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INTERNATIONAL MASTER PROGRAMME IN ENERGY AND GREEN HYDROGEN (IMP-EGH)

Master Thesis

Speciality: Economics/Policies/Infrastructures and Green Hydrogen Technology

Topic: The Economic and environmental implications of E-ammonia and E-methanol production in three industrial sites in Liberia, Kenya and Egypt

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Dedication

With utmost honor and deep respect, I dedicate this thesis to the cherished memory of my beloved parents, the late Mrs. Victoria Maima Monger Morgan and Mr. Stephen M. Sellie, Sr., whose invaluable support shaped my entire academic journey. Although they are no longer alive to witness the fulfilment of my long-standing goal, "transforming natural phenomena into physical functions for the benefit of humanity," their enduring love and guidance will forever live in my heart.

I also dedicate this work to my sons, Spriggs and Stephen, whose courage and unwavering support sustained me throughout my time away from Liberia. It is my fervent prayer that this thesis serves as a beacon for them to emulate, inspiring them to go even further in advancing the dream I have long pursued.

Lastly, this thesis is dedicated to the emerging generation of scientific scholars, with the hope that they will build upon these concepts, create new ones, and continue the quest of transforming natural phenomena into practical functions for the betterment of humankind.

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Acronyms and Abbreviations

CAPEX:	Capital Expenditure
CF :	Capacity Factor
CIE :	Compagnie Ivoirienne d'Électricité
CLSG :	Côte d’Ivoire–Liberia–Sierra Leone–Guinea electricity network interconnection project
CO_2:	Carbon Dioxide
CO_2e:	CO_2 equivalent
DAC:	Direct Air Capture
EEHC:	Egyptian Electricity Holding Company
EEUN:	Egyptian Electrical Unified Network
EETC:	Egyptian Electricity Transmission Company
EIA:	Energy Information Administration
EPA:	Environmental Protection Agency
€/a:	euro per annum
€/Kg:	euro per Kilogram
FAO:	Food and Agriculture Organization
FFI:	Fortescue Future Industries
FI:	Falkenmark Index
g/mol:	gram per mole
GDP:	Gross Domestic Product
GHG:	Greenhouse Gas
GHI:	Global Horizontal Irradiation
GSP:	Graduate school program

GW:	Gigawatt
GWh:	Gigawatt hour
HFO:	Heavy Fuel Oil
h/d:	hour per day
Km:	Kilometer
Km^2:	Kilometer Square
KIPPRA:	Kenya Institute for Public Policy Research and Analysis
KNBS:	Kenya National Bureau of Statistics
Kw:	Kilowatt
KWh/KWp:	Kilowatt hour per Kilowatt peak
$KWh/m^2/day$:	Kilowatt hour per square meter per day
$KWh/m^2/year$:	Kilowatt hour per square meter per year
LCA:	Life Cycle Assessment
LCOE:	Levelized Cost of Energy
$LCO_{E\text{-}MeOH}$:	Levelized Cost of E-Methanol
$LCO_{E\text{-}NH3}$:	Levelized Cost of E-Ammonia
LEC:	Liberia Electricity Corporation
LERC:	Liberia Electricity Regulatory Commission
LTWP:	Lake Turkana Wind Power Project
M^3:	Cubic meter
MCM:	Thousand cubic meters
MDO:	Marine diesel oil
MGO:	Marine gas oil
Mt:	Million ton

MW:	Megawatt
MWh/KWp:	Megawatt hour per Kilowatt peak
N_2:	Nitrogen
N_2O:	Nitrous Oxide
NH_3:	Ammonia
NREL:	National Renewable Energy Laboratory
OPEX:	Operation Expenditure
P2X:	Power to X
PSA:	Pressure Swing Absorption
PtX:	Power to X
PV:	Photovoltaic
PVOUT:	Photovoltaic power output
RES:	Renewable Energies
TEC:	Total Energy Consumption
TFEC:	Total Final Energy Consumption
TJ:	Terajoule
TRL:	Technology Readiness Level
TRWR:	Traveling-Wave Reactor
TWh:	Terawatt hour
USAID:	United States Agency for International Development
W:	Watt
W/m^2:	Watt per square meter
WAPP:	West Africa Power Pool

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Abstract

With response to the urgent global mandate to mitigate climate change and its far-reaching consequences, governments, industry leaders, and research institutions are increasingly exploring adaptive and sustainable energy solutions. The maritime transport sector, recognized as a significant contributor to global greenhouse gas emissions has emerged as one of the main focus areas for decarbonization. This study investigates the economic and environmental implications of two energy carriers (e-methanol and e-ammonia) as alternative marine fuels, with a specific focus on three industrial production sites located in Kenya, Egypt, and Liberia.

Employing a mixed-methodological approach, the study integrates quantitative modelling with qualitative case analysis. Key evaluation parameters include renewable energy potential, infrastructure requirements, water availability, land tenure considerations, and the application of carbon capture and nitrogen separation technologies. Operational expenditure, revenue streams, and levelized cost of e-methanol and e-ammonia are assessed to generate realistic profitability estimates.

We use the AnyLogic simulation tool to perform system dynamics modelling, offering an integrated perspective that encompasses both engineering and economic dimensions. This modelling approach enhances the robustness and applicability of the findings, contributing valuable insights to the strategic deployment of e-fuels in the maritime sector.

A key finding of the research is that green hydrogen represents a viable decarbonization pathway that facilitates sector coupling across the maritime transport domain. Leveraging this insight, the study conducts a cradle-to-gate and economic analysis of e-methanol and e-ammonia production, identifying the fuel that yields the most favorable balance of profitability and environmental benefit for shipping. Among the three sites examined, Liberia demonstrates the highest production output and profitability, outperforming Kenya and Egypt in overall viability.

Key words: Climate change mitigation; maritime decarbonization; green hydrogen; dynamic system modelling; economic analysis.

Résumé

En réponse au mandat mondial urgent visant à atténuer le changement climatique et ses vastes conséquences, les gouvernements, les dirigeants industriels et les institutions de recherche explorent de plus en plus des solutions énergétiques adaptatives et durables. Le secteur du transport maritime, reconnu comme un contributeur majeur aux émissions mondiales de gaz à effet de serre, est devenu l'un des principaux axes de décarbonation. Cette étude examine les implications économiques et environnementales de deux vecteurs énergétiques (l'e-méthanol et l'e-ammoniac) en tant que carburants marins alternatifs, en se concentrant spécifiquement sur trois sites industriels situés au Kenya, en Égypte et au Libéria.

En adoptant une approche méthodologique mixte, l'étude combine la modélisation quantitative avec l'analyse qualitative de cas. Les principaux paramètres d'évaluation incluent le potentiel en énergies renouvelables, les exigences en matière d'infrastructures, la disponibilité en eau, les considérations relatives à la tenure foncière, ainsi que l'application des technologies de capture du carbone et de séparation de l'azote. Les dépenses d'exploitation, les flux de revenus et le coût nivelé de production sont évalués de manière systématique afin de générer des estimations réalistes de rentabilité.

L'outil de simulation AnyLogic est utilisé pour réaliser une modélisation dynamique des systèmes, offrant une perspective intégrée englobant à la fois les dimensions techniques et économiques. Cette approche de modélisation renforce la robustesse et l'applicabilité des résultats, apportant des éléments précieux à la mise en œuvre stratégique des e-carburants dans le secteur maritime.

Un résultat clé de cette recherche est que l'hydrogène vert constitue la seule voie de décarbonation viable permettant un couplage sectoriel entre les domaines du transport, du résidentiel et de l'industrie. Fort de ce constat, l'étude réalise une analyse économique et du berceau à la porte de la production d'e-méthanol et d'e-ammoniac, identifiant le carburant offrant le meilleur équilibre entre rentabilité et bénéfice environnemental pour le transport maritime. Parmi les trois sites étudiés, le Libéria présente la production et la rentabilité les plus élevées, surpassant le Kenya et l'Égypte en termes de viabilité globale.

Mots-clés : Atténuation du changement climatique ; décarbonation maritime ; hydrogène vert; modélisation dynamique des systèmes ; analyse économique.

1.0 Introduction

This thesis is beneficial to prospective investors in green hydrogen and e-fuels in West Africa, as it highlights the profitability, scalability, and regional opportunities of e-methanol and e-ammonia production with Liberia emerging as the most viable site. The information and analysis presented provide concepts for policymakers, maritime industry stakeholders, and research institutions by identifying the infrastructure requirements, resources, and technological considerations necessary to support large-scale deployment of e-methanol and e-ammonia. The study also equips decision-makers with the evidence needed to align investments and strategies with the global mandate for maritime decarbonization.

As the concept of Sector Coupling (Letmathe, n.d. p.1) is gaining international recognition, so is Power-to-X (P2X) technology emerging as a viable platform for end-use dispatch, as well as for providing a feasible but highly capital-intensive decarbonization pathway to produce green fuel and chemicals. On the other hand, Power-to-X technologies address two key challenges: utilizing surplus green electricity generated on sunny and windy days, and enabling its use across sectors such as building heating, transport, and chemical production (US Equal Employment Opportunity Commission, 2019)

This paper evaluates the economic and environmental implications of e-ammonia and e-methanol production in three industrial sites situated in Monrovia, Bamburi and El Arish. These locations were chosen based on the feedstocks (water, CO_2, N_2, etc) required, land availability, limited geopolitical risks and distance from production site to seaports. We will conduct cost and environmental analysis of these e-fuels using cradle-to-gate boundaries. Our storyline envisages the use of these e-fuels for the shipping industry. The CO_2 needed for the production of e-Methanol will be obtained by Direct Air Capture Technology from El Arish Cement in Egypt, Bamburi Cement in Kenya and Cemenco in Liberia while Nitrogen will be obtained from air through a commonplace Pressure Swing Adsorption (PSA) Technology.

To answer the research question, the two P2X carriers (e-Methanol e-ammonia) are examined for the replacement of bunker fuel currently used in shipping.

Through AnyLogic, the study models the value chain through renewable energy production and distribution, CO_2 and N_2 capture; it assesses the environmental impact through tons of avoided CO_2 and evaluates the OPEX, CAPEX, revenue and operating profit for the production of e-Methanol and e-ammonia for use in shipping.

Electrolyzers are a core component of all P2X systems since they allow for the production of green hydrogen, a key ingredient in the synthesis of several green fuels. There are three (3) main types of electrolyzers: PEM, alkaline and solid oxide electrolyzers.

Polymer electrolyte membrane (PEM) electrolyzers are compact, operate flexibly, exhibit high production rates, produce hydrogen at purity, and have high efficiency (Escobar-Yonoff et al. 2021 p.1). Also, PEM shows greater responsiveness to fluctuating power inputs, which are typical of renewable energy sources (Buma, Peretto, and Matar 2023 p.5). We used PEM electrolyzers for modelling and considered a site of off-grid H_2 production linked to solar and / or wind power sources.

According to a recent report by the International Renewable Energy Agency (IRENA), by 2050, the transportation sector will consume a significant amount of renewable energy sources (RES), and hydrogen will play a key role in bringing RES to this industry. Although the technologies for creating this new carbon-free mobility are already available, efforts must be made to lower the costs of the hydrogen supply chains (Silvestri et al., 2022 p.2).

1.1 Current Fuels used in Shipping

Achieving decarbonization in the maritime industry is an essential objective, attainable through the transition to low and zero-carbon marine fuel alternatives. Today, most ships use Heavy Fuel Oil (HFO) or bunker fuel.

Currently, approximately 96% of marine bunker fuels consist of heavy fuel oil (HFO), marine diesel oil (MDO), or marine gas oil (MGO), all of which are carbon-intensive. The combustion of HFO alone results in emissions of up to 3.114 kg of CO_2 per kilogram of fuel burned (Energy 2021 p.1).

As a consequence, the shipping industry contributes approximately 2.8% of global annual greenhouse gas emissions, equivalent to around 1,036 million tonnes (Mt) of CO_2-equivalent (CO_2e) emissions per year. The sector emits approximately 1.4 million tonnes (Mt) of particulate matter (PM) annually, accounting for nearly 15% of global nitrogen oxides (NO_x) emissions and approximately 13% of global sulfur oxides (SO_x) emissions. This situation is unsustainable and solutions are being sought, with alternative fuels being researched intensively(Energy 2021 p.1).

Consequently, the pressing demand for alternative fuels in the shipping sector presents additional opportunities for the utilization of green hydrogen. The maritime transport industry, driven by decarbonization goals, is increasingly willing to pay a premium for green hydrogen-derived fuels (Yunfei Du, Xinwei Shen 2025 p.2).

1.2 Benefits of using e-fuels

- E-fuels allow for the efficient use of excess renewable energy, that would otherwise be curtailed since they can be used in internal combustion engines,

- they allow the integration of the existing transportation fleet in decarbonization goals,

- Finally, e-fuels are particularly relevant in heavy transportation and heavy industry, where electrification is not a viable decarbonization option.

1.3 Basic Principle of P2X Technology

P2X encompasses the processes and technologies by which renewable electricity is converted into energy carriers such as Hydrogen, Methane, Methanol, Ammonia, Ethanol, etc.

A common first step in the production of green fuels is the synthesis of hydrogen through the electrolysis of water. For the produced hydrogen to be green, this step must be powered by renewable energy, usually wind or solar. Depending on the end product, the second step might involve methanation, Fischer-Tropsch, ammonia synthesis or other steps. A more detailed description of the steps relevant to our case study's production of e-methanol and e-ammonia is given below.

First Step: Electrolysis of water: $2H_2O \longrightarrow 2H_2 + O_2$

Second Step: Optionally depending on target product to perform one of the following processes:

E-Methanol Synthesis: $CO_2 + 3H_2 \longrightarrow CH_3OH + H_2O$

Synthesis of liquid fuels / Fischer-Tropsch process:

$CO_2 + H_2 \longrightarrow CO + H_2O$ or $CO + H_2 \longrightarrow C_xH_yOH + H_2O$

E-ammonia Synthesis: $N_2 + 3H_2 \longrightarrow 2NH_3$

In the above reactions, CO_2 will be sourced from selected cement industries via direct air capture while N_2 will be obtained from the atmosphere via swing absorption.

Third Step: This step involves product upgrading, conversion, and conditioning for subsequent use (depending on the pathway), as well as the separation, cleaning, and further processing of gaseous and liquid products, including compression and pre-cooling.

Table 1.1 Technology overview of P2X systems including main technologies and their major inputs / outputs

No.	P2X pathway	Conversion step	Carbon atoms	Inputs	Technology	Outputs
1.00	Hydrogen (H_2)	1(+3)	0	Electricity, water,heat (incase of SOEC)	Electrolyzer, hydrogen storage	Hydrogen, oxygen, heat
2.00	Synthetic Methanol (CH_3OH)	1+2+3	1	Electricity, water, CO_2	Electrolyzer, methanol synthesis reactor	Methanol, Oxygen, heat
3.00	Ammonia (NH_3)	1+2+3	0	Electricity, water, Nitrogen (N_2)	Electrolyzer, Ammonia synthesis reactor	Ammonia, Oxygen, heat

Source: SCCER, 2019

1.4 Critical Reflection of Sustainability Assessment of Power to X in the Transport Sector

Based on existing knowledge and empirical literature reviews, several recommendations supporting the implementation of Power-to-X (P2X) technologies for policymakers, researchers, and other stakeholders apply.

The sustainability of e-fuels depends on the hydrogen production pathways, the carbon intensity of the electricity supply, and the origin and delivery pathway of carbon or nitrogen sources utilized in the synthesis process. Therefore, e-fuels produced using renewable electricity and sustainably sourced hydrogen can achieve a substantially reduced environmental footprint, rendering them sustainable energy carriers (Aversano et al. 2024 p.2) . E-fuels serve as efficient energy carriers that can be stored, transported, and utilized across different energy sectors, including transportation and industry.

Due to their structural similarity to conventional fuels, e-fuels can utilize existing storage and distribution infrastructure without significant modification, thereby minimizing emissions associated with the logistical processes of infrastructure transformation (Aversano et al. 2024 p.23).

Considering infrastructure requirements, safety considerations, transportation logistics, and supply chain dynamics alongside the projected decline in the cost of renewable electricity, electrolyzers, carbon dioxide capture and Nitrogen Separation technologies, the production of e-fuels presents a promising pathway for sustainable energy transition (Aversano et al. 2024 p.33).

1.5 Core Benefits of Power to X

P2X systems can enhance the flexibility of the energy system and reduce GHG emissions simultaneously (SCCER 2019 p.14). They can balance energy supply and demand over long time horizons, such as seasonal variations, through the storage of hydrogen or synthesis products, with the potential for re-electrification of these products. Additionally, P2X systems provide short-term power system flexibility by enabling smart load management through controlled electricity consumption of electrolyzers. Furthermore, they supply low-emission synthetic energy sources produced from renewable electricity and CO_2 or N_2 captured from the atmosphere, stationary sources, biogas plants, and industrial processes, serving as a substitute for fossil fuels and chemical feedstock for industrial processes (SCCER, 2019 p.14).

In the shipping industry, rapidly expanding and almost entirely reliant on fossil fuels, synthetic electricity-based fuels offer a viable option for CO_2 emission reduction. The high fuel energy density required for shipping presents challenges in finding alternative replacements. These challenges are tangent to both production cost and scalability ("Green Ammonia vs. Methanol: Which Is the Shipping Fuel of the Future?," n.d.).

Currently, e-ammonia is in its embryonic stages of commercialization and production cost is relatively high. E-ammonia which must be stored at moderate pressures and low temperatures, demands modifications in existing fuel infrastructure and its handling is complicated by its level of toxicity which requires robust safety protocols to protect personnel and the environment. Ensuring a robust safety system will demand the retrofitting of ports and ships, accompanied by considerable investment and regulatory oversight. In contrast, e-methanol benefits from its physical properties as a liquid at ambient temperature. This means that e-methanol can be stored and transported using infrastructure similar to that used conventional fuels. These features make it a more deployable alternative ("Green Ammonia vs. Methanol: Which Is the Shipping Fuel of the Future?," n.d.).

Current estimates of e-methanol production range widely by production pathway at 860 – 1585 USD per ton (Adnan and Kibria 2020 p.1). Despite the very wide range, the price of e-methanol remains two to four times above the market price ($300/ton–$500/ton) of methanol (Adnan and Kibria 2020 p.1). In terms of climate benefits, e-methanol has uncontested GHG reduction benefits if the source of electricity is renewable power and CO_2 is captured from air. The assumed production pathway of e-methanol strongly influences its GHG reduction benefits.

Although the current production cost of e-ammonia remains significantly higher than that of conventional ammonia, it is expected to decline in parallel with the decreasing cost of renewable energy. Presently, the price of green ammonia ranges between $700 and $1,400 per tonne (FutureBridge 2022) at locations with abundant renewable energy resources such as solar and wind. The cost estimates of green ammonia and its GHG reduction estimates, as with e-methanol, are highly specific to the production site and value chain. In the first half of 2024, vessels powered by alternative fuels represented 41% of the total tonnage of global new ship orders, including 49 methanol-fuelled ships (Yunfei Du, Xinwei Shen 2025 p.2).

Given the issues associated with the calculation of GHG reduction potential in grids that have not been fully decarbonized, our model assumes islanded production sites powered only by renewable energy in the form of wind and solar power.

1.6 E-Methanol Production Plants

Egypt has made progress towards the establishment of its first green methanol production project (Egyptian Methanex Plant) located at the Port of Damietta with an investment sum of $450M and a yearly production capacity of 40,000 tons ("Cop 27: FFI to Produce Green H2, Ammonia in Kenya" 2022). The project includes the planned construction of 40MW of solar and 120MW of wind and aims to supply ships with clean fuel.

Kenya has not made any effort so far in the production of e-methanol but the country is mainly involved in the import and distribution of methanol through Kenya Chemical. However, in 2023, Kenya's import of Methanol amounted to more than 6,000 tonnes and cost 3.2 million USD ("Cop 27: FFI to Produce Green H2, Ammonia in Kenya" 2022). This outlines that methanol is an important energy vector in Kenya's landscape and e-methanol production is worth exploring.

Liberia has had no trace of e-methanol production; however it imports methanol from China and other parts of the world. In 2021, Liberia's imports of methanol amounted to about 6 tonnes costing USD 184K ("Cop 27: FFI to Produce Green H2, Ammonia in Kenya" 2022).

Egypt, Liberia, and Kenya represent three different landscapes in e-fuels, with Egypt being at the most advanced stage with already some e-ammonia and e-methanol plants in place; Kenya has significant investments in renewable power (wind, solar), but lags in e-fuels. Liberia represents a landscape with little industrial presence and no e-fuels production; however, it has the renewable potential to be a future production site for them.

The production of e-methanol in Liberia, Kenya, and Egypt can deliver significant economic, environmental, and social benefits, particularly by positioning these countries as regional bunkering hubs for e-methanol-fuelled ships. Economically, it creates new revenue streams from fuel exports and port services, promotes job creation, and stimulates industrial growth in energy and logistics (Magazine 2024). Environmentally, e-methanol, especially when produced from renewable sources or captured CO_2, reduces greenhouse gas emissions by up to 95% compared to conventional marine fuels, supporting international decarbonization efforts in the shipping sector (World Health Organization 2023p). E-Methanol also improves air quality by lowering particulate matter and NO_x emissions, benefiting coastal communities and port cities (World Health Organization 2023g). Socially, the expansion of green fuel infrastructure can enhance energy access, promote technological transfer, and strengthen economic ties through increased maritime traffic and international trade (Olah et al., 2011 p.2).

1.7 e-Ammonia Plants

In July 2024, Scatec, an Egyptian petrochemicals holding company and Misr Fertilizer entered into agreement for the production of e-ammonia. This deal comprises of 480MW renewable energy capacity and close to 240MW electrolyzer facility for the production of green hydrogen to be used as a feedstock for producing of e-ammonia. The project has a planned production capacity of 150,000 tonnes of e-ammonia per annum ("Cop 27: FFI to Produce Green H2, Ammonia in Kenya" 2022).

Kenya enumerates several e-ammonia projects but most of them are still in their development stage including the Tarita Green Energy Solar Powered Fertilizer Plant, Talus Renewables Modular Green Ammonia System and the 300MW Green Ammonia Fertilizer Facility planned with Fortescue Future Industries (FFI) ("Green Ammonia vs. Methanol: Which Is the Shipping Fuel of the Future?," n.d.). However, despite the challenges involved in commissioning these e-ammonia plants, it has successfully installed its first commercial modular green ammonia system which aims to provide cleaner, cheaper and more reliable fertilizer production. The

Kenya Nut Company Talus One is powered by a 2.1MW Solar farm that produces approximately 1 ton NH_3 / day ("Cop 27: FFI to Produce Green H2, Ammonia in Kenya" 2022). However, these projects are all aiming to supply the fertilizer industry and not produce e-fuels.

To date, Liberia has no e-ammonia plant and no plans exist to build one even though the country has a significant potential for the production of e-ammonia due its abundant renewable resources (Solar, Bioenergy, etc,).

E-ammonia production presents significant benefits to Liberia, Kenya, and Egypt by advancing energy security, economic development, and climate goals. In Liberia, it can reduce dependence on imported fossil fuels, create jobs, and utilize the country's abundant renewable resources such as solar and hydropower (Yusuf et al. 2024 p.4). For Kenya, e-ammonia supports cleaner fertilizer production, boosts industrial growth, and leverages its strong solar and wind potential, with export opportunities through Mombasa Port (Sustainable Environmental Development Watch Kenya, 2023; 'Cop 27: FFI to Produce Green H2, Ammonia in Kenya,' 2022)."). Egypt, already home to established e-ammonia and fertilizer industries, can strengthen its position as a regional green fuel hub, benefit from export access via the Suez Canal, and accelerate progress toward its national decarbonization objectives (World Health Organization 2023y);(World Health Organization 2023ag); (World Health Organization 2023ab).

2.0 Literature Review

2.1 Geographical location / Liberia

Liberia is 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 as its highest peak. As shown in Fig. 1.1, Liberia borders Sierra Leone to the northwest, Guinea to the north, Côte d'Ivoire to the east; the country boasts a coastline along the Atlantic Ocean (Yusuf et al. 2024 p.2).

Figure 1.1 Map of Liberia

Source: (Yusuf et al. 2024 p.2)

2.2 Liberia Energy Mix

Liberia's energy mix has historically depended heavily on biomass, particularly firewood and charcoal, used for cooking and heating. This reliance on biomass has significant environmental and health impacts. The country has limited electricity generation capacity, with a merger of hydroelectric power, Solar PV and small-scale diesel generators being the primary sources of electricity. Liberia has been working towards diversifying its energy sources in terms of electricity generation (Yusuf et al. 2024 p.3).

According to IRENA, in 2019, biomass accounted for approximately 100 % of the total final energy consumption (TFEC) in Liberian households (Yusuf et al. 2024 p.6). The country's industrial and transportation sectors rely on fossil fuels, mainly gasoline and diesel. Its largest source of renewable supply is hydropower (See Fig 1.2).

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 electricity. The electricity generated by these plants is used in the residential and industrial sectors.

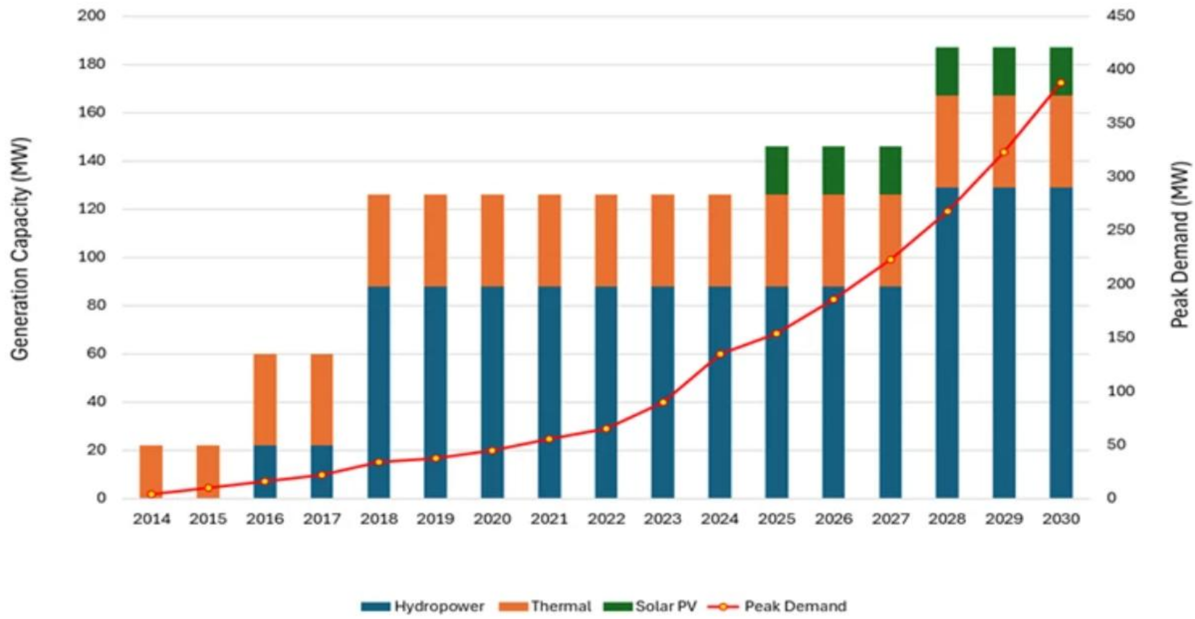

Figure 1.2: Electricity Generation and Demand in Liberia

Source: (Sherif 2025)

In Fig 1.2, from 2014 to 2030, Liberia is projected to experience significant growth in both electricity generation capacity and peak demand. The total generation capacity is expected to increase from 20 MW in 2014 to 188 MW in 2030. Concurrently, peak demand is projected to rise sharply from 5 MW in 2014 to 390 MW in 2030.

Also, Liberia's electricity generation primarily relies on Hydropower and Thermal sources, with Solar PV being introduced later in the projection period.

2.3 Electricity Access and Demand

Ongoing network expansions in transmission and distribution have witnessed more customer connections throughout the electricity service areas of licensed distribution operators (Report et al. 2022 p.10). Fig 1.3 and Fig 1.4 reveals that Liberia installed capacity has heavily depended on Hydropower for electricity generation.

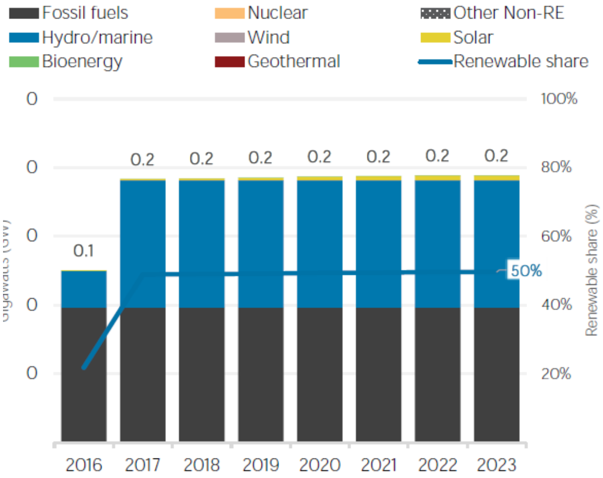

Figure 1.3 Installed Capacity Trend

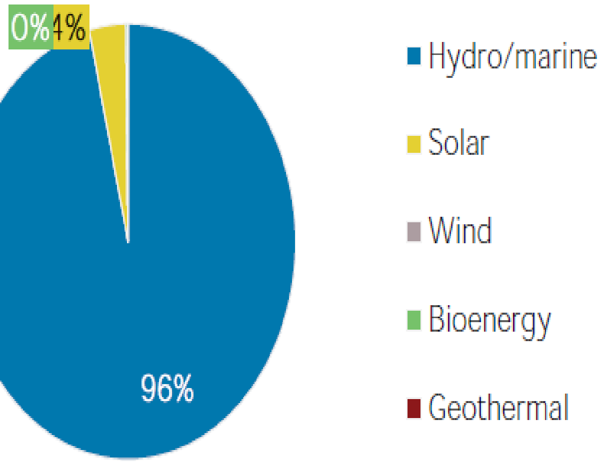

Figure 1.4 Renewable Energy in 2023

Source: Liberia energy profile, 2023

2.4 Liberia Renewable Energy Potential

2.4.1 Hydropower

Liberia has several rivers that could support small to medium-scale hydropower projects. Utilizing these resources can provide reliable electricity and reduce dependence on fossil fuels. To date, the country has two hydropower facilities. The largest is located at Mount Coffee, Harrisburg, Montserrado County with a supply capacity of 88MW during the wet season and the other is a mini grid located in Yandohum, Lofa County with a capacity of 60KW. Recently, Liberia's installed electricity capacity reached ~200 MW (Yusuf et al. 2024 p.3). Fig. 1.3 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 approximately 50 % of Liberia's installed capacity (see Fig. 1.3).

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 (Yusuf et al. 2024 p.3). See Table 1.2.

Table 1.2 Electricity generation from renewable energy

Community	County	Technology	Funder	Implementer	Capacity	Beneficiary	Start Date	Status	Ref
Yandohun hydropower mini grid	Lofa	Hydro	World Bank	RREA	60 k W	≥149 households	2013	Operational	"Yandohun Hydropower Mini-Grid," n.d.
Electricity from rubber wood chips in Kwendin	Nimba	Biomass	USAID	NRICA	100 Kw	≥200 households, a clinic, and a school	2016	Operational	"Electricity from Rubber Wood Chips in Kwendin, Nimba (RREA)," n.d.
Palm oil generated electricity in Sorlumba	Lofa	Biomass	USAID	NRICA	25 Kw	≤200 households	2017	Almost operational	"Palm Oil Generated Electricity in Sorlumba," n.d.
Totota	Bong	Solar / Diesel			25 kW		2016	Operational	"Totota Solar and Diesel Plant," n.d.
Mini hydropower / Diesel grid	Lofa	Hydro / Diesel	World Bank	RREA	2.5 MW	10,000 households	2019	Planned	"Mini Hydropower / Diesel Grid in Lofa County," n.d.
Langbemba	Lofa	Solar	EU	PLAN & VOSIEDA	31.1 Kw		2017	Needs rehabilitation after fire	"Langbemba Solar Project in Lofa County," n.d.
Taninahun	Lofa	Solar	EU	PLAN & VOSIEDA	28.5 kW		2017	Operational	"Taninahun Solar Project in Lofa County," n.d.
Mamikonedu	Lofa	Solar	EU	PLAN & VOSIEDA	25.5 kW		2017	Operational	"Mamikonedu Solar Project in Lofa County," n.d.
Koiyama	Lofa	Solar	EU	PLAN & VOSIEDA	22.5 kW		2017	Operational	"Koiyama Solar Project in Lofa County," n.d.
Harrisburg	Montserrado	Solar	World Bank, EU, AFDB, EIB, USA, Japan, KfW & WAPP	International Consolidated Contractors Offshore SAL	20 MW		2024	Ongoing	"Harrisburg Solar Project in Montserrado County," n.d.

Source: (Yusuf et al. 2024 p.9)

2.4.2 Solar Energy

Liberia experiences a humid, tropical climate characterized by consistently moderate temperatures year-round, averaging about 27 ◦C (81 ◦F). Recent investigation shows that the monthly average daily solar radiation on horizontal surfaces in Liberia is between 4.0 and 6.0 kWh/m^2 of solar radiation per day. 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/m^2/day or more (Yusuf et al. 2024 p.4).

This results in higher energy production from PV systems, as indicated in Fig. 1.5. In contrast, the wet season (May to October) is characterized by increased clouds covered with potential rainfall 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/m^2/day (Yusuf et al. 2024 P.5). Inland areas of Liberia receive slightly greater insolation than coastal areas, as recently reported by IRENA.

The country's abundant and stable solar energy potential contributes to an average of 1,714 kWh/m^2/year which is better than most regions in Central and West Africa (World Health Organization 2023s); (World Health Organization 2023af). This level of solar radiation can generate approximately1,400 to 1,500 kWh / kWp. Fig. 1.8 shows Liberia's installed capacity trend in terms of solar and wind potential. The country falls in the equatorial belt and receives the second-highest annual solar radiation on earth (Yusuf et al. 2024 p.5). Despite enormous solar energy potential, investments to generate electricity from solar lag behind.

However, Solar photovoltaic (PV) systems could be deployed for both large-scale projects and decentralized rural electrification.

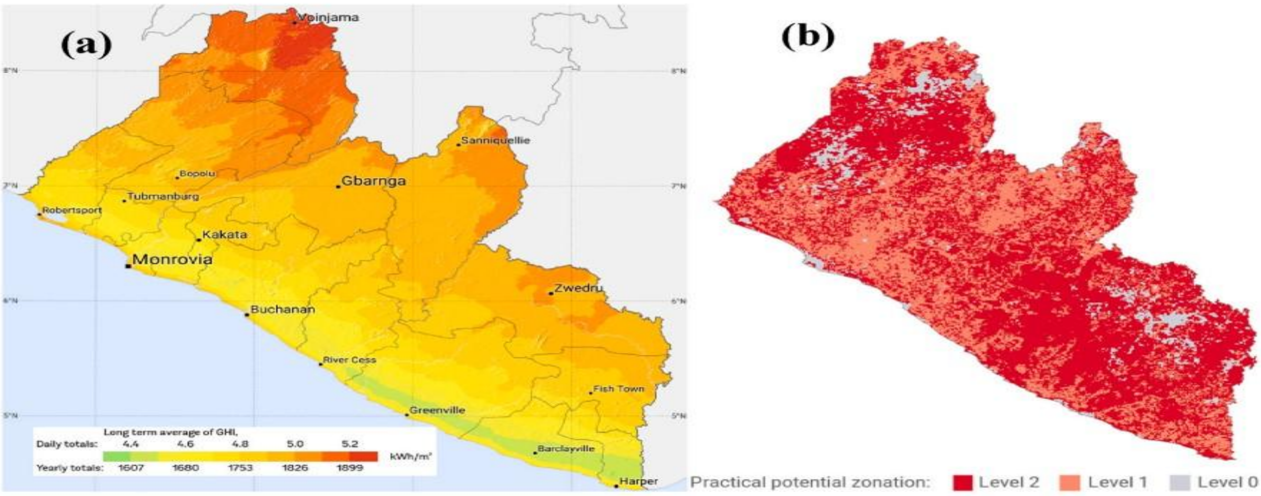

Figure 1.5 Long-term average annual profiles of (a) GHI and (b) practical PV Output in Liberia

Source: (Yusuf et al. 2024 p.5)

2.4.3 Wind Energy

The wind potential in Liberia is 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 5.0 m/s along the coast but yet considered moderate for wind power development (World Health Organization 2023ag) The potential for wind energy development is more favorable in areas such as River Gee, Bong, and Maryland Counties respectively. Wind resource assessment studies are essential to accurately determine the wind potential of specific locations 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 (See Fig. 1.6).

As exhibited in Fig. 1.6, the chart shows the distribution of the country's land windiest area with respect to distribution of mean power density and Locations within the 10% of windiest areas display the highest wind speed. These studies consider factors such as topography, local wind patterns, and other meteorological conditions to assess the viability of wind energy projects. Coastal areas of Liberia experience consistent winds, which makes them suitable for wind power generation. Wind turbines could be installed to harness this renewable resource.

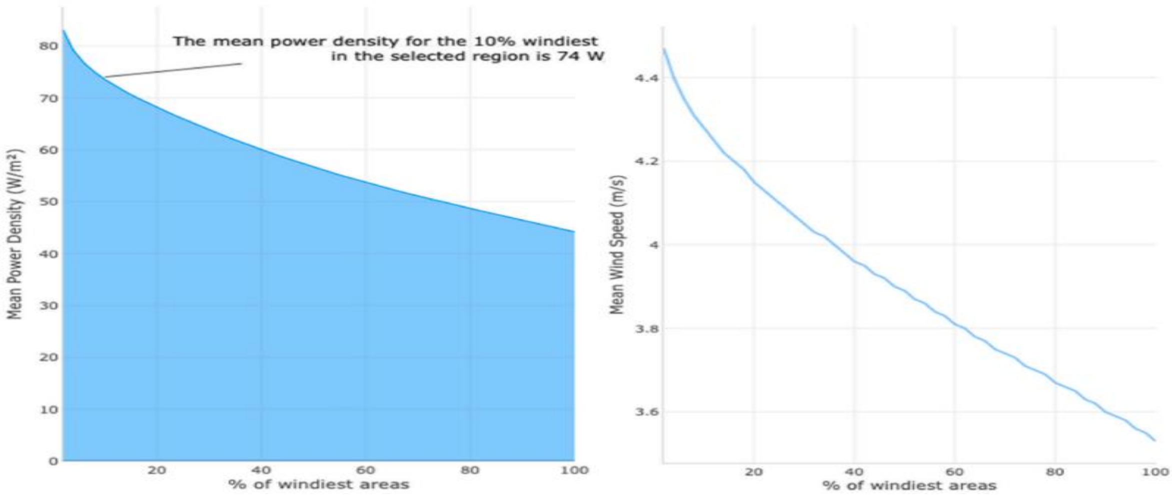

Figure 1.6 Distribution of wind potential in Liberia

Source:(Yusuf et al. 2024 p.4)

Liberia has a moderate annual solar generation potential per unit of installed PV capacity at around 1.4 -1.6 MWh / KWp. This makes Liberia an ideal location for PV investments as a main source of renewable energy. Although the country has good wind power potential, it is not competitive with areas of excellent wind resources (See Fig. 1.7).

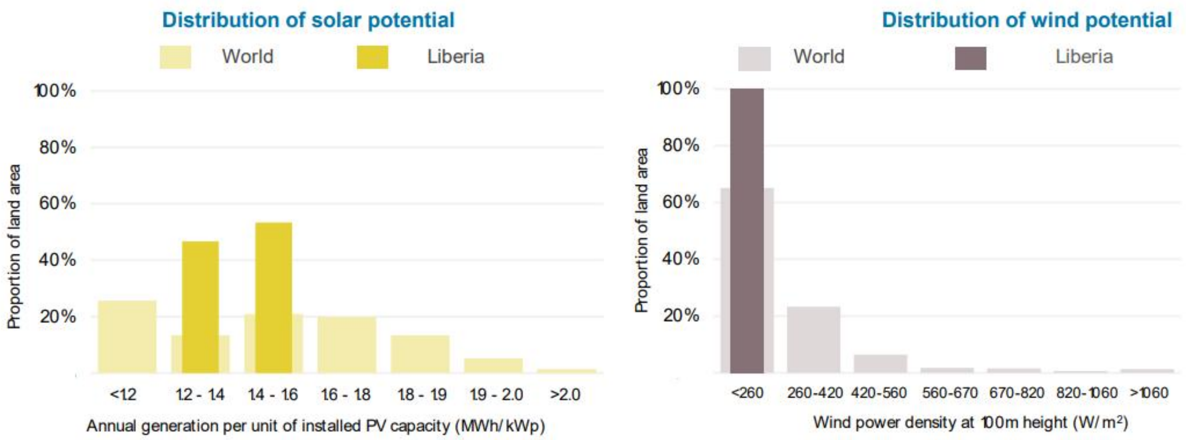

Figure 1.7 Liberia Installed Capacity Trend

Source : IRENA Energy Profile

2.4.4 Energy Access

In Liberia, the availability of grid-connected electricity is limited, with the country having one of the world's lowest electricity consumption rates with <50 kWh per capita per year. Estimate shows that only 32 % of the population has access to modern electricity (World Health Organization 2023s) .

The national electricity grid is characterized by aging infrastructure, 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. 1.9 shows that the Liberia Electricity Corporation (LEC) grid's reach limited regions in Liberia. Liberia's current electricity grid infrastructure is constrained in its capacity and coverage, necessitating substantial expansion and modernization to cater to the increasing nationwide electricity demand. (See Fig 1.9)

To expand energy access, the government has embarked on several plans (e.g. Ongoing construction of a 20MW solar farm, expansion of transmission and distribution networks and the construction of additional substations in order to bolster its electricity grid and provide reliable power supply to its growing population ("Harrisburg Solar Project in Montserrado County," n.d.).

Yet, expanding the power infrastructure to rural areas remains a challenge due to the lack of adequate road networks.

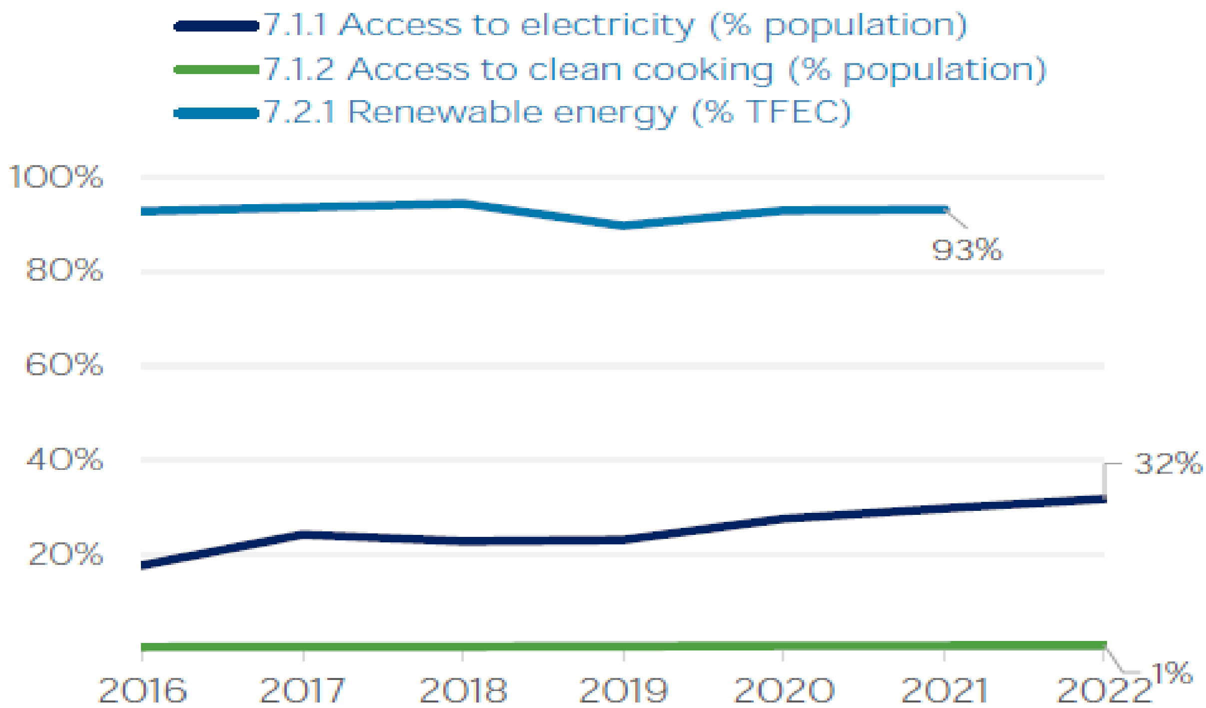

Figure 1.8 The population served with electricity connections in Liberia

Source: (Yusuf et al. 2024 p.6)

Over the past decade, Liberia's electricity sector has seen significant progress; access to electricity has doubled (32.5%), while residential tariffs have fallen by 53.8%, dropping from $0.52 per kilowatt-hour in 2014 to $0.24 in 2024 (Sherif 2025).

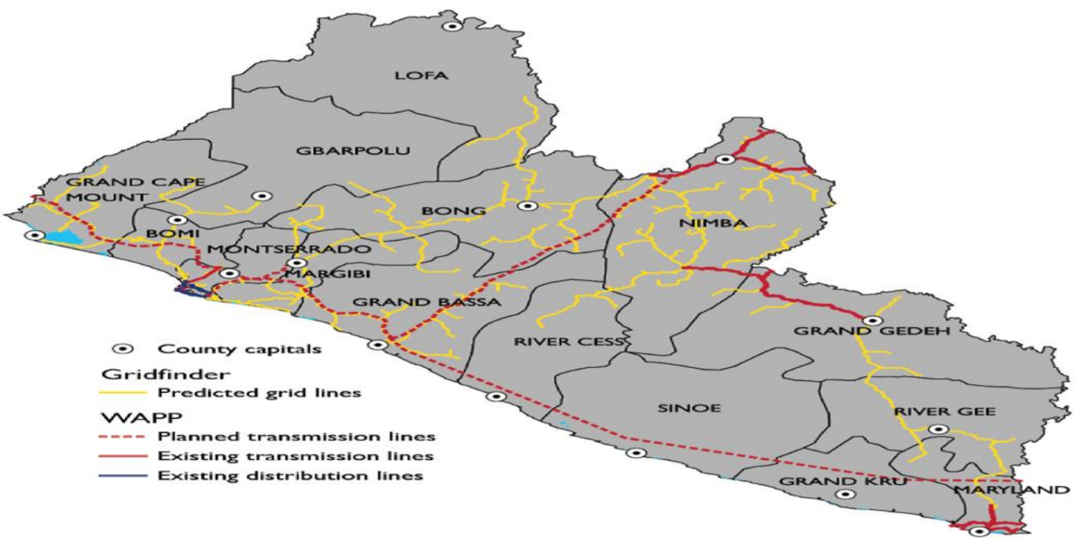

Figure 1.9 Electricity grid in Liberia from existing, planned, predicted lines

Source: (Yusuf et al. 2024 p.6)

2.5 Liberia Water Availability

Water is an essential input for green hydrogen production by electrolysis. Liberia has abundant water resources (Resources and Series, n.d. p.1) and as per water availability per capita, the country stands as the third highest in Sub-Saharan Africa at 49,028 m^3 and is significantly higher than the Falkenmark Index (FI) for water stress (Resources and Series, n.d. p.1). The Falkenmark Index is an indicator used to measure water scarcity and it uses the annual renewable freshwater availability in m^3 per person as a key criteria (Khan et al. 2022 p.6) . Water abstractions are also quite low (Resources and Series, n.d. p.1) . A FI value below 1700m^3 denotes water stress for green hydrogen production; water scarcity occurs below 1000m^3 and absolute water scarcity occurs below 500m^3. See Table 1.3 below.

Table 1.3 Falkenmark Index for Water Stress

Sr. No.	Index (m^3/capita/year)	Category
1.	>1,700	No Stress
2.	1,000-1,700	Stress
3.	500-1,000	Scarcity
4.	<500	Absolute scarcity

Source: (Khan et al. 2022 p.6)

Table 1.4 Liberia Water Resources Data

Water Resources Profile Data	**Year**	**Liberia**	**Sub-Sahara Africa (Median)**
Long term average precipitation	2017	2,391.00	1,032.00
Total renewable freshwater resources	2017	232,000.00	38,385.00
Falkenmark index - TRWR per capita (m^3/ year)	2017	49,028.00	2,519.00
Total renewable surface water (MCM / year)	2017	232,000.00	36,970.00
Total renewable ground water (MCM / year)	2017	45,000.00	7,470.00
Total freshwater withdrawal (MCM / year)	2002	130.80	658.00
Total dam capacity (MCM)	2015	238.60	7,085.00
Dependency ratio (%)	2017	13.79	23.00
Interannual variability	2013	0.80	1.55
Seasonal variability	2013	2.80	3.15
Environmental flow requirements (MCM)	2017	176,800.00	18,570.00
SDG 6.4.2 water stress (%)	2002	2.60	5.70

Source: FAO Aquastat

Despite abundant surface water, dry season flows can be low. Low flows on the St. Paul River significantly reduce hydropower generation at the Mount Coffee Dam, which is the largest source of municipal power and a major source of electricity for Monrovia (Resources and Series, n.d. p.1). Thus, for the water required for the production of hydrogen, our case study will consider connection to the Liberia Water and Sewer Corporation lines and charges will be applied as required. Figure 1.10 below is a map illustrating water resources distribution within the country.

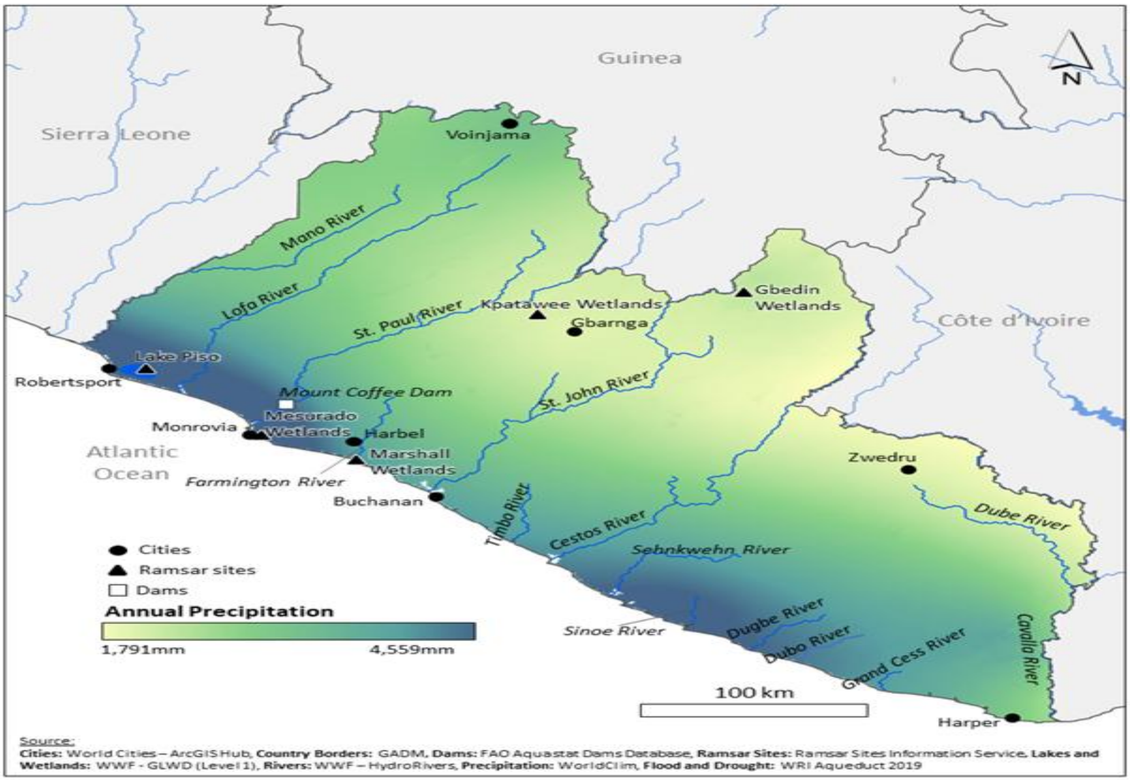

Figure 1.10 Water resources map of Liberia

Source: FAO Aquastat

2.6 Land Availability in Liberia

Liberia is a relatively small country with a low population density (Worldometer, n.d.) of about 60 persons per square kilometers. Liberia's current land use patterns include agriculture, forestry, and some urban development. Identifying suitable land for renewable energy projects involves balancing these existing uses with new developments.

A sharp increase in the demand for land that is to be used for large-scale hydrogen and derivative production will increase the demand and competition between resources. This competition also introduces difficult trade-offs between the conservation goals of hyper-sensitive areas and the prospects of creating much needed jobs, new income opportunities and new long term development prospects.

2.7 Land Tenure System

Liberia possesses one of the highest land concession rates in Africa, positioning it as a strategic gateway for investors on the continent. A 2012 report (Kaba and Madan 2014 p.6) found that land allocated to agricultural and forestry concessions covers approximately 25% of the country.

The new Land Right policy of 2013 delineates four land rights categories: public land, government land, private land and customary land, together with a cross-cutting category of protected areas intended for resource conservation of national interest. The new laws are intended to have minimal impact on existing customary practices (Brown 2017 p.6).

Land ownership has never been well documented in Liberia, and land records are poor, with an incomplete national registry, confined largely to the major urban areas, and with some records partly or wholly dispersed to other departments such as the Forest Development Authority. There are few registries at county level, and the records held there tend to be unreliable and unsystematised. Much of the existing documentation is of uncertain value and legitimacy, particularly for the hinterland. Two decades of civil unrest and conflict have confused the picture further, with many people having fled their homes at short notice, with any documents they possessed being lost, stolen or destroyed. There may well be numerous claimants at both individual and customary levels who have valid claims but cannot support them with written proofs of ownership. War-related movements of population have also led to some rural resettlement of poor people outside of their natal areas (Brown 2017 p.7). In an effort to these challenges, the Liberia Land Authority (LLA), an autonomous agency of the Government with operational independence, subsumes land functions that were performed by several agencies of the Government.

2.8 Population

In terms of population, Montserrado County is the largest with more than 1.9 million people. Nimba, Bong, Lofa, and Margibi are large counties with populations ranging from 301,000 to 500,000 people each Grand Bassa, Grand Gedeh, Grand Cape Mount, and Maryland are medium-sized counties with populations between 150,000 and 300,000. Small counties are those with a population of less than 150,000, such as Bomi, River Gee, Grand Kru, Gbarpolu, and Rivercess (“Irena” 2019).

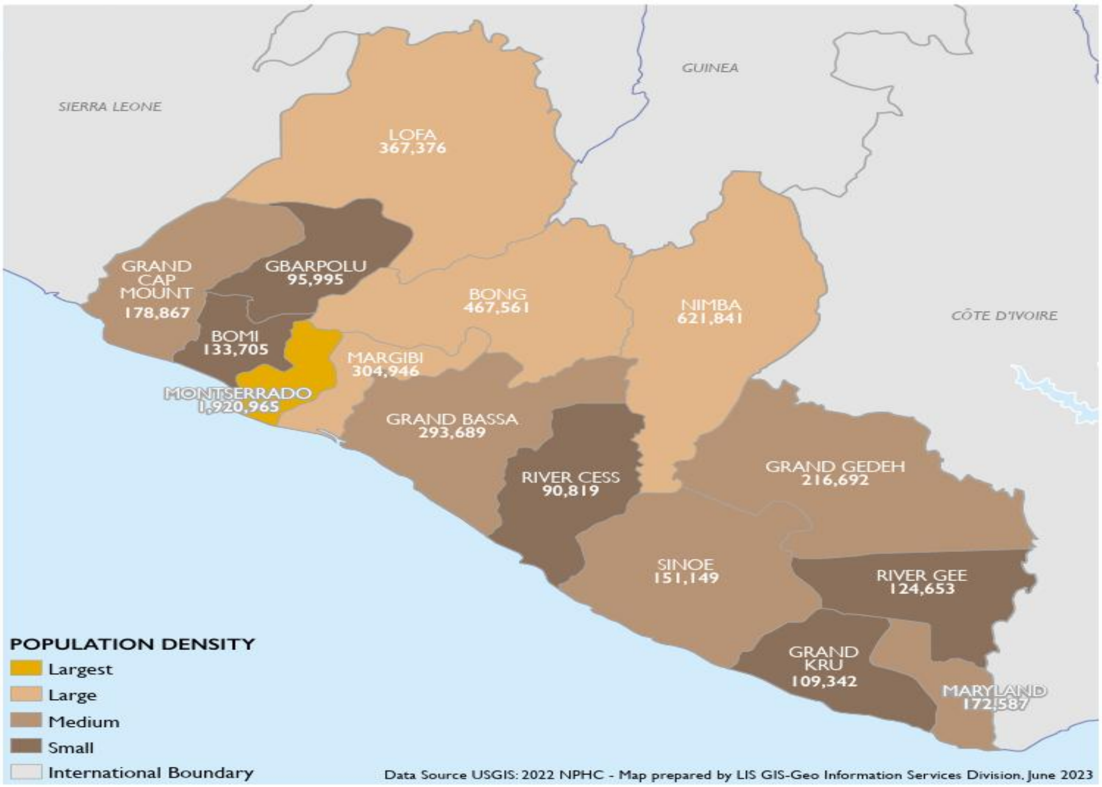

Figure 1.11 Map of Liberia Indicating Population by County

Source: (Statista 2025)

As in most developing countries, agriculture in Liberia is foundational to the country’s poverty alleviation efforts. Agriculture is the main source of livelihood in Liberia, employing nearly 50% of the labor force and providing a livelihood to about two-thirds of the population. Liberia’s agriculture sector is a fundamental component of the country’s economy, and in 2021 accounted for 37 percent of GDP (“Worldometer” 2025).

Despite the agricultural sector’s economic importance, a recent assessment of food insecurity in Liberia by the FAO estimates that 83.6 percent of households were affected by moderate to severe food insecurity in 2020. The rate is particularly high due to the disruption of most economic activities by the COVID-19 pandemic. As with poverty, a more granular analysis reveals that crop producers are the most vulnerable group to food insecurity with 90 percent of them compromising on food quality and variety, skipping meals, or going without food for a day or more.

2.9 Education and Employment

Education serves as the foundation and driving force behind sustainable development and national growth. It is particularly important in providing a skilled workforce in the construction and operation of green hydrogen facilities. However, Liberia faces significant challenges, particularly in cultivating a productive human capital base capable of effectively managing its abundant natural resources. These resources have, in many cases, been either mismanaged or left underutilized, yielding limited developmental outcomes (Sumaworo 2023 p.1).

Meanwhile, during the Liberian Civil War (1989 – 2003), a massive migration of professionals, qualified teachers and academics fled to exile for survival. As a result of the outflux, there exist an adverse effect on tertiary and education as a whole (Sumaworo 2023 p.1).

According to the World Bank Group, Liberia's employment-to-population ratio increased from approximately 73% in 2021 to 75% in 2024 (Statista 2025). In Liberia, individuals aged fifteen (15) years and older are generally classified as part of the working-age population (modelled ILO estimates).

3.0 Egypt

Egypt occupies the north-eastern corner of Africa and extends beyond the Isthmus and Gulf of Suez into Asia to the Sinai Peninsula. Egypt covers an area of approximately 1million km^2 and is bounded by the Mediterranean Sea to the north, the Republic of the Sudan to the south, the Republic of Libya to the west, and the Red Sea, the Gulf of Aqaba, and Palestine/Israel to the east (See Fig 1.12). Egypt lies in the tropical and subtropical arid climate. (Sayed Embabi 2017 p.3).

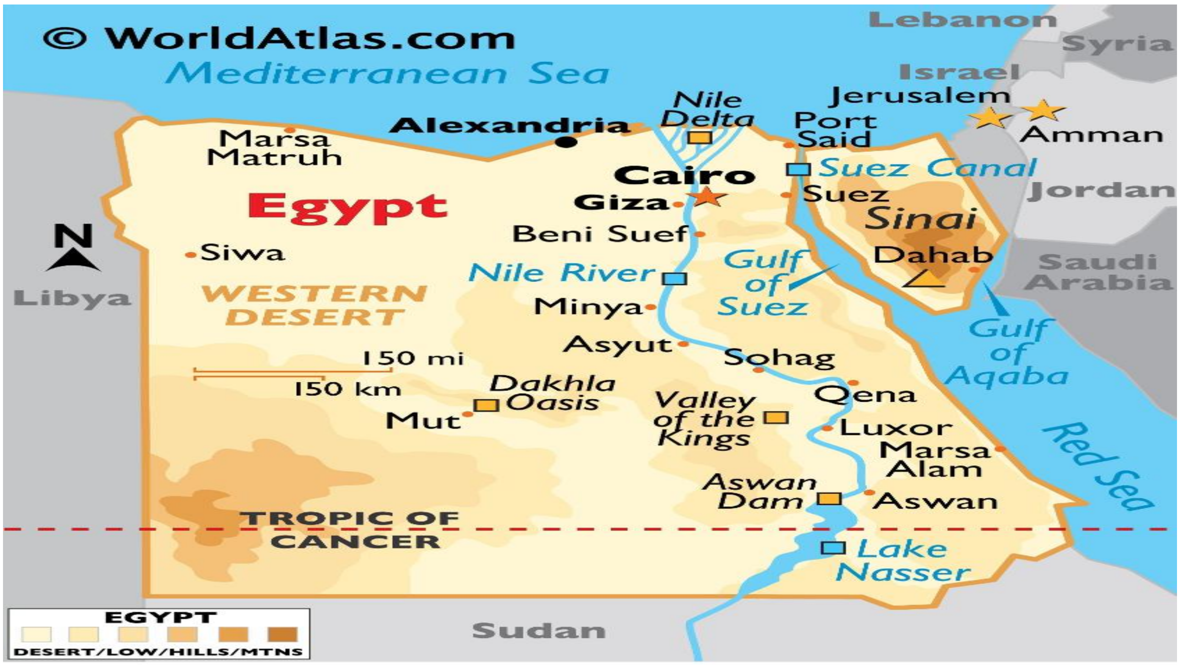

Figure 1.12 Map of Egypt showing geographical names mentioned

Source: WorldAtlas

3.1 Egypt Energy Mix

Energy plays a central role in Egypt's economy, contributing over 13% to the country's GDP and supporting nearly all major sectors such as industry, transportation, and services. The country's large oil and natural gas reserves drive domestic energy production, export earnings, and job creation. Additionally, Egypt's efforts to expand renewable energy and modernize its power infrastructure are key to sustaining industrial growth and attracting foreign investment. Moreover, the energy sector is considered a significant contributor to employment in Egypt (Abdelmeguid and M. Ibrahiem 2025 p.5).

The energy sector in Egypt has traditionally centred around the production and export of oil and natural gas. Egypt is the third (US Energy Information Adminsitration (EIA) 2022 p.1) largest natural gas producer in Africa. The country also functions as a critical channel for oil transported from the Persian Gulf to Europe and the United States of America (World Health Organization, 2023). However, Egypt is also making strides towards decarbonization with ambitious goals of transforming the country's energy landscape towards a low-carbon future (World Health Organization, 2023). The primary objective of this vision is boosting the share of renewables in the energy mix, improving energy efficiency and enhancing energy security.

Table 1.5 Electricity in 2022 / 2023

Description	Unit	2021 / 2022	2022 / 2023	Variation (%)
Total Installed Capacity:	**MW**	**59,866.00**	**59,442.18**	**0.70**
Hydro	MW	2,832.00	2,832.00	-
Thermal (Affiliated Companies & EEHC Plants)	MW	52,405.00	52,622.50	0.42
New & Renewable Energy (Wind, Solar and Thermal / Solar)	MW	3,264.00	3,308.00	1.35
Private Sector Power Plants (Thermal)	MW	1,365.00	682.50	50.00
Peak Load	**MW**	**33,800.00**	**34,200.00**	**1.18**
Total Power Generated (on country level):	**GWh**	**214,220.00**	**216,252.00**	**0.95**
Hydro	GWh	14,646.00	15,458.00	5.50
Thermal	GWh	179,977.00	184,578.00	5.60
New & Renewable Energy	GWh	10,537.00	10,642.00	0.99
Private Sector (BOOT)	GWh	8,890.00	5,399.00	39.30
Unconnected Plants and Reserves	GWh	147.00	163.00	10.88
Industrial Companies Surplus	GWh	23.00	12.00	47.83

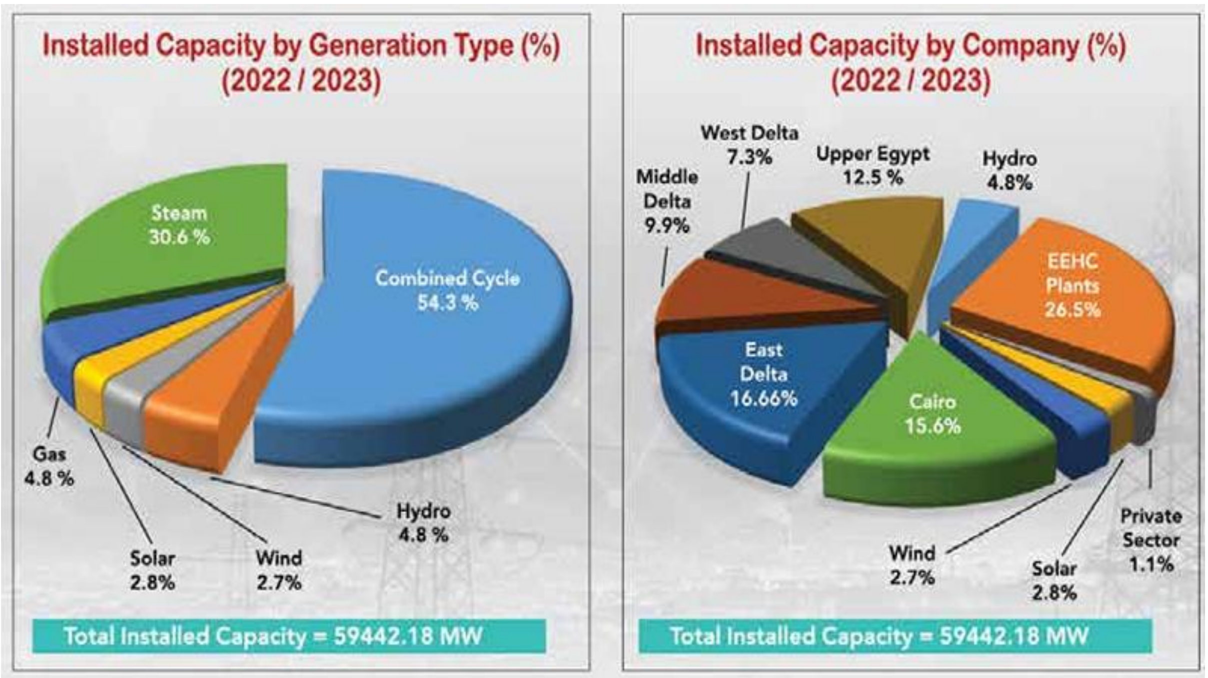

Figure 1.13 Egypt Installed Capacity by Generation Type

Source: (Salma I. Salah a, Mahmoud Eltaweel b, n.d.)

Figure 1.14 Development in Peak Load

Source: (Salma I. Salah a, Mahmoud Eltaweel b, n.d.)

3.2 Renewable Energy Potential

In the process of planning to increase the renewable energy establishments of a country, it is important to identify its position compared with other countries that are on the same journey.

3.2.1 Hydropower

Egypt has a hydropower generation capacity of about 2,700 megawatts. In 2023, the North African nation relied on about 2,800 megawatts, contributing 7.2% of the total energy generated in the Egyptian Electrical Unified Network (EEUN) (Statista 2025). The power generated reached 101% (Statista 2025) of the actual capacity of Egyptian hydropower stations. The increase in the generated energy is due to the station workers optimizing the water use and flow passing through the turbines.

Egypt has six hydroelectric power plants: the High Dam, the Aswan Dam, the Esna Barrages, the Nagaa Hammadi Barrages, and the Assiut Barrages. These stations generate electricity for the Egyptian Electrical Unified Network.

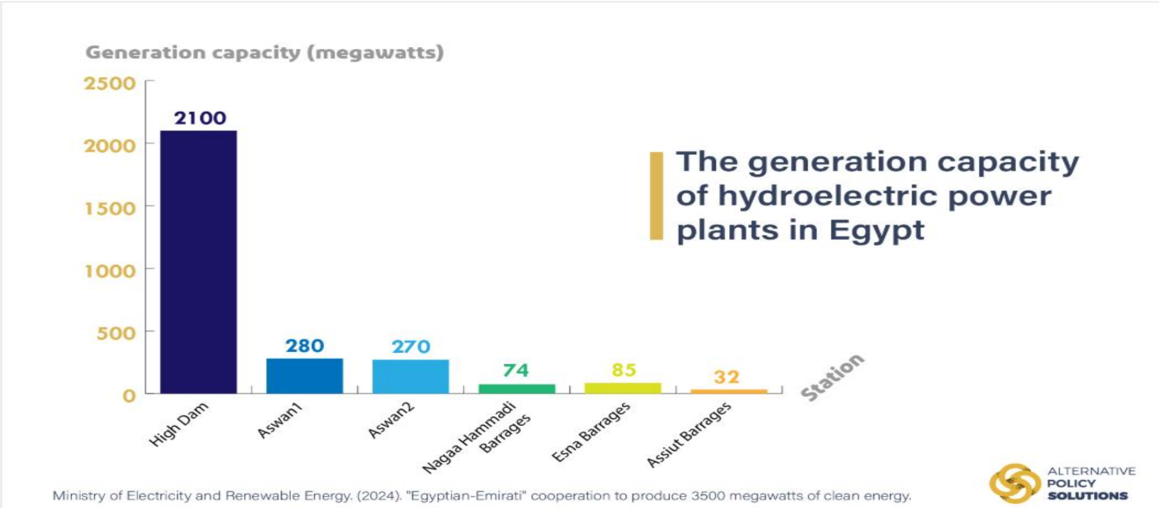

Figure 1.15 The generation capacity of hydroelectric power plants in Egypt

Source: (Statista 2025)

Figure 1.16 illustrates a significant increase in solar and wind energy capacity, which may be attributed to substantial financial support from international donors for renewable energy projects implemented across the country.

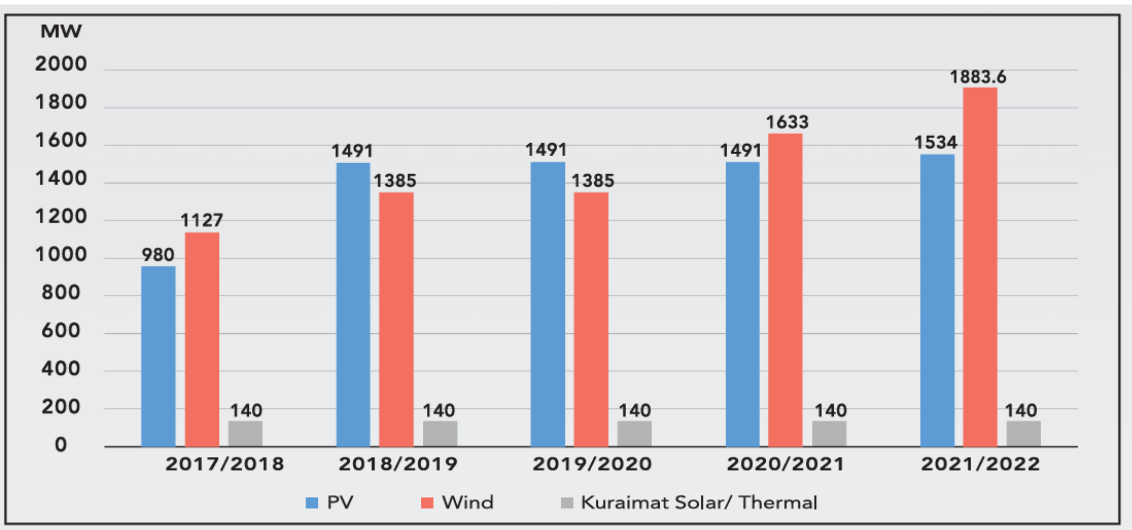

Figure 1.16 Installed Capacity of Renewable Energies as of 2022 / 2023

Source: (World Health Organization, 2023)

3.2.2 Solar Energy

Egypt has an average direct solar radiation ranging from 5.5 to more than 9.0 kWh/m^2/d and a sunshine duration of 9 – 11h/d. Egypt's current solar capacity ranges from 1.4 to 1.8GW (Magazine 2024). According to the Egyptian government, the solar energy generation capacities could be extended further by 3500 MW by 2027 (Salah, Eltaweel, and Abeykoon 2022 p.3). In 2020, solar energy in Egypt accounted only for 1.9% of the produced electricity, making it the country's second-highest renewable energy source after hydropower. Egypt is the second-highest solar energy generator in Africa after South Africa, whilst it is the thirty-first worldwide (World Health Organization, 2023).

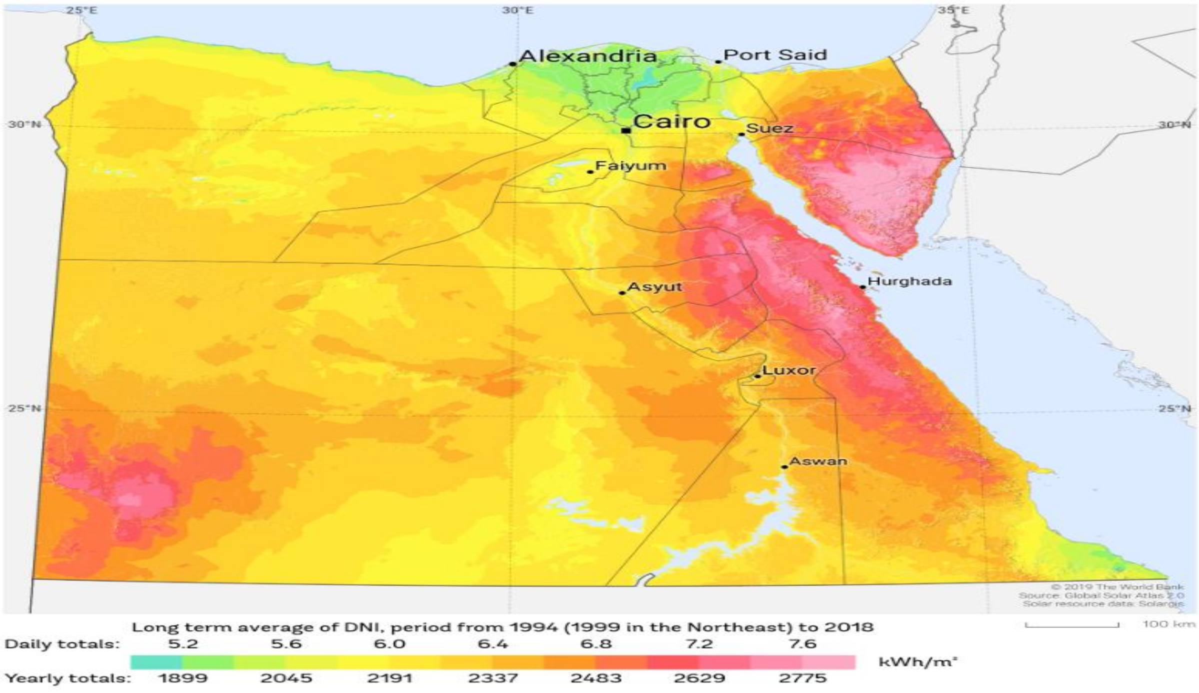

Figure 1.17 Egypt's Solar Atlas with the details of direct normal radiation

Source: Energy Data

3.2.3 Wind Energy

In 2001, Egypt installed 5.4 MW in wind power and as of 2018 it had grown its capacity to 545 MW. As part of the country's strategy to increase wind power to 7.2 GW by 2022, the Egyptian government intends to develop wind energy generation capacity during the next few years. In 2020, wind energy was responsible for 1.44% of the total produced electricity, making it the third-highest renewable energy source in Egypt (Salma I. Salah a, Mahmoud Eltaweel b, n.d. p.3). (See Fig 1.18)

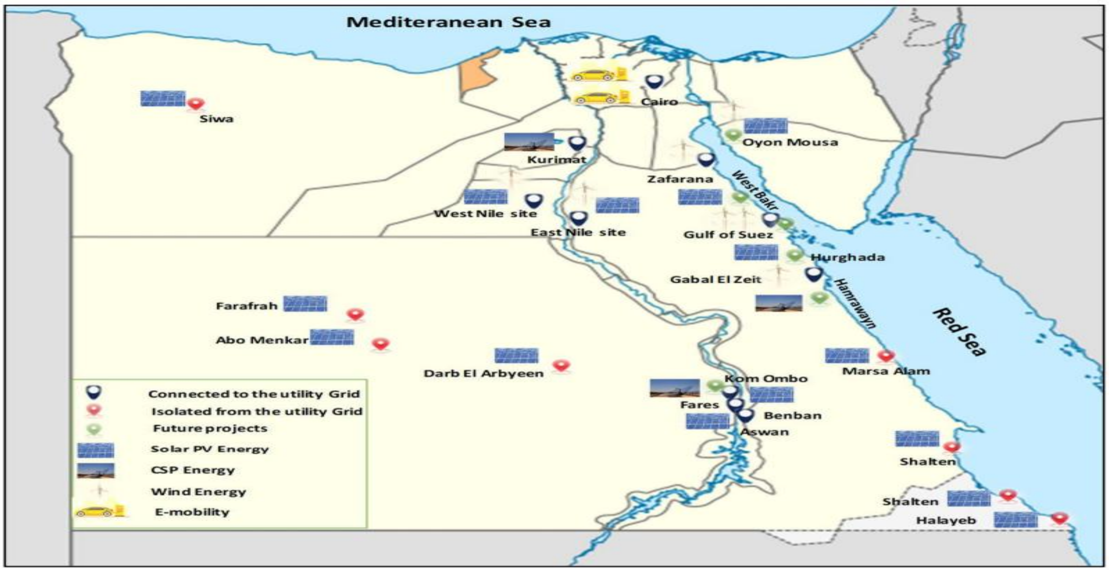

Figure 1.18 Present and future sites of renewable energy sources or projects in Egypt

Source: (HUSSEIN ABUBAKR, KARAR MAHMOUD 2022)

Egypt has very high solar annual generation potential per unit of installed PV capacity at around 1.9 to 2MWh/KWp. This renders Egypt an ideal location for PV investments as a main source of renewable energy for PtX production. In terms of wind power, although Egypt has some capacity rated at 260 – 420 W per square meter, it does not compare well with areas deemed to have excellent wind resources (See Fig. 1.19).

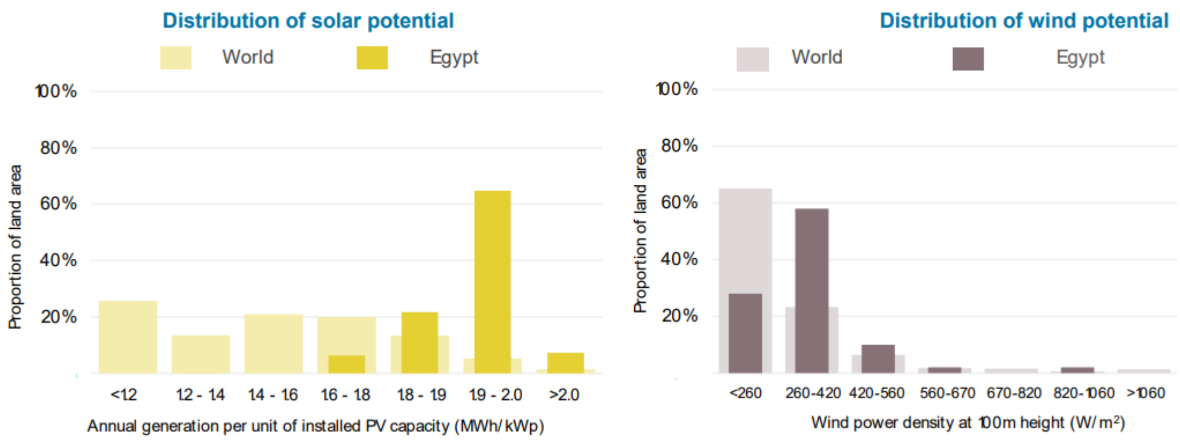

Figure 1.19 Egypt Installed Capacity Trend

Source: IRENA Energy Profile

3.2.4 Electricity Access in Egypt

In 2022, a report published from the World Bank Group reveals that access to electricity was 100%. See Fig 1.20

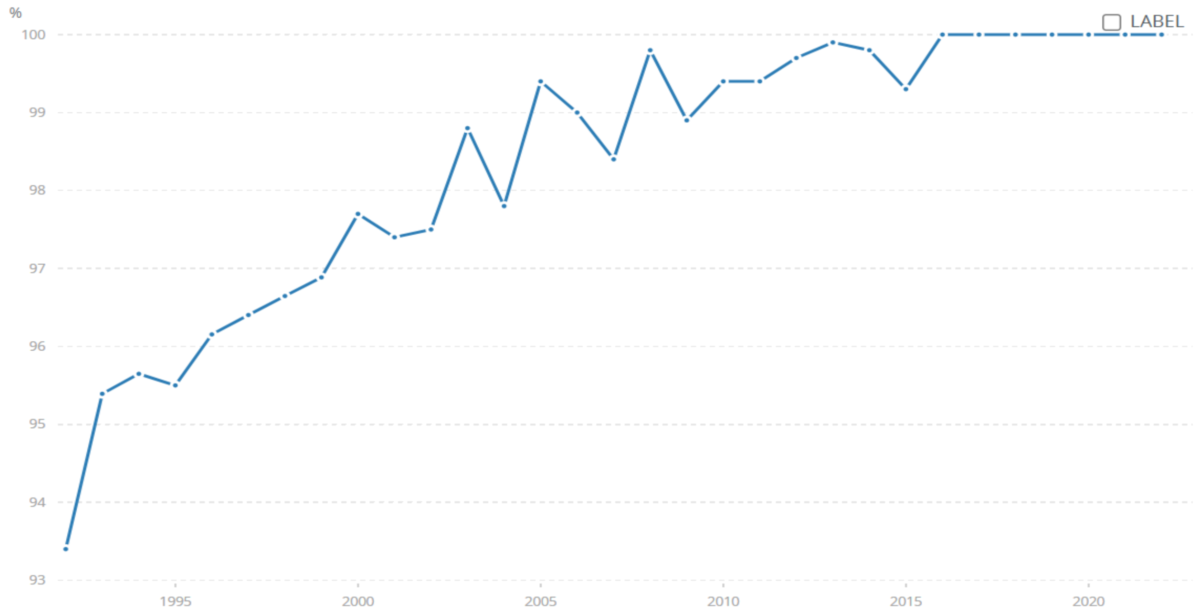

Figure 1.20 Egypt Electricity Access from 1992 to 2022

Source: World Bank Group

3.3 Egypt Water Availability

Egypt's freshwater resources are limited and potential for improvement is equally limited. Egypt is an arid country, with a rapidly growing population driving water demand beyond its annual supply. According to Falkenmark Water Stress Indicator, Egypt has reached a high and chronic water scarcity level that restricts its ability to accomplish economic development goals (Wahba, Scott, and Steinberger 2018 p.1).

3.4 Land Availability in Egypt

Egypt, with a population of approximately 100 million people, is the 14th most populated country in the world, the 3rd largest in Africa and the largest Arab country ("Worldometer" 2025). It has a total land area of almost 1 million km^2 of which nearly 96% is uninhabited desert (Sayed Embabi 2017 p.3). The combination of unbalanced distribution and dramatic population growth (around 2% annually) has caused severe socio-economic problems including a reduction in living standards, high levels of unemployment, and increasing crime rates (Radwan et al. 2019 p.2).

The ratio between human resources and land resources is a critical issue in Egypt. Such a high annual rate of increase in population means that considerable attention needs to be given to preserve the limited land resources to optimize agricultural productivity, and to help conserve the highly fertile soil of the Nile Delta which is the primary source of staple cereal crops for the nation (Radwan et al. 2019 p.2).

The history of capitalism in Egypt has long been synonymous with cotton cultivation and dependent development. Egypt's dependent development refers to a historical pattern where its economy became heavily reliant on external forces, particularly U.S and European powers, for trade, investment, and economic policies (Abd and Hamid 2013 p.1). This dependence led to various consequences, including increased debt, a focus on export crops like cotton, and limited industrialization.

Figure 1.24 below shows the percentage variation in Egypt employment as of June 2023 for the different sectors. However, amongst all sectors, agriculture is the greatest employer (18.8%).

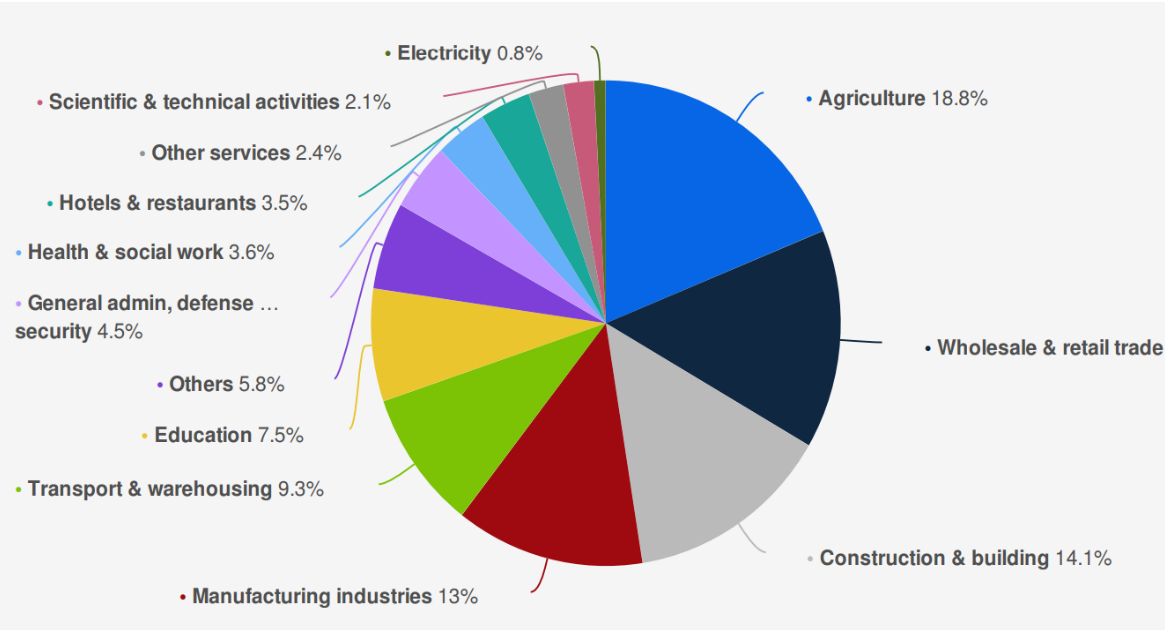

Figure 1.21 Distribution of employment in Egypt as of June 2023 by sector

Source: CAPMAS (Egypt) © Statista 2025

3.5 Education and Employment

According to projections by the IMARC Group, Egypt's education market is expected to grow significantly, reaching approximately USD 615.90 million by 2033, with a compound annual growth rate (CAGR) of 21.89% during the forecast period of 2025 to 2033 (IMARC, 2025).

This projected expansion is driven by several interrelated factors, including the increasing demand for a skilled labor force, rising public investment in the education sector, the continued growth of private educational institutions, demographic pressures linked to a growing youth population, and the strategic emphasis on international collaboration and technological integration within academic programs (IMARC, 2025).

The total labor force in Egypt increased yearly by 2.9% (Statista 2025) , rising from 31.149 million in 2023 to 32.041 million individuals in 2024. Of this workforce, approximately 26.08 million were male and 5.961 million were female. Urban labor force participation also experienced growth, reaching 44.0% in 2024, compared to 42.7% in the previous year.

4.0 Kenya

The Republic of Kenya is located on the eastern side of the Continent of Africa where it is bounded by the Indian Ocean, which serves as an important drainage outlet for the entire East and Central Africa and provides means of international maritime contact. Kenya shares borders with the Republic of Uganda in the west, united Republic of Tanzania in the south, Sudan and Ethiopia in the north, and Somalia in the east. The country covers an area of about 592,000 km^2, lakes occupy about 11,200 km^2 (2%) while arid and semi-arid lands occupy about 490,000 km^2 (83%). According to the World Health Organization, in 2023, Kenya's population was approximately 55.3 Million people and an annual growth rate of 2%.

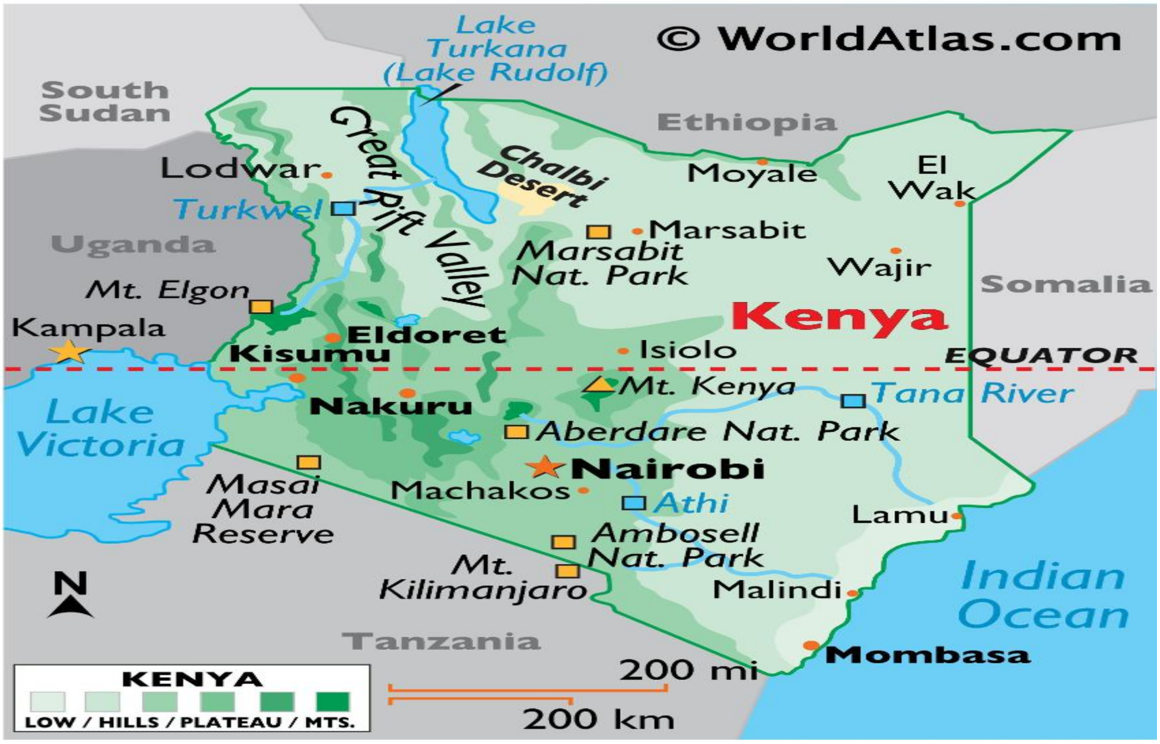

Figure 1.22 Map of Kenya showing geographical names mentioned

Source: WorldAtlas

4.1 Kenya Energy Mix

The major players in the Kenya energy market are oil companies and electricity utilities. Wood used for fuel supplies the primary energy needs in remote areas, to low-income urban dwellers through informal markets. The national energy review shows that 68% of the country's total energy consumption comes from wood and other forms of biomass. In comparison, oil accounts for 22%, electricity for 9%, and all other sources make up the remaining 1%.

Kenya is a leader in East Africa for expanding electricity access, increasing from 37% in 2013 to 79% in 2023. The country is on track to achieve universal access by 2030, and urban electrification has already reached 100%. However, affordability of electricity remains a challenge (Ministry of Environment and Gender Equality 2023).

Table 1.6 below provides an overview of Kenya's generation mix as of 2019. It suggests that only 28% of the generation comes from geothermal energy while the rest is based on hydropower, solar, wind and bioenergy. (See Table 1.6)

Table 1.6 Generation Mix 2019

Generation Type	2019 / MW	% Contribution
Hydro	837.00	29.00
Geothermal	823.00	28.00
Solar	95.00	3.00
Wind	336.00	11.00
Bioenergy	88.00	3.00
Total Renewable	**2,178.00**	**74.00**
Non - Renewable	**750.00**	**26.00**
Total Capacity	**2,929.00**	**100.00**

Source : (World Health Organization, 2023)

Table 1.7 Division of Kenya's energy demand in sectors in 2017

Sectors	Energy Consumption
Residential	77% of final consumption
Transport	14%
Industry	7%
Commercial and Public	1%
Agriculture and Forest	Less than 1%

Source: (World Health Organization, 2023)

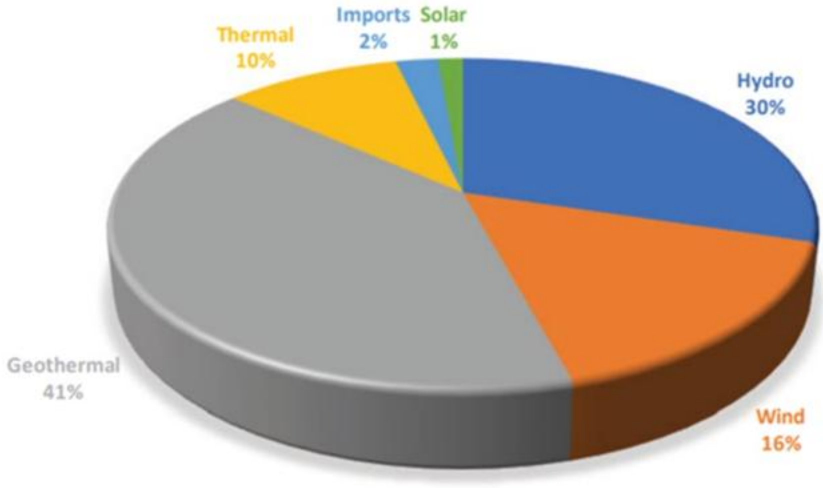

Figure 1.23 Proportion of Electricity Generation by Source in Kenya, 2021

Source: Kenya National Bureau of Statistics

4.3 Kenya Renewable Energy Potential

Kenya has promising potential for power generation from renewable energy sources. Abundant solar, hydro, wind, biomass and geothermal resources has led the government to seek the expansion of renewable energy generation in both urban and rural areas. Currently, the government has prioritized the development of geothermal and wind energy plants (Sustainable Environmental Development Watch Kenya 2023 p.10) as well as solar-fed mini-grids for rural electrification. The Kenyan government is prioritizing geothermal and wind due to their abundant resources potential, low cost, reliability and attractive investment opportunities (Ministry of Environment and Gender Equality 2023).

4.3.1 Wind Power

Kenya has promising wind power potential. In the windiest areas, where the annual capacity factor (CF) for wind turbines is above 40%, the potential wind power production is estimated to 1,739 TWh/year (World Health Organization 2023q). In areas with Capacity Factor (CF)> 30%, the potential production is estimated to 4,446 TWh/year while if all areas with CF > 20% are included, the potential production is estimated to an impressive 22,476 TWh/year which makes up 12% of Africa’s wind power potential (Ministry of Environment and Gender Equality 2023).

Presently, the Lake Turkana Wind Power Project (LTWP) and the Ngong Hills Wind Power Project are the only grid-connected wind farm, with capacities of 310 MW and 25.5 MW respectively (Sustainable Environmental Development Watch Kenya 2023 p.14). The LTWP is the largest wind power plant in Africa having achieved full commercial operation in March 2019 (Ibid, 2023). Rift Valley contains the two large windiest areas (average wind speeds above 9 m/s at 50 m altitude). The coast is also a place of interest though the wind resources are less substantial (average wind speeds about 5-7 m/s at 50 m altitude).

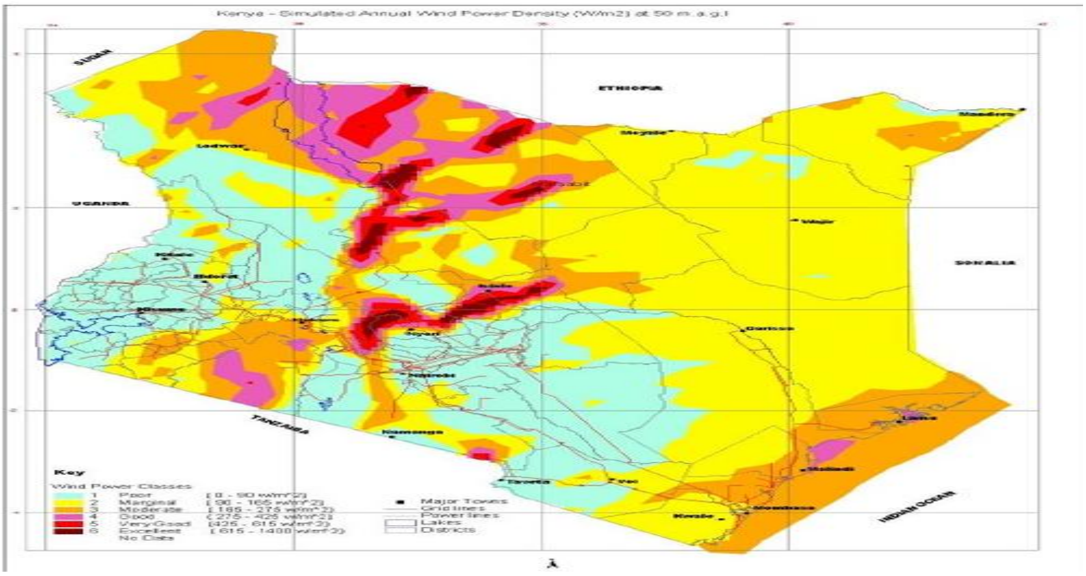

Figure 1.24 The Map showing standard wind power density at 50 m above ground in Kenya

Source: Kenya Country Report: Solar and Wind Energy Resource Assessment by UNEP co-financed by GEF, 2008,

4.3.2 Solar Energy

Kenya has great potential for the use of solar energy throughout the year because of its location near the equator with 4 to 6 kWh/m^2/day of insolation. Now the installed capacity is more than 100 MW with the largest installation, Garissa Solar power project, accounting for 55 MW capacity. According to Kenya's Institute for Public Policy Research and Analysis (KIPPRA), Kenya achieved notable progress in its energy transition in 2021, with approximately 88% of the country's electricity generation derived from renewable energy sources.(See Fig 1.25).

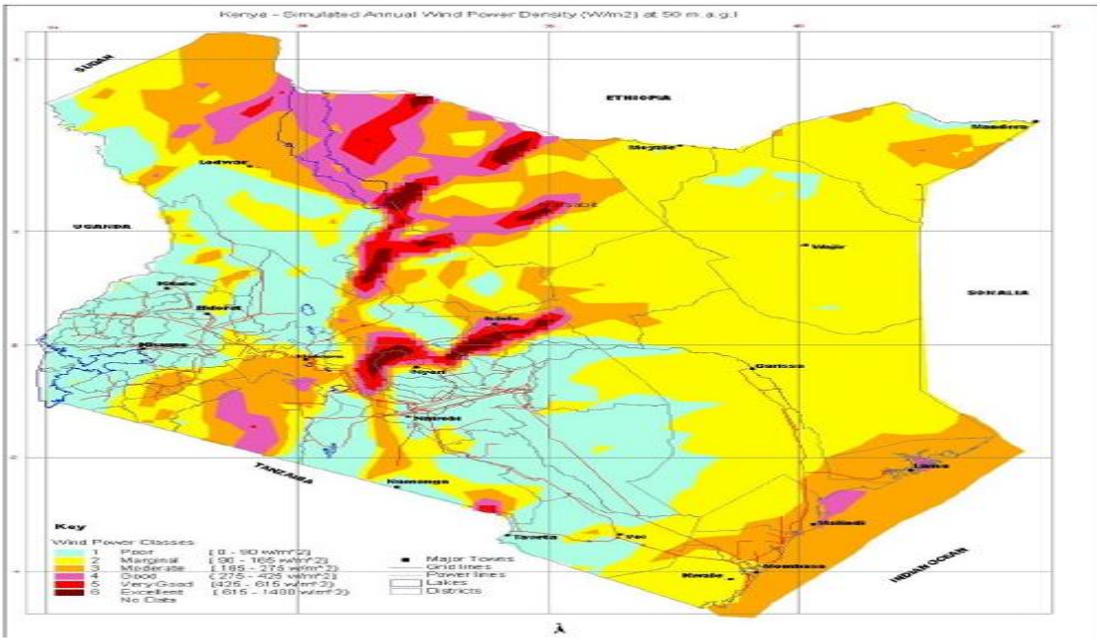

Figure 1.25 Map showing direct solar irradiation in Kenya

Source: GeoModel Solar

4.3.3 Hydropower

Kenya has a well-developed hydro power sector with installed capacity of 826 MW. In 2017, hydro electricity production was 4.45 TWh. The country has an estimated hydropower potential of up to 6,000 MW comprising large hydro (sites with capacity of more than 10MW) and also a potential of small hydro, but several of the small sites are expensive to develop or comes with considerable environmental issues (Sustainable Environmental Development Watch Kenya 2023 p.18).

Kenya has moderate annual solar generation potential per unit of installed PV capacity at around 1.6 to1.8 MWh / KWp. This makes Kenya a favored location for PV investments. With respect to wind power, Kenya has excellent potential rated at 260 – 1060 W per square meter and compares well to areas with excellent wind resources (See Fig. 1.26).

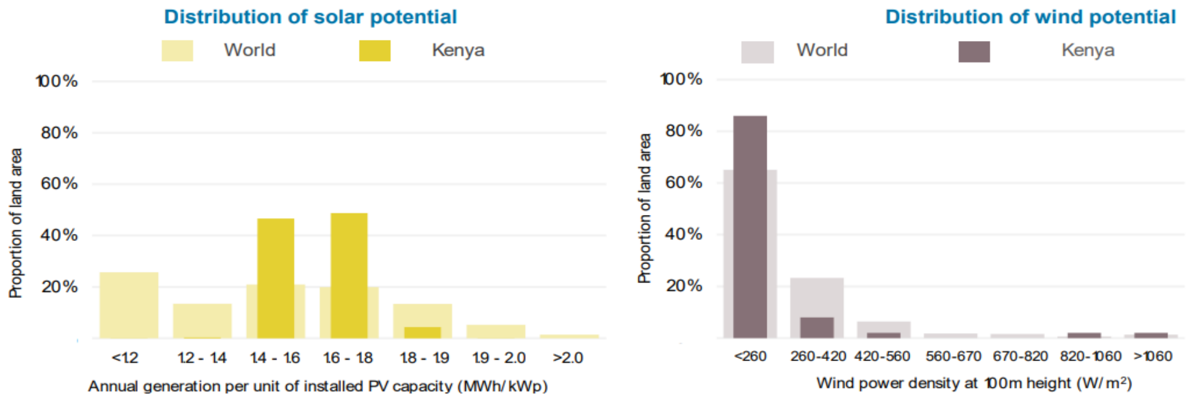

Figure 1.26 Kenya Installed Capacity Trend

Source: Liberia Energy Profile

4.4 Kenya Water Availability

Kenya is classified as water-scarce, with only 452 m^3 of freshwater per person annually, far below the UN threshold of 1,000 m^3. About 40% of the population lacks access to safe drinking water within a short distance (200m). With expected population growth and economic expansion, per capita water availability could halve, posing a serious challenge to water-intensive processes like e-fuel production (Ministry of Environment and Gender Equality 2023).

4.5 Land Availability in Kenya

Kenya is the most recent African state to acknowledge customary tenure as lawful property rights, not merely rights of occupation and use on government or public lands. This promises land security for 6 to 10 million Kenyans, most of whom are members of pastoral or other poorer rural communities. Most of the information in this section derives from Kenya's Community Land Act, 2016, the framework through which customary holdings are to be identified and registered (World Health Organization 2023aa).

While Kenya's land law is progressive in many respects, legal ambiguities and overlapping claims between national and local authorities pose risks to community land tenure (World Health Organization 2023aa). These issues, coupled with limited political will for enforcement, threaten the security and integrity of community lands during the formalization process (ibid, 2018).

However, farmers and investors in Kenya enjoy stronger and secure land rights, since customary communal land can be registered and legally managed, encouraging agricultural investment and enhancing food security (World Health Organization 2023aa).

4.6 Education and Employment

According to data from the World Bank and UNESCO, Kenya education system continues to evolve, particularly through the expansion of public secondary schools to accommodate rising demand. Simultaneously, the growth of private institutions offering British and American curricula reflects increasing preference among the urban middle class for alternative education models (Statista 2025).

Kenya's education system is structured across pre-primary, primary, secondary/vocational, and tertiary levels, as defined by the Kenya National Qualifications Authority. Each stage is designed to develop foundational competencies and prepare learners for successive academic and career pathways (Statista 2025).

In 2023, Kenya's employed population reached approximately 20 million, reflecting an increase of about 900,000 individuals from the previous year (Statista, 2025) . The majority of these workers approximately 16.7 million were engaged in the informal sector, while nearly 3.3 million (Statista, 2025) were employed in the formal sector. The informal sector plays a critical role in Kenya's economy, contributing significantly to employment generation, production, and income creation.

5.0 Comparative Analysis for e-ammonia and e-methanol production in Egypt, Kenya and Liberia

The table below presents key variables that illustrate each country's potential for the production of e-ammonia and e-methanol

Table 1.8 key variables for E-Methanol and E-Ammonia production

	Egypt	**Kenya**	**Liberia**
Solar potential	+++	++	++
Wind potential	++	+++	+
Water resources	++	++	+++
Land availability	+++	+++	+++

GDP per capita (000s $) (World Bank)	3.34	2.20	0.846
Growth rate in GDP per capita (%)	+0.6	+2.5	+ 2.6
Gini index (%)	28.5	38.7	35.3
Population electricity access (%)	100	77	32.5
Electric power consumption per capita (KWh)	1,415	191	71
Pre-existing industries (fuels or e-fuels)	+++	++	+
Industrial infrastructure	+++	++	+
Strength of legal framework (e.g., land ownership)	+	++	+++
Ease of navigating regulatory framework	+	+	++
Literacy rate	75%	83%	48%
Share of youth not in education, employment, or training (%)	24.6	18.7	40.7
Ease of doing business Index	114	56	175
Sovereign Risk Indicator (Standard and Poor's)	B-	B-	N/A

+++ - excellent; ++ - good; + - poor

6.0 Economic Analysis of Green Hydrogen Production

We consider a scenario in which a designated locality operates an off-grid energy system exclusively dedicated to e-methanol and e-ammonia production. It is further assumed that the examined countries establish partnerships with Germany for exporting both e-methanol and e-ammonia. Under this arrangement, Germany is assumed to finance both the power generation infrastructure and the electrolyzer capacity required for hydrogen production.

Based on the RE Potential of the studied countries, the proposed total system capacity in our modelled scenario shall be 50MW. Liberia and Egypt will harness this capacity entirely from solar power while for Kenya, ¾ will be harnessed from solar power and ¼ from wind power. An economic analysis of the system follows below.

6.1 Solar PV Module

Given the huge R. E potential in Liberia, the proposed system capacity will be 50MW and the rated capacity of PV module to be used is 400W. In this context, System capacity is the total power output of the system and while rated capacity is the power output per PV module.

Therefore, the number of PV module required $= \frac{\text{Total System Capacity (W)}}{\text{Power(W)/Module}}$

$$= \frac{50000000\text{W}}{400\text{W}}$$

$$= \mathbf{125,000\ No.\ of\ PV\ Module}$$

To account for efficiency losses we add 25% to the number of PV modules obtained.

So, we have 125,000 x 1.25 $= \mathbf{156,250\ numberof\ PV\ modules\ required.}$

6.2 Land Required (Solutions, n.d.)

Land Required (m^2) $=$ No. of PV Modules x Area per Module

Area per Module = 2.5 m^2

Land area Required (m^2) = 156,250 x 2.5m^2

Therefore, Land Required = 390625m^2

6.3 Water Electrolysis

In this case, $2H_2O \longrightarrow 2H_2 + O_2$

We assume that if 1MWh of electricity is used to decompose 180kg of H_2O, how many mass(kg) of H_2 will be produced?

Molar mass of $H_2O = 18\text{g/mol}$

Molar mass of $H_2 = 2\text{g/mol}$

We rely on the stoichiometry of the water electrolysis reaction shown above to find the quantity of H_2 that will be produced. The results for an annual run for the e-fuels (e-methanol and e-ammonia) facility are displayed in AnyLogic.

6.4 CO_2 Capture System

There are several carbon-capture technologies which have been proposed for use in the cement industry (World Health Organization 2023f). However, based on their technology and commercial development level, and the major challenges facing the retrofitting of existing cement plants, direct air capture is selected. DAC is very close to commercial maturity. Currently, a commercialized DAC plant in Switzerland captures CO_2 from air at the cost of $500-$600/ton (World Health Organization, 2023). DAC also presents real benefits in terms of permanent reduction in GHG emissions relative to the use of CO_2 recycled from industrial waste (e.g., cement, steel).

Table 1.9 Proposed specification of CO_2 Separator Plant

Specification of the proposed CO_2 Separator Plant	
CO_2 Separator System to be used	DAC
Technology readiness Level (TRL)	TRL 7
Typical Capture Rate	90 <
Retrofitting or brand new?	Retrofitting
Operational Lifetime	25 years
Power source of DAC Separator System	Renewables (Solar and / or Wind)

6.5 Nitrogen (N_2) Separator System

The are few available processes used to produce nitrogen but this case study focuses on the Pressure Swing Adsorption Technique. This is a process by which gases from a mixture can be separated. However, the method requires high pressure, which is an energy-intensive process (Benn 2023). The table below provides key specifications of the proposed PSA plant.

Table 1.10 Proposed Specification of Nitrogen Separator Plant

Specification of the proposed Nitrogen Separator Plant	
Nitrogen Separator System to be used	Pressure Swing Adsorption (PSA)
Technology readiness Level (TRL)	TRL 9
Typical Capture Rate	[90 - 99]
Retrofitting or brand new?	Retrofitting
Operational Lifetime	20 to 30 years
Power source of Nitrogen Separator System	Renewables (Solar and / or Wind)

6.6 Wind power (12.5MW)

For Kenya, a quarter of the capacity of 50 MW will originate from wind power. A wind turbine of rated capacity 2.5 MW is selected as the reference for the case study.

$$\text{Number of Wind Turbines} = \frac{\text{System Size (MW)}}{\text{Turbine Rated Capacity (MW)}}$$

$$\text{Number of Wind Turbines} = \frac{12.5\text{MW}}{2.5\text{MW}}$$

$$\text{Number of Wind Turbines} = \mathbf{5\ No.\,of\ Turbines}$$

6.7 Land Required (m^2) (Benn 2023)

For the proposed land required, 'we will use the Scout Moor Wind Farm' as an example. This site is located in North-West England and occupies an area of 1,347 acres of open Moorland with a total capacity of 65MW.

Based on the proportion (1,347acres:65MW), the land required for a 12.5MW Wind Farm will be approximately $\mathbf{83,863.40\ m^2}$ **/ MW**

7.0 Methodology

7.1 Study Area

With an emphasis on the infrastructure requirements, renewable energy potential, water availability, land tenure, Carbon Capture and Nitrogen Separation Technologies used, operation expenditure, revenue and levelized cost will ensure a more realistic computation in terms of the profit, associated with deployment of e-methanol and e-ammonia in the shipping sector.

In order to carryout all of the above, we will use AnyLogic (a simulation software) to analyze the system. This software allows to model a project from an engineering and economic perspective.

Table 1.11 and Table 1.12 provides the main technical assumptions as well as CAPEX and OPEX components:

Table 1.11 Assumptions considered in the Model for E-Ammonia Production

	Power Source		Energy Distribution					
City / Production Sites	Solar Capacity	Wind Capacity	H_2 Share	N_2 Separation	N_2 Separation Tech.	PSA (TRL)	N_2 Capture Rate (%)	PSA Oper. Lifetime (yrs)
Monrovia / Somalia Drive	50MW	0	0.7 * Energy	1-H_2 Share	PSA (Retrofitting)	TRL-9	90-99	20-30
El Arish	50MW	0						
Bamburi	37.5MW	12.5MW						

	Land Rental Cost (€ / m^2)	Electricity Cost (€ / KWh)	Water Cost (€ / Kg)
Monrovia / Somalia Drive	8	0.22	0.012
El Arish	0.27	0.041	0.0000014
Bamburi	15.81	0.2	0.00176

Table 1.12 Assumptions considered in the Model for E-Methanol Production

	Power Source		Energy Distribution					
City / Production Sites	**Solar Capacity**	**Wind Capacity**	**H_2 Share**	**CO_2 Separation**	**CO_2 Separation Tech.**	**DAC (TRL)**	**DAC Capture Rate (%)**	**DAC Oper. Lifetime (yrs)**
Monrovia / Somalia Drive	50MW	0	0.7 * Energy	1-H_2 Share	DAC (Retrofitting)	TRL-7	90 <	25
El Arish	50MW	0						
Bamburi	37.5MW	12.5MW						

	Land Rental Cost (€ / m^2)	Electricity Cost (€ / KWh)	Water Cost (€ / Kg)
Monrovia / Somalia Drive	8	0.22	0.012
El Arish	10	0.041	0.0000014
Bamburi	15.81	0.2	0.00176

These technical assumptions are modified in AnyLogic by sliders to accommodate the scenario runs that correspond to the three countries specific circumstances. In this way, our model's end results are tailored at the country level.

7.2 Data synthesis and presentation

The key findings and common themes extracted from the included studies were summarized, and a thorough analysis of renewable energy sources, Falkenmark (Water Stress Threshold), Carbon Capture and Nitrogen Separation Technologies, opex, revenue, Levelized Cost of E-Methanol and E-Ammonia, operating profit, associated challenges and disadvantages of the studied P2X Carriers (e-methanol and e-ammonia) was conducted. Studies were grouped by country's energy scenarios, Water Resources Availability, Land Tenure System, Techno-economic analysis, Results and Discussion to facilitate meaningful synthesis. The results were presented using tables, graphs, and narrative summaries to illustrate the key findings effectively.

8.0 Results and Discussion

Quantitative modelling through AnyLogic was used to determine which P2X carrier and which location ensures the most profitable and environmentally beneficial production (cradle-to-gate) of the e-fuel for use in the shipping industry.

From the specifications and assumptions made in Table 1.12 and Table 1.13, all parameters were modified in AnyLogic by sliders to accommodate the scenario runs to the country's specific circumstances. In this way, our model's end results are tailored at the country level.

However, our entire analysis began with the process of electrolysis in which electric current is being used to decompose water molecule into Hydrogen and Oxygen. As per the total energy produced, 70% is used to produce Hydrogen and 30% for the capture and gas separation technology used (See Table 1.12 and Table 1.13). We assume that if we use 1MWh of electricity to break down 180Kg of water; theoretically hydrogen obtained will be 20Kg, but assuming associated losses and the specific electrolysis technology, 18.898Kg of Hydrogen will result. Also, we considered both the rate at which Nitrogen was being separated from air ($3.33m^3$/KWh) and CO_2 capture rate ($0.001m^3$/KWh). In our model, we expressed the amount of nitrogen, carbon dioxide and hydrogen produced daily in moles.

In order to answer the research question, we have considered the associated cost components such as CAPEX, OPEX, Revenue, $LCO_{E\text{-}MeOH}$, $LCO_{E\text{-}NH3}$ and Operating Profit. Our CAPEX Component include several subcomponents such as Power, Land, Electrolyzer, Installation, E-Ammonia and E- Methanol Storages, Water Transmission, DAC and PSA Plants. OPEX Components included costs such as Maintenance, Water and Salary.

Given the maritime sector's increasing acceptance of the cost premium associated with green hydrogen-derived fuels, we assume that there will be willing buyers to take up green methanol and green ammonia in the early stages while accounting for its environmental benefits (Yunfei Du, Xinwei Shen 2025). Also, in order to ensure an error-free model, equations are written in a way that is understandable by the model. Each country run in our model lasted for 365 days.

Table 1.13 and Table 1.14 below provide a summary of results from AnyLogic to produce E-Ammonia and E-Methanol (Cradle to gate).

Table 1.13 Results from AnyLogic – E-Ammonia Production

E-AMMONIA PRODUCTION			
Results	**Kenya**	**Liberia**	**Egypt**
CAPEX (€)	151,860,505.02	125,122,375.59	126,153,294.33
OPEX (€/a)	3,397,549.69	3,210,356.61	3,610,000.04
Revenue (€/a)	20,004,904.88	17,569,406.13	18,062,180.09
$LCO_{E\text{-}NH3}$ (€/Kg)	5.79	4.67	4.83
Price (€/Kg)	6.79	5.67	5.83
Annual Yield (Kg/a)	2,948,874.79	3,099,207.29	3,099,207.29

Table 1.14 Results from AnyLogic – E-Methanol Production

E- METHANOL PRODUCTION			
Results	**Kenya**	**Liberia**	**Egypt**
CAPEX (€)	112,132,546.38	85,991,125.25	86,710,297.29
OPEX (€/a)	3,397,549.69	3,210,356.61	3,610,000.04
Revenue (€/a)	19,591,402.80	17,358,519.75	17,826,456.21
$LCO_{E\text{-}MeOH}$ (€/Kg)	2.21	1.71	1.78
Price (€/Kg)	3.21	2.71	2.78
Annual Yield (Kg/a)	6,093,091.46	6,410,088.53	6,410,088.53

9.0 Conclusion

In conclusion, P2X Carriers (E-Methanol and E-Ammonia) are economically feasible for production in Egypt, Kenya and Liberia. Meanwhile, these three (3) countries represent different landscapes in e-fuels, with Egypt being at the most advanced stage and already having some e-ammonia and e-methanol plants in place; Kenya has significant investments in renewable power (wind, solar) (World Health Organization 2023ah), but lags in e-fuels. Liberia represents a landscape with little industrial presence and no e-fuels production; however, it has the renewable potential to be a future production site for them. Although the economic feasibility of these P2X Carriers depends on series of variables, our analysis shows that a handful of variables such as land rental cost, water cost and salary were of highest relevance in determining project profitability at the country level.

Green methanol, characterized by relatively low production costs and well-established synthesis and utilization technologies, is increasingly recognized as a leading candidate for large-scale alternative fuel applications (See Table 1.13 and Table 1.14).

However, the urgent need for low-emission alternatives in maritime transportation is opening new avenues for the application of green hydrogen. In response to regulatory pressures and sustainability commitments, the shipping industry is progressively accepting the cost premium associated with green hydrogen-based fuels (Yunfei Du, Xinwei Shen 2025)

10.0 Limitations

The analysis is subject to several limitations that may influence the accuracy and generalizability of the findings:

I. Some data are reported in different formats and there is need for unit conversion (e.g., \$/acre to €/ m^2, EGP/l to €/Kg etc) – This introduces some error.

II. Difficulty in obtaining Construction and Litigation Costs which are also components of CAPEX

III. No consideration of seasonality changes (Wind speed, Solar Irradiation) and geographical specifications

IV. Relying on theoretical yields of reactions (E-Ammonia, E-Methanol Syntheses, etc)

V. Difficulty in obtaining most recent data

VI. Several top-down assumptions about jobs created per MW capacity and salary level. Usually this information is reported at global or continental scale, which introduces estimation errors.

11.0 Findings

From an economic perspective and based on our simulations conducted using the AnyLogic model, Liberia exhibits the highest economic profitability and the greatest annual yield of e-ammonia among the three countries analyzed, followed by Egypt and Kenya.

Although all three countries demonstrate economic feasibility and comparatively high e-methanol production yields, Liberia again outperforms the others in terms of both profitability and output, with Egypt and Kenya ranking second and third, respectively.

12.0 Recommendation

Based on the comprehensive analysis of economic simulations through AnyLogic and scientific literature, the following recommendations are provided:

I. Prioritize Liberia for Initial Investment and Scaling

Given Liberia's consistent economic superiority in both e-ammonia and e-methanol production (lowest LCOE, highest annual yield, and profitability), it should be prioritized for initial large-scale investments in power-to-X facilities. This strategic focus will maximize economic returns and establish a robust supply chain for green shipping fuels.

II. Develop Egypt as a Secondary Hub with Strategic Focus

Egypt presents a strong second-best option, particularly for e-methanol, with economic metrics closely approaching Liberia's. Strategic investments in Egypt should leverage its existing and planned green energy infrastructure and its geographical advantage for bunkering in the Suez Canal region. Focus should be on optimizing production processes to further reduce LCOE and enhance competitiveness.

III. Invest in Research and Development for Kenya

While Kenya currently lags economically, its potential for renewable energy should not be overlooked. Investments should be directed towards research and development to identify and mitigate the factors contributing to its higher LCOE and lower yields. This could include exploring novel production technologies, optimizing renewable energy integration, and developing supportive policy frameworks to improve its long-term competitiveness.

IV. Emphasize Cradle-to-Gate LCA in Project Development

For all projects, a rigorous cradle-to-gate LCA must be integrated into the planning and operational phases. This ensures that the environmental benefits are maximized by selecting the most sustainable production pathways, optimizing energy efficiency, and minimizing fugitive emissions (e.g., N_2O from ammonia production). Continuous monitoring and reporting of GHG emissions are essential for verifying environmental claims and achieving true decarbonization.

V. Implement Supportive Policy and Regulatory Frameworks

Governments in all three countries should develop and implement supportive policies, including carbon pricing mechanisms, lifecycle emissions standards and incentives for green shipping corridors. These policies will create a favorable investment climate, accelerate the adoption of e-fuels, and ensure that environmental benefits are realized across the entire value chain.

VI. Foster International Collaboration and Technology Transfer

Promote international collaboration and technology transfer to share best practices, accelerate technological advancements (e.g., in electrolyzer efficiency and CO_2 capture technologies), and reduce the overall cost of e-fuel production. This is particularly important for countries like Kenya to bridge the technological and economic gaps.

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14.0 Appendices

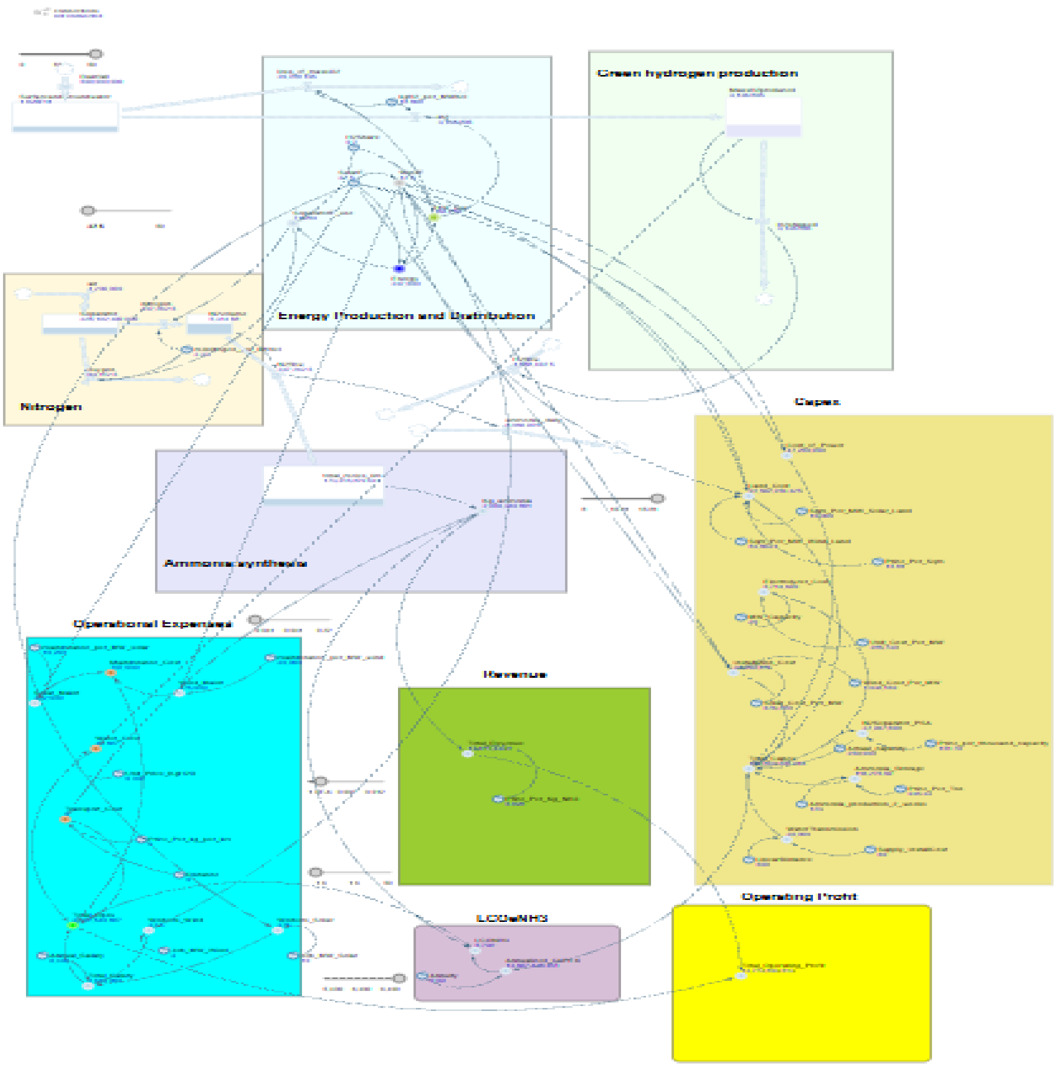
13.1 Key Parameters and Formulars used in AnyLogic

Key Parameters and Formulars used in AnyLogic				
Item #	**Description**	**Formular**	**Explanation**	**Sources**
1.00	Hydrogen (H_2)	H_2E Use * KgH_2 / MWh	Our assumed electrolysis process uses 1MWh. Mass of hydrogen produced per kWh available for producing H_2 (H_2E_use). so the flow is in kg of H_2.	
2.00	CapsysE_use	(1-H_2Share)*Energy	As per the distribution of our energy, we have proposed that 70% of the energy will be used for H_2 production while 30% will be used for capturing CO_2	
3.00	H2E_use	H_2Share*Energy	H2E_Use shall constitute 70% of the total energy	
4.00	Energy	WindE*1000*4+SolarE*1000*5	Amount of green energy is defined as sum of solar and wind energy. We defined it through a formula, deterministically, rather than through a probability. However, an average onshore wind turbine with capacity of 2.5MW to 3MW can produce more than 6,000,000 KWh in a yr and while for solar, 1MW capacity of solar utility farm can give about 4,000 KWh / day	European Wind Energy Association, bgb innovation, amplussolar
5.00	CO_2_Flow	CapsysE Use* m^3 CO_2 / kwhel	Using the DAC, 1000kwh is needed to capture 1ton CO_2 or 0.001$m^3$$CO_2$_per_kwh	Ozkan et al. 2024
6.00	Cost_of_Power	SolarE*0.87*1,000,000+WindE*1.17*1,000,000	0.87M euro / MW is the cost for solar and 1.17M euro / MW is the cost for Onshore wind	Danish Energy Agency
7.00	Land_Cost	Sqm_Per_MW_Solar_Land*SolarE*Unit_Price_Per_Sqm+Sqm_Per_MW_Wind_Land*WindE*Unit_Price_Per_Sqm	Both the area required for solar and wind turbine project differs and as such were computed separately and added to make up the total land to be considerd.	Benn 2023, Property Finder, jiji, Liberia Land Rights Commission
8.00	Electrolyzer_Cost	MW_Capacity*Unit_Cost_Per_MW	The proposed Electrolyzer shall have a capacity of 20MW and a production capacity of 335Kg H2 / hr. It is made up of 24-Stack and is referenced to the Trailblazer Project for Hydrogen production in Germany.	Siemens Energy

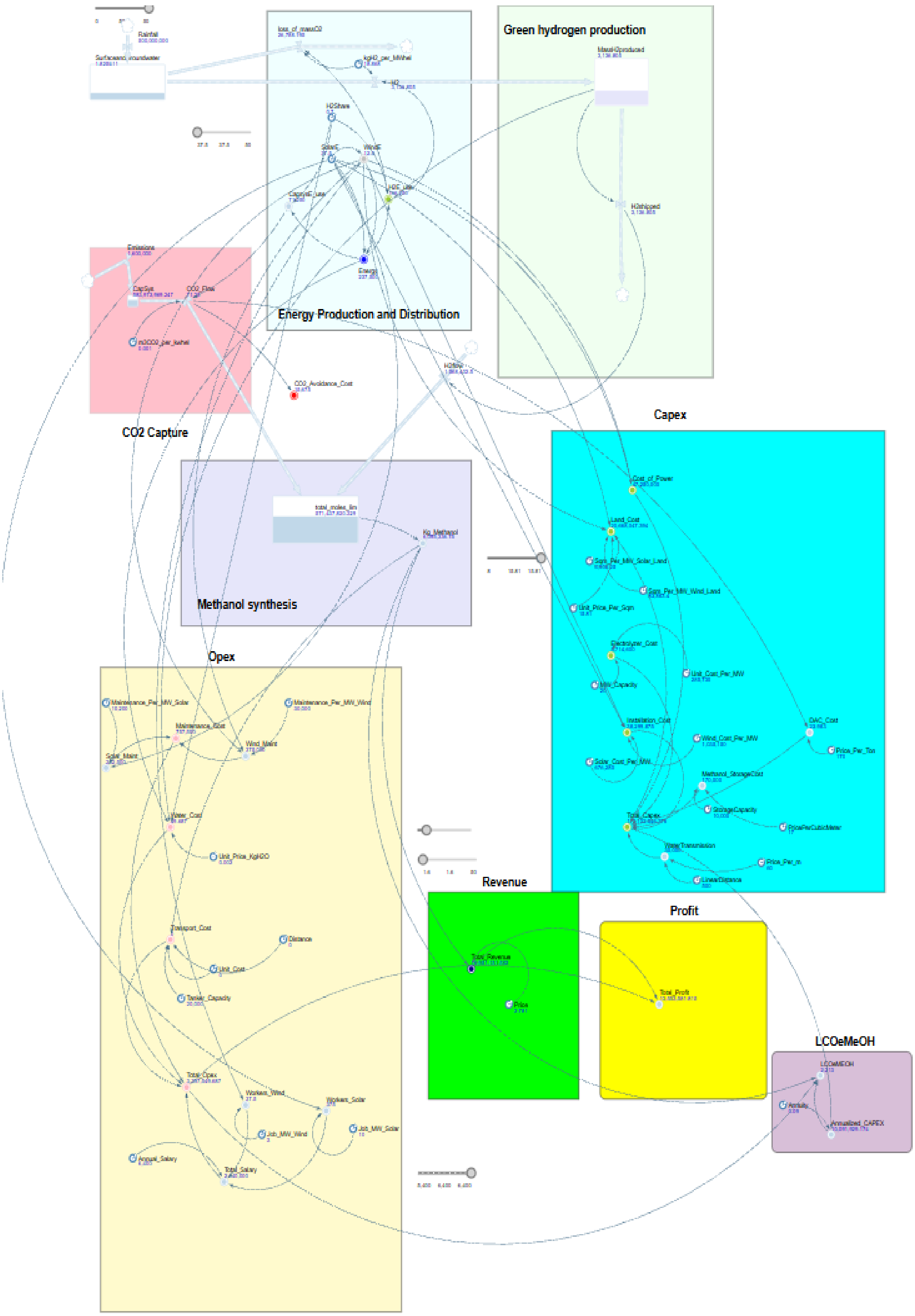
9.00	Installation_Cost	Solar_Cost_Per_MW*SolarE+Wind_Cost_Per_MW*WindE	In 2023, the average installation cost of Solar PV Systems stood at $758/Kw or 676280euro/MW.	IRENA-Renewable Power Generation Costs in 2023
10.00	Ammonia Storage	Tank_Capacity*Price_Per_Ton	We will allow a prime cost for the procurement of a 25 tons Ammonia storage tank.	lpggastankertruck.com
11.00	N_2Separator_PSA	Capacity*Price	We will install a PSA Separator of a capacity of 1000Nm^3/h that provides purity of 99.99%	Alibaba
12.00	Methanol_Storage Cost	StorageCapacity*PricePerCubicMeter	We have propose a storage capacity of 10,000m^3 since our daily production is less or equal to 14,049.51 Ton	Alibaba
13.00	Water Transmission	LinearDistance*Supply_InstallCost	For water transmission network, we assume that the distances from water point to production site shall be equal or less than 500m.	Jolly Plumbing
14.00	Total_Capex	Cost_of_Power+Land_Cost+Electrolyzer_Cost+Installation_Cost+N2Separator_PSA+Ammonia_Storage+WaterTransmission	Total CAPEX is the sum of all associated CAPEX components	
15.00	Maintenance_Cost	Solar_Maint+Wind_Maint	Maintenance Cost is the sum of both Solar maintenance and wind maintenance	solarpanel.org, UKRAINIAN WIND
16.00	Solar_Maint	SolarE*Maintenance_Per_MW_Solar	This refers to the cost require to carryout periodic maintenance for the solar utility farm.	
17.00	Wind_Maint	WindE*Maintenance_Per_MW_Wind	This refers to the cost require to carryout periodic maintenance for the wind farm.	
18.00	Water_Cost	0.18*H_2Share*Energy*Unit_Price_KgH_2O	We assume that 1MWh of electricity is used to decompose 180Kg of H_2O. Therefore, we can say that the cost of water is dependent on the energy used in the decomposition.	owl-research, Capitalfm, Richard Togbah, resident of Monrovia
19.00	Workers_Wind	WindE*Job_MW_Wind	Cummulative onshore wind turbine installed provides 1 to 4 Jobs per MW	G.J. Dalton, T. Lewis, 2011
20.00	Workers_Solar	SolarE*Job_MW_Solar	commercial and utility solar installations follow behind at 19 jobs created per MW	SEIA installation data for 2020
21.00	Total_Salary	(Workers_Wind+Workers_Solar)*Annual_Salary	The total average annual salary for renewable energy workers differs from country to country as in the case of Egypt, Liberia and Kenya respectively.	Economic Research Institute, Payscale, World Salaries
22.00	Total_Opex	Maintenance_Cost+Water_Cost+Transport_Cost+Total_Salary	Total Opex is the sum of all associated OPEX components	
23.00	Total_Revenue	(Kg_Methanol / Kg_Ammonia)*Price	Theoretically, Revenue is the product of price and quantity	
24.00	Total_Operating_Profit	Total_Revenue-Total_Opex	The difference in Revenue and Total OPEX yields Operating Profit	

13.2 A SWOT Analysis of Kenya, Egypt, and Liberia Regarding the Production of E-Methanol and E-Ammonia

Outlook	Egypt	Kenya	Liberia
Strength	High Solar Potential (Source: IRENA Energy Profile)	High Geothermal and wind energy potential (Source: IRENA Energy Profile)	Abundant water sources (Source: FAO Aquastat)
	Established Methanol, Ammonia and Fertilizer Industries (Methanex.com, https://ammoniaenergy.org/articles/renewable-ammonia-opportunities-in-egypt/	Access to port of Mombasa	Potentially available land
	Government support for Green Hydrogen (Source: Egypt vision 2030)	Established Ammonia Industry (Source: Lubello et al. 2025)	High Solar Potential (Source: IRENA Energy Profile)
	Strong Industrial Infrastructure (Source: Daily news Egypt)	Growing RE Sector (Source: IEA Report 2025)	Access to ports (Source: Yusuf et al. 2024)
	Strategic location (Suez canal)	Regional Trade Hub	May offer strong FDI incentives (Source: U.S Department of State)
Weaknesses	Water Scarcity especially inland areas (Source: Wahba, Scott, and Steinberger 2018)	High cost of electricity (Source: Steve Biko Wafula 2025)	Unstable power grid (Source: Liberia Electricity Corporation)
	Regulatory complexity (Source: Thiemann 1808)	Infrastructure gap in inland area (Source: International Trade Administration)	Limited skilled labor (Source: U.S Department of State)
	High competition with existing producers	Access to port of Mombasa	Weak industrial base (Source: Ministry of Commerce and Industry 2011)
Opportunities	Use excess solar power (Source: IRENA Energy Profile)	Regional Fertilizer supply gap (Source: Rahnema, Paola, and Otieno 2017)	Dunor and world bank interest in development projects
	Export e-methanol and e-ammonia to Europe (EU Green Deal Support)	support from International climate finance (Source: European et al. 2025)	Export e-methanol and e-ammonia to Europe (EU Green Deal Support)
	Leverage bilateral energy partnership (Source: Alexandra Gritz 2024)	Government Green Energy Policies (Source: IEA, 2024)	Potential to integrate Agri-Industrial zones
Threats	Regional political tensions (Source: Marchionna 2025)	Weather-dependent energy production (Source: Kariuki and Sato 2018)	High investor risk perception (Source: U.S Department of State)
	Water-Energy-Food tradeoffs (Source: International Food Policy Research Institute)	Bureaucratic delays (Source: Business Delay Africa)	Lower RE development progress



13.3 Design and Development of an AnyLogic Model for E-Ammonia Production in Kenya



13.4 Design and Development of an AnyLogic Model for E-Methanol Production in Kenya