A Climate, Land, Energy and Water Systems (CLEWs) analysis of Ghana across three scenarios:

- Business as usual
- No biofuels
- A2 extreme climate

- F014618
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- CW3 Report Assessment 70%
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Introduction

The Climate, Land, Energy and Water systems (CLEWs) approach assesses interlinkages between resource systems (SDG Integration, 2024). The approach is based on the concept of nexus thinking which emphasises the interconnected nature of various systems (Martindale et al., 2023) enabling an enhanced understanding of their operation and associated challenges thus supporting holistic decision making. A quantitative CLEWs analysis can be performed using the Open Source Modelling Energy System (OSeMOSYS). While OSeMOSYS was originally developed for long-term energy systems analysis, its flexibility and range of functions make it highly applicable to CLEWs (Ramos et al., 2022). The OSeMOSYS code was developed to meet future energy demand by considering different energy resources and finding the most cost-effective route to meet the demand while remaining within parameters defined by the user. Climate, land and water can also be represented and thus optimised in OSeMOSYS, enabling a full integrated assessment (Ramos et al, 2022).

With the utility of the CLEWs approach and its relationship with OSeMOSYS in mind, the following research questions were proposed:

- What are the cost optimal options for continuing a business-as-usual (BAU) approach to energy and land resources in Ghana?
- In the context of achieving the Sustainable Development Goals (SDGs), should Ghana have a commitment to meeting its transport energy demands (partially or fully) through use of biofuels?
- What are the projected impacts of IPCC's A2 climate change scenario on land use, crop patterns and water usage for Ghana?

Given the interrelated factors involved in the research questions, a CLEWs approach is highly appropriate to address them. Additionally, given the research questions are set at the national scale, the cost optimisation provided by the model would not be feasible by a human in a timely manner. Importantly, the research questions address three separate scenarios. This renders a CLEWs approach using OSeMOSYS highly useful as the baseline model can be duplicated and factors such as climate and fuel availability can easily be reconfigured. In combination with the comparison feature provided by OSeMOSYS Cloud, this makes visualising the scale of change needed and the implications of each future state relatively easy.

Baseline model assumptions

The model has several supply side assumptions. Firstly, the model is limited to select from six types of power plant: gas, hydro, coal, nuclear, wind and off-grid solar (Annex I, Table 2). The land cover types available to the model were agriculture, built-up land, forest and other. Within the agricultural area, the crops available to the model were cocoa beans, maize, soya beans (to act as a biofuel) and all other crops. Each crop type had 2 versions: rainfed and irrigated, except for other crops which were exclusively rainfed. Values for the key water inputs (precipitation and irrigation) were calculated using AQUASTAT (2024) data (Annex I, Table 7) while values for the key water outputs (evapotranspiration, groundwater recharge and surface runoff) were based on global averages for each crop/land cover type (Annex I, Table 8).

The model also includes demand side assumptions. Specified annual demand (Annex I, Table 1) for electricity was based off Climate Compatible growth (CCG) starter kit data (Allington et al., 2022) while accumulated annual demand for biofuels (Annex I, Table 9) was based on IEA biofuel and waste consumption data (IEA, 2024) scaling with an annual population growth factor based on the most recent year of population growth data available (Statista, 2024). Demand for crops (Annex I, Table 6) was calculated with FAOSTAT (2024) data to fulfil the equation: demand = production + imports - exports. Finally, public demand for water was calculated by adding industrial and municipal water withdrawal figures (Annex I, Table 7) sourced from AQUASTAT (2024) and adding an annual population growth factor.

Baseline model results

The baseline model represents a BAU scenario (Annex III, Table 1). In 2022 Ghana generated 35% of its electricity through hydropower and 63% through gas (IEA, 2024) compared to 55% and 45% respectively in the model (Annex II, Figure 1, 2). This suggests greater utilisation of Ghana’s residual hydropower capacity would be more cost optimal than current practice due to the absence of variable costs. However, this may not be feasible in practice as reservoir levels are crucial for water security meaning gas may be required more frequently than the model suggests to cover periods of high demand. The model invests in hydro as existing capacity expires (Annex II, Figure 3) but is limited to 1.9 GW due to the total annual max capacity parameter (Allington et al., 2022) associated with geographical constraints (e.g., availability of suitable sites) and other environmental factors. Consequently, whenever hydro is at maximum installed capacity, the model prioritises investment in gas to meet demand due to low capital and fixed costs. This is in line with Ghana's current investment strategy with gas-fired plants already under construction or recently commissioned due to add 936 MW of dispatchable capacity (Ackah, 2021).

Ghana's Renewable Energy Master Plan (REMP) aims to increase renewable generation to 1364 MW by 2030 (ITA, 2023a). This target relates to SDGs 7 (affordable and clean energy) and 13 (climate action) and reflects Ghana's desire to mitigate climate change potentially at the expense of being cost optimal. However, recent large investments suggest hydropower (African Energy, 2024) could be the dominant renewable in pursuit of this target. If this trend continues, Ghana will simultaneously be investing in energy near cost optimally while contributing to SDGs 7 and 13. When increasing the capital cost of gas to $9999 million in the model, the energy mix changes drastically (Annex II, Figure 4). Hydro remains at maximum capacity while coal takes over from gas as the dominant fossil fuel in 2024 as residual gas capacity begins to expire. With the variable cost of coal increasing each year along with demand for electricity, nuclear becomes financially viable in 2029 thus the model begins to invest in nuclear until it surpasses coal as Ghana's primary energy source in 2047 in a gas free scenario. This relates to Ghana's ambition to establish a 1 GW nuclear plant by 2030 (Milne et al., 2024). In a gas free scenario, establishment of nuclear by 2030 would be cost optimal while simultaneously enhancing energy security and decarbonisation (SDGs 7 and 13).

The model maximises agricultural land area while respecting the demand and lower limit parameters for other land cover types (Annex II, Figure 5). Cocoa and soya bean imports are a feature in the first year and throughout the model suggesting there is not enough land area to satisfy demand for food and biofuel without breaching parameters. There is some similarity to the real world here, as Ghana's 2022 food imports totalled $2.6 billion in 2022 (ITA, 2023b) and domestic production of soya beans has not always kept up with demand resulting in imports (IFPRI, 2020). Despite demand for crops increasing annually, agricultural land decreases each year to meet the annual increases in demand for built-up land associated with population growth, meaning imports are forced to increase to meet demand. This somewhat matches recent land cover trends in Ghana (Annex II Figure 6). It is rainfed cropland which makes way for built-up land as the model prefers to maximise irrigated land while respecting the water balance in order to minimise expensive imports. Despite being Ghana’s largest crop by area (Annex II Figure 7), due to space limitations, the model prefers to import cocoa beans due to its low output per unit of land area. The same is true for soya beans, with the model preferring to allocate land to maize and other crops due to their higher yields (Annex I, Table 5). Limitations of these import suggestions by the model are discussed in the conclusion.

No biofuel scenario

This scenario simulates the replacement of transport fuelled by biofuel with electric vehicles (EVs) powered by the grid. This results in massive initial investment in gas-fired power stations (Annex III, Figure 1) worth 8.6% of Ghana’s GDP to meet the increased demand for electricity associated with the EVs. The EV market in Ghana is currently in a nascent stage (ITA, 2023c) thus such an aggressive transition is not realistic. However, the model does highlight some interesting implications the transition would have on the energy sector in the context of achieving the SDGs. Firstly, despite being a lower carbon alternative to coal and oil, the significant increase in gas-fired power stations results in significant increases in power sector CO_2 emissions (Annex III, Figure 2) which would be detrimental to Ghana’s progress on SDG 13. Additionally, the increased demand for electricity in combination with the massive capital investment in new gas-fired power stations may be passed on to the consumer in the form of higher energy bills which is detrimental to SDG 7.

When focusing on land, the benefits of a transition away from biofuel become more apparent. Firstly, there is a huge reduction in pressure on Ghana’s land resources as no biofuel crop area is needed. Consequently, Ghana’s demand for food can be met exclusively through rainfed cropland (Annex II, Figure 3) without reliance on expensive crop imports and irrigation. This would be beneficial in driving Ghana towards SDG 2 (zero hunger). In addition, the reduced pressure on land area enables the model to allocate significantly more land to forests which are incentivised by a negative variable cost which can offset some of the increased power sector emissions, contributing to SDG 13. This increased tree cover will also result in enhanced biodiversity, contributing to SDG 15 (life on land). As demand for food and built-up land increases annually with population in this scenario, deforestation is the mechanism by which the model frees up space for cropland. While tree cover increased by 12.5% in Ghana between 2000 and 2020 (Annex II, Figure 6), in 2022

18,000 hectares of primary forest were lost (Afele, 2024). If this trend continues, the annual reductions in tree cover in the no biofuel scenario may be reflective of those in Ghana in the real world. Finally, the reductions in water demand associated with no irrigation far outweigh the increases in demand for cooling of the new gas-fired plant meaning water is only abstracted from surface water resources enabling groundwater to recharge (Annex III, Figure 4) thus contributing to SDG 6 (access to clean water).

A2 extreme climate scenario

The IPCC's A2 climate scenario simulates drought conditions (Annex III, Table 1). Crop composition, imports and water use emerge as the key areas impacted by this scenario. In 2035, the previous cropland composition becomes insufficient to meet the demand for biofuel (soya beans). As a result, irrigated land which was previously dominated by maize becomes exclusively farmed for soya beans (Annex III, Figure 5). Simultaneously, rainfed soya beans see a significant annual reduction in land area to provide space for the previously irrigated maize (Annex III, Figure 6). Increasing the irrigated land area of soya beans is still insufficient to meet demand, thus soya bean imports increase significantly by 7 Mt relative to the baseline in 2035 (Annex III, Figure 7). Between 2035 and 2041, land area allocated to rainfed soya beans decreases annually as increasing imports satisfy the demand. By 2042 no more rainfed land is allocated to soya beans and irrigated soya beans give way to maize annually until irrigated land hosts exclusively maize in 2047. Concurrently, rainfed maize is decreasing while rainfed 'other' crops are increasing to meet demand. Consequently, by 2048, the model is forced to import maize in increasing annual quantities (Annex III Figure 7). This is significant from a policy perspective, as previously imports proposed by the model were biofuel only while now there is a food crop which could be vulnerable to disruption in the supply chain and price fluctuations which may be detrimental to SDG 2. Additionally, with global food-miles accounting for nearly 20% of total food-system emissions (Li et al., 2022), the transport associated with these increased imports may be disadvantageous to SDG 13.

Conclusions and policy recommendations

In a BAU scenario, Ghana should maximise hydropower capacity as part of a cost optimal approach to power generation. This approach will simultaneously support Ghana in its pursuit of 1364 MW of renewable power generation by 2030 and SDGs

7 and 13. Once hydro capacity has reached a limit of 1.9 GW associated with geographical constraints (Allington et al., 2022), Ghana should prioritise developing gas-fired plant due to their relatively low capital and fixed costs while acting as a lower carbon alternative to coal and oil in the pursuit of SDG 7 and 13.

Ghana should have a partial commitment to meeting its transport energy demands through biofuels. Too much reliance on biofuels is detrimental to food and water security (SDGs 2 and 6) while no utilisation of biofuels requires massive initial capital investment in gas-fired plant which may threaten SDG 7 and 13 due to the huge spike in power sector emissions. Therefore, partial reliance on biofuels for transport along with steady introduction of EVs fuelled by the BAU power generation recommendations could ensure each SDG is achieved without severely compromising another. An A2 climate scenario would place significant strain on Ghana's crops, threatening food security and SDG 2. It would result in maize imports of increasing quantities from 2047 meaning Ghana would need to review import regulations and consider negotiating new trade agreements. To avoid increasing reliance on imports for food security and SDG 2, Ghana should consider low reliance on biofuels in an A2 climate scenario to maximise land area available for food crops.

These policy recommendations have been formulated cautiously with some of the model's limitations in mind. Firstly, the model only considers crop yield and not value per tonne when deciding which crop to import, meaning suggestions may not be cost optimal when there is a large discrepancy in crop values (e.g., cocoa beans/maize). Regarding energy, the model is limited as it can only select from the 6 power generation technologies made available to it. Finally, annual increases in demand for energy, food and water are scaled with population growth which is a simplified relationship as various other factors can influence these in the real world.

Considering the growing prominence of the climate crisis, it would be useful to investigate a scenario where renewable and low-carbon technology costs are reduced to represent subsidies in support of SDG 13 while fossil fuel prices are increased to signify taxes and high carbon prices. This would allow other low-carbon technologies outside of hydro to emerge as cost-effective solutions to climate change. Parameterisation of this model would require projections of future carbon prices and an optimistic estimate of future subsidies and taxes for each technology.

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Annex I – Data in brief and model structure

Table 1. Ghana's specified annual energy demand. Figures are the sum of INDELC, RESELC and COMELC values in the Climate Compatible Growth's starter data kits SAND spreadsheet (Allington et al., 2022).

Energy	2020	2030	2040	2050
Specified annual demand (PJ)	40.68	79.545	164.1	296.6

Table 2. Capital/fixed costs and operational life for the power generation technologies included in the model. Data source: CCG SAND spreadsheet (Allington et al., 2022).

	Capital cost ($/kW)				Fixed cost ($/kW)				Operational life (years)
Technology	2020	2030	2040	2050	2020	2030	2040	2050	N/A
PWRGAS	1200	1200	1200	1200	35	35	35	35	30
PWRHYD	3000	3000	3000	3000	90	90	90	90	50
PWRCOA	2500	2500	2500	2500	78	78	78	78	35
PWRNUC	6137	6137	6137	6137	184	184.1	184.1	184	50
PWRWND	1489	1087	933	933	59.6	43.48	37.32	37.3	25
PWRPVR	4320	2700	2091	2091	86.4	54	41.82	41.8	24

Table 3. Variable cost and emission activity ratio for the fuels included in the model. Data source: CCG SAND spreadsheet (Allington et al., 2022).

	Variable cost ($/kW)				
Technology	2020	2030	2040	2050	Emission activity ratio (kgCO2eq/GJ)
MINGAS	7.1	8.5	9.9	9.9	0.06
MINHYD	0	0	0	0	0
MINCOA	3.4	3.6	3.8	3.8	0.09
MINURN	0	0	0	0	0
MINWND	0	0	0	0	0
MINSOL	0	0	0	0	0
DEMAGRDSL	0	0	0	0	0.07

Table 4. Residual capacity of the power generation technologies included in the model. Data source: CCG SAND spreadsheet (Allington et al., 2022).

	Residual capacity (GW)			
Technology	2020	2030	2040	2050
PWRGAS	1.251	0.16	0	0
PWRHYD	1.598	1.598	1.598	0.56
PWRCOA	0	0	0	0
PWRNUC	0	0	0	0
PWRWND	0	0	0	0
PWRPVR	0.08	0.08	0.001	0

Table 5. Area harvested, production quantity, output activity ratio, capital costs and operational life of the crops included in the model.

Crop	Area harvested (1000 km2)	Production quantity (Mton)	Output activity ratio (Mton / 1000 km2)	Capital costs (million dollars / 1000 km2)	Operational life (years)
Cocoa beans (rainfed)	14.76	0.79	0.05	10	15
Cocoa beans (irrigated)	0.09	0.01	0.08	80	15
Maize (rainfed)	11.89	3.04	0.26	10	15
Maize (irrigated)	0.07	0.03	0.40	80	15
Soya beans (rainfed)	1.08	0.18	0.17	10	15
Soya beans (irrigated)	0.006	0.002	0.26	80	15
All other crops (rainfed)	49.45	48.40	0.98	10	15

Table 6. Accumulated annual demand for the crops included in the model.

	Accumulated annual demand (Mton)			
Crop	2020	2030	2040	2050
Cocoa beans	0.18	0.22	0.27	0.32
Maize	3.03	3.66	4.41	5.32
Soya beans	0.17	0.21	0.25	0.30
Other	48.40	58.36	70.38	84.88

Table 7. Ghana's key water data used to calculate water parameters for the model. Data source: AQUASTAT (2024).

Variable	Value
Long-term average annual precipitation in volume (10^9 m3/year)	283.14
Area equipped for full control irrigation: total (1000 ha)	30.90
Irrigation water requirement (10^9 m3/year)	0.16
Agricultural withdrawal (10^9 m3/year)	1.07
Industrial withdrawal (10^9 m3/year)	0.10
Municipal withdrawal (10^9 m3/year)	0.30
Irrigation potential (1000 ha)	1900.00
% of irrigation potential equipped for irrigation (%)	1.63
Total renewable surface water (10^9 m3/year)	54.90
Total renewable groundwater (10^9 m3/year)	26.30
Total water withdrawal (10^9 m3/year)	1.47

Table 8. Output activity ratios for evapotranspiration (WTREVT), groundwater recharge (WTRGWT) and surface runoff (WTRSUR) for the crops included in the model. Values based on the global average for each crop type.

Crop	WTREVT	WTRGWT	WTRSUR
Cocoa beans rainfed	0.523	0.075	0.647
Maize rainfed	0.373	0.043	0.825
Soya beans rainfed	0.279	0.048	0.913
Cocoa beans irrigated	1.977	0.282	2.448
Maize irrigated	0.409	0.042	0.790
Soya beans irrigated	0.471	0.038	0.730
Forests	0.884	0.031	0.330
Built-up land	0.784	0.037	0.423
Water bodies	0.411	0.087	0.747
Other land	0.884	0.025	0.336

Table 9. Ghana's accumulated annual demand for biofuels. Data source: IEA (2024).

Biofuels	2020	2030	2040	2050
Accumulated annual demand (PJ)	120.21	144.96	174.81	210.81

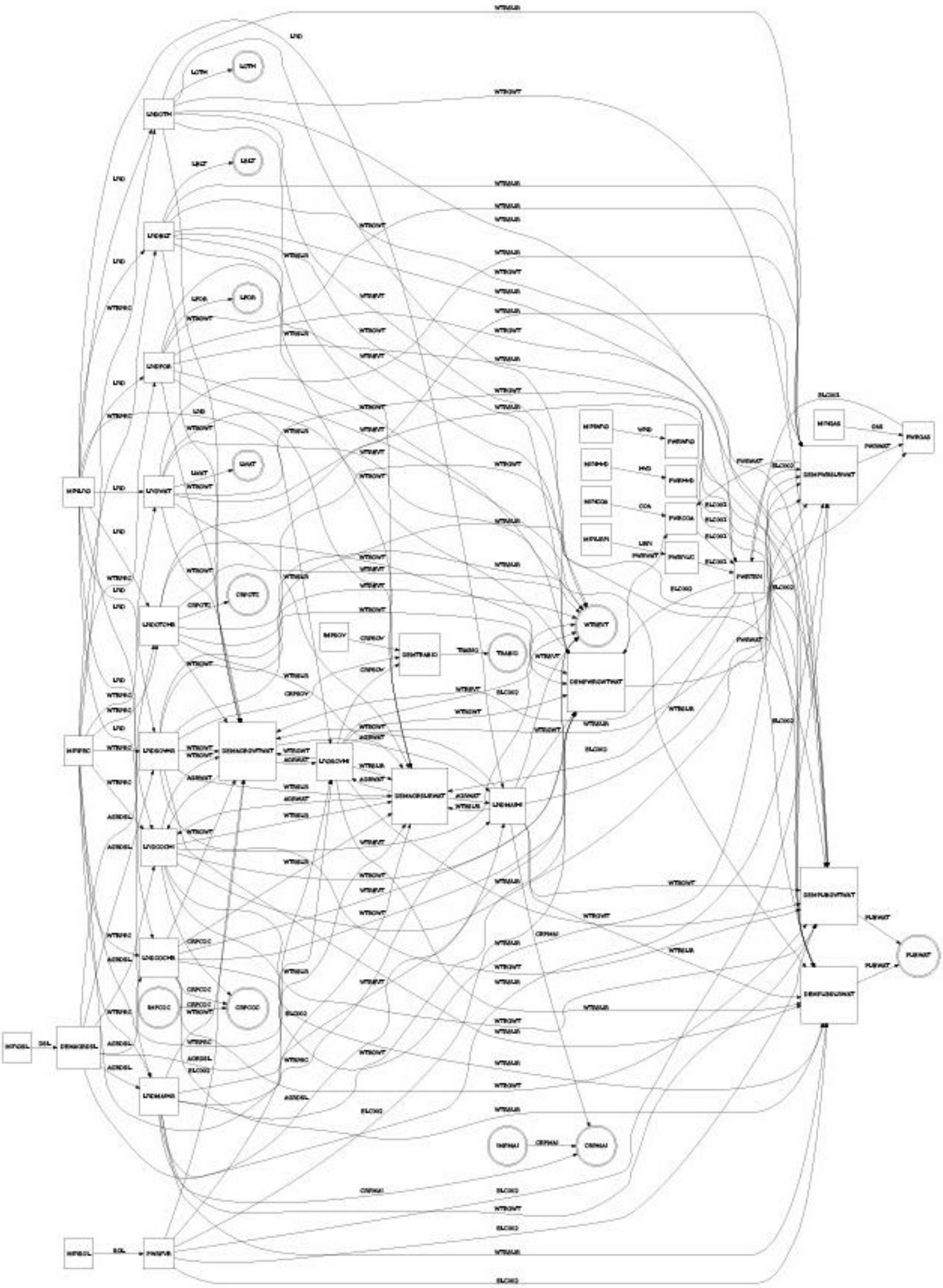
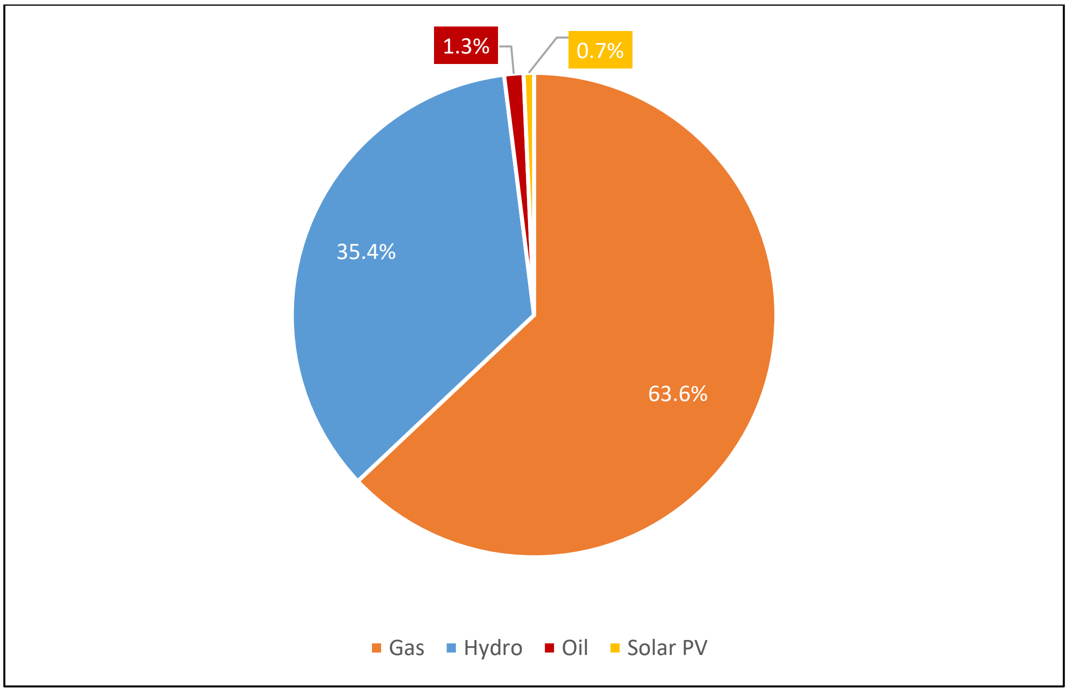


Figure 1. Ghana baseline model (BAU) structure. Source: OSeMOSYS Cloud.

Annex II – Baseline model results

a.)



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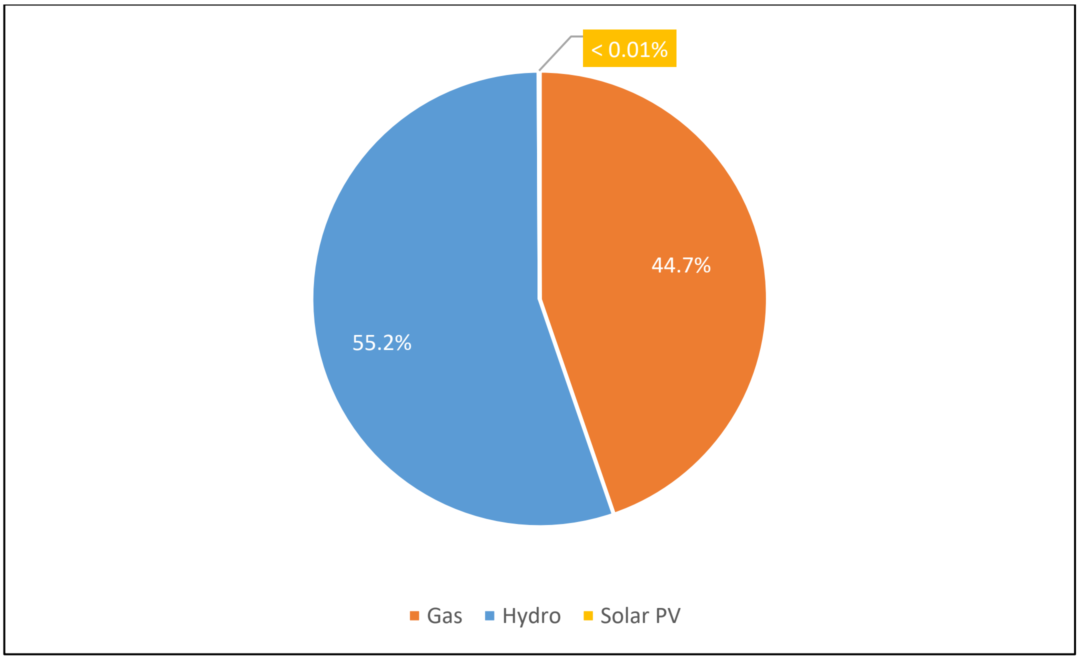

Figure 1. Ghana 2022 power generation in a.) the real world, b.) the baseline model. Data source for b.): IEA (2024).

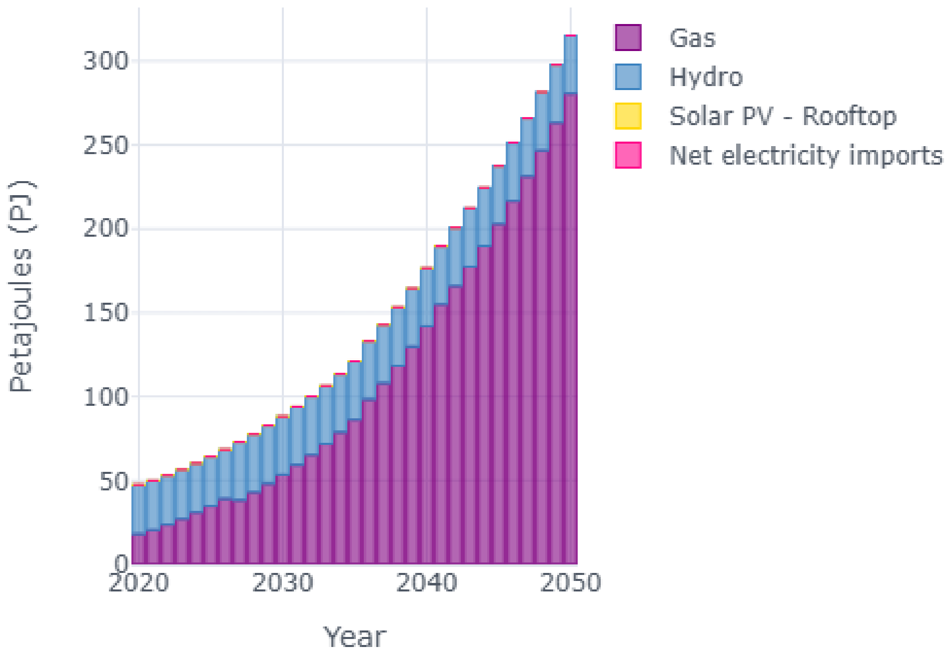

Figure 2. Electricity generation mix proposed by the baseline model for Ghana 2020-2050. Source: OSeMOSYS Cloud.

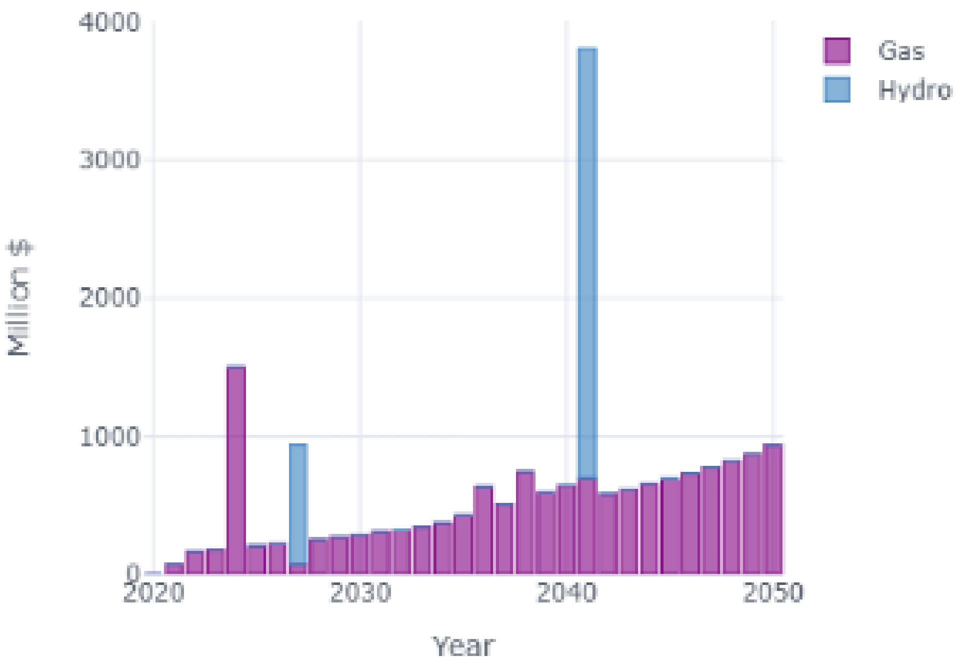

Figure 3. Proposed capital investment in energy infrastructure by the baseline model for Ghana 2020-2050. Source: OSeMOSYS Cloud.

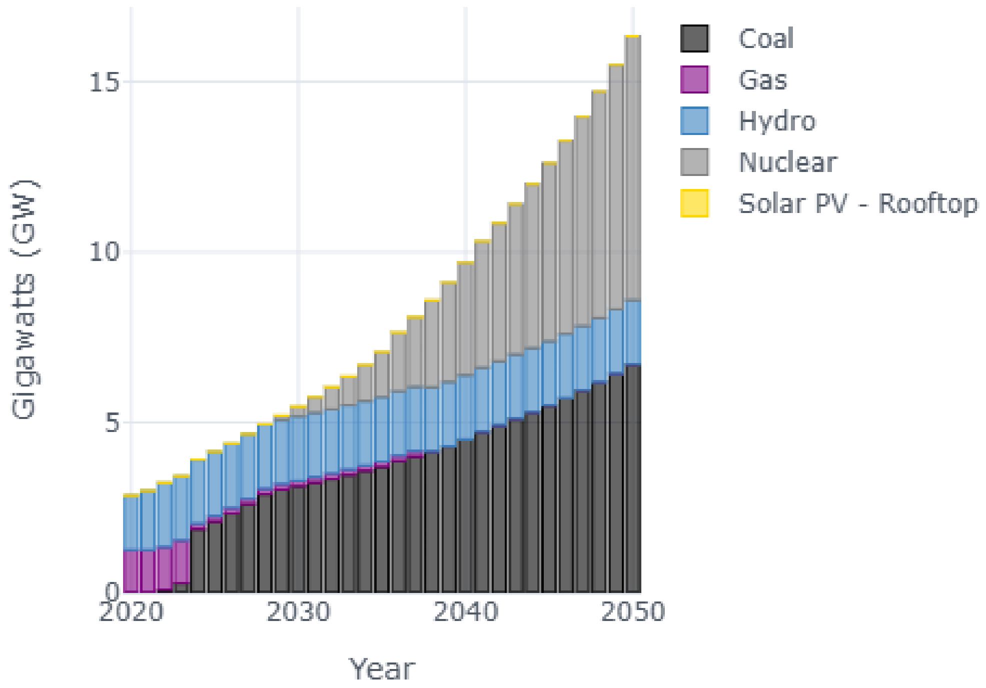

Figure 4. Power generation capacity breakdown of Ghana 2020-2050 in a scenario where the price of gas infrastructure is extortionate. Source: OSeMOSYS Cloud.

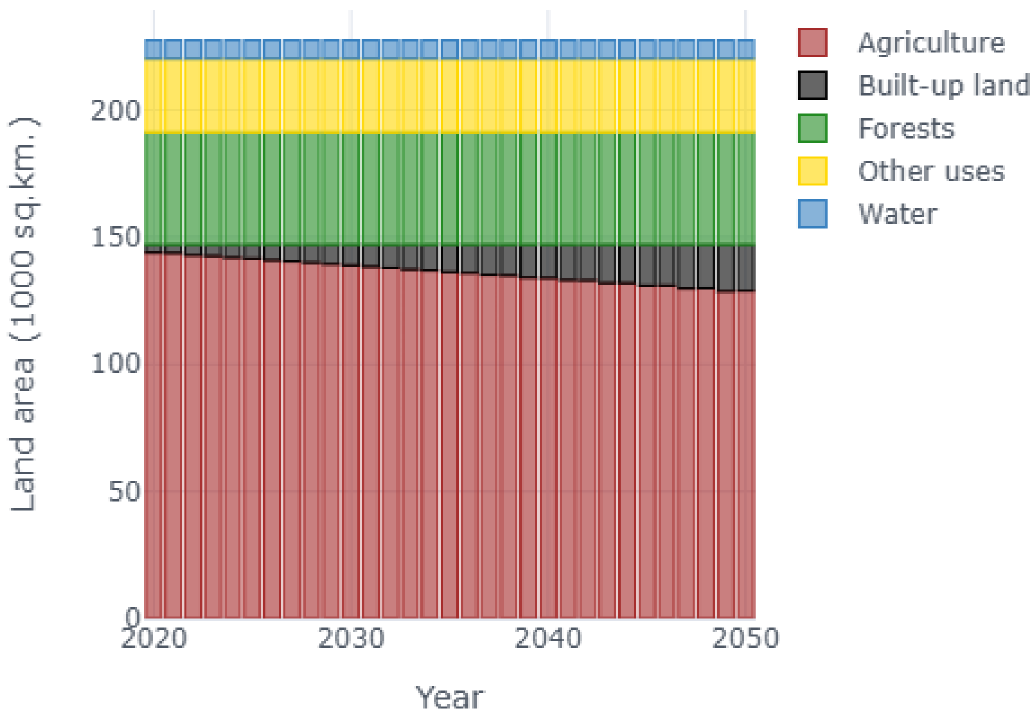

Figure 5. Area by land cover type for Ghana 2020-2050 proposed by the baseline model. Source: OSeMOSYS Cloud.

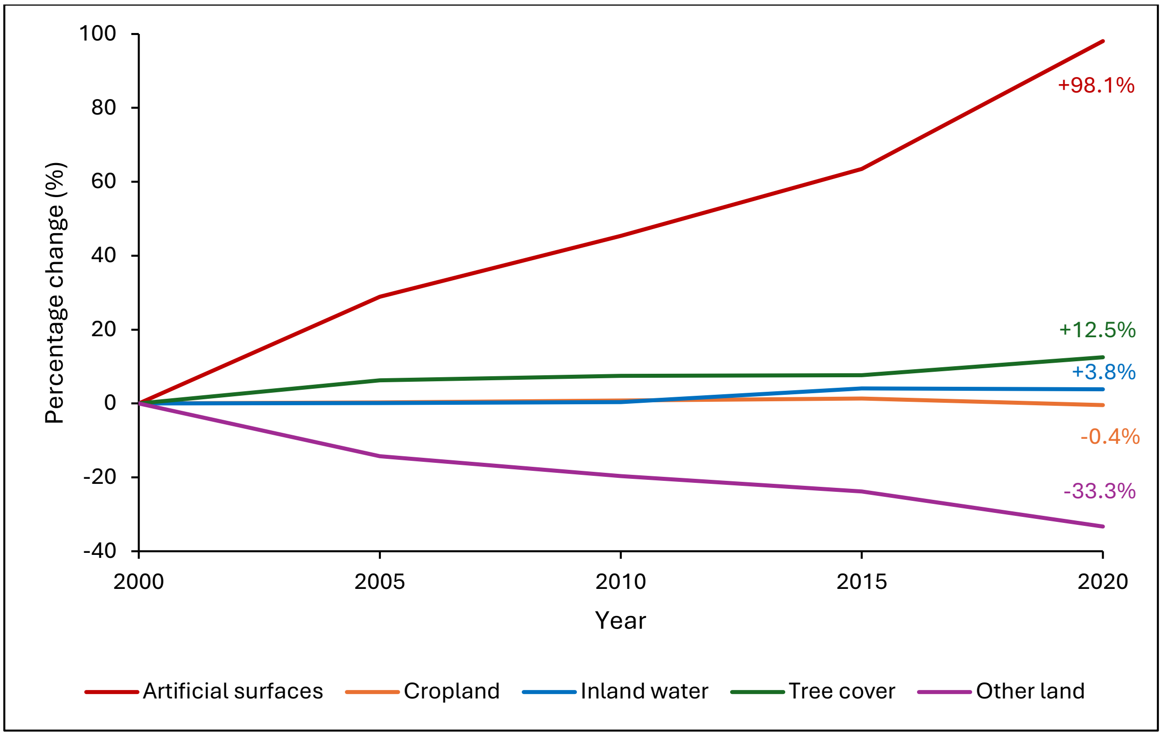

Figure 6. Percentage change (%) in land area of different land cover types in Ghana between 2000 and 2020. Data labels represent the total cumulative change for each land cover type over the period of interest. Data source: OECD (2024)

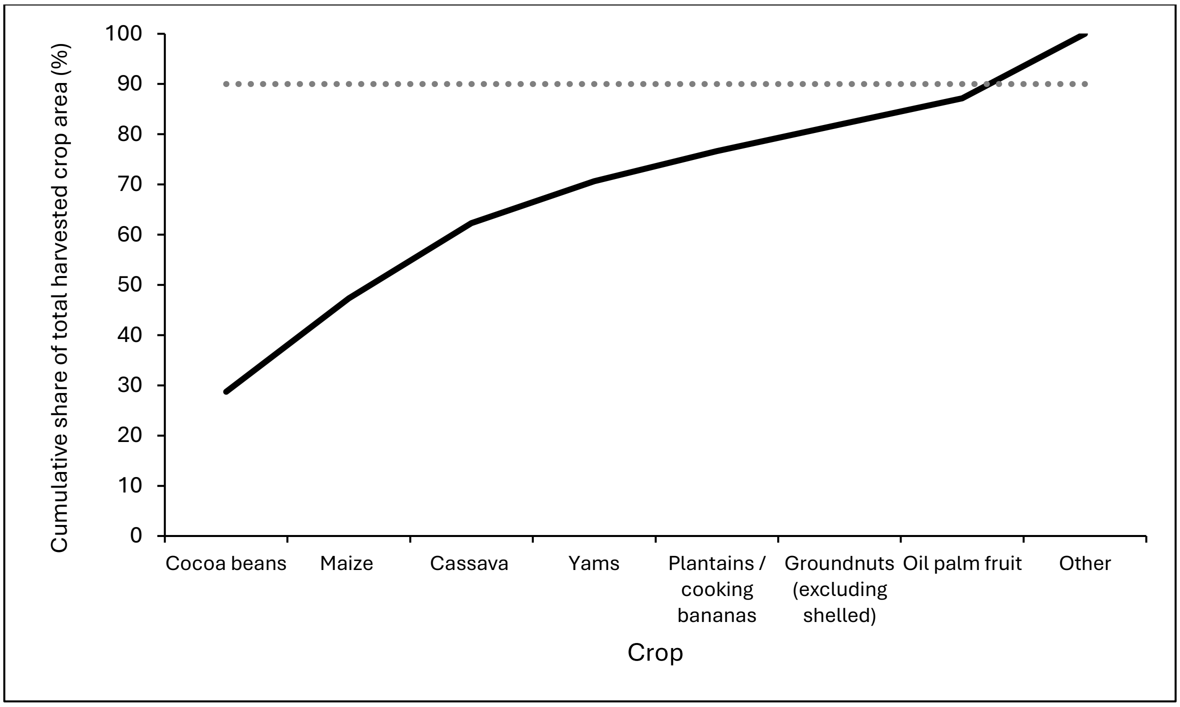

Figure 7. Cumulative percentage (%) of total crop area of the largest crop types in Ghana up to a 90% area threshold. Data source: FAO (2024).

Annex III – Scenario results and descriptions

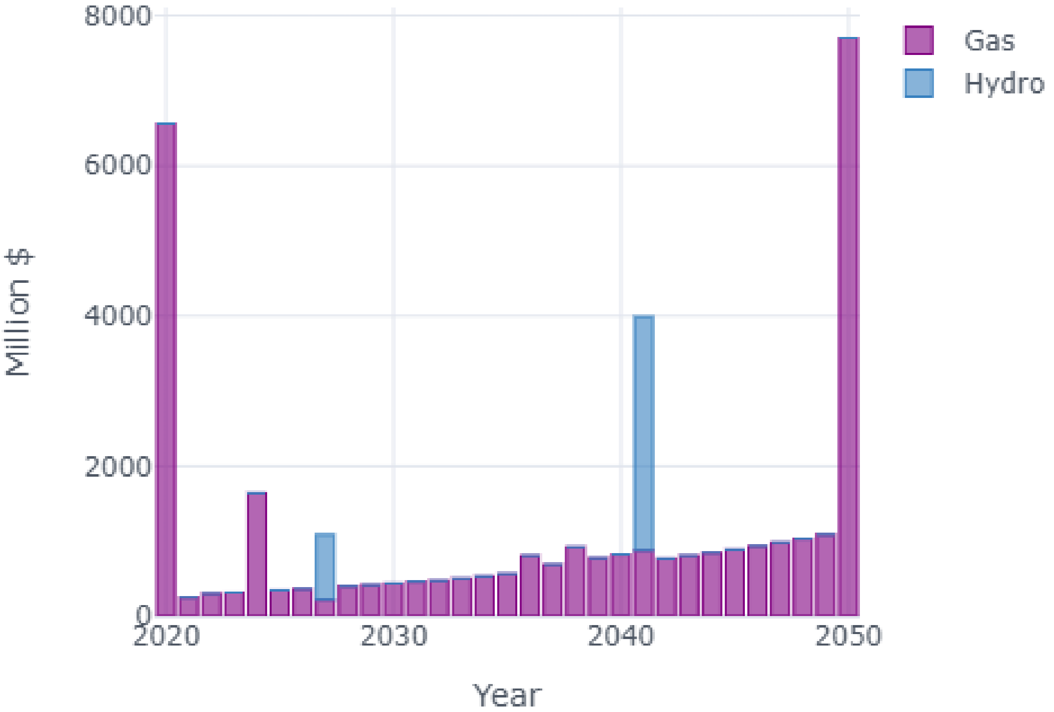

Figure 1. Proposed capital investment in energy infrastructure for Ghana 2020-2050 in a no biofuel scenario. Source: OSeMOSYS Cloud.

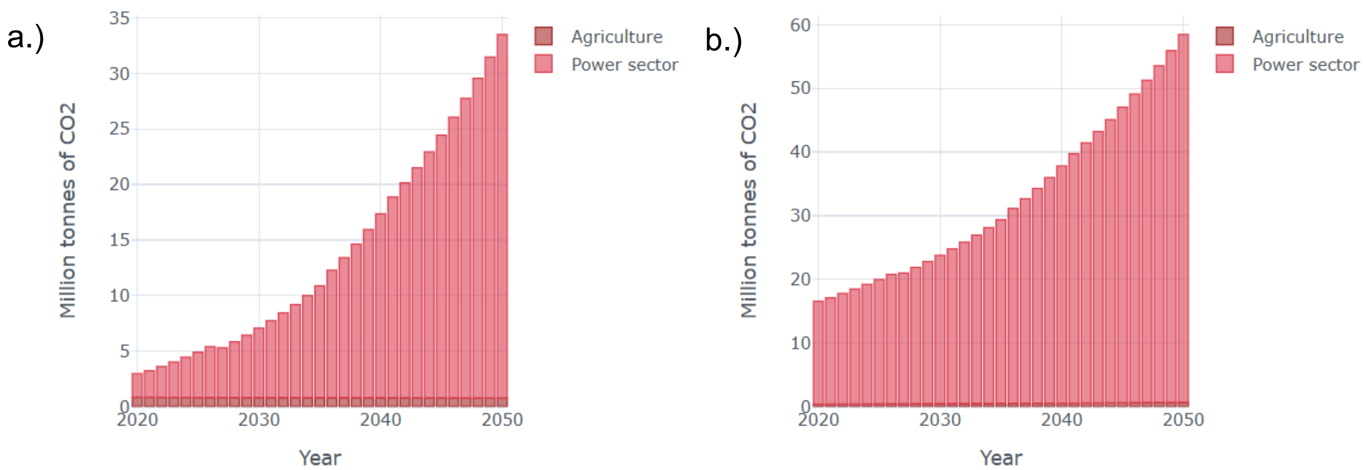

Figure 2. Projected CO_2 emissions by sector in a.) business-as-usual (BAU) scenario, b.) no biofuel scenario. Source: OSeMOSYS Cloud.

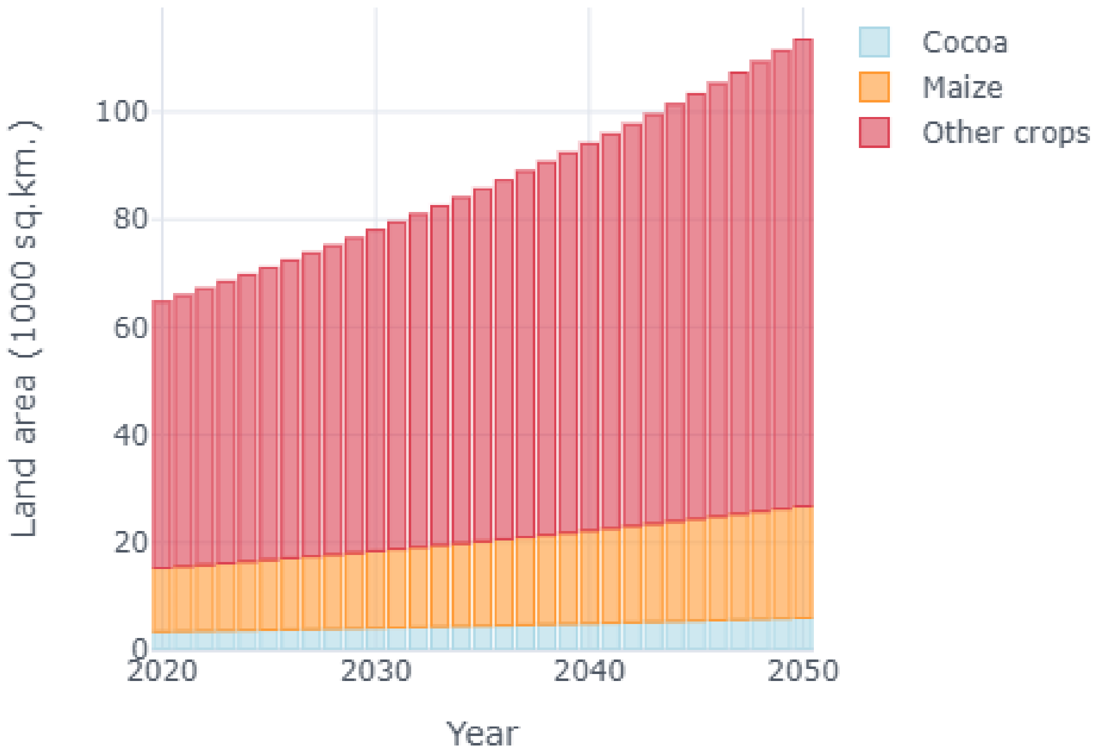

Figure 3. Ghana rainfed crops by land area in a no biofuel scenario 2020-2050. Data source: OSeMOSYS Cloud.

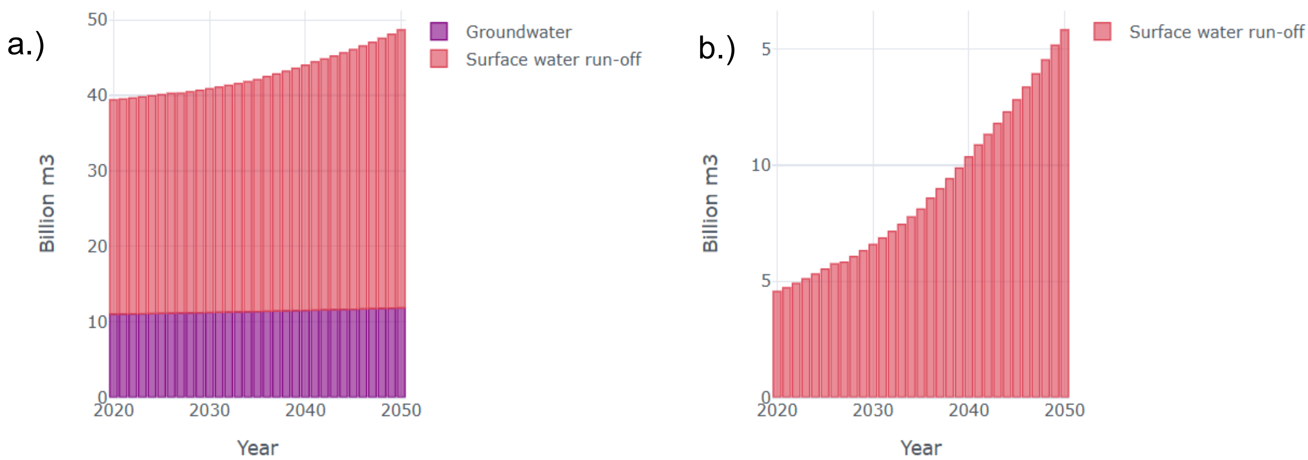

Figure 4. Water withdrawal by source in a.) BAU scenario, b.) no biofuel scenario. Source: OSeMOSYS Cloud.

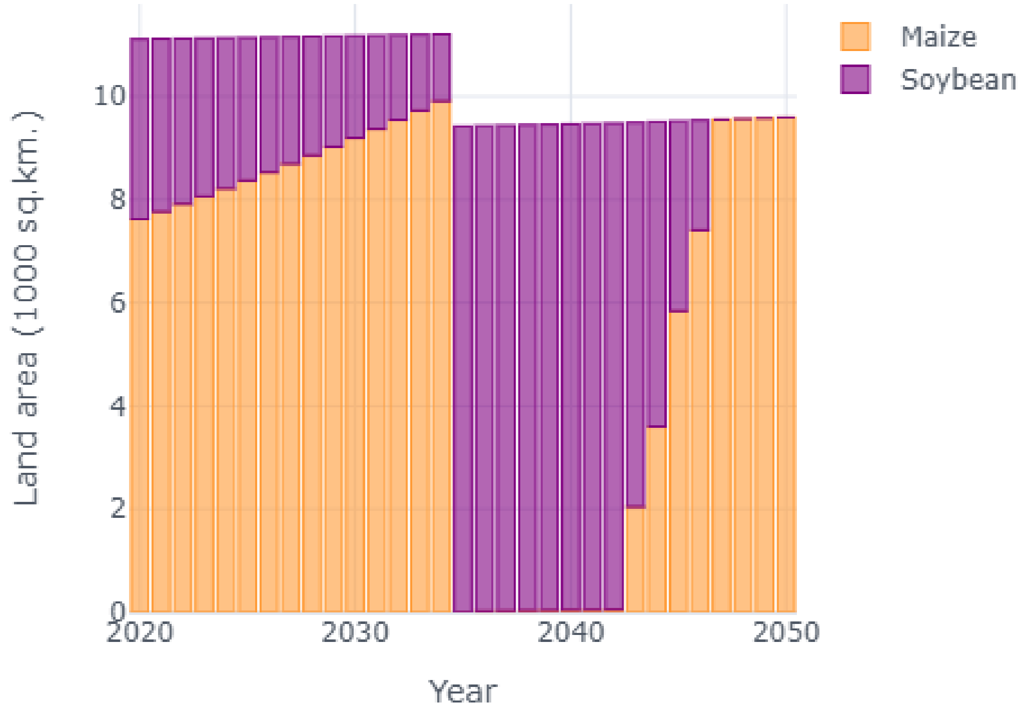

Figure 5. Land area allocated to irrigated crops in Ghana 2020-2050 under the IPCCs A2 climate scenario. Source: OSeMOSYS Cloud.

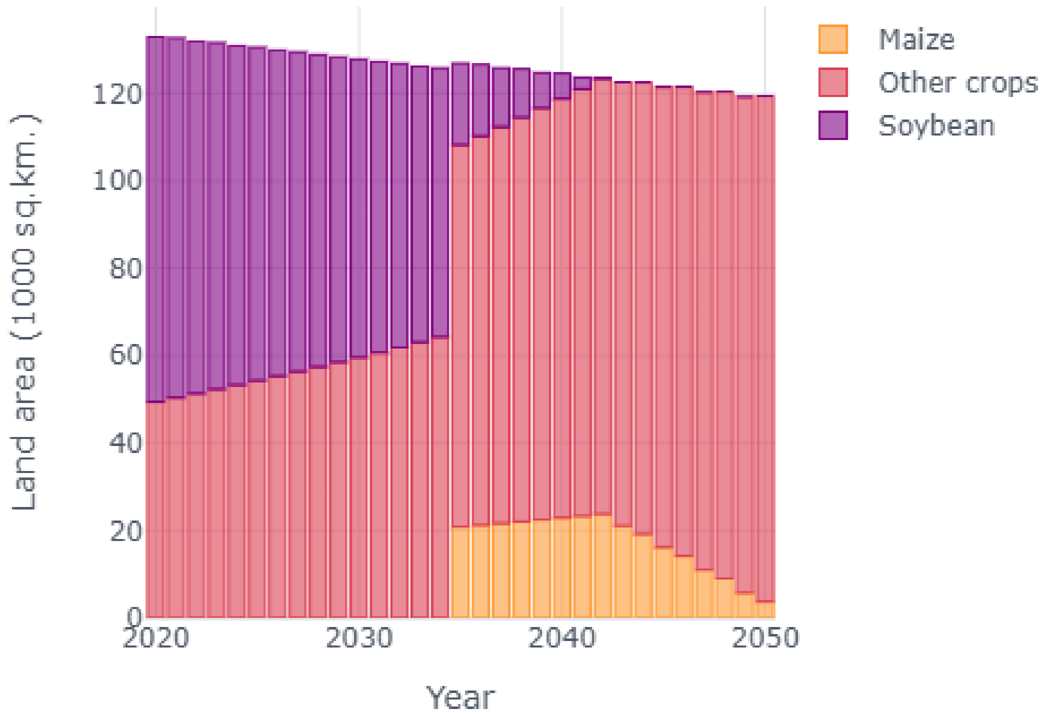

Figure 6. Land area allocated to rainfed crops in Ghana 2020-2050 under the IPCCs A2 climate scenario. Source: OSeMOSYS Cloud.

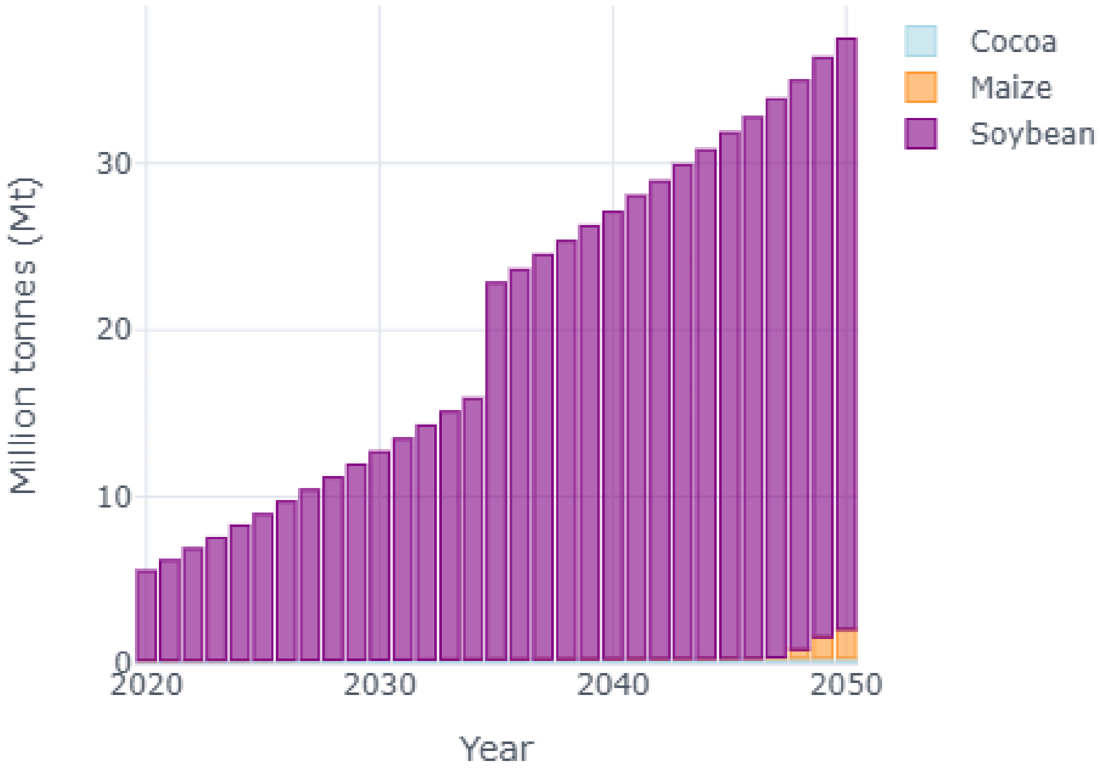

Figure 7. Ghana crop imports proposed by the model 2020-2050 under the IPCC's A2 climate scenario. Source: OSeMOSYS Cloud.

Table 1. Scenario descriptions and methodology.

Scenario	Definition
Business-as-usual (BAU)	The baseline, or BAU model is used as a reference point to compare the other scenarios against. Parameters are based on the most recent year of real-world data for Ghana meaning conditions are similar to that of Ghana in the real world. Projected population growth is used to scale up annual demand for energy, land and water resources.
No biofuel	To simulate a no biofuel scenario, the BAU model was duplicated, and all biofuel technologies and commodities were removed. With biofuels no longer in the model, their accumulated annual demand was added to the specified annual demand for energy to simulate increased demand for electricity associated with the introduction of EVs in place of biofuel-powered transport.
A2 extreme climate	The IPCC's A2 extreme climate scenario was used to represent future drought from 2035 onwards. To simulate this, the BAU model was duplicated, and the productivity of both rainfed and irrigated cropland was reduced by 25% from 2035 onwards. Additionally, the water required to irrigate crops was increased by 15% while precipitation, evapotranspiration, groundwater recharge and surface runoff values were decreased by 15% from 2035 onwards.