

Article

Assessment of Impacts of Climate Change on Hydropower-Dominated Power System—The Case of Ethiopia

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Abstract: The Ethiopia energy mix is dominated by hydro-generation, which is largely reliant on water resources and their availability. This article aims to examine the impacts of severe drought on electric power generation by developing a Drought Scenario. OSeMOSYS (an open source energy modelling tool) was used to perform the analyses. The results were then compared with an existing reference scenario called “New Policy Scenario”. The study looked at how power generation and CO₂ emissions would be altered in the future if reservoir capacity was halved due to drought. Taking this into account, the renewable energy share decreased from its 90% in 2050 to 81% in 2065, which had been 98% to 89% in the case of New Policy Scenario. In another case, CO₂ emissions also increased from 0.42 Mt CO₂ in 2015 to 7.3 Mt CO₂ in 2065, a 3.3 Mt CO₂ increase as compared to the New Scenario. The results showed how a prolonged period of drought would reduce the river flows and lead to an energy transition that may necessitate the installation of other concurrent alternative power plants. The study suggested ways to approach energy mix, particularly for countries with hydro-dominated power generation and those experiencing drought.

Keywords: ethiopian electric power; OSeMOSYS; NEP 2; energy planning



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1. Introduction

One of the four pillars of the Ethiopian Climate Resilience Green Economy (CRGE) initiative was to increase electricity generation from renewable energy sources for local and regional markets [1]. As per the second National Electrification Program (NEP-2), by 2025, grid solutions are expected to account for 65% of access provision while off-grid technology is expected to cover the remaining 35% [2]. Ethiopia has abundant water resources with a capacity to generate over 45,000 Mega Watts (MW) [3]. In just over a decade, the country's power generating capacity had quadrupled, raised from about 850 MW to 4300 MW in 2017. The Government's investments have positioned the country well to become a power hub for their East African neighbours, in harmony with the nation's resilience to climate change and its reputation for being a green economy front-runner, with the hydro Gibe-III Hydropower (1870 MW) and other well-advanced large-scale hydropower projects, most notably, the 5000 MW Grand Ethiopian Renaissance Dam, which is more than halfway through construction [2]. However, ensuring reliable and consistent access to electricity remains the major concern [2,4–8]. In recent years, with increasing load demand, the Ethiopian power system has faced more frequent, widely spread and long lasting blackouts [9]. Alongside this initiative, the government is committed to limiting the country's 2030 GHG emissions to today's 150 Mt CO₂ [10]. The emission is mainly due to the traditional and unsustainable ways of utilizing natural resources [11].

As one of the Sub-Saharan countries, Ethiopia is prone to a variety of climatic extremes, including devastating droughts and floods [6]. Drought can be caused by a variety of natural factors including topography. However, it is more linked with climate change. A dual relationship exists between hydropower and climate change. On the one hand, hydropower is a valuable renewable energy source that helps to reduce greenhouse gas emissions and mitigate global warming. Climate change, on the other hand, is anticipated to alter river discharge, affecting water availability, consistency, and hydropower generation [12–14]. Rivers and reservoirs can dry up as a result of drought. In countries like Ethiopia where hydropower plants are predominant, drought may significantly reduce electrical power generation. Extreme and exceptional drought conditions have been affecting much of the Ethiopian periodic droughts that disrupted hydroelectric power generation, exacerbating the problem and may force decision makers to invest more. One of the largest hydropower plants in Ethiopia (Tekeze) was out of production for most of its first year as a result of drought. Research studies have also revealed varying levels of climate change impacts on water availability, which is the only input for hydropower [15–19]. Many researchers have carried out an investigation to look at the effects of climate change on hydroelectric power generation and to propose solutions to the problem.

In Kainji Dam, Niger State, Nigeria, empirical research was conducted to examine the effect of reservoir inflow patterns on hydroelectric power generation capacity. First, the study period's overall mean power generation was determined. The effects of inflow on power generation during high and low inflow periods were then explored. The research indicated that reservoir inflow has a strong relationship on the amount of power generated [17,20].

A study in Ecuador used climate change impact modelling and demonstrated it through application to a hydropower plant in the Rio Jubones Basin. According to its scenario analysis, while hydropower generation will increase during the wet season, the plant will experience a significant power shortage during the dry season, up to 13.14% less from the reference scenario, due to a 17% reduction in streamflow under the assumption of a 2.9 °C increase in temperature and a 15% decrease in rainfall [21]. Another study in Ecuador Modelled climate change effects on Ecuador electricity sector, which heavily depends on hydropower, shows that changes in water availability could induce a variation in electrical hydropower generation for supplying total electricity demand of between 29% and 86% [22].

The impact of climate change on the potential of several basins across South America was studied and investigated. Three downscaled global climate models were taken into consideration. For most regions in Brazil, the historical observations and regional climate change modelling results showed a significant reduction in rainfall and a rise in temperature. They have come to the conclusion that hydroelectric power plant output will likely decrease in the coming years [12]. The study used a partial equilibrium bottom-up optimization model (TIMES PT) to estimate the implications of climate change on the Portuguese electrical system by 2050, focusing on the impacts on water resource availability and hydropower generation. According to the findings, hydropower generation might decline by 41% by 2050, with higher electricity prices (up to a 17% rise) and higher greenhouse gas emissions (up to 7.2% increase) [23].

In the Upper Yangtze River Basin (one of the most vigorous hydropower regions in China), the effects of climate change and greenhouse gas emissions on hydropower supply and demand in the twenty-first century were investigated [14]. In drought affected areas, it is recommended to have ready concurrent other plants to compensate for the reduction in power generation due to climate change from hydropower plants. In Colombia, two partial equilibrium and two general equilibrium models were employed to discover potential energy system pathways. This research also revealed that climate change-related hydropower losses must be balanced by the emergence of other alternative technologies [13].

Using an integrated hydro reservoir and power system dispatch model, a study specific to Ethiopia reported the susceptibility of Ethiopian power systems to extreme hydrological

circumstances. The findings showed that hydropower may assist in obtaining the lowest cost generation of electricity. Cost of power, on the other hand, was shown fluctuating greatly depending on many other parameters. It was discovered that, disregarding the cost of unserved energy, the low inflow scenario had a cost of electricity that was around four times more than the moderate inflow scenario [8]. In the future, climate change is expected to cause droughts to be longer and more intense in terms of precipitation shortage, which will decrease hydropower plants' capacity factor [5]. For hydrological forecasting and reservoir operation, a precise estimate of reservoir input is critical [24]. This article aims to show the impacts of climate change on hydropower generation and the environment in Ethiopia. It examines the impacts of severe drought to electricity generation by developing a scenario (named Drought Scenario) and comparing it with the reference scenario (named New Policy Scenario) using OSeMOSYS energy system modelling tool. Under drought conditions, the study looked at how electricity generation and its CO₂ emission would be altered in the future if reservoir capacity was halved (50%) due to drought. The characterization of the Drought Scenario is expected to enlighten decision-makers in the plan of future renewable power systems, including the provision of backup solutions.

2. Methods

An Open Source energy Modeling SYSTEM (OSeMOSYS) tool was used to assess the required energy supply (electricity capabilities) and CO₂ emissions using a broad representation of diverse technologies in the industry, residential, transportation, agricultural, and other sectors. OSeMOSYS is specifically designed as a tool to inform the development of local, national and multi-regional energy strategies and support them with capacity building activities. Unlike other long established energy systems modeling frameworks such as MARKAL/TIMES, MESSAGE, PRIMES, EFOM and POLES), it potentially requires a less significant learning curve. Additionally, by not using proprietary software or commercial programming languages and solvers, OSeMOSYS requires no upfront financial investment. This feature increases its affordability, particularly in developing countries [25,26].

It starts with energy demand development, driven by annual average GDP growth, average yearly population growth, average household size, and percentage urban population. A detailed description of the basic layout, Reference Energy System, of the model can be found in the supplementary material in [27]. The methodology applied in this paper is based on a model produced in the Energy system development pathways for Ethiopia (PATHWAYS) project, which optimized Ethiopian long-term energy system development pathways through 2065 using existing policy, the country's second National Electrification Plan (NEP-2), and techno-economic data from the different reputable international organization. The PATHWAYS project aimed to unlock barriers in the energy system planning process and policy analysis by developing energy system models that adopt an inclusive approach through stakeholder engagement. It has used the social science research output (qualitative scenarios for both supply and demand side defined via interviews, questionnaire survey, focus group workshop, and institutional regulatory frameworks) to quantify the energy, economics and environmental impacts of energy system development pathways in Ethiopia [7].

The scenarios, modelling assumptions, and the data used to develop this study were collected and handled through several capacity-building activities with local stakeholders, country analysts, and involved institutions and government agencies (Ministry of Water, Irrigation and Energy; Ministry of Mining, Petroleum and Natural Gas; Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ); UK aid funded Energy and Economic Growth Applied Research Programme; Addis Ababa Institute of Technology; Policy Studies Institute in Addis Ababa; University College of London Energy Institute; KTH Royal Institute of Technology) in Addis Ababa, Ethiopia, between 2018 and 2020.

Two workshops involving directors and sectoral and key technical experts were organized to develop the electrification pathways and narratives according to experts'

views from different backgrounds. Four workshops were held in total, engaging with around 30 people on multiple occasions to conceptualize the study and evaluate the modelling inputs and results. There were four scenarios developed and examined in this project, which are New Policy, Slowdown, Big Business, and High Ambition, capturing different levels of electrification, capital costs in power generation technologies, discount rates, levels of exported electricity, and the implementation year of future power plants. These are mainly driven by differences in future electricity demand, achieving universal access in different years, electricity consumption per capita, availability of future power generation projects, discount rates, and technology cost changes over time [7,28].

Steps Used

This paper tried to build on an already developed scenario (New Policy Scenario) in the model developed for the PATHWAYS project, which is then used here as a baseline in order to compare with a Drought Scenario, which shows the effect of climate change in Ethiopia's Power Generation System and Environment. The study [28] developed different scenarios including the New Policy Scenario targeting the requirement of electric supply and CO₂ emissions within an energy system modelling framework. The steps used are as follows:

Step 1: It starts with energy demand development, driven by the aforementioned factors, which consist of gathering data for energy demand projections, primary energy resources and transmission and distribution system collected from 18 different offices under the Ministry of Water Irrigation and Energy (MoWIE), Minister for Mines, Petroleum and Natural Gas (MoMNG) and a literature survey.

Step 2: To estimate the generation capacity, the generation mix, and the CO₂ emission, some basic modelling assumptions were considered. Some of them are:

- The modelling period was from 2015 to 2065, with one-year intervals.
- The electric demand includes the electricity demand of the current electrified people in the residential sector as well as the demand of the rest of the sectors (industry, commercial and public services)
- In accordance with the national policy plan, an 18% reserve margin was contemplated.
- In order to capture the key features of electricity demand load pattern, each year has been divided into four seasons and two day parts. (Season 1: March–May, Season 2: June–August, Season 3: September–November, Season 4: December–February; Day part 1: 09:00–18:00, Day part 2: 19:00–08:00).
- In the OSeMOSYS model, a country-specific hourly load profile was used to reflect the power demand profile.
- Only the capacity of the committed future projects (power plants, electricity trade links), which their contract has been signed or the construction has started are forced to be installed into the model. The rest of the future power plants and trade links are provided as an option for the model to invest in.
- The grid-connected power generation technologies are distinguished in “old” (existing capacity until 2014) and “new” (capacity investments 2015–2065). The study researchers were able to collect data about the country's power generation technologies by capacity and generation since 2015 from the country's national load dispatching centre. As a result, the Electricity demand projection is started at 2015.
- Techno-economic assumptions for the power generation technologies are derived from international organizations such as IEA and World Energy Outlook 2016 [29].
- In the analysis, carbon dioxide emission factors per fuel were employed.
- Country specific fossil fuels reserves and renewable energy potential.
- Country specific capacity factors for renewable energy technologies (solar, wind) in the OSeMOSYS model are derived from www.renewables.ninja (accessed on 6 November 2021), which is relevant to estimate amount of energy that could be generated by wind or solar farms at any location [30]. The parameter Capacity Factor is used to specify the generation curve of the wind and solar technologies.

- Generic capacity factors are assumed for hydropower plants. The hydropower plants are divided into the following categories: small (<20 MW), medium (20–100 MW), large (>100 MW). The capacity factor 50% is assumed.
- Electricity trades are considered in the analysis. It has been assumed that a lower amount of electricity based on historical values and the respective installed capacity of the electricity interconnector will be exported to the other countries (Djibouti, Sudan, Kenya, and Tanzania).
- The power generation technologies (centralized, decentralized) used in the models are mentioned in Table 1. In this article, the centralized power generation technologies are only discussed.

Table 1. List of centralized and decentralized technologies included in the model [28].

	Fossil and Nuclear	Renewables
Centralized	Diesel Heavy Fuel Oil Natural Gas: OCGT, CCGT Coal Nuclear	Geothermal Biomass and waste CHP Hydro: small, medium, large Wind: onshore Solar PV (utility scale) Solar PV (roof top) Solar PV with storage CSP with storage CSP without storage
Decentralised	Diesel Genset Micro Grid (rural, urban) Diesel Genset Stand Alone (rural, urban)	Small Hydro Micro Grid (rural, urban) Solar PV Micro Grid (rural, urban) Solar PV 1–5 Stand Alone (0.02 kW, 0.05 kW, 0.1 kW, 0.2 kW, >0.2 kW; urban, rural) Wind Micro Grid (rural, urban)

Step 3: the open-source cost optimization tool, OSeMOSYS [25,26], was applied for long-term energy planning and to assess the required electricity capacity and CO₂ emissions. The objective of this tool is to identify the least-cost energy supply mix that meets the electric services demands. A model for Ethiopia included historical energy sector data and the year 2015 was considered as the starting year to forecast up to 2065.

New Policy Scenario: The New Policy Scenario considers current energy policy and plans detailed in NEP-2 [1,2,31,32], will be mostly accomplished and implemented as intended. It is assumed that infrastructure projects that are still in the planning stages will be completed. The scenario does not include the fundamental institutional or public sector reforms that would promote fast-paced and efficient growth as a relative status quo future. As a result, projects with recognized concerns, as well as related infrastructure projects facing similar risks, are delayed in their implementation and also considers country experiences of project completion and delays for various hydropower projects. With strong overall power demand growth, the scenario maintains a core level of optimism. The speed of change within society is slow, electrification proceeds, and national objectives are accomplished in this scenario, however the energy access agenda is not as ambitious as it could be [28].

Drought Scenario: Putting the above procedures into practice, the Drought Scenario considered in this article was developed and cloned with the New Policy Scenario assuming the foreseeable future climate change would reduce hydroelectric capacity by 50%. In the Drought Scenario, the same policy goals [1,2,31,32] as that of the New Policy Scenario were considered to be implemented as intended. Given the expected negative impacts of climate change on precipitation, runoff, and water resources availability, as well as the expected low

negative impacts of climate change on the wind, biofuels, solar irradiance, and geothermal resources [33], the analysis in this study is limited to climate change impacts on water resources and hydropower technology that uses this resource for electricity production. Additionally, in the Drought Scenario, the following assumption was considered: Between now and 2065, the capacity factor of hydroelectric technology was expected to drop by half (by 50%) compared to the baseline scenario-New Policy (a capacity reduction over the entire simulation period). The severity of the situation was worsened by probable drought. Finally, the results of the Drought Scenario were compared with the results of the New Scenario. The reason for comparing the two scenarios will provide detailed information about power generating capacity, renewable energy penetration, and the difference in hydropower technology generation due to severe drought.

3. Result and Discussion

3.1. Power Generation Capacity

In the drought scenario, electricity power generation capacity increases progressively from 3 GW in 2015 to 30 GW in 2030, 110 GW in 2050, and 179 GW in 2065 as compared to New Policy Scenario, the power generation rise from 3 GW in 2015 to 23 GW in 2030, 88 GW in 2050, and 169 GW (see Figures 1 and 2 and Table 2). The Drought Scenario has slightly higher power generation capacity, which is 7 (30.4%), 21 (19%), and 10 (5.9%) GW, than the New Policy scenario by 2030, 2050, and 2065, respectively, to compensate for the capacity shortage created by hydro.

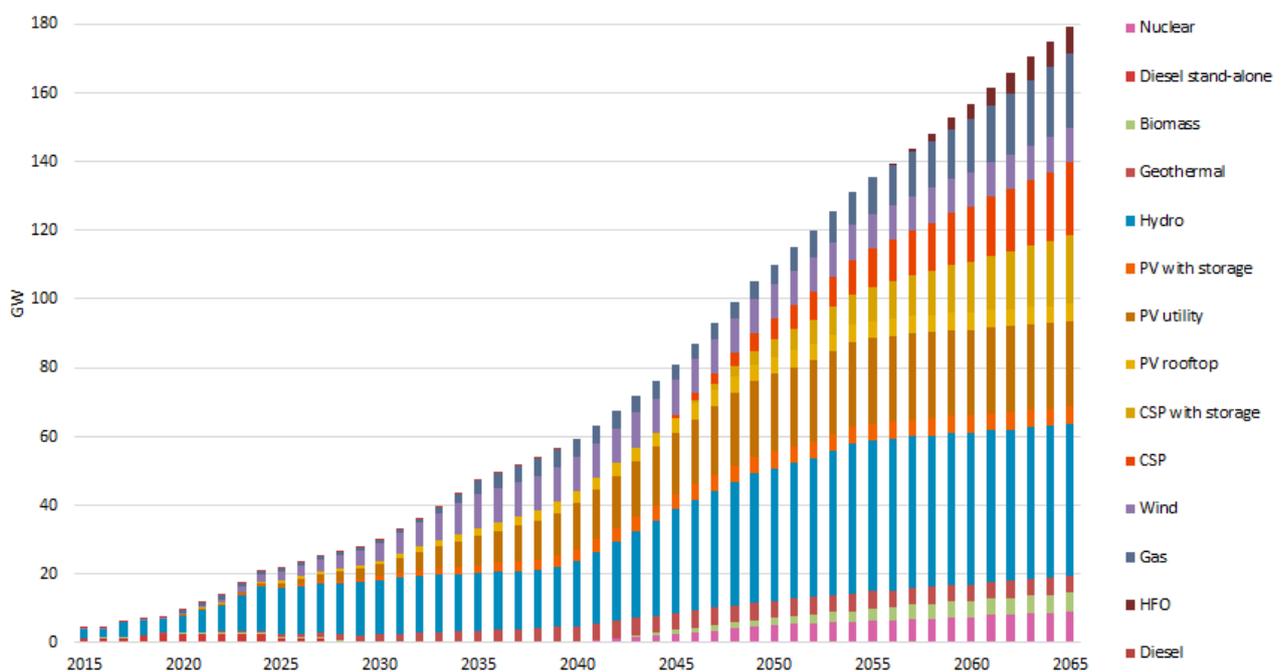


Figure 1. Power generation capacity of grid-connected technologies in the Drought Scenario.

Hydropower, in particular, reaches its maximum potential of 44 GW in 2056; to keep the reserve margin, solar PV, CSP, and nuclear technologies will gradually expand their share of total capacity in the power system in the future, reaching 35 GW, 41 GW, 22 GW and 9 GW in 2065, respectively. This new mix in electricity generation implies that the installed capacity in solar technologies increases by around 12 GW (+18.75%). despite the slight reduction in electrical generation in the presence of climate change impacts.

Even though both scenarios have increasing renewable energy penetration, the investment outlook generation from non-renewable technologies such as HFO in the Drought Scenario increased from 0.3 GW in 2056 to 8 GW by 2065 compared to 0.3 GW in 2062 to 3.72 GW in 2065 in the New Policy Scenario. Specifically, HFO gradually penetrates

the power system to maintain an adequate reserve margin as other technologies like hydropower, reach maximum potential 12 years later than the optimal.

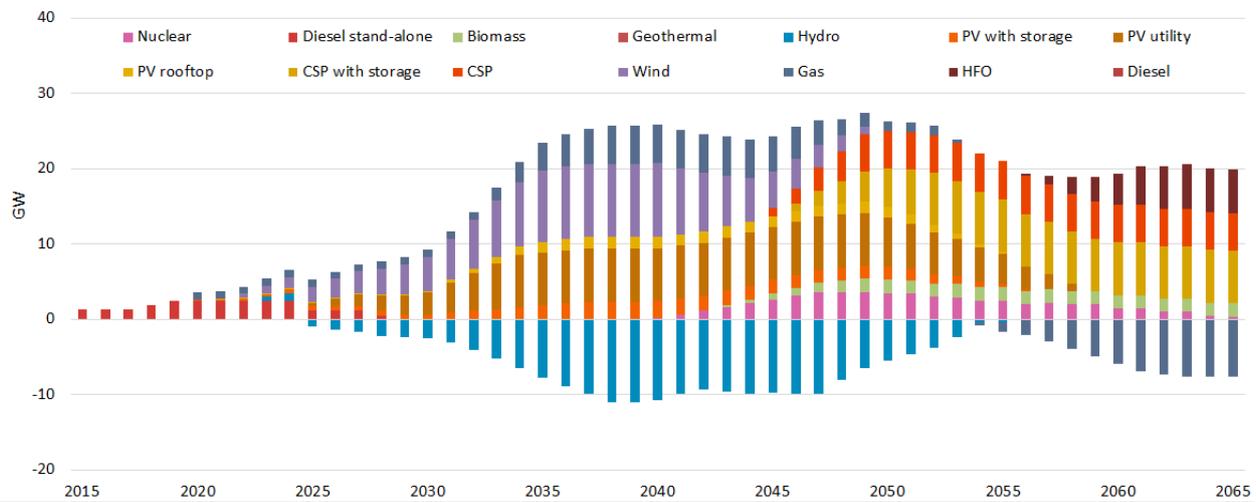


Figure 2. Comparison of power generation capacity between Drought vs. New Policy Scenarios.

Table 2. Comparison of Power Generation Capacity of Drought and New Policy Scenario.

Capacity (GW)	2015	Drought Scenario			New Policy Scenario [28]		
		2030	2050	2065	2030	2050	2065
Biomass	0.20	0.33	2.28	5.75	0.33	0.53	4.00
LFO/HFO	0.14	0.07	0.00	7.97	0.07	0.00	3.72
Gas	0.00	0.97	5.69	21.82	0.00	0.00	4.42
Nuclear	0.00	0.00	5.00	8.89	0.00	0.00	1.50
Hydro	2.36	15.94	38.53	44.01	2.36	18.48	44.01
Geothermal	0.01	2.05	5.00	5.00	0.01	2.05	5.00
Wind	0.32	4.96	10.00	10.00	0.32	0.46	10.00
Solar PV	0.01	5.56	32.50	35.00	1.82	22.75	35.00
Solar CSP	0.00	0.00	11.00	41.00	0.00	1.00	29.02
Total	3	30	110	179	23	88	169
RET share	95%	97%	90%	78%	99%	95%	77%
Djibouti exports	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Kenya exports	0.00	1.00	1.40	1.40	1.40	1.40	1.40
Sudan exports	0.10	3.10	3.10	3.10	3.10	3.10	3.10
Tanzania exports	0.00	0.41	0.41	0.41	0.41	0.41	0.41
Exports	0.20	4.61	5.01	5.01	5.01	5.01	5.01

3.2. Electricity Supply Mix Drought

Figure 3 and Table 3 show that the electricity supply in the Drought Scenario increased from 12 TWh in 2015 to 83 TWh in 2030, 308 TWh in 2050, which gradually reached 503 TWh in 2065. This is slightly lower than the New Policy Scenario’s 12 TWh in 2015 to 98 TWh in 2030, 305 TWh in 2050, gradually reaching 517 TWh in 2065.

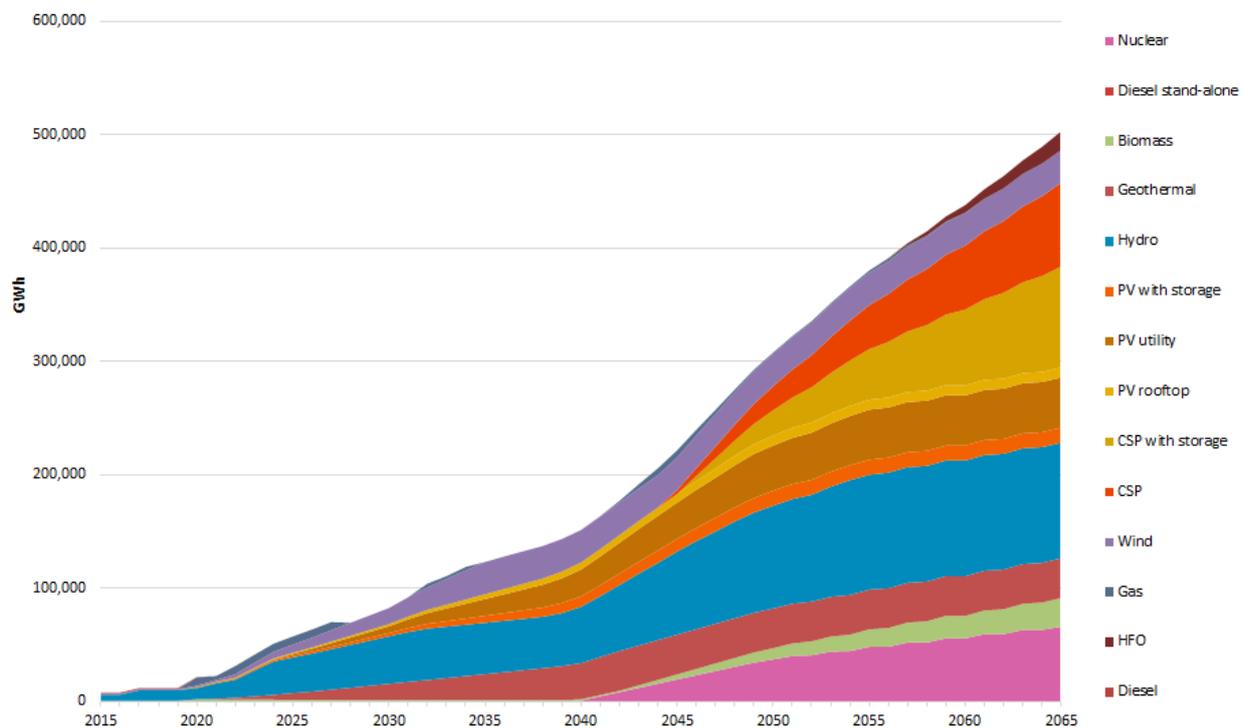


Figure 3. Electricity supply mix of grid-connected technologies in the Drought scenario.

Table 3. Comparison of Electricity supply of Drought and New Policy Scenario.

ELC Supply (GWh)	Drought Scenario				New Policy Scenario		
	2015	2030	2050	2065	2030	2050	2065
Biomass	783	1410	10,013	25,296	1410	2314	17,597
LFO/HFO	949	-	-	16,536	-	-	4732
Gas	-	-	1024	-	-	10,716	3604
Nuclear	-	-	37,230	66,209	-	11,169	63,500
Hydro	5299	41,855	90,570	101,964	76,895	183,104	183,104
Geothermal	60	14,341	35,040	35,040	14,341	35,040	35,040
Wind	925	14,225	28,700	28,700	1310	28,700	28,700
Solar PV	18	10,807	61,937	66,365	3662	43,137	66,365
Solar CSP	-	-	43,407	163,058	-	3523	114,362
Total	12,151	82,638	307,920	503,167	98,186	305,081	517,004
RET share (not includes Nuclear)	97%	97%	90%	81%	100%	98%	89%
Djibouti exports	416	754	520	130	832	608	389
Kenya exports	0	11,195	7746	4157	11,651	11,474	7274
Sudan exports	416	13,693	12,672	-	25,006	16,141	9415
Tanzania exports	0	-	725	534	2143	2143	888
Exports	832	25,642	21,663	4821	39,632	30,366	17,966

In both scenarios, renewable energy technologies constitute most of the power generation mix, from 95% (12 TWh) in 2015, increasing to 97% (82 TWh) in 2030, gradually decreasing to 90% (270 TWh) in 2050 and finally reaching 81% (420 TWh) in 2065 compared to 95% (12 TWh) in 2015, increasing to 100% (98 TWh) in 2030, gradually decreasing to 98% (299 TWh) in 2050 and finally reaching 89% (458 TWh) in 2065 in New Policy Scenario. In both scenarios, the share of renewable would be slightly decreasing over time, which is the same for Hydro. Throughout the modelling period, the percentage of renewable energy technologies in comparison to all other technologies is nearly identical. The most common cause is that when hydropower technology generation is reduced due to severe drought,

other renewable technologies (PV and CSP) will enter the system and compensate for the generation deficit.

The Drought scenario electricity generation from hydropower technology is expected to reduce between 44.3% and 50.5% during the modeling period compared to New policy scenario. In the case of Drought, hydropower reaches its peak in 2056 (101 TWh), twelve years later after the New Policy Scenario reached its peak. Following the hydropower, the other technologies will increasingly supply electricity up to 2065, with solar PV accounting for 13% (66 TWh), CSP for 32.5% (163 TWh), nuclear for 13% (66 TWh), Heavy Fuel Oil (HFO) for 3.4% (16 TWh), geothermal for 7% (35 TWh), wind for 6% (29 TWh), and biomass for 5% (25.3 TWh). While hydropower will continue to be the most common form of power generation until 2057, accounting for supplying 25.2% (101. TWh) of all technologies, CSP will overtake hydropower in 2057, accounting for supplying 32.5% (163 TWh). However, biomass and HFO significantly come to the electricity mix to 25.3 TWh and 16.5 TWh in Drought Scenario compared to 17.5 TWh and 4.7 TWh in New Policy Scenario in 2065, respectively (See Figure 4). Consequently, power generation drops due to droughts can be (at least partially) compensated for by technologies with different technology mixes, which are less or even positively affected by drought.

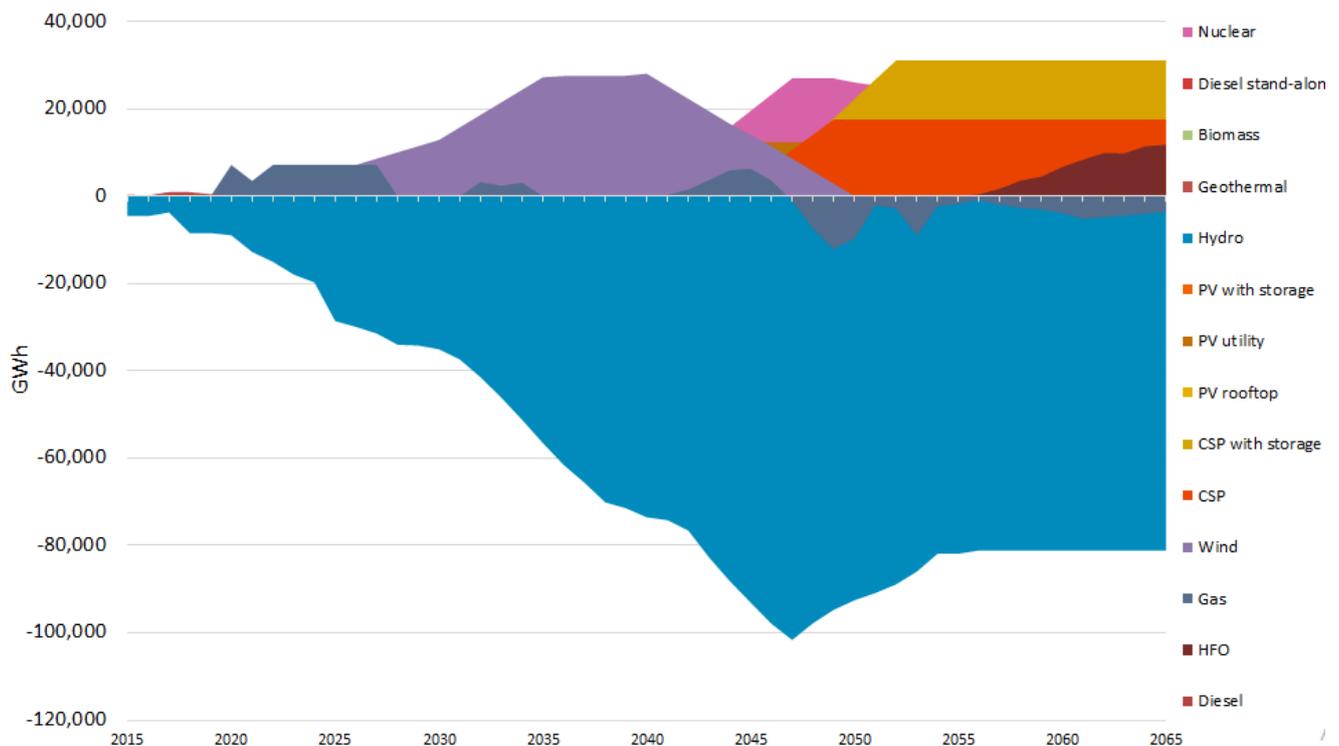


Figure 4. Comparison of electricity supply mix between Drought vs. New Policy Scenario.

The maintenance of an adequate supply of energy in a region depends on how its energy mix is composed, taking into account the existence and availability of a set of energy sources. In the Drought Scenario, the Electricity supply mix, dominated by hydro, gradually diversifies as solar PV, CSP, biomass and from non-renewables such as HFO increasingly make inroads into the system. The energy demand mostly covered by widespread deployment of renewable energy sources between 81 and 97% of the total generation between 2015 and 2065, respectively. The performance of each individual source (hydro, wind and solar) over a period varies due to its seasonality, which may require emission intensive technologies to add to the mix.

In comparison to the New Policy Scenario, the use of renewable energy in the electrical mix results in a reduction of up to 8% at the end of modeling period. The loss in hydropower

generation in Drought Scenarios, along with the inadequacy of other renewables' capacity to meet demand, means that non-renewable technologies such as HFO is reinforced by 12 TWh to supply mix. However, renewable sources exhibit a different level of complementarity. Thus, hydropower has proved to be efficient, yet not sufficient enough to cover Ethiopian energy demand, making necessary the search for new energy alternatives. The involvement of renewable complementary sources could represent a solution to this problem, reducing the influence of the seasonal fluctuations of the hydro energy supply. The future electric mix of Ethiopia has a high potential for complementarity with respect to solar (up to 45%), geothermal (7%), wind (5.7%), and Biomass (5%) energy, in relation to the already widely used hydroelectricity.

3.3. Electric Export

The country aspires to become a cornerstone of the Eastern Africa Power Pool's (EAPP) regional power market, owing to its vast clean energy potential that can be produced at a low cost. Ethiopia already exporting electrical power to Sudan and Djibouti through its high-voltage (HV) connections. Ambitious infrastructure developments in eastern Africa and beyond are creating the groundwork for a genuinely regional, integrated electricity market. The construction of a high-voltage direct current (HVDC) transmission line between Ethiopia and Kenya, capable of carrying up to 1000 MW has already begun. The Ethiopia–Kenya link is part of a larger, continent-wide plan to connect the EAPP via Kenya, Tanzania, and Zambia [2].

In the New Policy Scenario, the electricity exports increase from 0.83 TWh in 2015 to 18 TWh in 2065. However, in a Drought Scenario, the electricity exports 4.8 TWh at the end of modeling period, which is not increased significantly compared to New Policy. As can be seen in Figure 5, electricity export is negatively affected by the severe drought. Eventually, it will affect the country's ambitious plans to become the export hub of the EAPP.

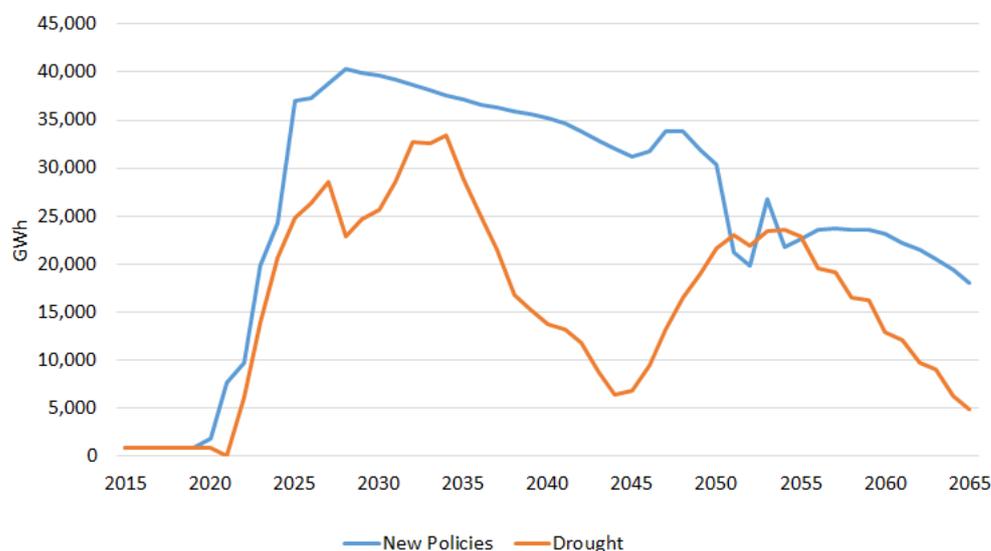


Figure 5. Comparison of electricity exports (GWh) between Drought and New Policy Scenarios.

3.4. Carbon Dioxide Emissions

The residual balance between hydropower generation and electricity demand represents the remaining electric demand that must be fulfilled with alternative electricity technologies (both renewable and non-renewable). This may result in extra GHG emissions depending on the mix of electrical resources utilised for this purpose. The additional GHG emissions associated with supplying the remaining power demand with various energy resources contributed yearly average emissions, as shown in Figure 6 for the period of 2015–2065.

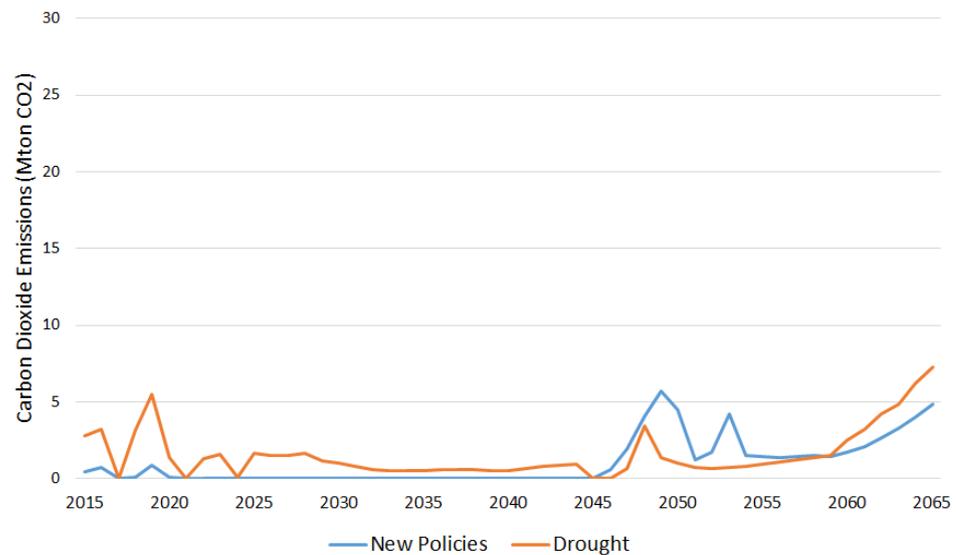


Figure 6. Comparison of carbon dioxide emissions between Drought and New Policy Scenarios.

The government's vision is to achieve universal access and meet its future electricity needs without increasing greenhouse gas (GHG) emissions during 2010–2030. Overall, the emission from the New Policy and Drought Scenarios seem to experience more or less comparative similar trends in the modelling period. Renewable energies are gradually replacing fossil fuels and increasing electrification rates across the sector. The CO₂ emissions in both scenarios will be below 1 Mt CO₂ starting in 2015 and will steadily decline over the next 20 years until 2045 (see Figure 6), owing to the absence of emission-intensive technologies, and CO₂ emissions could be significantly reduced, as almost all electric power will come from renewable generation technologies. There will be small increases in CO₂ emissions following the penetration of emission intensive technologies between 2045 and 2065, with some fluctuation over time between 2045 and 2055. In both scenarios, the fluctuation is due to the use of HFO and natural gas technologies in 2049, 2054 and 2065 to cover the sharp increase in electrified total demand: 253 TWh (2049), 317 TWh (2054), 461 TWh (2065).

Under the New Policy Scenario, Ethiopia's CO₂ emissions increase from 0.42 Mt CO₂ in 2015 to 4 Mt CO₂ in 2065, peaking in 2049 at 7 Mt CO₂. The CO₂ emission is expected to increase slightly from 2045 on, as some renewable technologies, especially hydro in 2046, reach their maximum potential before 2065. Furthermore, in the New Policy scenario, CO₂ emissions will be cumulative 2.4 Mt CO₂ during 2015–2030, on average 0.22 Mt CO₂ annually [28]. Under the Drought Scenario, Ethiopia's CO₂ emissions slowly increase from 0.42 Mt CO₂ in 2015 to 7.3 Mt CO₂ in 2065 while cumulative 4.1 Mt during 2015–2030, on average 0.22 Mt CO₂ annually.

Our results demonstrate that any effort to satisfy the demand during drought season will impact the electricity generation emission. At the end of the modelling period, HFO will be the only fossil fuel based technology introduced into the system since the scarcity created by hydropower is balanced by other renewable technologies such as solar, wind, and geothermal. The CO₂ as a result of HFO electricity production (which is below 16.5 TWh in 2065) is not significant enough to exceed the emission limit; the CO₂ emitted in 2065 is less than 7.3 Mt CO₂. As a result, the demand can be satisfied while maintaining environmental standards. When it compared with INDC 2030 targets year, by 2030, the nation's electric power generation could create less CO₂ than the national average objective of 5 Mt CO₂. The Ethiopia electric production strategy in both scenarios could help the country achieve higher climate targets than the national average, such as below, 1.5 °C due to the aforementioned reasons of high proportion of renewable technologies in the power sector.

4. Conclusions

Ethiopia is already experiencing the effects of climate change-induced droughts on hydroelectric resources. Water levels at a reservoir also fell to their lowest level many times. Economic recovery in recent years meant that demand rapidly outpaced the limited supply, while periodic droughts disrupted hydroelectric power generation, exacerbating the problem. Overall, considering 50% capacity reduction due to drought in hydro plants, the total installed capacity has to increase by 5.9% compared to the New Policy Scenario from 169 GW to 179 GW. However, the electric production has to decrease by 2.7% compared to the New Policy Scenario from 517 TWh to 503 TWh, respectively. In both scenarios, renewable energy technologies constitute most of the power generation mix, which is 89% in the New Policy and 81% in the Drought Scenario, at the end of the modelling period.

Drought phenomenon contributes to a significant impact on renewable energy technologies, especially hydropower and it reaches its peak electricity generation in 2056 (101 TWh), twelve years later after the New Policy Scenario reached its peak. Thus, considering climate change impacts, major changes in the electricity mix correspond to the strengthening of solar power technologies, which reach around 45% of total generation in Drought Scenarios. Different technologies are very differently affected by drought, which creates trade-offs or sometimes synergies between technologies. Following the hydropower, the other technologies will increasingly supply electricity up to 2065, nuclear for 13%, HFO for 3.4%, geothermal for 7%, wind for 6%, and biomass for 5%. While hydropower will continue to be the most common form of power generation until 2057, accounting for supplying 25.2% of all technologies. CSP will overtake hydropower in 2057 and account for supplying 32.5% by 2065.

Due to the challenges of hydropower reduction, the scenarios showed a fundamental substitution in the structure of the renewable power sector, and even if there is a massive increase in electricity production from Solar PV, CSP, nuclear, and biomass, the supply will not meet the demand unless reinforced by fossil fuels. As a result, new power plants from non-hydro power technologies will be needed to sustain a growing population electricity demand.

In addition, the government aims to achieve universal access and become an electricity exporter in the region by 2025, however, due to the severe drought, the electricity exports in the Drought Scenario will be 66.6% lower than the New Policy at the end of the modelling period. Therefore, drought may have a substantial impact on Ethiopia's ambitions plan to be EAPP

The remaining balance between hydropower generation and electricity demand represents the remaining electric demand that must be met with other electricity resources. Satisfying the increased gap between hydropower supply and electricity demand will produce greenhouse gas emissions, however these can be significantly reduced if low-carbon resources are used. The results show Ethiopia's CO₂ emissions slowly increase in the Drought Scenario between 2015 and 2065 due to the mix of emission intensive technologies such as HFO as a substitute to loss of hydro generation although the demand can be satisfied while maintaining environmental standards.

This study suggests that the climate-driven losses in hydropower must be compensated by the introduction of mega new infrastructures, which could provide sufficient power to secure the future Ethiopian electric system. The hydro dominated nation's energy mix should increase the share of non-hydro new plants equipped with modern technology and less vulnerable to drought is recommended.

Future work could also further examine the potential impacts of climate change on other aspects of the power sector, such as wind and solar resources. This study concludes that to develop a decarbonized electricity system under climate change conditions, Ethiopia should prioritize the replacement of fossil-fuel generation with renewable energy resources. Additionally, there is a need to explore the tradeoffs/synergies among alternative expansion pathways and their potential impacts on other sectors (e.g., water and land), and for effective policies to incentivize their adoption in Ethiopia.

Furthermore, for electricity grids with an increasing share of intermittent renewables, the power generation mix can have significant daily variations. This leads to time-dependent emission. We suggest that a country has the high potential to achieve greater emission reduction by adopting the dispatch protocols to deal with the emission. It needs to establish a framework to compare the impacts of adopting different dispatch protocols on the efficacy of using renewable generation units to reduce emissions. Moreover, integrating carbon capture and storage (CCS) technologies on thermal power plants can provide low-carbon generation for Ethiopia's transition to low-carbon electricity infrastructure.

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