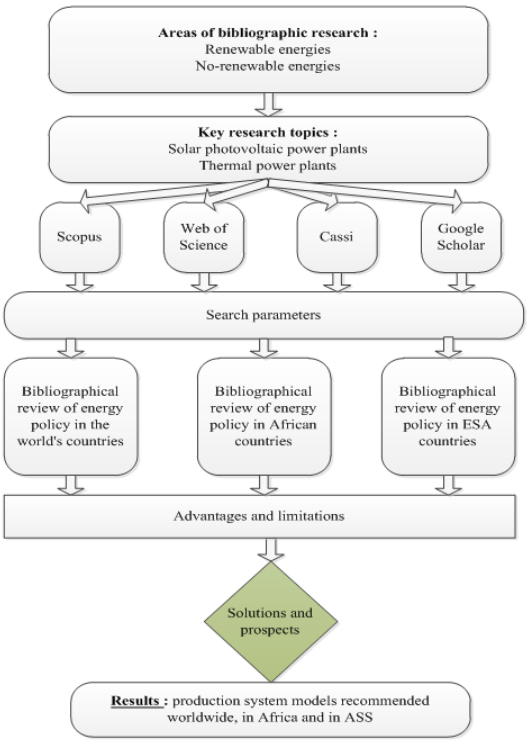

Figure 1. *Study methodology.*

3. Results

The analysis of energy policy in the countries of the world, Africa and the ASS region permitted to consider energy mixes, their advantages, limitations and perspectives.

3.1. Energy Policy in the World's Countries

In the world, coal- and gas-fired thermal power generation is the most widely used. Among low-carbon energy sources, hydroelectricity and nuclear power are the biggest contributors, although wind and solar power are growing rapidly [62]. In addition, the world's energy demand is growing rapidly, and to overcome these challenges, we rely more and more on non-renewable energy sources such as thermal, nuclear and diesel power plants [43]. This section illustrates the energy production trajectories of the world's five (05) major economies, described as major carbon emitters: the United States of America (USA), China, Japan, Germany and India [44]. Indeed, in the USA, nuclear power, renewable energy sources and fossil fuels (coal, natural gas and oil) are the three (03) main types of energy used for electricity generation [55]. Renewable energies have seen an upward trend, with wind power making a significant contribution [44]. China is one of the world's largest energy producers and consumers, accounting for over 24% of the total global energy consumption. Due to its special resource endowment, China's energy production has long been dominated by coal, which accounts for almost 70% of the total energy consumption [36]. In 2020, coal accounted for 57% of primary electricity generation in China [37], with installed thermal power plant capacity reaching 55.85% [40]. Japanese industry continues to depend on mineral oil, which remains an important source of energy, but not as much as before. If necessary, strategic reserves (power plants) can be activated to meet peaks of demand or compensate for the failure of other electrical facilities [44]. As a result of the reactors, severely damaged by the nuclear accident, which made the reactors unusable at Fukushima, 24 of the 43 operational units that could be restarted are currently on standby. The only nuclear reactors in Japan currently producing power are the two reactors at the Sendai nuclear power plant in Kagoshima, which were reactivated in August and October 2015. The other reactors are currently undergoing maintenance [56]. Germany is still dependent on fossil fuels, despite declining coal consumption. Since 2015, fossil gas has increased and now accounts for 16% of Germany's energy mix. While the total fossil production has fallen by only 31% since 2015, coal production has fallen by 51% [44]. Since 2015, renewable energy production has doubled, accounting for around 45% of Germany's electricity production. As a result, renewable energy sources first exceeded fossil fuels in 2020, setting a historic precedent. The rate of electricity generation from fossil fuels in 2020 was 44% [32]. With a total installed capacity of 403.759 GW in 2022, India is the world's second largest energy consumer and the third largest energy producer. Coal is a major contributor to the country's power generation, accounting for around 50.7% of the total installed capacity [46].

3.2. Energy Policy in African Countries

Benin's energy policy includes key initiatives such as the renewable energy policy, the solar energy promotion project and the renewable energy development program [9]. In addition, with the implementation of various energy projects and the construction of a 127 MW power plant at Maria Gléta, 30 MW of Benin power plant, 4 MW of mini power plant, 20 MW of gas turbine and 0.5 MW of yeripao, Benin's installed capacity rises to 181.5 MW in 2020 [8]. Cameroon has a huge, diversified renewable energy resource that has not been fully exploited. Total electricity production was 8626 GWh, with 58.23% of hydroelectric, 0.22% of solar photovoltaic, 0.46% of biofuels and 41.09% of fossil fuels [33]. A study also showed that Egypt and Morocco, with, respectively, an installed capacity of 5980 and 3447 MW, have the highest installed renewable energy capacity among Arab countries in 2020. Indeed, it is worth to mention that most Arab countries focus on solar and wind energy, and very little attention is paid to geothermal, biomass and hydroelectric power. Unfortunately, there is no comprehensive study until 2030 on the capacities and strategies of renewable energy in Arab countries at the transnational level [18]. The Nigeria's energy policy was adopted by the Energy Commission of Nigeria (ECN), which was created by Act No. 62 of 1979 and amended by Act No. 32 of 1989, following a meeting with the Heads of State of the Economic Community of West African States (ECOWAS) in 1992. Indeed, the country's capacity was of the order of 6,000 MW in 2013, of which 4,730 MW, or meaning that 79% of the energy is generated from fossil fuels and only 1,270 MW or meaning 21% from hydropower, which is the only existing and current renewable energy source in Nigeria. Today, the country's power supply is around 12,500 MW, 87% of which comes from fossil fuels (gas and thermal) and 13% from hydropower [24]. Ghana is a sub-Saharan African country bordered by Burkina Faso to the north, by Côte d'Ivoire to the west and by Togo to the east. The country has experienced some difficulties in the past, leading it to the inclusion of thermal power generation capacity to support electricity production from its hydroelectric plants. In August 2020, the total installed capacity of existing power plants in Ghana was is 4132 megawatts (MW), composed of hydropower at 38%, thermal at 61%, and solar at less than 1%. In addition, surveys of to civil society organizations revealed that 63.1% of the population is in favor of solar photovoltaic power generation, and 21.4% in favor of nuclear power. On the other hand, none of the respondents stated that coal was a viable source of electricity generation to help solving Ghana's problems [5]. In addition, the country recently a nuclear power program, but the study revealed weaknesses in the

implementation of the nuclear power. Indeed, the poor maintenance culture of the Ghanaian people is the major weakness. In addition, there is the country's non-strict loose security system, porous borders, fossil fuel dominance and lack of adequate financing policy [7]. In addition, the extremely high capital investment cost of nuclear power and its conflicts with the requirements (flexibility) of the future power system are the two main reasons for excluding this energy source from Nigeria's energy mix [15].

3.3. Energy Policies in the ASS Region

According to the 2020 report, the nominal installed capacity of the National Electricity Company of Burkina Faso power generation fleet was 366.05 MW. This comprised 299.95 MW of diesel thermal generation, 32 MW of hydroelectric and 34.1 MW of solar photovoltaic. The report highlights the predominance of diesel thermal power generation. In addition, more than half of the electricity consumed in Burkina Faso comes from neighboring countries such as Côte d'Ivoire and Ghana [47]. Mali's energy system is characterized by its heavy dependence on imported energy. Thus, the total installed capacity of the Energy Of Mali SA (EOM-SA) generating fleet was 719.9 MW in 2018, mainly from thermal sources (48.76%), hydroelectric (25.52%) and the interconnection with the Republic of Côte d'Ivoire (25.73%) [60]. As for Niger, it remained highly dependent on electricity from Nigeria [59]. According to Electricity Company of Niger, the part of imported energy reached 86.5% in 2017. In addition, a 20 MW diesel thermal power plant was installed near Niamey, and permitted to provide, alone, over 45% of Niger's generation capacity on its own [38].

3.4. Advantages and Limitations of Energy Policies

3.4.1. In the World

The energy policies of the world's five largest economies (USA, India, China, Germany and Japan) have permitted enabled them to meet and even exceed their energy needs and develop their economies on a sustainable basis. Thermal energy production is the most developed in these countries, with the use of energy sources such as coal, natural gas and oil. However, traditional fossil energy reserves are limited, and economic development requires large quantities of energy to sustain it, leading to a series of complex problems such as an energy crisis and environmental pollution [35]. For example, China has limited coal reserves and more obvious geographical restrictions, with major production areas including Shanxi, Inner Mongolia, Shaanxi, SHebei, Shandong and other provinces [36].

3.4.2. In Africa and the ASS Region

Despite exporting its energy production to neighbors such as Niger and Benin, Nigeria faces the challenge of transition from its traditional dependence on fossil fuels to more sustainable alternatives [19]. Indeed, several challenges have been identified as factors limiting the implementation of renewable energy in the country. These include the lack of financial investment, infrastructure limitations and regulation [4]. In addition, unfavorable energy mixes with regular power shortages, erratic power blackouts and dependence on electricity imports are to be considered. Indeed, the main problems associated with renewable energies in African countries are: little interest and unbalanced policy on renewable energies, implementation of existing policies, high costs for renewable energies and the lack of adequate infrastructure [26]. The energy systems of ASS countries are characterized by high import dependency. Indeed, these electricity imports contribute enormously to the energy mix, as the cost per kilowatt-hour is relatively cheaper. Domestic production is dominated by diesel thermal power, using imported fuels. However, climate change, growing energy needs and recurrent breakdowns of production facilities in supplier countries have led to a reduction in energy exports to ASS countries. In addition, political instability in the ASS region has had a negative impact on its relations with its neighbors, leading to serious energy crises characterized by energy shortages and a reduction in the rate of access to electricity for the region's populations [39]. According to specialists from the World Meteorological Organization and the UK Met Office, the last eight years have been marked by record high temperatures. Over the next five years, we are likely to experience the hottest year on ever recorded. Moreover, according to their prevision, the years 2023-2027 will be the hottest ever recorded. The effects of global warming are clear, and efforts maintain the planet's average temperature to below 2 ℃ and the pursuit of 1.5 ℃ is going on [44].

3.5. Solutions and Perspectives

3.5.1. Progress in Research into Electricity Generation Worldwide

The solar photovoltaic power generation market in China has experienced strong growth in recent years, with a clear upward trend. Indeed, in 2022, China's installed capacity reached an impressive 87 GW, representing 36% of the world's 240 GW. By the end of 2023, China's new solar power capacity was expected to reach 200 GW. The Chinese government's strong support for renewable energies, coupled with urgent domestic demand for own energy, has given a significant boost to the development of photovoltaics [66]. Consequently, installed renewable energy capacity is expected to grow by 50% between 2019 and 2024, with solar photovoltaics accounting for the majority (60%) of this growth. Renewable energies are expected to supply 70-85% of electricity by 2050 [29]. India relies mainly on coal, which is not a viable long-term option. Consequently, the future of

energy supply is renewable energy, and solar power is the most important and reliable renewable energy source [51]. One study indicates that solar energy could meet more than 50% of India's power sector demand by 2040. This study also determined that the impact of solar energy in India is around 5000 billion kWh (kilowatt-hours) every year. Therefore, India's central government launched the Jawaharlal Nehru National Solar Mission to promote solar energy and foster its implementation across the country [49]. Japan's Strategic Energy Plan has set a target that the part of renewable energy reached 22% to 24% by 2030. A target of 100% renewable energy by 2050 has also been suggested. However, as the cost of installing renewable energies is generally much higher than that of conventional energy resources, this could be an obstacle to the expansion of renewable energies in the future [23]. In Germany, the Energiewende is the result of a national consensus to abandon nuclear power and reduce greenhouse gas (GHG) emissions by 80% by 2050 through thanks to an accelerated adoption of renewable energies. However, the Energiewende remains a power sector transition policy with a low impact on coal-fired generation and to accelerate the transition in the heating and transport sectors [25]. In 2018, renewables shared more than 17% of total electricity generation in the US, and photovoltaics, 1.5%. In 2020, the ITC law will reduce the cost of photovoltaic production to 26%, and 22% in 2021, to 10% for public services and commercial projects and to 0% for residential projects. This change will have a significant impact on the US PV Photovoltaic (PV) deployments, which are expected to slow over the next few years. However, the general trend is still upward, due to the rapid decline in photovoltaic production costs. IRENA forecast that the U.S. PV market would reach 393 GW by 2030, making it the second largest PV market in the world [64].

3.5.2. Progress in of Research on Power Generation in Africa

In Nigeria, renewable energy sources seems to have gained in relevance and contributed significantly to the electricity generation mix. The projected plan for the year 2030 shows that renewable energy sources will contribute with 68,345 MW of the total 190,000 MW [15]. In Benin, a study examined key strategies so that to achieve the country's targets of integration of 24.6%, 44% and 100% of renewable energy (RE) into the final electricity mix, by 2025, 2030 and 2050, respectively. Therefore, a combination of 563 MW of natural gas (NG), 125 MW of PV, 200 MW of wind, 600 MW hydroelectricity and 60 MW of concentrated solar energy would permit to achieve 50% of RE by 2050 in the 50% RE scenario [8]. Many countries have set renewable energy targets in their electricity supply mix to encourage investment in renewable energy technologies. For example, Ghana has set itself a target of 10% renewable content in its electricity generation by 2030, a target originally set for 2020. In addition, a demonstrated model has indicated that the country will need a budget of at least 1% of GDP to invest in generation capacity if it wants to meet its 10% renewable electricity generation target by 2030, while keeping unmet demand at reasonable levels [4]. Electricity generated from fossil fuel sources explains significantly of the headwind gap, suggesting that Ghana is too dependent on conventional energy sources. The study forecasts that the installed renewable energy capacity will know a considerable growth by 2036, constituting the major part of the energy mix [12]. In 2021, Morocco reached an important milestone step by increasing the proportion of its own energy in its mix to 37.6%, with wind power contributing to 45%. With regard to this success, Morocco intents to further increase its renewable energy capacity, targeting 52% of the total capacity from renewable sources by 2030 [13]. At the end of 2019, Egypt's generating capacity was 58.4 GW, composed mainly of combined-cycle power plants (55.7%), the total demand load turning around 31.4 GW according to the Egyptian Electricity Holding Company (EEHC). However, the share of renewable energy sources (RES) today, including wind farms and solar photovoltaics, represents only 3.8% of total generation capacity. Thus, the Egyptian government, in affirming the Integrated Strategy for Sustainable Energy 2035, has set targets for RES to reach 20% of the total energy required for electricity generation by 2022 and 42% by 2035 [1].

3.5.3. Progress of Research on Electric Power Generation in the ASS Area

In Burkina Faso, the 2019-2023 energy strategy was oriented towards the development of solar photovoltaic energy. Indeed, we can notice the installation of 4 solar photovoltaic power plants with a total capacity of 51 MWp distributed between the sites of Gonsin, Dori, Diapaga and Gaoua [16]. In the quest for energy independence, the country has inaugurated a new 30 MWp solar photovoltaic plant in Pa [57]. Similarly, the production capacity of the Kossodo thermal power plant has been increased by from 20% to 55 MW [2]. Finally, the Minister of Energy has indicated that Burkina Faso hopes to be able to build a nuclear power plant by 2030 to solve the energy shortage problem [53]. According to the 2017 JRC recommendations for Burkina Faso, the marginal cost of electrification could be reduced through the establishment of 374 MW of decentralized photovoltaic systems, with an estimated cost of 1.7 billion euros to achieve the universal access to electricity by 2030 in Burkina Faso [48]. The adjusted cost technique of electricity shows that the configuration with 80% solar photovoltaic is more attractive and profitable to Burkina Faso [11]. In 2015, the country adopted a plan to increase the share of renewable energy sources in the national energy balance from 10% to 25% by 2033 [10, 28, 45]. In addition, the National Renewable Energy Action Plan plans for a significant contribution of renewable energies to the energy mix. It should be pointed out that these objectives are based on realistic projections based on current projects, instructed projects and innovations

planned for medium and long term. The capacity of renewable energy power plants will increase from 32 MW in 2010 to 150 MW in 2020 and to 318 MW in 2030. A fall of the contribution of renewable energy generation to the energy mix (excluding electricity imports) will be noticed around 2020, it will decrease from 21% in 2010 to 17% in 2020, before rising to 27% in 2030. This is due to the need to increase the capacity of thermal power plants, which must exceed that of renewable energy plants by 2020 [58]. In Mali, several central hydroelectric and solar photovoltaic projects are about to be developed, as well as a wind farm project. In addition, there is an agreement for the implementation of gas-fired power plant projects, maintenance of existing thermal power plants, electric transmission lines and the establishment of partnerships with operators for the import of butane gas [60]. The Economic Community of West African States (ECOWAS) has drawn up National Renewable Energy Action Plans (NREAPs) and the United Nations National Action Programme for Sustainable Energy for All. These plans and programs for Mali aim to increase the grid-connected renewable energy capacity to 977.4 MW, or meaning 52.5% by 2030 (including 538 MW of solar, 389 MW of hydroelectricity, 20 MW of wind and 30 MW of bioelectricity), in order to contribute to the economic and social development, improve access to energy and to protect environment [27]. In Niger, a 30 MW solar photovoltaic power plant has been initiated in Gorou Banda, in order to solve energy shortages resulting from the interr uption of power supply by Nigeria since the coup d'état of July 2023. In addition, other similar renewable energy projects are underway [22].

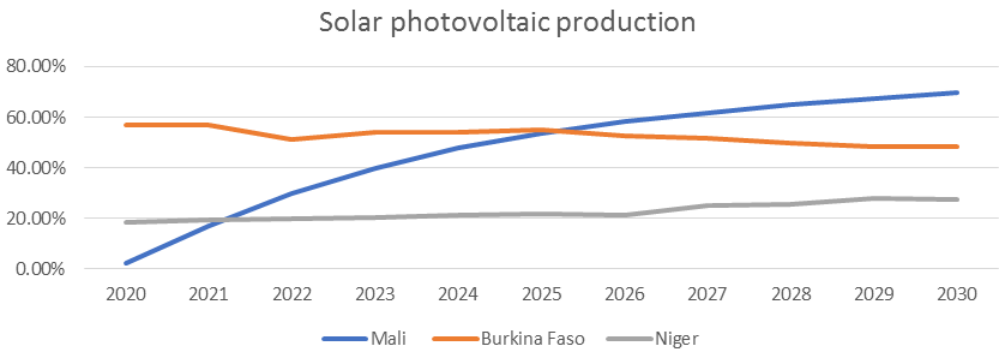

Figure 2. *Share of grid-connected solar power plants (%) from 2020 to 2030 (Togola, 2023); (Peters et al., 2024).*

Figure 2 above illustrates the national action plans for renewable energies in the ASS region from 2020 to 2030. In fact, they show the growth perspectives for of solar photovoltaic production in these countries. In Mali, for example, exponential growth of around 70% has been observed. The one of Burkina Faso, on the other hand, is on the decline, decreasing from 56.86% to 48.46%. Finally, Niger's solar photovoltaic capacity remained stable at 20% from 2020 to 2026, expected to rise between 2026 and 2029, and before falling to 27.48% in 2030. For example, in Mali, Kant é et al. made a study at Taoussa for the period of 2020-2035 with the MESSAGE model (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) of IAEA (International Atomic Energy Agency) for three scenarios: LS (low scenario), RS (reference scenario) and HS (high scenario). The results show that the largest part of the future total electricity generation capacity should be based on photovoltaics, meaning around 49% for the low scenario (LS), 57% for the reference scenario (RS) and around 66% for the high scenario (HS).

4. Discussion

In this study, the energy policies of several countries in the world, Africa and especially ASS have been reviewed, with a the view to of considering an adapted policy to the ASS countries. The literature permitted to know that the majority of countries in the world and in Africa have adopted thermal power generation, which accounts for 60% on average, to meet their energy needs, with consequences on environment. Most of these countries exploit their own resources, such as oil, coal or natural gas. In addition, some have easy ways to import them [6, 31, 48, 58, 65]. Similarly, in ASS countries, domestic energy production is dominated by thermal power plants at over 80% and 60% on average for in imports with foreign countries [2, 27]. The current trend in of the energy policies of countries around in the world and in the ASS is to promote the use of renewable energies such as solar photovoltaic, hydroelectric and wind power plants, in order to respect the COP 27 agreements in Paris [8, 9, 39, 60, 61]. Moreover, in ASS countries, studies have suggested future-oriented policy models to increase the production capacities of national electricity companies, to improve the rate of access to electric power for populations and, above all, to reduce the rate of carbon released into the environment. The Malian model plans to produce 977.4 MW or 52.5% by 2030 (including 538 MW of solar, 389 MW of hydroelectricity, 20 MW of wind and 30 MW of bioelectricity), while the Burkina Faso model suggests the establishment of 374 MW by the same deadline. According to the results of a

study made on the basis of installation and maintenance costs, we only note that the solar electric potential is much higher than that of wind power in Niger, Burkina Faso and Mali [3, 22]. In view of the perspectives for the ASS countries, solar photovoltaic power plants are seen as the energy production source of the future by the public authorities in these countries. However, studies conducted on solar photovoltaic power plants already installed in these countries have not been reassuring. In Burkina Faso, for example, decoupling by injection, module temperatures reaching around 47 ℃ and a reduction in plant performance have been observed [11, 30]. In addition, the largest solar photovoltaic plant in operation in the country is suffering from performance losses linked to external climatic and environmental factors and solar radiation capture losses due to clogging of photovoltaic modules [17]. In addition, the issue of a nuclear power plant is raised in ASS countries, specifically in Burkina Faso, which will, in medium and long term, reinforce the capacities of the country's national electricity company. In fact, Ghana has already conducted a study on a nuclear program, and the results show that there are many strengths and opportunities that make the investment in nuclear power an economically viable option. However, issues such as a porous security system, corruption, porous borders, financing and policy discontinuity due to changes in political power, are threats to the smooth implementation and operation of a nuclear power plant [63]. Comparing solar photovoltaic and thermal generation, it is clear that renewable energy system technologies are already mature and competitive, and it is already widely recognized that their production costs are lower than those of traditional generation systems. As they are dependent on natural resources and therefore variable and intermittent, they cannot ensure their availability to start operating when energy is needed, but only when there are sufficient resources, which means they are not dispatchable [41].

5. Conclusion

The literature review provided an overview of the energy mix in countries in the world, in Africa and especially in the ASS. It revealed that countries such as India, China, Germany, the United States and Japan still make much greater use of thermal generation (natural gas, coal, etc.) in their energy mixes. This production model enables them to ensure access to energy for their populations, but is harmful to the environment. Moreover, in Africa, thermal power generation is also dominant in countries such as Nigeria and Ghana. Nevertheless, in the ASS countries, imports have occupied a significant part of the energy mix. However, the agreement of the COP 27 in Paris obliged all participating countries to agree to adopt renewable energies (solar photovoltaic, hydroelectric, wind power, etc.) in order to save humanity and prevent the depletion of oil reserves. To this day, countries have shown a willingness for change, but this is slow to happen. In ASS countries, projects to install solar photovoltaic power plants have already been implemented, and others are underway. Countries such as Benin and Cameroon have developed energy production models based on renewable energies, especially solar photovoltaics. However, this type of generation remains a mystery to ASS countries, as many difficulties being identified with the already operating plants. Hence, the question: what kind of energy production system for the ASS countries? This will be the subject of further research, in order to suggest an appropriate system for Burkina Faso, Mali and Niger.

Abbreviations

ASS	Alliance of Sahel States
NREC	Non-renewable Energy Consumption
REC	Renewable Energy Consumption
SONABEL	National Electricity Company of Burkina Faso
EOM-SA	Energy of Mali SA
EEHC	Egyptian Electricity Holding Company
RES	Renewable Energy Sources
LS	Low Scenario
RS	Reference Scenario
HS	High Scenario
MW	Mega Watt

Author Contributions

Ilboudo Zoewendbem Alain: Conceptualization, Resources

Bationo Frédéric: Methodology, Supervision, Validation

Doumbia Mamadou Lamine: Formal Analysis, Investigation

Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Abubakr, H., Vasquez, J. C., Mahmoud, K., Darwish, M. M. F., & Guerrero, J. M. (2022). Comprehensive Review on Renewable Energy Sources in Egypt-Current Status, Grid Codes and Future Vision. IEEE Access, 10, 4081-4101. https://doi.org/10.1109/ACCESS.2022.3140385

[2] Ackah, I., Kyem, E., Bobio, C., & Ohene, A. O. (2024). Cross-Border Power Trading Model for SSA; Challenges and Opportunities of Operationalizing Power Pools in Africa. In I. Ackah & C. Gatete, Energy Regulation in Africa: Dynamics, Challenges, and Opportunities (p. 337-360). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-52677-0_16

[3] Adedeji, P. A., Akinlabi, S., Madushele, N., & Olatunji, O. (2019). The Future of Renewable Energy for Electricity Generation in sub-Saharan Africa. IOP Conference Series: Earth and Environmental Science, 331(1), 012039. https://doi.org/10.1088/1755-1315/331/1/012039

[4] Afful-Dadzie, A., Afful-Dadzie, E., Abbey, N. A., Owusu, B. A., & Awudu, I. (2020). Renewable electricity generation target setting in developing countries: Modeling, policy, and analysis. Energy for Sustainable Development, 59, 83-96. https://doi.org/10.1016/j.esd.2020.09.003

[5] Agbodemegbe, V. Y., Awua, A. K., Appiah, G. K., & Ahialey, E. K. (2023). A study of stakeholders' perspectives to inform management of the development of a civil nuclear power program for electricity generation in Ghana. International Journal of Knowledge-Based Development, 13(1), 3-22. https://doi.org/10.1504/IJKBD.2023.130188

[6] Ağbulut, Ü., Yıldız, G., Bakır, H., Polat, F., Biçen, Y., Ergün, A., & Gürel, A. E. (2023). Current practices, potentials, challenges, future opportunities, environmental and economic assumptions for Türkiye's clean and sustainable energy policy: A comprehensive assessment. Sustainable Energy Technologies and Assessments, 56, 103019. https://doi.org/10.1016/j.seta.2023.103019

[7] Agyekum, E. B., Ansah, M. N. S., & Afornu, K. B. (2020). Nuclear energy for sustainable development: SWOT analysis on Ghana's nuclear agenda. Energy Reports, 6, 107-115. https://doi.org/10.1016/j.egyr.2019.11.163

[8] Akpahou, R., Mensah, L. D., & Quansah, D. A. (2023). Renewable energy in Benin: Current situation and future prospects. Clean Energy, 7(5), 952-961. https://doi.org/10.1093/ce/zkad039

[9] Akpahou, R., Odoi-Yorke, F., Mensah, L. D., Quansah, D. A., & Kemausuor, F. (2024). Strategizing towards sustainable energy planning: Modeling the mix of future generation technologies for 2050 in Benin. Renewable and Sustainable Energy Transition, 5, 100079. https://doi.org/10.1016/j.rset.2024.100079

[10] Alsharif, A., Ahmed, A., Khaleel, M., Hebrisha, H., Almabsout, E., Sif, M. A., & Al-Naas, Y. (2023). Applications of Solar Energy Technologies in North Africa: Current Practices and Future Prospects. Int. J. Electr. Eng. and Sustain., 164-173.

[11] Anfom, K., Xioyang, X., Adu, D., & Darko, R. O. (2023). The state of energy in sub-Saharan Africa and the urgency for small hydropower development. Energy Reports, 9, 257-261. https://doi.org/10.1016/j.egyr.2023.10.011

[12] Atuahene, S. A., & Sheng, Q. X. (2023). Powering Ghana's future: Unraveling the dynamics of electricity generation and the path to sustainable energy. Environmental Sciences Europe, 35(1), 25. https://doi.org/10.1186/s12302-023-00732-5

[13] Bakkari, M., Bossoufi, B., El Kafazi, I., Bouderbala, M., & Karim, M. (2024). A review of wind energy potential in Morocco: New challenges and perspectives. Wind Engineering, 48(1), 101-120. https://doi.org/10.1177/0309524X231200582

[14] Bamisile, O., Dongsheng, C., Li, J., Adun, H., Olukoya, R., Bamisile, O., & Huang, Q. (2023). Renewable energy and electricity incapacitation in sub-Sahara Africa: Analysis of a 100% renewable electrification in Chad. Energy Reports, 9, 1-12. https://doi.org/10.1016/j.egyr.2023.05.049

[15] Bamisile, O., Huang, Q., Xu, X., Hu, W., Liu, W., Liu, Z., & Chen, Z. (2020). An approach for sustainable energy planning towards 100 % electrification of Nigeria by 2030. Energy, 197, 117172. https://doi.org/10.1016/j.energy.2020.117172

[16] Bank, A. D. (2023). Burkina : Le lancement du projet Yeleen de développement de centrales solaires suscite beaucoup d'espoir. Banque africaine de développement; https://www.afdb.org/fr/news-and-events/burkina-le-lancement-du-projet-yeleen-de-developpement-de-centrales-solaires-suscite-beaucoup-despoir-60187

[17] Benveniste, H., Boucher, O., Guivarch, C., Treut, H. L., & Criqui, P. (2018). Impacts of nationally determined contributions on 2030 global greenhouse gas emissions: Uncertainty analysis and distribution of emissions. Environmental Research Letters, 13(1), 014022. https://doi.org/10.1088/1748-9326/aaa0b9

[18] Dadashi, Z., Mahmoudi, A., & Rashidi, S. (2022). Capacity and strategies of energy production from renewable sources in Arab countries until 2030: A review from renewable energy potentials to environmental issues. Environmental Science and Pollution Research, 29(32), 47837-47866. https://doi.org/10.1007/s11356-022-20544-z

[19] Divine, U. N., Stephen, A. T., Lanrewaju, S. K., & Hillary, A. O. (2024). The impact of petrol subsidy removal on the adoption of solar power in Nigeria. Proceedings of the Nigerian Academy of Science, 16(1s), Article 1s. https://doi.org/10.57046/PJXF6604

[20] Edo, G. I. (2023). The German Energy System: Analysis of Past, Present, and Future Developments. Advanced Energy Conversion Materials, 18-28. https://doi.org/10.37256/aecm.4120232207

[21] Espoir, D. K., Sunge, R., & Bannor, F. (2023). Economic growth, renewable and non-renewable electricity consumption: Fresh evidence from a panel sample of African countries. Energy Nexus, 9, 100165. https://doi.org/10.1016/j.nexus.2022.100165

[22] Eyita, -Okon Ekeminiabasi, & Mongae, M. (2023). Coordinating an Energy Transition in Africa: Challenges and Opportunities. Journal of Public Administration, 58(3-1), 826-837. https://doi.org/10.53973/jopa.2023.58.3.1a6

[23] Gao, L., Hiruta, Y., & Ashina, S. (2020). Promoting renewable energy through willingness to pay for transition to a low carbon society in Japan. Renewable Energy, 162, 818-830. https://doi.org/10.1016/j.renene.2020.08.049

[24] Garba, N., Adamu, A., & Idris Augie, A. (2021). Energy Policy in Nigeria: Prospects and Challenges. International Journal of Energy and Power Engineering, 15, 388-393.

[25] Gielen, D., Boshell, F., Saygin, D., Bazilian, M. D., Wagner, N., & Gorini, R. (2019). The role of renewable energy in the global energy transformation. Energy Strategy Reviews, 24, 38-50. https://doi.org/10.1016/j.esr.2019.01.006

[26] Ibrahim, I. D., Hamam, Y., Alayli, Y., Jamiru, T., Sadiku, E. R., Kupolati, W. K., Ndambuki, J. M., & Eze, A. A. (2021). A review on Africa energy supply through renewable energy production: Nigeria, Cameroon, Ghana and South Africa as a case study. Energy Strategy Reviews, 38, 100740. https://doi.org/10.1016/j.esr.2021.100740

[27] Ilboudo, A., & Bationo, F. (2022). Maintenance strategy focused on the specific consumption of diesel generators in sub-saharan countries: Case of National Electricity Company of Burkina Faso. International Journal of Engineering and Applied Physics, 2(3), 492-501.

[28] Isah, A., Dioha, M. O., Debnath, R., Abraham-Dukuma, M. C., & Butu, H. M. (2023). Financing renewable energy: Policy insights from Brazil and Nigeria. Energy, Sustainability and Society, 13(1), 2. https://doi.org/10.1186/s13705-022-00379-9

[29] Jackson, M. M., Lewis, J. I., & Zhang, X. (2021). A green expansion: China's role in the global deployment and transfer of solar photovoltaic technology. Energy for Sustainable Development, 60, 90-101. https://doi.org/10.1016/j.esd.2020.12.006

[30] Jahangiri, M., Khorsand Dehkordi, M., & Khorsand Dehkordi, S. (2023). Potential measurement of electricity supply. International Journal of Low-Carbon Technologies, 18, 1067-1076. https://doi.org/10.1093/ijlct/ctac072

[31] Kilinc-Ata, N., & Dolmatov, I. A. (2023). Which factors influence the decisions of renewable energy investors? Empirical evidence from OECD and BRICS countries. Environmental Science and Pollution Research, 30(1), 1720-1736. https://doi.org/10.1007/s11356-022-22274-8

[32] Klein, S., Adams, M., Traub, M., Biermann, T., Hoffmann, H.-D., & Haefner, C. L. (2023). Industry and academia: Pursuing a PhD at Fraunhofer, the best of both worlds. High Power Lasers for Fusion Research VII, 12401, 68-71. https://doi.org/10.1117/12.2664343

[33] Koholé, Y. W., Fohagui, F. C. V., & Tchuen, G. (2022). A holistic overview of Cameroon renewable energy sources: Potentials, achievements, challenges and perspectives. International Journal of Ambient Energy, 43(1), 7308-7320. https://doi.org/10.1080/01430750.2022.2068065

[34] Libra, M., Mrázek, D., Tyukhov, I., Severová, L., Poulek, V., Mach, J., Šubrt, T., Beránek, V., Svoboda, R., & Sedláček, J. (2023). Reduced real lifetime of PV panels – Economic consequences. Solar Energy, 259, 229-234. https://doi.org/10.1016/j.solener.2023.04.063

[35] Lin, B., & Li, M. (2022). Understanding the investment of renewable energy firms in the face of economic policy uncertainty – Micro-evidence from listed companies in China. China Economic Review, 75, 101845. https://doi.org/10.1016/j.chieco.2022.101845

[36] Liu, C., Jiang, S., Zhang, H., Lu, Z., & Desideri, U. (2024). China and Italy's Energy Development Trajectories : Current Landscapes and Future Cooperation Potential. Energies, 17(4), Article 4. https://doi.org/10.3390/en17040897

[37] Liu, S., Wei, N., Jiang, D., Nie, L., Cai, B., Tao, Y., & Li, X. (2023). Emission reduction path for coal-based enterprises via carbon capture, geological utilization, and storage: China energy group. Energy, 273, 127222. https://doi.org/10.1016/j.energy.2023.127222

[38] MAN Energy Solutions installe une capacité de production électrique de plus de 225 MW en Afrique de l'Ouest. MAN Energy Solutions. https://www.man-es.com/fr/company/press-releases/press-details/2021/05/19/man-energy-solutions-installe-une-capacite-de-production-electrique-de-plus-de-225-mw-en-afrique-de-louest

[39] Mariko, S., Sanogo, S., Adamou, R., Bhandari, R., Sessa, V., & Ba, A. (2023). Sustainability assessment of energy supply scenarios: Case study of Mali. Environmental Research Communications, 5(10), 105017. https://doi.org/10.1088/2515-7620/ad028c

[40] Meng, Y., Cao, Y., Li, J., Liu, C., Li, J., Wang, Q., Cai, G., Zhao, Q., Liu, Y., Meng, X., Ge, W., & Yang, Q. (2022). The real cost of deep peak shaving for renewable energy accommodation in coal-fired power plants: Calculation framework and case study in China. Journal of Cleaner Production, 367, 132913. https://doi.org/10.1016/j.jclepro.2022.132913

[41] Mewenemesse, H. T., & Yan, Q. (2023). Policy Analysis of the Challenges to an Effective Switch to Low-Carbon Energy in the Economic Community of West African States. Energies, 16(5), Article 5. https://doi.org/10.3390/en16052191

[42] Ming, H., Lin, M., Gao, C., Zhang, N., Xie, L., & Mou, Y. (2024). Towards the prospect of carbon-neutral power system 2060: A Power-Meteorology-Society systematic view. Heliyon, 10(6). https://doi.org/10.1016/j.heliyon.2024.e27970

[43] Naik, S., Bandi, S., & Sohel, M. (2023). Impact of Sustainable Development on Climate Change and Student Learnings. 36, 257-261.

[44] Obiora, S. C., Bamisile, O., Hu, Y., Ozsahin, D. U., & Adun, H. (2024). Assessing the decarbonization of electricity generation in major emitting countries by 2030 and 2050: Transition to a high share renewable energy mix. Heliyon, 10(8). https://doi.org/10.1016/j.heliyon.2024.e28770

[45] Osman, A. I., Chen, L., Yang, M., Msigwa, G., Farghali, M., Fawzy, S., Rooney, D. W., & Yap, P.-S. (2023). Cost, environmental impact, and resilience of renewable energy under a changing climate: A review. Environmental Chemistry Letters, 21(2), 741-764. https://doi.org/10.1007/s10311-022-01532-8

[46] Pablo-Romero, M. P., Sánchez-Braza, A., & Galyan, A. (2021). Renewable energy use for electricity generation in transition economies: Evolution, targets and promotion policies. Renewable and Sustainable Energy Reviews, 138, 110481. https://doi.org/10.1016/j.rser.2020.110481

[47] Palm, S. F., Youssef, L., Waita, S., Nyangonda, T. N., Radouane, K., & Chebak, A. (2023). Performance Evaluation of Burkina Faso's 33 MW Largest Grid-Connected PV Power Plant. Energies, 16(17), Article 17. https://doi.org/10.3390/en16176177

[48] Parashar, S., & Dhankhar, S. (2014). Increase efficiency of solar photovoltaic system by data acquisition process. 2014 IEEE 6th India International Conference on Power Electronics (IICPE), 1-5. https://doi.org/10.1109/IICPE.2014.7115741

[49] Patra, S. K., & Muchie, M. (2017). Science, technology and innovation in BRICS countries to the special issue. African Journal of Science, Technology, Innovation and Development, 9(5), 499-501. https://doi.org/10.1080/20421338.2017.1380586

[50] Peters, R., Berlekamp, J., Kabiri, C., Kaplin, B. A., Tockner, K., & Zarfl, C. (2024). Sustainable pathways towards universal renewable electricity access in Africa. Nature Reviews Earth & Environment, 5(2), 137-151. https://doi.org/10.1038/s43017-023-00501-1

[51] Prakash, O., Ahmad, A., Kumar, A., Chatterjee, R., Sharma, S., Alayi, R., & Monfared, H. (2022). The compressive study of energy security prospects in India through solar power. International Journal of Low-Carbon Technologies, 17, 962-979. https://doi.org/10.1093/ijlct/ctac075

[52] Quansah, D. A. (2018). Performance degradation studies on field-aged solar photovoltaic modules [Doctoral thesis, Norwegian University of Life Sciences]. https://nmbu.brage.unit.no/nmbu-xmlui/handle/11250/2614547

[53] Rabaia, M. K. H., Sayed, E. T., Abdelkareem, M. A., & Olabi, A. G. (2023). Chapter 2.2. Developments of solar photovoltaics. In A. G. Olabi, Renewable Energy—Volume 1 : Solar, Wind, and Hydropower (p. 175-195). Academic Press. https://doi.org/10.1016/B978-0-323-99568-9.00011-X

[54] Schulte, J., Figgener, J., Woerner, P., Broering, H., & Uwe Sauer, D. (2023). Forecast-based charging strategy to prolong the lifetime of lithium-ion batteries in standalone PV battery systems in Sub-Saharan Africa. Solar Energy, 258, 130-142. https://doi.org/10.1016/j.solener.2023.03.029

[55] Shaffer, B., Flores, R., Samuelsen, S., Anderson, M., Mizzi, R., & Kuitunen, E. (2018). Urban Energy Systems and the Transition to Zero Carbon – Research and Case Studies from the USA and Europe. Energy Procedia, 149, 25-38. https://doi.org/10.1016/j.egypro.2018.08.166

[56] Sharma, V., Heynen, A. P., Bainton, N., & Burton, J. (2021). The Papua New Guinea Electrification Partnership: Power and diplomacy in the Pacific. Energy Research & Social Science, 79, 102186. https://doi.org/10.1016/j.erss.2021.102186

[57] Stephenson, S. R., Oculi, N., Bauer, A., & Carhuayano, S. (2019). Convergence and Divergence of UNFCCC Nationally Determined Contributions. Annals of the American Association of Geographers, 109(4), 1240-1261. https://doi.org/10.1080/24694452.2018.1536533

[58] Tilahun, F. B., Bhandari, R., & Mamo, M. (2019). Supply optimization based on society's cost of electricity and a calibrated demand model for future renewable energy transition in Niger. Energy, Sustainability and Society, 9(1), 31. https://doi.org/10.1186/s13705-019-0217-0

[59] Tınnı, I. H. (2023). Analysis of Niger's Renewable Energy Potential. Brilliant Engineering, 4(2), 1-7. https://doi.org/10.36937/ben.2023.4822

[60] Togola, A. (2023). Energy Transition Policy and Forest Protection in the Republic of Mali and Azerbaijan: Analysis of Potentialities and Assets for Sustainable Development. Bulletin of Science and Practice, 9(11), 106-114. https://doi.org/10.33619/2414-2948/96/14

[61] Touré, A. F., Addouche, S. A., Danioko, F., Diouté, B., & Mhamedi, A. E. (2019). Hybrid Systems Optimization: Application to Hybrid Systems Photovoltaic Connected to Grid. A Mali Case Study. Sustainability, 11(8), Article 8. https://doi.org/10.3390/su11082356

[62] Valavanidis, A. (2024). Global Electricity Generation from Renewable Sources. Renewables are expected to account for almost half of the world's electricity generation by 2026. 1, 1-27.

[63] Vijayan, D. S., Koda, E., Sivasuriyan, A., Winkler, J., Devarajan, P., Kumar, R. S., Jakimiuk, A., Osinski, P., Podlasek, A., & Vaverková, M. D. (2023). Advancements in Solar Panel Technology in Civil Engineering for Revolutionizing Renewable Energy Solutions - A Review. Energies, 16(18), Article 18. https://doi.org/10.3390/en16186579

[64] Wen, D., Gao, W., Qian, F., Gu, Q., & Ren, J. (2021). Development of solar photovoltaic industry and market in China, Germany, Japan and the United States of America using incentive policies. Energy Exploration & Exploitation, 39(5), 1429-1456. https://doi.org/10.1177/0144598720979256

[65] Yolcan, O. O. (2023). World energy outlook and state of renewable energy: 10 Year evaluation. Innovation and Green Development, 2(4), 100070. https://doi.org/10.1016/j.igd.2023.100070

[66] Zhao, K., Liu, L., & Xing, C. (2024). The Application Status and Prospects of Solar Photovoltaic Power Generation Technology in China. International Journal of Energy, 4(1), Article 1. https://doi.org/10.54097/ije.v4i1.005

Biography

Ilboudo Zoewendbem Alain is a PhD student enrolled at the University Norbert ZONGO of Koudougou, in the industrial engineering sector. He holds a Master's degree in industrial engineering. He has 4 scientific articles published in indexed journals. He is currently appointed head of the energy department in a state-owned company in Burkina Faso.

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Doumbia Mamadou Lamine is a professor at the University of Quebec in Trois-Rivières, department of electrical engineering and computer engineering. He obtained his PhD in electrical engineering at the École Polytechnique de Montréal in Canada, his M.Sc.A. in Industrial Electronics at the University of Quebec in Trois-Rivières in Canada and his M.Sc. in Electromechanical Engineering at the Moscow Energy Institute in Russia. He was appointed Department Director of the Department of Electrical and Computer Engineering. Its field of interest is Renewable Photovoltaics and Wind Energy (RPV), Distributed Energy resources (DVE) Power Electronics, and Variable Speed Drives (Adjustable Speed Dives), Wave Quality. He has several scientific publications to his credit.

Research Field

Ilboudo Zoewendbem Alain: Industrial engineering, electric power generation.

Bationo Frédéric: Industrial engineering, electric power generation.

Doumbia Mamadou Lamine: Electrical and computer engineering research.