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Article title

A Techno-economic Dataset for Climate, Land, Energy, Water, Waste, and Industry for all Sectoral Emissions (CLEWISE) modelling in Ghana

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Keywords

CLEWs modelling; dataset; sustainable development; Transition strategies; OSeMOSYS.

Abstract

As countries pursue low-emission development pathways, the need for integrated and evidence-based modelling approaches has become increasingly vital. Integrated system modelling, which captures the interlinkages between climate, land, energy, and water systems, offers a powerful framework for understanding the trade-offs and synergies that shape sustainable development. By reflecting these cross-sectoral dynamics, such models enable policymakers to design informed, cost-effective, and coherent decarbonization policies that align with both national development priorities and international climate commitments. The Climate, Land, Energy, Water, Waste, and Industry for all Sectoral Emissions (CLEWISE) approach serves as a cornerstone of this integrated perspective. It supports comprehensive analysis of the interdependencies between energy demand and supply, land use, water availability, and environmental impacts, offering critical insights for policymakers, industry leaders, and researchers alike. This article presents a comprehensive, open-access dataset developed to support the modelling of Ghana's Climate, Land, Energy, and Water systems and to inform the design of the country's Long-Term Low Emission Development Strategy. The dataset, publicly available on Zenodo, compiles detailed information on installed energy capacities, resource potentials, historical and projected electricity production and consumption, crop yields, agricultural and non-agricultural land use, water utilization, capacity factors, and key techno-economic parameters such as capital, fixed, and variable costs. Data were rigorously compiled from national institutions through a stakeholder engagement process, international organizations, and peer-reviewed literature, and are organized into a user-friendly Excel workbook for ease of use and transparency. Designed primarily for application with the open-source OSeMOSYS energy modelling framework and its graphical user interface, the dataset fully adheres to the U4RIA principles (Ubuntu, Retrievability, Repeatability, Reconstructability, Interoperability, and Auditability). ensuring openness, reproducibility, and interoperability. Furthermore, its structure allows for adaptation across multiple modelling frameworks.

SPECIFICATIONS TABLE

Subject	Climate, Land, Energy, Water, Waste, and Industry for all Sectoral Emissions (CLEWISE)
Specific subject area	Climate, Land, Energy, and Water systems modelling
Type of data	Table, Graph. Raw, Analyzed, Processed.
Data collection	This data has been collected from publicly available sources such as scientific literature, feasibility studies, international databases, data from existing modelling efforts in Ghana, and local stakeholders.
Data source location	Raw data sources are provided in Section 3 of this document
Data accessibility	Repository name: Zenodo.

List of Acronyms and Abbreviations

CLEWISE	Climate, Land, Energy, Water, Waste, and Industry for all Sectoral Emissions Ghana
CLEWISE-Gh	CLEWISE model
OSeMOSYS	Open Source Energy Modelling SYStem
U4RIA	Ubuntu, Retrievability, Repeatability, Reconstructability, Interoperability, and Auditability
GW	Gigawatt
PJ	Petajoules
GAEZ	Global Agro-Ecological Zones
BCM	Billion cubic meters
IRENA	International Renewable Energy Agency
D2D	Data-to-Deal
LT-LEDS	Long-Term Low-Emission Strategy
MUI	Model User Interface
MEST	Ministry of Environment, Science and Technology
NDPC	National Development Planning Commission
EPA	Environmental Planning Commission
RFO	Residual Fuel Oil
LPG	Liquefied Petroleum Gas
DVLA	Driver and Vehicle Licensing Authority
OECD	Organization for Economic Co-operation and Development
FAO	Food and Agriculture Organization
IPCC	International Panel on Climate Change
MoFA	Ministry of Food and Agriculture
IEA	International Energy Agency
ECOWAS	Economic Community of West African States
WAEIS	ECOWAS Energy Information System
GDP	Growth Domestic Products

EIA	Energy Information Administration
WRI	World Research Institute

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VALUE OF THE DATA

- This dataset aims to enable the continuation of modelling activities and in-country capacity building within Ghana, supporting evidence-based planning and decision-making.
- The dataset can be used to develop a long-term transition framework for Ghana and to explore the interconnections between land, food, water, and energy systems.

- It allows for the development and comparison of different scenario frameworks, providing useful insights for policymakers on sustainable development pathways.
- The data collection approach used in constructing this database helps to address existing data gaps in the literature, particularly in Ghana, by providing a functional CLEWs dataset for the country.
- It is an open-source dataset that can support efforts to mitigate challenges such as power shortages and water scarcity through better-informed policy design and project selection.
- The dataset can also inform national investment needs in key technologies and infrastructure projects, following the principles of the 'Data-to-Deal' framework [1].
- In addition, it can help development partners and private investors identify viable, high-impact opportunities aligned with Ghana's long-term sustainability goals.

1. Background

Growing attention to the energy, land, and water nexus arises from concerns about maintaining the sustainable availability and management of these interconnected resources amid increasing socioeconomic pressures and climate change impacts [2]. Integrated assessment of resource systems offers a valuable approach to support sustainable development-oriented decision-making by identifying potential trade-offs, opportunities, conflicts, and synergies across interconnected systems [3]. For effective long-term energy planning, accurate and accessible data are essential to enable robust energy systems modelling. In the context of a developing country such as Ghana, achieving sustainable development requires a holistic understanding of the interlinkages among Climate, Land, Energy, and Water systems. Modelling these interactions is essential for designing long-term strategies that address critical challenges, including energy access, food security, and water resource management, while simultaneously mitigating the impacts of climate change.

Despite the importance of such integrated approaches, many developing countries in Sub-Saharan Africa face persistent difficulties in obtaining accurate, comprehensive, and reliable data. Relevant datasets are often scarce, fragmented, or outdated, and in some cases, undocumented or unavailable. These data limitations arise from weak institutional data management systems, inconsistent reporting practices, and limited technical and financial capacity for systematic data collection [4]. Consequently, the effective application of energy modelling and the formulation of context-specific strategies for sustainable energy transitions remain severely constrained across much of the region [5].

Ghana has made significant progress in long-term development and climate planning through initiatives such as the Climate Prosperity Plan, the National Energy Transition Framework, and the Energy Transition and Investment Plan. However, the country is yet to develop its Long-Term Low Emission Development Strategy (LT-LEDS) that sets a vision for a low-emission and climate-resilient future, aligning with national priorities and the goals of the Paris Agreement. This study presents an open dataset developed to support Ghana's LT-LEDS and to enable integrated assessment analyses by researchers, practitioners, and policymakers. The dataset is intended to strengthen evidence-based modelling and support future research and policy design.

2. Description

This paper presents a dataset developed to model the interactions between Climate, Land, Energy, Water and Waste, Industry, and Sectoral Emissions (CLEWISE) in Ghana, utilizing the Open-Source Energy Modelling System (OSeMOSYS) framework. OSeMOSYS is a bottom-up optimization tool that offers a detailed representation of different technologies and system flows, considering performance, costs, resource use, and environmental impacts [6]. Although the dataset is compatible with OSeMOSYS, its Model User Interface (MUI), and Data-to-Deal (D2D) framework [1], it remains an independent, openly accessible resource that can also be adapted for other modelling frameworks. The dataset was compiled through a rigorous, collaborative data collection process involving national institutions, local consultants, and sectoral stakeholders, including the Energy Commission, Ministry of Environment, Science, and Technology (MEST), Environmental Protection Agency (EPA), and the National Development Planning Commission (NDPC). It integrates detailed information across multiple domains, including installed energy capacities, historical generation, capacity factors, technology lifespans, harvested and built-up land areas, forest cover, water bodies, crop production statistics, and water resource data such as availability, usage patterns, precipitation, groundwater and surface water, and evapotranspiration. In addition, it includes key techno-economic parameters covering capital, fixed, and variable costs. This dataset forms a robust foundation for evidence-based modeling and analysis, enabling researchers, policymakers, and practitioners to explore sustainable development and low-emission transition pathways. This resource enhances understanding of the complex interdependencies within Ghana's CLEWs and supports long-term strategic planning for the country's sustainable energy future.

2.1 Energy

This section presents the energy sector input and output data from the Ghana CLEWISE (CLEWISE-Gh) model. This includes installed generation capacity, historical and projected power generation, electricity import and export, capacity factors, renewable energy resources, transmission and distribution, and cost data.

2.1.1 Time Slices and Year Split

Ghana's load profile data for 2023 was obtained from the Energy Commission of Ghana and used to estimate the required year split for configuring the model, as shown in Table 2. Two seasons with eight time slices are currently represented in the CLEWISE-Gh model, with a dry season between November and March, a wet season from April to October [7]. Each season has a typical day represented by timeslices (peak, shoulder peak, intermediate, and base) that capture the daily fluctuation of electricity demand. This allows for a more accurate representation of daily load patterns and the operational dynamics of the power system across different seasons.

Table 2 : Year Split

Timeslice	Code	Season	Yearsplit	Days in Timeslice
Peak	S11	Dry Season	0.01724	151
Shoulder Peak	S12	Dry Season	0.0517	453
Intermediate	S21	Dry Season	0.1379	1208
Base	S22	Dry Season	0.20686	1812
Peak	S31	Wet Season	0.0244	214
Shoulder Peak	S32	Wet Season	0.0733	642
Intermediate	S41	Wet Season	0.1954	1712
Base	S42	Wet Season	0.2932	2568
Total			1	8760

2.1.2 Installed capacity

Table 3 provides a summary of historical generation capacity for power plants aggregated by technology/fuel type, based on data reported in the 2024 Ghana Energy Statistics [8]. This includes hydropower, thermal, and renewable energy power plants currently in operation in Ghana. Table 4 presents the residual capacity of individual power plants included in the CLEWISE-Gh model. These plant-level data were compiled from multiple sources and disaggregated according to the categories used in Table 3 to more accurately represent the country's generation technologies within the model. Table 5 reports the projected installed generation capacity, while Figure 1 depicts the evolution of total installed capacity in Ghana from 2020 to 2055. Detailed plant-level capacity data are available in the Ghana data sheet on the Zenodo repository

Table 3 : Historical Installed Capacity (Aggregated)

	Historical Installed Capacity (GW)								
Plants	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Hydro	1.584	1.584	1.584	1.584	1.584	1.584	1.584	1.584	1.584
Thermal	1.607	2.189	2.993	3.113	3.473	3.639	3.849	3.914	3.923
Renewables	0.023	0.023	0.023	0.043	0.043	0.059	0.112	0.112	0.133
Total	**3.213**	**3.795**	**4.599**	**4.740**	**5.100**	**5.282**	**5.545**	**5.610**	**5.639**

Table 4 : Residual Capacity (GW)

Technologies\Year	2020	2025	2030	2035	2040	2045	2050	2055
Biomass power plant	$1x10^{-4}$	$1x10^{-4}$	$1x10^{-4}$	$1x10^{-4}$	$1x10^{-4}$	$1x10^{-4}$	0	0
Large hydro power plant	1.584	1.584	1.584	1.584	1.584	1.584	1.584	1.584

Gas power plant (CCGT)	1.793	1.8	1.8	1.35	0.9	0.45	0	0
Gas power plant (SGCT)	1.856	2.123	2.123	1.59	1.06	0.53	0	0
Oil-fired gas turbine (SCGT)	0.37	0.37	0.37	0.2775	0.185	0.0925	0	0
Utility-scale solar PV	0.059	0.132	0.132	0.099	0.066	0.033	0	0
Off-grid distributed PV	0.0096	0.0024	0.0024	0.0018	0.0012	0.0006	0	0

Table 5: Installed Generation Capacity (GW)

Technology/Year	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**2055**
Biomass power plant	$1x10^{-4}$	$1x10^{-4}$	$1x10^{-4}$	$1x10^{-4}$	$1x10^{-4}$	$1x10^{-4}$	$1x10^{-4}$	$1x10^{-4}$
Gas power plant (CCGT)	1.79	1.942	2.77	3.77	5.11	5.89	7.16	8.55
Gas power plant (SGCT)	1.856	2.12	2.65	3.54	4.18	5.49	6.03	6.71
Landfill gas power plant	0.0	0.075	0.09	0.11	0.14	0.16	0.2	0.24
Large hydropower plant	1.584	1.584	1.584	1.584	1.584	1.584	1.584	1.584
Off-grid distributed PV	0.010	0.003	0.003	0.002	0.002	2.502	5.0	7.50
Oil-fired gas turbine (SCGT)	0.37	0.37	0.37	0.28	0.18	0.09	0.04	0.04
Utility-scale solar PV	0.06	0.132	0.132	0.90	1.2	1.5	1.8	2.8
Total	**5.67**	**6.23**	**7.59**	**10.19**	**12.40**	**17.23**	**21.80**	**27.43**

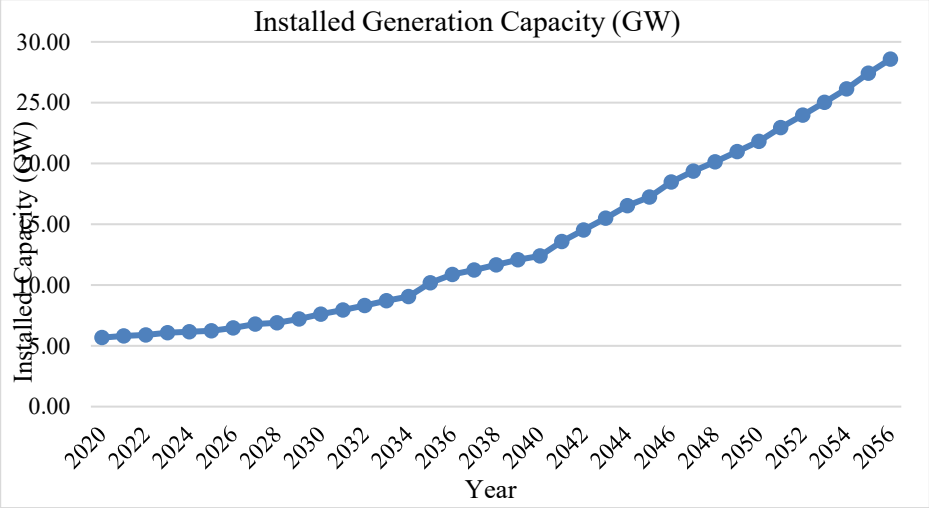


Figure 1: Annual Installed Generation Capacity from 2020 to 2056

2.1.3 Power generation

The power generation represents the electricity generated in Petajoules by the different installed power plants. Table 6 displays historical power generation on existing power plants associated with the installed capacity presented in Table 3. Table 7 presents the specific power plant electricity generation projection for key years in the CLEWISE-Gh model. Full power generation data are available in the Ghana data sheet on the Zenodo repository

Table 6: Historical Generation (PJ)

Plants	2015	2016	2017	2018	2019	2020	2021	2022	2023
Hydro	21.04	20.02	20.22	21.66	26.11	26.26	27.07	29.49	33.07
Thermal	20.32	26.76	30.33	36.70	39.22	46.13	51.90	53.35	53.75
Renewables	0.01	0.1	0.10	0.12	0.19	0.21	0.44	0.58	0.53
Total	**41.37**	**46.88**	**50.65**	**58.48**	**65.52**	**72.58**	**79.41**	**83.42**	**87.35**

Table 7: Electricity Generation for Key Years (PJ)

Technology	2020	2025	2030	2035	2040	2045	2050	2055
Biomass power plant	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
Gas power plant (CCGT)	21.42	52.05	74.21	101.24	137.08	157.84	174.37	193.6
Gas power plant simple cycle (SGCT)	24.74	12.43	12.43	12.42	12.41	12.41	12.40	12.39
Landfill gas power plant		2.37	2.88	3.49	4.25	5.16	6.27	7.61
Large hydropower plant	26.26	28.97	28.97	28.97	28.97	28.97	28.97	28.97
Off-grid distributed PV	0.06	0.014	0.014	0.014	0.014	14.2	28.38	42.57
Oil-fired gas turbine (SCGT)	1.99	1.02	1.02	1.019	1.019	1.018	1.018	1.017
Utility-scale solar PV	0.40	0.89	0.89	6.09	8.13	10.16	12.19	18.97
Total	**74.872**	**97.764**	**120.416**	**153.245**	**191.875**	**229.76**	**263.6**	**305.129**

2.1.4 Energy demand

Tables 8 to 11 present the total fuel consumption in different end-use sectors of Ghana from 2020 to 2023. The consumption data for each sector has been used to estimate demand and make the different projections for data integration into the model. Tables 12 and 13 present the estimated historical annual fuel demand for each end-use sector activity from 2020 to 2023, along with projection data for key years up to 2056. It is noted that fuels such as electricity, biomass, kerosene, and LPG are used in the residential and commercial sectors, with the addition of diesel, natural gas, and residual fuel oil (RFO) in the industry sector. The agriculture sector uses diesel and Premix, while the use of Gasoline and diesel dominates the transport sector. Detailed information can be obtained on the Zenodo repository.

Due to the lack of adequate country-specific data on the share of end-use fuel consumption by sector, some assumptions have been made to obtain the data in Tables 12 and 13. In the residential sector, biomass use is assumed to be primarily for cooking (70%), with the remaining 30% allocated to low-temperature heating. Liquefied petroleum gas (LPG) is evenly split between cooking and low heating, while kerosene is assumed to be used exclusively for cooking purposes.

Electricity use in households is distributed across multiple end uses, with 10% allocated to cooking, 10% to heating, and the remaining 80% used for other electrical appliances. In the commercial sector, both biomass and LPG are assumed to be used solely for low-temperature heating. Electricity consumption in this sector is allocated with 10% for low heating and 90% for other electrical end uses. In the industrial sector, natural gas, diesel, LPG, and residual fuel oil (RFO) are assumed to be used exclusively for high-temperature heating processes, while biomass is restricted to low-temperature heating applications. Electricity use in industry is divided among high-heating (10%), low-heating (10%), and other electrical equipment (80%). These end-use allocation assumptions are informed by findings from similar studies conducted in Ghana and reflect prevailing sectoral energy-use patterns [5].

Table 8: Fuel Consumption in the Residential Sector from Ghana Energy Balance (2020-2023)

Total energy consumption (energy balance) - PJ					
Sector	**Fuel**	**2020**	**2021**	**2022**	**2023**
Residential	**Biomass**	107.48	96.30	106.68	103.25
	Electricity	27.95	30.54	25.90	26.92
	Kerosene	0.21	0.21	0.17	0.13
	LPG	10.13	10.55	6.91	6.99
	Total	**145.77**	**137.60**	**139.66**	**137.29**

Table 9: Fuel Consumption in the Commercial Sector from Ghana Energy Balance (2020-2023)

Total energy consumption (energy balance) - PJ					
Sector	**Fuel**	**2020**	**2021**	**2022**	**2023**
Commercial and public services	**Biomass**	5.48	3.64	4.19	4.31
	Electricity	11.71	13.80	10.74	11.05
	LPG	0.963	1.05	0.88	0.921
	Total	**18.15**	**18.49**	**15.81**	**16.28**

Table 10: Fuel Consumption in the Industry Sector from Ghana Energy Balance (2020-2023)

Total energy consumption (energy balance) - PJ					
Sector	**Fuel**	**2020**	**2021**	**2022**	**2023**
Industry	**Biomass**	11.68	11.56	12.28	11.58
	Electricity	19.80	20.69	26.53	29.70
	DSL	14.11	17.35	17.47	16.80
	LPG	1.26	1.34	1.64	1.85
	RFO	1.97	3.23	2.14	3.23
	NGS	4.94	6.824	8.96	10.34
	Total	**53.76**	**60.99**	**69.02**	**73.50**

Table 11: Fuel Consumption in Agriculture and Transport Sectors from 2020 to 2023 (PJ)

Sector	Fuel	2020	2021	2022	2023
Agriculture	**Diesel**	2.97	2.6	2.48	2.68
	Premix	3.91	3.48	1.3	1.13
	Electricity	0.04	0.08	0.13	0.13
Transport	**LPG**	2.85	2.89	4.52	4.69
	Diesel	67.41	69.25	63.6	70.72
	Gasoline	67.11	75.24	70.13	74.78
	Electricity	0.042	0.042	0.042	0.042
	Total	**144.33**	**153.58**	**142.20**	**154.17**

Table 12: Historical Fuel Demand for End-Use Activities from 2020 to 2023 (PJ)

Activity	2020	2021	2022	2023
Residential Other Electrical Appliances	22.36	24.43	20.72	21.54
Residential Cooking Demand	19.20	18.27	18.09	19.49
Residential Low Heating Demand	34.00	31.69	32.07	31.37
Commercial Other Electrical Appliances	10.54	12.42	9.67	9.94
Commercial Low Heating Demand	6.26	5.35	5.33	5.51
Industrial Other Electrical Appliances	15.84	16.55	21.23	23.76
Industrial High Heating	21.97	27.83	29.41	31.36
Industrial Low Heating	12.38	12.35	13.58	13.27
Transport electricity	0.042	0.042	0.042	0.042
Agricultural Electricity Demand	0.042	0.084	0.13	0.13
Total	**142.55**	**148.89**	**150.10**	**156.24**

Table 13: Fuel Demand Projection for End-Use Activities for key years (PJ)

Activity	2025	2030	2035	2040	2045	2050	2055
Residential Other Electrical Appliances	24.09	34.00	44.67	58.77	75.28	93.90	117.19
Residential Cooking Demand	20.22	22.75	25.48	28.38	31.30	34.16	37.19
Residential Low Heating Demand	32.54	36.61	41.00	45.68	50.37	54.97	59.84
Commercial Other Electrical Appliances	10.76	14.03	18.34	23.97	30.52	37.86	46.95
Commercial Low Heating Demand	5.71	6.43	7.20	8.02	8.84	9.65	10.51
Industrial Other Electrical equipment	25.71	33.53	43.83	57.28	72.93	90.45	112.18
Industrial High Heating	33.46	41.63	51.88	64.65	78.85	94.10	112.30
Industrial Low Heating	14.16	17.62	21.95	27.36	33.37	39.82	47.52
Transport electricity	0.05	0.06	0.07	0.09	0.11	0.14	0.17
Agricultural Electricity Demand	0.13	0.15	0.16	0.18	0.19	0.21	0.26
Total	**166.83**	**206.81**	**254.58**	**314.38**	**381.76**	**455.26**	**544.11**

2.1.5 **Vehicle demand**

To estimate vehicle demand in Ghana, historical vehicle registration data were obtained from the Driver and Vehicle Licensing Authority (DVLA). Figure 2 illustrates projected trends in vehicle

ownership from 2022 to 2055. Vehicle ownership is defined as the number of vehicles per person per year and serves as an indicator of motorization levels. In 2022, vehicle ownership in Ghana was estimated at 0.097 vehicles per person, increasing to 0.26 vehicles per person by 2055. This represents a growth of approximately 168% over the period, reflecting the combined effects of population growth, rising incomes, urbanization, and increasing mobility needs. In addition, Table 14 presents the projected transport demand up to 2056 as represented in the CLEWISE-Gh model, covering both road and rail transport modes. Road vehicle and passenger rail demand are expressed in billions of passenger-kilometres, while freight rail demand is reported in billions of tonne-kilometres.

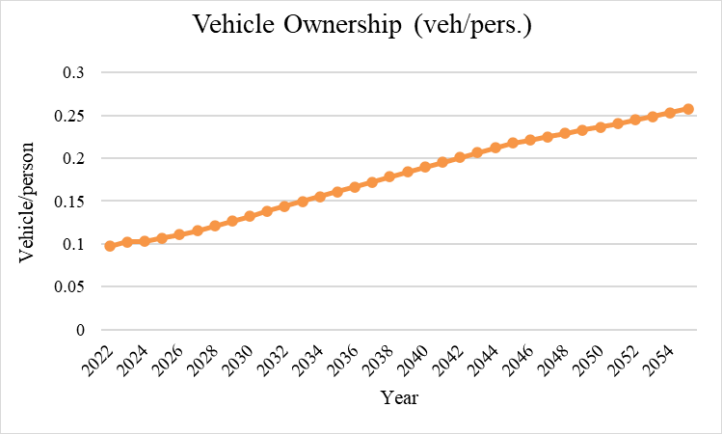


Figure 2: Vehicle ownership from 2020 to 2055

Table 14: Transport Vehicle Demand projection (Unit: 10^9 passenger-kms for passenger, 10^9tonne-kms for freight)

Vehicle	2024	2025	2030	2035	2040	2045	2050	2055	2056
Bus	193.82	198.33	223.14	249.92	278.43	307.03	335.05	364.76	371.02
Car	45.29	48.96	73.44	104.58	139.44	177.77	209.06	244.14	251.83
Motorcycle	11.08	11.43	13.31	15.26	17.16	19.02	20.62	22.27	22.61
Transport Heavy trucks	23.49	24.36	30.03	37.03	45.62	55.07	65.14	77.00	79.62
Transport Medium Truck	9.58	9.93	12.25	15.10	18.60	22.46	26.57	31.41	32.47
Freight trains	0.03	0.03	0.04	0.05	0.07	0.08	0.09	0.11	0.11
Passenger trains	0.002	0.002	0.003	0.003	0.003	0.004	0.004	0.004	0.004

2.1.6 Cement and Aluminum Production

In 2023, Ghana's cement production increased by 3.2%, reaching 6.5 million tonnes per annum, compared to 6.3 Mt in 2022 [9]. The Volta Aluminum Company (VALCO) has an installed production capacity of approximately 200,000 tonnes per year [10]. Aluminum production rose

significantly in 2022, reaching approximately 55,600 metric tonnes, up from about 39,200 metric tonnes in 2021. Despite this recent increase, aluminum output in Ghana has generally fluctuated over the observed period. Tables 15 and 16 present historical and projected cement and aluminum production data.

Table 15 : Historical Cement Aluminum Production

Historical Production (Mt)	2020	2021	2022
Cement	6.7	7.2	6.3
Aluminum	0.038	0.039	0.056

Table 16 : Cement and Aluminum Production Projection

Production (Mt)	**2024**	**2030**	**2040**	**2050**	**2055**
Aluminum	0.058	0.066	0.081	0.096	0.105
Cement	6.590	7.586	9.466	11.391	12.402

2.1.7 Electricity Import and Export

In the western African region, Ghana is one of the major exporters of electricity. Historical electricity import and export data from 2020 to 2023 in Petajoules, obtained from the Ghana Energy Statistics of 2024, are presented in Table 17. In addition, Table 18 shows projected electricity import and export trends for key years up to 2055. Under the model assumptions, electricity imports remain constant until 2025 and then decline linearly to zero by 2035, reflecting the national goal of eliminating import dependence. Conversely, electricity exports are assumed to stay constant until 2030 before increasing by 0.5% annually. The complete dataset supporting these estimates is available on the Zenodo repository.

Table 17: Historical Electricity Import/Export

	Historical (PJ)			
Technology	**2020**	**2021**	**2022**	**2023**
Electricity imports	0.2088	0.1584	0.1332	0.2844
Electricity exports	6.678	6.2424	7.974	9.101

Table 18: Electricity Import/Export projection

	Projection (PJ)						
Technology	**2024**	**2030**	**2035**	**2040**	**2045**	**2050**	**2055**
Electricity imports	0.28	0.14	0.03	0	0	0	0

Electricity exports	9.10	9.10	9.28	9.57	9.81	10.06	10.31

2.1.8 Average Capacity Factors

The capacity factor measures the efficiency of a power-generating unit by comparing the actual energy it produces over a given period to the maximum possible energy it could generate if operating continuously at full capacity [11]. Table 19 summarizes the average capacity factors (%) for the various power generation technologies included in the model. Furthermore, capacity factors are also estimated for end-use electrical appliances, derived from Ghana's electrical load profiles. This ensures that the modelled operation of end-use technologies accurately reflects real consumption patterns across different sectors. The corresponding capacity factor values for end-use technologies are presented in Table 20, and the full dataset is accessible through the Zenodo repository

Table 19: Estimated electricity generation technology average capacity factors in %.

Sector	Technology	Capacity factor %
Residential	Electric best efficiency appliances	27.675
	Electric stoves	27.675
	Electric heating low	27.675
	Electric good efficiency appliances	27.675
	Electric current efficiency appliances	27.675
Commercial	Electric best efficiency appliances	26.838
	Electric heating low	26.838
	Electric good efficiency appliances	26.838
	Electric current efficiency appliances	26.838
Industry	Electric best efficiency equipment	25.275
	Electric boilers	25.275
	Electric heating low	25.275
	Electric good efficiency equipment	25.275
	Electric current efficiency equipment	25.275

Table 20: End-use Electrical Technology Average Capacity factors in %

Technology	Average Capacity factor (%)
Biomass power plant	50
Gas power plant (CCGT)	85
Gas power plant simple cycle (SGCT)	85
Nuclear Power Plant	85
Large hydropower plant (>100MW)	58
Off-grid distributed PV	21.338
Oil-fired gas turbine (SCGT)	80
Utility-scale solar PV	25.488
Wind Power Plant (Grid Connected)	30

2.1.9 Operational life

The operational life represents the useful lifetime of a technology in years. Tables 21 and 22 present the operational life of generation and end-use sector technologies, respectively.

Table 21: Power Sector Technology Operational Life

Technology	Operational Life
Biomass resource	100
Hydro resource	100
Natural gas resource	100
Crude oil resource	100
Solar PV resource	100
Wind resource	100
Battery charging	20
Battery discharging	20
Biomass power plant	30
Large hydropower plant	50
Landfill gas power plant	20
Gas power plant (CCGT)	30
Gas power plant simple cycle (SGCT)	25
Nuclear power plant	50
Oil-fired gas turbine (SCGT)	25
Utility-scale solar PV	24
Off-grid distributed PV	24
Power transmission	50
Wind power plant (Grid-connected)	24

Table 22: Other Energy Sector Technology Operational Life

Sector	Technology	Operational life
Residential	Residential Biomass stove	25
	Residential Biomass heating low	25
	Residential electrical best efficiency appliances	10
	Residential electric stoves	25
	Residential electrical current efficiency appliances	10
	Residential electrical good efficiency appliances	10
	Residential electricity heating low	25
	Kerosene used for cooking in residential sector	25
	Residential oil stoves	25
	Residential oil heating low	25
Commercial	Commercial Biomass heating low	25
	Commercial best efficiency appliances	10
	Commercial electrical current efficiency appliances	10
	Commercial good efficiency appliances	10
	Commercial Electricity heating low	25
	Commercial oil heating low	25

Industry	Industry biomass heating	25
	Industrial Gas oil heating high	25
	Industrial best efficiency appliances	10
	Electricity demand for industry	10
	Industrial efficient appliances	10
	Industry electric high heat	25
	Industry electric low heat	25
	Industry LPG heating low	25
	Natural gas HIGH heating in the industry sector	25
	Industrial RFO heating high	25
Transport	Kerosene used in aviation transport	10
	New Hybrid Car	20
	New Hybrid Bus	25
	New Hybrid Motorbike	15
	Current Diesel bus	25
	New Diesel Bus	10
	Current Diesel cars	20
	New Diesel Car	15
	Current Diesel Heavy truck	25
	New Diesel Heavy Truck	20
	Current Diesel Medium Truck	15
	New Diesel Medium Truck	25
	Freight trains powered by diesel	20
	Passenger trains powered by diesel	20
	Current Electric bus	15
	New Electric Bus	20
	Current Electric car	15
	New Electric Car	20
	Current Electric Heavy Truck	20
	New Electric Heavy Truck	25
	Current Electric motorcycle	10
	New electric Motorbike	20
	Current Electric Medium Truck	20
	New Electric Medium Truck	25
	Freight trains powered by electricity	20
	Passenger trains powered by electricity	20
	Current Gasoline transport car	10
	New Gasoline Car	20
	Current Gasoline motorcycle	10
	New Gasoline Motorbike	20
	New LPG Bus	25
	Current LPG Cars	11
	New LPG Car	20

2.1.10 Fossil Fuel Reserves and Renewable Energy Potential

Ghana benefits from a diverse mix of energy resources, ranging from natural gas and crude oil to hydropower, biomass, solar, and wind energy. Information on both fossil fuel reserves and renewable energy potential was compiled from a combination of official government publications, peer-reviewed studies, reputable websites, and technical reports. Table 23 provides an overview of these resource potentials, offering a clear snapshot of the country's energy landscape.

Table 23: Fossil Fuel Reserves and Renewable Energy Potential

Technology	Code	Unit	Potential
Natural gas resource	MINNGS	PJ	1899
Crude Oil	MINOIL	PJ	51684.1
Solar Potential	MINSOL	PJ	28342.8
Hydro power potential	MINHYD	GW	1.9
Biomass Potential	MINBIO	GW	4.45
Wind resource	MINWND	PJ	2190.24

2.1.11 Transmission and Distribution Losses

Table 24 presents the transmission and distribution losses data in Ghana from 2020 to 2023. The data was obtained from the recent energy statistics of Ghana [8].

Table 24: Transmission and Distribution Losses (%)

	2020	2021	2022	2023	Average
Transmission	4.5	5	4.1	3.86	4.365
Distribution	26.2	29.6	30	27	28.2

2.1.12 Emission Factor

The emission factors were obtained from the Intergovernmental Panel on Climate Change (IPCC) database. The associated Global Warming Potential for Ghana has been collected from the 2022 emission inventory report of Ghana [12] as presented in Table 25. This has helped estimate the CO2-equivalent emissions and emissions associated with fossil-fuel-based technologies represented in the CLEWs model. The emission factors data are presented in Table 26.

Table 25 : Ghana Global Warming Potential

GHG	GWP (ton CO2e/ton)
CO2	1
CH4	28
N2O	265

Table 26: Emission factors

	Stationary Combustion				Mobile Combustion			
Fuel	**CO_2 (Mt/PJ)**	**CO_2eq (Mt/PJ)**	**CH_4 (kt/PJ)**	**N_2O (kt/PJ)**	**CO_2 (Mt/PJ)**	**CO_2 (Mt/PJ)**	**CH_4 (kt/PJ)**	**N_2O (kt/PJ)**
Bituminous Coal	0.0946	0.0950255	0.001	0.0015	–		–	–
Lignite	0.101	0.1014255	0.001	0.0015	–		–	–
Crude Oil	0.0733	0.073543	0.003	0.0006	–		–	–
Diesel Oil	0.0741	0.0743682	0.0039	0.0006	0.0741	0.0741405	0.0005	0.0001
Gasoline	0.0693	0.069543	0.003	0.0006	0.0693	0.06935095	0.0004	0.00015
Kerosene	0.0719	0.072143	0.003	0.0006	0.0715	0.0715293	0.0001	0.0001
Fuel Oil	0.0774	0.077643	0.003	0.0006	0.0774	0.0774433	0.0006	0.0001
Natural Gas	0.0561	0.0561545	0.001	0.0001	0.0561	0.0563734	0.0003	0.001
LPG	0.0631	0.0631545	0.001	0.0001	0.0631	0.0633734	0.0003	0.001

2.1.13 Capital Cost

In OSeMOSYS, the capital cost is calculated as a function of the Interest During Construction (IDC), which represents the escalation applied to the overnight construction cost. Table 27 presents the reference-year overnight costs, construction periods, and resulting total capital costs for each technology. Tables 28 to 30 summarize the capital costs of the energy technologies included in the CLEWISE-Gh model. These capital costs reflect the overnight investment required for each technology from 2020 through the end of the modelling horizon. Both historical and projected cost data were compiled from multiple reputable sources and are presented for selected key years. The full capital cost dataset is available in the Zenodo repository.

Table 27: Techno-economic parameter for capital cost

Technology	Overnight cost 2022 ($/kW)	Interest Rate IDV (%)	Construction Year	Cost multiplier	Total cost ($/kW)
Large hydropower plant	4226	10	8	1.35	5706
Gas power plant (CCGT)	855	10	4	1.164	995
Gas power plant simple cycle (SGCT)	684	10	3	1.128	772
Nuclear power plant	3485	10	6	1.408	4907
Oil-fired gas turbine (SCGT)	-	10	3	-	-
Utility-scale solar PV	1268	10	1	1.049	1330
Off-grid distributed PV	1747	10	1	1.049	1832
Wind power plant (Grid-connected)	1626	10	2	1.149	1869
Biomass Power Plant	4327	10	4	1.186	5131

Table 28: Power Sector technologies Capital Cost (10^6USD/GW)

	Capital Cost							
Technology	2020	2025	2030	2035	2040	2045	2050	2055
Battery charging	0	0	0	0	0	0	0	0
Battery discharging	1164.18	1013.09	861.95	808.25	754.48	700.73	0	0
Biomass power plant	5131	5097	5011	4981	4952	4922	4892	4892
Large hydropower plant	5706	5706	5706	5706	5706	5706	5706	5706
Landfill gas power plant	1200	1200	1200	1200	1200	1200	1200	1200
Gas power plant (CCGT)	995	995	995	995	995	995	995	995
Gas power plant simple cycle (SGCT)	772	772	772	772	772	772	772	772
Nuclear power plant	4907	4907	4907	4907	4907	4907	4907	4907
Oil-fired gas turbine (SCGT)	1450	1450	1450	1450	1450	1450	1450	1450
Utility-scale solar PV	1330	1184	820	752	685	617	550	550
Off-grid distributed PV	1832	1629	1121	1029	936	843	751	751
Power transmission	365	365	365	365	365	365	365	365
Wind power plant (Grid-connected)	1869	1840	1767	1741	1716	1690	1665	1665

Table 29: End-Use Sector Technologies capital cost (10^6USD/GW)

	Capital Cost							
Technology	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**2055**
Residential Biomass stove	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Residential Biomass heating low	359.25	358.65	357.9	357.04	356.03	354.83	353.47	351.84
Residential electrical best efficiency appliances	2368	2368	2368	2368	2368	2368	2368	2368
Residential electric stoves	76.2	76.2	76.2	76.2	76.2	76.2	76.2	76.2
Residential electrical current efficiency appliances	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Residential electrical good efficiency appliances	1184	1184	1184	1184	1184	1184	1184	1184
Residential electricity heating low	182.5	182.27	181.94	181.58	181.2	180.72	180.14	179.54
Kerosene used for cooking in residential sector	3.18	3.18	3.18	3.18	3.18	3.18	3.18	3.18
Residential oil stoves	6.1	6.1	6.1	6.1	6.1	6.1	6.1	6.1
Residential oil heating low	93.63	98.5	100.94	103.38	103.09	104.43	107.31	107.46
Residential electricity distribution	1468.67	1468.67	1468.67	1468.67	1468.67	1468.67	1468.67	1468.67
Commercial electricity distribution	4637.77	4637.77	4637.77	4637.77	4637.77	4637.77	4637.77	4637.77
Commercial Biomass heating low	359.25	358.65	357.9	357.04	356.03	354.83	353.47	351.84
Commercial best efficiency appliances	2368	2368	2368	2368	2368	2368	2368	2368

Commercial electrical current efficiency appliances	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Commercial good efficiency appliances	1184	1184	1184	1184	1184	1184	1184	1184
Commercial Electricity heating low	182.5	182.27	181.94	181.58	181.2	180.72	180.14	179.54
Commercial oil heating low	93.63	98.5	100.94	103.38	103.09	104.43	107.31	107.46
Industrial electricity distribution	3279.14	3279.14	3279.14	3279.14	3279.14	3279.14	3279.14	3279.14
Industry biomass heating	359.25	358.65	357.9	357.04	356.03	354.83	353.47	351.84
Industrial Gas oil heating high	447	447	447	447	447	447	447	447
Industrial best efficiency equipment	2368	2368	2368	2368	2368	2368	2368	2368
Industry Current efficiency equipment	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Industrial good efficiency equipment	1184	1184	1184	1184	1184	1184	1184	1184
Industry electric high heat	227	227	227	227	227	227	227	227
Industry electric low heat	182.5	182.27	181.94	181.58	181.2	180.72	180.14	179.54
Industry LPG heating low	447	447	447	447	447	447	447	447
Natural gas HIGH heating in the industry sector	447	447	447	447	447	447	447	447
Industrial RFO heating high	447	447	447	447	447	447	447	447

Table 30: Road transport technologies capital cost (10^3USD/vehicle)

	Capital Cost							
Technology	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**2055**
Current Diesel Car	19.15	11.84	12.06	11.96	12.01	12.00	11.97	11.97
Current Electric Motorbike	3	3	3	3	3	3	3	3
Current Electric Car	51.77	31.55	22.64	21.49	21.15	20.98	20.87	20.87
Current Electric Bus	120	120	120	120	120	120	120	120
Current Gasoline motorbike	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Current Diesel Bus	48	48	48	48	48	48	48	48
Current Diesel Heavy Truck	60	60	60	60	60	60	60	60
Current LPG Car	19.15	11.84	12.06	11.96	12.01	12.00	11.97	11.97
Current Diesel Car	22.33	14.09	14.48	13.46	13.42	13.38	13.43	13.43
New Gasoline Car	47.88	29.61	30.14	29.89	30.01	30.00	29.92	29.92
New Diesel Car	55.83	35.21	36.19	33.64	33.56	33.45	33.57	33.57
New LPG Car	47.88	29.61	30.14	29.89	30.01	30.00	29.92	29.92
New Hybrid Car	53.37	33.14	33.13	33.07	32.99	32.90	32.82	32.82
New Electric Car	86.29	52.58	37.73	35.81	35.25	34.97	34.78	34.78
New Gasoline Motorbike	3.5	3.5	3.5	3.5	3.5	3.5	3.5	3.5
New Diesel Motorbike	4	4	4	4	4	4	4	4

New Electric Motorbike	5	5	5	5	5	5	5	5
New Diesel Bus	130	130	130	130	130	130	130	130
New LPG Bus	125	125	125	125	125	125	125	125
New Hybrid Bus	140	140	140	140	140	140	140	140
New Electric Bus	250	250	250	250	250	250	250	250
New Diesel Heavy Truck	180	180	180	180	180	180	180	180
Current Electric Heavy truck	150	150	150	150	150	150	150	150
New Electric Heavy Truck	300	300	300	300	300	300	300	300
Current Diesel Medium Truck	32	32	32	32	32	32	32	32
New Diesel Medium Truck	90	90	90	90	90	90	90	90
Current Electric Medium Truck	72	72	72	72	72	72	72	72
New Electric Medium Truck	150	150	150	150	150	150	150	150

2.1.14 Fixed Cost

The fixed cost is the operation and maintenance (O&M) cost that is independent of each year's production output of a technology. The data is collected from various sources and presented for key years for the power sector (Table 31), end-use sector technologies (Table 32), and the transport sector technologies (Table 33).

Table 31: Power Sector Technologies Fixed Cost for Key Years (10^6 USD/GW)

	Fixed Cost							
Technology	2020	2025	2030	2035	2040	2045	2050	2055
Biomass power plant	75	75	75	75	75	75	75	75
Large hydropower plant	90	90	90	90	90	90	90	90
Landfill gas power plant	0	0	0	0	0	0	0	0
Gas power plant (CCGT)	35	35	35	35	35	35	35	35
Gas power plant simple cycle (SGCT)	20	20	20	20	20	20	20	20
Nuclear power plant	184.11	184.11	184.11	184.11	184.11	184.11	184.11	184.11
Oil-fired gas turbine (SCGT)	45	45	45	45	45	45	45	45
Utility-scale solar PV	17.914	12.792	11.518	10.4	9.399	9.399	9.399	9.399
Off-grid distributed PV	86.4	68.3	54	47.52	41.82	41.82	41.82	41.82
Wind power plant (Grid-connected)	59.56	47.64	43.48	37.32	37.32	37.32	37.32	37.32

Table 32: End-Use Sector Technologies Fixed Cost for Key Years (10^6 USD/GW)

		Fixed Cost				
	Technology	2020	2030	2040	2050	2055
Residential	Residential Biomass stove	0	0	0	0	0
	Residential Biomass heating low	14.39	14.47	14.58	14.74	14.86

	Residential electrical best efficiency appliances	0	0	0	0	0
	Residential electric stoves	0	0	0	0	0
	Residential electrical current efficiency appliances	0	0	0	0	0
	Residential electrical good efficiency appliances	0	0	0	0	0
	Residential electricity heating low	0	0	0	0	0
	Kerosene used for cooking in residential sector	0	0	0	0	0
	Residential oil stoves	0	0	0	0	0
	Residential oil heating low	9	9	9	9	9
Commercial	Commercial Biomass heating low	14.39	14.47	14.58	14.74	14.86
	Commercial best efficiency appliances	0	0	0	0	0
	Commercial electrical current efficiency appliances	0	0	0	0	0
	Commercial good efficiency appliances	0	0	0	0	0
	Commercial Electricity heating low	0	0	0	0	0
	Commercial oil heating low	9	9	9	9	9
Industry	Industry biomass heating	14.39	14.47	14.58	14.74	14.86
	Industrial Gas oil heating high	27	27	27	27	27
	Industrial best efficiency equipment	0	0	0	0	0
	Electricity demand for industry	0	0	0	0	0
	Industrial efficient equipment	0	0	0	0	0
	Industry electric high heat	0	0	0	0	0
	Industry electric low heat	0	0	0	0	0
	Industry LPG heating low	27	27	27	27	27
	Natural gas high heating in the industry sector	27	27	27	27	27
	Industrial RFO heating high	27	27	27	27	27

Table 33: Transport Technologies Fixed Cost for Key Years (10^3 USD)

	Fixed Cost				
Technology	**2020**	**2030**	**2040**	**2050**	**2055**
New Hybrid Car	0.5	0.5	0.5	0.5	0.5
New Hybrid Bus	5.5	5.5	5.5	5.5	5.5
New Hybrid Motorbike	7	7	7	7	7
Current Diesel bus demand	6.5	6.5	6.5	6.5	6.5
New Diesel Bus	1.2	1.2	1.2	1.2	1.2
Current Diesel cars	0.8	0.8	0.8	0.8	0.8
New Diesel Car	10	10	10	10	10
Current Diesel Heavy truck demand	9	9	9	9	9
New Diesel Heavy Truck	0.27	0.27	0.27	0.27	0.27
Current Diesel Medium Truck	4	4	4	4	4
New Diesel Medium Truck	3.5	3.5	3.5	3.5	3.5
Freight trains powered by diesel	0	0	0	0	0
Passenger trains powered by diesel	0	0	0	0	0
Current Electric bus demand	4	4	4	4	4
New Electric Bus	3.5	3.5	3.5	3.5	3.5
Current Electric car demand	0.9	0.9	0.9	0.9	0.9
New Electric Car	0.24	0.24	0.4	0.4	0.4
Current Electric Heavy Truck	4	4	4	4	4
New Electric Heavy Truck	3.5	3.5	3.5	3.5	3.5

Current Electric motorcycle demand	0.15	0.15	0.15	0.15	0.15
New electric Motorbike	0.12	0.12	0.12	0.12	0.12
Current Electric Medium Truck	2	2	2	2	2
New Electric Medium Truck	1.8	1.8	1.8	1.8	1.8
Freight trains powered by electricity	0	0	0	0	0
Passenger trains powered by electricity	0	0	0	0	0
Current Gasoline transport car	1	1	1	1	1
New Gasoline Car	0.85	0.85	0.85	0.85	0.85
Current Gasoline motorcycle	0.3	0.3	0.3	0.3	0.3
New Gasoline Motorbike	0.25	0.25	0.25	0.25	0.25
New LPG Bus	6	6	6	6	6
Current LPG Cars	1.294	1.294	1.294	1.294	1.294
New LPG Car	1.1	1.1	1.1	1.1	1.1

2.1.15 Variable Cost

Table 34 presents the energy sector variable cost in million US dollars per Petajoules ($ 10^6/PJ). The variable cost represents other various O&M expenses, with the associated fuel costs. All cost data information can be obtained on the Zenodo repository.

Table 34: Energy Sector Technologies variable cost (10^6 USD/PJ)

	Variable Cost				
Technology	**2020**	**2030**	**2040**	**2050**	**2056**
Diesel import	10.83	15.39	15.08	14.77	14.61
Gasoline import	10.58	15.73	15.38	15.03	14.85
Kerosene import	10.58	15.73	15.38	15.03	14.85
LPG import	7.43	11.81	11.52	11.22	11.07
Residential Biomass stove	3.113	3.113	3.113	3.113	3.113
Gas oil export	-9.63	-14.19	-13.88	-13.57	-13.41
Gasoline export	-9.38	-14.53	-14.18	-13.83	-13.65
LPG export	-6.23	-10.61	-10.32	-10.02	-9.87
Crude oil export	-10.83	-15.39	-15.08	-14.77	-14.61
Natural gas import	11.85	5.88	6.88	6.97	7.01
Uranium import	0.14	0.155	0.17	0.19	0.20
Crude oil import	7.89	12.39	12.39	12.39	12.39
Import RFO	7.89	12.39	12.39	12.39	12.39
Biomass resource	1.6	1.6	1.6	1.6	1.6
Hydropower resource	0.0001	0.0001	0.0001	0.0001	0.0001
Natural gas extraction	6.81	5.246	5.246	5.246	5.246
Crude oil extraction	11.09	12.97	15.36	17.75	19.18
Solar PV resource	0.0001	0.0001	0.0001	0.0001	0.0001
Wind resource	0.0001	0.0001	0.0001	0.0001	0.0001
RFO export	-6.58	-11.29	-11.29	-11.29	-11.29
Crude oil refinery option 1	0.72	0.72	0.72	0.72	0.72

2.2 Agriculture and Land Use

This section presents the land use data used in developing the CLEWISE-Gh model

2.2.1 National Land Cover Estimates

Tables 35 and 36 present the land cover estimate data in thousand square kilometers (10^3 km^2) for Ghana. This includes data on crop area, built-up land, forest area, water bodies, grassland, and other land types. Historical years' data were collected from the Organization for Economic Co-operation and Development (OECD) [13]. A total surface area of about 239.139 10^3 km^2 is obtained for Ghana [14].

Table 35: Historical Land Cover Estimate (10^3 km^2)

Land Cover type	2020	2021	2022	2023
Agricultural crop land	111.357	111.507	111.853	111.639
Built-up land	3.098	3.274	3.459	3.656
Forest land	88.341	88.341	88.341	88.341
Grassland	28.883	28.539	27.986	27.986
All other lands	0.127	0.127	0.130	0.130
Water bodies	7.334	7.352	7.370	7.388

Table 36: Land Cover Estimate Projection (10^3 km^2)

Land Cover type	2024	2030	2040	2050	2055
Agricultural crop land	97.701	92.046	90.01	105.68	118.35
Built-up land	3.863	5.378	9.337	16.209	21.357
Forest land	89.100	105.82	101.824	81.87	65.34
Grassland	41.108	28.816	30.265	31.967	32.880
All other lands	0.130	0.130	0.130	0.130	0.130
Water bodies	7.406	7.515	7.700	7.890	7.987
Total	**239.139**	**239.139**	**239.139**	**239.139**	**239.139**

2.2.2 Crop selection

The first eight crops were selected and represented in the model based on land area and value of production, as illustrated in Figure 3. This includes Cassava, Cocoa beans, Groundnuts, Maize, Oil palm fruit, Plantains and Bananas, Rice, and Yam. All other crops are grouped under other crop categories in the model.

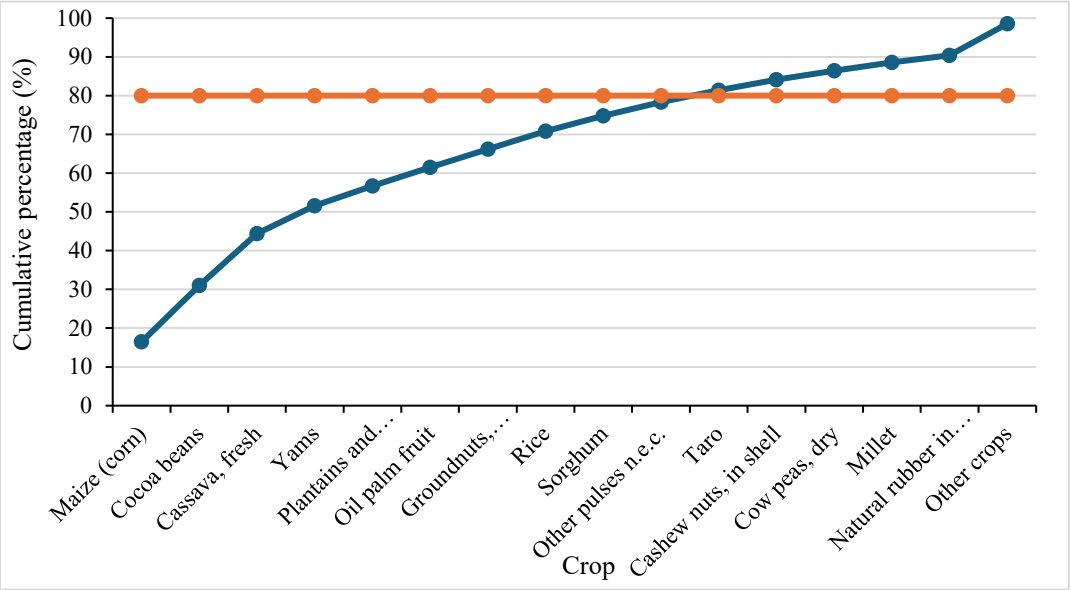


Figure 3: Selected Crops

2.2.3 Historical Crop Area

Historical crop area information was obtained from the Food and Agriculture Organization (FAO) statistics for Ghana. Table 37 presents historical crop area (kHa) from 2018 to 2023 for the selected crops.

Table 37: Historical crop area (kHa)

	Planted area					
kHa	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Cocoa	1,726.6	1,536.6	1,476.8	1,895.4	1,219.3	1,150.5
Maize	1,021.0	1,150.0	1,189.0	1,266.0	1,300.0	1,300.0
Cassava	977.0	1,021.0	1,061.0	1,051.0	1,049.5	1,056.2
Yam	470.0	500.0	505.0	551.0	582.5	565.6
Plantain and Banana	419.2	388.8	407.0	405.0	400.3	404.1
Oil palm fruit	366.7	372.8	366.9	373.4	374.8	376.0
Groundnuts	320.0	337.0	337.0	273.0	370.0	370.0
Rice	206.0	282.0	291.0	357.0	360.0	370.0
Other crops	2,018.3	2,041.0	2,078.6	2,151.4	2,247.4	2,300.3

2.2.4 Historical crop production and accumulated annual demand

Annual crop production data from 2018 to 2023 are obtained from FAO and summarized in Table 38. The production data is used together with import export trade quantity data to estimate crop demand as presented in Table 39, with associated crop demand projection in Table 40. Total

irrigation land area is about 229 kHa [15], including rice, other crops, and vegetables. The model assumes 25% of irrigated land is allocated to rice, and the remaining to other crops. Irrigated crop production projection data is presented in Table 41. The complete dataset is available on the Zenodo repository for Ghana.

Table 38: Historical Production (kTonnes)

Production rainfed						
kTonnes	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Cocoa	904.7	811.7	800.0	1,047.4	683.3	653.7
Maize	2,306.4	2,911.0	3,071.0	3,203.0	3,255.7	3,619.0
Cassava	20,846.0	22,750.0	24,368.0	24,997.0	25,652.4	26,520.8
Yam	7,858.2	8,754.0	8,946.0	10,278.0	10,707.6	10,510.6
Plantain and Banana	4,688.3	4,322.5	4,429.9	4,480.2	4,410.9	4,440.3
Oil palm fruit	2,543.9	2,605.8	2,545.1	2,564.9	2,571.9	2,560.7
Groundnuts	521.0	563.0	565.0	502.0	611.0	600.0
Rice	769.4	925.0	973.0	1,143.0	1,283.0	1,463.0
Other crops	6,216.9	6,423.2	6,572.2	6,633.6	6,876.7	6,993.9

Table 39: Historical Demand (kTonnes)

Demand						
kTonnes	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Cocoa	61.1	168.1	277.8	454.7	189.2	226.5
Maize	2,386.2	2,919.6	3,062.4	3,285.3	3,320.8	3,646.6
Cassava	20,846.0	22,750.0	24,368.0	24,997.0	25,652.4	26,520.8
Yam	7,840.9	8,726.8	8,896.7	10,228.1	10,650.0	10,474.4
Plantain and Banana	4,688.1	4,320.7	4,425.6	4,474.0	4,402.2	4,439.5
Oil palm fruit	2,543.9	2,605.8	2,545.1	2,564.9	2,571.9	2,560.7
Groundnuts	521.1	563.2	564.9	502.0	611.0	599.8
Rice	776.5	925.0	972.4	1,141.6	1,281.6	1,463.2
Other crops	9,642.7	10,211.5	9,803.0	10,591.6	8,635.1	8,784.0

Table 40: Crop Demand Projection (kTonnes)

Crop	**2024**	**2030**	**2035**	**2040**	**2045**	**2050**
Cocoa	233.57	294.88	358.11	434.93	528.26	641.68
Maize	3728.86	4239.28	4693.18	5167.31	5657.92	6163.08

Cassava	27119.11	30831.30	34132.39	37580.60	41148.74	44822.63
Yam	10302.65	11955.71	13446.71	15020.57	16662.91	18365.24
Plantain and Banana	4539.66	5161.07	5713.66	6290.88	6888.18	7503.18
Oil palm fruit	2618.42	2976.84	3295.57	3628.51	3973.02	4327.74
Groundnuts	613.35	697.31	771.97	849.96	930.66	1013.75
Rice	1496.16	1700.96	1883.08	2073.32	2270.18	2472.87
Other crops	10623.89	14825.46	19448.33	25344.09	32806.22	42199.06

Table 41 : Irrigated Crop Production (kTonnes)

Crop type	**2024**	**2030**	**2040**	**2050**	**2055**
Other Crop Irrigated High Input	699.68	1,239.52	3,215.00	8,338.87	13,429.83
Other Crop Irrigated Low Input	584.80	429.88	257.39	154.11	139.08
Rice Irrigated High Input	170.77	302.53	784.67	1,808.96	2,320.85
Rice Irrigated Low Input	142.78	104.96	62.84	37.63	29.11
Total	**1,598.03**	**2,076.89**	**4,319.90**	**10,339.56**	**15,918.88**

2.2.5 Residual Capacity

The residual capacity for a crop represents the existing area harvested for the crop, considering its operational life. Four different levels of agricultural input have been modelled for each crop using the high-resolution Global Agro-Ecological Zones datasets (GAEZ) [16]. This includes rainfed high input, rainfed low input, irrigated high input, and irrigated low input. Table 42 summarizes the residual capacity data for the selected crops for key years, and detailed data can be obtained on the Zenodo repository.

Table 42: Crop Technology residual capacity for selected crops for Ghana (2020-2055)

	Residual Capacity (kHa)					
Crop type	2020	2025	2030	2040	2050	2055
Irrigated Banana high fertilizer input	0	0	0	0	0	0
Rainfed Banana high fertilizer input	40.5	35.02	21.55	0	0	0
Irrigated Banana low fertilizer input	0	0	0	0	0	0
Rainfed Banana low fertilizer input	364.49	315.18	193.96	0	0	0
Irrigated cassava high fertilizer input	0	0	0	0	0	0
Rainfed cassava high fertilizer input	105.1	91.54	56.33	0	0	0
Irrigated cassava low fertilizer input	0	0	0	0	0	0
Rainfed cassava low fertilizer input	945.9	823.85	506.98	0	0	0

Irrigated cocoa beans high fertilizer input	0	0	0	0	0	0
Rainfed cocoa beans high fertilizer input	189.54	99.71	61.36	0	0	0
Irrigated cocoa beans low fertilizer input	0	0	0	0	0	0
Rainfed cocoa beans low fertilizer input	1705.86	897.35	552.22	0	0	0
Irrigated groundnuts high fertilizer input	0	0	0	0	0	0
Rainfed groundnuts high fertilizer input	27.3	32.07	19.73	0	0	0
Irrigated groundnuts high fertilizer inputs	0	0	0	0	0	0
Rainfed groundnuts low fertilizer input	245.7	288.6	177.6	0	0	0
Irrigated maize high fertilizer input	0	0	0	0	0	0
Rainfed maize high fertilizer input	126.6	112.67	69.33	0	0	0
Irrigated maize low fertilizer input	0	0	0	0	0	0
Rainfed maize low fertilizer input	1139.4	1014	624	0	0	0
Irrigated oil palm fruit high fertilizer input	0	0	0	0	0	0
Rainfed Oil palm fruit high fertilizer input	37.34	32.59	20.05	0	0	0
Irrigated oil palm fruit low fertilizer input	0	0	0	0	0	0
Rainfed Oil palm fruit low fertilizer input	336.09	293.3	180.49	0	0	0
All other crops irrigated high fertilizer input	42.94	37.21	22.90	0	0	0
All other crops rainfed high fertilizer input	203.69	176.53	108.63	0	0	0
All other crops irrigated low fertilizer input	128.81	111.64	68.70	0	0	0
All other crops rainfed low fertilizer input	1833.18	1588.75	977.70	0	0	0
Irrigated Rice high fertilizer input	14.31	14.31	7.63	0	0	0
Rainfed Rice high fertilizer input	29.98	32.07	19.73	0	0	0
Irrigated Rice low fertilizer input	14.31	37.21	22.90	0	0	0
Rainfed Rice low fertilizer input	269.78	288.60	177.60	0	0	0
Irrigated yam high fertilizer input	0	0	0	0	0	0
Rainfed yam high fertilizer input	55.1	49.02	30.17	0	0	0
Irrigated yam low fertilizer input	0	0	0	0	0	0
Rainfed yam low fertilizer input	495.9	441.17	271.49	0	0	0

2.2.6 Operational life of land technologies

Table 43 presents the operational life data for the land technologies represented within the CLEWISE-Gh model. It represents the time period during which the land area of a particular crop technology remains productive for crop harvesting. The data were gathered from available data sources at the country and international levels.

Table 43: Land Technologies Operational Life

Technology	Operational Life
Deforestation	50
Plantain and Banana export	1
Cocoa beans export	1
Export Groundnuts	1

Maize export	1
Export all other crops	1
Export Sorghum	1
Yam Export	1
Import Plantain and cooking Bananas	15
Cassava import	15
Cocoa beans import	15
Import Groundnuts	15
Maize import	15
Import Oil Palm Fruit	15
All other crop imports	15
Import rice	15
Yam import	15
Agricultural land	15
Built up land technology	15
Irrigated Banana high fertilizer input	15
Rainfed Banana high fertilizer input	15
Irrigated Banana low fertilizer input	15
Rainfed Banana low fertilizer input	15
Irrigated cassava high fertilizer input	15
Rainfed cassava high fertilizer input	15
Irrigated cassava low fertilizer input	15
Rainfed cassava low fertilizer input	15
Irrigated cocoa beans high fertilizer input	15
Rainfed cocoa beans high fertilizer input	15
Irrigated cocoa beans low fertilizer input	15
Rainfed cocoa beans low fertilizer input	15
Irrigated groundnuts high fertilizer input	15
Rainfed groundnuts high fertilizer input	15
Irrigated groundnuts high fertilizer inputs	15
Rainfed groundnuts low fertilizer input	15
Irrigated maize high fertilizer input	15
Rainfed maize high fertilizer input	15
Irrigated maize low fertilizer input	15
Rainfed maize low fertilizer input	15
Irrigated oil palm fruit high fertilizer input	15
Rainfed Oil palm fruit high fertilizer input	15
Irrigated oil palm fruit low fertilizer input	15
Rainfed Oil palm fruit low fertilizer input	15
All other crops irrigated high fertilizer input	15
All other crops rainfed high fertilizer input	15
All other crops irrigated low fertilizer input	15
All other crops rainfed low fertilizer input	15
Irrigated Rice high fertilizer input	15
Rainfed Rice high fertilizer input	15
Irrigated Rice low fertilizer input	15
Rainfed Rice low fertilizer input	15

Irrigated yam high fertilizer input	15
Rainfed yam high fertilizer input	15
Irrigated yam low fertilizer input	15
Rainfed yam low fertilizer input	15
Fallow land	1
Forest land technology	15
Grassland	1
Other lands	15
Water bodies technology	15
Technology for current agricultural practices	1
Technology for climate-friendly agricultural practices	1
Reforestation	50

2.2.7 Crop Yield (t/Ha)

The crop yield or output activity ratio (t/Ha) represents the quantity of a crop harvested per unit of land area. It is a key indicator of agricultural productivity, efficiency, and food security. Table 44 shows the yield information for the selected crop in Ghana based on the level of agricultural input.

Table 44: Crop Yield

Crop type	**Yield**
Irrigated Banana high fertilizer input	0
Rainfed Banana high fertilizer input	24.63
Irrigated Banana low fertilizer input	0
Rainfed Banana low fertilizer input	9.50
Irrigated cassava high fertilizer input	0
Rainfed cassava high fertilizer input	55.43
Irrigated cassava low fertilizer input	0
Rainfed cassava low fertilizer input	20.19
Irrigated cocoa beans high fertilizer input	0
Rainfed cocoa beans high fertilizer input	1.45
Irrigated cocoa beans low fertilizer input	0
Rainfed cocoa beans low fertilizer input	0.45
Irrigated groundnuts high fertilizer input	0
Rainfed groundnuts high fertilizer input	5.22
Irrigated groundnuts high fertilizer inputs	0
Rainfed groundnuts low fertilizer input	1.33
Irrigated maize high fertilizer input	0
Rainfed maize high fertilizer input	6.96
Irrigated maize low fertilizer input	0
Rainfed maize low fertilizer input	2.1
Irrigated oil palm fruit high fertilizer input	0
Rainfed Oil palm fruit high fertilizer input	14.64
Irrigated oil palm fruit low fertilizer input	0
Rainfed Oil palm fruit low fertilizer input	6.03

All other crops irrigated high fertilizer input	15.87
All other crops rainfed high fertilizer input	12.99
All other crops irrigated low fertilizer input	5.12
All other crops rainfed low fertilizer input	4.01
Irrigated Rice high fertilizer input	11.62
Rainfed Rice high fertilizer input	9.51
Irrigated Rice low fertilizer input	3.75
Rainfed Rice low fertilizer input	2.93
Irrigated yam high fertilizer input	0
Rainfed yam high fertilizer input	50.97
Irrigated yam low fertilizer input	0
Rainfed yam low fertilizer input	14.52

2.2.8 Capital and Fixed Cost

Tables 45 and 46 present crop capital and fixed cost in thousand US dollars per hectare ($1000/Ha) data for keys. The crop capital cost represents the initial investment in equipment and facilities required for a crop to be grown and harvested under a specific management regime. No Ghana-specific data was available, and the cost estimates here are adapted from academic studies from countries with similar incomes and management practices. Detailed cost information is available on the Zenodo repository.

Table 45: Crop Capital Cost ($1000/Ha)

	Capital Cost			
Crop Technology	2020	2030	2040	2050
Irrigated Banana high fertilizer input	14.91	14.91	14.91	14.91
Rainfed Banana high fertilizer input	7.46	7.46	7.46	7.46
Irrigated Banana low fertilizer input	11.19	11.19	11.19	11.19
Rainfed Banana low fertilizer input	1.49	1.49	1.49	1.49
Irrigated cassava high fertilizer input	14.91	14.91	14.91	14.91
Rainfed cassava high fertilizer input	7.46	7.46	7.46	7.46
Irrigated cassava low fertilizer input	11.19	11.19	11.19	11.19
Rainfed cassava low fertilizer input	1.49	1.49	1.49	1.49
Irrigated cocoa beans high fertilizer input	2.28	2.28	2.28	2.28
Rainfed cocoa beans high fertilizer input	2.25	2.25	2.25	2.25
Irrigated cocoa beans low fertilizer input	2.25	2.25	2.25	2.25
Rainfed cocoa beans low fertilizer input	1.58	1.58	1.58	1.58
Irrigated groundnuts high fertilizer input	17.31	17.31	17.31	17.31
Rainfed groundnuts high fertilizer input	10.09	10.09	10.09	10.09
Irrigated groundnuts high fertilizer inputs	15.14	15.14	15.14	15.14
Rainfed groundnuts low fertilizer input	2.02	2.02	2.02	2.02
Irrigated maize high fertilizer input	0.14	0.14	0.14	0.14
Rainfed maize high fertilizer input	0.07	0.07	0.07	0.07
Irrigated maize low fertilizer input	0.11	0.11	0.11	0.11

Rainfed maize low fertilizer input	0.01	0.01	0.01	0.01
Irrigated oil palm fruit high fertilizer input	2.28	2.28	2.28	2.28
Rainfed Oil palm fruit high fertilizer input	2.25	2.25	2.25	2.25
Irrigated oil palm fruit low fertilizer input	2.25	2.25	2.25	2.25
Rainfed Oil palm fruit low fertilizer input	1.58	1.58	1.58	1.58
All other crops irrigated high fertilizer input	0.84	0.84	0.84	0.84
All other crops rainfed high fertilizer input	0.46	0.46	0.46	0.46
All other crops irrigated low fertilizer input	0.67	0.67	0.67	0.67
All other crops rainfed low fertilizer input	0.12	0.12	0.12	0.12
Irrigated Rice high fertilizer input	0.14	0.14	0.14	0.14
Rainfed Rice high fertilizer input	0.07	0.07	0.07	0.07
Irrigated Rice low fertilizer input	0.11	0.11	0.11	0.11
Rainfed Rice low fertilizer input	0.01	0.01	0.01	0.01
Irrigated yam high fertilizer input	14.91	14.91	14.91	14.91
Rainfed yam high fertilizer input	7.46	7.46	7.46	7.46
Irrigated yam low fertilizer input	11.19	11.19	11.19	11.19
Rainfed yam low fertilizer input	1.49	1.49	1.49	1.49

Table 46: Crop Fixed Cost ($1000/Ha)

	Fixed Cost			
Crop Technology	**2020**	**2030**	**2040**	**2050**
Irrigated Banana high fertilizer input	2.35	2.35	2.35	2.35
Rainfed Banana high fertilizer input	2.18	2.18	2.18	2.18
Irrigated Banana low fertilizer input	2.26	2.26	2.26	2.26
Rainfed Banana low fertilizer input	2.02	2.02	2.02	2.02
Irrigated cassava high fertilizer input	2.35	2.35	2.35	2.35
Rainfed cassava high fertilizer input	2.18	2.18	2.18	2.18
Irrigated cassava low fertilizer input	2.26	2.26	2.26	2.26
Rainfed cassava low fertilizer input	2.02	2.02	2.02	2.02
Irrigated cocoa beans high fertilizer input	0.16	0.16	0.16	0.16
Rainfed cocoa beans high fertilizer input	0.09	0.09	0.09	0.09
Irrigated cocoa beans low fertilizer input	0.1	0.1	0.1	0.1
Rainfed cocoa beans low fertilizer input	0.07	0.07	0.07	0.07
Irrigated groundnuts high fertilizer input	2.35	2.35	2.35	2.35
Rainfed groundnuts high fertilizer input	2.13	2.13	2.13	2.13
Irrigated groundnuts high fertilizer inputs	2.91	2.91	2.91	2.91
Rainfed groundnuts low fertilizer input	1.9	1.9	1.9	1.9
Irrigated maize high fertilizer input	0.31	0.31	0.31	0.31
Rainfed maize high fertilizer input	0.31	0.31	0.31	0.31
Irrigated maize low fertilizer input	0.31	0.31	0.31	0.31
Rainfed maize low fertilizer input	0.31	0.31	0.31	0.31
Irrigated oil palm fruit high fertilizer input	0.16	0.16	0.16	0.16
Rainfed Oil palm fruit high fertilizer input	0.09	0.09	0.09	0.09

Irrigated oil palm fruit low fertilizer input	0.1	0.1	0.1	0.1
Rainfed Oil palm fruit low fertilizer input	0.07	0.07	0.07	0.07
All other crops irrigated high fertilizer input	0.13	0.13	0.13	0.13
All other crops rainfed high fertilizer input	0.12	0.12	0.12	0.12
All other crops irrigated low fertilizer input	0.13	0.13	0.13	0.13
All other crops rainfed low fertilizer input	0.11	0.11	0.11	0.11
Irrigated Rice high fertilizer input	0.31	0.31	0.31	0.31
Rainfed Rice high fertilizer input	0.31	0.31	0.31	0.31
Irrigated Rice low fertilizer input	0.31	0.31	0.31	0.31
Rainfed Rice low fertilizer input	0.31	0.31	0.31	0.31
Irrigated yam high fertilizer input	2.35	2.35	2.35	2.35
Rainfed yam high fertilizer input	2.18	2.18	2.18	2.18
Irrigated yam low fertilizer input	2.26	2.26	2.26	2.26
Rainfed yam low fertilizer input	2.02	2.02	2.02	2.02

2.2.9 Variable Cost

Tables 47 to 49 show the variable cost for crop technologies, crop import and export, and land technologies, respectively, as represented in the CLEWISE-Gh model. Agricultural crop technologies variable cost information was collected from international reports and African countries with similar crop production patterns to Ghana. The variable cost of land use technologies, as presented in Table 49 is assumed and used to guide projected land use allocation, with negative values assigned to forest and fallow lands.

Table 47: Variable Cost of Crop Technologies ($1000/Ha)

	Variable Cost				
Crop Technology	**2020**	**2030**	**2040**	**2050**	**2055**
Irrigated Banana high fertilizer input	3.51	3.51	3.51	3.51	3.51
Rainfed Banana high fertilizer input	2.8	2.8	2.8	2.8	2.8
Irrigated Banana low fertilizer input	3.15	3.15	3.15	3.15	3.15
Rainfed Banana low fertilizer input	1.97	1.97	1.97	1.97	1.97
Irrigated cassava high fertilizer input	3.51	3.51	3.51	3.51	3.51
Rainfed cassava high fertilizer input	2.8	2.8	2.8	2.8	2.8
Irrigated cassava low fertilizer input	3.15	3.15	3.15	3.15	3.15
Rainfed cassava low fertilizer input	1.97	1.97	1.97	1.97	1.97
Irrigated cocoa beans high fertilizer input	2.09	2.09	2.09	2.09	2.09
Rainfed cocoa beans high fertilizer input	1.48	1.48	1.48	1.48	1.48
Irrigated cocoa beans low fertilizer input	2.05	2.05	2.05	2.05	2.05
Rainfed cocoa beans low fertilizer input	1.05	1.05	1.05	1.05	1.05
Irrigated groundnuts high fertilizer input	6.04	6.04	6.04	6.04	6.04
Rainfed groundnuts high fertilizer input	4.65	4.65	4.65	4.65	4.65
Irrigated groundnuts high fertilizer inputs	5.62	5.62	5.62	5.62	5.62
Rainfed groundnuts low fertilizer input	2.8	2.8	2.8	2.8	2.8
Irrigated maize high fertilizer input	0.72	0.72	0.72	0.72	0.72

Rainfed maize high fertilizer input	0.45	0.45	0.45	0.45	0.45
Irrigated maize low fertilizer input	0.58	0.58	0.58	0.58	0.58
Rainfed maize low fertilizer input	0.15	0.15	0.15	0.15	0.15
Irrigated oil palm fruit high fertilizer input	2.09	2.09	2.09	2.09	2.09
Rainfed Oil palm fruit high fertilizer input	1.48	1.48	1.48	1.48	1.48
Irrigated oil palm fruit low fertilizer input	2.05	2.05	2.05	2.05	2.05
Rainfed Oil palm fruit low fertilizer input	1.05	1.05	1.05	1.05	1.05
All other crops irrigated high fertilizer input	0.716	0.716	0.716	0.716	0.716
All other crops rainfed high fertilizer input	0.622	0.622	0.622	0.622	0.622
All other crops irrigated low fertilizer input	0.264	0.264	0.264	0.264	0.264
All other crops rainfed low fertilizer input	0.205	0.205	0.205	0.205	0.205
Irrigated Rice high fertilizer input	0.716	0.716	0.716	0.716	0.716
Rainfed Rice high fertilizer input	0.622	0.622	0.622	0.622	0.622
Irrigated Rice low fertilizer input	0.264	0.264	0.264	0.264	0.264
Rainfed Rice low fertilizer input	0.205	0.205	0.205	0.205	0.205
Irrigated yam high fertilizer input	3.51	3.51	3.51	3.51	3.51
Rainfed yam high fertilizer input	2.8	2.8	2.8	2.8	2.8
Irrigated yam low fertilizer input	3.15	3.15	3.15	3.15	3.15
Rainfed yam low fertilizer input	1.97	1.97	1.97	1.97	1.97

Table 48: Variable Cost of Crop Import/Export Technologies

	Variable Cost (Million USD/kton)				
Crop Technology	**2020**	**2030**	**2040**	**2050**	**2055**
Plantain and Banana export	-1.37	-1.04	-1.04	-1.04	-1.04
Cocoa beans export	-2.66	-4.89	-4.43	-4	-3.81
Export Groundnuts	-1.88	-1.47	-1.47	-1.47	-1.47
Maize export	-0.19	-0.16	-0.16	-0.16	-0.16
Export all other crops	-1.579	-1.694	-1.694	-1.694	-1.694
Export Sorghum	-0.56	-0.45	-0.45	-0.45	-0.45
Yam Export	-0.56	-0.41	-0.41	-0.41	-0.41
Import Plantain and cooking Bananas	1.37	1.04	1.04	1.04	1.04
Cassava import	0.17	0.51	0.51	0.51	0.51
Cocoa beans import	2.66	4.89	4.43	4	3.81
Import Groundnuts	1.88	1.47	1.47	1.47	1.47
Maize import	0.19	0.16	0.16	0.16	0.16
Import Oil Palm Fruit	0.84	0.73	0.73	0.73	0.73
All other crop imports	1.579	1.694	1.694	1.694	1.694
Import rice	0.56	0.45	0.45	0.45	0.45
Yam import	0.56	0.41	0.41	0.41	0.41

Table 49: Variable cost of land use technologies (Thousand USD/km^2)

Technology	**Variable Cost**

Agricultural land	-2
Built-up land technology	2
Fallow land	-0.5
Forest land technology	-6
Grassland	-3.5
Other lands	0
Water bodies technology	2

2.2.10 Livestock

The CLEWISE-Gh model includes the six most widely produced livestock types in Ghana: asses, cattle, goats, horses, sheep, and pigs. Historical and projected demand for these livestock categories is presented in Table 50. Historical livestock production data for Ghana are obtained from FAO Crops and Livestock Statistics [17]. Although livestock production in Ghana operates on a relatively modest scale, the sector remains a crucial component of the agricultural economy, supporting food security, income generation, and rural livelihoods. Traditionally, cattle, sheep, goats, pigs, and poultry have dominated the country's livestock landscape, reflecting long-standing production practices and consumption patterns [18]. About 200 kton of methane was emitted from selected livestock for an equivalent of 6 Mt of CO2eq in 2020. Total methane emission is projected to reach about 250 kton in 2050, as presented in Table 51. Livestock emission factor information is obtained from the IPCC reports [19], [20].

Table 50: Livestock production (Million)

	Livestock Production (Million)						
Livestock	**2020**	**2021**	**2022**	**2023**	**2030**	**2040**	**2050**
Asses	0.0150	0.0150	0.0151	0.0151	0.0176	0.0223	0.0291
Cattle	2.1090	2.1740	2.2475	2.2915	2.3641	2.4827	2.6220
Goat	8.1800	8.4110	8.6606	9.2698	9.5636	10.0436	10.6068
Horse	0.0033	0.0034	0.0034	0.0034	0.0036	0.0039	0.0043
Sheep	5.5440	5.6950	5.8427	5.9749	6.1642	6.4736	6.8366
Pigs	0.9460	0.7850	0.8530	0.9236	0.9529	1.0007	1.0568

Table 51 : Livestock Methane Emission

Livestock	**2020**	**2021**	**2022**	**2023**	**2030**	**2040**	**2050**
Asses	0.150	0.150	0.151	0.151	0.176	0.223	0.291
Cattle	110.2	113.592	117.430	119.729	123.523	129.722	136.997
Goats	42.291	43.485	44.776	47.925	49.444	51.925	54.837
Horses	0.065	0.065	0.066	0.067	0.071	0.077	0.083
Pig	1.419	1.178	1.280	1.385	1.429	1.501	1.585
Sheep	45.405	46.642	47.852	48.934	50.485	53.019	55.992

Total	**199.53**	**205.111**	**211.553**	**218.192**	**225.127**	**236.468**	**249.786**

2.3 Water use

2.3.1 Water Demand

The total public water supply for Ghana in 2020 is about 0.4 $10^9 m^3$ [21], and annual GDP growth data [22] is applied to estimate future public water demand. Table 52 shows water demand projections for key years across different sectors.

Table 52: Public water demand

	Water Demand (10^9 m^3)					
Sector	**2022**	**2025**	**2030**	**2040**	**2050**	**2055**
Public	0.74	0.68	0.71	1.13	2.30	2.91
Agriculture	0.41	0.45	0.53	0.72	0.98	1.14
Thermal power plants	0.18	0.21	0.30	0.51	0.81	0.99
Total	**1.33**	**1.34**	**1.53**	**2.36**	**4.09**	**5.04**

2.3.2 Input Activity Ratio

Power generation technologies require water primarily for cooling. The input activity ratios reported in Table 53 quantify the amount of water required per unit of energy produced for each generation technology. Similarly, land-based technologies depend on water inputs to achieve productivity. Table 54 presents the corresponding input activity ratios for land technologies, indicating the volume of water required per unit of output. Similarly, Table 55 presents the input activity ratios for agricultural water demand. This corresponds to the crop water demand (cwd) data directly obtained from the GAEZ. The cwd shows how suitable the land is for crop production. Detailed water data are available on the Zenodo repository.

Table 53: Water-specific input activity ratios for all energy technologies ($10^9 m^3$/PJ)

Technology	**Commodity**	**Input Activity Ratio**
Gas Plant (CCGT)	Water for cooling in thermal power plants	0.003
Gas Plant (SCGT)	Water for cooling in thermal power plants	0.003
Oil-fired gas turbine (SCGT)	Water for cooling in thermal power plants	0.004

Table 54: Water-specific input activity ratios for all land technologies ($10^6 m^3/km^2$)

Technology	**Commodity**	**Input Activity Ratio**
Rainfed crops	Precipitation water	1.20
Forests	Precipitation water	1.20
Built-up areas	Precipitation water	1.20
Water bodies	Precipitation water	1.20
Other land	Precipitation water	1.20

Table 55 : Irrigated Crop Input Activity Ratio

Technology	Commodity	Input Activity Ratio
Agricultural Water Input (m^3/m^2)		
Irrigated Cocoa beans high input	Agricultural Water	0.1046
Irrigated Cocoa beans low input	Agricultural Water	0.0049
Irrigated Maize high Input	Agricultural Water	0.191
Irrigated Maize low Input	Agricultural Water	0.107
Irrigated Cassava high input	Agricultural Water	0.226
Irrigated Cassava low input	Agricultural Water	0.0973
Irrigated Yam High Input	Agricultural Water	0.0621
Irrigated Yam Low Input	Agricultural Water	0.094
Irrigated Banana and Plantains high input	Agricultural Water	0.216
Irrigated Banana and Plantains low input	Agricultural Water	0.0146
Irrigated Palm Oil Fruit high input	Agricultural Water	0.0844
Irrigated Palm Oil Fruit low input	Agricultural Water	0.0014
Irrigated Groundnuts high input	Agricultural Water	0.0034
Irrigated Groundnuts low input	Agricultural Water	0.0463
Irrigated Rice high input	Agricultural Water	0.01176
Irrigated Rice low input	Agricultural Water	0.0098
Irrigated other crops high input	Agricultural Water	0.00062
Irrigated other crops low input	Agricultural Water	0.00094
Agricultural Diesel Input (PJ/kHa)		
Rainfed Cocoa beans high input	Agricultural Diesel	0.0034
Irrigated Cocoa beans high input	Agricultural Diesel	0.0034
Rainfed Maize high Input	Agricultural Diesel	0.0034
Irrigated Maize high Input	Agricultural Diesel	0.0034
Rainfed Cassava high input	Agricultural Diesel	0.0034
Irrigated Cassava high input	Agricultural Diesel	0.0034
Rainfed Yam High Input	Agricultural Diesel	0.0034
Irrigated Yam High Input	Agricultural Diesel	0.0034
Rainfed Banana and Plantains high input	Agricultural Diesel	0.0034
Irrigated Banana and Plantains high input	Agricultural Diesel	0.0034
Rainfed Palm Oil Fruit high input	Agricultural Diesel	0.0034
Irrigated Palm Oil Fruit high input	Agricultural Diesel	0.0034
Rainfed Groundnuts high input	Agricultural Diesel	0.0034
Irrigated Groundnuts high input	Agricultural Diesel	0.0034
Rainfed Rice high input	Agricultural Diesel	0.0034
Irrigated Rice high input	Agricultural Diesel	0.0034
Rainfed other crops high input	Agricultural Diesel	0.0034
Irrigated other crops high input	Agricultural Diesel	0.0034

2.3.3 Output Activity Ratio

The output activity ratio of a water technology represents the amount of water lost by each land technology, in the form of either evapotranspiration, groundwater recharge, or surface water run-off. Table 56 outlines the output activity ratio for each land and crop technology.

Table 56: Output activity ratios for crop technologies and water commodities ($10^6 m^3/km^2$)

Technology	Commodity	Output Activity Ratio
Irrigated Banana high input	Water lost to evapotranspiration	0.7826
Irrigated Banana high input	Groundwater recharge	0.2262
Irrigated Banana high input	Surface water run-off	0.2262
Rainfed Banana high input	Water lost to evapotranspiration	0.7012
Rainfed Banana high input	Groundwater recharge	0.2494
Rainfed Banana high input	Surface water run-off	0.2494
Irrigated Banana low input	Water lost to evapotranspiration	0.5436
Irrigated Banana low input	Groundwater recharge	0.3457
Irrigated Banana low input	Surface water run-off	0.3457
Rainfed Banana low input	Water lost to evapotranspiration	0.505
Rainfed Banana low input	Groundwater recharge	0.3475
Rainfed Banana low input	Surface water run-off	0.3475
Irrigated cassava high input	Water lost to evapotranspiration	0.6404
Irrigated cassava high input	Groundwater recharge	0.2973
Irrigated cassava high input	Surface water run-off	0.2973
Rainfed cassava high input	Water lost to evapotranspiration	0.7075
Rainfed cassava high input	Groundwater recharge	0.24625
Rainfed cassava high input	Surface water run-off	0.24625
Irrigated cassava low input	Water lost to evapotranspiration	0.6908
Irrigated cassava low input	Groundwater recharge	0.2721
Irrigated cassava low input	Surface water run-off	0.2721
Rainfed cassava low input	Water lost to evapotranspiration	0.6451
Rainfed cassava low input	Groundwater recharge	0.27745
Rainfed cassava low input	Surface water run-off	0.27745
Irrigated cocoa beans high input	Water lost to evapotranspiration	0.6162
Irrigated cocoa beans high input	Groundwater recharge	0.3094
Irrigated cocoa beans high input	Surface water run-off	0.3094
Rainfed cocoa beans high input	Water lost to evapotranspiration	0.6433
Rainfed cocoa beans high input	Groundwater recharge	0.27835
Rainfed cocoa beans high input	Surface water run-off	0.27835
Irrigated cocoa beans low input	Water lost to evapotranspiration	0.4604
Irrigated cocoa beans low input	Groundwater recharge	0.3873
Irrigated cocoa beans low input	Surface water run-off	0.3873
Rainfed cocoa beans low input	Water lost to evapotranspiration	0.4384
Rainfed cocoa beans low input	Groundwater recharge	0.3808
Rainfed cocoa beans low input	Surface water run-off	0.3808
Irrigated groundnuts high input	Water lost to evapotranspiration	0.2962
Irrigated groundnuts high input	Groundwater recharge	0.4694
Irrigated groundnuts high input	Surface water run-off	0.4694
Rainfed groundnuts high input	Water lost to evapotranspiration	0.303
Rainfed groundnuts high input	Groundwater recharge	0.4485
Rainfed groundnuts high input	Surface water run-off	0.4485
Irrigated groundnuts high inputs	Water lost to evapotranspiration	0.2978

Irrigated groundnuts high inputs	Groundwater recharge	0.4686
Irrigated groundnuts high inputs	Surface water run-off	0.4686
Rainfed groundnuts low input	Water lost to evapotranspiration	0.3207
Rainfed groundnuts low input	Groundwater recharge	0.43965
Rainfed groundnuts low input	Surface water run-off	0.43965
Irrigated maize high input	Water lost to evapotranspiration	0.3247
Irrigated maize high input	Groundwater recharge	0.45515
Irrigated maize high input	Surface water run-off	0.45515
Rainfed maize high input	Water lost to evapotranspiration	0.4618
Rainfed maize high input	Groundwater recharge	0.3691
Rainfed maize high input	Surface water run-off	0.3691
Irrigated maize low input	Water lost to evapotranspiration	0.3846
Irrigated maize low input	Groundwater recharge	0.4252
Irrigated maize low input	Surface water run-off	0.4252
Rainfed maize low input	Water lost to evapotranspiration	0.4263
Rainfed maize low input	Groundwater recharge	0.38685
Rainfed maize low input	Surface water run-off	0.38685
Irrigated oil palm fruit high input	Water lost to evapotranspiration	0.5791
Irrigated oil palm fruit high input	Groundwater recharge	0.32795
Irrigated oil palm fruit high input	Surface water run-off	0.32795
Rainfed Oil palm fruit high input	Water lost to evapotranspiration	0.5387
Rainfed Oil palm fruit high input	Groundwater recharge	0.33065
Rainfed Oil palm fruit high input	Surface water run-off	0.33065
Irrigated oil palm fruit low input	Water lost to evapotranspiration	0.3806
Irrigated oil palm fruit low input	Groundwater recharge	0.4272
Irrigated oil palm fruit low input	Surface water run-off	0.4272
Rainfed Oil palm fruit low input	Water lost to evapotranspiration	0.3735
Rainfed Oil palm fruit low input	Groundwater recharge	0.41325
Rainfed Oil palm fruit low input	Surface water run-off	0.41325
All other crops irrigated high input	Water lost to evapotranspiration	0.3204
All other crops irrigated high input	Groundwater recharge	0.4573
All other crops irrigated high input	Surface water run-off	0.4573
All other crops rainfed high input	Water lost to evapotranspiration	0.4244
All other crops rainfed high input	Groundwater recharge	0.3878
All other crops rainfed high input	Surface water run-off	0.3878
All other crops irrigated low input	Water lost to evapotranspiration	0.363
All other crops irrigated low input	Groundwater recharge	0.436
All other crops irrigated low input	Surface water run-off	0.436
All other crops rainfed low input	Water lost to evapotranspiration	0.3928
All other crops rainfed low input	Groundwater recharge	0.4036
All other crops rainfed low input	Surface water run-off	0.4036
Irrigated Rice high input	Water lost to evapotranspiration	0.4399
Irrigated Rice high input	Groundwater recharge	0.39755
Irrigated Rice high input	Surface water run-off	0.39755
Rainfed Rice high input	Water lost to evapotranspiration	0.4352
Rainfed Rice high input	Groundwater recharge	0.3824
Rainfed Rice high input	Surface water run-off	0.3824
Irrigated Rice low input	Water lost to evapotranspiration	0.4592
Irrigated Rice low input	Groundwater recharge	0.3879
Irrigated Rice low input	Surface water run-off	0.3879
Rainfed Rice low input	Water lost to evapotranspiration	0.4324
Rainfed Rice low input	Groundwater recharge	0.3838

Rainfed Rice low input	Surface water run-off	0.3838
Irrigated yam high input	Water lost to evapotranspiration	0.809
Irrigated yam high input	Groundwater recharge	0.213
Irrigated yam high input	Surface water run-off	0.213
Rainfed yam high input	Water lost to evapotranspiration	0.6527
Rainfed yam high input	Groundwater recharge	0.27365
Rainfed yam high input	Surface water run-off	0.27365
Irrigated yam low input	Water lost to evapotranspiration	0.6491
Irrigated yam low input	Groundwater recharge	0.29295
Irrigated yam low input	Surface water run-off	0.29295
Rainfed yam low input	Water lost to evapotranspiration	0.6423
Rainfed yam low input	Groundwater recharge	0.27885
Rainfed yam low input	Surface water run-off	0.27885

2.4 Waste

The waste representation in the CLEWISE-Gh model includes solid and liquid wastes. Solid waste data collection in Ghana continues to present challenges due to limited coverage, inconsistent reporting, and the informal nature of much of the waste management system. The solid waste sector encompasses a range of disposal and treatment methods, including landfilling, open dumping, open burning, incineration, anaerobic digestion, composting, organic waste separation, and recycling of metals, paper, and plastics. Available data are often aggregated and lack details on waste composition, treatment methods, and disposal practices. Emission estimation in the CLEWISE model relies on the IPCC guidelines, calculating solid waste emissions using default values and assumptions when local data are unavailable. Most country-specific data were obtained from the latest emission inventory of Ghana [23], which includes data up to 2022 on waste composition and classifies the country as low-middle-income.

Ghana's wastewater sector is primarily managed through a mix of centralized sewer systems in major cities and on-site sanitation systems like pit latrines and septic tanks in rural and peri-urban areas. Centralized treatment coverage remains low, with most wastewater discharged untreated into the environment. Industrial wastewater is also generated from sectors such as agro-processing and manufacturing, but treatment facilities are limited. Total liquid waste generation, covering both domestic and industrial wastewater, is projected to increase from 1,432.2 kilotonnes in 2022 to approximately 2,696 kilotonnes by 2055. Biochemical Oxygen Demand (BOD) load data for domestic and industrial wastewater were obtained from Ghana's CRT [24] and used to calibrate and validate the model, ensuring consistency with national wastewater emissions accounting. As urbanization increases, improving wastewater management is becoming more critical for both public health and environmental sustainability. Tables 57 and 58 display solid and liquid waste technologies represented in the CLEWISE-Gh model.

Table 57: Solid Waste (Mt)

Solid Waste (Mt)	**2020**	**2024**	**2030**	**2040**	**2050**	**2055**
Landfill	0.518	0.999	1.665	3.449	6.554	8.852

Open burning	1.271	2.171	2.336	2.452	2.152	1.724
Waste composting	0.110	0.195	0.246	0.362	0.535	0.649
Waste digestors	0.000	0.000	0.000	0.000	0.000	0.000
Waste dumping	3.033	5.374	6.785	10.01	14.765	17.94
Waste incineration	0.298	0.528	0.667	0.984	1.451	1.763
Total	**5.230**	**9.266**	**11.699**	**17.255**	**25.458**	**30.925**

Table 58: Liquid Waste (Mt)

Liquid Waste (Mt)	**2020**	**2024**	**2030**	**2040**	**2050**	**2055**
Advanced aerobic	0.014	0.014	0.012	0.010	0.008	0.007
Anaerobic lagoon	0.069	0.069	0.061	0.050	0.041	0.037
Centralized aerobic	0.854	0.930	1.095	1.402	1.775	1.988
Latrines	0.303	0.330	0.375	0.457	0.545	0.593
Septic tanks	0.138	0.156	0.160	0.158	0.108	0.071
Total	**1.377**	**1.498**	**1.703**	**2.076**	**2.476**	**2.696**

Emissions from the solid waste sector in 2020 consist of approximately 92.2 kt of methane (CH_4), 0.215 kt of nitrous oxide (N_2O), and 0.467 million tonnes (Mt) of carbon dioxide (CO_2). Methane emissions from solid waste are projected to increase substantially, reaching about 503.5 kt by 2055, with associated CO_2-equivalent emissions rising from 5.02 Mt in 2020 to approximately 18.8 Mt by 2055. Landfilling is the dominant source of methane emissions, accounting for about 49.45% of total CH_4 emissions from solid waste, followed by dumping (48%), while open burning contributes 2.2%. Waste composting and incineration together account for the remaining 0.35%, as presented in Table 59. Total emissions from the wastewater sector are projected to increase from approximately 162 kt in 2022 to about 264 kt by 2055. These emissions are largely driven by methane, which represents about 98.6% of total wastewater emissions, with nitrous oxide accounting for the remaining 1.4%. Total methane emissions from wastewater are estimated at around 159.7 kt in 2022. Of this amount, latrines contribute the largest share (39.45%), followed by centralized aerobic systems (33.4%), septic tanks (17.93%), anaerobic lagoons (9%), and advanced aerobic treatment systems (0.22%) (Table 60).

Table 59: Methane Emission from Solid Waste

	Methane Emission (kt)					
Solid Waste Method	**2020**	**2024**	**2030**	**2040**	**2050**	**2055**
Landfill	51.311	47.449	56.418	98.607	184.275	248.919
Open burning	8.134	13.89	14.95	15.69	13.775	11.036
Waste composting	0.22	0.389	0.491	0.725	1.069	1.299
Waste incineration	0.018	0.032	0.04	0.059	0.087	0.106
Waste dumping	32.504	46.383	73.68	127.34	199.299	242.142
Total	**92.186**	**108.144**	**145.58**	**242.426**	**398.506**	**503.5**

Table 60 : Methane Emission from Liquid Waste

	Methane Emission (kt)					
Disposal Method	**2020**	**2024**	**2030**	**2040**	**2050**	**2055**
Advanced aerobic	0.413	0.413	0.366	0.299	0.244	0.221
Anaerobic lagoon	13.772	13.755	12.184	9.956	8.134	7.353
Centralized aerobic	51.232	55.799	65.688	84.098	106.492	119.262
Latrines	60.597	65.912	74.934	91.338	108.962	118.625
Septic tanks	27.544	31.185	32.095	31.562	21.582	14.215
Total	**153.558**	**167.063**	**185.266**	**217.252**	**245.415**	**259.676**

3. Experimental design, Materials and Methods

The dataset was collected through an extensive literature review, integrating information from national and international databases, peer-reviewed publications, and technical reports from institutions such as the Ministry of Energy of Ghana, the Ministry of Food and Agriculture (MoFA), the Energy Commission, the Environmental Protection Agency (EPA), the International Renewable Energy Agency (IRENA), the International Energy Agency (IEA), and the Food and Agriculture Organization (FAO). All collected data were subsequently processed to align with the specific requirements of the modeling framework. To ensure consistency and comparability, data from diverse sources were converted into common units such as gigawatts (GW) for power plant capacity, petajoules (PJ) for energy, and billion cubic meters (BCM) for water. Additional standardization procedures were applied, including harmonizing reporting periods, resolving inconsistencies between sources, and addressing gaps or missing values through interpolation or validated assumptions. Detailed descriptions of the data processing and standardization steps are provided in the subsequent sections.

3.1 Energy

3.1.1 Time slice and Year split

Two seasons with four-day types were considered, making 8 time slices. The daily load of Ghana for the year 2023 was used and grouped on a monthly basis and time of day to estimate a given time slice using Eq. (1):

$$T\,(n) = \frac{\sum of\ load\ data\ for\ number\ of\ months\ in\ a\ given\ season}{Total\ load}(n) \qquad (1)$$

With n representing the number of intraday (n= 1, 2,3,4). The values were rounded appropriately to make the sum of the eight slices equal to one.

For the year split, a typical year of 8760 hours was assumed, and the year split was calculated as the fraction of hours for each period with Eq. (2):

$$YearSplit\ season\ (i) = \frac{hours\ in\ timeslice\ in\ season\ (i)}{8760} \qquad (2)$$

The calculation process is presented in the Excel sheet called 'Electricity demand profile Ghana' and is available in the Zenodo repository.

3.1.2 Installed capacity

In the power sector, historical data on installed capacity were gathered from the Ghana Energy Statistics and other national sources. However, data for thermal power plants were originally presented in aggregated form, without disaggregation by technology or fuel type. To address this, we disaggregated thermal power plants into three categories: natural gas (simple-cycle), natural gas (combined-cycle), and oil-fired plants, using available literature and reasonable estimates. The split share was estimated with the data from the Energy Commission [8] and installed capacity data provided by the ECOWAS Energy Information System (WAEIS) [25]. When plant-level generation data were unavailable, an average capacity factor approach was used to estimate output, drawing on information from the Energy Commission of Ghana. For modelling existing technologies, hydropower technologies are assumed to have a constant existing capacity until the end of the modelling period. For other technologies, a constant existing capacity was assumed until 2030, then a linear decrease was implemented until reaching 0 GW in 2035. This aligns with the average lifetime of power plant technologies, which ranges between 20 and 40 years on average. The list of sources for historical installed and residual capacities for different power technologies is presented in Tables 61 and 62, respectively.

Table 61: List of sources for historical installed capacity

Plants	Source	Assumption
Hydro	[8]	
Thermal	[8]	
Solar	[8]	

Table 62: List of sources for residual capacity

Technologies	**Source**	**Assumption**
Biomass power plant	[8]	
Large hydro power plant	[8]	
Gas power plant (CCGT)	[8], [25], [26]	Estimated based on information from [8], [25], and [26]
Gas power plant simple cycle (SGCT)	[8], [25], [26]	Estimated based on information from [8], [25], and [26]
Oil-fired gas turbine (SCGT)	[25]	
Utility-scale solar PV	[8], [25]	
Off-grid distributed PV	[8], [25]	

3.1.3 Electricity production

Power generation data were obtained from Ghana Energy Statistics and available reports [8], [27], [5]. Similarly, with the installed capacity, individual plant generation data was estimated based on generation data from the Energy Commission and available resources. Where the data is not available, an estimation approach is adopted using the average capacity factor and the residual capacity based on Eq. (3):

$$Estimated\ power\ production\ (PJ) = Residual\ Capacity(GW) \times Average\ capacity\ factor \times 31.536\ \left(\frac{PJ}{GW}\right) \quad (3)$$

Table 63 presents the list of sources for power generation data.

Table 63: List of sources for power generation technologies

Technologies	Source	Assumption
Biomass power plant	[8]	
Large hydro power plant	[8]	
Gas power plant (CCGT)	[8], [25], [26]	Estimated based on information from [8], [25], and [26]
Gas power plant simple cycle (SGCT)	[8], [25], [26]	Estimated based on information from [8], [25], and [26]
Oil-fired gas turbine (SCGT)	[25]	
Utility-scale solar PV	[8], [25]	
Off-grid distributed PV	[8]	

3.1.4 Energy demand

The Energy demand data was estimated using Eq. (4) [11], [28], based on historical energy consumption information from Ghana Energy Balances from the Ghana Energy Database System [29] and Energy statistics [30]. The energy demand in CLEWs is primarily represented based on end-use energy consumers, capturing how different fuels and electricity are used to support end-use activities. The model links energy demand in each sector to key drivers such as economic growth (e.g., GDP), sectoral value added, or production outputs. Energy carriers are assigned to specific sector demand nodes, allowing CLEWISE to simulate how shifts in fuel availability, cost, or policy (e.g., fuel switching or efficiency improvements) impact total energy demand and emissions. The end-use sectors represented include residential, commercial, industrial, agricultural, and transport sectors.

$$Final\ Demand\ (PJ) = \sum Energy\ Consumption \div Input\ Activity\ Ratio\ (IAR) \quad (4)$$

For demand projection, a CLEWs demand forecasting is developed, combining a core set of cross-cutting parameters and datasets that influence all sectors. These include key macroeconomic and demographic drivers such as GDP growth rates, population projections, and urbanization trends.

These variables shape demand across sectors, affecting energy use. A list of sources for final electricity consumption per sector in Ghana is presented in Table 64.

Table 64: List of sources for end-use fuel consumption per sector

Sector	Fuel	Source	Assumption
Residential	**Biomass**	[29], [30]	
	Electricity	[29], [30]	
	Kerosene	[29], [30]	
	LPG	[29], [30]	
Commercial and public services	**Biomass**	[29], [30]	
	Electricity	[29], [30]	
	LPG	[29], [30]	
Industry	**Biomass**	[29], [30]	
	Electricity	[29], [30]	
	DSL	[29], [30]	
	LPG	[29], [30]	
	RFO	[29], [30]	
	NGS	[29], [30]	
Agriculture	**Diesel**	[29], [30]	
	Premix	[29], [30]	
	Electricity	[29], [30]	
Transport	**LPG**	[29], [30]	
	Diesel	[29], [30]	
	Gasoline	[29], [30]	
	Electricity	[29], [30]	

3.1.5 Vehicle demand

Currently, the most recent data incorporated into the model comes from the Driver and Vehicle Licensing Authority (DVLA) [31] and reflects the number of vehicles registered in the country as of 2022. However, the format in which this data was provided did not fully align with the model's requirements. For instance, certain vehicle categories, particularly trucks, were reclassified into heavy and medium trucks based on expert judgment. The demand for different categories was estimated using the fuel consumption data from the energy statistics and the registration data. A transport sector sheet was developed for various estimations and is available on the Zenodo repository. The final vehicle demand is calculated using Eq. (5), and the data is taken into the CLEWs forecast template to make projections accordingly.

$$Vehicle\ demand = Stock \times Capacity\ to\ Activity\ Unit \times Output\ Activity\ Ratio \quad (5)$$

Railway demand data for freight and passenger trains is collected from Daniel Obeng et al [32]. Diesel consumption data in railways was obtained from the Energy Commission of Ghana and was used to estimate the average input activity ratio for passenger and freight trains. Eq (6) was used to calculate the input activity ratio for each diesel train type:

$$Input\ Activity\ Ratio\ (MJ/(pass\ or\ tons-kms) = \frac{Diesel\ Used\ (PJ)}{Demand\ (Billion\ pass\ or\ ton-kms)} \quad (5)$$

3.1.6 Electricity imports and exports

Historical electricity import and export information was gathered from the Ghana Energy Statistics [8]. For model calibration and projection for future years, it was assumed that electricity imports remain constant until 2025 and then decline linearly to zero by 2035, reflecting the national goal of eliminating import dependence. Conversely, electricity exports are assumed to remain constant until 2030, before increasing at a rate of 0.5% annually, with sources presented in Table 65.

Table 65: List of Sources of Historical Electricity Import/Export Source

Technology	Source	Assumption
Electricity imports	[8]	
Electricity exports	[8]	

3.1.7 Capacity factor

For power generation technologies, the capacity factor information was collected from existing literature for the available power plant technologies in Ghana [33], [34]. Country-specific capacity factors for solar Photovoltaic (PV) technologies were collected from the International Renewable Energy Agency (IRENA) [35]. Furthermore, capacity factors are also estimated for off-grid solar PV technologies and end-use electrical appliances, derived from Ghana's electrical load profiles. This ensures that the modelled operation of end-use technologies accurately reflects real consumption patterns across different sectors. Eq. (7) represents the formula for estimating the average capacity factor for power generation technology. Table 66 presents the list of sources for electricity generation technology capacity factors.

$$Annual\ Capacity\ Factor = \frac{Annual\ Power\ Generation\ [GWh]}{Theoretical\ Max\ Power\ Generation\ [GWh]} \quad (7)$$

Table 66: List of Sources for Electricity Generation Technology Average Capacity Factors

Technology	Sources	Assumption
Biomass power plant	[33], [34]	
Gas power plant (CCGT)	[33], [34]	
Gas power plant simple cycle (SGCT)	[33], [34]	
Nuclear Power Plant	[33], [34]	
Large hydropower plant (>100MW)	[33], [34]	
Off-grid distributed PV	[34], [35]	
Oil-fired gas turbine (SCGT)	[33]	
Utility-scale solar PV	[33], [34]	
Wind Power Plant (Grid Connected)	[36]	

3.1.8 Fossil Fuel Reserves and Renewable Energy Potentials

The fossil fuel reserves and renewable energy potentials data were collected from different available sources, and key sources are presented in Table 67.

Table 67: List of Sources of Data for Fossil Fuel Reserves and Renewable Energy Potential

Technology	Source	Assumption
Natural gas resource	[33]	
Crude Oil	[33]	
Solar Potential	[33], [35]	
Hydro power potential	[33], [35]	
Biomass Potential	[33], [35]	
Wind resource	[33], [35]	

3.1.9 Transmission and Distribution losses

National electricity transmission and distribution losses from the Ghanaian electricity network were obtained from [37] and [27] as presented in Table 68.

Table 68: List of Sources of Transmission and Distribution Losses data

	Source	Assumption
Transmission	[27], [37]	
Distribution	[27], [37]	

3.1.10 Technology cost

Tables 69 to 75 present the sources for energy technology cost. Capital costs for power generation technologies were derived primarily from International Energy Agency (IEA) data, specifically the Stated Policies Scenario [38], and adjusted to reflect Ghana's economic context. All costs were converted to 2022 U.S. dollars, and a GDP deflator from the World Resources Institute (WRI) was applied to ensure consistency across years. Detailed technology-specific cost data and estimation procedures are provided in the "IDC Template Ghana" file available on Zenodo.

Fuel distribution costs were obtained from the Ghana Energy Statistics 2024 dataset; values originally reported in Ghanaian cedis per energy unit were converted into U.S. dollar-based units. Fuel import and export prices were sourced from the World Bank's commodity price forecasts and the IEA's World Energy Outlook [39], while national GDP deflator indices were taken from the World Bank's World Development Indicators [40]. For transport technologies, cost estimates from the U.S. Energy Information Administration (EIA) were used solely to determine the relative differences in fuel economy and price across vehicle types rather than to set absolute cost levels.

Table 69: List of Sources of Power Sector technologies Capital Cost

Technology	Source	Assumption

Biomass power plant	[38]	Estimated based on the cost projection under the Stated Policies Scenario
Large hydropower plant	[38]	Estimated based on the cost projection under the Stated Policies Scenario
Landfill gas power plant	[38]	Estimated based on the cost projection under the Stated Policies Scenario
Gas power plant (CCGT)	[38]	Estimated based on the cost projection under the Stated Policies Scenario
Gas power plant simple cycle (SGCT)	[38]	Estimated based on the cost projection under the Stated Policies Scenario
Nuclear power plant	[38]	Estimated based on the cost projection under the Stated Policies Scenario
Oil-fired gas turbine (SCGT)	[38]	Estimated based on the cost projection under the Stated Policies Scenario
Utility-scale solar PV	[38]	Estimated based on the cost projection under the Stated Policies Scenario
Off-grid distributed PV	[38]	Estimated based on the cost projection under the Stated Policies Scenario
Power transmission	[33], [34]	
Wind power plant (Grid-connected)	[38]	Estimated based on the cost projection under the Stated Policies Scenario

Table 70: List of Sources of End-Use Sector Technologies capital cost

Technology	**Source**	**Assumption**
Residential Biomass stove	[34], [33]	
Residential Biomass heating low	[34], [33]	
Residential electrical best efficiency appliances	[34], [33]	
Residential electric stoves	[34], [33]	
Residential electrical current efficiency appliances	[34], [33]	
Residential electrical good efficiency appliances	[34], [33]	
Residential electricity heating low	[34], [33]	
Kerosene used for cooking in residential sector	[34], [33]	
Residential oil stoves	[34], [33]	
Residential oil heating low	[34], [33]	
Residential electricity distribution	[34], [33]	
Commercial electricity distribution	[34], [33]	
Commercial Biomass heating low	[34], [33]	
Commercial best efficiency appliances	[34], [33]	
Commercial electrical current efficiency appliances	[34], [33]	
Commercial good efficiency appliances	[34], [33]	
Commercial Electricity heating low	[34], [33]	
Commercial oil heating low	[34], [33]	
Industrial electricity distribution	[34], [33]	
Industry biomass heating	[34], [33]	
Industrial Gas oil heating high	[34], [33]	
Industrial best efficiency appliances	[34], [33]	
Electricity distribution for industry	[34], [33]	

Industrial efficient appliances	[34], [33]	
Industry electric high heat	[34], [33]	
Industry electric low heat	[34], [33]	
Industry LPG heating low	[34], [33]	
Natural gas HIGH heating in the industry sector	[34], [33]	
Industrial RFO heating high	[34], [33]	

Table 71: List of Sources of Road Transport Technologies Capital Cost

Technology	**Source**	**Assumption**
New Hybrid Car	[41]	Estimated based on the United States Energy Information Administration
New Hybrid Bus	[41]	Estimated based on the United States Energy Information Administration
New Hybrid Motorbike	[41]	Estimated based on the United States Energy Information Administration
Current Diesel bus demand	[41]	Estimated based on the United States Energy Information Administration
New Diesel Bus	[41]	Estimated based on the United States Energy Information Administration
Current Diesel cars	[41]	Estimated based on the United States Energy Information Administration
New Diesel Car	[41]	Estimated based on the United States Energy Information Administration
Current Diesel Heavy truck demand	[41]	Estimated based on the United States Energy Information Administration
New Diesel Heavy Truck	[41]	Estimated based on the United States Energy Information Administration
Current Diesel Medium Truck	[41]	Estimated based on the United States Energy Information Administration
New Diesel Medium Truck	[41]	Estimated based on the United States Energy Information Administration
Current Electric bus demand	[41]	Estimated based on the United States Energy Information Administration
New Electric Bus	[41]	Estimated based on the United States Energy Information Administration
Current Electric car demand	[41]	Estimated based on the United States Energy Information Administration
New Electric Car	[41]	Estimated based on the United States Energy Information Administration
Current Electric Heavy Truck	[41]	Estimated based on the United States Energy Information Administration
New Electric Heavy Truck	[41]	Estimated based on the United States Energy Information Administration
Current Electric motorcycle demand	[41]	Estimated based on the United States Energy Information Administration
New electric Motorbike	[41]	Estimated based on the United States Energy Information Administration
Current Electric Medium Truck	[41]	Estimated based on the United States Energy Information Administration

New Electric Medium Truck	[41]	Estimated based on the United States Energy Information Administration
Current Gasoline transport car	[41]	Estimated based on the United States Energy Information Administration
New Gasoline Car	[41]	Estimated based on the United States Energy Information Administration
Current Gasoline motorcycle	[41]	Estimated based on the United States Energy Information Administration
New Gasoline Motorbike	[41]	Estimated based on the United States Energy Information Administration
New LPG Bus	[41]	Estimated based on the United States Energy Information Administration
Current LPG Cars	[41]	Estimated based on the United States Energy Information Administration
New LPG Car	[41]	Estimated based on the United States Energy Information Administration

Table 72: List of Sources of Power Sector Technologies Fixed Cost

Technology	**Source**	**Assumption**
Biomass power plant	[34], [33]	
Large hydropower plant	[34], [33]	
Landfill gas power plant	[34], [33]	
Gas power plant (CCGT)	[34], [33]	
Gas power plant simple cycle (SGCT)	[34], [33]	
Nuclear power plant	[34], [33]	
Oil-fired gas turbine (SCGT)	[34], [33]	
Utility-scale solar PV	[34], [33]	
Off-grid distributed PV	[34], [33]	
Wind power plant (Grid-connected)	[34], [33]	

Table 73: Source of End-Use Sector Technologies Fixed Cost

	Technology	**Source**	**Assumption**
Residential	Residential Biomass stove	[34], [33]	
	Residential Biomass heating low	[34], [33]	
	Residential electrical best efficiency appliances	[34], [33]	
	Residential electric stoves	[34], [33]	
	Residential electrical current efficiency appliances	[34], [33]	
	Residential electrical good efficiency appliances	[34], [33]	
	Residential electricity heating low	[34], [33]	
	Kerosene used for cooking in residential sector	[34], [33]	
	Residential oil stoves	[34], [33]	
	Residential oil heating low	[34], [33]	
Commercial	Commercial Biomass heating low	[34], [33]	
	Commercial best efficiency appliances	[34], [33]	
	Commercial electrical current efficiency appliances	[34], [33]	

	Commercial good efficiency appliances	[34], [33]	
	Commercial Electricity heating low	[34], [33]	
	Commercial oil heating low	[34], [33]	
Industry	Industry biomass heating	[34], [33]	
	Industrial Gas oil heating high	[34], [33]	
	Industrial best efficiency appliances	[34], [33]	
	Electricity demand for industry	[34], [33]	
	Industrial efficient appliances	[34], [33]	
	Industry electric high heat	[34], [33]	
	Industry electric low heat	[34], [33]	
	Industry LPG heating low	[34], [33]	
	Natural gas HIGH heating in the industry sector	[34], [33]	
	Industrial RFO heating high	[34], [33]	

Table 74: Source of Transport Technologies Fixed Cost

Technology	**Source**	**Assumption**
New Hybrid Car	[41]	Estimated based on the United States Energy Information Administration
New Hybrid Bus	[41]	Estimated based on the United States Energy Information Administration
New Hybrid Motorbike	[41]	Estimated based on the United States Energy Information Administration
Current Diesel bus demand	[41]	Estimated based on the United States Energy Information Administration
New Diesel Bus	[41]	Estimated based on the United States Energy Information Administration
Current Diesel cars	[41]	Estimated based on the United States Energy Information Administration
New Diesel Car	[41]	Estimated based on the United States Energy Information Administration
Current Diesel Heavy truck demand	[41]	Estimated based on the United States Energy Information Administration
New Diesel Heavy Truck	[41]	Estimated based on the United States Energy Information Administration
Current Diesel Medium Truck	[41]	Estimated based on the United States Energy Information Administration
New Diesel Medium Truck	[41]	Estimated based on the United States Energy Information Administration
Freight trains powered by diesel	[41]	Estimated based on the United States Energy Information Administration
Passenger trains powered by diesel	[41]	Estimated based on the United States Energy Information Administration
Current Electric bus demand	[41]	Estimated based on the United States Energy Information Administration
New Electric Bus	[41]	Estimated based on the United States Energy Information Administration
Current Electric car demand	[41]	Estimated based on the United States Energy Information Administration
New Electric Car	[41]	Estimated based on the United States Energy Information Administration

Current Electric Heavy Truck	[41]	Estimated based on the United States Energy Information Administration
New Electric Heavy Truck	[41]	Estimated based on the United States Energy Information Administration
Current Electric motorcycle demand	[41]	Estimated based on the United States Energy Information Administration
New electric Motorbike	[41]	Estimated based on the United States Energy Information Administration
Current Electric Medium Truck	[41]	Estimated based on the United States Energy Information Administration
New Electric Medium Truck	[41]	Estimated based on the United States Energy Information Administration
Freight trains powered by electricity	[41]	Estimated based on the United States Energy Information Administration
Passenger trains powered by electricity	[41]	Estimated based on the United States Energy Information Administration
Current Gasoline transport car	[41]	Estimated based on the United States Energy Information Administration
New Gasoline Car	[41]	Estimated based on the United States Energy Information Administration
Current Gasoline motorcycle	[41]	Estimated based on the United States Energy Information Administration
New Gasoline Motorbike	[41]	Estimated based on the United States Energy Information Administration
New LPG Bus	[41]	Estimated based on the United States Energy Information Administration
Current LPG Cars	[41]	Estimated based on the United States Energy Information Administration
New LPG Car	[41]	Estimated based on the United States Energy Information Administration

Table 75: Source of Energy Sector Technologies variable cost

Technology	**Source**	**Assumption**
Diesel import	[39]	
Gasoline import	[39]	
Kerosene import	[39]	
LPG import	[39]	
Residential Biomass stove	[39]	
Gas oil export	[39]	
Gasoline export	[39]	
LPG export	[39]	
Crude oil export	[39]	
Natural gas import	[39]	
Uranium import	[39]	
Crude oil import	[39]	
Import RFO	[39]	
Biomass resource	[39]	

Hydropower resource	[39]	
Natural gas extraction	[39]	
Crude oil extraction	[39]	
Solar PV resource	[34], [33]	
Wind resource	[34], [33]	
RFO export	[34], [33]	
Crude oil refinery option 1	[34], [33]	

3.1.11 Energy Sector Emission Factor Sources

Tables 76 and 77 present the GWP and emission factor sources for stationary and mobile combustion. GWP data specific to Ghana was obtained from the latest emission inventory report. The emission factors were obtained from the Intergovernmental Panel on Climate Change (IPCC) database.

Table 76 : Ghana Global Warming Potential Sources

GHG	Source
CO2	[12]
CH4	[12]
N2O	[12]

Table 77: Emission factors sources

	Stationary Combustion			**Mobile Combustion**			**Assumption**
Fuel	**CO_2**	**CH_4**	**N_2O**	**CO_2**	**CH_4**	**N_2O**	
Bituminous Coal	[42]	[42]	[42]	–	–	–	IPCC default factor
Lignite	[42]	[42]	[42]	–	–	–	IPCC default factor
Crude Oil	[42]	[42]	[42]	–	–	–	IPCC default factor
Diesel Oil	[42]	[42]	[42]	[43]	[43]	[43]	IPCC default factor
Gasoline	[42]	[42]	[42]	[43]	[43]	[43]	IPCC default factor
Kerosene	[42]	[42]	[42]	[43]	[43]	[43]	IPCC default factor
Fuel Oil	[42]	[42]	[42]	[43]	[43]	[43]	IPCC default factor
Natural Gas	[42]	[42]	[42]	[43]	[43]	[43]	IPCC default factor
LPG	[42]	[42]	[42]	[43]	[43]	[43]	IPCC default factor

3.2 Agriculture and Land Use

3.2.1 National Land Cover Estimates

National land cover estimates data were collected from the OECD land cover and land cover changes data explorer [13]. The total land area is kept constant for the entire modelling period. Table 78 presents the sources for Ghana land cover estimates data.

Table 78 List of Sources for Historical Land Cover Estimate

Land Cover type	Source	Assumption
Agricultural crop land	[13]	
Built-up land	[13]	
Forest land	[13]	
Grassland	[13]	
All other lands	[13]	
Water bodies	[13]	
Total surface area	[14]	

3.2.2 Historical Crop Area

Table 79 shows the list of sources for the selected crops represented in the CLEWs-Gh model. The historical crop area data were obtained from the FAO crop and Livestock statistics and from the Ministry of Food and Agriculture (MoFA) of Ghana [17], [44].

Table 79: List of Sources for Historical Crop Area

Crop	Source	Assumption
Cocoa	[17], [44]	
Maize	[17], [44]	
Cassava	[17], [44]	
Yam	[17], [44]	
Plantain and Banana	[17], [44]	
Oil palm fruit	[17], [44]	
Groundnuts	[17], [44]	
Rice	[17], [44]	
Other crops	[17], [44]	

3.2.3 Historical Crop Production

The historical crop production data were collected from the recent FOA crops, livestock, and trade statistics. Crop demand is estimated using Eq. (8).

$$Demand = production + imports - exports \quad (8)$$

Projection for future demands is estimated using the CLEWs Demand Forecast template, which combines key drivers such as population, GDP, and GDP per capita. Table 80 presents the sources for historical crop production in Ghana.

Table 80: List of Sources for Historical Production and Trade Value

Crop	Source	Assumption

Cocoa	[17], [45]	
Maize	[17], [45]	
Cassava	[17], [45]	
Yam	[17], [45]	
Plantain and Banana	[17], [45]	
Oil palm fruit	[17], [45]	
Groundnuts	[17], [45]	
Rice	[17], [45]	
Other crops	[17], [45]	

3.2.4 Residual Crop Capacity

In addition, four different levels of agricultural input have been modelled for each crop using the high-resolution Global Agro-Ecological Zones datasets (GAEZ). This includes rainfed high input, rainfed low input, irrigated high input, and irrigated low input [16]. First, the total rainfed area ($TR_{crop(i)}$) and irrigated area ($TI_{crop(i)}$) are estimated using eq (9) and eq (10):

$$(\text{TIcrop(i)}) = \%\ \text{of the cultivated area equiped for irrigation} \times \text{Area haversted}_{\text{crop(i)}} \quad (9)$$

$$(\text{TRcrop(i)}) = (100 - \%\ \text{of the cultivated area equiped for irrigation}) \times \text{Area haversted}_{\text{crop(i)}} \quad (10)$$

An agriculture calibration template is developed for the estimation and calibration of the agriculture sector and is available on Zenodo repository.

3.2.5 Operational Life of Land Technologies

A list of sources for land technologies' operational life is presented in Table 81.

Table 81: List of Sources of Land Technologies Operational Life

Technology	**Sources**	**Assumption**
Deforestation	[46]	
Plantain and Banana export	[46]	
Cocoa beans export	[46]	
Export Groundnuts	[46]	
Maize export	[46]	
Export all other crops	[46]	
Export Sorghum	[46]	
Yam Export	[46]	
Import Plantain and cooking Bananas	[46]	
Cassava import	[46]	
Cocoa beans import	[46]	
Import Groundnuts	[46]	
Maize import	[46]	
Import Oil Palm Fruit	[46]	

All other crop imports	[46]	
Import rice	[46]	
Yam import	[46]	
Agricultural land	[46]	
Built up land technology	[46]	
Irrigated Banana high fertilizer input	[46]	
Rainfed Banana high fertilizer input	[46]	
Irrigated Banana low fertilizer input	[46]	
Rainfed Banana low fertilizer input	[46]	
Irrigated cassava high fertilizer input	[46]	
Rainfed cassava high fertilizer input	[46]	
Irrigated cassava low fertilizer input	[46]	
Rainfed cassava low fertilizer input	[46]	
Irrigated cocoa beans high fertilizer input	[46]	
Rainfed cocoa beans high fertilizer input	[46]	
Irrigated cocoa beans low fertilizer input	[46]	
Rainfed cocoa beans low fertilizer input	[46]	
Irrigated groundnuts high fertilizer input	[46]	
Rainfed groundnuts high fertilizer input	[46]	
Irrigated groundnuts high fertilizer inputs	[46]	
Rainfed groundnuts low fertilizer input	[46]	
Irrigated maize high fertilizer input	[46]	
Rainfed maize high fertilizer input	[46]	
Irrigated maize low fertilizer input	[46]	
Rainfed maize low fertilizer input	[46]	
Irrigated oil palm fruit high fertilizer input	[46]	
Rainfed Oil palm fruit high fertilizer input	[46]	
Irrigated oil palm fruit low fertilizer input	[46]	
Rainfed Oil palm fruit low fertilizer input	[46]	
All other crops irrigated high fertilizer input	[46]	
All other crops rainfed high fertilizer input	[46]	
All other crops irrigated low fertilizer input	[46]	
All other crops rainfed low fertilizer input	[46]	
Irrigated Rice high fertilizer input	[46]	
Rainfed Rice high fertilizer input	[46]	
Irrigated Rice low fertilizer input	[46]	
Rainfed Rice low fertilizer input	[46]	
Irrigated yam high fertilizer input	[46]	
Rainfed yam high fertilizer input	[46]	
Irrigated yam low fertilizer input	[46]	
Rainfed yam low fertilizer input	[46]	
Fallow land	[46]	
Forest land technology	[46]	
Grassland	[46]	
Other lands	[46]	
Water bodies technology	[46]	
Technology for current agricultural practices	[46]	

Technology for climate-friendly agricultural practices	[46]	
Reforestation	[46]	

3.2.6 Capital and Fixed Costs

Tables 82 and 83 present the list of sources for capital and fixed costs for different crops.

Table 82: List of Sources for Crop Capital Cost

Crop Technology	Source	Assumption
Irrigated Banana high fertilizer input	[47]	
Rainfed Banana high fertilizer input	[47]	
Irrigated Banana low fertilizer input	[47]	
Rainfed Banana low fertilizer input	[47]	
Irrigated cassava high fertilizer input	[47]	
Rainfed cassava high fertilizer input	[47]	
Irrigated cassava low fertilizer input	[47]	
Rainfed cassava low fertilizer input	[47]	
Irrigated cocoa beans high fertilizer input	[47]	
Rainfed cocoa beans high fertilizer input	[47]	
Irrigated cocoa beans low fertilizer input	[47]	
Rainfed cocoa beans low fertilizer input	[47]	
Irrigated groundnuts high fertilizer input	[47]	
Rainfed groundnuts high fertilizer input	[47]	
Irrigated groundnuts high fertilizer inputs	[47]	
Rainfed groundnuts low fertilizer input	[47]	
Irrigated maize high fertilizer input	[47]	
Rainfed maize high fertilizer input	[47]	
Irrigated maize low fertilizer input	[47]	
Rainfed maize low fertilizer input	[47]	
Irrigated oil palm fruit high fertilizer input	[47]	
Rainfed Oil palm fruit high fertilizer input	[47]	
Irrigated oil palm fruit low fertilizer input	[47]	
Rainfed Oil palm fruit low fertilizer input	[47]	
All other crops irrigated high fertilizer input	[47]	
All other crops rainfed high fertilizer input	[47]	
All other crops irrigated low fertilizer input	[47]	
All other crops rainfed low fertilizer input	[47]	
Irrigated Rice high fertilizer input	[47]	
Rainfed Rice high fertilizer input	[47]	
Irrigated Rice low fertilizer input	[47]	
Rainfed Rice low fertilizer input	[47]	
Irrigated yam high fertilizer input	[47]	
Rainfed yam high fertilizer input	[47]	
Irrigated yam low fertilizer input	[47]	

Rainfed yam low fertilizer input	[47]	

Table 83: List of Sources for Crop Fixed Cost

Crop Technology	Source	Assumption
Irrigated Banana high fertilizer input	[47]	
Rainfed Banana high fertilizer input	[47]	
Irrigated Banana low fertilizer input	[47]	
Rainfed Banana low fertilizer input	[47]	
Irrigated cassava high fertilizer input	[47]	
Rainfed cassava high fertilizer input	[47]	
Irrigated cassava low fertilizer input	[47]	
Rainfed cassava low fertilizer input	[47]	
Irrigated cocoa beans high fertilizer input	[47]	
Rainfed cocoa beans high fertilizer input	[47]	
Irrigated cocoa beans low fertilizer input	[47]	
Rainfed cocoa beans low fertilizer input	[47]	
Irrigated groundnuts high fertilizer input	[47]	
Rainfed groundnuts high fertilizer input	[47]	
Irrigated groundnuts high fertilizer inputs	[47]	
Rainfed groundnuts low fertilizer input	[47]	
Irrigated maize high fertilizer input	[47]	
Rainfed maize high fertilizer input	[47]	
Irrigated maize low fertilizer input	[47]	
Rainfed maize low fertilizer input	[47]	
Irrigated oil palm fruit high fertilizer input	[47]	
Rainfed Oil palm fruit high fertilizer input	[47]	
Irrigated oil palm fruit low fertilizer input	[47]	
Rainfed Oil palm fruit low fertilizer input	[47]	
All other crops irrigated high fertilizer input	[47]	
All other crops rainfed high fertilizer input	[47]	
All other crops irrigated low fertilizer input	[47]	
All other crops rainfed low fertilizer input	[47]	
Irrigated Rice high fertilizer input	[47]	
Rainfed Rice high fertilizer input	[47]	
Irrigated Rice low fertilizer input	[47]	
Rainfed Rice low fertilizer input	[47]	
Irrigated yam high fertilizer input	[47]	
Rainfed yam high fertilizer input	[47]	
Irrigated yam low fertilizer input	[47]	
Rainfed yam low fertilizer input	[47]	

3.2.7 Variable Cost

Agricultural crop technologies variable cost information was collected from international reports and African countries with similar crop production patterns to Ghana. Table 84 presents the list of sources for variable costs for different crops.

Table 84: List of Sources for Variable Cost of Crop Technologies

Crop Technology	Source	Assumption
Irrigated Banana high fertilizer input	[47]	
Rainfed Banana high fertilizer input	[47]	
Irrigated Banana low fertilizer input	[47]	
Rainfed Banana low fertilizer input	[47]	
Irrigated cassava high fertilizer input	[47]	
Rainfed cassava high fertilizer input	[47]	
Irrigated cassava low fertilizer input	[47]	
Rainfed cassava low fertilizer input	[47]	
Irrigated cocoa beans high fertilizer input	[47]	
Rainfed cocoa beans high fertilizer input	[47]	
Irrigated cocoa beans low fertilizer input	[47]	
Rainfed cocoa beans low fertilizer input	[47]	
Irrigated groundnuts high fertilizer input	[47]	
Rainfed groundnuts high fertilizer input	[47]	
Irrigated groundnuts high fertilizer inputs	[47]	
Rainfed groundnuts low fertilizer input	[47]	
Irrigated maize high fertilizer input	[47]	
Rainfed maize high fertilizer input	[47]	
Irrigated maize low fertilizer input	[47]	
Rainfed maize low fertilizer input	[47]	
Irrigated oil palm fruit high fertilizer input	[47]	
Rainfed Oil palm fruit high fertilizer input	[47]	
Irrigated oil palm fruit low fertilizer input	[47]	
Rainfed Oil palm fruit low fertilizer input	[47]	
All other crops irrigated high fertilizer input	[47]	
All other crops rainfed high fertilizer input	[47]	
All other crops irrigated low fertilizer input	[47]	
All other crops rainfed low fertilizer input	[47]	
Irrigated Rice high fertilizer input	[47]	
Rainfed Rice high fertilizer input	[47]	
Irrigated Rice low fertilizer input	[47]	
Rainfed Rice low fertilizer input	[47]	
Irrigated yam high fertilizer input	[47]	
Rainfed yam high fertilizer input	[47]	
Irrigated yam low fertilizer input	[47]	
Rainfed yam low fertilizer input	[47]	

3.3 Water use

The GeoCLEWs simulation results obtained evapotranspiration data for the different crop types. The ground and surface water data were estimated by subtracting the evapotranspiration data from the annual average precipitation as in Eq. (11):

$$G_W = S_W = \frac{Precipitation - Evapotranspiration}{2} \qquad (11)$$

A list of sources for water system data is presented in Table 85.

Table 85: List of sources for water system data for Ghana

Variables	Source
Long-term average annual precipitation in volume	[21]
Area equipped for full control irrigation total	[21]
Irrigation water requirement	[21]
Irrigation water withdrawal	[21]
Industrial water withdrawal	[21]
Municipal water withdrawal	[21]
Irrigation Potential	[21]
% of irrigation potential equipped for irrigation	[21]
Total renewable surface water	[21]
Total renewable groundwater	[21]
Total water withdrawal	[21]
Ratio between rainfed and irrigated yields	[48]
% of cultivated area equipped for irrigation	[48]

LIMITATIONS

A primary challenge arises from the limited availability of data on energy demand patterns within different sectors, crop production, and areas harvested in Ghana. Some of the data described here is derived from international databases and based on trends in West African developing countries, so it is not necessarily specific to Ghana. Future demand projections are based on trends and growth rate assumptions; however, sophisticated approaches would be required for accurate estimations.

ETHICS STATEMENT

Not applicable

CRediT Author Statement

Romain Akpahou: Methodology, Data curation, Writing, Original draft preparation, Writing – review and editing. Thomas Alfast: Methodology, Data curation, Writing, Original draft preparation, Writing – review and editing. J. Quirós-Tortós: Supervision, Conceptualisation, Methodology, Project administration, Writing – review and editing.

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DECLARATION OF COMPETING INTERESTS

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

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