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A Tale of Sustainable Energy Transition Under New Fossil Fuel Discoveries: The Case of Senegal (West Africa)

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Abstract: The transition to renewable and sustainable energy sources is critical to solving the environmental and socioeconomic problems associated with the use of fossil fuels. This study uses an interdisciplinary approach to analyze the challenges and prospects of a sustainable energy transition in contexts with the recent discovery and exploitation of fossil resources. We study the case of Senegal from 2000 to 2027 and the role of recent discoveries of natural gas in its energy transition. In 2000, Senegal's energy mix consisted of about 97% fossil energy and only 3% renewable energy. Since then, the country has developed renewable energy sources, including solar, hydro, and wind power, which currently account for about 30% of the total energy mix. At the same time, Senegal's population and electricity production have grown significantly, leading to a fivefold increase in per capita energy consumption over the past two decades. Projections based on a long short-term memory model that predicts future electricity demand and energy balance suggest a structural shift in the energy mix, with natural gas, oil, and renewables at 47%, 32%, and 21%, respectively, by 2027. Overall, this study presents a comprehensive analysis that highlights the benefits of strategically using natural gas as a transition energy source in contexts with increased electricity demand and continued development of renewable energy sources.

Keywords: energy transition; renewable energy; fossil fuels; natural gas; Senegal

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1. Introduction

The transition to more sustainable energy sources has become a global priority in response to the environmental, climate, and socioeconomic problems associated with the use of fossil fuels. The United Nations (UN) Sustainable Development Goals (SDGs), particularly SDG 7, aim to ensure access to affordable, reliable, sustainable, and modern energy for everyone by 2030 [1]. SDG 7 also sets several goals for 2030. These include increasing the share of renewable energy sources, improving global energy efficiency indicators, strengthening international cooperation to promote access to clean energy research and technology, and developing infrastructure and technologies to deliver modern and sustainable energy services for all [2]. The energy sector accounts for nearly 75% of worldwide greenhouse gas (GHG) emissions and is a major source of fugitive emissions [3,4]. Much effort is also needed to reduce emissions of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) and air pollutants such as nitrogen oxides (NOx), sulfur dioxide (SO_2), and particulate matter (PM). These reductions are necessary to achieve the key goals of the Paris Agreement, which was adopted at the 21st Conference of the Parties (COP21) [5].

At the same time, the global economy is becoming increasingly electrified, particularly through the introduction of hybrid and electric vehicles and industrialization in low-income and middle-income countries, which will lead to increased demand for electricity [6,7]. Current trends show that energy consumption is projected to continue to grow over the next 30 years, with fossil fuels currently accounting for more than 80% of global energy consumption [8]. If current trends in fossil fuel consumption continue, the world will not be able to mitigate the impacts of climate change on the population [9]. According to climate change mitigation targets set by various organizations, including the United Nations (UN), the International Atomic Energy Agency (IAEA), and British Petroleum (BP), the share of fossil fuel in global energy consumption is expected to decrease to 22–40% by 2050 if committed actions are implemented [10,11].

As such, the optimal approach to achieve the transition from fossil fuel to renewable energy is heavily debated. Some experts and organizations argue that to meet sustainability goals, all electricity demands must be satisfied exclusively with renewable and clean energy sources. In contrast, other experts argue that relying solely on renewable energy sources is unrealistic, given the growing demand for electricity [12–16]. Despite these divergent perspectives, the international community continues to advocate for a sustainable transition in response to the observed impacts and consequences of climate change.

To balance sustainability goals with increased electricity demand, natural gas can play a significant role in the energy transition due to its reputation as the least polluting fossil fuel [17,18]. Natural gas is increasingly recognized as a viable option for reducing carbon dioxide emissions in the energy sector, as its CO_2 emissions are approximately 50% lower than those of other fossil fuels [19–21]. Recent studies underscore the environmental benefits of natural gas, which emits nearly 90% fewer pollutants into the atmosphere compared to other fossil fuels [22,23]. These factors enhance the potential of natural gas to play a key role in the transition to a low-carbon economy by providing a cleaner and more flexible alternative to traditional fossil fuels [24,25]. Indeed, a "low-carbon economy" aims to reduce greenhouse gas emissions by 80 to 95% by 2050 relative to 1990 levels, with a share of renewable energy ranging between 50 and 80% of the energy mix and necessitating annual investments of USD 140 to 220 billion in low-carbon technologies [26]. However, there are at least three different views on the role of natural gas: first, as a transition fuel for a future dominated by clean and renewable technologies; second, as a barrier to the development of new technologies due to its flexibility and accessibility; and third, as an enabler of a continued dependence of most economies on fossil fuels [27,28].

Senegal provides a good context for studying the role of natural gas in achieving sustainable energy generation, given its historical reliance on fossil fuels and the growing electricity demand. Senegal's energy mix is currently dominated by fossil fuels, which account for a significant share of electricity production. In 2020, approximately 80% of Senegal's electricity was produced from fossil fuels (oil, coal), while only 20% came from renewable energy sources (solar energy, wind power, and hydropower) [29]. As a low-income country, Senegal faces significant challenges related to its local energy demand and its GHG emissions. An analysis of Senegal's GHG emissions by sector reveals a distribution of 49% from agriculture, 40% from energy, 7% from waste, and 4% from industrial processes [30]. The total emissions amount to 13,084 Gg CO_2, which is equivalent to approximately 1.2 tons of CO_2 per capita emitted by a population of 10,817,844 inhabitants in 2005 [31]. In the transportation sector, GHG emissions reached 1462 Gg of CO_2 in 2005, 91% originating from the road sub-sector. The remaining emissions were divided between inland shipping (7%) and civil aviation (2%). Within road transportation, emissions linked to diesel/diesel–oil accounted for the majority of emissions, contributing 85%, while petrol contributed 15% [30]. To increase the share of renewable sources in its energy mix, Senegal has already undertaken steps to encourage the integration of renewable energy sources through a supportive policy and regulatory framework that offers good incentive schemes to private developers [14,29]. Senegal possesses significant renewable resources, particularly solar energy. The country has substantial solar potential, with solar radiation levels ranging from 4.2 to 6 kWh/m^2/day [32–35]. Approximately 90% of the country benefits from direct general irradiation of 1600 to 1800 kWh/m^2 per year, which is almost 70% higher per square meter than in northern Germany [36,37]. In 2018, the country's energy potential was estimated at 53,253.77 MW, while the total installed capacity on the national grid was only 1249.29 MW [38]. The International Renewable Energy Agency (IRENA) estimates Senegal's solar potential at 37,233 MW [39]. In addition to solar resources, Senegal has significant wind resources that can be harnessed to produce clean, reliable, and affordable energy. Coastal areas, particularly along the northern and southern coasts, have the strongest and most reliable wind resources in West Africa, with wind speeds ranging from 4 to 7 m/s [40–42]. The World Bank estimates the offshore wind power potential at 45 GW per year, consisting of 13 GW of fixed potential and 32 GW of floating potential [43]. The daily production of these two types of renewable energy is complementary. Solar energy peaks at noon, while strong winds are typically recorded in the evening and night [44–46]. Moreover, according to the Organization for the Development of the Senegal River (OMVS) [47], about 10 dam sites have been identified along the Senegal River and its tributaries, with a hydroelectric potential estimated at more than 4000 GWh per year. These diverse renewable resources provide Senegal with the opportunity to diversify its energy mix and promote sustainable growth.

Taking into account the anticipated exploitation of fossil resources, Senegal has decided to reorient its energy policy, which previously prioritized the gradual integration of renewable energy sources into its energy structure. Now, the country has decided to rely on natural gas as a transitional energy source while continuing to develop renewable energy sources to significantly reduce its dependence on oil and coal. The technical and economic challenges associated with this policy include the modernization of existing energy infrastructure and the development of new energy storage capabilities to address the intermittency of renewable energy sources [10,48] and to convert thermal power plants into more efficient energy facilities/plants. Importantly, these recent large offshore oil and gas discoveries, along with upcoming developments, may pose serious challenges to sustainable development and energy transition. The increase in fossil fuel production could delay investments in renewable energy and hinder the achievement of climate goals [49,50].

This study uses an interdisciplinary approach to provide a comprehensive analysis of the energy transition in Senegal. The study begins with a detailed examination of the country's socioeconomic and energy indicators from 2000 to the present. This is followed by an in-depth analysis of Senegal's energy structure from 2000 to 2022. Finally, we use the long short-term memory (LSTM), which is an enhanced variant of the recurrent neural network (RNN) model, to predict the total number of electricity subscribers and the energy balance in Senegal. These models allow us to project future scenarios of energy mix based on historical trends and predicted demand. Our primary goal is to identify and assess the economic and technological challenges faced by Senegal while considering future prospects for the country's sustainable energy transition. This study thus combines an in-depth analysis of historical trends and a robust predictive model of the energy transition dynamics in Senegal to identify the challenges (related to energy demand) and opportunities (related to recent oil and gas discoveries and the potential for renewable energy) associated with integrating renewable energy sources into the national energy mix.

This paper contributes to the literature on energy transition in three ways. First, most work on sustainable energy transition focuses on economies in which the stock of fossil resources remains static or decreases, whereas that of renewable resources increases. Unlike these studies, our paper focuses on a context in which sustainability goals coexist with an increasing stock of fossil resources driven by recent oil and gas discoveries. This dynamic scenario, which considers the increasing availability of fossil resources, is particularly relevant for low-income countries that have experienced recent fossil fuel discoveries in the past decade (e.g., Mauritania, Ivory Coast, etc.). Second, unlike descriptive or sector-specific studies, our study adopts a comprehensive approach by combining quantitative data on energy production with a predictive model of energy mix, along with an analysis of current policies and strategies. The secondary data used for the analysis can easily be obtained, and the LSTM model is easily replicable across various countries in Africa and Asia [51,52]. Finally, by emphasizing the importance of a sustainable transition that aligns with increased electricity demand, this research provides valuable insights that are relevant for both regional and global energy transition discussions. While focusing specifically on Senegal, the study highlights energy transition principles applicable to other developing countries experiencing similar demographic trends and energy consumption behaviors. Overall, the challenges faced by Senegal in managing (increased) fossil resources, handling increased demand, and developing renewable energy reflect those encountered by many other developing nations [53–55]. Our study highlights the benefits of utilizing natural gas as a transitional energy source to meet the growing energy demand, concurrent with efforts to increase renewable energy capacity [56].

More broadly, a study of the sustainable energy transition must integrate climate aspects, which directly affect the availability and efficiency of energy resources. In particular, climate change, characterized by rising temperatures and changing precipitation patterns, significantly impacts both energy production and demand. Reducing the reliance on fossil fuels is crucial for lowering greenhouse gas emissions, an important step in combating global warming. Additionally, diversifying energy sources and adopting innovative technologies will enhance the resilience of energy systems, contributing to a sustainable energy future.

This paper is organized as follows: Section 2 describes the data and methods used in this study. Results and discussion are presented in Section 3. Finally, Section 4 summarizes the main findings and provides conclusions and recommendations for a sustainable energy transition in Senegal.

2. Data and Methods

2.1. Methodology

The methodology used in this study takes an interdisciplinary approach in order to provide a comprehensive analysis of the energy transition in Senegal. The combination of secondary data analysis and energy modeling allows us to capture both the present and future dynamics of the energy sector. Analyzing data from reliable sources provides an accurate diagnosis of the current energy system, while modeling allows for the projection of future scenarios based on historical trends. This methodology ensures consistency between the current situation and the forecasts, offering essential tools for effectively informing energy policy decisions. To assess the country's energy structure from 2000 to 2022, data are collected from government sources such as the Senegalese National Electricity Company (SENELEC), international organizations such as the IAEA, the World Bank, and relevant scientific publications. These data include statistics on energy production and consumption, along with greenhouse gas emissions, access to electricity, and national energy policies.

Quantitative and statistical analysis methods are used to analyze access to electrification and estimate energy consumption by sector while allowing for an efficient processing of available data. Various data processing tools are used to process, sort, and pre-analyze the data. We use geographic information systems (GIS) for the geographic visualization and analysis of spatial data related to electricity access and population distribution. The quantitative analysis includes descriptive statistics and time series analysis. The analysis aims to understand historical and present trends along with future prospects for energy sources, as well as the trends in access to electricity and energy consumption in sectors such as agriculture, industry, and transportation. Additionally, greenhouse gas emissions are analyzed by sector to identify the primary factors contributing to climate change and assess the impact of energy policy on these emissions. A detailed analysis of the evolution of electricity generation by energy source is also conducted, focusing on production trends and the respective contributions of fossil and renewable energy sources. By combining these different analyses, our study aims to provide a comprehensive assessment of Senegal's current energy landscape and its prospects for a sustainable energy transition against the backdrop of near-term fossil fuel development.

To predict the total number of electricity subscribers and the energy balance in Senegal, we employ the long short-term memory (LSTM) model. LSTM is an advanced variant of the recurrent neural network (RNN) designed to learn autonomously from historical data without explicit programming. The LSTM model has proven to be highly efficient in energy prediction [57–60], making it a valuable tool for our analysis. The LSTM model offers several significant advantages over other time series prediction algorithms, notably by managing long-term dependencies, avoiding the problem of vanishing gradients, and allowing better modeling of complex relationships between variables, in contrast to the RNN model, which has a major drawback for long-term projection. The RNN has a very short memory, as it only depends on the previous value, while the LSTM network was specifically designed to solve this problem. In fact, the LSTM model has a specific structure by transforming traditional neurons into blocks, capable of modeling a mechanism for forgetting and remembering information over long periods, which is essential for electricity subscriber and energy balance forecasts. The LSTM's three-gate structure (forget gate, input gate, output gate) allows it to determine which information to retain or discard, enhancing its effectiveness for predicting/forecasting complex data, such as those incorporating factors such as population, GDP, or infrastructure. LSTMs are also better suited to handling large amounts of historical data, which improves the accuracy of long-term forecasts [61,62]. The modeling process begins with the collection of the data needed to build the model. Then, after a preliminary cleaning and analysis phase, a clean and complete database is created, where missing values or outliers are dealt with, errors corrected, and data recorded if necessary. Preliminary analyses and consistency tests are carried out before modeling begins. The data are then normalized, as non-normalized variables can slow down the learning process or make it unstable. In our case, the data was recalibrated using the Min–Max method, which reduces the values in a range from 0 to 1, thus optimizing model performance. The data are then divided into a training set (80%) and a test set (20%) to assess the robustness of the model. The training set is based on daily consumption data, demographic information (total population, number of households), and economic indicators such as GDP. The characteristic selection approach is used to determine the most relevant explanatory variables for the modeling. To validate the model, metrics such as root mean square error (RMSE) and mean absolute error (MAE) are used to measure post-training performance. The weights in the network are initialized with small random values and then updated throughout the training. Finally, the model has been tested on data spanning from January 2010 to April 2022, taking into account fluctuations in consumption due to specific events (religious festivals, holidays) and other external factors such as network losses. The analysis includes daily consumption, number of customers, demographics, infrastructure, and utilization of fossil resources, particularly natural gas. Economic factors and electrification rates have also been included to improve the forecast up to the year 2027.

2.2. Data Collection Strategy

To conduct this study, we use a methodological approach combining secondary data analysis and energy modeling. The data sources include national and international reports, energy agencies, government databases, and scientific publications to ensure a comprehensive and reliable coverage of the required information [63–66]. Secondary energy data for Senegal was obtained from databases such as the World Bank [67], the IAEA [68], and Climatewatch [69]. These data provide both global and regional information on energy consumption, energy balance, and future projections. The Global Renewable Energy Report (REN21) provides statistics and analysis on the integration of renewable energy into the energy structure of countries, including Senegal, while a report by IRENA specifically highlights the potential and challenges associated with renewable energy in Africa, with a focus on Senegal [70,71]. Annual reports from the Senegalese Ministry of Petroleum and Energy were used to obtain detailed data on energy production, consumption, and import/export activities in Senegal from 2000 to 2022 [72,73]. In addition, data from organizations such as the National Action Plan for Renewable Energy (PANER) report [74] and the national electricity utility company SENELEC [75] were used. Demographic data were obtained from the National Agency of Statistics and Demography (ANSD) [76], while GDP data were provided by the Department of Planning and Economic Policy (DGPPE) [77]. Quantitative insights into the challenges and opportunities of the energy transition were gathered through interviews with energy experts in Senegal. To ensure the validity and reliability of the findings, we triangulated information from multiple sources and cross-checked the data for accuracy and consistency by comparing it with various publications and reports.

3. Results and Discussion

3.1. Socioeconomic Profile and Electricity Generation: A Comprehensive Analysis

Figure 1 shows the annual increase in the total energy production (top panel) and total population (bottom panel) in Senegal from 2000 to 2023. Both indicators show an almost linear increasing trend over the years. On average, energy production increased by about 215.74 GWh per year, starting from a base production of 894.89 GWh. In particular, electricity production doubled in 10 years from 2918 GWh in 2012 to 5908.32 GWh in 2022, reflecting a compound annual growth rate (CAGR) of 7.62%. Production in 2023 is estimated at 6654.02 GWh, resulting in an increase of 11.40% compared to 2022. Likewise, the country's population also doubled between 2000 and 2022, which explains the growing energy demand. This growth highlights the importance of implementing policies and measures to improve energy efficiency, diversify energy sources, and promote sustainable development. These measures are critical to meet the growing energy demand while minimizing environmental impacts.

Figure 2 shows the spatial distribution of the total population by region in 2023 (Figure 2a) and the distribution of the total number of domestic customers by zone (region) in 2023 (Figure 2b). According to the 2023 general population census, most of the population is concentrated in the western coastal regions, especially in Dakar, Thiès, and Diourbel. In contrast, the southern region has the lowest population. Likewise, the major urban centers in the west, such as Dakar, Thiès, and Diourbel, have the highest number of domestic electricity subscribers. Conversely, the southern regions (Ziguinchor, Kolda, and Sedhiou) and the northern regions have a lower number of domestic subscribers. This can be explained by the small population size in these regions and the limited access to the electricity grid. This information is important for regional development, infrastructure planning, and public policy implementation. By taking into account population distribution and energy needs, authorities can better target infrastructure investment and development plans to meet the specific needs of each region, improve energy access, and promote balanced economic development across the country.

Future projections indicate that the number of domestic subscribers is expected to increase from 2,198,624 in 2022 to 3,156,473 in 2027, representing an increase of 27% over this period.

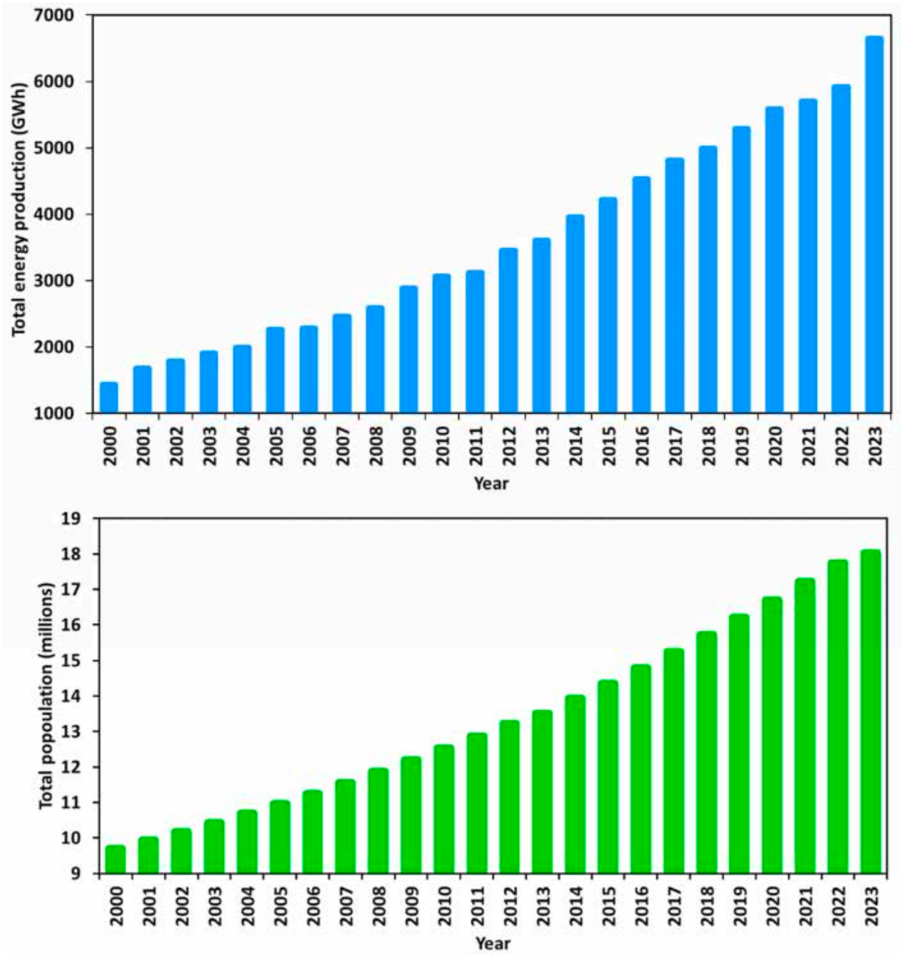

Figure 1. Evolution of total annual energy production (GWh, **top**) and total population (millions, **bottom**) in Senegal from 2000 to 2023.

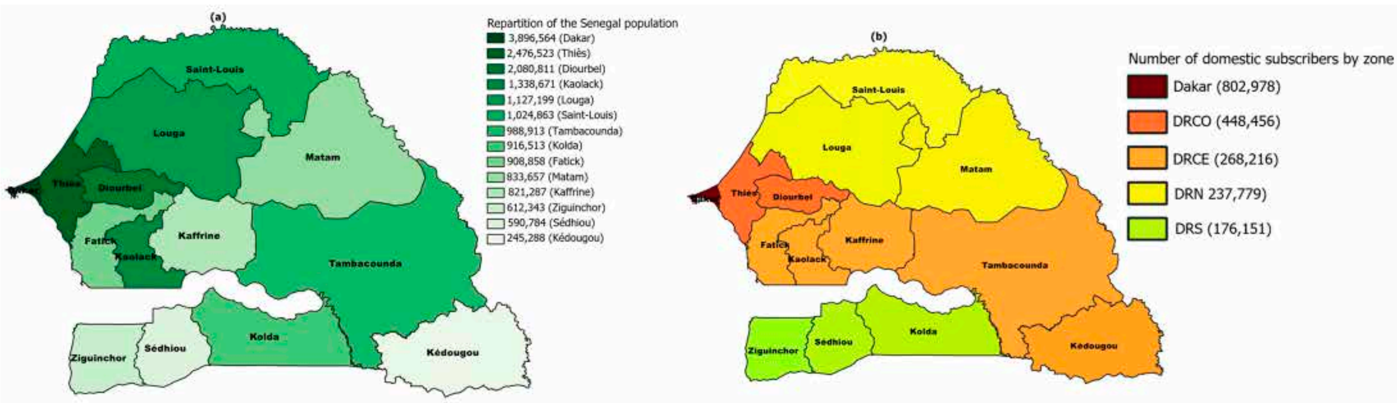

Figure 2. Geographical (regional) distribution across the 14 regions of (**a**) the population in 2023 and (**b**) the number of domestic subscribers by zone in 2023.

3.2. Access to Electrification and Energy Consumption: Current Status Since 2000 and Outlook

Figure 3 presents the electrification rate (%) for the total population (Figure 3a), as well as the rural population (Figure 3b) and urban population (Figure 3c) in Senegal from 2000 to 2021. All three indicators show a progressive increase, indicating significant progress in electricity over this period. For instance, electricity access for the total population has increased from less than 40% in 2000 to more than 70% in 2021. During the same period, urban population access to electricity increased from 73% in 2000 to nearly 95% in 2021, suggesting that the majority of the urban population has access to electricity. However, in rural areas, the proportion remained low, increasing from less than 15% in 2000 to about 48% in 2021 (see Figure 3c). These results confirm the country's official data, showing that about 4.3 million rural people in approximately 14,000 localities do not have access to electricity [30]. Consequently, ensuring access to electricity for the most vulnerable rural populations still remains a major challenge.

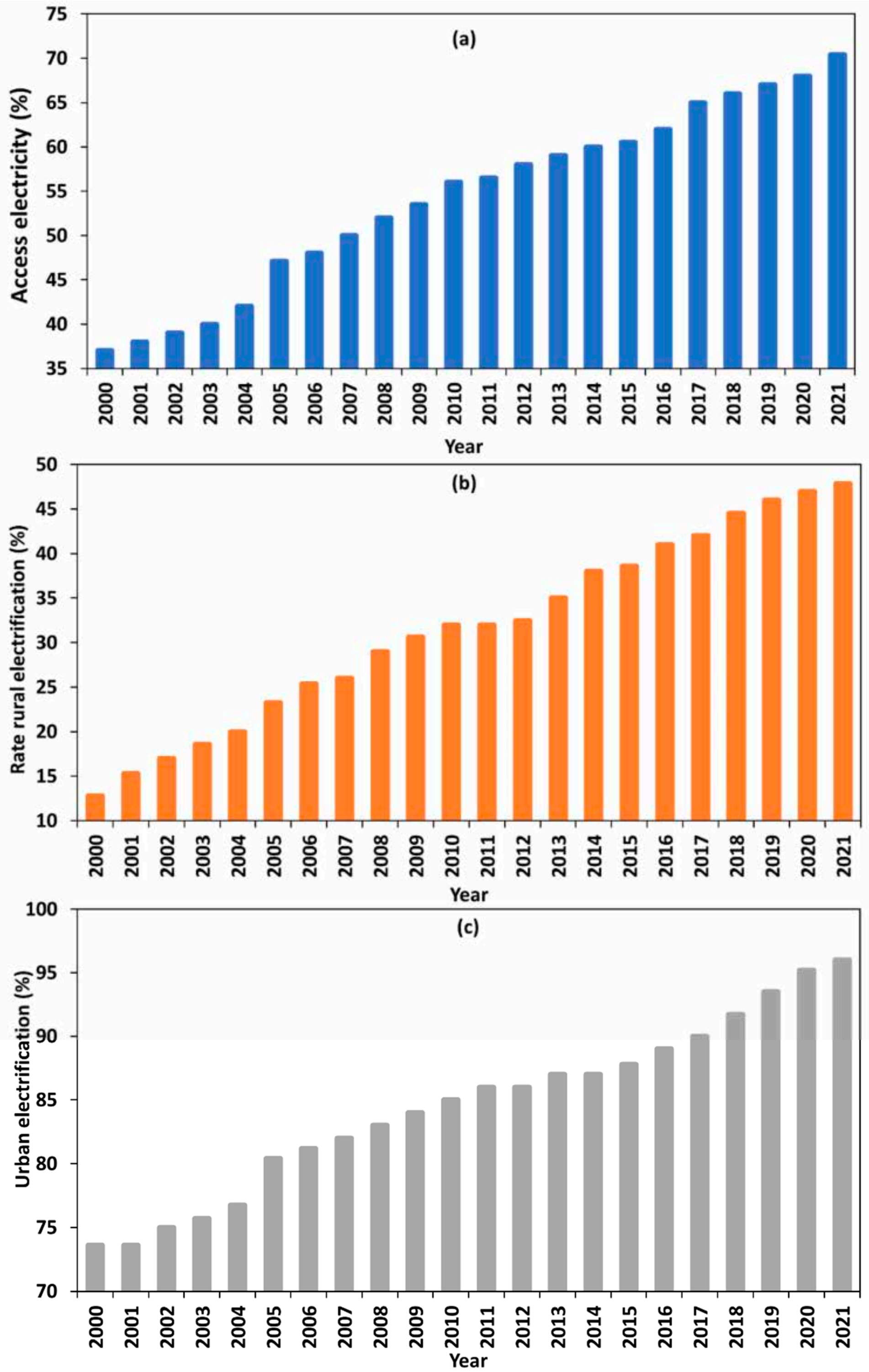

Figure 3. Rate of electricity access (in %) for the entire population (**a**), rural population (**b**), and urban population (**c**) from 2000 to 2021.

Figure 4 shows a comparison between GDP per capita and energy consumption per capita in Senegal from 2000 to 2022. It can be seen that the growth in GDP per capita is correlated with the increase in total and per capita energy consumption. This correlation is explained by the increasing energy demand of the population, which leads to a gradual increase in per capita energy consumption. These trends indicate improvement in living standards, population growth, and advancements in industrial development [65].

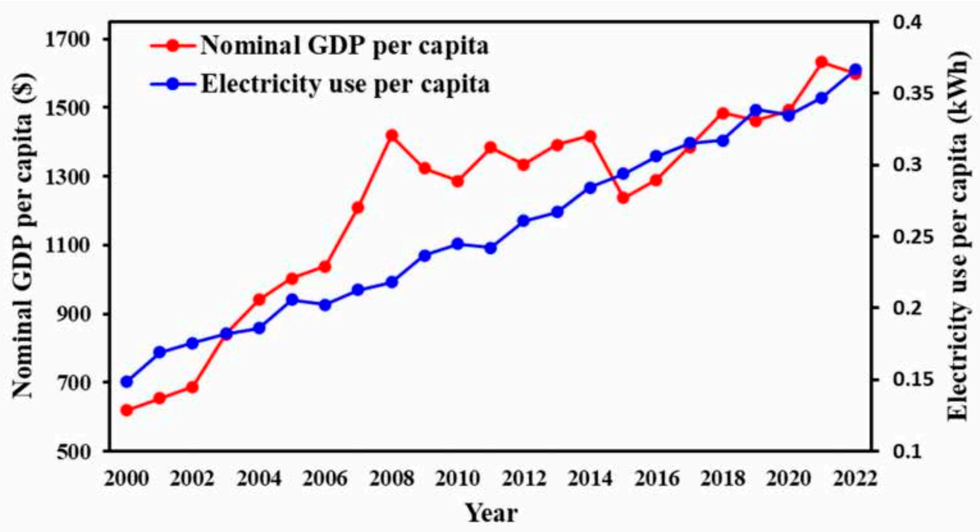

Figure 4. Trends in nominal GDP per capita (red, in USD) and electricity consumption per capita (blue, in kWh) from 2000 to 2022 in Senegal.

The energy pricing system in Senegal is structured into three power tiers: low voltage (LV), medium voltage (MV), and high voltage (HV), as summarized in Table 1.

Table 1. Characteristics of different client types in the Senegalese electricity market.

Voltage Levels	Subscribed Power	Client Type
Low	0–34 kW	Domestic + Commercial
Medium	34 kW–1000 kW	Small and medium industrial
High	>1000 kW	Large industrial

LV customers are those with a subscribed power demand of less than 34 kW and are served at a nominal voltage ranging from 220 to 380 volts (with a tolerance of 10%). The LV group includes residential, commercial, and public lighting. Within LV residential and commercial clients, there are three categories: small, medium, and large. Small clients are those with subscribed power of less than 6 kW, while medium clients are those with subscribed power between 7 kW and 17 kW. Large LV clients are those with subscribed power between 17 kW and 34 kW. Small and medium LV customers are priced based on an ascending block price, where the marginal price of the kWh varies and increases as the level of kWh consumed increases. There are three tiers, and the tier cutoffs vary based on the customer group (small vs. medium vs. large) and the usage type (residential vs. commercial). Public lighting customers are charged a fixed price per kWh. Large LV customers/clients are charged on a time-of-use (ToU) pricing, with a higher marginal price during peak hours (between 7 pm and 11 pm) and a lower marginal price during off-peak hours. The average price per kWh for these LV clients is 115.35 FCFA/kWh (0.2 USD (here we used: 1.0 USD ($) = 600.00 CFA)/kWh) in 2022.

MV clients are those with a subscribed power of between 34 kW and 1 MW (1000 kW) and are served at a nominal voltage ranging from 1000 volts to 50,000 volts. MV clients include small and medium-sized industrial clients, large service providers and businesses, and rural electrification concessionaires, which are entities in charge of supplying electricity to very remote areas in private markets. The pricing for MV clients also follows time-of-use (ToU) pricing with three different categories: short usage, long usage, and general usage. Short usage is for clients with an average usage of less than 1000 h per year, general usage is for clients with an average usage of between 1000 h and 4000 h per year, and long usage is for clients with average usage above 4000 h per year. The average price per kWh for these medium-voltage clients is 111.98 FCFA/kWh (~0.19 USD/kWh) in 2022.

HV clients are those with a subscribed power of more than 1 MW (1000 kW) and are served at a nominal voltage exceeding 50,000 volts. The HV group applies to large industries and major projects exceeding 3000 kW. The average price per kWh for these medium voltage clients is 83.73 FCFA/kWh (~0.14 USD/kWh) in 2022. The number of HV clients is very small, for instance, it was only nine in 2022.

Figure 5 shows the share of each category in the country's total electricity production in 2000, 2010, and 2022 [68]. Electricity consumption in Senegal is mainly dominated by domestic usage as well as professional uses and public lighting, accounting for between 50% and 64% of the total. However, this share has slightly decreased from 64% in 2010 to 62% in 2022, indicating a diversification towards other energy sources. Medium-sized enterprises and concessionaries, which mainly utilize medium voltage (MV), have seen their share decrease from 34% in 2000 to 30% in 2010 and further to 26% in 2022, possibly in response to energy optimization or new efficiency standards. Conversely, high voltage (HV) consumption by large industries declined from 16% in 2000 to 6% in 2010 before rising to 12% in 2022, suggesting a potential industrial recovery or improvements in energy efficiency.

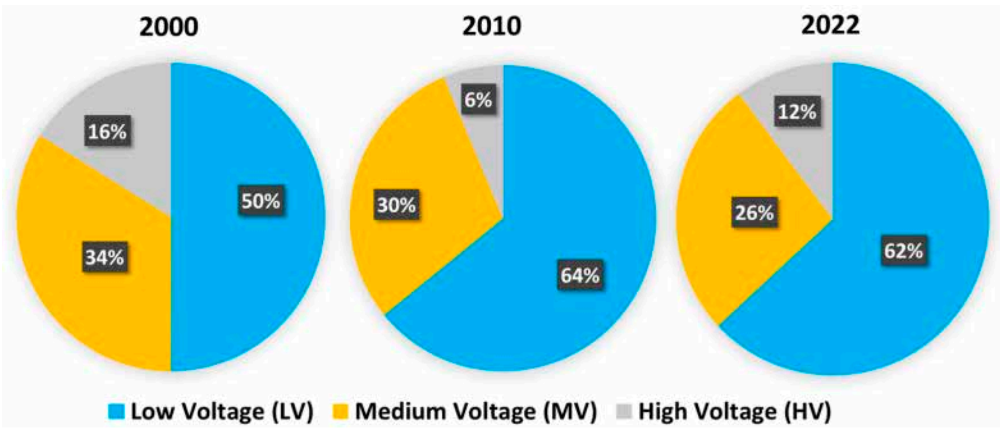

Figure 5. Consumption share (%) for each subscription type LV (households), MV (small-scale industry) and HV (large-scale industry) in 2000 (**left**), 2010 (**middle**), and 2022 (**right**).

In summary, electricity consumption in Senegal is primarily driven by domestic and commercial uses, with the industrial sector playing a minor role but subject to fluctuations. These trends reflect economic and technological developments, as well as the country's energy policy directions, and highlight the relatively limited contribution of the industrial sector to the national economy in terms of electricity consumption.

3.3. Sectoral Analysis of Energy Consumption

Figure 6 shows the distribution of electricity consumption by sector in 2000, 2010, and 2021 [69]. First, it should be noted that the most energy-intensive sector is the residential sector, followed by transportation and industry, which account for over 95% of total consumption. A closer look reveals that, despite the overwhelming share of the residential sector, it has declined from 57% in 2000 to 45% in 2021. This decline can be explained by various factors, including lifestyle changes resulting from improved energy efficiency in homes and increased adoption of energy-saving technologies, along with increased dependence on other sectors for energy services. At the same time, the share of the transportation sector has increased from 26% between 2000 and 2010 to 33% in 2021. This is likely due to increased energy demand due to economic growth, accelerating urbanization, and expanding transportation networks. During the same period, energy consumption in the industrial sector increased from 12% in 2000 to 19% in 2021. This growth could be driven by the expansion of existing manufacturing and industrial facilities, which require more energy to power machinery and industrial processes. This analysis highlights notable shifts in Senegal's energy distribution, characterized by a decline in the share of residential energy consumption and an increase in the share of consumption by the industrial and transport sectors (see Figure 6). The corresponding actual consumption values in GWh shown in the bottom panels (see Figure 6) confirm the results and trends of the top panels with shares. In fact, the residential and industrial sectors are the most energy intensive. However, unlike the residential sector, which remained flat from 2010 to 2020, the share of the industrial and transport sectors has steadily increased from 2000 to 2021.

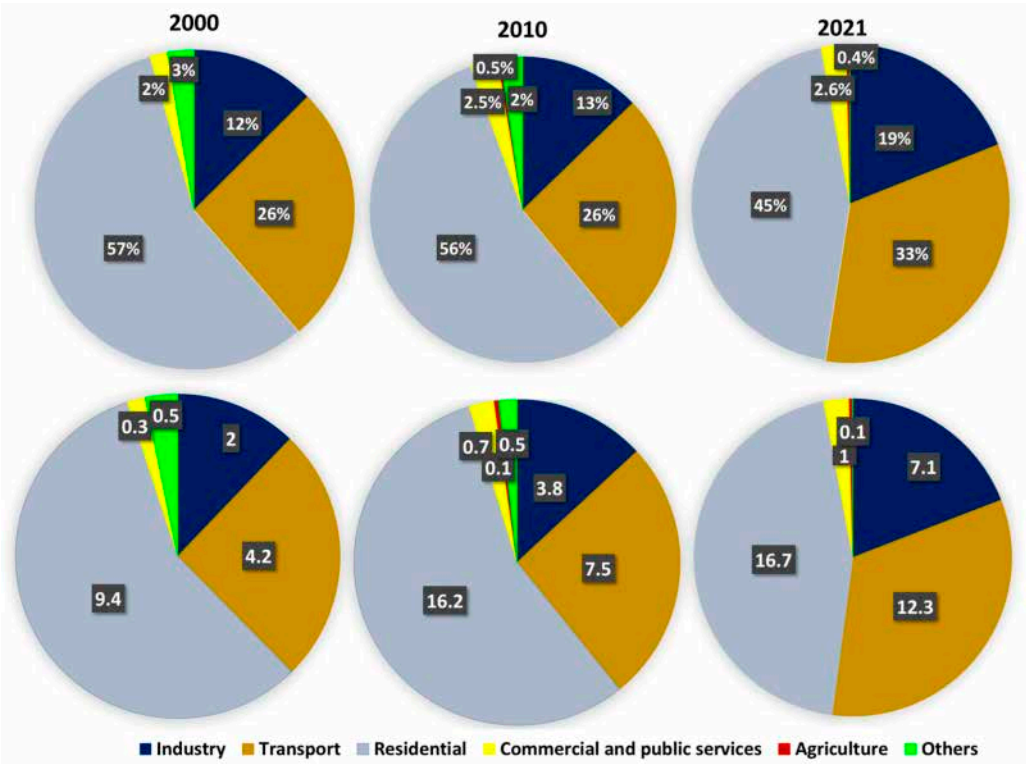

Figure 6. Distribution of energy (% and GWh) consumption by sector in 2000 (**left**), 2010 (**center**), and 2021 (**right**). The **top** panels represent the percentage for each sector, while the **bottom** panels present the corresponding relative data.

3.4. Greenhouse Gas Emissions Assessment

Figure 7 shows greenhouse gas emissions by sector for 2000, 2010, and 2021. Overall, agriculture stands out as the main source of emissions, accounting for almost half of the emissions, followed by the energy sector. Indeed, emissions from agriculture have remained high over the past three decades, consistently accounting for about 50% of total national emissions. The primary gases emitted by the agricultural sector are mainly methane (CH_4) and nitrous oxide (N_2O). Methane is largely derived from enteric fermentation, while nearly all nitrous oxide is emitted from agricultural soils [30].

Likewise, greenhouse gas emissions from the energy sector have slightly increased by about 5% (electricity and transport) between 2000 and 2021. Other sectors, such as waste management and industrial processes, have relatively low emissions, with a decreasing trend since 2000. However, it is important to continue efforts to reduce emissions by mitigating climate change and promoting sustainable development, in particular, by encouraging sustainable agricultural practices, investing in clean energy, introducing more efficient industrial technologies, and improving waste management.

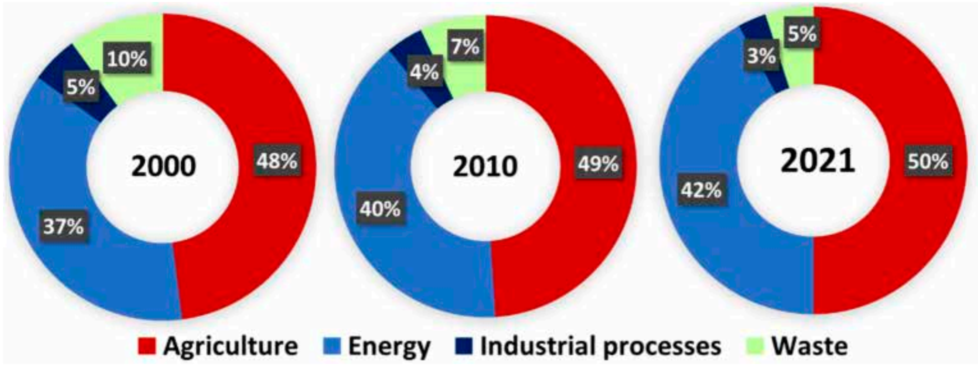

Figure 7. Estimated greenhouse gas emissions (in %) by sector in Senegal in 2000 (**left**), 2010 (**center**), and 2021 (**right**).

Figure 8 compares per capita CO_2 emissions between Senegal (red) and several other countries (France, China, United States of America, Vietnam, Niger, and Ivory Coast) from 2000 to 2021. The chart in the upper right corner provides a close-up view of emissions from developing countries, including Senegal, Cote d'Ivoire, and Niger. In terms of emissions, two distinct groups are evident. Industrialized countries (France, China, United States of America) have higher emissions, typically in the range of 5 to 20 tCO_2 per capita per year, due to their significant energy consumption and dependence on fossil fuels. Conversely, emissions in developing countries (Senegal, Vietnam, Niger, and Côte d'Ivoire) are lower, at less than 1 tCO_2 per capita per year. However, a closer look at Senegal (inset above) shows a notable increase in emissions compared to both Niger and Ivory Coast. Overall, although emissions per capita are still very low compared to developed countries, they have doubled between 2000 and 2021, which, indeed, are in line with economic activity growth.

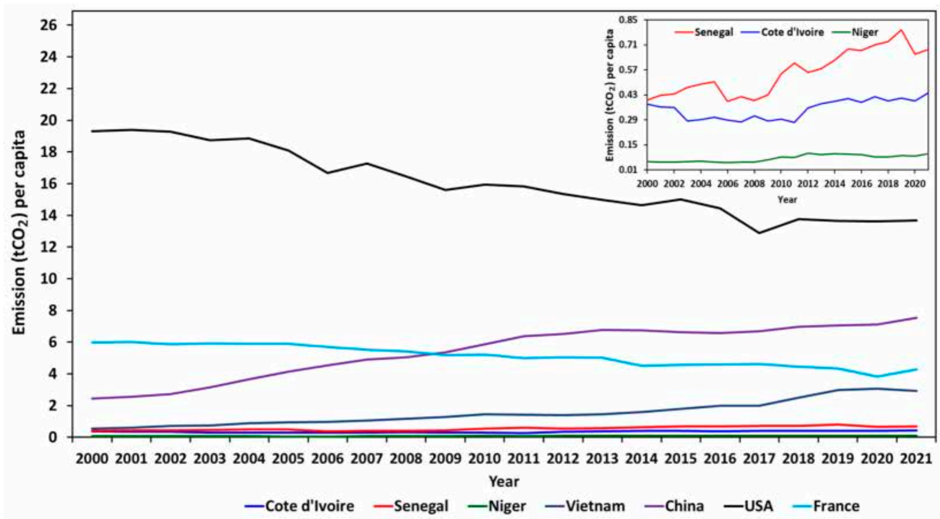

Figure 8. Comparison of greenhouse gas emission trends (in tCO_2) per capita between Senegal and several other countries from 2000 to 2021. The upper right corner chart is a close-up of Senegal, Niger, and Cote d'Ivoire emissions.

The analysis of per capita CO_2 emissions reveals diverse trends among countries, reflecting differences in their economic development, environmental policies, and patterns of energy production and consumption. It is crucial for all countries to implement measures to reduce their CO_2 emissions in order to combat climate change and promote sustainable development.

3.5. Electricity Production by Energy Source from 2000 to 2022

Figure 9 shows the change in energy production by energy source in Senegal from 2000 to 2021 [74]. In 2000, almost all energy production came from fossil fuels. However, other types of fossil fuels have progressively been added, including coal and gas. In addition, the use of renewable energy sources, such as hydropower, solar, and wind energy, has increased significantly, leading to an important increase in the country's installed capacity. By 2020–2021, Senegal's installed capacity is estimated at 1.2–1.5 GW, producing 5.61 TWh of electricity. This capacity increased from 1.79 GW in 2022 to 1.95 GW in 2023 [78–80]. The transition to renewable energy sources has meant a significant increase in installed capacity, which has reduced the initial dominance of fossil fuels observed in the early 2000s.

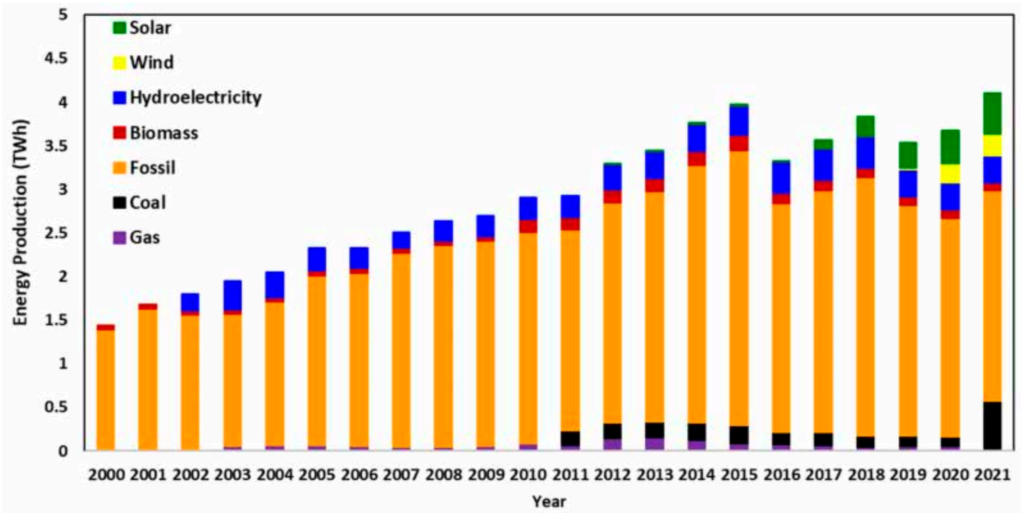

Figure 9. Distribution of energy production (in TWh) by energy source in Senegal from 2000 to 2021.

The total installed capacity of renewable energy sources is on an upward trajectory. For instance, between 2021 and 2023, solar capacity is projected to increase from 226 MW to 249.68 MW, representing a growth rate of 9%. Likewise, according to the SENELEC, hydropower capacity has increased from 75 MW in 2021 to 121 MW in 2023, representing a growth rate of 38%. Despite progress in diversification with a significant increase in renewable energy production, fossil fuels and heating oil still remain the main sources of electricity generation. This dependence on fossil fuels exposes the country to volatility in global markets for coal, oil, and gas. The need to import these fuels at elevated prices has a significant negative impact on Senegal's economy, which is already struggling with high electricity prices.

Figure 10 shows the share of fossil fuels in Senegal's energy mix from 2000 to 2021. Overall, it is clear that a significant portion of Senegal's energy comes from fossil fuels, particularly oil and its derivatives. From 2000 to 2002, fossil fuels accounted for approximately 97% of the country's energy production. But in 2003, this percentage dropped to about 80% due to the connection of the Manantali hydroelectric dam. However, between 2007 and 2009, the share of fossil fuels increased to about 90%. During this period, the country experienced regular power outages. To overcome these blackouts, the Senegalese government launched an initiative called the "Takkal Plan" (literally means "Lighting Plan"). During the "Takkal plan", large diesel generators were used to provide electricity to the public, which could explain the rising use of fossil fuels during this period. Finally, from 2012 to the present, with the increasing integration of renewable energy sources, such as solar and wind power, the share of fossil fuels has further decreased to approximately 85%. Overall, this result clearly demonstrates Senegal's commitment to achieve a more sustainable energy transition and reduce its reliance on fossil fuels.

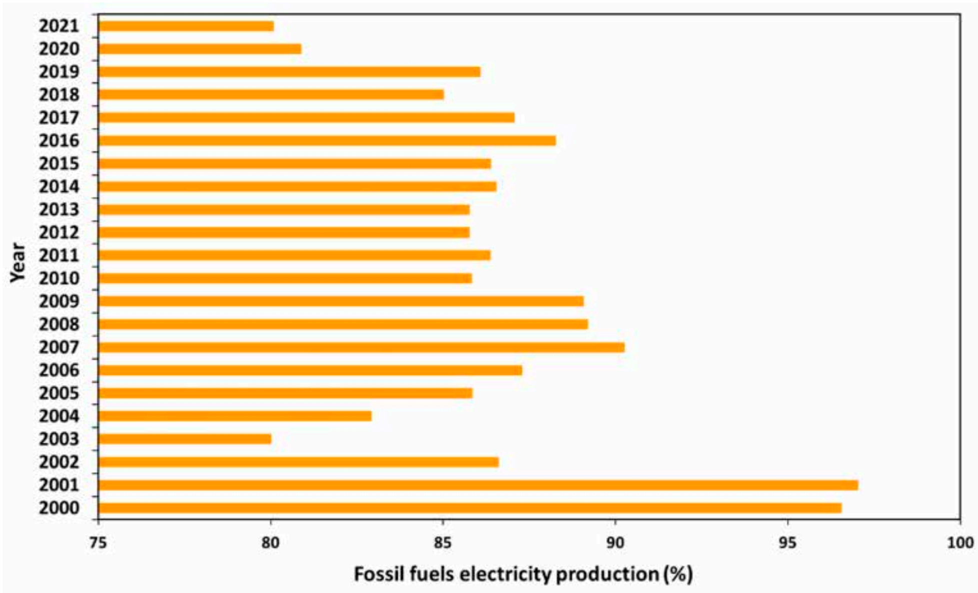

Figure 10. Evolution in the share of fossil fuels in Senegal's total energy mix from 2000 to 2021.

Figure 11 shows the integration of renewable energy sources into Senegal's energy mix from 2010 to 2022. In 2010, the only renewable energy source was hydroelectricity, introduced in 2002 through the connection of the Manantali Dam, which added about 25 to 30 GWh per year. Senegal began to gradually integrate solar energy with the operation of the Bohol Solar Power Plant in the northern region in 2013. Since 2016, additional solar power plants, such as Kahone, Malicounda, Tenmerina, Mekhe, Sakal, and Diass, have also come online, further increasing the share of solar energy in the energy mix. At the same time, a new wind farm was installed in Taïba Ndiaye in 2017, promoting the development of renewable energy sources. The wind farm became operational in 2017 and has reached its maximum capacity of 158.7 MW by 2021–2022. In addition, hydroelectric power production increased significantly in 2022 with the construction of the 128 MW Sambangalou hydropower dam. With several additional projects currently in various stages of planning or construction, Senegal is making substantial progress toward achieving its hydropower capacity targets.

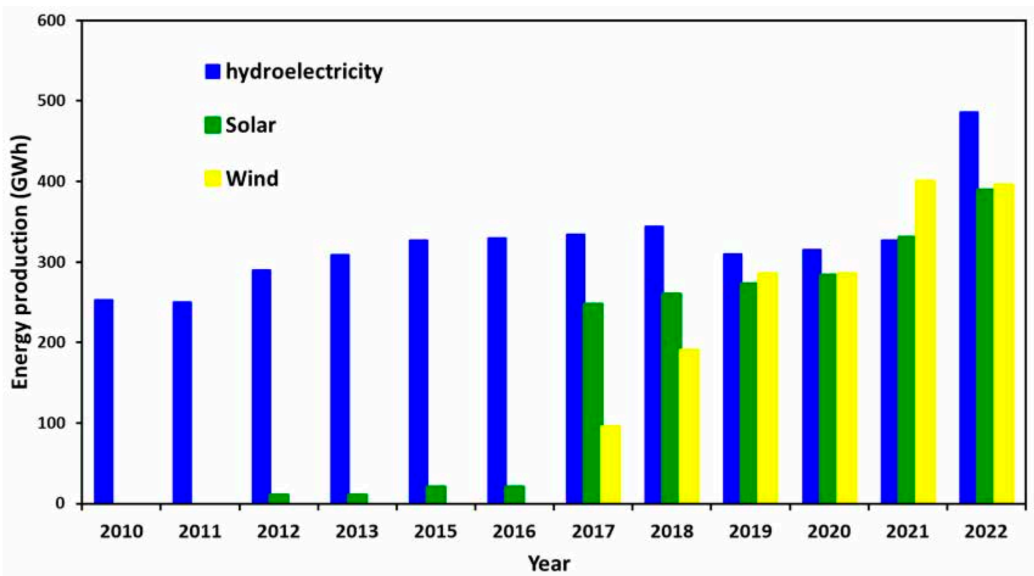

Figure 11. Change in production (GWh) of different types of renewable energy in Senegal from 2010 to 2022.

3.6. Evolution of the Energy Mix from 2000 to 2022

Figure 12 illustrates Senegal's energy mix in 2000, 2010, and 2022. In 2000, Senegal primarily relied on fossil fuels (97%, predominantly oil and its derivatives) and a minor share of biomass (3%), mainly used in rural areas. In 2010, although fossil fuels still dominated with 89% of the total share, the hydroelectricity produced by the Manantali dam contributed 9% of the total share, while the share of biomass decreased to 2%. In 2022, significant progress was made in the integration of renewable energy sources into Senegal's energy mix. Overall, in 2022, fossil fuels decreased to 70%, while the share of solar energy, wind energy, and hydroelectricity increased to 12%, 9%, and 7%, respectively. The biomass remained steady at 2%.

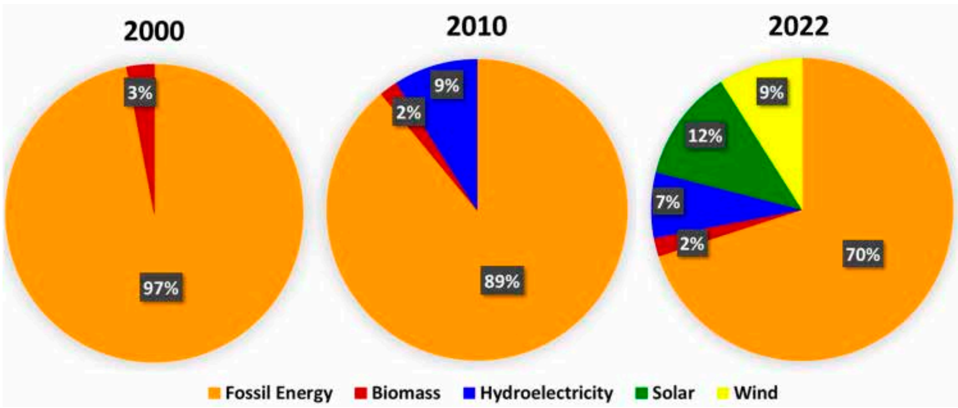

Figure 12. Share of Senegal's energy mix in 2000, 2010, and 2022.

3.7. Short and Medium-Term Energy Transition Strategies in the Context of Fossil Fuel Exploitation

In its energy transition strategy, Senegal has made a strategic decision to use natural gas as a medium-term transitional energy source while continuing to promote the development of renewable energy sources. The Grand Tortue/Ahmeyim gas field is considered the largest deposit in West Africa, with estimated reserves of 450 billion cubic meters, and is expected to produce approximately 2.5 million tons of liquefied natural gas (LNG) annually by 2025. Currently, the country prioritizes LNG to enable long-distance transport and access to international markets, given the lack of a pipeline network. The exploitation of this Senegalese gas will create wealth and stimulate the country's economic growth [81]. Figure 13 presents the projections for 2027 based on the LSTM model, which incorporates both the oil and gas production plans starting in 2025. According to this model, the energy mix in 2027 is expected to consist of 47% of natural gas, 32% of petroleum products, 12% of hydropower, 5% of solar energy, and 4% of wind energy. Senegal should phase out heavy oil from its power generation mix while continuing to expand its renewable energy capacity, according to a parallel analysis conducted during a 2019 loan operation supported by the World Bank. However, by 2026, the share of natural gas is projected to increase to reach levels consistent with these results [50].

Figure 14 summarizes the evolution of the energy structure over the last 24 years, categorized into fossil, renewable, and transition energy sources, and the projections for the next three years (up to 2027). In 2000, fossil fuels accounted for 97% of the total energy mix, while renewable energy accounted for only 3%. By 2010, the share of fossil fuels decreased to 87%, while that of renewable energy sources rose to 13%. Throughout the 2020s (here 2022), the share of fossil fuels has continued to decline, reaching 70% of the total, while the share of renewable energy has continued to rise, reaching 30% of the total energy mix. The forecast for the next few years leading up to 2027 indicates a significant shift in the energy mix, along with the expected depletion of the country's oil and gas reserves. Therefore, by 2027, the energy mix is expected to consist of 47% natural gas, 32% oil, and 21% renewable energy, with the latter being considered a transitional energy source.

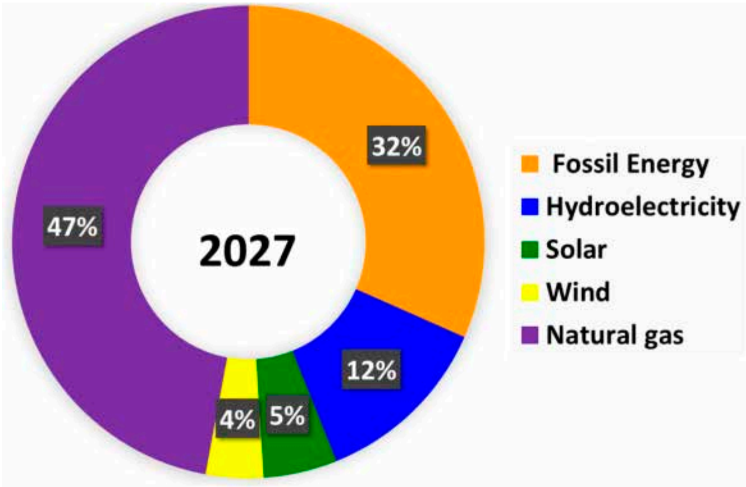

Figure 13. Projected energy transition by energy source in Senegal in 2027 (%) using the LSTM model.

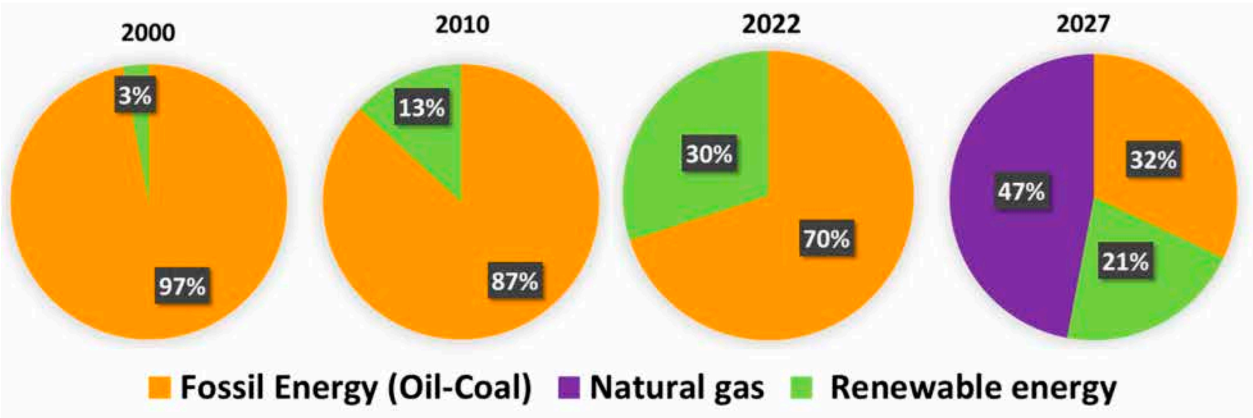

Figure 14. Evolution of Senegal's energy mix in 2000, 2010, 2022, with projections for 2027.

3.8. Economic Impact of the Energy Mix

Beyond the environmental importance of the energy mix, the energy sources also merit specific attention because they affect the marginal cost of electricity production, which influences the retail prices paid by households and firms (e.g., businesses). Indeed, the regulatory body, the Regulatory Commission for the Electricity Sector (CRSE), establishes consumer rate schedules based on the variable costs associated with energy production. The CRSE starts by projecting electricity consumption across different customer groups. This projected demand is then used to estimate the required production based on an assumed ratio of sales to production. The costs associated with this required level of production are then estimated based on the anticipated production expenses. These estimated production costs are combined with transportation and distribution costs to obtain an overall estimated total production cost. Taxes, import duties, amortization payments, and projected capital investments are added to the calculated costs to obtain a required level of revenue per kWh, which is then used to establish rate schedules for customers. Thus, the energy mix in Senegal has a socioeconomic impact on consumers' well-being since electricity constitutes a substantial portion of expenditures for both households and businesses. Table 2 provides an overview of Senegal's electricity system in 2022, highlighting the primary power plants, their classifications, energy sources, annual production per plant, and the corresponding production costs. Likewise, Table 2 shows the variable price per kWh of electricity produced by each of the different power plants in the country.

Table 2. Variable cost in FCFA of electricity production by power plant in 2022.

Plant	Type	Energy Source	Production in 2022 (GWh)	Variable Cost of Production (FCFA/kWh)
C3 Cap des Biches Power Plant + C3	Interconnected grid network	Heavy Fuel Oil + LNG (Liquefied Natural Gas)	9.37	123.43
Diesel	Interconnected grid network	Heavy Fuel Oil	1539.02	155.07
Gas Turbines	Interconnected grid network	--	10.07	321.39
Solar-CICAD	Interconnected grid network	Solar	2.16	NA
Solar-DIASS	Interconnected grid network	Solar	28.90	NA
Boutoute	Non-interconnected grid network	Heavy Fuel Oil	26.71	96.81
Secondary plants	Non-interconnected grid network	--	39.27	184.62
Contour Global	IPP (Independent Power Producer)	Thermal	512.88	89.40
Kounoune Power	IPP	Heavy Fuel Oil	132.09	108.05
Tobene Power	IPP	Heavy Fuel Oil	239.62	94.76
Karpowership plant	IPP	Heavy Fuel Oil	1398.06	94.76
CES Sendou	IPP	Coal	340.55	109.37
Malicounda Power	IPP	Natural Gas	--	90.52
ICS	Autoproduction	Coal	15.59	43.00
PV-Bokhol	IPP	Solar	41.00	79.88
PV-Malicounda	IPP	Solar	33.10	70.36
PV-Synergy	IPP	Solar	48.10	78.91
PV-Ten Merina	IPP	Solar	48.50	75.50
PV Kahone	IPP	Solar	33.00	83.22
PV Sakal	IPP	Solar	41.20	69.78
PV Kahone	IPP	Solar	53.00	24.78
Kael Solar plant	IPP	Solar	51.00	26.26
Taïba Ndiaye	IPP	Wind	395.56	69.42
Manantali Dam	Purchase	Hydro	232.00	20.68
Felou Dam	Purchase	Hydro	69.29	20.77
Gouina Dam	Purchase	Hydro	184.72	20.81

Table 3 presents the distribution of production costs by energy source across the different power plants outlined in Table 2. The table highlights that solar, wind, and hydroelectric power are relatively inexpensive, with average costs of 0.102, 0.035, and 0.116 USD/kWh, respectively. Globally, the costs of these renewable energy sources have been declining over the last few decades and are projected to continue decreasing in the coming decades [81]. On the other hand, electricity generated from fossil fuels is much more expensive to produce, with the marginal cost of production greater than 100 FCFA/kWh (~0.1667 USD/kWh) for both heavy fuel oil and coal. Natural gas seems to be a more economical alternative, with the production costs ranging between those of renewable sources and fossil fuels (see Table 3). Additionally, as Senegal begins to exploit its own natural gas reserves in 2025, it is anticipated that the cost of natural gas production will further decrease, enhancing its competitiveness in the energy market.

Table 3. Distribution of variable cost (USD) of electricity production by energy source in 2022.

Energy Source	Minimum	Maximum	Weighted Average Mean
Solar	0.041	0.139	0.102
Hydro	0.034	0.035	0.035
Wind	0.116	0.116	0.116
Gas	0.151	0.151	0.151
Coal	0.072	0.182	0.177
Heavy Fuel Oil	0.149	0.308	0.200

4. Summary and Conclusions

The aim of this study was to analyze the challenges and opportunities associated with the energy transition in Senegal, taking into account the exploitation of fossil fuels, especially natural gas, alongside the gradual integration of renewable energy sources.

Based on the findings of the study, several quantitative conclusions can be drawn and used to provide a clear outlook for a sustainable energy future in Senegal. Over the past two decades, electricity production has increased significantly, rising from 1100 GWh in 2000 to approximately 4000 GWh in 2020, corresponding to a nearly quadrupling of capacity. This remarkable growth is primarily driven by population growth of 2.8% per year and increased energy demand due to rapid urbanization. Our results show that while the energy mix is still dominated by fossil fuels, which accounted for 70% of electricity production in 2020, renewable energies have made remarkable progress, increasing from less than 3% of installed capacity in 2000 to approximately 30% of installed capacity in 2022. Among the renewable energy sources, solar power generation has shown a more rapid growth, with installed capacity reaching 245 MW in 2022 and representing growth of more than 40% within five years. In addition, the construction of the Taïba Ndiaye wind farm, along with its connection to the Manantali and Sambagalou hydroelectric dams, contributed significantly to increasing the share of renewable energy sources to 30%. This important development marks a major turning point in Senegal's energy landscape, highlighting the country's commitment to diversifying its energy portfolio and increasing reliance on sustainable sources. Moreover, the recent discovery of natural gas represents a unique opportunity for the country's economic development. As an energy source with low greenhouse gas and pollutant emissions, natural gas offers an opportunity for both economic development and energy transition. As a transitional energy source, natural gas can reduce CO_2 emissions by up to 30% compared to coal while supporting the development of renewable energy infrastructure. By consolidating the 500 MW of natural gas production capacity, Senegal can enhance the reliability of its electricity grid and save approximately 700 billion FCFA (nearly USD 1.147 billion) annually by reducing its dependence on oil imports [82]. However, to ensure a sustainable energy transition while building climate resilience, it is crucial for Senegal to balance the short-term economic benefits of natural gas with long-term environmental sustainability and social well-being. In particular, there is a need to assess the potential social, economic, and environmental impacts of natural gas development, especially on vulnerable communities. Engaging these communities in a just energy transition is essential to create green jobs and avoid exacerbating existing inequalities. Significant challenges remain, as the development of energy infrastructure requires substantial investment. To achieve universal access to energy, modernize the power grid, and develop reliable battery storage facilities for renewable energies, total investments are estimated at around 660 billion FCFA (USD 1.6 billion) [83]. Currently, access to electricity is geographically unequal, with over 95% of urban areas having access to electricity while only about 50% of rural areas do. Promoting decentralized energy systems and mini-grids in rural areas will contribute to improving access to energy and help alleviate rural poverty. Finally, to achieve a sustainable energy transition, Senegal needs to strengthen its energy policy with a focus on energy efficiency, the integration of renewable energy sources, and the development of the necessary climate-resilient infrastructure, but also to raise public awareness and to provide better access to electricity at affordable rates in rural areas.

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