

A comprehensive review of Liberia's energy scenario: Advancing energy access, sustainability, and policy implications

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ABSTRACT

Liberia, a developing nation, faces significant challenges in its energy sector, with limited access to electricity and heavy reliance on traditional biomass and imported fossil fuels. This review explores Liberia's energy landscape, policies, challenges, and opportunities, aiming to identify ways to improve energy access and foster sustainable development. Our methodology employed a systematic search strategy, examining relevant literature from various sources, encompassing research articles, reports, and studies related to Liberia's energy landscape from 2010 onward. Our findings indicate that Liberia's energy mix is historically dominated by traditional biomass fuels such as firewood and charcoal, accounting for more than 80 % of the country's total energy consumption. Petroleum products, including gasoline and diesel, contribute to about 10 % of energy consumption, while hydroelectric power makes up just over 6 %. The remaining energy comes from various sources, including solar energy. This heavy reliance on traditional biomass and limited access to affordable energy has significant social and economic implications. Efforts have been made in recent years to improve Liberia's energy situation. Yet, significant challenges, including financial constraints, inadequate infrastructure, affordability issues, and an outdated energy policy, continue to hinder progress. However, the review identifies opportunities for improving energy access, including abundant renewable energy resources, international support, public-private partnerships, off-grid solutions, and energy efficiency measures. Additionally, regular reviews and updates of policies, informed by accurate data and forward-looking strategies, are also essential to ensure that the energy sector remains aligned with changing circumstances and technological advancements.

1. Introduction

Access to reliable and affordable energy is crucial in driving socio-economic development in any country. Energy access impacts various sectors of the economy, including education, healthcare, agriculture, industry, and infrastructure [1]. It is also a fundamental requirement for improving the quality of life, promoting economic growth, and reducing poverty. Like many other developing nations, Liberia faces significant challenges in its energy sector [2]. Limited access to electricity, over-reliance on traditional biomass for cooking, and inadequate infrastructure hinder the country's progress [3–5]. According to the International Energy Agency (IEA), only 3 % of Liberians had access to grid electricity in 2019 [6], which is one of the lowest electrification rates in the world [7].

Efforts have been made in recent years to improve Liberia's energy situation. The government has introduced policies to attract private investment in the energy sector and promote renewable energy development [3,4]. In 2015, the government launched the Liberia Electricity Regulatory Commission (LEC) to provide oversight of the electricity sector and attract private investment [8]. In addition, the government signed a Power Purchase Agreement with a solar energy company to provide the country ≥ 20 MW of electricity in 2020 [9]. Despite these efforts, much work remains to be done to improve access to reliable and affordable energy in Liberia. The lack of access to reliable and affordable electricity limits economic growth and development, as businesses and industries cannot operate effectively [10]. The country will need to invest heavily in energy infrastructure to achieve universal access to electricity by 2030 [11].

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The primary energy sources in Liberia are traditional biomass fuels such as firewood and charcoal, which account for more than 80 % of the country's total energy consumption [5,12,13]. Petroleum products, including gasoline and diesel, account for about 10 % of energy consumption, while hydroelectric power accounts for just over 6 % [5]. The remaining energy consumption comes from other sources such as solar energy. Low access to affordable energy and heavy reliance on traditional biomass fuels have significant social and economic implications for Liberia. The combustion of these fuels in poorly ventilated spaces can lead to indoor air pollution, which poses significant health risks [14]. The World Health Organization (WHO) has highlighted the health consequences of indoor air pollution from traditional biomass fuels [15]. Prolonged exposure to indoor air pollution can cause respiratory and cardiovascular diseases and other health issues [1,16], particularly among women and children who spend more time indoors and near the cooking area.

The purpose of this review article is to provide an overview of the energy situation in Liberia, including the various sources of energy used in the country, policies and regulations that govern the energy sector, challenges to energy access, and the potential for renewable energy. By examining these issues in detail, we aim to identify opportunities for improving energy access and promoting sustainable development in Liberia.

2. Methodology

This methodology provides a rigorous and systematic framework for conducting a comprehensive review of Liberia's energy situation, policies, challenges, and opportunities. It ensures a thorough analysis of the available literature and its implications for the country's development.

2.1. Study area

Liberia, located on the west coast of Africa, covers approximately 111,369 square kilometers of diverse terrain, featuring coastal plains, tropical rainforests, rolling hills, and mountain ranges, including Mount Wuteve, its highest peak. As shown in Fig. 1, Sierra Leone borders Liberia to the northwest, Guinea to the north, Ivory Coast to the east, and the Atlantic Ocean to the south and southwest. Liberia boasts a coastline along the Atlantic Ocean. Liberia's estimated population was around 5.4 million as of 2023, with Monrovia as its capital and largest city. The country is home to various ethnic groups, including the Kpelle, Bassa, Gio, Mano, and Krahn, and English serves as the official language, alongside over 20 indigenous languages. Liberia has a developing education system, improving healthcare infrastructure, and an economy historically reliant on agriculture, mining, and forestry, with ongoing efforts to attract investment and foster economic growth.

2.2. Search strategy and data collection

A systematic and exhaustive search strategy was employed to comprehensively review Liberia's energy landscape, policies, challenges, and opportunities. The search was carried out across various databases and relevant sources. A search string comprising keywords and their variations was developed to ensure the capture of a wide range of pertinent literature. This search string included terms such as "Liberia energy," "Liberia electricity," "Liberia power," "Liberia electrification," "Liberian energy policy," "Renewable energy in Liberia," "Liberia energy challenges," "Liberia energy opportunities," "Liberia energy regulations" AND "Liberia energy investment," "Liberia energy access" OR "Liberia energy sources" OR "Energy sector in Liberia" OR "Liberia energy development" and many others.



Fig. 1. Location map of Liberia.

The databases used for this search included Google Scholar, Scopus, Web of Science, and authoritative sources such as the Environmental Protection Agency of Liberia (EPA Liberia) and the World Bank. While there is a scarcity of published articles and literature on energy in the country, our inclusion criteria for studies encompass research articles, reports, and studies on Liberia's energy landscape. These materials must have been published in English and have a publication date from 2010 onward. Any studies failing to meet these criteria were excluded from consideration.

2.3. Data synthesis and presentation

The key findings and common themes extracted from the included studies were summarized, and a thorough analysis of challenges and opportunities was conducted. Studies were grouped by energy sources and policies to facilitate meaningful synthesis. The results were presented using tables, graphs, and narrative summaries to illustrate the key findings effectively.

3. Energy sources in Liberia

Liberia's energy mix has historically depended heavily on biomass, particularly firewood and charcoal, used for cooking and heating [6]. This reliance on biomass has significant environmental and health impacts.

The country also has limited electricity generation capacity, with a merger of hydroelectric power and small-scale diesel generators being the primary sources of electricity [9]. However, the energy combinations can change over time due to various factors such as policy decisions, infrastructure development, and renewable energy investments. Liberia has been working towards diversifying its energy sources in terms of electricity generation. The country's energy merger primarily consists of the following sources.

3.1. Diesel generators

Due to limited grid infrastructure and intermittent power supply, diesel generators play a vital role in meeting electricity demand, especially in urban areas and for commercial and industrial activities [17]. Many businesses, institutions, and households rely on diesel generators as a backup source of electricity to mitigate the impact of power outages and ensure continuous operations. Additionally, in remote regions and areas not connected to the grid, diesel generators serve as the primary source of electricity for communities and businesses.

Initially, the LEC commissioned high-speed diesel generators with a supply capacity of 22 MW in 2015 [18,19], which are now partly decommissioned. The total installed generation capacity in the country has increased from the previous 22 MW to a new capacity of 126 MW during the wet season [2]. This increase was due to the completion of three heavy fuel oil (HFO) thermal plants. These HFO plants serve as cost-effective alternatives to high-speed diesel generators.

Even though non- and- LEC diesel generators accounted for a significant portion of the country's electricity supply. These constituted about 48 % of the total electricity generation in the country [20], indicating its substantial role in meeting the electricity demand. However, the reliance on diesel generators has drawbacks. The cost of diesel fuel, which needs to be imported, can be high and subject to price fluctuations, impacting the electricity affordability for consumers. Moreover, the environmental impact of engines is a concern, as they emit more carbon dioxide (CO₂), contributing to greenhouse gas emissions and climate change, and produce air pollutants that can have adverse health effects [21–23].

3.2. Imported electricity

Liberia imports electricity from neighboring Côte d'Ivoire and

Guinea through the West African Power Pool (WAPP) interconnection [19], which involved 650 km of 225 kV transmission lines [24], with a transit capacity of ≤ 290 MW [25] – making it the largest source of imported electricity for the country in 2020. This medium accounted for a substantial portion of Liberia's overall electricity supply. Furthermore, Liberia has also been exploring electricity imports from Guinea. The two countries have been engaged in discussions and initiatives to establish a cross-border transmission infrastructure, enabling the import of electricity from Guinea to Liberia. While specific data on the amount of electricity imported from Guinea is limited, it signifies the efforts being made to diversify the sources of imported electricity for Liberia.

These electricity imports from neighboring countries play a vital role in meeting Liberia's electricity demand and addressing the challenges its domestic power generation and distribution systems face. By collaborating with neighboring nations and leveraging regional power interconnections, Liberia aims to enhance its energy security and expand access to reliable electricity for its citizens and industries.

3.3. Renewable energy sources

3.3.1. Hydropower

Recently, Liberia's installed electricity capacity reached ~ 200 MW. Most of this capacity comes from HFO and diesel power plants, with limited contributions from hydroelectric and biomass sources [9]. Fig. 2 provides an overview of the installed capacity trend available as an alternative to the grid-based approach and the needs they meet.

Hydropower accounts for ~ 52 % of Liberia's renewable electricity generation (see Fig. 3). The total installed electricity capacity is almost 200 MW. The generation mix is composed of hydropower from the plant at Mount Coffee, with a supply capacity of 88 MW during the wet season and some certain percent from HFO and diesel [13]. The utility LEC also handles the electricity supply of rural areas outside Monrovia through small isolated power systems with a total installed capacity of 13 MW [6, 12].

Electricity generation from renewable energy, including small-medium-scale hydro/marine, accounted for 50 % of total electricity production in 2020 [20], as shown in Table 1. Modern energy services based on electricity and petroleum products are predominantly used for economic production, electricity generation, and transportation, mainly in Monrovia [9]. Liberia's 2020 electricity generation capacity shows the problem of low access to grid-connected power supply from LEC. The gap between grid-connected electricity and that produced by standalone self-generation systems is still wide.

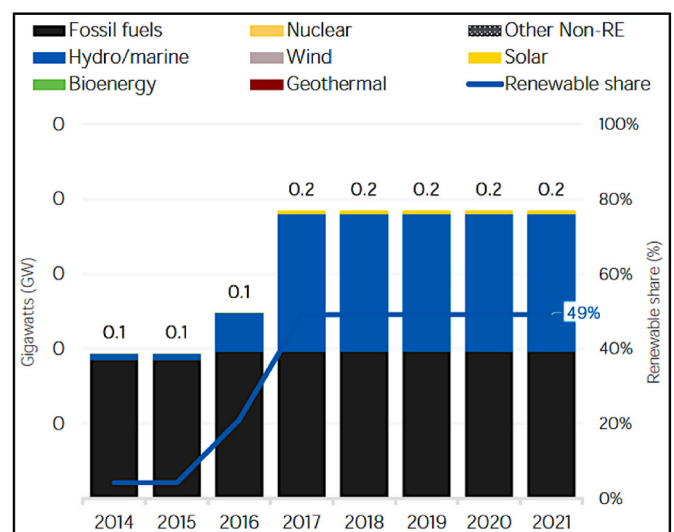


Fig. 2. Installed electricity capacity trend [20].

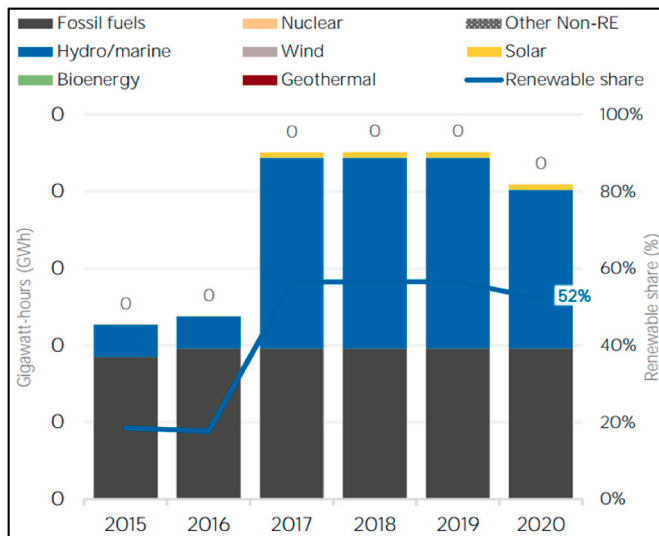


Fig. 3. Electricity generation trend in Liberia [20].

Table 1

Electricity generation in 2020.

Generation	GWh	Percentage (%)
Non-renewable	98	48
Renewable	107	52
Hydro	103	50
Solar	4	2
Wind	0	0
Bioenergy	0	0
Geothermal	0	0
Total	205	100

However, Liberia has other hydroelectric potentials, including the St John River, St Paul River, and Cavalla River, conducive for hydropower development. Reports show that Liberia could be a net exporter of electricity if its hydroelectric potentials are substantially developed

[18].

3.3.2. Wind energy

The wind potential in Liberia is generally higher in the southern and southeastern parts of the country compared to the northern areas. This is due to the influence of the West African Monsoon, which brings stronger winds during the dry season. However, wind speeds in Liberia typically range from 3.0 to 4.5 m/s on average, with higher speeds occasionally reaching up to 5 m/s along the coast [26]. The potential for wind energy development is more favorable in areas such as River Gee, Bong, and Maryland.

It was observed that wind resource assessment studies are essential to accurately determine the wind potential at any specific location in Liberia. The potential wind power density (W/m^2) is shown in different classes used by the National Renewable Energy Laboratory (NREL), measured at a height of 100 m [20]. As exhibited in Fig. 4, the chart shows the distribution of the country's land windiest area with respect to distribution of mean power density and speed. Locations in the first region or below 10 % of windiest places are considered minimal wind resources. These studies consider factors such as topography, local wind patterns, and other meteorological conditions to assess the viability of wind energy projects.

3.3.3. Solar energy

Liberia experiences a humid, tropical climate characterized by consistently moderate temperatures year-round, averaging about 27 °C (81 °F). Rarely does the temperature deviate beyond the range of 20 °C (68 °F) to 36 °C (97 °F) [13].

Recent investigation shows that the monthly average daily solar radiation on horizontal surfaces in Liberia is between 4.0 and 6.0 kWh/m² of solar radiation per day [27]. This level of solar irradiation provides a favorable environment for solar energy projects, including photovoltaic (PV) systems and solar thermal applications [28]. During the dry season, the months of October to February usually show higher levels of solar radiation, with global horizontal irradiation (GHI) levels potentially reaching up to 5.2 kWh/m²/day or more. This results in higher energy production from PV systems, as indicated in Fig. 5. In contrast, the wet season is characterized by increased cloud cover with potential rainfall,

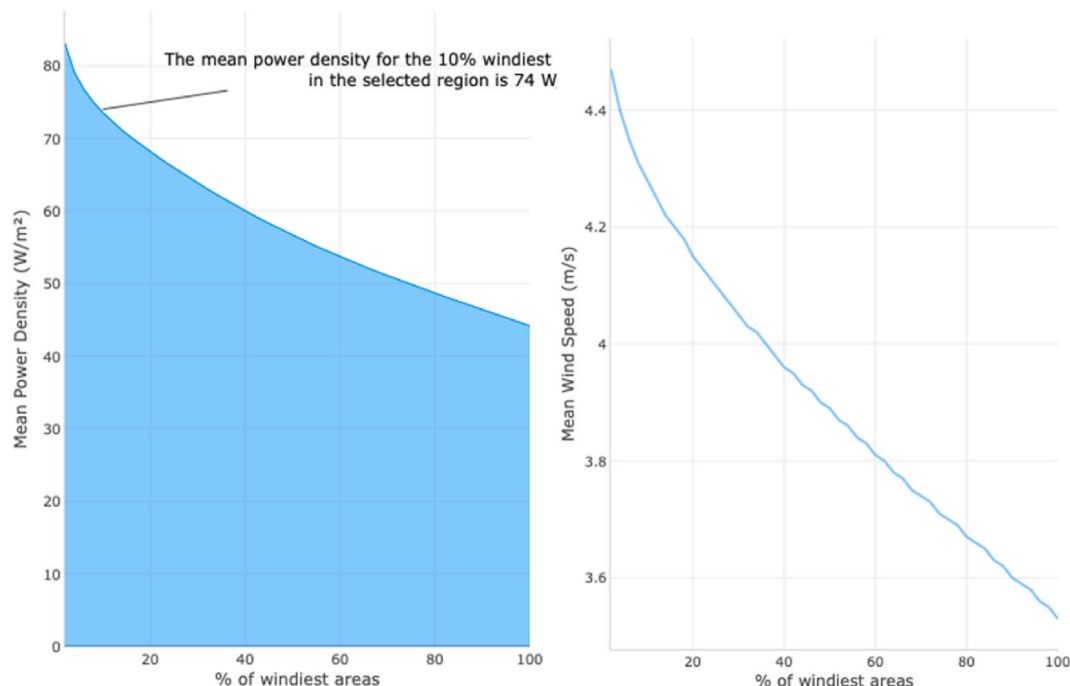


Fig. 4. Distribution of wind potential in Liberia [26].

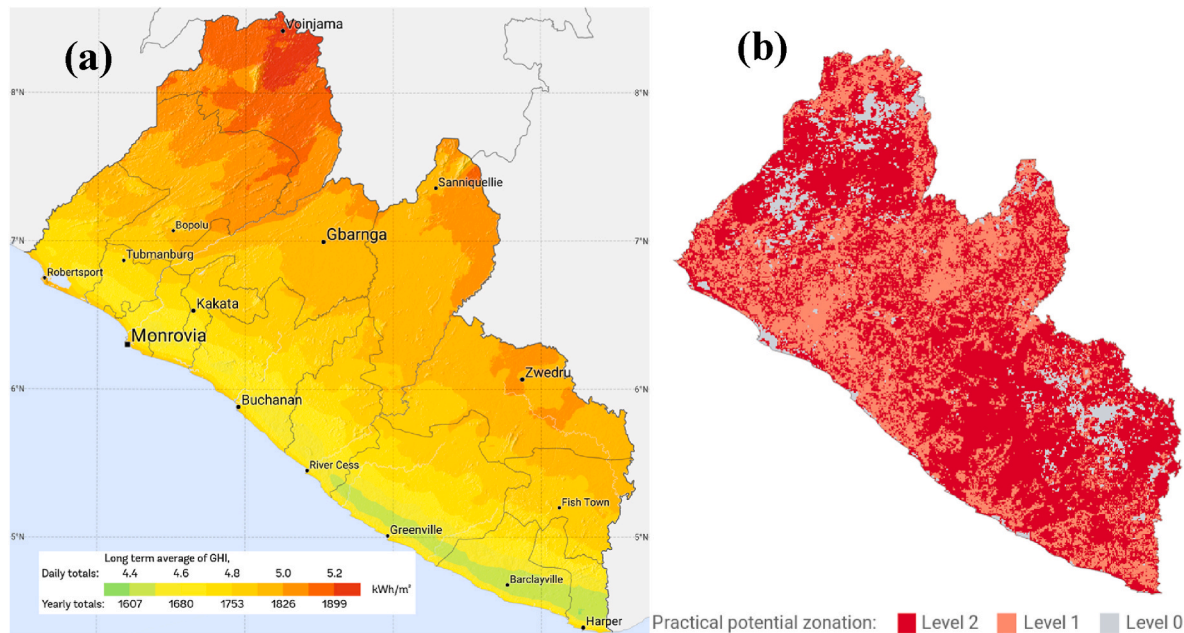


Fig. 5. Long-term average annual profiles of (a) GHI and (b) practical PVOUT in Liberia [27].

which can reduce the amount of solar irradiance reaching the PV panels. As a result, PV power output (PVOUT) during this period may be lower compared to the dry season, ranging from around ≤ 3.6 to ≤ 4.0 kWh/m²/day (see Table 2) [27].

Inland areas of Liberia receive slightly greater insolation than coastal areas, as recently reported by IRENA [20]. Additionally, the annual average of direct normal irradiation (DNI) is 1168 kWh/m²/year. The country's abundant and stable solar energy potential contributes to an average of 1712 kWh/m²/year [17]. This level of solar radiation can generate ~1400 to 1500 kWh/kWp. Fig. 6 shows Liberia's solar energy potential because it falls in the equatorial belt and receives the second-highest annual solar radiation on earth [20]. Despite these enormous solar energy potentials, not much has been done to generate electricity from solar [29].

3.3.4. Renewable energy consumption (TFEC) in Liberia

The residential sector in Liberia heavily relies on traditional biomass, primarily wood and charcoal, for cooking and heating [6]. According to IRENA, in 2019, biomass accounted for ~100 % of the total final energy consumption (TFEC) in Liberian households [20], as illustrated in Fig. 7. The country's industrial and transportation sectors rely on fossil fuels, mainly gasoline and diesel. IRENA data indicates that bioenergy accounted for a negligible amount of the renewable energy consumption TFEC in 2019.

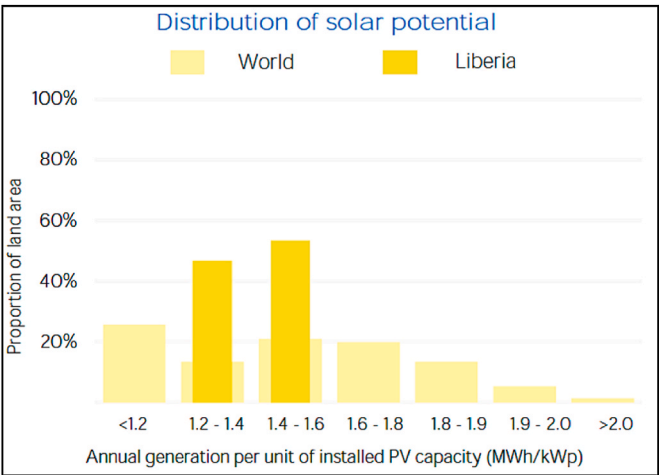


Fig. 6. Distribution of solar potential in Liberia [20].

3.4. Thermal power plant

Thermal power plants have been important to Liberia's electricity generation infrastructure. These plants utilize heavy fuel oil (HFO), diesel, or other liquid fuels as their primary energy source to produce

Table 2				
Distribution of photovoltaic power output.				
kWh/kWp	60.6 %	93.0 %	100.0 %	of evaluated area
over 4.0	11.1 %	15.7 %	17.7 %	<div><div></div><div></div><div></div></div>
4.0 — 3.8	36.2 %	53.9 %	58.5 %	<div><div></div><div></div><div></div></div>
3.8 — 3.6	11.3 %	19.8 %	20.2 %	<div><div></div><div></div><div></div></div>
below 3.6	2.0 %	3.6 %	3.6 %	<div><div></div><div></div><div></div></div>
Practical potential: ■ Level 2 ■ Level 1 ■ Level 0				

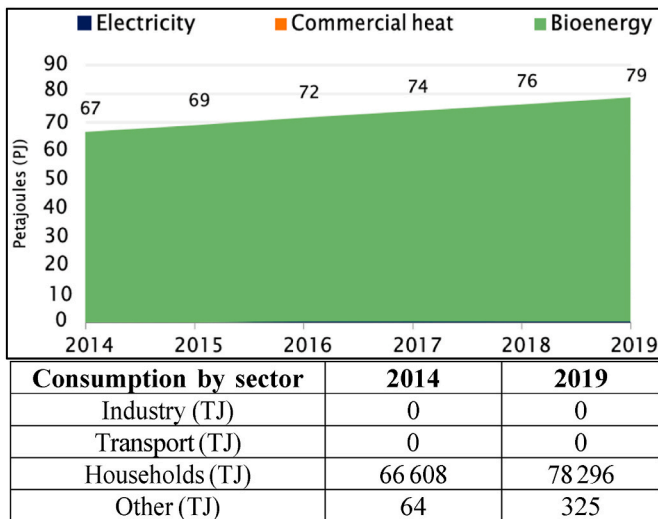


Fig. 7. Renewable energy consumption trend from 2014 to 2019.

electricity.

The reliance on imported fuels for thermal power generation poses several challenges for Liberia [6,17]. There is a significant cost associated with importing these fuels. The prices of HFO, diesel, and other liquid fuels are subject to global market fluctuations, making the cost of electricity generation susceptible to changes in fuel prices. This dependency on imported fuels exposes Liberia's energy sector to price volatility and financial risks [8], which can affect the affordability and stability of electricity supply. Energy security is another concern associated with the reliance on imported fuels. Liberia's ability to ensure a consistent supply of imported fuels for thermal power plants is vulnerable to factors beyond its control, such as geopolitical tensions, disruptions in global fuel supply chains, or changes in international trade policies. Any interruption or delay in the availability of imported fuels could lead to power shortages and affect the reliability of the electricity supply in the country.

To overcome these challenges, Liberia has been exploring alternative solutions to reduce its dependency on imported fuels for thermal power generation. One strategy is to diversify the energy mix by increasing the share of domestic renewable energy sources, such as solar and wind power, for electricity generation. By harnessing these indigenous and sustainable energy resources, Liberia can decrease its reliance on imported fuels and enhance its energy security. Furthermore, energy efficiency measures and initiatives can play a vital role in reducing the overall electricity demand [2,8], reducing the need for thermal power generation. Implementing energy efficiency practices in various sectors, such as buildings, industries, and transportation, can help optimize energy use and decrease dependence on imported fuels.

Liberia may also explore more regional energy cooperation and integration opportunities, such as developing cross-border transmission infrastructure and establishing power exchange mechanisms with neighboring countries. These initiatives can facilitate the exchange of electricity resources, promote regional energy trade, and enhance energy security by diversifying power generation sources.

4. Energy access in Liberia

In Liberia, the availability of grid-connected electricity is limited, which has one of the world's lowest electricity consumption rates with <50 kWh per capita per year. As shown in Fig. 8, it was estimated that only about 28 % of the population has access to modern electricity [20]. Out of the 28 % of the population with access to electricity, a large portion is dropped in urban areas and the low portion in rural areas [5]. The national electricity grid is characterized by aging infrastructure,

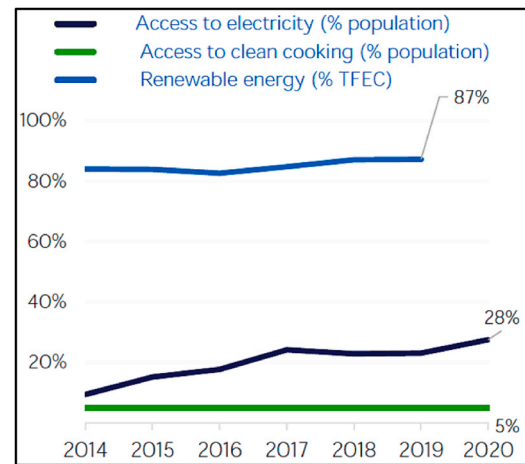


Fig. 8. The population served with electricity connections in Liberia [20].

frequent power outages, and an inadequate distribution network, which results in unreliable electricity supply. Several factors contribute to this situation, including limited grid infrastructure and the high costs of connecting remote communities.

Fig. 9 shows that the LEC grid reaches limited regions in Liberia. As evident from the figure, Liberia's current electricity grid infrastructure is constrained in its capacity and coverage, necessitating substantial expansion and modernization efforts to cater to the increasing electricity demand across the nation. Detailed studies and future infrastructure development plans are essential to facilitate the proposed enhancements to the grid system. These plans may encompass a range of initiatives, such as extending transmission lines to underserved regions, establishing new substations, and expanding distribution networks. By undertaking these measures, Liberia aims to bolster its electricity grid, improve accessibility, and provide a reliable power supply to a larger population.

Expanding the power infrastructure to rural areas, which often need more proper road networks and other basic facilities, can be prohibitive.

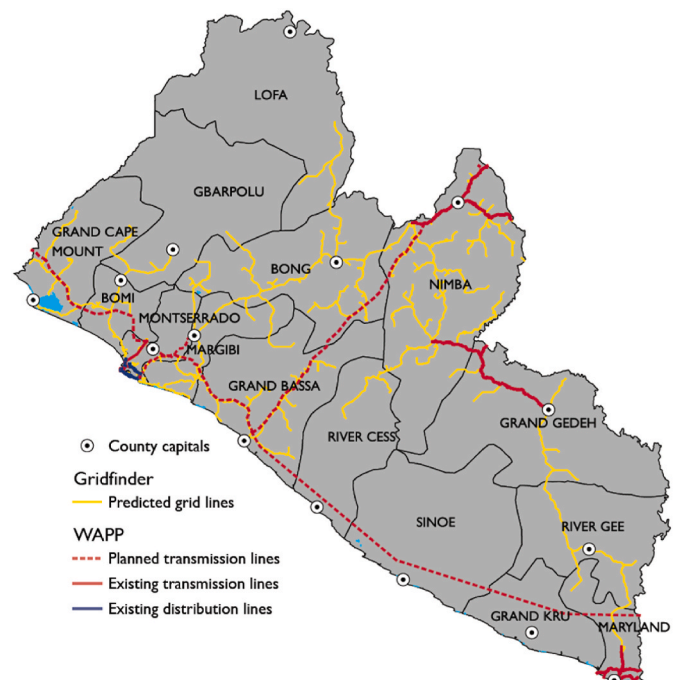


Fig. 9. Electricity grid in Liberia from existing, planned, predicted lines [19].

The expense of installing power lines and transformers over long distances, combined with the low population density and diminutive economic viability of these areas, makes it financially unsustainable to connect them to the centralized grid. To overcome these challenges, the Liberian government should implement various strategies to increase electricity access in collaboration with international organizations and development partners. These strategies include off-grid and decentralized solutions, renewable energy development, public-private partnerships, policy and regulatory reforms, and International support and funding.

5. Challenges and opportunities to energy access in Liberia

5.1. Challenges

The primary challenge to energy access in Liberia is the limited and underdeveloped energy infrastructure. The lack of adequate power generation, transmission, and distribution systems contributes to this low access rate. The electrification rate is significantly lower in rural areas, where most of the population resides [17]. The country's energy infrastructure faces numerous deficiencies, including outdated equipment and insufficient capacity to meet the growing electricity demand. Additionally, Liberia's heavy dependence on imported fossil fuels is another significant challenge. The country relies on imported petroleum products for $\geq 90\%$ of its energy consumption. This reliance on imports increases energy costs and exposes Liberia to the volatility of global fuel prices. The high cost of imported fuels poses a barrier to energy access, especially for low-income households who struggle to afford electricity services. Fig. 10 highlights some of the challenges and opportunities related to energy sources in Liberia.

Financial constraints pose another significant challenge. Insufficient funding and investment in the energy sector limit the country's ability to develop and improve its infrastructure. In recent years, Liberia has allocated only a small percentage of its national budget to the energy sector, hindering progress in expanding energy access [30]. There is a need for more institutional capacity and robust governance to ensure effective planning, policy implementation, and regulation in the energy sector.

Moreover, the affordability of electricity remains a major concern. Energy costs in Liberia are high compared to the average income levels, making electricity unaffordable for many Liberians. The cost of electricity can be up to two times higher in Liberia compared to neighboring

countries. The tariffs imposed by the LEC are USD 0.50 per kWh, resulting in significant consumer expenses [9]. Furthermore, electricity in Liberia is predominantly generated from fossil fuels, contributing to environmental concerns and potential price volatility.

5.2. Opportunities for overcoming challenges and expanding access to energy

Liberia has significant opportunities for improving energy access, including abundant renewable energy potential, international support and investments, public-private partnerships, off-grid and mini-grid solutions, and energy efficiency measures. Leveraging these opportunities can lead to improved energy access, enhanced livelihoods, and sustainable development in the nation.

Liberia has substantial renewable energy generation capacity, mainly from solar and hydro sources. According to estimates by the World Bank Group, Liberia has a solar potential of ~ 5.4 kWh/m² per day, with up to 6.5 h of sunshine per day on average [27]. Similarly, Liberia has considerable hydroelectric power potential due to its numerous rivers and other resources. The country's rivers offer opportunities for small to medium-scale hydropower projects. Liberia also has abundant biomass resources, with estimates suggesting that the government can produce up to 27,452 GWh of electricity from biomass annually [4]. Expanding these resources can provide sustainable and decentralized energy solutions, particularly in rural and remote areas.

Additionally, adopting off-grid and mini-grid solutions presents another opportunity for energy access in Liberia [19]. Given the challenges of extending the central grid to remote areas, off-grid and mini-grid systems offer cost-effective alternatives. Some of the energy sources utilized in Liberia are summarized in Table 3.

Liberia benefits from international support and investments in energy access projects. The United Nations Development Programme (UNDP), the African Development Bank (AfDB), and the World Bank are among the organizations that provide financial and technical support to Liberia's energy sector. These partnerships create opportunities for funding, expertise, and technology transfer, facilitating the implementation of energy projects in the country.

The government and private sector collaboration can leverage both sectors' strengths to develop and operate energy infrastructure, attract investments, and ensure sustainable service delivery. PPPs can help address energy access projects' financial and technical challenges, leading to more efficient and effective implementation.

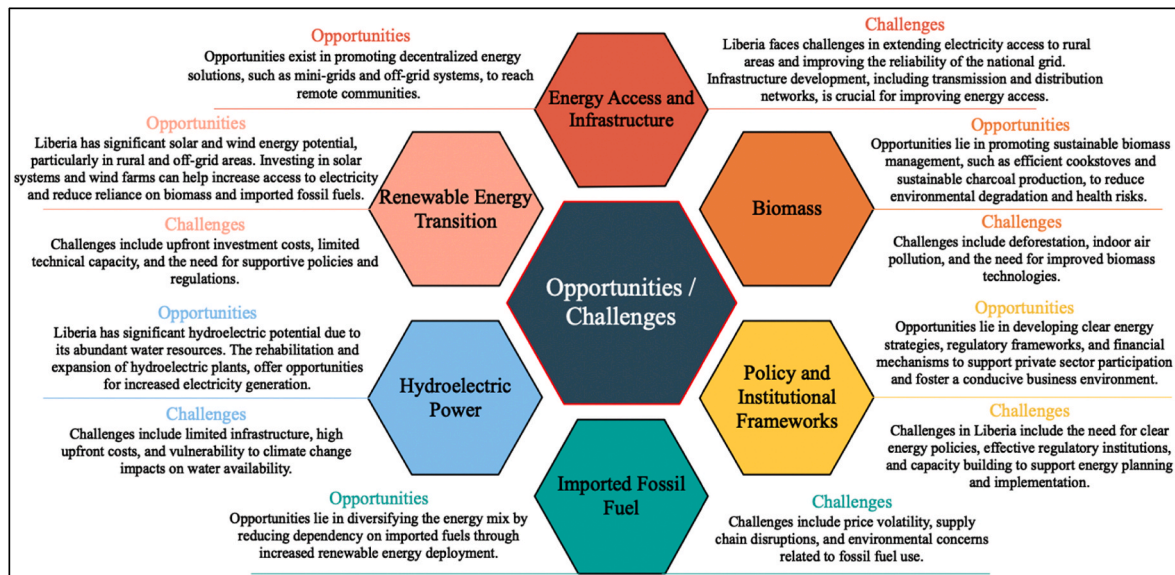


Fig. 10. An overview of the opportunities and challenges related to energy sources in Liberia.

Table 3
Various energy sources in Liberia.

Sources	Details	Advantages	Disadvantages
Traditional Biomass Fuels	Heavy reliance on traditional biomass is primarily due to limited access to modern energy sources, especially in rural areas.	There are widely available and low-cost, derived from local resources. It can be sustainable if managed properly.	Health risks associated with indoor air pollution and respiratory diseases. Environmental concerns, including deforestation and land degradation.
Petroleum Products	Petroleum products, including gasoline and diesel, contribute a significant to Liberia's energy consumption. These fuels are primarily used in transportation, power generation from small diesel and gasoline generators and industrial applications. Liberia is a net importer of petroleum products, relying on imports to meet its energy needs.	It has a high energy density and is convenient for transportation and electricity generation.	Reliance on imported fuels, vulnerability to price fluctuations, and contribution to greenhouse gas emissions.
Hydroelectric Power	The main hydroelectric facility in the country is the Mount Coffee Hydropower Plant, with a capacity of 88 MW [17]. Liberia has untapped potential for further hydroelectric power development, but still needs to be utilized.	Renewable and low-carbon energy source, potential for large-scale electricity generation.	Dependence on suitable water resources, environmental impacts on river ecosystems, and vulnerability to droughts.
Renewable Energy Potential	Liberia also utilizes other energy sources on a smaller scale. These include small-scale renewable energy systems such as solar and biomass. However, the contribution of these sources to the overall energy mix in Liberia is limited.	Abundant and clean energy sources, reducing reliance on fossil fuels. Potential for decentralized energy systems and off-grid solutions.	Varied challenges include high upfront costs, intermittent availability (solar and wind), and the need for infrastructure development.

5.3. Analysis of the impact of energy poverty on Liberia's development

Energy poverty significantly impacts Liberia's development, as it hinders economic growth, social development, and environmental sustainability [2]. It affects social development, particularly in education, health, and gender equality. Lack of electricity in schools limits students' learning opportunities and affects the quality of education. Energy poverty also affects gender equality, as women and girls are disproportionately affected by lack of access to electricity. Women and girls spend significant time and effort collecting firewood and other

traditional fuels for cooking, which affects their health, education, and economic opportunities.

The lack of access to reliable and affordable energy affects the ability of communities to access essential services, such as healthcare, education, and communication. Health centers and schools that lack electricity often have limited or no capacity to operate effectively, leading to reduced quality of healthcare and education. The impact of energy poverty on education is particularly significant, with many children unable to study after dark due to the lack of electricity, reducing their ability to learn and perform well in school. Furthermore, the lack of access to communication, such as television, radio, and the internet, affects the ability of communities to access information, including news, weather updates, and emergency alerts.

While the electricity output from mini-grid systems in rural Liberia might be modest, these systems play a pivotal role in mitigating the energy access challenges faced by remote communities [31]. Through localized and decentralized electricity generation and distribution, they provide valuable solutions. These mini-grids commonly rely on renewable energy sources such as solar, hydro, or biomass [19]. For a glimpse of some mini-grid initiatives in rural Liberia, refer to Table 4.

6. Overview of energy-related policies, regulations, and initiatives in Liberia

Over the years, the government has embarked on numerous policy initiatives and regulatory measures to tackle the issues surrounding energy access, sustainability, and overall development. Conversely, implementing these energy-focused policies in Liberia has encountered many challenges, primarily rooted in the nation's economic, social, and infrastructural circumstances. Additionally, many energy-related policies and regulations have been in place for a long time and need proper evaluations or updates (see Table 5). This can lead to several issues, including inefficiencies, outdated practices, and missed opportunities for adopting new technologies and approaches. However, a situation like this arises for several reasons. Firstly, the rapid pace of technological advances in the energy sector can outstrip the ability of policies to keep up, rendering them less effective or irrelevant. Secondly, the inertia of political systems can make introducing new policies or revising existing ones challenging, especially if powerful interests are involved, or immediate benefits are absent.

Moreover, the absence of accurate and up-to-date data significantly hinders practical policy evaluation. Governments and regulatory bodies need more resources, expertise, or funding to conduct comprehensive assessments, perpetuating outdated policies. Several solutions can be considered to address these challenges, as outlined in Table 5. Regular reviews of energy policies at scheduled intervals could ensure that they remain relevant and practical in light of changing circumstances.

The outcomes of this study, elucidating Liberia's energy dynamics and strategies, extend beyond its borders, offering pertinent recommendations for researchers, planners, and engineers in analogous regions globally. Researchers can explore the effects of blended fuels on engine performance and emissions, emphasizing the potential for improved efficiency. Planners are encouraged to shift policies towards low-aromatic, low-sulfur alternative jet fuels and promote investment in domestic renewable resources for enhanced energy sustainability. As exemplified by Liberia's import initiatives, regional energy cooperation should be considered to bolster energy reliability. Engineers are advised to optimize energy mixes, incorporating wind, biomass, and solar energy into existing grids, and developing mini-grid initiatives for rural areas to address energy access challenges. These generalizable recommendations contribute to a global pursuit of sustainable, efficient, and accessible energy solutions.

7. Conclusion

This study provides a comprehensive overview of the energy

Table 4
Some of the mini-grid systems in rural Liberia.

Community	County	Technology	Funder	Implementer	Capacity	Beneficiaries	Start date	Status	Reference
Yandohun hydropower mini-grid	Lofa	Hydro	World Bank	RREA	60 KW	120 households	2013	Operational	[32]
Electricity from rubber wood chips in Kwendin	Nimba	Biomass (wood)	USAID	NRICA	100 KW	≥248 households, a clinic, and a school	2016	Operational	[33]
Palm oil generated electricity in Sorlumba	Lofa	Biomass (palm oil)	USAID	NRICA	25 KW	≤205 households	2017	almost operational	[34]
Totota	Bong	solar/diesel	–	–	25 KW	–	2016	Operational	[13]
Mini-hydropower/Diesel grid	Lofa	hydro/diesel	World Bank	RREA	2.5 MW	10,000 households	2019	Planned	[31]
Langbemba	Lofa	solar	EU	PLAN & VOSIEDA	31.1 KW	–	2017	Needs repair after fire	[13]
Taninahun	Lofa	solar	EU	PLAN & VOSIEDA	28.5 KW	–	2017	Operational	[13]
Mamikonedu	Lofa	solar	EU	PLAN & VOSIEDA	25.5 KW	–	2017	Operational	[31]
Koiyama	Lofa	solar	EU	PLAN & VOSIEDA	22.5 KW	–	2017	Operational	[19]

Table 5
Prominent challenges and implications of energy-related policies in Liberia.

Policies and Regulations	Year	Initiatives Aim	Prominent Challenges	Implications
National Energy Policy (NEP)	2009	The policy aims to increase energy access, promote renewable energy sources, and enhance energy efficiency across sectors.	<ul style="list-style-type: none"> Lack of accurate and up-to-date energy data can hinder policy formulation, monitoring, and evaluation. 	<ul style="list-style-type: none"> The government of Liberia (GoL) must conduct regular policy reviews to identify overlaps and gaps and make necessary adjustments.
Rural and Renewable Energy Agency (RREA)	2015	The RREA was established to implement rural electrification projects and promote renewable energy solutions in off-grid and underserved areas.	<ul style="list-style-type: none"> Lack of coordination between government departments and agencies results in conflicting priorities and disjointed efforts. 	<ul style="list-style-type: none"> GoL must encourage local manufacturing of energy components to reduce dependence on imports.
Liberia Electricity Regulatory Commission (LERC)	2015	To accelerate universal access to affordable, reliable, and safe electricity services for consumers in a competitive market, ensuring adequate electricity supply for sustained economic growth and enhanced quality of life.	<ul style="list-style-type: none"> Insufficient funds to upgrade and maintain power distribution networks in rural areas, resulting in unreliable electricity supply. 	<ul style="list-style-type: none"> To reach remote areas, GoL must invest in decentralized energy solutions, such as mini-grids and off-grid systems.
Renewable Energy and Energy Efficiency Policy and Action Plan (REEEP)	2015	To increase national awareness of renewables and energy efficiency and remove barriers to investment and market development through a national policy instrument.	<ul style="list-style-type: none"> Adopting new technologies and innovative solutions may require overcoming barriers such as high upfront costs, lack of local expertise, and resistance to change. 	<ul style="list-style-type: none"> Tailor policies to address specific challenges in different regions, considering local needs and resources.
Sustainable Energy for All (SE4ALL) Action Agenda	2015	This focus on affordable, sustainable, environmentally friendly modern energy services for urban and rural areas, enhancing socio-economic opportunities and improving quality of life.	<ul style="list-style-type: none"> Political changes and shifts in government priorities can disrupt policy continuity and hinder long-term planning. Lack of community involvement can lead to delays, disputes, or even cancellations. Weak regulatory capacity can lead to non-compliance and undermine policy objectives. 	<ul style="list-style-type: none"> Invest in data collection by collaborating with research institutions and NGOs to conduct energy-related surveys and studies. Implement community engagement programs to educate and involve residents in project planning.
Rural Energy Strategy and Master Plan (RESMP)	2016	This RESMP serves as a strategic roadmap for providing access to improved energy services and integrating energy into Liberia's rural development programs and activities.	<ul style="list-style-type: none"> Remote communities lacking proper road access struggle to receive equipment and materials needed for energy projects, causing delays. 	<ul style="list-style-type: none"> The government must implement a monitoring and reporting system to track compliance and address violations. The government must actively seek international support and partnerships to secure funding for energy projects. Invite international experts to provide technical guidance, support and develop a skilled workforce for local professionals.

situation in Liberia, highlighting the challenges and opportunities the country faces in its quest to improve energy access and promote sustainable development. Like many developing nations, Liberia struggles with limited access to reliable and affordable energy, primarily relying on traditional biomass and imported fossil fuels. Overcoming these challenges requires strategic energy mix diversification through increased utilization of indigenous renewable resources such as solar and biomass energy. These resources hold immense potential, with Liberia boasting abundant solar irradiation and promising bioenergy in specific regions.

Efforts to expand energy access also hinge on vital factors such as international partnerships, public-private collaborations, and innovative off-grid and mini-grid solutions. The support of UNDP, AfDB, and the World Bank aids in funding, technology transfer, and expertise

crucial for implementing energy projects. Public-private partnerships offer avenues for efficient infrastructure development and investments, while decentralized solutions cater to remote areas where traditional grid extension is unfeasible.

Insufficient access to electricity limits learning affects healthcare quality, and hampers women's empowerment. However, initiatives like mini-grid systems exemplify localized solutions that contribute to a brighter future for rural communities. Regular reviews and updates of policies, informed by accurate data and forward-looking strategies, are essential to ensure that the energy sector remains aligned with changing circumstances and technological advancements.

In the journey to expand energy access and secure sustainable development, Liberia has many opportunities to harness its renewable potential, foster international collaboration, and embrace innovative

solutions. By addressing challenges through strategic policies, investments, and partnerships, Liberia can pave the way for a brighter and more electrified future for its citizens.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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