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Long-term electricity supply modelling in the context of developing countries: The OSeMOSYS-LEAP soft-linking approach for Ethiopia

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ABSTRACT

Long-term power supply modelling is particularly important for developing countries in providing sustainable solutions to electricity problems. This study presents the first detailed and complete model of the Ethiopian electricity system while considering the unique features (dominance of traditional energy, informal economy, urban-rural divide, low electrification, supply shortage, etc.) and context of developing countries that is developed by soft-linking the OSeMOSYS (Open-Source energy Modelling System) and LEAP (Long-range Energy Alternatives Planning System) modelling frameworks. Better system representation and design of plausible scenarios that explore the potential pathways of the future power supply and demand evolution until 2050 is done by performing sensitivity analysis. Sector wise and technological representation of supply and end-uses at a disaggregated level, assessment of centralized grid-based means and decentralized off-grid methods for improving electricity access are the main methodological contributions. Five policy scenarios are employed to explore different possible futures and balance the long-term electricity needs and resources. The improved efficiency scenario reduces the installed capacity by 9 GW which translates into approximately 11% total discounted cost saving (USD $ 4 billion). This economic benefit has made the efficiency scenario the most desirable compared to the other scenarios. Attributed to lower investment costs and abundant resource availability, the results show that renewable technologies are more competitive and favourable.

1. Introduction

The United Nations set the 17 Sustainable Development Goals (SDGs) to guide the world during the fifteen-year period from 2015 to 2030. Specifically, SDG 7 states “Ensure access to affordable, reliable, sustainable and modern energy for all”. Sustainability, security, and affordability of energy supply are important aspects in shaping future energy policies and countries’ energy-mixes [1]. These aspects are also expected to play a crucial role in the future evolution of the power sector. A long-term view spanning decades into the future is necessary to develop effective policy measures that ensure that investment is leading to sustainable and cost-effective ways of energy supply [2]. The issue of sustainability, security and affordability of energy supply is unique to each decision maker depending on their circumstances, including geographical location, sectoral coverage, and available resources [3].

In compliance with policy scenarios that impose technical, economical and environmental constraints, energy modelling tools can identify optimal supply and capacity mixes to meet the future electricity demand. Decision makers increasingly rely on model assessments to foresee how the electricity sector might evolve in the future, inform the development of policy and national renewable targets. Long-term energy modelling frameworks are widely recognized as useful approaches in analyzing the future energy utilization patterns and trends, strategy formulation and energy policy recommendations with respect to effective utilization of energy resources, improvements in energy efficiency and energy reliability, and emissions reductions [4].

Long-term energy planning models are generally characterized by a wide scope and low level of temporal detail, to avoid the exercise to become computationally unwieldy [5]. Energy models can also be developed to capture more sector-specific detail, such as the power sector that aim to calculate a path for power generation expansion which combines technologies that collectively meet the variable demand.

Abbreviations: OSeMOSYS, Open-Source energy Modelling System; LEAP, Long-range Energy Alternatives Planning System.

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Several studies have examined issues of power generation expansion in developing countries of Africa, Asia and Latin America. These studies have proposed and discussed a number of methodologies and models for electricity planning in developing countries. In this regard, the OSeMOSYS, LEAP, MESSAGE, MAED, MARKAL and TIMES modelling frameworks have been applied in various settings to assess the future energy sector. Despite the differences between the existing models and methods, they all usually assess the cost-optimal technological options which matches the future energy demand. The least cost long-term electricity supply mix strategies are determined for different countries under various policy scenarios designed while considering their context.

Among the existing scientific literature, Rady et al. developed an OSeMOSYS-Egypt model to determine the lowest cost electricity generation mix that is required to satisfy two different demand scenarios within a time period between 2018 and 2040 [1]. Dhakouani et al. presented an OSeMOSYS-based long-term model of the Tunisian electricity system aimed at showing the potential benefits of increasing renewable energy source production [6]. Awopone and Zobaa also used the OSeMOSYS to examine the future possible energy policy direction in Ghana. Alternative policy scenarios of energy emission targets, carbon taxes and transmission and distribution losses improvements were developed [7]. Ouedraogo employed the LEAP modelling framework to assess five scenarios that represent alternative development pathways of Africa's energy future from 2010 to 2040. The study highlighted economic policies will have a significant impact on energy demand and greenhouse gas emissions [4]. Kumar developed three major scenarios to analyze the renewable energy potential in Indonesia and Thailand from 2010 to 2050. It used the LEAP energy model to estimate the future electricity supply options and CO_2 mitigation possibilities. The results showed that expanding the share of renewables in the energy mix can bring extensive socio-economic benefits to the Southeast Asian countries [8]. Yophy et al. employed the LEAP model to assess several alternative scenarios of energy policy and energy sector evolution of Taiwan. The model was used to compare future energy demand and supply patterns, as well as greenhouse gas emissions [9].

The MESSAGE modelling framework has been applied by Marong et al. to explore the possible optimal electricity supply expansion of Gambia with and without hydroelectricity imports for the horizon 2015–2030 [10]. Dountio et al. presented three economic growth rate scenarios to analyze the electricity demand and the expansion of electricity generation in Cameroon. The energy demand assessment was made by MAED model while MESSAGE modelling framework was used to optimize the supply system and quantify associated emissions [11]. Das et al. tried to investigate the alternative ways for future expansion of the Bangladesh power system aiming to address the issue of affordability and reliability. Focusing on power imports and higher use of renewables, the study employed the TIMES modelling framework to explore four power supply scenarios [12]. Ruijven et al. presented a global integrated assessment model for assessing the rural electrification and associated investment needs focusing on regions with low electricity access, mainly in Latin America, Asia and Sub-Saharan Africa. From the different set of electrification scenarios investigated in the model, it was found that electrification varies across the three regions where Latin America and Asia gain access at lower income levels than Africa [13]. Mondal et al. presented an assessment of alternative, long-term energy supply strategies of Ethiopia using the MARKAL energy system model. The results showed that higher investment costs will be required to achieve policy goals in near-term, but also include long-term benefits such as sustainable energy system development, expansion of access with modern sources of energy and the development of a low carbon society [14].

Despite the extensive use of LEAP [4,7–9], OSeMOSYS [1,6,7] and MESSAGE [10,11] for assessing the long-term energy development in various developing countries, little attention has been paid to incorporating the unique features: traditional energy consumption, informal economy, urban-rural divide, low electrification, supply shortage, data and skill needs [15]. It is essential to consider these features during modelling to prevent inaccurate analysis and the prescription of wrong policies, particularly the feasibility of including new technologies to the existing system. i.e. Electricity supply can be provided either by centralized grid-based means, or by decentralized methods; and detailed analysis is required to strategize and evaluate which options that are applicable and effective in improving the poor performance of the power system and low electricity access of developing countries.

This paper focuses on Ethiopia since the country's electricity system is facing unique challenges that can highly relate to other less developed and developing countries. Modern and reliable energy sources are crucial to society's well-being and to a country's economic development but the primary source of energy in Ethiopia is still traditional biomass. In addition, previous studies that attempted to assess the future expansion of the electricity supply system in Ethiopia are quite scarce. The Ethiopian Power System Expansion Master Plan [16], completed in 2014, was done for the Ethiopian Electric Power (EEP) Utility for the period 2013–2037. It uses the WASP generation planning program to determine the 25-year least-cost generation system development plan. Recently, a new update of the master plan was developed [17] which used screening analysis to rank generation options and the PLEXOS production simulation and optimization model to plan the generation expansion until 2030. These two national level studies aimed to forecast the future electricity supply without providing alternative possible futures that can be meaningful for policy development. In this regard, Dereje [18] considered business as usual (BAU), moderate shift and advanced shift scenarios of economic development to assess the future LEAP-based energy demand and supply in Ethiopia. Even though the studies of Dereje and Mondal et al. [14,18] attempted to explore the future Ethiopian power generation sector by providing alternative scenarios, the developed scenarios did not fully consider the context of the country in terms of technology and policy choices that can overcome its particular problems.

Thus, the overall objective of this study is to identify potential pathways and provide a quantitative analysis of the future power generation sector in Ethiopia while considering the context of and applicability to developing nations. It tries to provide the best possible representation of electricity system of developing countries with consideration of unique features as well as independent assessments of alternative technologies and policy choices. With this objective in mind, this paper seeks to answer the following questions.

- What are the optimal (least-cost) supply mix alternatives of the future power system which could ensure generation adequacy, reliability and reduce greenhouse gas emission and which renewable technologies play a key role in the future energy mix?
- How does decentralized renewable energy contribute towards improving the national electricity access?
- What is the effect of introducing energy efficiency policies on future energy investments?

The model development in this paper is based on a contextual representation of the electricity system on RES diagram and soft-linking approach that is adopted by coupling two independent models: the OSeMOSYS and LEAP. In addition, this study contributes to the existing body of knowledge and overcome some of the limitations that exist in the literature. Sector wise and technological representation of supply and end-uses at a disaggregated level (i.e. urban-rural divide, centralized vs decentralized), plausible scenario analysis of technology selection for improving electricity access, and demand side and supply side efficiency measures are the novelties and main methodological contributions of this paper. Moreover, feasibility of both grid-extension and off-grid supply options, feasibility of 100% renewable and intermittent resource (solar and wind) target are investigated as presented below. Finally, a sensitivity analysis is conducted by identifying the underlying factors that affect the model output. This provides crucial information regarding the effects of changes in critical inputs and assumptions.

The structure of the article is as follows. Section 2 gives an overview of the country's power sector. Section 3 discusses the methodology employed in this study including the model choice and development, the Reference Energy System (RES) and applied scenarios. Section 4 presents the results of the models. Finally, Sections 5 and 6 provide discussion and conclusion of the main findings.

2. Background-Ethiopia's power sector

In Ethiopia, the national energy balance is dominated by a heavy reliance on firewood, crop residues and dung [19–22]. This dependence has serious environmental and health risks that needs intervention to accelerate the transition to modern energy sources. The country has

managed to achieve universal electricity access to almost all urban areas, while access to electricity in rural areas is very limited. The electrification rate of households in the country is presently at 40% total access with per capita consumption of 143 kWh.

Ethiopia has a high potential of renewable resources including solar, wind and hydropower in addition to geothermal and bioenergy, summarized in Table 1. However, the potential is largely untapped. The power generation is dominated by hydropower accounting for about 90% of the total. The generation and capacity mix consists of 13 hydro, six diesel standbys, one geothermal and three wind farm plants with installed capacities of 3814 MW, 87 MW, 7.5 MW and 324 MW, respectively. This amounts to a total of 4233 MW [23]. The strong dependence on hydropower has been a serious challenge to Ethiopia in the past decades, sometimes to a level where the country experienced sequences of blackouts and enforced load shedding (e.q. severe load shedding in 2009 due to water shortage in the dams). Over the years, droughts and inconsistent rainfall across the country have resulted in a low water level at different hydropower plants. In addition, as a developing country, Ethiopia has a strongly increasing electricity demand due to growing population, rapid urbanization, energy export plan, rise in living standard and income. Together with poor performance of the power system, this has resulted in electricity supply insecurity [24].

The hydropower vulnerability and supply insecurity could be mitigated with an appropriate energy-mix by developing renewable and other sources-including natural gas, solar, wind and geothermal energy. Knowing this, the Government of Ethiopia (GoE) has focused on diversifying its energy-mix with solar, wind and geothermal sources to complement the large base of hydropower development. In line with Pillar Three of Ethiopia's 2011 'Climate Resilient Green Economy (CRGE) Strategy', which requires 15–20% of the energy supply to come from non-hydropower based renewable resources by 2020, the GoE targets to contribute towards mitigating climate change [25,27].

3. Methodology

In this study, there are three main phases namely: choice of modelling framework, demand projection and generation expansion. The model choice and soft-linking of two tools is done considering the context of the country and applicability to developing nations while the supply-demand balance is based on the system representation on RES diagram and identification of relevant scenarios. Sector-wise & technological representation of supply & end-uses at a disaggregated level are the core of the modelling approach employed in the LEAP and OSeMOSYS models. An overview of the methodology used is outlined in Fig. A1. of the appendix which is discussed further in detail below.

Table 1
National renewable energy potential [23,25,26].

Technologies	Unit	Exploitable reserve
Hydropower	MW	45,000
Solar	kWh/m^2/day	Avg. 5.5
Wind	MW	1,350,000 (@50 m height, wind speed 7 m/s)
Geothermal	MW	10,000

3.1. Model choice

The choice of appropriate modelling framework depends on the kind of insights the model is intended to provide and should therefore start from an assessment of the context, the challenges, and the policy questions to be answered [6]. Long-term energy modelling tools that aim to provide insights into investment and infrastructure needs, usually with a cost-optimization perspective include the long-established MESSAGE, MARKAL and TIMES models, and recent open-source alternatives, such as Balmorel and OSeMOSYS [28]. Each of these tools have their own features and the selection of appropriate modelling tool depends on the level of use of the features for a particular application. MESSAGE, TIMES and OSeMOSYS are widely used optimization models that have been applied in different countries to address a variety of research questions. It is important to develop a comparative overview of these models in terms of several criteria, particularly their applicability to developing countries where unique features of traditional energy consumption, informal economy, urban-rural divide, low electrification, poor performance of the power sector, supply shortage, data and skill needs, etc. should be considered [15,29]. In this regard, MESSAGE and OSeMOSYS share most features including purpose (investment decision), analytical approach (bottom-up), time horizon (long-term), geographical and sectoral coverage, scenario-analysis and traditional fuels. However, OSeMOSYS has the advantage of accommodating the urban-rural divide, being open-source and an easy-to-use optimization modelling framework. For this reason, the authors chose OSeMOSYS for carrying out the electricity supply analysis of Ethiopia within a time period between 2018 and 2050. In addition, the Long-range Energy Alternatives Planning System (LEAP) modelling tool is employed to unfold the future evolution of the electricity demand and analyze the end-use energy demand through alternative scenarios.

As in most long-term optimization models, OSeMOSYS in its standard configuration assumes a perfect foresight and perfect competition on energy markets [30]. In mathematical terms, OSeMOSYS is a deterministic, linear optimization framework. However, mixed-integer linear programming may also be applied in the case of unit commitment. OSeMOSYS has been used as a long-term optimization model in many countries such as Egypt, Tunisia, Ghana, Saudi Arabia, Iran and Bangladesh [1,6,7,31–35], and thus its functionality has been tested in large models in the past.

3.2. Coupling of LEAP with OSeMOSYS

Our hybrid modelling approach of coupling LEAP with OSeMOSYS attempts to achieve a better system representation by taking advantage of the strengths of both modelling frameworks, particularly in regard to capturing the specific features of developing countries. As thoroughly discussed in Ref. [15], the use of a single modelling framework inadequately captures the developing country characteristics while the development of LEAP-OSeMOSYS hybrid model would enhance the electricity system representation by incorporating most unique features. In this approach, the respective models developed in LEAP and OSeMOSYS are executed separately, and the exchange of data is controlled by the modelers. The pathways represented by the demand scenarios and results generated by the LEAP model will be given as an input to the exogenously defined energy demand parameters of the OSeMOSYS model. These exogenous variables, e.g. the projected yearly electricity demand by sector and scenario, GHG emission, energy efficiency, cost, etc. will be soft-linked between the models.

3.3. Optimization mechanism and logic

The least-cost power generation and capacity mixes are identified considering various alternative policy scenarios to explore different possible futures and balance the long-term electricity needs and resources. The objective function of the core model in OSeMOSYS is given by Eqs. (1) and (2) where the minimum total discounted cost is determined for a time domain of decades. Technologies compete to gain a share in the electricity supply, based on their techno-economic characteristics and on a number of constraints-e.g. demand, minimum renewable generation, emissions, use of resources, etc.

$$\text{Minimise} \sum_{y,t,r} \text{TotalDiscountedCost}_{y,t,r} \tag{1}$$

$$\begin{aligned}\forall_{y,t,r}:\ \text{TotalDiscountedCost}_{y,t,r} &= \text{DiscountedOperatingCost}_{y,t,r}\\ &+ \text{DiscountedCapitalInvestment}_{y,t,r}\\ &+ \text{DiscountedTechnologyEmissionsPenalty}_{y,t,r}\\ &- \text{DiscountedSalvageValue}_{y,t,r}\end{aligned} \tag{2}$$

[1]Subscripts y,t and r represent the year in time horizon, technology representing a type of power plant and region or country modelled, respectively. The costs are annualized over the years in which the asset is active. In the case of late investments (e.g. made in 2050), OSeMOSYS gives a 'salvage value' for benefits after the investment period. Constraints are mainly defined on: i) rate of demand for each combination of commodity, time slice and year, ii) capacity adequacy in each time slice and year, and iii) energy balance in each time slice and year.

3.4. Model application

The long-term electricity supply model is developed considering Ethiopia as a case, with alternative policy scenarios as discussed in detail below.

3.4.1. Model development and reference energy system

The OSeMOSYS-Ethiopia model performs linear programming-based optimization of supply options through meeting the demands specified in the LEAP model that are structured sector-wise, namely: residential, industrial, commercial, agriculture and transport. LEAP has been used to investigate electricity sector and energy sector of several countries [33,36–39]. In particular, it is a widely used tool for energy demand prediction and scenario analysis in developing economies [21,40,41]. Both the OSeMOSYS and LEAP models consider a spatial scope of a single-region in a time horizon between 2018 and 2050.

The Reference Energy System (RES) is a schematic representation of the real energy system in the country that is being modelled. It provides the routes/links of energy flows from primary energy supply, via energy conversion technologies to the products/services satisfying the demands. The RES-diagram developed with the context of Ethiopia which is the basis of the OSeMOSYS model is shown in Fig. 1. It represents the current energy system and is flexible enough to include future system extensions. Primary energy sources are presented to the left while the sector-wise demands are to the right of the diagram. Energy conversion technologies are indicated by boxes. Boxes with solid-lines represent existing technologies in the country while broken-lines indicate future technologies under consideration. The lines connect the outputs of primary energy resources to the inputs/outputs of various technologies, and all the way to the final demand.

- Primary energy resources

Primary energy resources include all energy products not transformed to electricity, that is, the resources or unconverted fuels that could be exploited by technologies for electricity generation. They take many forms, including nuclear energy, fossil energy (oil, coal and natural gas) and renewable sources. In the Ethiopian context, eight different primary energy resources are considered: renewables (solar, wind, geothermal, biomass and hydropower) and non-renewables natural gas, nuclear and oil (i.e. imported diesel)). The country has very large exploitable reserves of renewable and clean energy resources (see Table 1) while it relies on imported fuels for nuclear and diesel energy.

- Power generation technologies

Power generation technologies convert the primary resources into electricity. Two types of supply technologies are considered: centralized grid-based and decentralized off-grid methods. The decentralized/distributed technologies are the main source of electricity in many rural areas of Ethiopia. Considering their type of input fuel sources and power plant size, sixteen types of power technologies are available in the Ethiopian RES (see Table 2). Hydropower plants are classified as large-scale (>100 MW), medium-scale (20–100 MW) and small-scale (<20 MW). Other renewables include photovoltaic plants (utility-scale and small-scale rooftop), concentrated solar power plants, wind plants (utility-scale and small-scale), geothermal and biomass plants (cogeneration and incineration). Thermal candidates include diesel (Distributed small-scale and centralized utility-scale), natural gas (combined-cycle and open-cycle) and nuclear power plants. Existing thermal generation includes reciprocating diesel generators which are mostly used as emergency reserve. It is assumed that these plants will continue to provide service for the next few years until the end of 2022 when it is planned for decommissioning [17].

- Transmission and distribution infrastructure

The energy conversion system includes electricity transmission and distribution (T&D) infrastructure. Centralized utility-scale power generation technologies are connected to the transmission system at a high-voltage level which carry and transport power to long-distances. On the contrary, decentralized off-grid technologies are either connected to the distribution system at a medium-voltage level or directly to the customer-end, at low-voltage level. The distribution system is the final stage in the delivery of electric power that carries electricity from the transmission system to final consumers. It is disaggregated into different categories such as distribution to

residential sector, agricultural sector, industrial sector, transport sector and service sector. In addition, electricity export to neighbouring countries is represented with long-distance high-voltage ac and dc transmission lines.

- Final demand

The final demand is disaggregated into industry, agriculture, services, residential and transport. Moreover, power export to neighbouring countries is also represented as a final demand.

3.4.2. Data and key assumptions

Data used in this study is based on extensive data collection, mainly from the reports available in the Ethiopian electric power sector [16,17,19,23,26,27] but also from international studies and reports [4,42–62]. Tables 2 and 3 summarize the main input data and key assumptions for making the OSeMOSYS-Ethiopia model. Literature-based costs and efficiency values are used for various power generation technologies while considering the context of the country.

The construction of hydropower plants usually involves substantial civil work (dams, river diversion, etc.), the cost of which largely depends on labor costs, which results in much lower hydropower investment costs for developing countries than in industrialized countries. Consequently, after considering the context and referring to local studies, a specific investment cost of 2000 USD/kW, 2400 USD/KW and 3533

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[1] DiscountedSalvageValue represents the fraction of the initial capital cost that can be recouped at the end of a technologies operational life that is discounted to each year with the considered discount rate.

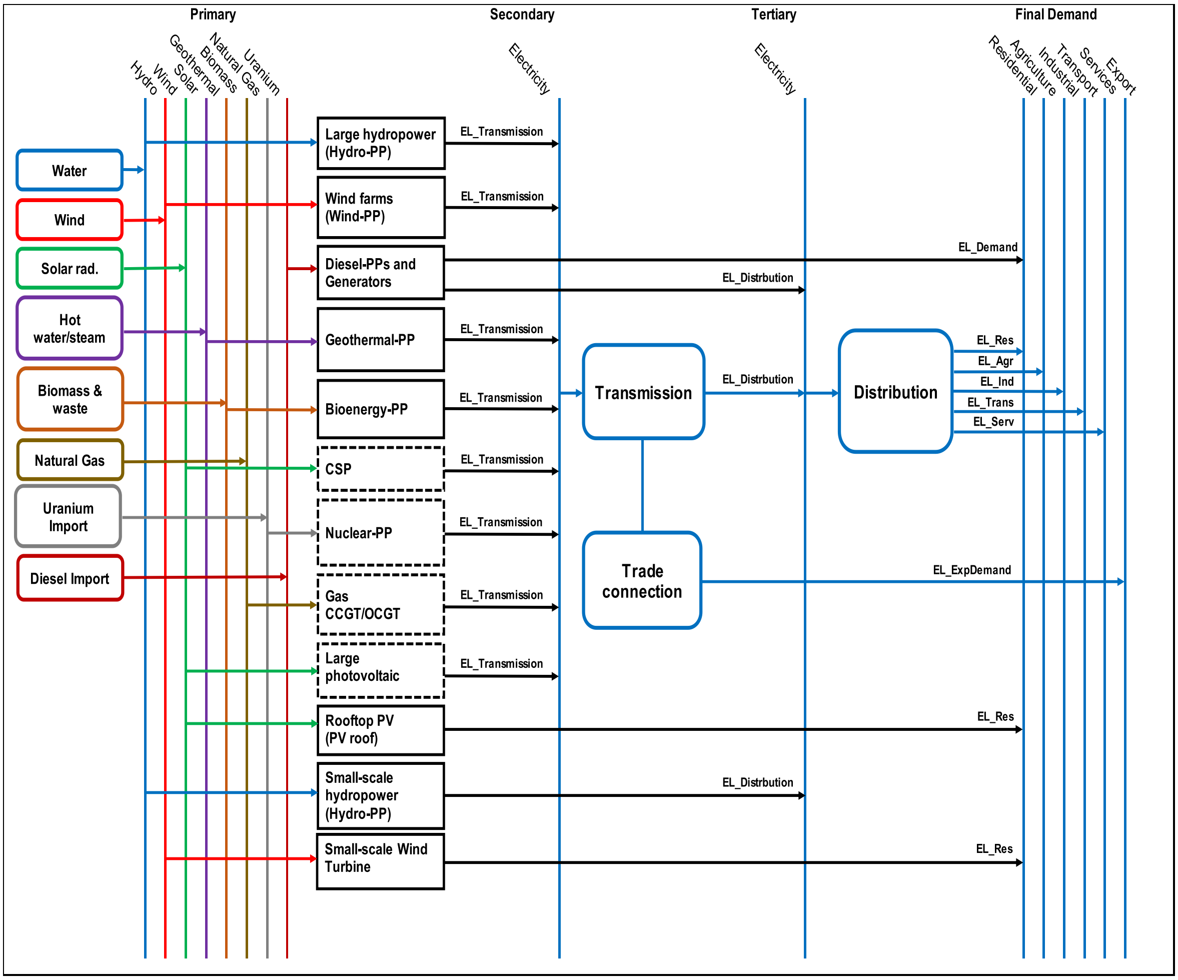

Fig. 1. The reference energy system (RES) of Ethiopian electricity sector.

Table 2

Techno-economic input parameters of various power generation technologies in OSeMOSYS-Ethiopia model [4,16,17,19,23,26,27,42–59].

Unit	Input parameter[a]									
	Capital cost	Fixed cost	Variable cost	Capacity factor	Availability factor	Capacity credit	Efficiency	Life cycle	CO_2 emission	NO_x emission
	USD $\$_{2018}$/kW	USD $\$_{2018}$/kW	USD $\$_{2018}$/MWh	%	%	%	%	Years	kg/MWh	kg/MWh
Power generation technology										
Hydro-large	2000	18	0.1	41	91	100	–	80	–	–
Hydro-med.	2400	50	0.36	41	91	100	–	50	–	–
Hydro-small	3533	50	0.36	46	91	–	–	30	–	–
Geothermal	4000	88.8	8.4	80	95	100	–	25	–	–
PV-utility	1100	21	0.4	25	99	5	–	25	–	–
PV-rooftop	2770	21	–	25	99	–	–	25	–	–
CSP (storage)	5238	67.3	1.5	63	92	100	–	25	–	–
Wind-utility	1700	46	0.8	30	97	20	–	25	–	–
Wind-small	2900	46	–	30	97	–	–	20	–	–
Biomass	3333	75.6	6.5	50	98	100	38	30	–	0.065
Waste inciner.	7900	75.6	6.5	50	92	100	34	25	1195	0.66
Nuclear	4500	164	20	85	93	100	33	40	–	–
NGCC	1100	24	2.6	80	95	100	55	25	400	0.03
NGOC	700	17	3.5	80	97	100	36	30	575	0.05
Diesel-utility	1600	60	6	80	95	100	35	25	700	6.4
Diesel-small	692	27.6	6	80	95	–	35	20	1270	19
T&D infrastructure [16]										
Transmission	1135[b]	17[b]	–	–	–	–	96.5[c]	30	–	–
Distribution	1090	16.35	–	–	–	–	91[c]	30	–	–

[a] Dashed cells: not applicable, zero.

[b] It also includes substation cost.

[c] Efficiency level after the year 2030; Capital cost is evolving during time horizon.

Table 3
Model setup, electricity demand and key assumptions [4–6,17,21,24,41,43,49].

Time domain	2018 to 2050
Time slices	6, one-year divided into two seasons as dry and rainy season, then the day divided as day, night and peak
Electricity demand	25.1 TWh/year in 2018 and then rapidly increasing growth based on LEAP model predictions (See Table 4)
Fuel prices (in 2018)	• 3.89 USD/GJ for biomass • 18.8 USD/GJ for diesel import • 7.66 USD/GJ for natural gas • 2.59 USD/GJ for uranium import
Discount rate	10%
Reserve margin	10%

Table 4
Electricity demand projections in LEAP-BAU scenario, 2018–2050 [64].

In TWh	2018	2020	2030	2040	2050
Industry	13	15.1	28.2	46.9	69.3
Household	4.6	6.4	20.6	40.7	62.5
Commercial	2.6	3.1	6.6	12.5	21.0
Agriculture	0.1	0.5	4.4	10.4	16.4
Transport	3.3	3.9	15.0	20.4	24.9
Export	1.5	4.5	13.8	32.0	35.3
Total	**25.1**	**33.5**	**88.6**	**162.9**	**229.4**

USD/kW are used for large, medium and small-scale plants respectively (see Table 2).

Future renewable technologies are expected to show capital cost reductions due to increased learning-rates. Solar PV is one of the biggest benefactors of the accelerated transition and moves quickly down the cost curve [46]. Investment costs for 2030 and 2050 are calculated using a 3% and 1% yearly technology cost reduction factor for utility-scale PV and rooftop PV (with 1 kWh battery) respectively.

Cost reductions are also accelerated for other renewable energy technologies that are not yet fully mature. Capital cost of wind power is considered to fall by 1.5% and 1% every year for utility-scale and small-scale technologies respectively. Concentrated Solar Power (CSP with storage) achieves cost reductions of 30% by 2030 (i.e., 30% over a decade, from 5238 USD/kW to 3650 USD/kW to 2555 USD/kW).

The investment cost of biomass power plants falls to 2750 USD/kW by 2030 from 3333 USD/kW in 2020 [51]. Geothermal power plant installation costs are highly site sensitive due to the reservoir quality, the type of power plant and number of wells [53]. In the past decade, geothermal capital cost increased from 2588 USD/kW in 2010–3916 USD/kW in 2019. Thus, a slow cost reduction to 3100 USD/kW in 2030 is assumed. Waste incineration plants are assumed to show a 3% capital cost fall in ten years. Other technologies, that is, the hydropower and thermal plants are not assumed to show cost reductions in time as they are capital-intensive often requiring long lead times. Costs have been annualized and discounted to the value of the year 2018 assuming corresponding plant life assumptions as shown in Tables 2 and 10% discount rate.

The reserve margin (RM) is defined as the amount of firm electricity generation capacity minus the system's maximum annual demand as a ratio of maximum annual demand [4]. An evaluation criterion is shown in (3) which states that the total firm capacity should always be greater than the annual peak demand (Dp). Where α_i is the capacity credit of power plant/technology i which is considered as "firm" and C_{pi} is the generating installed capacity of the corresponding power plant. Many studies on Sub-Saharan African countries use a reserve margin constraint of below 10% [4,5,24,63]. Given the importance of having sufficient firm capacity to system reliability, an average reserve capacity of 10% is considered as reasonable in this study.

$$\sum_{i=1}^{n} \alpha_i \times C_{pi} \geq (1+RM_{min})D_p \tag{3}$$

The LEAP electricity demand projection employs different scenarios to show the maximum expected rise in demand under different drivers and the best-case energy saving opportunities. The developed scenarios are Business-As-Usual (BAU), Growth in Electrification and Urbanization (E&U), High Economic Growth (HEG) and Improved Energy Efficiency (IEE) scenarios.

The electricity demand projection under the BAU scenario is shown in Table 4. It is evident that the country expects a strongly increasing electricity demand in the future three decades. A comparison of the scenarios shows that the highest demand is expected for the E&U scenario since more electricity-based end-uses are utilized. In 2050, the total electricity demand under the E&U scenario is expected to reach 256 TWh while HEG and BAU demand 253 TWh and 229 TWh respectively. Total energy savings under the IEE scenario are mainly due to technology improvement, demand-side management, industrial energy audit and efficiency measures, network loss reduction, etc. which are estimated to be about 43 TWh.

In the context of the country, where variable sources account only for a negligible part of the power system, time slices are defined primarily according to the variability of demand (according to the seasonality of rivers, in a system with a high share of hydropower). Therefore, the model is not required to capture the variability of the supply. In order to represent the variability of demand, the 8760 h that make up a year are broken down into time blocks or time slices capturing seasonal, weekly and daily variations. In this study, 6 time-slices are used in which the year is sub-divided into two seasons: dry (September–May) and rainy (June–August). The 24-h day is then sub-divided into three time blocks as: day (06:00am-06:00pm), night (10:00pm-06:00am) and peak (06:00pm-10:00pm).

3.4.3. *Scenarios*

The literature survey has shown that there is a gap in providing independent assessments of alternative technologies (centralized vs decentralized) and policy choices that can be essential for developing countries in a way that addresses their particular needs and constraints. In this study, five different scenarios are employed, namely: reference scenario (ref), grid extension scenario (grx), multiple-resource mix scenario (mix), renewable and intermittent resource target scenario (vRE) and improved efficiency scenario (Eff). The scenarios are developed as potential pathways of the future power supply that are selected by considering the country's context in terms of electricity access, future governmental direction, and technological change.

3.4.3.1. Reference scenario. The reference scenario (ref) is a policy-driven scenario which is a continuation of current policy, program, and target of the government. The GoE aims to achieve universal access to electricity nationwide by 2025 where 65% of households are expected to be supplied through grid-connection while the remaining 35% access electricity via off-grid technologies [25,27]. Therefore, the reference scenario considers both grid and off-grid technologies to be used for meeting the future demand. Centralized power plants will be contributing to the grid while decentralized technologies are connected to the off-grid system. As shown in Table 1, the country's absolute hydropower resource potential is estimated up to 45,000 MW, but the existing studies do not specifically define this potential at different sizes. In our model, we considered maximum installed capacity restrictions of 30 GW, 2 GW and 1 GW for large-scale, medium-scale and small-scale hydropower plants. Geothermal and utility-scale wind have maximum capacity restrictions of 10 GW and 20 GW respectively while solar PV and other technologies are not assumed to have any capacity restrictions. These constraints on installing new capacities consider the exploitable potential and have a very optimistic view with regards to future government direction & policy that support the use of particular technology, faster construction period and maximum capacity investment.

Grid access to household sector will be growing from 20.5% in 2018 to 65% in 2025 and off-grid access falling from 79.5% in 2018 to 35% in

2025. From 2025 onwards, grid and off-grid systems will meet their respective demands with 65%/35% household shares (see Table 5).

3.4.3.2. Grid extension scenario. The grid extension (grx) scenario is based on the reference scenario. The GoE aims to expand the grid from 65% by 2025 to 96% by 2030 and only 4% will be supplied via off-grid systems. Accordingly, this scenario will be used to test the feasibility of the above policy. It intends to expand the network to all households by eliminating the off-grid systems. This means that decentralized technologies will be excluded from alternative supply resources by constraining their installed capacities and output. In addition, no specified demand profile would be given to off-grid customers.

3.4.3.3. Multiple-resource mix scenario. The multiple-resource mix (mix) scenario is based on the grid extension scenario and tries to mitigate the hydropower vulnerability and supply insecurity by adding multiple renewable and thermal resource mixes. The model is forced to include certain technologies by constraining their minimum installed capacities and output as shown below.

- Biomass-1.5 GW by 2025 and 2 GW by 2030,
- Geothermal-2GW by 2025 and 5 GW by 2030,
- NGCC-1GW by 2030,
- NGOC-0.5 GW by 2030,
- Nuclear-0.5 GW by 2030 and 1.5 GW by 2035,
- PV, utility-1.5 GW by 2030 and 3 GW by 2035,
- Waste inciner. −0.1 GW by 2030,
- Wind, utility-1.5 GW by 2030 and 3 GW by 2035.

The operation year and minimum capacities of the power plants are assumed considering the speed of construction for each technology and future government direction.

3.4.3.4. Renewable and intermittent resource target scenario. The GoE has a plan to diversify the country's energy mix with wind, solar and geothermal resources to create a low-carbon future and complement the large base of hydro [65,66]. An ideal power system is one that delivers affordable, reliable, and socially and environmentally responsible clean energy. A 100% renewable based grid with high share of variable generation would fulfill the above criteria. Accordingly, the renewable and intermittent resource target (vRE) scenario is based on the grid extension scenario which investigates the feasibility of 100% renewable energy penetration (included hydropower, geothermal and biomass) and high penetrations of variable renewable generation (solar, wind). Unlike the other scenarios, large-hydro is allowed to be dispatched up to 40 GW. In this scenario, 100% renewable target is assumed to be achieved by 2030 out of which 20% is from solar and wind. In the remaining years, the share of variable generation is set to increase from 20% by 2030 to 30% by 2035 and up to 40% by 2040.

3.4.3.5. Improved efficiency scenario. The improved efficiency (Eff) scenario is also based on the grid extension scenario that is designed to increase the demand and supply side energy efficiency. It is a policy-driven scenario that seeks to increase the long-term power generation by implementing efficiency improvement policies on the electricity sector. Demand-side management (DSM) activities intend to obtain a load curve favourable to both customers and utility through peak shaving, valley filling, load shifting, strategic load reduction and growth, etc. [67,68]. Some of the mechanisms include standards and labeling, energy management and auditing, technology improvement, etc.

Table 5
Household electricity access and demand projection-ref scenario, 2018–2050 [64].

	2018	2025	2030	2040	2050
Grid					
Coverage (%)	20.5	65	65	65	65
Demand (TWh)	0.94	7.7	13.4	26.5	40.6
Off-grid					
Coverage (%	79.5	35	35	35	35
Demand (TWh)	3.6	4.1	7.2	14.2	21.8

These DSM measures and efficiency improvements are applied in the LEAP demand model. Progressive efficiency gain is assumed to be effective in the industry sector through energy audits and industrial efficiency measures. These can have the potential to save up to 30% of the electricity consumed in the industry sector by 2040. Improved lighting standards and DSM programs are expected to reduce the energy intensity of urban households by 1% every year. In addition, electric stove energy intensity is expected to achieve 0.5% per year. Similar assumptions are applied for other home appliances. Replacement of streetlights with efficient light emitting diodes (LEDs) with smart control can also reduce the electricity consumption by 60%.

In Ethiopia there are significant transmission and distribution (T&D) supply side losses affecting the reliability and quality of service provided to customers. The government is expected to implement network rehabilitation resulting in power quality and system efficiency improvements. Accordingly, this scenario assumes a total power loss reduction from the average historical loss of 23%–12.5% by 2030 and down to 9% by 2035.

4. Optimization results and analysis

In this section, the modelling results for each of the developed scenarios are presented and compared in terms of composition of electricity generation, energy resource diversity, economic cost and emissions.

4.1. Comparison of electricity generation and installed capacity mixes under various scenarios

Fig. 2 shows the electricity generation and corresponding installed capacities for the reference scenario. The electricity generation for the base year 2018 is 31 TWh. The predicted growth in electricity for the year 2030 is more than 300% with a total generation of 99 TWh. In the next two decades, the generation is expected to show rapid increase to meet the rising demand in different sectors. In 2050, the total generation is expected to reach about 255 TWh. Comparison of reference and other alternative scenarios (see Figs. 3–6) shows that the generation growth pattern is similar for all scenarios except for the improved efficiency scenario, in which the total generation is 6 TWh and 39 TWh lower in 2030 and 2050, respectively, due to energy savings at the demand and supply-sides (see Fig. 6).

Looking at the electricity generation mix, the transition from a hydro-dominated source to diversified sources is slow. In all the scenarios, the OSeMOSYS-Ethiopia model prioritizes hydropower due to the abundant resource availability, flexible properties, low capital, and fixed costs together with a negligible variable cost. Between the years 2018 and 2030, the penetration of hydro in the energy mix is mostly above 90% for all scenarios. However, in later years, the electricity supply share of hydro decreases to about 40% by 2050. CSP, natural gas combined cycle (NGCC) and wind energy are the major alternative sources used in ref, grx and Eff scenarios.

In the mix and vRE scenarios, solar PV and geothermal sources displace the CSP and NGCC technologies. In the ref scenario, small-scale wind turbine is the major distributed technology that is used to supply off-grid customers in addition to small-scale hydropower and rooftop solar PV. Small-scale wind turbines account 21%, 42% and 62% of the off-grid demand in the years 2030, 2040 and 2050 respectively while the remaining 44% and 22% are covered by small-scale hydropower in the years 2030 and 2040. By 2050, rooftop solar PVs gradually increase their share to 14% while small-scale hydropower decreases. The model

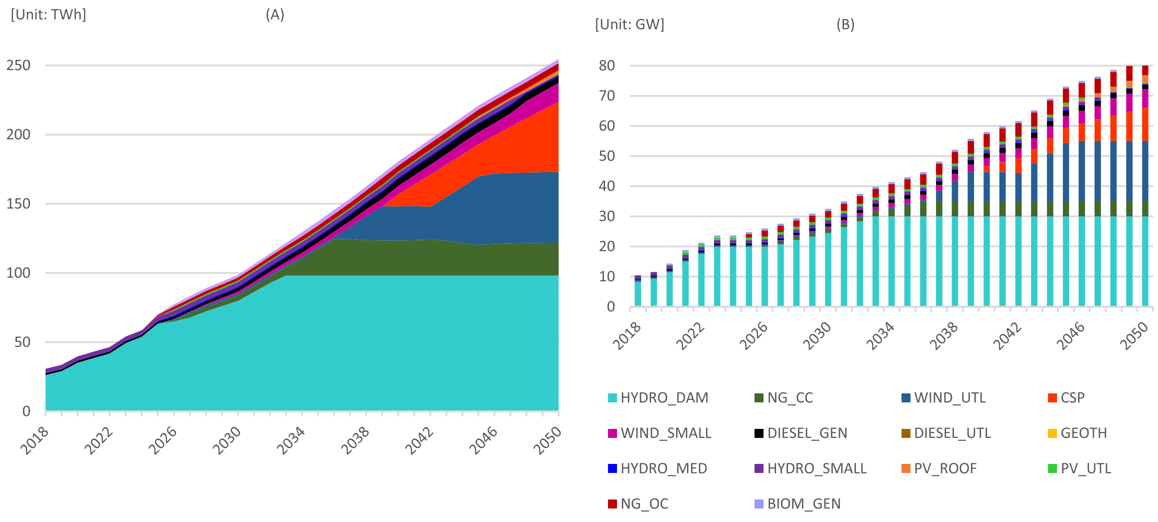

Fig. 2. Electricity generation mix (A) and installed capacity (B) under the reference scenario.

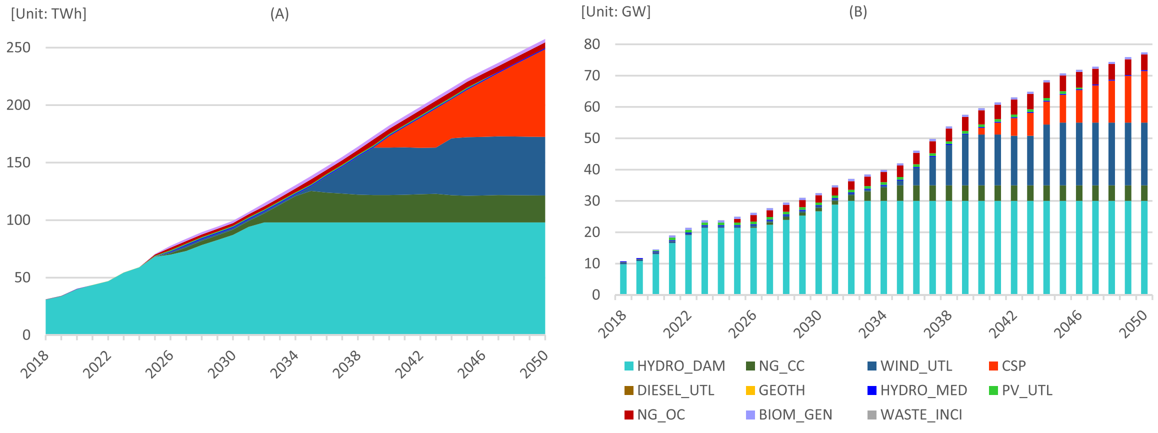

Fig. 3. Electricity generation mix (A) and installed capacity (B) under the grid extension scenario.

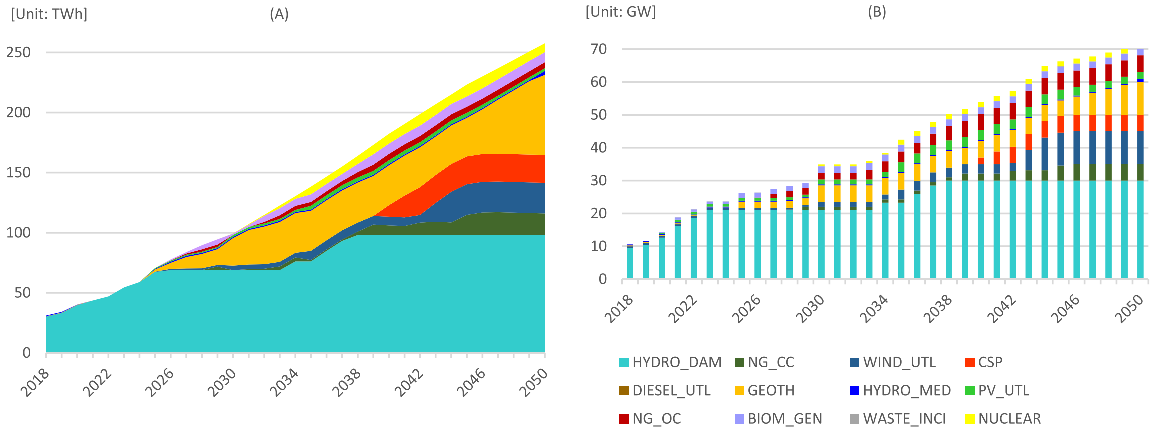

Fig. 4. Electricity generation mix (A) and installed capacity (B) under the multiple resource mix scenario.

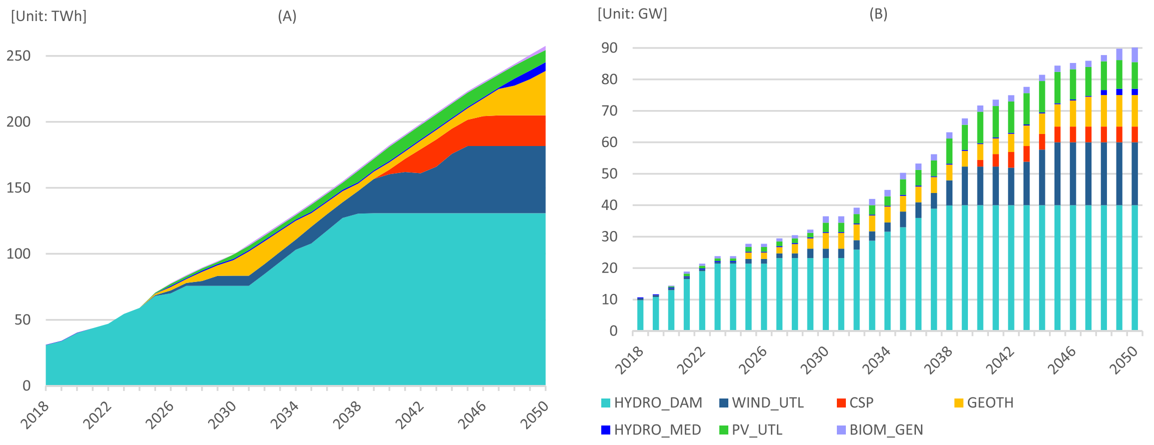

Fig. 5. Electricity generation mix (A) and installed capacity (B) under the intermittent resource target scenario.

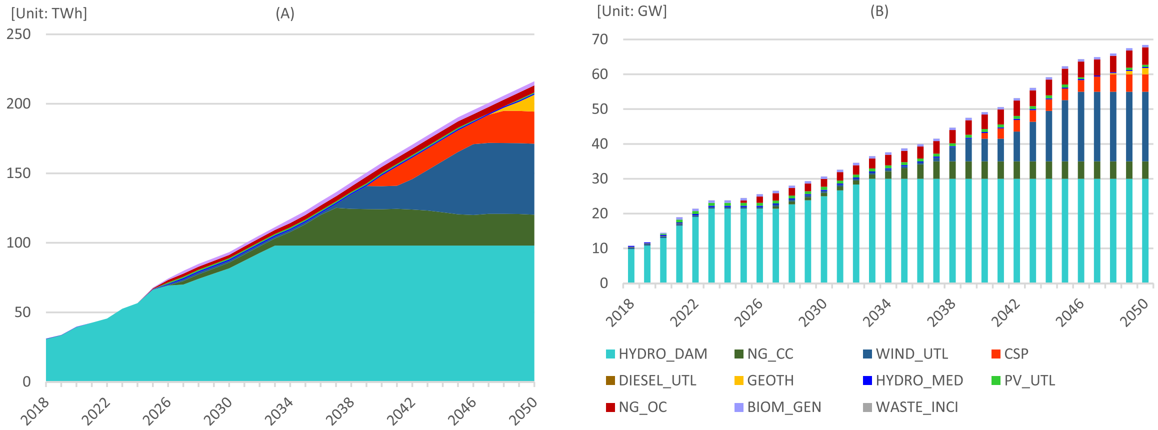

Fig. 6. Electricity generation mix (A) and installed capacity (B) under the improved efficiency scenario.

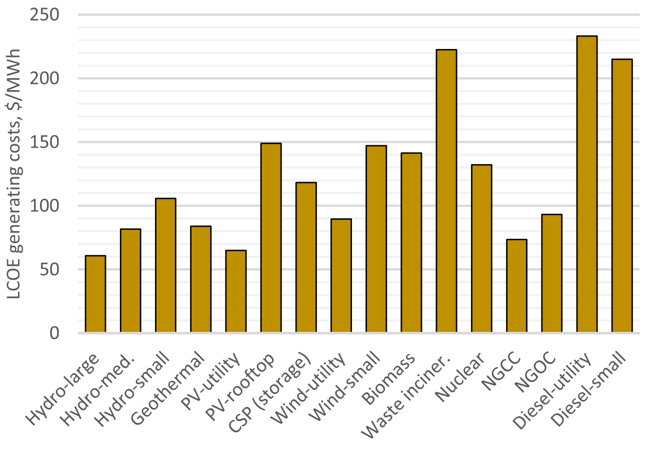

Fig. 7. Levelized cost of electricity (LCOE) for modelled technologies.

has also deployed distributed small-scale diesel generators to meet the remaining off-grid demand.

Nuclear power and waste incineration plants are not favored by the model in any of the scenarios except when it is forced to include minimum capacities in the mix scenario. Biomass is also not included in the energy mix due to high investment, fixed and variable costs. This is reflected in the levelized cost of electricity (LCOE) shown in Fig. 7 that measures the cost per unit of electricity supplied from various technologies. LCOE is lowest for hydro, utility PV, wind and natural gas, and highest for diesel, waste incinerator, biomass and nuclear.

Even though the LCOE primarily determines the ranking of technologies, it does not guarantee higher dispatchability in the model. This is demonstrated by the larger deployment of CSP over utility PV. This is because the objective of finding the minimum annual cost also includes capacity and energy balance constraints that depend on the availability and capacity factor (annual operation time) of the technology. CSP is equipped with a heat storage system to allow for electricity generation at night or when the sky is cloudy. This will offer additional flexibility and significantly increase the capacity factor in comparison to solar PV.

In 2018, more than 90% of the total installed capacity is accounted to hydropower (see Fig. 2-B). This proportion decreases to about 54% by 2040 and 37% by 2050 as a result of increased capacity mixes from other alternative resources. By 2050, the total installed capacities are expected to reach 91 GW, 83 GW, 77 GW, 72 GW and 68 GW for the scenarios vRE, ref, grx, mix and Eff respectively. Compared to the grx scenario, the Eff scenario has reduced the installed capacity by 9 GW. As discussed below in subsection 4.2., this capacity reduction has resulted in a significant financial saving by avoiding unnecessary future power plant investments.

4.2. Economic cost

Fig. 8 (subplot a) shows the total (MUSD) and unit discounted cost of

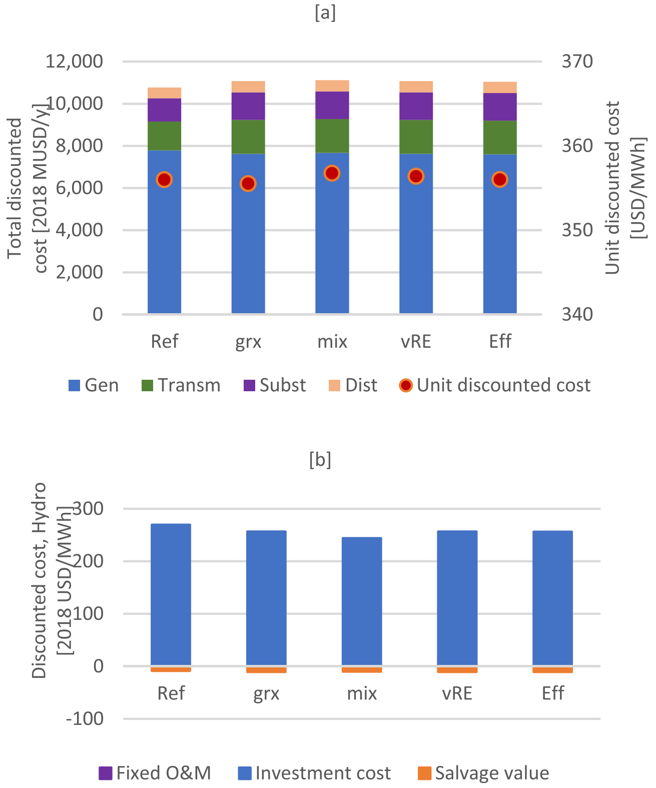

Fig. 8. Total and unit discounted costs (a) and discounted cost of hydropower technology (b).

energy (USD/MWh) for all the scenarios. The technology costs are discounted to the base year 2018 considering the period between 2018 and 2050. Total cost comprises of capital cost, fixed O&M cost and fuel cost for generation and T&D infrastructure. The generation system has the highest share of discounted cost accounting more than 69% in all the scenarios. Transmission, substation and distribution infrastructure come next accounting 14%, 12% & 5% share respectively. Comparing the total discounted costs over the time horizon (2018–2050) between the scenarios shows that the mix and vRE scenarios (about 37 BUSD each) are approximately 12% higher than the grx scenario (about 32 BUSD). The ref scenario (about 35 BUSD) is higher by about 9% while the Eff scenario (about 28 BUSD) is less by 11% compared to the grx scenario. The lower cost in the Eff scenario which is close to 4 BUSD is mainly as a result of loss reduction on the T&D network but also due to efficiency improvements on the supply and demand-sides.

Fig. 8 (subplot b) shows the discounted cost of energy from hydropower plant. Almost all of the discounted cost is due to capital investment with negligible fixed operation and maintenance (O&M) cost and salvage value. The difference among the discounted costs of the five scenarios is due to economy of scale of the capacity and produced energy from the corresponding hydropower plants.

4.3. *Emissions*

Given the higher use of renewable technologies to generate electricity in all scenarios, the greenhouse gas emissions resulted from generation technologies is quite low. Overall annual CO_2 emissions for the period between 2030 and 2050 is estimated to be about 15 kton/y. NO_x emissions are also negligible. These low-level CO_2 and NO_x emissions are mainly generated from the natural gas power plants.

4.4. *Model validation*

In order to verify that the OSeMOSYS-Ethiopia model is performing as expected, the energy balance of the output is checked according to the RES developed for Ethiopia (see Fig. 1). For instance, under the grx scenario in 2018, the produced electric energy from various technologies amounts to 31 TWh, transmission lines transported about 29 TWh and distribution lines about 24 TWh which equals the total exogenously given domestic demand. The reduction in value from generation to transmission and all the way to final demand is because of T&D losses. Such pattern is similar to all the remaining scenarios and years that confirms the model is executing correctly.

4.5. *Sensitivity analysis*

Sensitivity analysis has been carried out on the results found from the OSeMOSYS-Ethiopia model by varying the discount rates and capital cost of hydro. This will provide crucial information regarding the effects of changes in critical inputs and assumptions.

4.5.1. *Electricity generation sensitivity to different discount rates*

Four different discount rates: 5%, 7%, 12% and 15% are applied in the reference and alternative scenarios and compared with the 10%-rate used in the study. Such comparison of different discount rates is intended to show the investment, choice, and capacity-mix implications for power generation technologies. Table 6 presents the total discounted cost (MUSD/y, 2018) with the alternative discount rates applied to each of the considered scenarios. The results generally show that the total discounted cost decreases as discount rates are incremented from 5% to 15%. This is consistent with the theory that "the larger the discount rate, the lower the impact of the future extra costs" [69]. In addition, the OSeMOSYS discounted cost equations (refer Eqs. (1) and (2)) also justify this result. The effect of the discount rate on choice of technologies and energy-mix is shown in Fig. 9 for discount rates of 5% and 15%. The results show that the electricity generation mix vary according to the assumed discount rates. Natural gas, utility-scale wind technology and small-scale diesel generators are partly displaced by CSP, medium-scale hydropower plant and rooftop solar PVs (i.e. with higher investment cost) as the value of the discount rate decreases. On the contrary, the share of natural gas and distributed diesel generators increases by displacing rooftop solar PV and a small portion of hydro as the discount rate increases. This shows that higher discount rates favour expansion of natural gas power plants, and the country may be required to invest more on the technology.

4.5.2. *Electricity generation sensitivity to increased hydro capital cost*

Increased capital costs of hydro will change the shape of the energy-mix of the grid extension scenario as demonstrated in Fig. 10 with increments of 20% (i.e. 2400 USD/kW) and 50% (i.e. 3000 USD/kW). 20% increase in capital cost partly displaces hydro by raising the production level of NGCC. Further increase of capital cost results in reduction of the share of hydro that is replaced with other competitive sources such as natural gas, geothermal, wind and CSP. With 50% increase in capital cost, the model chooses not to allocate any additional new capacity to

Table 6
Sensitivity analysis of the total discounted cost with discount rates of 5%, 7%, 12% and 15% relative to 10%.

Total discounted cost [2018 MUSD/y]					
	5%	7%	10%	12%	15%
ref	14,543	12,516	10,927	10,085	8898
grx	12,605	12,188	11,086	10,265	9078
mix	12,605	12,188	11,125	10,329	9213
vRE	12,605	12,188	11,086	10,265	9078
Eff	12,564	12,149	11,050	10,232	9049

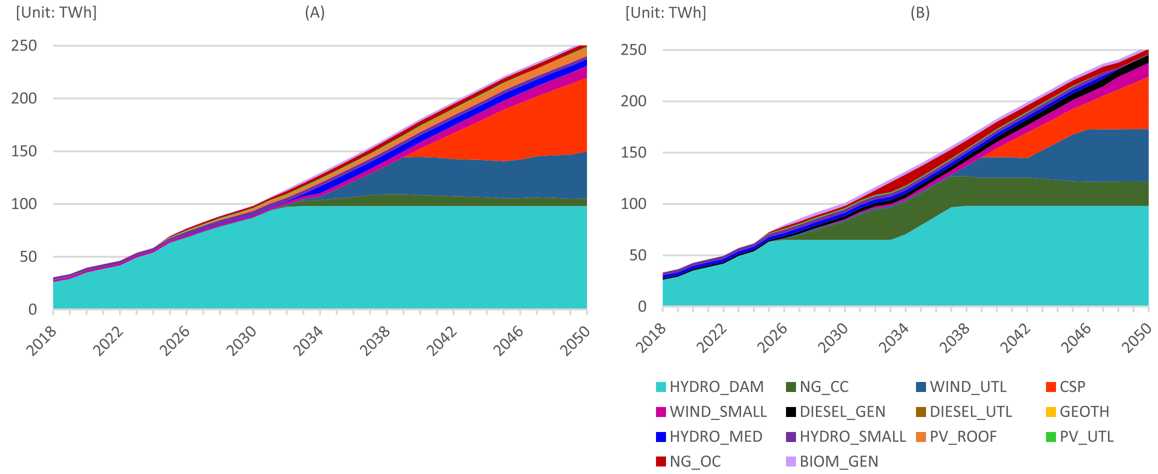

Fig. 9. Electricity generation mix under the reference scenario with a 5% (A) and 15% (B) discount rates.

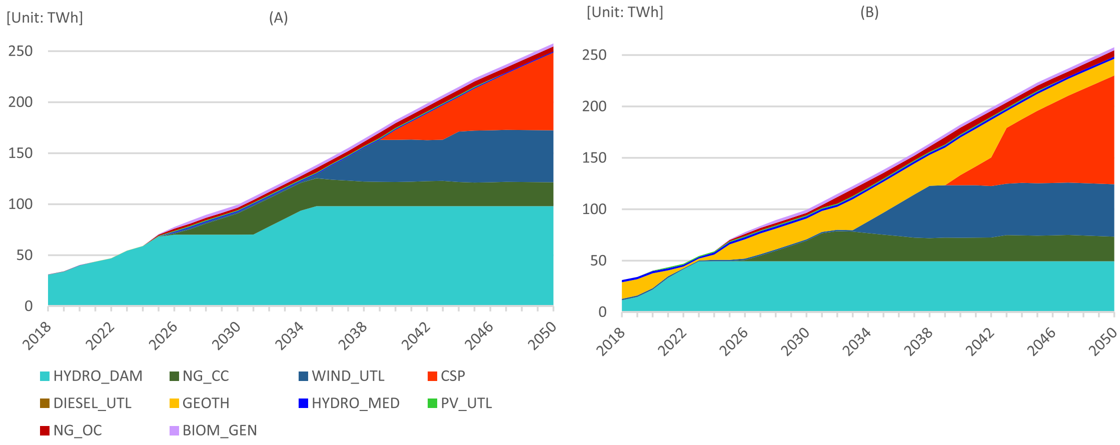

Fig. 10. Electricity generation mix under grid extension scenario with a capital cost increase by 20% (A) and 50% (B).

hydro, keeping only the residual capacity.

4.5.3. *Electricity generation sensitivity with no thermal storage of CSP*

Fig. 11 shows the model outputs of the electricity generation mix without considering the thermal storage of CSP. CSP is entirely excluded from the energy mix being replaced mainly by geothermal and some part by biomass. This shows that CSP without storage is not competitive as it is with storage mainly due to the unavailability of the technology in most periods of the year where there is no sunlight and no production.

5. Discussion

This paper identifies potential pathways of the Ethiopian power sector using an improved electricity system representation that considers unique features and characteristics of developing countries. Five scenarios were developed, namely, reference scenario (ref), grid extension scenario (grx), multiple resource mix (mix), renewable and intermittent resource target scenario (vRE) and improved efficiency scenario (Eff) to specifically address developing country conditions

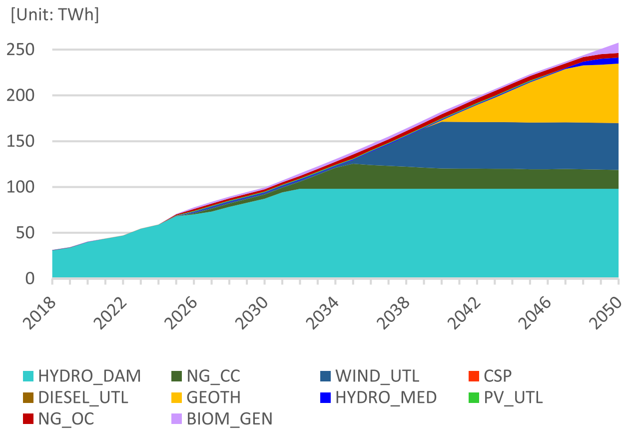

Fig. 11. Electricity generation mix under grid extension scenario with no thermal storage of CSP.

using Ethiopia as a case. They represent alternative technologies, policy choices and strategies addressing electricity access, security, sustainability, and affordability issues.

The study is applying an approach based on soft-linking of the LEAP and OSeMOSYS models. A somewhat similar approach has been used employing OSeMOSYS [1,6,7] and LEAP [4,7–9,21], but the methodology applied by the current work is different compared to the published literature. Due to the unique features and characteristics of energy and electricity systems of developing countries (as introduced in section 1), an improved representation of the electricity system is needed in both the supply and demand models. None of the published studies fully address these features.

In the present study, sector wise and technological representation of end-uses at a disaggregated level in terms of urban-rural divide, electrified and non-electrified areas, economic and/or technological transitions, informal sector and supply shortage features are included in the LEAP model. Moreover, the effects of unsustainable use of traditional energy sources, high population growth and modernization and urbanization are analyzed while making the projection of the energy demand. Few of these aspects are reflected in Ref. [21] that attempts to forecast the future demand of Ethiopia using the LEAP framework. However, that assessment was not complete in considering the rate-of-change in socio-economy, technological change, informal economy, supply shortage and future governmental direction. Further, the time horizon was constrained up to 2030.

Furthermore, with the intention of improving the low electricity access and poor performance of the power sector, the feasibility of including new technologies to the system is analyzed with centralized and decentralized technologies in the developed Ethiopian OSeMOSYS model. In connection with this point [10], considered off-grid technologies of the rooftop solar PV and mini-hydro to contribute to the universal electricity access targeted in Gambia by 2030, however, the authors did not further explore the feasibility of rural electrification through assessment of grid-extension and/or off-grid systems options.

Technology learning and investment cost reduction aspects were included in Refs. [10,12,14,40] and high system losses were represented in Refs. [4,7,10,14], while in the current study and model, all these, declining cost with technology learning, high system losses and future policy-driven energy savings, are included and thus accounted for. Further, in addition to taking into account reliable sources and estimations, the data used in the current study considers the context of the country in terms of resource availability, technology maturity, governmental plan, construction period and labor cost. As opposed to trying to use correct absolute costs, more attention is given to the relative costs of different technologies since the relative costs are determining the model's technology selection. These factors are important in improving the data quality which would have some impact on capacity, generation, technology mix, and costs.

Comparison of the findings with these of other studies is difficult due to differences in approaches and scenarios. Considering the first period, 2018–2030, and second period, 2031–2045, in accordance with in Refs. [14,17], the current study shows the electricity mix to be dominated by hydropower. The least-cost optimization model employed in Ref. [14] also found greater investment in hydro and wind power while solar PV, geothermal and combined gas plants only contributed to a limited extent. However, CSP was not selected by their model in the entire time horizon because of the unavailability of heat storage which led to zero production at night or when the sky is cloudy. The current study shows that CSP equipped with heat storage and declining cost with technology learning increases its competitiveness and leads to a higher contribution in the context of Ethiopia.

Compared to the present study [14], anticipated a much lower value of the annual electricity production. In the best-case scenario, the electricity production grew from 11 TWh in 2015 to 170 TWh in 2045. The main reason for the difference is assumption of annual growth in electricity demand for various sectors. The average growth rate of electricity demand by sector (2012–2030) was used to estimate electricity demand till 2045. The present study draws a feasible assumption of reducing gross domestic product (GDP) growth rates of 9%, 7% and 4% over the years 2018–2030, 2031–2040 and 2041–2050 respectively. Similar to Ref. [17], it also uses multi-variable regression and disaggregated model that represents the useful energy demand in all sectors. Apart from demand forecasting, this study provides a way of exploring different possible futures that can show the maximum expected rise in demand under different drivers and the best-case energy saving opportunities. Cooking and baking appliances (injera, bread, etc.) that are the major power consuming loads in Ethiopia are represented in the energy use by households. Moreover, latest developments and governmental plans are also considered in estimating the capacity and operation period of future industrial parks, export plans and railway lines.

The selection of a certain temporal resolution strongly influences the resulting long-term generation and capacity-mixes, particularly with the increasing penetration of vRE [70–77]. In our case, increasing the number of time slices beyond six (dry & rainy season with day, night, peak hours) would likely result in higher vRE deployment of the generation and capacity-mix outputs, specifically under the vRE scenario, mainly since solar PV likely would have a significantly higher share due to a better capture of diurnal matching between solar generation and demand [76]. This could in turn greatly improve the contribution of vRE capacity investment to firm capacity, which in turn would lead to reduction of peak-capacity investment.

However, increasing a model's resolution of time requires detailed and quality datasets which are not readily available in developing countries like Ethiopia. Therefore, the representation of vRE impact in the generation-mix needs further study over time, with the advancement of data availability, scope and quality of models. In addition, the model and analysis consider a spatial scope of a single-region and did not consider the disaggregation of the country based on socio-economic status (level of urbanization, size, economic structure, human resources, etc.), resource availability, political challenges, or climate conditions by region. A detailed disaggregated/multi-regional modelling analysis may provide better insight into sector wise regional energy assessment with regard to electricity access, penetration of renewable energies, total system costs and identification of cost-optimal locations for renewable and grid development considering the network bottlenecks [78].

6. Conclusion and policy implications

A soft-linking approach of coupling two modelling frameworks has been adopted in this study while considering the unique features and context of developing countries. Unique features of traditional energy consumption, informal economy, urban-rural divide, low electrification, supply shortage, data and skill needs are reflected while developing the energy supply and demand models that resulted in better electricity system representation. The open-source long-term energy modelling framework - OSeMOSYS is used to analyze the long-term capacity expansion of the electricity supply system while the future energy demand is analyzed in the LEAP framework. The results may provide useful information to policymakers in developing effective policies that address their particular needs and also support the technological and efficiency innovations in the power sector.

In all the assumed scenarios, the model always prioritizes hydropower and utility-scale wind energy attributed to abundant resource availability, complementary nature to tackle variation [79] and low economic cost of the technologies compared to others. This results in a slow transition of the historically hydro-dominated source into a more diversified energy resource mix. Other alternative technologies used in the energy mix in most scenarios are natural gas combined cycle, concentrated solar power, wind, and geothermal. Technologies such as nuclear, biomass and waste incineration plants are not included in most scenarios unless they are forcefully policy-driven. This is associated with higher economic cost of the technologies and cost of imported fuel. The results show that renewable technologies are more competitive and favourable in the context of Ethiopia. Moreover, the higher use of renewable technologies to generate electricity maintained the country's greenhouse gas emission at a low level.

In the reference scenario, centralized technologies of hydropower, NGCC, CSP and wind are mainly utilized to meet the grid-demand while off-grid demand is supplied through distributed technologies of small-scale wind turbine, small-scale hydro, and rooftop solar PV. The rapidly declining cost of PV and wind technologies can potentially stimulate both grid and off-grid investments. By 2050, the improved efficiency scenario is expected to reduce the installed capacity by 9 GW which translates into approximately 11% total discounted cost saving over the entire time horizon. This economic benefit evidently made the Eff scenario the most desirable compared to the other scenarios.

The sensitivity analysis carried out by taking alternative discount rates of 5%, 7%, 12% and 15% show that the total discounted cost and electricity generation mix vary according to the assumed discount rates. In line with [69], the sensitivity results in general show that higher discount rates favour expansion of natural gas power plants while lower discount rates lead to increased utilization of CSP, medium-scale hydropower plant and rooftop solar PVs.

Each of the assessed scenarios and policy options has serious implications on major aspects such as technology and capacity choice, investment cost, GHG emission, universal access, and supply security. Given that the electricity access of Ethiopia is currently at an early stage and there is a long way ahead for the power sector to expand and improve, policymakers can get useful information to evaluate and decide on how the electricity sector might evolve in the future.

The specific policy implications in view of the followed methodology and results obtained for the considered scenarios would be as discussed below.

The results show that Ethiopia needs to invest in renewable energy resources. Hydropower will continue to play a key role in the future electricity supply with the addition of alternative resources like wind, natural gas, geothermal, solar PV and CSP. Given the presence of a large hydropower capacity in the supply mix and its exposure to climate change, proper measures to enhance resilience to dry years are an important focus area for the energy policy in a hydro dominated country like Ethiopia. In this regard, the diversification of the power generation mix with alternative resources, particularly fuel-based dispatchable generation (e.g. natural gas) can enhance the system's resiliency to the adverse impacts of climate change. However, additional measures are also needed to effectively manage the dry periods. These include: 1) electric power exchange with neighbouring countries (i.e. adjusting export/import), 2) demand response management (i.e. change in end-user electricity consumption to help balance the generation), 3) redesigning infrastructure (e.g. enhance reservoir capacity).

CSP and natural gas are new technologies to the country that need local learning and increased number of skilled workforces. The country actually needs to build its own army of competence and capability in all renewable energy resources to successfully deploy and manage the future technologies. In addition, given the use of large-scale renewable resources, policymakers are expected to allocate adequate land for possible development of solar PVs, wind and CSP farms. Furthermore, vast expansion of the generation system and integration of variable energy resources of solar and wind to the grid will likely bring big challenges for energy providers and system operators in Ethiopia. Therefore, the T&D grid capacity should improve in parallel with the generation expansion.

Our analysis shows that the implementation of improved efficiency in the electricity system is expected to have important roles in future energy investment pathways. Accordingly, policymakers are suggested to develop effective policies that support the technological and efficiency innovations in the power sector. It is also worth mentioning that the followed approaches and developed supply-demand models can represent and highly relate to other less developed and developing countries outside Ethiopia where the model outputs and policy implications can indirectly be used to explore national and regional power sector development by making small changes and improvements.

Authorship contributions

Dawit Habtu Gebremeskel: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft, Visualization, **Erik O. Ahlgren**: Supervision, Writing – review & editing, **Getachew Bekele Beyene**: Supervision, Writing – review & editing.

Declaration of competing interest

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

Data availability

The authors do not have permission to share data.

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Appendix

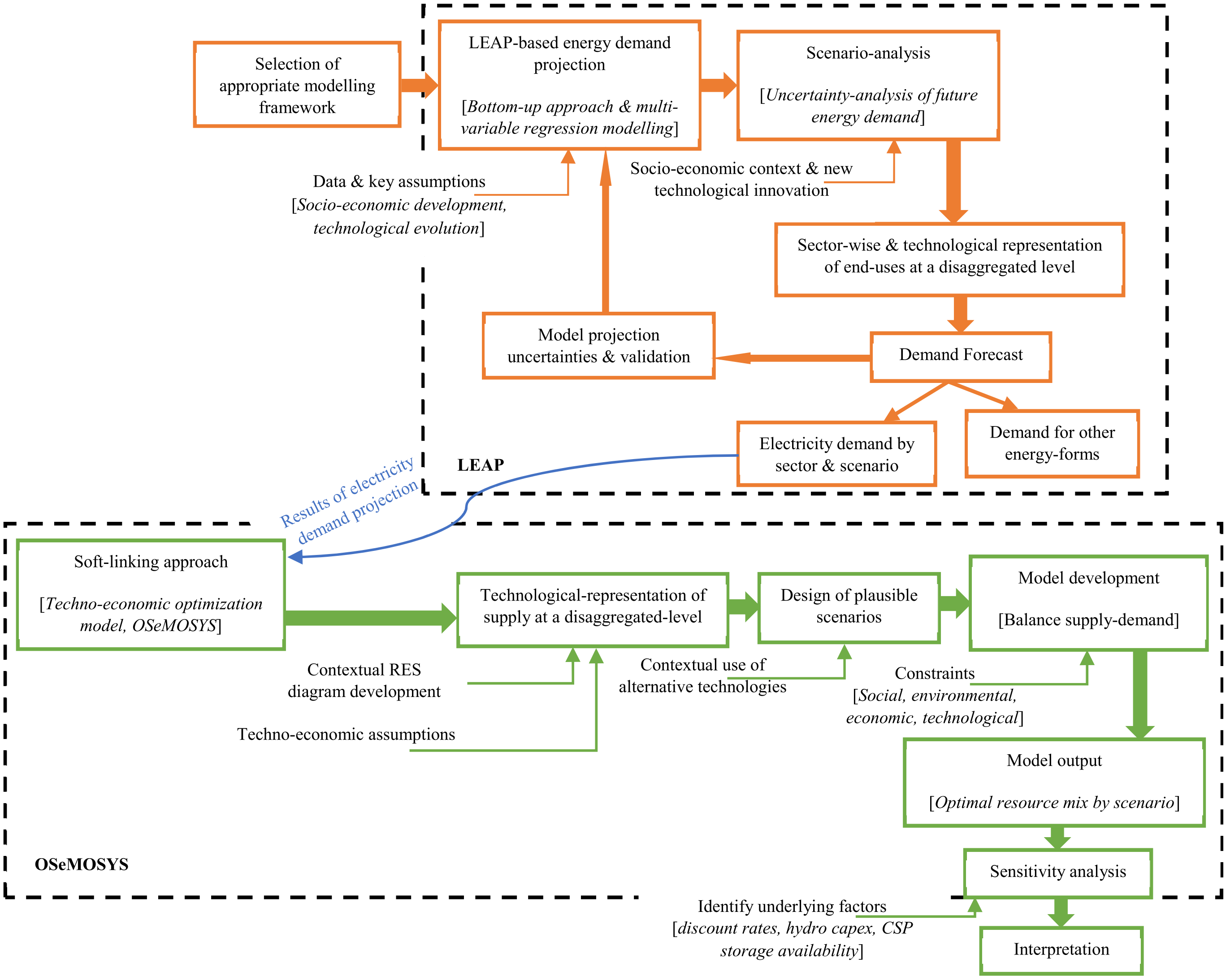

Fig. A1. Overview of the methodology used to explore the potential pathways of the future power supply and demand evolution in Ethiopia.

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