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Long-term optimization of renewable-based Ethiopia's power sector development strategies

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Abstract

This study analyzes Ethiopia's power sector's energy supply plans and pinpoints opportunities for meeting increased electricity demand while addressing energy security and carbon-neutral economic growth. We use Ethiopia's Homegrown Economic Reform Agenda 2030 Scenario (HERA2030Scen) and the Business as Usual Scenario (BAUScen), which examine the least expensive system development without any change in policy, respectively, to examine national energy policies under two different scenarios (Achieving middle-income country status with a clear pathway to prosperity through newest Homegrown Economic Reform Agenda by 2030). The result shows a 100% renewable energy system to supply national energy by 2050 can be achievable. The energy mix is dominated by hydropower and shifts to solar and wind energy development towards 2050. The result presents the first path towards the realization of carbon-neutral economic growth to achieve national targets of meeting middle-income country status for Ethiopia.

Keywords: Ethiopia; Optimization; Renewable energy; Sustainable development

1. Introduction

In September 2015, all member states of the United Nations (UN) endorsed the 2030 Agenda that includes 17 Sustainable Development Goals (SDGs), with SDG 7 specifically linked to the energy sector (UN, 2015), a call for action to ensure access to affordable, reliable, sustainable and modern energy for all. Investing in energy is an engine of economic growth (Ahmad and Zhao, 2018) and are crucial for achieving almost all of the SDGs from its role in the eradication of poverty, livelihood improvement and promote economic development (Panos *et al.*, 2016; Tomei *et al.*, 2018 and Santika *et al.*, 2019). Yet, progress is too slow to achieve SDG 7. Globally, 940 million (13%) do not have access to electricity, 3 billion (40%) people still lack clean cooking and technologies, posing a grave threat to human health and per-capita electricity consumption varies more than 100 fold across the world (Richie and Roser, 2019). In sub-Saharan Africa, where the rate of access to modern energy is significantly low, these issues are severing to impede modern economic activities, public services delivery, quality of life, and adoption of new technologies (Blimpo and Cosgrove Davies, 2019).

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Ethiopia is a country located in the East of Africa lies between 3° to 15°N latitude and 33° to 48°E longitudes with the largest energy access deficit. Only about 45% of the Ethiopian population has access to electricity, varying widely between urban (97%) and rural (31%) areas (Beyene and G/Hiwot, 2018). Besides, Ethiopia's current annual electricity consumption per capita of 133 kWh (Ritchie and Roser, 2019), when 500 kWh per year is considered the average minimum level consumption per capita for a reasonable quality of life (van Heesch, 2014) and is still an order of magnitude smaller than that of average per-capita consumption in sub-Saharan Africa (553 KWh/c) and other developing countries such as Venezuela (3313 KWh/c), Iran (2649kWh/c) and Ecuador (1192 KWh/c), among others (Khraief *et al.*, 2016). Despite this shortage, Ethiopia is blessed with abundant renewable energy resources and has the potential to generate more than 11,700TWh of electricity from renewable energy sources (Tucho *et al.*, 2014).

Ethiopia has set out a clear pathway to prosperity through its newest Home-grown Economic Reform Agenda (HERA) intended to deliver high-quality growth and a poverty reduction, and enabling Ethiopia to reach the status of a middle-income country by 2030 (Tomomi, 2019). The reform agenda prioritizes the creation of industrial parks and export processing zones as an important factor for a country's economic growth and development to support its goal which needs aggressive investments in power generation. The relevance of energy as an engine of economic prosperity has been substantially documented for countries in different phases of development including, lower-income economies (Sekantsi and Okot, 2016), upper-middle economies (Cetin, 2016; Rathnayaka *et al.*, 2018; Liu *et al.*, 2017; Kuo and Wang, 2017), and high-income economies (Khoshnevis and Shakouri, 2018). Besides, economic growth leading to increasing per capita energy consumption would further require accelerated investment in energy infrastructure. The overarching goal of the power sector will therefore be to ensure an adequate, clean and efficient supply of power for all consumers at the lowest possible cost. Against this backdrop, it is essential to quantitatively assess the energy supply security and clarify the path of sustainable energy development to be taken to inform decision-makers for a better understanding of the options for the power sector.

Energy system models have been used for several decades to guide decision-makers in regards to energy planning (Huntington *et al.*, 1982) and for planning future investments towards a viable and sustainable national power sector, identifying the future energy mix to meet electricity at the lowest cost, with due regard to technical, environmental and political constraints (Bhattacharyya, 2011). It is a well-established practice to use energy models calibrated with high-quality data to support policymaking and energy planning activities in developed countries. However, this cannot be said for developing countries where financial availability and access to high-quality data are the major challenges. Despite this, attempts to extend the availability of energy modelling to energy research communities, government analysts and graduate students in developing countries are increasing.

Designed to fill a gap in the analytical toolbox available to the energy researcher's community and energy planners in developing countries, the Open Source energy Modelling System (OSeMOSYS), was born from an effort of multiple institutions (Gardumi *et al.*, 2018). Unlike long establishment energy system models such as Market Allocation Model (MARKAL), Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE), Energy Flow Optimization Model (EFOM), OSeMOSYS potentially requires a less significant learning curve and time commitment to build and operate as well as requires no upfront financial requirement (Howells *et al.*, 2011). Previous studies have used OSeMOSYS to assess the strong penetration of renewables into the Irish energy system (Welsch *et al.*, 2012), planning for electricity capacity in the context of uncertain climate policy (Leibowicz, 2018), trade-in electricity across borders in South America (de Moura *et al.*, 2018), and balance between economic and environmental objectives in the Saudi Arabian power sector (Groissböck and Pickl, 2016), among others. As these examples demonstrate, OSeMOSYS applications have a significant role in the energy planning process and highlight its importance for society.

There have been several recent studies to look at Ethiopia's energy system. Access to Sustainable energy was examined by (Tessema *et al.*, 2014), where the existing challenges and prospects of integrating sustainable energy access into national development planning and its policy implication was investigated. (Mondal *et al.*, 2017) analyses power sector development using the MARKAL energy system model to identify alternative sustainable energy supply options to meet Ethiopia's rising demand for energy. Present energy system and available potentials were investigated by (Tucho *et al.*, 2014). Previous national studies also projected energy demand using a variety of methods. (Mondal *et al.*, 2018) projected electricity demand for Ethiopia using the Long-range Energy Alternatives Planning (LEAP) model for alternative policy scenarios. The Ethiopian power system master plan also uses a combination of regression analysis and end-user models to forecast electricity demand in Ethiopia (Brinckerhoff, 2013). However, there are limitations to these studies thus demand is underestimated. As the analysis considers only access rate without objectively defining the average per-capita consumption target as per the middle-income country status, this could have an impact on the power expansion capacity to meet the target demand. Moreover, the previous studies do not optimize the supply-side energy mix to meet the expected demand with the least possible cost.

This paper aims to objectively assess the challenges and prospects of energy security of Ethiopia by 2030 and 2050 under different scenarios. More specifically, this paper attempts to answer three fundamental questions. The first question is: how much power will need to be generated to meet the HERA of achieving middle-income country status by 2030 and beyond? The second question is, what is the required generation capacity to be installed, trends in the optimum technology mix and the corresponding cost of capacity expansion? The third question is; does Ethiopia has an option to achieve energy security based on 100% renewable energy resources? The study applies the OSeMOSYS energy modelling framework for the period of 2020 to 2050. The study synthesizes the results and provides policy directions at a national level.

The remainder of the paper is as follows: section 2 presents material and methods with emphasis on the description of OSeMOSYS, Reference Energy System (RES), basic model assumptions and data, model setup and the description of scenarios. The results are discussed in section 3 and section 4 concludes the discussion.

2. Materials and methods

2.1. Open Source energy Modeling System (OSeMOSYS)

The Open-Source Energy Modelling System (OSeMOSYS) is a long term energy system modelling framework originally developed at KTH Royal Institute of Technology and released under a permissive open license (Howells *et al.*, 2011). OSeMOSYS is based on a linear optimization problem that aims to minimize the total discounted cost for satisfying the demand for energy services of the considered region over a given period.

The ethos, structure, and aspects of the development of OSeMOSYS including model's formulation, mathematical formulation, operation principle, implementation as well as a detailed description of the model inputs, parameters and outputs are described in (Howells *et al.*, 2011). The wide range of application of OSeMOSYS as of 2018 including its dissemination, its use for sustainable policymaking and the link between modelling practice and the engagement with decision-makers are described in (Gardumi *et al.*, 2018). The updated model infrastructure is available on the GitHub repository of the tool (KTH DESA OSeMOSYS GitHub repository 2019) and the user manual is available on an open Read the Docs platform (KTH DESA OSeMOSYS Documentation 2018). The original code of OSeMOSYS consists of several blocks of functionality, computing balances for costs, storages, capacity adequacy, energy balances and emissions. Its simple block structure (Fig. 1) and flexibility, as well as its open-source nature with no upfront financial investment, makes OSeMOSYS extending the availability of energy modelling for academic research and government organizations in development countries to study the impacts of policy decisions on an energy system.

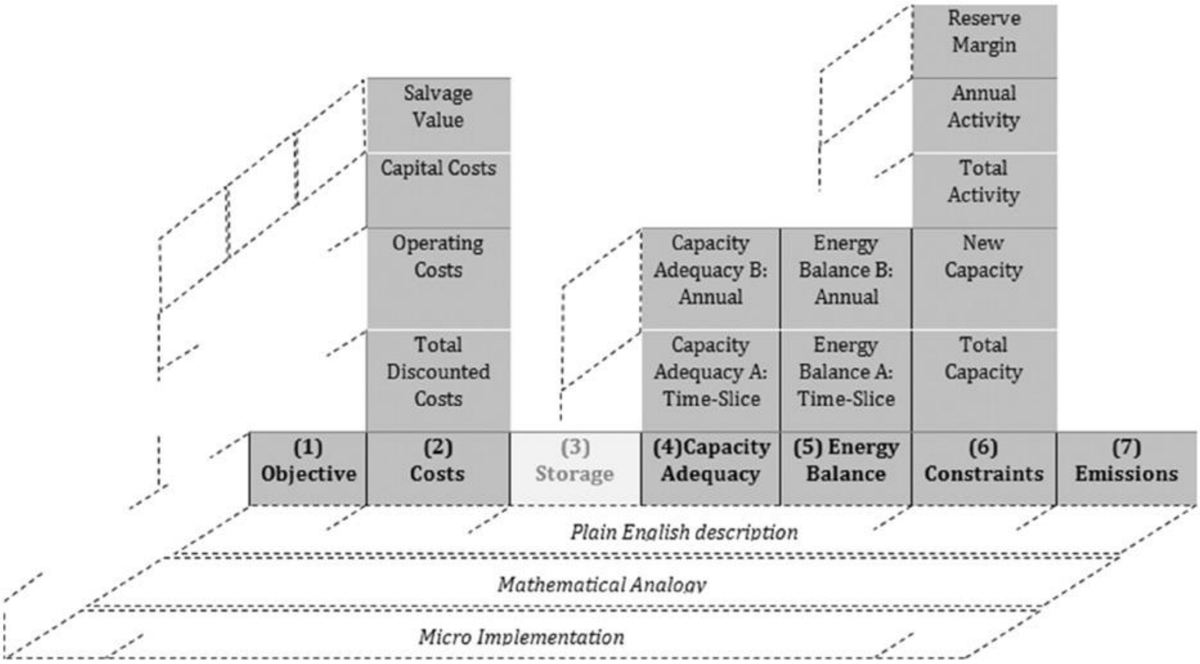

Figure 1. OSeMOSYS 'blocks' and levels of abstraction (Source: Howells, 2011)

2.2. Reference Energy System (RES)

RES is a simplified and aggregate graphical representation of all technical activities required to supply energy to end-use activities (Fig. 2). It shows the flow of energy horizontally from the resource base on the far left, going through different transformation technologies, to reach final energy use on the far right and it is generally composed of three modules. This includes primary energy resources (availability, imports and exports), process technologies (conversion technologies, transmission and distribution), and electricity demand by sectors. Technologies can use and produce energy carriers, satisfy energy services and generate emissions as a by-product and represented by boxes in RES. Fuels include any energy vector, energy services or proxies entering or exiting technologies and is represented by lines in RES. Techno-economic (power plant capacities, capacity factors, efficiencies, lifetime, and costs) and environmental (CO2 emissions) parameters are assigned to the technologies. Final demand has been divided into five sectors and is being supplied by different energy chains based on the least cost option computed by the model for the timeframe of 2020 to 2050.

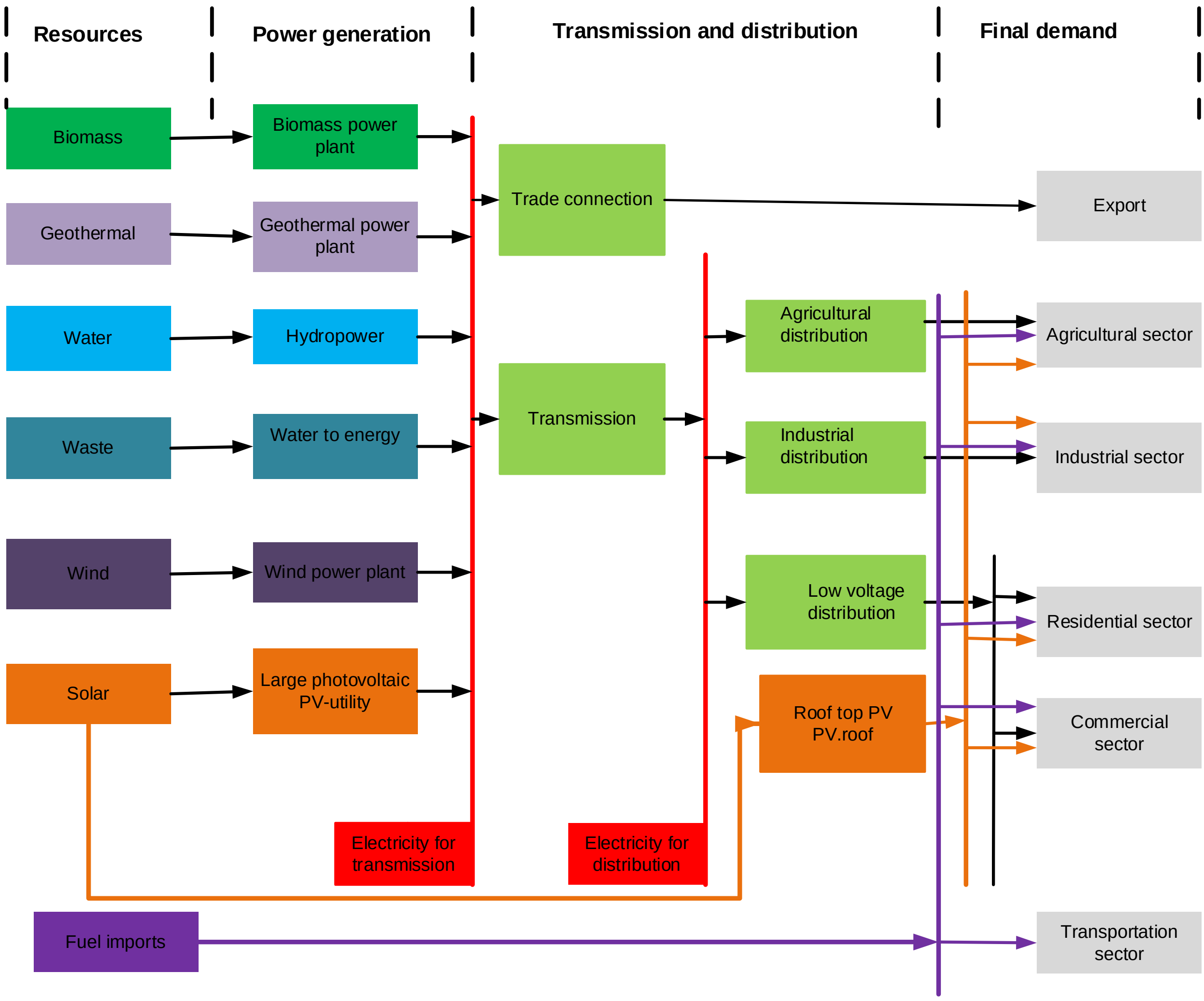

Figure 2. Simplified Reference energy system of Ethiopia

2.3. Basic assumptions and data input

The study develops a national OSeMOSYS model which considers the energy supply, transformation and transmission/distribution technologies to generate the least cost energy supply mix to meet the national energy demand target. The inputs of the model include primary energy resources (availability, imports and exports), process technologies (conversion technologies, transmission and distribution), energy demand by sector (agricultural, commercial, industrial, residential and transport), emission factor, as well as other model parameters and boundaries such as the techno-economic specification of technologies, discount rate and period of analysis.

The primary energy supply includes extraction of the potential of renewable energy sources (biomass, geothermal, Hydro, Solar, Waste to energy, and Wind) for power generation and imported fuels. The process technology consists of existing and planned power plants. Technical and cost parameters for each technology are incorporated into the modelling framework. As

OSeMOSYS is demand-driven, energy demand is determined from scenario assumptions and interred into the model to determine energy supply and technology options. The study considers 2020 as the base year and the analysis covers 2020 to 2050. The discount rate has been set in the model as 10% based on the average discount rate used for Ethiopia (Mondal *et al.*, 2017; Kebede, 2015). A straight method of depreciation is assumed and all monitory values are presented in US dollars. The national model is designed only for grid-connected electricity generation, transmission and distribution. Electricity loss for Ethiopia is 20% (Gartner and Stamps, 2014) and assumed accordingly. End-use electricity demands are combined into each respective sector demands. The load profile considered in the model includes three seasons (intermediate, summer and winter) and differentiate loads between day and night.

The existing capacity in the model is based on the Ethiopia power system expansion master plan study data set (Brinckerhoff 2013). This data give information about the power plant concerning the installed capacity, when it was installed, and the operational life of the power plant. This information uses further to calculate the residual capacity of the existing power plants at the base year. The total energy conversion efficiency, capacity factor and availability factor of each generating technology have been derived from (Brinckerhoff 2013) and the related CO2 emissions factors have been derived from (Luckow *et al.*, 2015). The economic cost of each technology is represented in the model by capital, fixed and variable costs and these are derived from (Cost 2020). Other constraints imposed in the OSeMOSYS concern the upper and lower bounds for endogenous variables are the energy resource potential and installed capacities limited based on national data (Mondal *et al.*, 2018). Based on these model assumptions and input data the basic parameters estimated to setup the OSeMOSYS are presented in table one below.

Table 1. Description of parameters used to setup OSeMOSYS

Parameters	Unit / Value	Description	Use in a model
Availability factor	-/ between 0 and 1	Gives the ratio between the time when the technology is available and the total time of a period	To model the availability of technologies
Capacity Factor	-/ Between 0 and 1	The capacity factor gives the ratio between the real output of technology and the output of the same technology working 8760 h/year.	To model the capacity factor of technologies
Fixed Cost	MUSD/Gigawatt(GW)	Costs connected to the installed capacity of a specific technology and year	Fixed O&M costs
Input Activity Ratio	-	Gives the ratio between the input of an energy carrier/fuel and the activity of the technology.	Together with the Output Activity Ratio, it represents the efficiency of technology.
Output Activity Ratio	-	Gives the ratio between the output of an energy carrier/fuel and the activity of the technology.	Used with Input Activity Ratio to represent the efficiency of technology.
Residual Capacity	GW	The capacity that is already installed when the model period starts.	Used to model technologies put into use before the base year.
Specified Annual Demand	Peta Joule (PJ)	The demand for specified energy and year	Represents the projected electricity demand.
Specified Demand Profile	- (value between 0-1)	Defines the share of the Specified Annual Demand that belongs to a specific time slice.	Used to model how the demand varies over a year.
Total Annual Max Capacity Investment	GW	The maxim capacity of a specific technology that can be invested in a specific year.	Used to limit the yearly investments in technology.
Total Annual Min Capacity Investment	GW	The minimum capacity of a specific technology to be invested in for a specific year.	Used to model planned investments in specific technologies.
Total Technology Annual Activity Upper Limit	PJ	The maximum amount of energy that can be produced by a specific technology in a specific year.	Used to model limited resources.
Variable cost	MUSD (Million US Dollar)/PJ	Costs connected to the energy output of a technology.	Variable O&M costs.
Capacity To Activity Unit	-	The relation between the units for capacity and activity.	The conversion factor from GW to PJ and is set to 31.536.
Discount Rate	-	Gives the discount rate that should be used for a specific technology. Used to calculate the NPV.	Based on a national discount rate, it is set to 10 %.
Operational Life	Years	The lifetime of technology, not specified for residual capacities.	Gives the maximum time new technology can be used without new investments.
Time Slice	-	An optional number of time slices can be used to subdivide every year into smaller parts.	Used to model how the demand and capacity factors vary over the hours of a day/or between seasons.
Year Split	- (value between 0-1)	The share of a year that a specific time slice represents.	Used to model the length of the different periods (time slices) of the year.

2.4. Model setup and application

The RES described above with all assumptions and parameters estimated in the previous sections is implemented into OSeMOSYS. OSeMOSYS provides a modelling workspace to define sets and parameter as well as to inter technologies, fuels and to connect them with parameters. Sets define the physical structure of a model which define the time domain and time split, the spatial coverage, the technologies and fuels to be considered. Parameters are estimated numerical inputs to the model and are a function of the elements in one or more sets. Basic parameters used to set up the model are presented in table one. As indicated in RES, power generation technologies and fuels are defined within a modelling framework and connected with their specific input and output fuels. The installation of technologies and their operation and maintenance imply a cost for the system as well as the penalties that can be related to the emissions and described by technical parameters. The demand for energy service was quantified from scenarios and technologies are described in terms of efficiencies, production potential, capital and operation cost, capacity factor, emission factor, operation life of technologies, the residual capacity of technology.

The model is driven by the demand for final energy which is split into different demand sectors of agricultural, commercial, industrial, and residential and transport defined in the model. The generated electricity by power generation technologies are then connected to transmission technologies and finally to end demand sectors by distribution technologies. Using this framework, a national model of an energy system is developed. The resolution of the optimization problem of a model, through the decision variables, defined the new capacity of each technology installed each year and the corresponding rate of activity (energy production). The optimal mix of technologies results as an output in terms of installed capacity of a technology, costs and emission balance. The developed OSeMOSYS considers a spatial scope of a single-region economy of Ethiopia, in a time horizon 2020 to 2050. The model is then properly calibrated to produce a base year (2020) dispatch solution that roughly matches the actual installed capacity and generation mix from the same year.

2.5. Scenarios description

Considering the national vision of energy security and the importance of energy to support a national vision of achieving the middle-income country category in 2030 and beyond, two scenarios were considered.

Business as Usual Scenario (BAUScen): This scenario has been considered as an essential point of reference and is based on a set of assumptions that build on historical norms, projecting the configuration of the energy system from 2020 to 2050 into the future and serves as a baseline to compare alternative scenario. The overall assumption of this scenario considers the energy access rate and consumption per capita growth rate continues consistent with the baseline year (2020) with implicit improvement related to urbanization and economic growth. The growth of the total demand is driven mainly by population and urbanization growth. The electricity access rate of 45% and per-capita consumption rate of 133kWh/c were considered and will be assumed to be evolved in the future in the same way as they were in the last decade (8% annual growth for access rate and 13% annual growth for per-capita consumption).

Homegrown Economic Reform Agenda 2030 Scenario (HERA2030Scen): Ethiopia has set out a clear pathway to prosperity through its newest Home-grown Economic Reform Agenda (HERA) intended to deliver high-quality growth and a poverty reduction, and enabling Ethiopia to reach the status of a middle-income country by 2030. National plans indicate, the country will attain 100% coverage of electricity by 2030. HERA2030Scen stipulates Ethiopia will satisfy its energy requirements by 2030 and fulfils the 2030 SDG goals in energy. The population and urbanization growth continues at the same rate; the annual GDP growth rate is conveniently assumed to grow with the same rate as the BAUScen. It is also assumed that the country graduates from a low-income country to lower-middle-income country status by 2030 as planned and continue to grow to a medium middle-income country by 2040 and higher middle-income country by 2050. The key features of this scenario are the per capita electricity consumption of the country is assumed to match the current average consumption rates of lower-middle (760KWh/c), medium-middle (2064KWh/c) and higher middle-income country (3496KWh/c) by 2030, 2040 and 2050 respectively (Ritchie and Roser, 2019).

3. Result and Discussion

3.1. Generation capacity mix

Based on the result of the electricity demand projection obtained from scenarios, OSeMOSYS determines the least-cost capacity mix needed to meet the demand. The expansion of power plant capacity in the Ethiopian power system based on designed scenarios is shown in fig 4 [sub plot a]. Under BAUScen of maintaining the statuesque, Ethiopia needs to install the generation capacity of about 11.24GW and 13.68 GW by 2030 and 2050 respectively. Hydropower remains the main contributor of the national electricity generation with 10.02GW which contributes 89% and 73% of the total installed capacity by 2030 and 2050 respectively. Wind power is the second contributor with 9.9% and 26.8% by 2030 and 2050 respectively. Together, Hydropower and wind power are the most optimum contributing with 98.9% and 99.8% of the total installed capacity by 2030 and 2050.

Under the HERA2030Scen of middle-income scenario, the installed power generation capacity is expected to rise to a significant high capacity of 31.22 GW and 334.22GW by 2030 and 2050 respectively in response to the projected high electricity demand compared to BAUScen. The structure of power generation capacity is expected to change over this period, mainly due to exhaustion of the available hydropower potential. The optimum installed capacity mix shows that by 2030; hydropower, wind, and geothermal shares 57%, 26% and 16% of the total installed capacity respectively. By 2050 the installed capacity shifts to 48% wind, 34% solar, 13% hydro and 2.9% geothermal. The enormous required increase in power production by 2050 is associated with the assumption that Ethiopia moves progressively from lower-middle-income country by 2030, to medium middle-income country by 2040 and upper middle income by 2050. This indicates that, compared to BAUScen, the installed capacity should be raised by 22% in 2030 and by 970% in 2050 to maintain the increasing demand.

3.2. Electricity generation mix

Generated electricity based on BAU scenario reaches 49.47TWh and 65.73TWh by 2030 and 2050 respectively. These products will increase by 328% in 2030 and 540% in 2050 compared to base year generation. Electricity will mainly produce by technology running on hydropower. Alone, hydropower generates 35.23 TWh (71%) in 2030. Under the HERA2030Scen, the total electricity generation peaks to 127.80TWh and 768.88TWh by 2030 and 2050 respectively. Compared to BAUScen, this is an increase of 158% and 1454% by 2030 and 2050 respectively. The generation mix has undergone significant change with increasing electricity demand where hydropower share reduces to 57% in 2030 and 13% in 2050. Besides, to replace hydropower, solar energy will penetrate at the highest rate towards 2050. In 2039 solar power technology starts to make a significant share of the electricity generation of 33.94 TWh, and increases to 208.08TWh by the end of the presented period time (2050). As a result, national energy generation gradually shifts to solar technologies towards 2050 and solar and wind technologies are the most used technologies towards 2050. The shift from hydropower to solar is mainly attributed to exhaustion of the available hydropower potential.

Previous national studies on energy have projected energy demand using a variety of methods. (Mondal *et al.*, 2018) projected electricity demand for Ethiopia using the Long-range Energy Alternatives Planning (LEAP) model from 2015 to 2045 for universal electrification scenario to be 119.7TWh by 2045 under the universal electrification scenario. This translated to the per-capita power consumption of 669 KWh/c, which is very low compared to the expected average per-capita consumption of 2780 KWh/c by 2045 based on countries economic transition to middle-income countries. The Ethiopian power system master plan also uses a combination of regression analysis and end-user models to forecast electricity demand in Ethiopia (Brinckerhoff, 2013) to be 111.4TWh by 2037 which translates to per-capita consumption of 703 KWh/c. This indicates that demand is thus underestimated. As the previous analysis considers only access rate without objectively defining the average per-capita consumption target as per the middle-income country status, thus could have an impact on the power expansion capacity to meet the targeted national demand. Moreover, the previous study lacks to optimize the supply-side energy mix to meet the projected demand. Besides, Ethiopia has sufficient potential renewable energy sources to cover all national demands. Compared to the national power generation potential of more than 11, 700TWh from renewable energy resources (Tucho et al 2014), the projected energy demand of 768.88TWh is by far lower than the national generation potential and national electricity demand to achieve middle-income country status will be meet with the development of 100% clean energy sources. Thus, there will not physical energy scarcity issue in regards to the availability of renewable energy sources at the national level.

4. Conclusion and Policy Implication

The main purpose of the current study was to provide policymakers with a comprehensive set of information to better plan for optimal development of renewable energy resources and technology selection in strive made to achieve a national target of meeting middle-income country categories. The model result confirms that Ethiopia has adequate renewable energy resource potential to meet national targets of achieving middle-income country status. Our current results indicate that a 100% renewable energy system by 2050 can be achieved. The result also demonstrates how different power generation technologies and energy supply mix can be chosen to adequately address the projected national power demand. With an increasing demand for electricity in HERA2030Scen, the generation mix gradually shifts to solar and wind technologies. The shift is due to the exhaustion of hydropower potential and solar power plant inters to the national generation mix to substitute and meet the growing energy demand. Solar and wind technologies are the most used technologies towards 2050.

Major investments in power infrastructure will be needed in the coming decades due to the increasing electricity demand. The cost of achieving the national target of 100% access rate and middle-income country status from the current low access rate and consumption rate involves a substantial increase in total investment cost (151% increase compared to BAUScen). Economic energy scarcity is therefore a daunting challenge for a country to meet the national target of energy security. To overcome this issue, political decisions are needed to promote and attract large investment and capacity building activities.

The insights gained from this study could help decision-makers gain a comprehensive understanding of the options for optimum development path for renewable energy resources. With a better understanding of the power sector evolution, policymakers responsible for long-term expansion planning will make better-informed decisions to update current national plans, support policy and future investment decisions in the energy sector. The study supports Ethiopia's vision of transformation from traditional to modern energy sources and drives a country to be a renewable energy hub in the region, a well-intentioned policy path to pursue. It is also consistent with carbon-neutral economic growth ambition in its green growth strategic plan (Paul 2019) and the optimal renewable energy system mix and technologies would allow Ethiopia to its clean and sustainable energy development goal.

There are several limitations to the analysis in this paper, some of which can be addressed in further work. The cost of electricity from renewable energy technologies specifically from wind and solar technologies has fallen steadily and further research can improve upon the current findings by performing sensitivity analysis according to possible future cost scenarios of these technologies. Despite sufficient renewable energy resources for power generation, Ethiopia currently relies on imported fuels for the transportation sector and its emission scenario will need further consideration. Moreover, potential improvement in technology efficiency and electricity trade will need to be further evaluated and implemented in the model.

5. Conflict of interests

The authors state that they have no conflicting interests.

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