Addis Ababa University

LONG-TERM MODELING AND ANALYSIS OF OPTIMAL PATHWAYS AND SCENARIO ALTERNATIVES FOR THE ETHIOPIAN POWER SECTOR

Doctoral Dissertation of:

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May 2023.

To the loving memory of my mother.

Declaration

This PhD Dissertation is a presentation of my own work and that any material used from other sources has been clearly identified and properly acknowledged and cited.

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Abstract

The United Nations launched a new set of Sustainable Development Goals (SDGs) to guide the world during the next fifteen-year period from 2015 to 2030. With the "Goal 7-Ensure access to affordable, reliable, sustainable and modern energy for all", the agenda 2030 recognizes the importance of sustainability, security, and affordability of energy supply to all countries but in particular for developing countries. And the greatest increase in demand for energy is envisaged to come from developing countries where, with rapid urbanization, large-scale electricity generation with a reliable and optimum supply will be required.

To achieve the SDG7 and ensure energy security, countries are required to develop sustainable and appropriate approaches to electricity planning. In this regard, policymakers increasingly rely on techno-economic assessments both to inform policy development and to help set the right national targets. Accordingly, the modeling and investigation of different optimal pathways and possible future scenarios has become a critical planning tool in the power sector. This type of assessment is currently lacking in developing countries, specifically in Ethiopia.

Consequently, in line with the global and local needs, this dissertation deals with strategies and practices for sustainable energy system development in Ethiopia. It focuses on long-term electric power security to make timely investments on various energy resources and supply energy matched with the economic developments and environmental needs of the country. In this framework, the goal is pursued by setting the following three specific objectives: *(1) To review and evaluate energy development, power sector reforms, policies and resource adequacy in Ethiopia*. This objective is pursued to assess and evaluate the effectiveness of existing reforms and policies in Ethiopia in terms of meeting the country's rising demand for energy by breaking the "business-as-usual" trajectory of the past. An analytical method to calculate resource planning indices such as reserve margin and expected unserved energy is used. The results indicate that the near-future generation reserve is not adequate to supply the increasing demand resulting mainly from expansion of electricity access, development of industrial parks, extensive expansion of railway network, extensive agriculture irrigation schemes, new sugar factories and export plan to East African Power Pool (EAPP) countries.

The second specific objective is *(2) To assess the fundamental dynamics, variables and policies that characterize the energy development and determine the evolution of electricity demand.* The scientific literature reveals a weak understanding of the inherent characteristics and

specific features of energy systems in developing countries. As a result, this specific objective is pursued by knowing the trend and capturing the relationship between demand and other independent socio-economic and technological variables. Comparative overview of various existing modeling frameworks is done in terms of several criteria, particularly their applicability to developing countries. Appropriate modelling frameworks are identified for assessing and projecting the long-term energy use in a systematic manner within the context of developing countries. A better system representation and applicable alternative policy scenarios are also developed by considering the unique characteristics of energy systems in developing countries (unsustainable use of traditional energy sources, high population growth, modernization and urbanization, low electricity access, supply shortage, high system losses, informal economy, etc.).

Extensive and detailed dataset is used to simulate the alternative policy scenarios. The pathways represented by the scenarios can show the maximum expected rise in demand under different drivers and the best-case energy saving opportunities. The current methodologies employed for long-term energy demand projection are then evaluated, particularly focusing on the electricity demand. The result of the policy scenarios shows that while the application of energy efficiency policies and measures would only have a minor impact on the energy demand, their impact on the electricity demand is large, and that the application of such policies is a very important measure to combat supply-demand mismatch causing power shortages and black-outs. The projection results are compared with previous studies and reasons for the deviations and strength of the followed approaches are discussed.

The last objective is *(3) To identify the best power generation and capacity mixes to meet future electricity demands subject to various technical, economic, and environmental constraints.* This is pursued by developing a soft-linked OSeMOSYS and LEAP model to determine the lowest cost electricity generation and capacity mixes to meet long-term electricity demands subject to certain policy scenarios that may impose technical constraints, economic realities and environmental targets. The model has various data requirement that describe the current and historical installed capacities, efficiencies, costs (capital, operating and maintenance, fuel costs), capacity factors, losses, expansion plans, etc.

From the literature survey, it is observed that there is a gap in providing independent assessments of alternative technologies and policy choices that can be essential for developing countries in a way that addresses their particular needs and constraints. Thereby, the model

explores the feasibility of including new technologies to the existing system. This includes assessments of centralized and decentralized methods of electricity supply. Novelties are introduced in terms of better system representation on reference energy system diagram, development of appropriate model and identification of relevant scenarios considering the context of the country and applicability to developing nations. Moreover, sensitivity analysis is carried out to study the effect of critical assumptions and varying parameters on the results.

Five policy scenarios are employed (reference-ref, grid extension-grx, multiple resource mix-mix, renewable and intermittent resource target-vRE, improved efficiency-Eff) to explore different possible futures and balance the long-term electricity needs and resources. The improved efficiency scenario is the most desirable compared to the other scenarios because of lower installed capacity requirements and economic benefits. Attributed to lower investment costs and abundant resource availability, the results show that renewable technologies are more competitive and favorable in the context of Ethiopia. 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.

Keywords: Scenarios, Energy systems modelling, Energy-mix, Energy demand forecasting, Electricity, Developing country, Ethiopia, LEAP, OSeMOSYS.

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List of Abbreviations

BAU	Business-as-Usual
CO_2	Carbon dioxide
CSP	Concentrated Solar Power
DG	Distributed Generation
DP	Dynamic Programming
DSM	Demand Side Management
EAPP	East African Power Pool
EEA	Ethiopian Energy Authority
EEP	Ethiopian Electric Power
EEU	Ethiopian Electric Utility
E&U	Electrification and Urbanization
FDRE	Federal Democratic Republic of Ethiopia
GDP	Gross Domestic Product
GERD	Grand Ethiopian Renaissance Dam
GHG	Greenhouse Gas
GoE	Government of Ethiopia
grx	Grid Extension
GTP	Growth and Transformation Plan
HEG	High Economic Growth
HH	Household
HV	High Voltage
ICS	Interconnected System
IEE	Improved Energy Efficiency
IPP	Independent Power Producer
LEAP	Long-range Energy Alternatives Planning
LED	Light Emitting Diode
LP	Linear Programming
LV	Low Voltage
MARKAL	MARKet Allocation
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
MIP	Mixed Integer Programming
mix	Multiple Resource Mix
MoWIE	Ministry of Water, Irrigation and Energy
NDC	Nationally Determined Contribution
NEP	National Electrification Plan
NGCC	Natural Gas Combined Cycle
NGOC	Natural Gas Open Cycle
O&M	Operation and Maintenance
OSeMOSYS	Open-Source Energy Modelling System
PPP	Public Private Partnership
PV	Photovoltaic
RES	Reference Energy System
SCS	Self-Contained System

SDG	Sustainable Development Goal
T&D	Transmission and Distribution
TIMES	The Integrated MARKAL-EFOM System
UEAP	Universal Electricity Access
VRE	Variable Renewable Energy

List of Units

Power

kW	Kilowatt (1 watt x 10^3)
MW	Megawatt (1 watt x 10^6)
GW	Gigawatt (1 watt x 10^9)
TW	Terawatt (1 watt x 10^{12})

Energy

MJ	Megajoule (1 joule x 10^6)
GJ	Gigajoule (1 joule x 10^9)
TJ	Terajoule (1 joule x 10^{12})
PJ	Petajoule (1 joule x 10^{15})
Mtoe	Million tonnes of oil equivalent
MBtu	Million British thermal units
kWh	Kilowatt-hour
MWh	Megawatt-hour
GWh	Gigawatt-hour
TWh	Terawatt-hour

Mass

Kg	Kilogram

Emissions

$MtCO_{2e}$	Megatonnes of carbon-dioxide equivalent (amount of a GHG whose atmospheric impact has been standardized to that of one unit mass of carbon dioxide (CO_2), based on the global warming potential of the gas)
$kgCO_{2e}$	Kilograms of carbon-dioxide equivalent
kg CO_{2e}/kWh	Kilograms of carbon-dioxide per kilowatt-hour

Monetary

ETB	Ethiopian Birr
USD	US dollar
USD million	1 US dollar x 10^6
USD billion	1 US dollar x 10^9
USD/kW	US dollars per kilowatt
USD/MWh	US dollars per megawatt-hour

Other units

L	Liter
m^3	Cubic meter
m/s	Meter per second
kV	Kilo Volt
$kWh/m^2/day$	Kilowatt-hour per meter square per day
Kg/HH	Kilogram per household
kWh/HH	Kilowatt-hour per household
Kg/MWh	Kilogram per Megwatt-hour
Liter/HH	Liter per household

Unit conversion factors for energy

		Multiplier to convert to:		
		PJ	GJ	Mtoe
Convert from:	TWh	3.6	$3.6x10^{6}$	$8.59845x10^{-2}$
	GWh	$3.6x10^{-3}$	3600	$8.59845x10^{-5}$

Currency conversion

Exchange rate (2020 annual average)	1 US dollar (USD) equals:
Ethiopian Birr (ETB)	34.9505

Nomenclature

Chapter 3: Review of power sector in Ethiopia

α_i	*Capacity credit of power plant i (considered as firm).*
C_{pi}	*Installed capacity of power plant i.*
D_t	*Demand at hour t.*
D_p	*Annual Peak Power Demand*
D_i	*Annual Energy Demand for the year i.*
ENS	*Energy Not Supplied*
$Firm\ Capacity$	*Fraction of variable renewable energy capacity that is guaranteed to meet demand.*
G_i	*Annual Generated Energy of all existing units in the year i.*
PRM	*Planning Reserve Margin (represents the surplus generating capability above the sustained-peak annual demand).*
RA	*Resource Adequacy (ability of a utility's reliable capacity resource to meet the customers' energy demand at all hours).*
S_t	*Avaialable supply at hour t.*

Chapter 4: Long-term evolution of energy and electricity demand forecasting

TED_t	*Total country demand forecast for the year t.*
HHE_t	*Household demand forecast for the year t.*
$HVIE_t$	*High voltage industry demand forecast for the year t.*
$LVIE_t$	*Low voltage industry demand forecast for the year t.*
CME_t	*Commercial demand forecast for the year t.*
AGE_t	*Agriculture demand forecast for the year t.*
TRE_t	*Transport demand forecast for the year t.*
PBE_t	*Public demand forecast for the year t.*
$EXPE_t$	*Export demand forecast for the year t.*
EL_t	*Total transmission and distribution losses in year t.*
TL_t	*Transmission and distribution loss target in year t.*
$FTED_t$	*Final total country demand in year t.*
D_t	*Energy demand in year t (dependent variable).*
D_{t-1}	*Energy demand in previous year* $t-1$.
$B_0, B_1, \dots B_{n+1}$	*Regression weights that are computed in a way that minimizes the sum of squared deviations.*
$X_{1t}, X_{2t}, \dots X_{nt}$	*Independent variables that potentially impact demand in the specific customer group (GDP, historical consumption, per capita income, number of customers, number of households, etc.).*
NC_t	*Number of customers in year t.*
PI_t	*Per capita income in year t.*
R^2	*Coefficient of multiple determination.*
p_value	*Statistical significance.*

Chapter 5: Long-term modeling and analyses of optimum generation scenarios

Indexes used in equations (Sets)

y	$Year$
r	$Region$
f	$Fuel$
t	$Technology$
e	$Emission$
m	$Mode\ of\ operation$
l	$Timeslice: a\ fraction\ of\ the\ year\ with\ specific\ load\ chracteristics$
I_s	$Season$
I_d	$Day\ type$
I_h	$Daily\ time\ bracket: a\ time\ span\ within\ one\ specific\ day$

Parameters

$\boldsymbol{AccumulatedAnnualDemand}_{\boldsymbol{y,r,f}}$ *[PJ] --- Accumulated Demand for a certain commodity in one specific year.*

$\boldsymbol{AnnualEmissionLimit}_{\boldsymbol{y,r,e}}$ *[Mton] --- Annual upper limit for a specific emission generated in the whole modelled region.*

$\boldsymbol{AnnualExogenousEmission}_{\boldsymbol{y,r,e}}$ *[kton] --- Accounts for additional annual emissions on top of those computed endogenously by the model.*

$\boldsymbol{AvailabilityFactor}_{\boldsymbol{y,t,r}}$ *[-] --- One minus the fraction of the year during which planned maintenance takes place.*

$\boldsymbol{CapacityFactor}_{\boldsymbol{y,t,r}}$ *[-] --- The ratio of available maximum capacity to the design capacity.*

$\boldsymbol{CapacityToActivityUnit}_{\boldsymbol{t,r}}$ *[-] --- Relates the energy that would be produced when one unit of capacity is fully used in one year.*

$\boldsymbol{CapitalCost}_{\boldsymbol{y,t,r}}$ *[Million \$/GW] --- Capital investment cost of a technology, per unit of capacity.*

$\boldsymbol{DaysInDayType}_{\boldsymbol{y,I_s,I_d}}$ *[Days] --- Number of days for each day type, within one week (natural number, ranging from 1 to 7).*

$\boldsymbol{DaySplit}_{\boldsymbol{y,I_h}}$ *[-] --- Length of one DailyTimeBracket in one specific day as a fraction of the year.*

$\boldsymbol{DiscountRate}_{\boldsymbol{r}}$ *[-] --- Region-specific rate of return used to discount future cash flows back to the present value, expressed in decimals.*

$\boldsymbol{EmissionActivityRatio}_{\boldsymbol{y,t,r,e,m}}$ *[Mton/PJ] --- Emission factor of a technology per unit of activity, per mode of operation.*

$\boldsymbol{EmissionsPenalty}_{\boldsymbol{y,r,e}}$ *[Million \$/Mton] --- Penalty per unit of emission.*

$\boldsymbol{FixedCost}_{\boldsymbol{y,t,r}}$ *[Million \$/GW] --- Fixed O&M cost of a technology per unit of capacity.*

$\boldsymbol{InputActivityRatio}_{\boldsymbol{y,t,r,f,m}}$ *[-] --- Rate of input of a fuel by a technology, as a ratio of the rate of activity.*

$\boldsymbol{OperationalLife}_{\boldsymbol{t,r}}$ *[Years] --- Useful lifetime of a technology, expressed in years.*

$\boldsymbol{OutputActivityRatio}_{\boldsymbol{y,t,r,f,m}}$ *[-] --- The ratio of output of fuel as a ratio to the rate of activity in which a technology is operating.*

$\boldsymbol{REMinProductionTarget}_{\boldsymbol{y,r}}$ *[PJ] --- Minimum ratio of all renewable commodities tagged in the RETagCommodity parameter, to be produced by the technologies tagged with the RETechnology parameter.*

$\boldsymbol{ReserveMargin}_{\boldsymbol{y,r}}$ *[-] --- Minimum level of the reserve margin required to be provided for all the tagged commodities, by the tagged technologies.*

ReserveMarginTagTechnology$_{y,t,r}$ *[-] --- Binary parameter tagging the technologies that are allowed to contribute to the reserve margin.*
ResidualCapacity$_{y,t,r}$ *[GW] --- Capacity left over from a period prior to the modelling period.*
RETagFuel$_{y,r,f}$ *[-] --- Binary parameter tagging the fuels to which the renewable target applies to.*
RETagTechnology$_{y,t,r}$ *[-] --- Binary parameter tagging the renewable technologies that must contribute to reaching the indicated minimum renewable production target.*
SpecifiedAnnualDemand$_{y,r,f}$ *[PJ] --- Total specified demand for the year, linked to a specific 'time of use' during the year.*
SpecifiedDemandProfile$_{y,r,f,l}$ *[-] --- Annual fraction of energy-service or commodity demand that is required in each time slice.*
TotalAnnualMaxCapacity$_{y,t,r}$ *[GW] --- Total maximum existing (residual plus cumulatively installed) capacity allowed for a technology in s specified year.*
TotalAnnualMaxCapacityInvestment$_{y,t,r}$ *[GW] --- Maximum capacity of a technology expressed in power units.*
TotalAnnualMinCapacity$_{y,t,r}$ *[GW] --- Total minimum existing (residual plus cumulatively installed) capacity allowed for a technology in a specified year.*
TotalAnnualMinCapacityInvestment$_{y,t,r}$ *[GW] --- Minimum capacity of a technology expressed in power units.*
TotalTechnologyAnnualActivityLowerLimit$_{y,t,r}$ *[PJ] --- Total minimum level of activity allowed for a technology in one year.*
TotalTechnologyAnnualActivityUpperLimit$_{y,t,r}$ *[PJ] --- Total maximum level of activity allowed for a technology in one year.*
TotalTechnologyModelPeriodActivityLowerLimit$_{t}$ *[PJ] --- Total minimum level of activity allowed for a technology in the entire modelled period.*
TotalTechnologyModelPeriodActivityUpperLimit$_{t}$ *[PJ] --- Total maximum level of activity allowed for a technology in the entire modelled period.*
TradeRoute$_{y,r,f}$ *[-] --- Binary parameter defining the links between region r and region rr, to enable or disable trading of a specific commodity.*
VariableCost$_{y,t,r,m}$ *[Million $/PJ] --- Cost of a technology for a given mode of operation (Variable O&M cost), per unit of activity.*
YearSplit$_{y,l_s}$ *[-] --- Duration of a modelled time slice expressed as a fraction of the year.*

Decision Variables

AccumulatedNewCapacity	*[GW]*
AnnualEmissions	*[Kton]*
AnnualFixedOperatingCost	*[-]*
AnnualTechnologyEmission	*[-]*
AnnualTechnologyEmissionByMode	*[Kton]*
AnnualTechnologyEmissionPenaltyByEmission	*[Million $/Kton]*
AnnualTechnologyEmissionsPenalty	*[Million $/Kton]*
AnnualVariableOperatingCost	*[-]*
CapitalInvestment	*[Million USD]*
Demand	*[PJ]*
DiscountedCapitalInvestment	*[Million USD]*
DiscountedOperatingCost	*[-]*
DiscountedSalvageValue	*[Million USD]*

$DiscountedTechnologyEmissionsPenalty$	*[-]*
$ModelPeriodEmissions$	*[Kton]*
$NewCapacity$	*[GW]*
$OperatingCost$	*[Million USD]*
$ProductionAnnual$	*[-]*
$ProductionByTechnology$	*[PJ]*
$ProductionByTechnologyAnnual$	*[PJ]*
$RateOfProductionByTechnology$	*[-]*
$RateOfTotalActivity$	*[-]*
$RateOfUseByTechnology$	*[-]*
$RETotalProductionOfTargetFuelAnnual$	*[-]*
$SalvageValue$	*[-]*
$TotalAnnualTechnologyActivityByMode$	*[-]*
$TotalCapacityAnnual$	*[GW]*
$TotalCapacityInReserveMargin$	*[-]*
$TotalDiscountedCost$	*[-]*
$TotalDiscountedCostByTechnology$	*[-]*
$TotalREProductionAnnual$	*[-]*
$TotalTechnologyAnnualActivity$	*[PJ]*
$Trade$	*[-]*
$TradeAnnual$	*[-]*
$UseAnnual$	*[-]*
$UseByTechnology$	*[-]*
$UseByTechnologyAnnual$	*[-]*
$VariableOperatingCost$	*[Million USD]*

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1. Introduction

The United Nations Conference on Sustainable Development- or Rio+20-took place in Rio de Janeiro, Brazil in June 2012. In the key conclusion of the Summit, the world's governments called for a new set of Sustainable Development Goals (SDGs) to guide the world during the next fifteen-year period from 2015 to 2030. A final document was adopted at the UN Sustainable Development Summit in Newyork in September 2015. The document, called "Transforming our world: the 2030 Agenda for Sustainable Development", set the official launch of the 17 SDGs. With the "Goal 7- Ensure access to affordable, reliable, sustainable and modern energy for all", the agenda 2030 recognizes the evident relation between energy and sustainable development. Energy is crucial for achieving almost all of the SDGs, from its role in the eradication of poverty through advancements in health, education, water supply, and industrialization, to combating climate change. By 2030, the goal aims to substantially increase the share of renewable energy in the global energy mix and ensure universal electricity access in developing countries [UN General Assembly, 2015].

Indeed, significant progress have been made in recent years with an increasing level of global electrification. However, the gap between the promise of energy for all and the fact that almost one billion people still do not have access to electricity is a serious disparity. The country-by-country assessment in many studies shows that the sub-Saharan African countries have the lowest energy access rates in the world. Despite significant steps forward in Ethiopia, Kenya and Rwanda; close to 600 million people are still without access to electricity. And about half of the sub-Saharan African population without access to electricity live in five countries: Ethiopia, Nigeria, DR Congo, Tanzania and Uganda. Access to clean cooking fuels is also lowest in the region where only 17% of households in 2018 had access, meaning that over 900 million people do not have access to clean cooking [IEA, 2019].

Developing and emerging economies face thus a two-fold energy challenge: Meeting the needs of hundred millions of people who lack access to basic, modern energy services while simultaneously participating in a global transition to clean, low-carbon energy systems [Ahuja D. and Tatsutani M., 2009]. These challenges which are part of other broad challenges should be tackled by making long-term planning over the course of 20-40 years. The objective of long-term planning is to ensure an affordable, competitive, secure, sustainable and reliable supply of energy to meet a country's development needs. The process of planning requires a good representation of the energy system under study by looking through the context of the country. And developing countries have unique characteristics. This enables planners and policymakers with an understanding of the complex economics, political and environmental interrelations and uncertainties surrounding their energy systems.

1.1. Background and problem statement

The greatest increase in demand for energy is envisaged to come from developing countries like Ethiopia where, with rapid urbanization, large-scale electricity generation with a reliable and optimum supply will be required. Adequate, reliable and affordable electricity access connectivity nationwide is a critical enabler for realizing Ethiopia's future growth and transformation, economic prosperity and well-being of all its citizens nationwide.

Ethiopia has a vision of becoming a middle-income country by 2025 after implementing three successive five-year development plans referred to as Growth and Transformation Plan (GTP). The main development objective is to eradicate poverty in a relatively short period of time by implementing broad-based development policies to enhance growth [GTP-II, 2016]. This development is translating into a large demand for electric power and energy in urban and rural areas. The planning period will see a significant demand increase due to fast-economic growth of the country reflected by developments in railway transport, large irrigation projects, industry zones, housing projects, etc. Moreover, power export to neighboring countries and population growth are also major factors.

Today, grid connected household connectivity is about 40 percent of the population with per capita consumption of 143 kWh per year. The Government of Ethiopia (GoE) through its national electrification program (NEP) has set an ambitious plan for achieving universal electricity access nationwide by 2025 [FDRE, MoWIE, 2017].

All the above plans and efforts are quite considerable moves and will accelerate rapid and sustainable growth. However, they need to be supported by rigorous researches and deep studies that aim to address pressing current and future policy issues to help shift energy systems, particularly the power sector towards a more sustainable, efficient, reliable and equitable paradigm. A number of electricity and energy-related questions and issues need to be comprehensively addressed to hit the ambitious targets set by GoE.

To achieve the SDG7 and ensure energy security through increasing renewable energy share, policymakers increasingly rely on techno-economic assessments both to inform policy development and to help set the right national targets. In this regard, the modeling and investigation of different optimal pathways and possible future scenarios has become a critical planning tool in the power sector. This type of assessment is currently lacking in Ethiopia.

Consequently, in line with the global goal and local needs, this research deals with strategies and practices for sustainable energy system, specifically it seeks to balance future electric energy needs (demand) and electric energy resources (supply) in Ethiopia. It focuses on long-term energy security to make timely investments on various energy sources and supply energy matched with the economic developments and environmental needs of the country.

Of course, countless reports and studies have been conducted about transition to a less carbon-intensive and more sustainable energy system. However, only few have approached this specifically from the perspective of developing country where access to clean and affordable energy remains a major development issue.

Another very important issue to be considered is the structural transition of energy providing entities from monopolized generation, transmission, distribution and sale of electricity to liberalized, deregulated market setting in which multiple privately owned companies compete for the provision and supply of electricity. In most developing countries like Ethiopia, a single, vertically integrated utility was responsible for the generation, transmission, distribution and supply of electricity. However, this is now gradually changing with the split of the single entity into separate organs with different duties and responsibilities, introducing public private partnership (PPP) and independent power producers (IPPs), etc.

With such progress, the introduction of competitive markets for generation and supply of electricity (retail) is inevitable in the long run. In such unbundled setting, investments in generation capacity are to be made by private generation companies which aim to maximize their profits. These generation companies face a significant amount of uncertainty regarding the return on investment which stems from the uncertainty regarding future demand, fuel costs, technological evolution, policy interventions, technological acceptance as well as investment decisions [Olsina et al, 2006]. In this regard, it is crucial for developing countries to conduct a long-term techno-economic assessment to identify the optimal power generation and capacity mixes that can meet future electricity demands.

1.2. Research objectives

The main objective of this research is to investigate the potential pathways of the future development of the power sector in Ethiopia while seeking to balance the long-term energy needs and resources. This goal is pursued by tackling the following research questions through three specific objectives.

Objective 1: To review and evaluate energy development, power sector reforms, policies and resource adequacy in Ethiopia (**Paper-I**).

This will be employed to answer the following research questions.

- What are the progresses and evolutions of power sector reforms in Ethiopia?
- What is the level of electricity access, affordability and reliability?
- What are the major challenges faced in the power sector?
- How diverse is the generation resource by type and what is its impact?
- Is the existing generation resource adequate to meet the demand?
- What are the existing regulations and policies?
- Existing and planned infrastructure for delivery, generation and distribution of energy in Ethiopia as well as the region?

Objective 2: To assess the fundamental dynamics, variables and policies that characterize the energy development and determine the evolution of electricity demand (**Paper-II, Paper-III**).

This will be used to answer the following research questions.

- What are the unique characteristics, major drawbacks and system shortcomings of the electricity grid?
- What is the future energy demand of the country?
- What are the major scenarios that detect emerging issues and plausible future trends?

- What methodologies and modeling tools have been used in the national electricity Master plan as well as other studies for demand forecasting and planning?

Objective 3: To identify the best power generation and capacity mixes to meet future electricity demands subject to various technical, economic and environmental constraints (**Paper-IV**).

With this objective in mind, it is possible to answer the following research questions.

- What are the long-term energy development pathways that can meet the rising electricity demand in Ethiopia?
- What are the optimal (least-cost) supply mix alternatives of the future power system which could ensure generation adequacy, reliability and reduce greenhouse gas (GHG) emission?

1.3. Scope of research

The study is focused on the long-term modeling and analysis of the energy sector, particularly the electricity sector within the context of a developing country-Ethiopia.

Modeling of the physical system under study is important for good energy planning. There are different types of long-term planning models (as will be discussed in Chapter 2). The focus of this study is on energy demand models and energy supply models. Demand models focus on either the entire economy or a certain sector and regard demand as a function of changes in population, income and energy prices. Supply models focus mainly on the technical aspects concerning energy systems and whether supply can meet a given demand, including a financial optimization approach [Beeck N.V., 1999].

Potential modeling tools such as TIMES/MARKAL, OSeMOSYS, MESSAGE, LEAP, WASP and BALMOREL are used to explore alternative policy scenarios that cover a broad range of uncertainties and policy options so as to evaluate concrete, least-cost investment pathways to providing reliable and affordable electricity [IRENA, 2017]. This research employs LEAP to explore the evolution of the future demand and OSeMOSYS as a supply optimization modeling tool to determine the long-term generation expansion paths. Future possible scenarios are developed and assessed with regard to technical, economic and environmental criteria.

The model resolution in time and space defines the level of detail in representing time periods and geographical area in models (as will be discussed in Chapter 2). This research is concerned on a planning time horizon of 30 years to make the long-term generation expansion investment decisions. It uses a time step of one year and the spatial representation is limited to one country-Ethiopia.

- Models and modelling tools

The distinction between models and modelling tools is not always made clear, but in this study, models refer to a set of mathematical equations with parameters that are equipped with an algorithm to solve the equations. On the contrary, modelling tools come in the form of a software package to generate models.

In this research, the models are developed using already existing modelling tools. Developing a new modelling tool requires significant investment and research and development which is beyond the scope of this study.

- Developing country

In this study, we define a developing country as “a country that generally lacks a high degree of industrialization, infrastructure, and other capital investment, sophisticated technology, widespread literacy, and advanced living standards among their populations as a whole” [Nfuka and Rusu, 2009].

1.4. Significance of the study

Ethiopia has a high potential for solar, wind and hydropower in addition to geothermal and bioenergy as alternative source. It is important to have a clear roadmap on how to utilize these resources. Development of long-term renewable integration and generation expansion requires good representation of the energy system, projection of demand, investigation of resource behavior and electricity system context. All of these can be done through long-term modelling and planning of the system under study.

Decision makers rely increasingly on techno-economic assessments, to set the right national targets for renewable power uptake. Developing long-term scenarios and strategies is an important part of the modelling and planning work that provides a rational basis for decision-making. It assesses the investment needs to meet demand, and also help prioritize alternative investment options based on economic criteria (cost minimization), as well as on social (import dependency, reliability of supply, rural electrification, etc.) and environmental (emissions of air pollutants and GHG, etc.) criteria. It is possible to study and quantitatively assess various "what-if" conditions to evaluate implications of different policy options.

The output of the long-term scenario alternatives provides quantitative targets for the energy mix that realize Ethiopia's overall policy goals, guiding the process of when, where and how to invest in the power sector. Policy instruments and regulations are crafted to achieve these targets.

The strategic assessment and planning of the power system will ensure (i) enough generation capacity and expansion of supply to meet demand, (ii) reliable and affordable electricity, (iii) adequate transmission capacity to dispatch power to demand centers, (iv) grid stability to accommodate short time variations, (v) optimized investments that capitalize on falling costs of low-carbon technologies to minimize the risk of stranded underperforming energy infrastructure assets into the future.

In many African countries including Ethiopia, the local capacity to develop or use modelling tools for power system planning is often limited. The electricity master plan is developed by foreign consultancy firms which makes it difficult to adjust or timely update it by local capacity. In addition, most energy modeling tools are initially designed for developed countries and adopting such tools without considering the context and unique characteristics of developing countries leads to inaccurate results and wrong policy implications.

This research will contribute to the knowledge-gap in power system modeling and planning by building local capacity. Interested energy planners and academicians can use the developed model to explore alternative scenarios for national and regional power sector development. The models can also represent and highly relate to other less developed and developing countries outside Ethiopia where the model outputs and policy implications can indirectly be applied by making small changes and improvements.

1.5. Thesis outline and contributions

1.5.1. Outline

The outline of the remainder of this dissertation is as follows:

Chapter 2 presents the classification and categorization of different types of long-term planning models including their comparison and context for developing countries.

Chapter 3 presents a review of the power sector in Ethiopia including socio-economic situation, organizational history and structure, energy resources, energy policies and strategies, assessment of resource adequacy and power sector reforms, etc.

Chapter 4 focuses on long-term evolution of energy and electricity demand forecasting in developing countries. Literature review is conducted to identify the relevant models and understand various approaches used to analyse energy demand, policy and planning concerns for the context of both developed countries and least developed countries. Appropriate scenarios are developed by studying the context of energy demand, socio-economy, demography, technological change and future governmental direction in a systematic manner. The Long-range Energy Alternatives Planning System (LEAP) modeling framework is employed to explore different possible futures and alternative policy scenarios. Characterization of the dynamics and specific features of developing countries is represented in the LEAP tool. Energy demand projection is then made for different sectors. Finally, the model output is compared with other studies and reasons for the deviations and strength of the followed approaches are discussed. In addition, comparison of the different scenarios is discussed in terms of demand projection, fuel consumption, greenhouse gas emission, etc.

Chapter 5 addresses the specific objective 3. It investigates the long-term electricity supply options by providing a quantitative analysis of the future power generation sector. It starts by reviewing and discussing studies that examined issues of power generation expansion in developing countries. Then, an Open-Source energy Modelling System (OSeMOSYS) based model is developed to determine the least cost electricity generation and capacity mixes to meet the long-term electricity demands subject to certain policy scenarios that may impose technical constraints, economic realities and environmental targets. The model provides independent assessment of alternative technologies and policy choices by including relevant scenarios and exploring the feasibility of adding new technologies to the existing system. This includes assessments of centralized and decentralized means of electric supply. Sensitivity analysis is carried out to study the effect of critical assumptions and varying parameters on the results. Finally, the optimization results are discussed by comparing the electricity generation and capacity mixes, economic cost, emissions, etc. under the considered scenarios.

Chapter 6 provides a critical reflection of the followed approaches and methods as well as the main choices made during the course of this study.

Chapter 7 finally summarizes the main findings of the work in this dissertation by pointing the limitations and topics to be addressed in the future.

1.5.2. Contribution

This thesis is based on the following publications, which are referred to in the text by their Roman numerals.

I. Dawit H. Gebremeskel, Getachew Bekele, Erik O. Ahlgren, Assessment of resource adequacy in power sector reforms of Ethiopia, 2019 IEEE PES/IAS PowerAfrica, Abuja, Nigeria, 2019, pp. 81-86.
II. Dawit H. Gebremeskel, Getachew Bekele, Erik O. Ahlgren, Energy System modeling tools: Review and comparison in the context of developing countries, 2020 IEEE PES/IAS PowerAfrica, Nairobi, Kenya, 2020.
III. Dawit H. Gebremeskel, Getachew Bekele, Erik O. Ahlgren, Long-term evolution of energy and electricity demand forecasting: The case of Ethiopia, Energy Strategy Reviews, Vol. 36(2021) 100671.
IV. Dawit H. Gebremeskel, Getachew Bekele, Erik O. Ahlgren, Long-term electricity supply modelling in the context of developing countries: The OSeMOSYS-LEAP soft-linking approach for Ethiopia, Energy Strategy Reviews, Vol. 45 (2023) 101045.

Dawit Habtu is the principal author of **Papers I-IV** and conducted all the modelling and analysis of these papers. Professor Erik O. Ahlgren and Dr. Getachew Bekele who are the supervisors contributed with discussions, reviewing and editing of all the four papers.

List of publication by the author not included in the thesis

The following publications have been produced by the author but not included in the thesis.

i. Dawit H. Gebremeskel, Getachew Biru Worku, Study on power distribution network automation to mitigate power outages, Journal of Ethiopian Engineers and Architects, Zede, ISSN: 0514-6216, 2017; Vol. 35: pp. 38-46.
ii. Dawit H. Gebremeskel, Interaction between distributed generation and the Addis Ababa distribution network, Journal of the Ethiopian Society of Electrical Engineers, 2013, 7th scientific conference on Electrical Engineering, CEE-2013.

2. Long-term energy system planning models

2.1. Classification of models

Energy system models can be classified using several criteria. A wide variety of literature have set different ways of categorizing models [Ringkjøb et al, 2018; Poncelet, 2018; Pfenninger et al, 2014; Nakata, 2004; Beeck, 1999; Helgesen, 2013; Irsyad et al., 2017; Prasad et al., 2014; Deshmukh, 2011; Hiremath, 2007; Pandey, 2002; Bhattacharyya and Timilsina, 2010].

Ringkjøb et al (2018) have identified four different purposes for generally grouping models. These are power system analysis tools, operation decision support tools, investment decision support tools and scenario modeling tools. Poncelet (2018) used two criteria to categorize different types of planning models: scope of the model (Integrated assessment models, energy-economy models, energy-system planning models and power-system planning models) and methodology (general equilibrium models, optimization models, equilibrium models, system-dynamics models and agent-based models). Nakata (2004) used four important criteria to categorize the energy planning models: the modeling approach (top-down and bottom-up), methodology (partial equilibrium, general equilibrium or hybrid), modelling technology (optimization, econometric, accounting) and the spatial dimension (national, regional and global). Nicole van Beeck (1999) proposed nine criteria to classify models for energy planning: purposes of energy models, model structure, analytical approach (bottom-up Vs. top-down), underlying methodology, mathematical approach, geographical coverage, sectoral coverage, time horizon and data requirements. Helgesen (2013) and Irsyad et al. (2017) presented a thorough discussion on the two contrasting modeling types:

the bottom-up engineering approach and the top-down macroeconomic approach. Prasad et al. (2014) categorized energy planning models based on their methodology and features as econometric models, optimization models, simulation models and computer-assisted tools. Deshmuk (2011) suggested an alternative classification based on methodology adopted (bottom-up Vs top-down), spatial coverage, sectoral coverage and temporal coverage. Hirematch et al. (2007) classified planning models into optimization models, decentralized energy models, energy supply/demand driven models, energy and environmental planning models, resource energy planning models and models based on neural networks. Pandey (2002) and Bhattacharyya and Timilsina (2010) used a set of attributes such as approach (top-down simulation, bottom-up optimization/accounting), spatial focus (global, regional, national, local), sector (macro-economy, energy) and time (short, medium or long-term).

Considering the above-mentioned works, we have come up with a more comprehensive and extended classification that is important for this thesis with regard to comparison of models as follows. (i) purpose (ii) model scope (iii) analytical approach (iv) methodology (v) mathematical approach (vi) geographical/spatial coverage (vii) sectoral coverage and (viii) time horizon. Category (i) is selected from [Ringkjøb et al,2018], category (ii) is selected from [Poncelet, 2018] and categories (iii) up to (viii) are referred from [Nakata, 2004; Nicole van Beeck, 1999; Pandey, 2002; Bhattacharyya and Timilsina, 2010; Deshmuk, 2011; Prasad et al., 2014; Helgesen, 2013; Irsyad et al., 2017].

Each of these classification criteria are thoroughly discussed below.

i. Purpose

This relates to the general objective of the modeling tool which can fit into the following categories.

Power system analysis tools- Tools developed to study power systems with a high degree of detail involving power flow study, short circuit or fault analysis, dynamic stability, etc.

Operation decision support- Tools developed to optimize the operation/dispatch of the energy/electricity system, considering economic, technical or environmental criteria.

Investment decision support- Tools that aim to optimize the long-term investments in the energy/electricity system.

Scenario- Tools that investigate the long-term alternative paths and possible futures through studying various policies.

Table 1 gives an overview of the common models and what purpose they usually focus on.

Table 1 Model groups considering their purpose [Pfenninger et al, 2014]

Model family	Examples	Primary focus
Energy system optimization	MARKAL, TIMES, MESSAGE, OSeMOSYS	Investment decision, normative scenarios
Energy system simulation	LEAP, NEMS, PRIMES	Forecasts, predictions
Power system and electricity market models	WASP, PLEXOS, ELMOD, EMCAS	Power system analysis, operational decision, business planning

ii. Model scope

The scope or coverage of planning models determines the endogenous interactions, type of questions that can be addressed, level of detail and complexity of executing the model. In this regard, there are four major types of long-term planning models as discussed below.

Integrated assessment models

Integrated assessment models (IAMs) are used to analyze long-term interdisciplinary questions of a global scope. They try to link, within a single modeling framework, main features of society and economy with the biosphere and atmosphere. The goal is to make more and more parts of the "earth system" endogenous to the modeling framework. IAMs not only include the energy system, but also incorporate macro-economic interactions, demographics and resource availability restrictions (e.g. materials, water, land) and health. Integrates assessment is a useful way of approaching highly complex issues like climate change, which involve a range of problems, disciplines, stakeholders and time and spatial scales. Modeling tools such as MESSAGE, IMAGE, GCAM and POLES are good examples of IAMs [Poncelet, 2018].

Energy-economy models

Energy-economy models address the interaction between the energy system and the overall economic system. Such models include multi-disciplinary fields-energy, economy and the environment as model components (see

Fig. 1) and allow accounting for the economy-level response to future changes in the energy-system. In addition, technological innovations and efficiency improvements are also factors that should be included in this model [Nakata, 2004]. Typical energy-economy models include NEMS, US-REGEN, MESSAGE-MACRO model and TIMES-MACRO model [Poncelet, 2018].

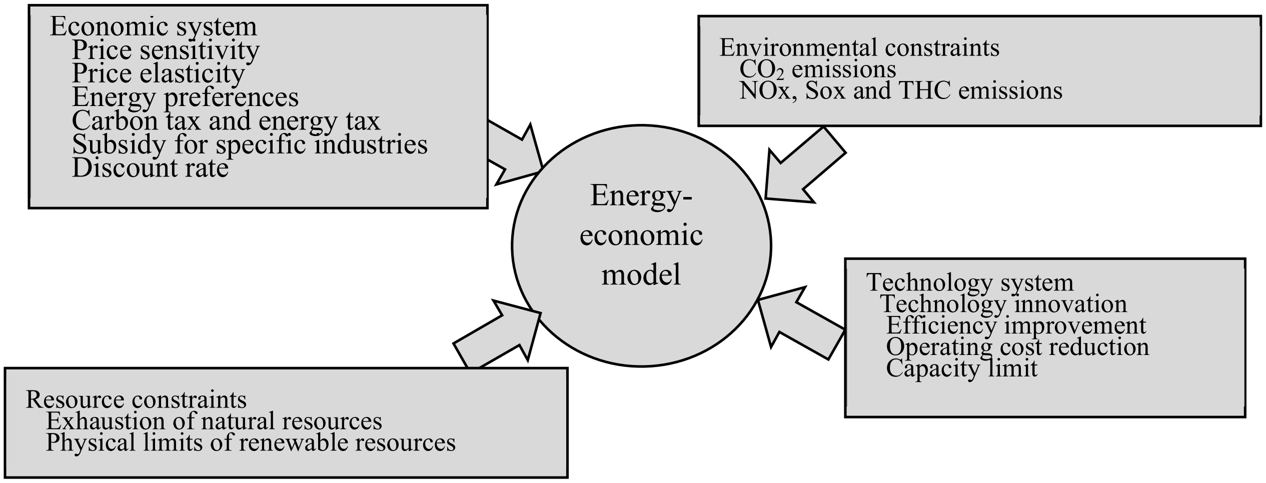


Fig. 1 Schematic of energy-economic model [Nakata, 2004]

Energy-system planning models

Energy-system planning models restrict the scope to the evolution of the energy system that covers the entire chain from extraction and refining of primary fuels to conversion and final consumption. In contrast to the energy-economy models discussed above, the interactions between the energy sectors and other economic sectors is not endogenously integrated. The main strength of these energy-system planning models is that they provide a comprehensive description of possible scenarios for the transition of the energy system by considering the inter-sectoral, inter-temporal and inter-regional relationships. They can also cover all energy sectors (e.g. electrical power, heating, transportation) with a high level of technological detail. This enables analyzing the complex interactions between different energy sectors and technologies. As a result, energy system models provide a consistent tool for decision making, planning and developing appropriate policies

[Poncelet, 2018]. Well-known energy system planning models include PRIMES, MARKAL/TIMES, LEAP, OSeMOSYS and EnergyPLAN.

Power-system planning models

Power-system planning models restrict the scope to the electrical power sector. This restricted scope allows increasing level of detail (temporal, technical and spatial) compared to the more broad energy-system planning models [Deane et al., 2012]. Power system models are mostly used to analyze the evolution of the power system with the aim of reducing the GHG emission. In this regard, these models have been used to determine the cost-optimal capacity mix to achieve certain policy targets, to analyze the need for different flexibility options, to provide projections of future wholesale electricity, etc. Typical power system planning models which are mostly developed for the North American and European power grids are ReEDs, LIMES, Switch, Resource Planning Model and WASP.

iii. Analytical approach

With the aim of meeting the demand in an economical fashion, energy models generally follow two contrasting modeling/analytical approaches; a top-down and a bottom-up approach. Bottom-up modeling approach or often referred to as engineering approach is based on detail technological and engineering descriptions of the energy system. Energy demand is typically provided exogenously, and the models analyze how the given energy demand should be fulfilled in a cost-optimal fashion [Helgesen, 2013].

On the other hand, top-down modeling approach follows an aggregated view and macroeconomic relationships. The influence of prices and markets is believed to have more impact than technical characteristics of the energy sector.

The two approaches differ considerably in their identification of the relevant system and can lead to opposite results for the same problem and may therefore produce different guidance for policymakers [Helgesen, 2013; Beeck, 1999]. The differences in outcomes of top-down and bottom-up models stem from the distinct manners in which these two types of models treat economic, market and technological interactions. Bottom-up approaches ignore macroeconomic interactions by assuming exogenous energy prices, demand and other economic related inputs. On the contrary, top-down approaches endogenize energy demand to other macro and microeconomic variables [Irsyad et al., 2017]. Technology is regarded as a set of techniques in which inputs such as capital, labor and energy can be transferred into useful outputs. As a result, economic modeling approaches treat technology as a black box without having explicit representation. Engineering models, on the other hand, describe the techniques, performances and the direct costs of all technological options so that possible improvements can be identified [Beeck, 1999].

Depending on the application, each of the discussed analytical approaches have their own advantages and disadvantages. In order to capture the advantages from both, models can also be combined in hybrid approaches. Hybrid models have a macro-economic element connected with a detailed end-use oriented energy sector description. However, computational limitations result in making trade-offs between technical/engineering detail and economic detail. The development of hybrid models has also not displaced the pure bottom-up and top-down approaches [Pfenninger et al, 2014].

iv. Methodology

The commonly used methodologies for the development of energy and electricity models are grouped into three main categories; optimization, simulation, and equilibrium methods.

Optimization models are used to balance demand and supply by optimizing energy investment decisions such as capacity and choice of technology alternatives. The outcome represents the best solution usually the least-cost path, while meeting a set of operative constraints. Such models require a relatively high degree of mathematical analysis to represent the included processes. The majority of optimization models use a linear programming approach with an objective function which is either maximized or minimized subject to the given constraints [Beeck, 1999; Ringkjøb et al, 2018].

Simulation models are descriptive models that simulate an energy system based on specified equations and characteristics. They allow testing of various system topologies, as well as, impacts and development of various scenarios. Such models are often bottom-up models, with a detailed technological description [Ringkjøb et al, 2018]. In contrast to optimization models, simulation-based models can be built modularly and incorporate a range of methods [Pfenninger et al, 2014].

Equilibrium models are used to study the energy sector as part of the whole economy and focus on interrelations between the energy sector and the rest of the economy [Beeck, 1999]. General equilibrium models determine important economic parameters such as the gross domestic product (GDP) endogenously while partial equilibrium models focus on balancing one market (e.q. energy or electricity) with the rest of the economy that is not modelled [Ringkjøb et al, 2018].

v. Mathematical approach

The mathematical approach refers to the mathematical techniques that are used to represent the complex correlations between different variables and components of the energy system. In addition, optimal operation of the energy system should also be determined. In this regard, commonly applied mathematical techniques include linear programming, mixed integer programming and dynamic programming.

Linear Programming (LP) is a technique for finding the arrangement of activities which maximizes or minimizes a defined criterion, subject to various technical, economic and environmental constraints. All relationships are expressed in fully linearized terms. LP is an extremely powerful tool for addressing a wide range of applied optimization problems such as resource allocation and production scheduling.

Mixed Integer Programming (MIP) is an extension of LP which allows greater detail in formulating technical properties and relations in modeling energy systems. Decisions such as yes/no or (0/1) are admitted as well as nonconvex relations for discrete decision problems [Beeck, 1999]. MIP problems might be harder to solve compared to LP problems. The solution time is increasing exponentially to the number of integer variables. MIP can be used when studying the unit commitment of thermal power plants that need characterization of different variables such as minimal up and down time, start-up, upper and lower limit, etc. They are also widely used in multi-energy systems planning problems, where various energy carriers with different units in terms of size and capacity are considered.

Dynamic Programming (DP) is a method that transforms a complex problem into a sequence of simpler problems. The solution of the original problem is obtained by dividing the original problem into simple subproblems for which optimal solutions are calculated. Consequently, the original problem is then optimally solved using the optimal solutions of the subproblems [Beeck, 1999].

In addition to the above techniques, most recent studies are using fuzzy programming or stochastic and interval programming methods to deal with uncertainties in the energy system such as energy demand, price market and learning rate of technologies [Salas, 2013].

vi. Geographical/spatial coverage

The geographical coverage refers to the spatial area or space in which the analysis is taking place. This is commonly divided into global, regional, national, local or single-project. Global scale models are concerned about the situation in the world with regard to climate change, sustainability, variable renewable energy, etc. while regional level models refer to international regions such as Europe, Latin American countries, North-America, South-East Asia, Sub-Saharan Africa, etc. National models are restricted to one country treating all major sectors endogenously, while the outside world energy parameters are considered exogenously. The local level is subnational, referring to regions within a country. The project level also is usually limited to subnational area focusing at a particular site, however it can also be applied on a greater national or international level.

The relationships between energy and society take different forms across space, as energy policies are pursued in different local, regional, national, and global settings [Ludger et al, 2019]. Therefore, emerging problems are often requiring geo-referencing to certain spatial scales. For instance, rural electrification, transmission expansion, renewables electric vehicle integration, and outage management systems require knowledge of where the sources, storage, and sinks of electric energy are located and relevant factors associated with those locations [Grijalva, 2017]. Electrification analyses in rural, peri-urban and urban requires spatially specific information such as renewable energy flows, location of transmission lines, sizes, and locations of settlements and their distances from the nearest electric grids. Tools that capture the spatial dimension of energy systems are essential for the development of spatially inclusive and comprehensive energy demand supply analyses. This is particularly important for developing countries which are investigating different electrification options including grid extension, mini-grid and stand-alone systems [Dimitrios et al, 2017].

vii. Sectoral coverage

Sectoral coverage refers to the scope and focus of the model with regard to fuel type, technology, economy, class of customer, etc. Based on this division, models can be classified, into sub-sectoral, sectoral and economy wide models. Sub-sectoral models provide only information in just one particular sector and do not take into account the macro-economic linkages of that sector with the rest of the economy. The other sectors of the economy are simplified in these models. On the other hand, sectoral models investigate more than one sector of the economy and the interaction between the studies sectors [Neshat et al, 2014].

viii. Time horizon

The time horizon is simply the timeframe in consideration under the study. It is very common to classify models into short-term, medium-term and long-term. However, there is no explicit definition of the exact timeframe for each of them. In this study, we consider short-term time horizon to be 1 year or less; medium-term, between 1 and 15 years; and long-term to be over 15 years.

2.2. Comparison of modeling tools

A number of modeling tools are available that are systematically used to analyse the energy and electricity system. In this section, the comparative overview of selected models is presented. [Ringkjøb et al, 2018] present a thorough review of 75 modelling tools that are currently used for analyzing energy and electricity systems. Out of the 75 models included in the review, six candidate models that are believed to be suitable for this study's purpose are identified. These are OSeMOSYS, MARKAL/TIMES, MESSAGE, MESAP PlaNet, EnergyPLAN and LEAP. A brief overview about each of these modeling tools is presented in Appendix B.

Comparison of the selected tools is based on the eight classification criteria presented in the previous section. These are listed below.

1. Purpose

Power system analysis, operation decision support, investment decision support, scenario.

2. Model scope

Integrated assessment, energy-economy, energy system planning, power system planning.

3. Analytical approach

Top-down, bottom-up, hybrid.

4. Methodology

Optimization, simulation, equilibrium.

5. Mathematical approach

LP, MIP, DP

6. Geographical/spatial coverage

Global, regional, national, local or single project.

7. Sectoral coverage

Energy, overall economy, sub-sectoral, sectoral.

8. Time horizon

Short-term, medium-term, long-term.

Considering the above eight classification criteria, the six candidate modeling tools can be compared as shown in Table 2. It can be seen that each tool has its own feature and selection of appropriate modeling tool depends on the level of use of the features for a particular application.

Table 2 Comparison of selected energy models based on the eight classification criteria.

Criteria	OSeMOSYS	MARKAL/TIMES	MESSAGE	MESAP PlaNet	EnergyPLAN	LEAP
Purpose	Investment decision, scenario	Investment decision, scenario	Investment decision, scenario	Scenario	Scenario, investment decision, operational decision	Scenario
Model scope	Energy-system	Energy-system	IAM, Energy-economy	Energy-system	Energy-system	Energy-system
Analytical approach	Bottom-up	Bottom-up	Bottom-up	Bottom-up	Bottom-up	Bottom-up
Methodology	Optimization	Optimization	Optimization	Simulation, econometric	Simulation, optimization	Simulation, econometric
Mathematical approach	LP, MIP	LP, DP	DP	LP, DP	Analytical programming	N/A
Geographical /spatial coverage	Local, national, regional	Local, national	Local, national	Local, national	Local, national, regional	All
Sectoral coverage	Energy	Energy	Energy	All	Energy	All
Time horizon	Medium, long-term	Medium, long-term	Short, medium, long-term	Short, medium-term	Short, medium-term	Medium, long-term

2.3. Modeling tools for developing countries

The energy and electricity system of developing countries is entirely different from industrialized countries. As a result, the analytical tools used for modeling should be able to capture the specific features of developing countries. Few literatures have attempted to identify the specific features and unique characteristics of developing countries compared to the developed countries.

[Pandey, 2002] pointed out that the existence of inequity and poverty, dominance of traditional lifestyles and markets in rural areas, transitions of populations from traditional to modern markets, existence of multiple social and economic barriers to capital flow and technology diffusion, and radical nature of policy changes being witnessed in energy sector cause developing countries' energy system entirely different from that of developed countries.

[Urban et al, 2007] indicated three specific features: poor performance of the power sector and traditional fuels, transition from traditional to modern economies, and structural deficiency in society, economy and energy systems. In the study, they have also compared the capabilities of different available models in terms of the unique characteristics of developing countries: performance of the power sector, supply shortage, low electrification, traditional biofuels, urban-rural divide, informal economy, structural economic change, investment decisions and subsidies.

Other studies [Bhattacharyya and Timilsina, 2010; Irsyad et al., 2017] have attempted to investigate the usefulness of existing energy models with regard to incorporating the above unique features of developing countries. [Bhattacharyya and Timilsina, 2010] considered two-step procedure to select the most appropriate analytical tool for developing countries. The first procedure uses the analytical approaches and methodology as a criteria to evaluate how the models perform in meeting the following features: incorporation of supply and demand modules, input data requirement, flexibility to incorporate new end-use, fuel and technology including those used in developing countries, rural energy specificities, informal sectors, data and skill concerns, and the possibility of capturing transition. The second procedure focuses on bottom-up and hybrid models and makes comparison based on the following: analytical approach, geographical, technical and activity coverage, data and skill needs, portability, disaggregation, price and non-price policy capabilities, rural energy capabilities, energy shortage, informal sector, subsidies, rural-urban divide and economic transition.

Considering the characteristics of the energy systems and economies of developing countries identified in the above studies, we use the following ten specific features to evaluate the suitability of energy models to developing countries. These are: (i) supply shortage (ii) performance of power sector (iii) traditional fuels (iv) urban-rural divide (v) informal economy (vi) economic transition (vii) subsidies (viii) data need (ix) skill requirement and (x) upfront financial cost.

Table 3 Comparison of specific models based on main characteristics of developing countries' energy systems and economies.

Criteria	**OSeMOSYS**	**MARKAL/TIMES**	**MESSAGE**	**MESAP**	**RESGEN**	**LEAP**
Supply shortage	Not explicitly	Not explicitly	Not explicitly	Not known	Not explicitly	Possible explicitly
Performance of power sector	Not possible	Not possible	Not possible	Not possible	Not possible	Implicitly modeled
Traditional fuels	Possible	Possible	Possible	Possible	Possible	Possible
Urban-rural divide	Possible	Possible and covered	Not explicitly	Not known	Possible but not covered usually	Possible and covered usually
Informal economy	Not possible	Not possible	Not possible	Not possible	Not possible	Possible
Economic transition	Not possible	Can be covered	Possible and covered	Not known	Not covered	Usually covered through scenarios
Subsidies	Not explicitly	Possible but normally ignored	Not explicitly	Not known	Difficult	Not considered explicitly
Data need	Extensive but can work with limited data	Extensive	Extensive	Extensive	Variable, limited to extensive	Extensive but can work with limited data
Skill requirement	Limited to High	Very high	High	High to very high	Limited	Limited
Upfront financial cost	Free, open source	Commercial	Free for academic and IAEA members	Commercial	Commercial	Free for developing countries

Considering the analytical approach and methodology as a criteria for comparison, alternative energy system models can be divided into:

- Bottom-up, optimization-based models
- Bottom-up, accounting models
- Top-down, econometric models
- Hybrid models
- Electricity system models

Accordingly, the comparison of features of different types of energy system models is shown in Appendix B, Table A - 1. It can be seen that the bottom-up accounting type of framework appear to be more appropriate to developing country contexts because of their flexibility, limited skill requirement, ability to capture rural-urban differences, traditional and modern energies and also can account non-monetary transactions. It is also seen that, even though the optimization models have a good representation of technological features, they have difficulties in capturing non-monetary policies and informal sector activities.

The comparison of some specific bottom-up and hybrid global models based on the second procedure is shown in Appendix B, Table A - 2 and Table A - 3. From the comparative overview, it is observed that most of the models are not suitable for developing country contexts as they do not explicitly cover the essential features of developing countries. From Table A - 2 and Table A - 4 of Appendix B, it can be seen that accounting type models like LEAP appear to be more suitable for the context of developing countries. Such tools are scenario-based and are better suited to capture rural-urban divide, economic transition, informal sector and energy shortage features.

The review of [Bhattacharyya and Timilsina, 2010] suggests that most of the existing models inadequately capture the developing country characteristics and that the problem is more pronounced with econometric and optimization models than with accounting models. Among the bottom-up optimization models, OSeMOSYS is an open-source model, which has an accessible, easy to use and freely modifiable code. This makes it particularly interesting to developing countries that are avoiding costly models and are looking tools with less skill requirement.

[Irsyad et al, 2017] considered the purpose of the analysis and specific issues of developing countries as a criteria for evaluating and selecting the most appropriate analytical tool. The analysis purposes are specified as: to determine best options, to estimate economic impacts of a policy, to estimate environmental impacts of a policy, to estimate energy mix impacts of a policy and to understand energy systems. And the specific issues in developing countries are rural electrification/energy access equity, data availability and analysis capability, informal economy, income inequality, affordability issue for green energy, traditional energy and free tools. The evaluation is shown in Appendix B, Table A - 5. It is observed that the top-down approaches are not suitable for developing countries. Top-down approaches rely on per capita demand, which are not applicable to developing countries with the fact that there is unequal electricity access. Instead, it is suggested that the number of electrified customers should be used. On the other hand, bottom-up approaches are not suitable for assessing the impacts of income inequality to the energy system since they usually use homogenous energy consumer in their analysis. In addition, most of the tools can not consider the informal economy in their analysis. As a result, [Irsyad et al, 2017] conclude that most energy analytical tools do not incorporate the inherent characteristics of developing countries. However, similar to [Bhattacharyya and Timilsina, 2010], [Irsyad et al, 2017] suggest that the accounting-based bottom-up models are suitable to simulate dynamic transition and forecasting in developing countries.

2.4. Summary and Conclusion

In this chapter, a detailed review and comparative study of frequently used models are presented with the aim of selecting suitable analytical tool for various applications; particularly, assessing whether the available tools are suitable for developing countries. Accordingly, we provide a guideline to select the appropriate analytical tool based on eight major classification criteria. These are (i) purpose (ii) model scope (iii) analytical approach (iv) methodology (v) mathematical approach (vi) geographical/spatial coverage (vii) sectoral coverage and (viii) time horizon. In addition, the specific features of developing countries that need to be considered during tool selection and modeling are also identified. These are: (i) supply shortage (ii) performance of power sector (iii) traditional fuels (iv) urban-rural divide (v) informal economy (vi) economic transition (vii) subsidies (viii) data need (ix) skill requirement and (x) upfront financial cost.

The review suggested that proper understanding of the unique characteristics and context of developing countries is crucial to prevent inaccurate analysis and the prescription of wrong policies. It is also shown that most of the existing standard energy models inadequately capture the developing country characteristics. The modeling tools were initially developed for industrialized countries considering mainly the situation in their energy system, technology and market. Inability to capture the specific developing country features listed above makes most of the tools less suitable.

The comparison of features of different types of energy system models shows that the bottom-up accounting type framework appears to be more appropriate for developing country contexts because of their flexibility, and their ability to capture rural-urban differences, traditional and modern energies, and to account for non-monetary transactions and informal sector activities. The informal economy is a significant business activity in developing countries that is not part of the GDP. Moreover, income inequality is also much higher compared to developed countries. As a result, the reviewed studies do not recommend economic-based models to be used for making energy analysis in developing countries. If such models are to be used for developing countries, one should make sure that necessary adjustments are made accordingly including modifying the model's assumptions as per the specific characteristics.

The model comparison showed that LEAP and OSeMOSYS are more suitable and have some attractive features to developing and emerging countries. LEAP is a scenario-based, demand-supply model that can capture rural-urban divide, economic transition, informal sector and energy shortage features. OSeMOSYS is also a scenario-based, bottom-up, flexible, open-source and easy to use optimization modeling framework. Developing economies may have the limitation of resource, data availability and technical capability. In this regard and in terms of capturing some of the other specific features of developing countries, such modeling tools can support the short to long-term planning in developing countries. However, in order to effectively address all the characteristics of developing countries' energy systems and economies, we either believe that the existing models need to be improved or new tools should be developed.

3. Review of power sector and assessment of electricity generation adequacy in Ethiopia

3.1. Socio-economic situation

Ethiopia is a country located in the horn of Africa. It is bordered by Eritrea to the north, Djibouti and Somalia to the east, Sudan and South Sudan to the west and Kenya to the south. The country is the second most populous country in Africa, with an estimated population of more than 100 million of whom more than 80 million live in rural areas (Table 4). Over the past decade, the Ethiopian economy has been one of fastest growing economies in the world. It had showed 10.3% average annual growth during the period 2005/06-2015/16 (Fig. 2). The country has a vision of becoming a lower-middle income country by 2025 after implementing three successive five-year development plans referred to as Growth and Transformation Plan (GTP). The main objective is to eradicate poverty in a relatively short period of time by implementing broad-based development policies to enhance growth [World Bank, 2017; GTP-II, 2016].

Table 4 Demographic and economic indicators in Ethiopia [Central Statistics of Ethiopia, 2013; National Bank of Ethiopia, 2016/17 and 2017/18; World Health Organization, 2018; World Bank, 2018]

Indicator	Contents
Country area (In Sq.Km)	1.14 million
Capital	Addis Ababa
Official Language	Amharic
Population (Million, 2017)	95.2
Life expectancy (years)	65
Total fertility rate per woman	4.6
Average household size (national census)	4.6
Annual population growth rate (%)	2.5
Urban population (millions)	19.5
Foreign exchange rate (Birr/USD, 2017)	23.10
Total GDP (billion USD)	80.6 (2017)

Growth rate of GDP	10.3% (average, 2005/06-2015/16)
GDP per capita (USD)	876 (2017)
Human development index	0.448 (2015)
Foreign trade	Total foreign trade in 2017/18 -Total export 2.84 billion USD -Total import 15.25 billion USD -Trade balance -12.41 billion USD Main products for trading -Export: Coffee, oilseeds, leather and its products, pulses, meat and meat products, fruit and vegetables, live animals, chat, gold, flower, electricity. -Import: fuel, cereals, aircraft, fertilizers, others. Main trading partner countries Export: Asia (39.8%): China, Saudi Arabia, Israel, Japan, India, South Korea, Yemen, Indonesia, Hong Kong; Europe (28.7%): Netherland, Germany, Switzerland, Belgium, Italy, Turkey, United Kingdom, France, Russia; Africa (20.9%): Somalia, Djibouti, Sudan, Kenya, Nigeria, Egypt, South Africa. America (9.9%): United States, Canada. Import: Asia (64.2%): China, Kuwait, India, U.A.E., Japan, Saudi-Arabia, Malaysia, South Korea, Indonesia, Thailand. Europe (19.3%): Turkey, Italy, Germany, United Kingdom, Netherland, France, Ukraine, Belgium, Russia, Rumania. America (9.4%): United States, Brazil, Canada. Africa (7%): Egypt, Morocco, South Africa, Sudan, Nigeria, Kenya.

The percentage share of the agriculture, industry and service sectors in GDP is shown in Fig. 3. Service sector dominated the economy with major share in GDP owing to the expansion of wholesale & retail trade, hotels & restaurants, transport & communication and real estate, renting

& business activities. The share of agriculture declined to 34.9% in 2017/18 from 42% in 2012/13. On the other hand, the industrial sector showed a continuous increase from 13% to 27% share in GDP. The agricultural sector is responsible for 90% of export earnings and 85% of employment, however, this sector is characterized by subsistence farming, almost entirely rain-fed and pastoralism, with very little technological input [World Health Organization, 2018]. As a result, the performance of the sector has been generally poor, with an annual growth rate of about 8% (Fig. 3).

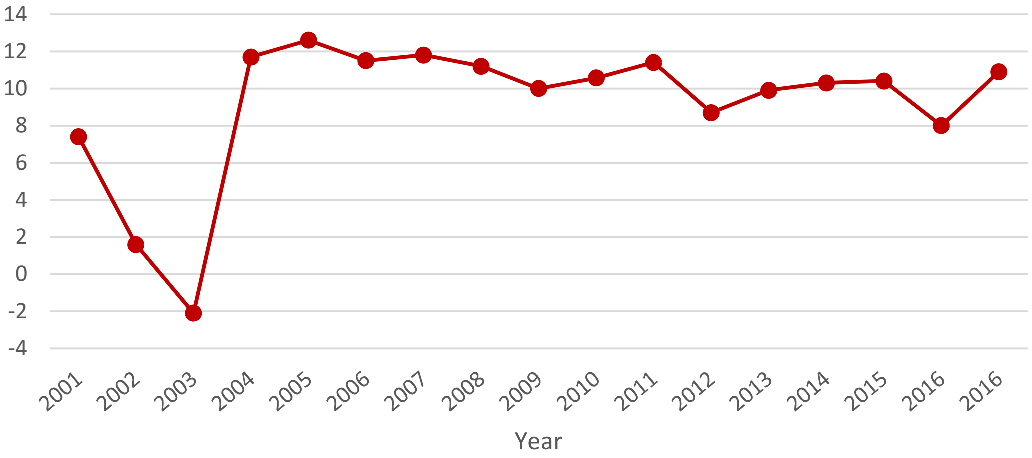


Fig. 2 Annual percentage growth in gross domestic product.

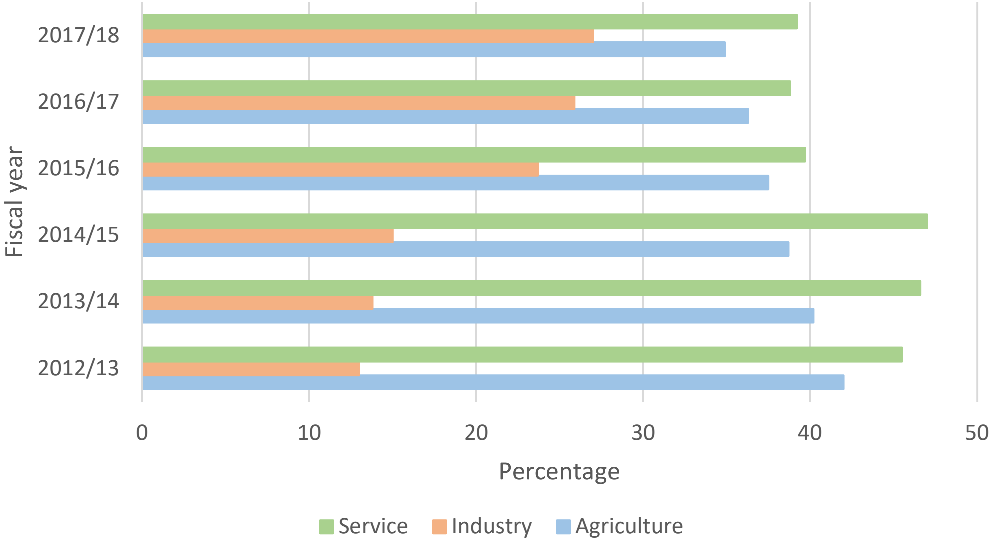


Fig. 3 Percentage share of GDP by major economic sectors.

The country’s second Growth and Transformation Plan (GTP-II) included targets to sustain a rate of increase in the GDP by 11% of which 8% growth in agriculture and 20% in industry by 2019-2020.

According to the projection made by Central Statistics Agency of Ethiopia in 2013 [Central Statistics of Ethiopia, 2013], the total population in 2017 was estimated to be 95.2 million, with an annual growth rate of 2.5%. The population density map shown in Fig. 4 shows that most of the population lives in the highlands and Oromia, Amhara and Southern regions. It also shows strong geographical clustering in the highlands and along major road networks.

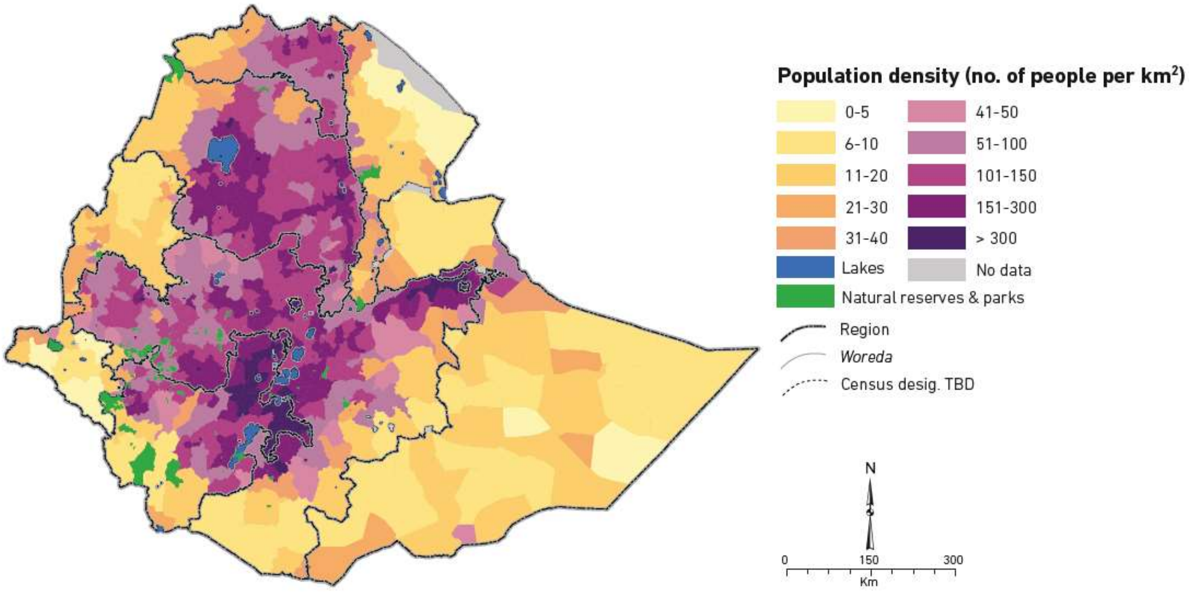


Fig. 4 Population density in Ethiopia [IFPRI, 2007]

3.2. Organizational history and structure

The Ethiopian Electric Light and Power Authority (EELPA) was established in 1956. It bundled all electricity activities in a single organization. In 1996, EELPA was split into two: The Ethiopian Electricity Agency (EEA) and the Ethiopian Electric Power Corporation (EEPCo). EEA was taking over with all regulating activities. It was mandated to determine quality and standards of electricity services; issue license for generation, transmission, distribution sales; import/export; recommend tariff and issue professional competency certificate. On the other hand, EEPCo was a single, state-owned and vertically integrated utility enterprise responsible for the generation, transmission, distribution and sales service of electric energy throughout Ethiopia. The corporation had two electric power supply systems: The Interconnected System (ICS) and the Self-Contained System (SCS). The ICS is a centralized, power grid that connects various generation stations at different geographical locations within the country. Whereas the SCS is a decentralized, off-grid system in which the generating stations are distributed to supply a specific group of customers at a particular location.

In 2013, EEPCo was again split up into two companies: Ethiopian Electric Power (EEP) and Ethiopian Electric Utility (EEU). EEP is a state-owned electricity producer engaged in development, investment, construction, operation and management of power plants, power generation and power transmission. It owns and operates the country’s power grid with all high voltage transmission lines above 66kV [EEP, Worldfolio, 2016]. It is a sole provider of bulk electricity to users, mainly to the EEU that focuses on the distribution and retail of electricity supply to end consumers. EEU is mandated to sell and purchase bulk electric power on transmission lines up to 66kV level. It is also responsible to administer, operate and maintain off-grid electricity generation up to 66kV.

At the same year in 2013, recognizing the importance of energy efficiency and conservation, the GoE upgraded the former Ethiopian Electric Agency into Ethiopian Energy Authority. As a result, the authority is mandated to undertake the regulatory activities of energy sector as well, particularly energy efficiency activities.

As shown in Fig. 5, the Ministry of Water Irrigation & Electricity (MoWIE) is the lead institution for the energy sector. It supervises the three institutions: EEP, EEU & EEA. The responsibilities of MoWIE fall into three broad categories: resource assessment & development, policy & regulation, and research & development.

Both the public utilities; EEP & EEU are led by a Management Board that is the supreme body responsible for the performance of the enterprises at the highest level. Its day-to-day operations and activities are led and managed by their respective CEOs. Then they have subsequent deputy CEOs and executive officers. EEU’s Deputy CEOs are responsible for leading the regional states and cities. And EEP’s Executive Officers are responsible for managing various departments such as generation operation, transmission construction & operation, finance, HR, project management, etc .

The EEA is also lead by Board of Directors who oversee the overall performance of the authority. Its daily activities are led and managed by the Director General and Deputy Director General. In addition, there are various Directorates who are responsible for various areas in different themes such as legal service, human resource, public relation & communication, audit service, finance & procurement, plan & budget, property administration & general service, good governance affairs, information technology, etc.

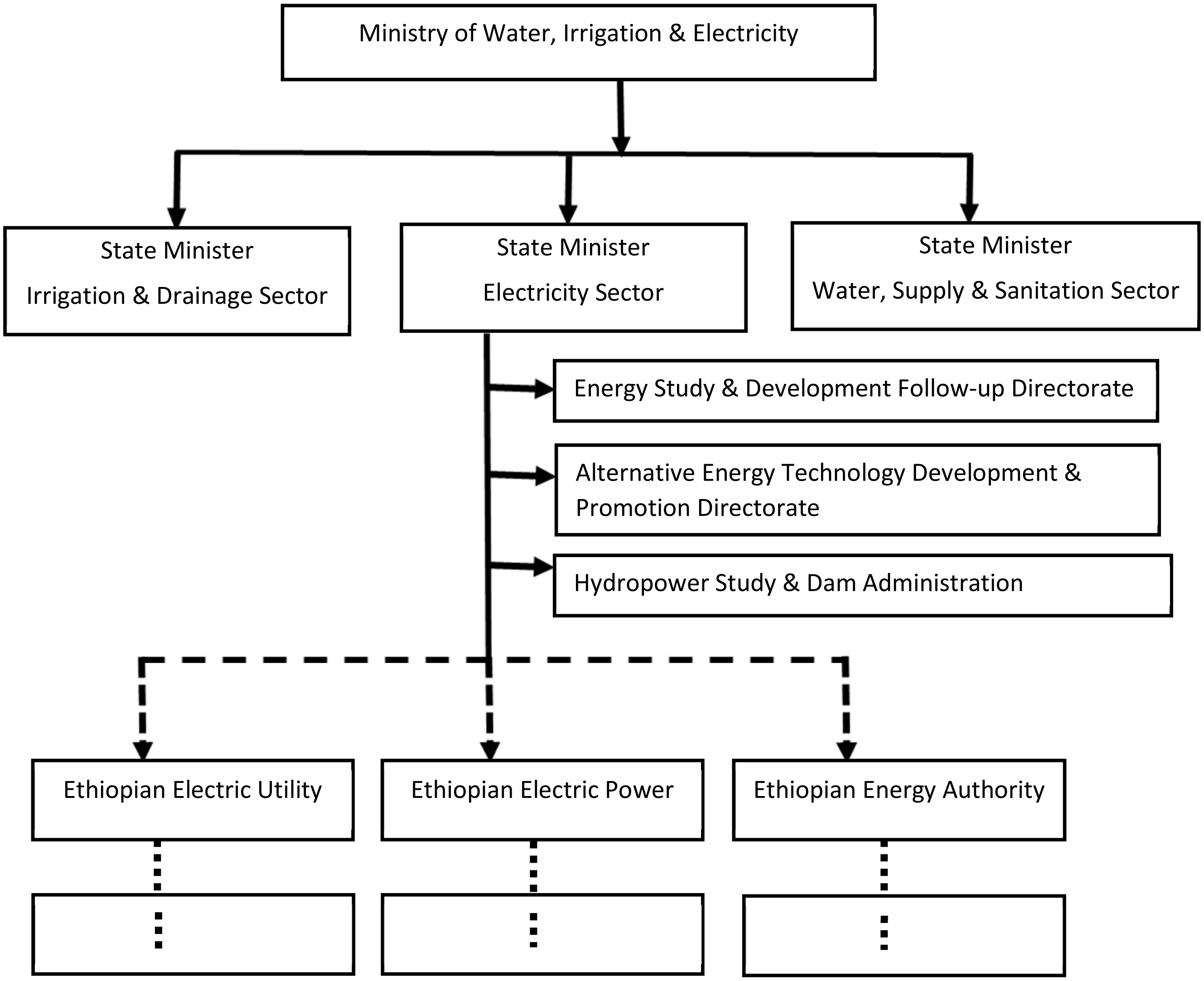


Fig. 5 Organizational structure of Ethiopian power sector

3.3. Energy resources

Ethiopia is one of the most suitable nations in Africa for tapping renewable energy resources. It has a high potential for solar, wind and hydropower in addition to geothermal and bioenergy as alternative source. Table 5 shows the summary of the estimated potential of the country from each resource. It can be seen that, despite the huge exploitable reserve of the various energy resources, the harnessed energy level is too low.

Table 5 Indigenous energy resources in Ethiopia [FDRE, MoWIE, 2017; EEP, 2018/19; Samuel and Getachew, 2014].

Resource	Unit	Exploitable reserve	Exploited percent
Hydropower	MW	45,000	<5%
Solar	kWh/m^2/day	Avg. 5.5	<1%
Wind power	GW	1,350	<1%
Wind speed	m/s	>6.5	-
Geothermal	MW	10,000	<1%
Wood	Million tons	1,120	50%
Agricultural waste	Million tons	15-20	30%
Natural gas	Billion m^3	113	0%
Coal	Million tons	300	0%
Oil shale	Million tons	253	0%

Hydropower

Ethiopia is endowed with abundant water resources distributed in many parts of the country. As shown in Fig. 6, there are eight major basins (Tekeze, Abbay, Baro-Akobo, Omo-Ghibe, Rift Valley, Awash, Wabbi-Shebelle and Genale-Dawa) with an exploitable hydropower potential of 45,000 MW. Over half of this potential is located in the Abbay and Omo river basins, where the Grand Ethiopian Renaissance Dam (GERD) and Gilgel Gibe-III power plants are located [Seleshi et al, 2007].

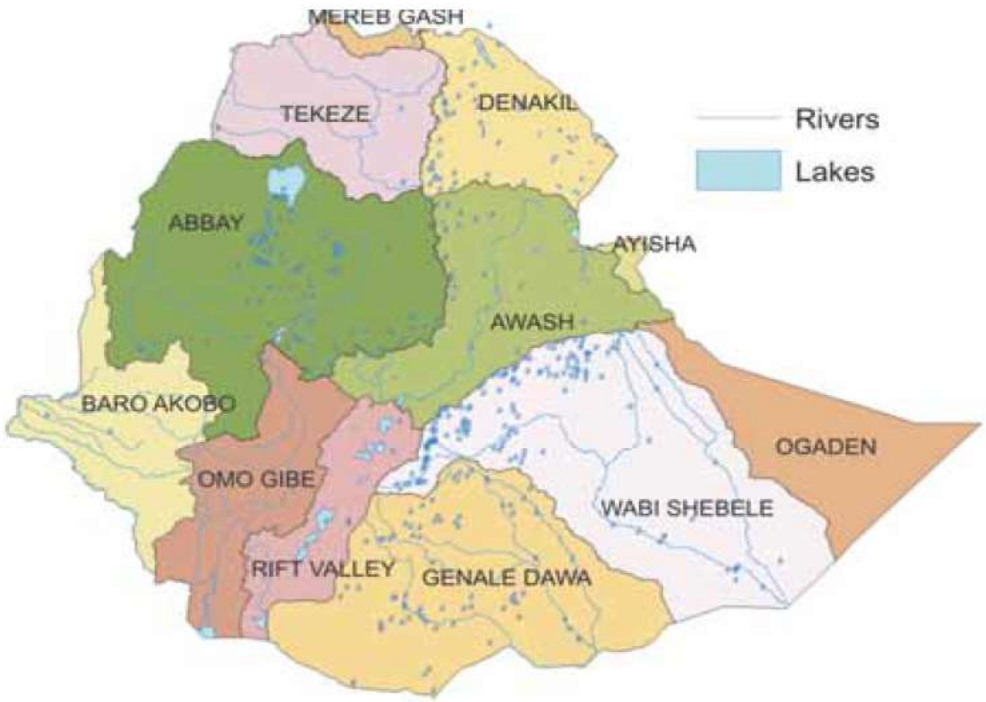


Fig. 6 Major river basins in Ethiopia [Seleshi et al, 2007].

Table 6 lists the installed capacity and average energy production of the existing and under construction power plants throughout the country. The total installed capacity of the existing hydro powerplants is about 3,815 MW while the total capacity of the plants under development amounts to 11,600 MW. The projects with numbered names indicate that they are linked (i.e. constructed on the same river basin).

Table 6 Existing and under construction hydropower plants [GMSP-SIS, 2019]

Name	Status	Capacity (MW)	Average Energy (GWh/year)
G. Gibe-I	Existing	184	882
G. Gibe-II	Existing	420	2,030
G. Gibe-III	Existing	1870	5,348
Tana Beles	Existing	460	2,749
Fincha	Existing	134	615
Tekeze	Existing	300	1,400
Melkawakena	Existing	153	555
Amertinesh	Existing	97	595
Koka	Existing	42	133
Awash-II	Existing	32	183
Awash-III	Existing	32	184

Aba Samuel	Existing	6.6	28
Tis Abay-I	Existing	12	52
Tis Abay-II	Existing	72	10
GERD	Under construction	Design changes (5,250 to 6,000 to 6,450) Current: 5,150	14,684
Genale Dawa-III	Under construction	254	1,690
Koysha	Under construction	2,160	6,460
Chemoga Yeda 1	Under construction	162	627
Chemoga Yeda 2	Under construction	118	460
Dabus	Under construction	798	3,433
Geba 1	Under construction	214	952
Geba 2	Under construction	157	753
Genale 5	Under construction	100	573
Genale 6	Under construction	246	1,528
Baro 1	Under construction	166	652
Baro 2	Under construction	507	1,955
Genji	Under construction	214	909
Wabi Shebele	Under construction	87	689

In addition to the existing and already under construction power plants, there are also candidate projects that are under plan (Table 7). Their total capacity is estimated to be more than 6,800 MW.

Table 7 List of candidate hydropower plants [GMSP-SIS, 2019]

Name	Capacity (MW)
Beko Abo	935
Birbir	467
Werabesa, Halele	436
Tams	1,700
Karadobi	1,600
Upper Mendaya	1,700

Geothermal

Geological surveys of the Ethiopian Rift Valley show that there is a geothermal development potential of up to 10,000 MW. The only geothermal plant currently available in the country is Aluto Langano with an installed capacity of 7.5 MW. However, as shown in Table 8, there are various power plants that are under construction and under plan which in total amount up to 1,400 MW.

Table 8 Existing, under construction and candidate geothermal power plants.

Name	Status	Capacity (MW)	Average Energy (GWh/year)
Aluto Langano	Existing	7.5	50
Aluto Langano 2	Under construction	70	552
Corbetti-I	Under construction	20	160
Corbetti-II	Under construction	50	204
Corbetti-III	Under construction	200	816
Tulu Moye-I	Under construction	50	204
Tulu Moye-II	Under construction	100	408
Tulu Moye-III	Under construction	100	408
Tulu Moye-IV	Under construction	250	1020
Various sites	Candidate	550	-

Biomass

The country's biomass resources include residual from agriculture, harvests from forests, crop residue, energy crops, animal manure, and residues from agro-industrial and food processes. The harvest from forests or wood is estimated to be about 1.1 billion tons while the agricultural waste is 15-20 million tons. Even though, most of the biomass energy use in the country is traditional combustion, there are also significant cogeneration and waste processing plants. Cogeneration is the electricity generation from residues remaining from sugar factories. The residue called bagasse is burned at the cogeneration plants to produce steam and electricity. The electricity is used for internal consumption of the sugar industries and the surplus is exported to the grid. The existing and future candidate cogeneration, waste processing and biomass generation plants are shown in Table 9.

Table 9 Existing and future candidate cogeneration and biomass plants

Name	Status	Capacity (MW)	Average Energy (GWh/year)
Reppi	Existing	25	90
Beles	Existing	60	53
Welkayt	Existing	82	72
Tendah	Existing	70	61
Kasem	Existing	64	56
Omokuraz	Under construction	220	193
Melka Sedi	Future candidate	137	1,080

Solar

Solar resource in Ethiopia is huge as the country is located near the equator. The annual average daily radiation reaching the ground is estimated to be 5.5 kWh/m^2. Solar photovoltaics are usually promoted to replace fuel-based lighting and to meet off-grid electrical needs in rural areas. In addition, solar power is also used for telecommunications, village well pumps, health care and school lighting, etc. So far, the country has about 5 MW of off-grid solar.

With the sharp cost reduction witnessed in photovoltaic technology, solar generation projects are considered favorable and cost competitive in the country. As a result, many candidate projects at different locations are planned in the future (Table 10).

Table 10: Existing and future candidate PV projects.

Name	Status	Capacity (MW)	Average Energy (GWh/year)
Off-grid solar	Existing	5	-
Metehara-1	Candidate	100	210
Metehara-2	Candidate	100	210
Dicheto	Candidate	125	263
Gad	Candidate	215	263
Diredawa	Candidate	200	420
Jijiga	Candidate	200	420
Harar	Candidate	200	420
Weranfo	Candidate	100	210
Humera	Candidate	200	420
Mekele	Candidate	200	420
Welenchiti	Candidate	200	420
Awash	Candidate	200	420
Bahirdar	Candidate	200	420
Adigrat	Candidate	100	210
Hurso	Candidate	200	420
Metema	Candidate	200	420

Wind

Wind energy like the other renewable energy sources is also very high in Ethiopia. According to the wind master plan prepared by the GoE in collaboration with Chinese government, the country has a capacity to produce an astounding 1,350 GW of energy with an average wind speed more than 6.5 m/s measured at 50m above ground [Habte et al, 2016; FDRE, MoWIE, 2017]. However, the existing and ongoing projects are limited to the northern and eastern parts of the country that amount to 324 MW. Various candidate sites for potential wind development in the country are identified as shown in Table 11 with their respective total capacity and average energy production.

Table 11 Existing and future candidate wind-farm plants.

Name	Status	Capacity (MW)	Average Energy (GWh/year)
Adama-I	Existing	51	134
Adama-II	Existing	153	430
Ashegoda-I	Existing	120	315
Aysha-I	Under construction	120	436
Assela	Under construction	100	365
Aysha-II	Candidate	310	950
Ashegoda-II	Candidate	300	815
Iteya	Candidate	150	460
Debrebirhan	Candidate	100	306
Adama-III	Candidate	300	920
Sure	Candidate	200	543
Denbel	Candidate	300	815
Diredawa	Candidate	300	815
Gode	Candidate	200	543
Adigala	Candidate	300	815
Mekele	Candidate	300	815

Thermal generation

Thermal generation refers to natural gas, coal, oil and nuclear-fired power plants. The country has 113 billion cubic meters of natural gas reserve. Currently, there are no existing natural gas-fired power plants, however, the GoE has announced that it will start natural gas export to the global market. And coal reserve is estimated to be about 300 million tons. There are no existing coal power plants for electricity generation, but a relatively smaller amount of coal is used as an energy source in the existing cement industries.

The country also has an oil reserve of 253 million tons. Currently, there are few reciprocating diesel generators that are used for backup as an emergency reserve. Table 12 shows the existing and future thermal electricity generation candidates including diesel, simple cycle and combined cycle gas turbines.

With respect to nuclear energy, the GoE has announced its long-term plan for development of nuclear power plant, and it has made a number of collaborations and signed memorandum of understanding on nuclear cooperation with Russian firms to pave the way for the construction of nuclear power plant, research reactor, uranium ore exploration, etc.

Table 12 Existing and future thermal generation candidates [GMSP-SIS, 2019].

Name	Status	Capacity (MW)
Diredawa diesel plant	Existing	40
Kaliti diesel plant	Existing	12
Awash Sebat kilo diesel plant	Existing	35
Reciprocating plant	Candidate	70
Simple cycle GT	Candidate	140
Combined cycle GT	Candidate	420

3.4. Energy policies and strategies

According to the second Growth and Transformation Plan [GTP-II, 2016], the main objectives of the energy and electricity sector are to expand power transmission considering environmental conservation issues, make service delivery reliable and efficient and transform institutions.

The following key strategic directions are developed to meet the above policy objective in the energy and electricity sector.

- Giving high priority and focus to generate sufficient power for both domestic consumption and export.
- Strengthening cross border energy trade.
- Increasing access to affordable and adequate modern energy.
- Expanding clean and carbon-free renewable energy sources in the order of priority as i) hydroelectric power generation ii) geothermal energy iii) wind power iv) solar energy. i.e. Hydropower is considered as the backbone of the country's energy generation while promoting and enhancing the other renewable sources development to increase security and reliability of energy supply.

- Expanding biomass energy and thereby reduce fuel wood consumption, reduce deforestation and protect desertification.
- Strengthening development of biofuel products for household services and transport sector through creating sustainable network with research institutions and universities, expand periodic monitoring and support, awareness creation, etc.
- Fully addressing power supply interruption problems by upgrading and expanding power transmission and distribution lines.
- Improving the energy efficiency of systems and operations.
- Strengthening energy sector governance and build strong energy institutions.
- Enable and encourage the private sector to participate in power generating activities through narrowing the gap in the areas of technology, finance and project administration.
- Strengthening energy sector financing.

3.5. Assessment of resource adequacy in Power sector reforms of Ethiopia

All sources of renewable energy would have huge contributions to Ethiopia's green energy development, as the government intends to achieve the middle-income status by 2025 [FDRE, MoWIE, 2017]. But the country's renewable energy potential is largely untapped. The interconnected system (ICS) consists of 13 hydro, six diesel standbys, one geothermal and three wind farm plants with installed capacities of 3,814 MW, 87 MW, 7.5 MW and 324 MW, respectively, implying a total of 4,233 MW national generating capacity. The generation is dominated by hydropower accounting for some 90% of the total generation. A number of hydropower plants are also under construction including the Grand Ethiopian Renaissance Dam, GERD (5,150 MW). The government's aim is to achieve 17,208 MW installed capacity by 2020. According to the second Growth and Transformation Plan (GTP-II), that is guiding the overall development endeavors of the country; in year 2020, 13,817 MW is planned to be generated from hydropower; 1,224 MW from wind, 300 MW from solar, 577 MW geothermal, 257 MW from biomass and the remaining from waste, gas and sugar-factory cogeneration [GTP-II, 2016].

3.5.1. Electricity Access

The country has managed to achieve universal electricity access to almost all urban areas, while access to electricity in rural areas is still very limited although expanding at a rapid pace. About

80% of the population resides in rural areas, largely relying on traditional biomass energy sources for cooking and heating. The current access rate is 29% rural and 85% urban population which translates to about 40% total electricity access with per capita consumption of 0.04 kW [USAID, 2018]. Majority of the supply is through the national grid, which accounts to about 28% and the remaining 12% is via off-grid access.

The first rural electrification project, launched in 1999/2000, resulted in electrification of 667 towns [FDRE, MoWIE, 2017]. It mainly focused on extending the network to major towns and small towns (commonly called 'Woreda') located close to substations or existing distribution lines. However, in 2005, a more ambitious endeavor called the Universal Electricity Access Program (UEAP) was launched that aimed to promote socioeconomic development of rural areas in the country by expanding the electricity network.

Between 2005 and 2015, UEAP has been able to spread out the electricity grid to about 6,000 towns and villages and achieve 60% grid coverage (geographical access) in the rural areas [FDRE, MoWIE, 2017]. The program also showcased the social and economic impact of electricity through creating business opportunities, improving health and education service as well as improving lifestyle. But considering the remoteness, large population and sparse density; extension of the grid is technically difficult, inefficient and costly.

3.5.2. Electricity reform activities and its challenges

Many literature have shown that the driving force behind power sector reforms in developing countries is the poor technical and financial performance of their electricity industry. The main technical problems are lags in generation capacity and high transmission and distribution (T&D) losses. Whereas, the financial problems are reflected by low-debt coverage, insufficient cash for new investments and subsidized prices [Gratwick and Eberhard, 2008; Erdogdu, 2013]. Ethiopia has faced both technical and financial problems. Technical problems in which rotational load shedding has been in practice due to insufficient generation and high T&D losses accounting for 23% [GTP-II, 2016] against a world average of 9% [World Bank, 2006], frequent interruption and poor power quality were the prevalent characteristics of the grid network. Lack of the provision of adequate and reliable electricity has also been the bottleneck for accelerating the government's major economic plan on growth of manufacturing industry. On top of solving all these problems, finding a way to boost the low-electricity access was a big assignment of the government. In order to deal with this crisis, the Government of Ethiopia (GoE) committed itself to embark on reforming the power sector.

The reform began in 2013 by restructuring the utility: Ethiopian Electric Power Corporation (EEPCo), which used to be fully state-owned and vertically integrated enterprise was in charge of generating, transmitting, distributing and selling electricity throughout Ethiopia. EEPCo has been split into two separate public enterprises, Ethiopian Electric Power and Ethiopian Electric Utility (EEP and EEU), each with a very different business, technical focus, and accountability for operation and results. EEP is responsible for generation, transmission and wholesale of electricity nation-wide and export the balance whereas EEU is engaged in power distribution, sales, and customer services. In addition, the Ethiopian Energy Authority (EEA) has also been established as the sector regulator.

In 2017, the GoE introduced an ambitious program, the National Electrification Program (NEP) with a theme 'Light to All' which aims to achieve universal access of electricity nationwide by 2025. The program is designed mainly to consider least-cost grid connection rollout strategy from both grid and off-grid supply that is based on spatial distribution of households. In 2016, 7.6 million households were settled proximately to the existing low voltage (LV) network of EEU, while the other 8 million households (assuming average 5.5 persons per household) were not proximate and could not be supplied by LV lines and required higher voltage levels [FDRE, MoWIE, 2017]. To provide urgent connection, the plan is to connect 4.5 million of the proximate households by 2022 through extending short LV service drops and metering which requires less investment while the other 5.4 million customers (3.1 million proximate and 2.3 million non-proximate customers) by 2025 through extending medium and high voltage lines. In addition, the remaining 5.7 million households are planned to be supplied with off-grid systems. These accounts for some 65% grid-connection and 35% off-grid supply by 2025 which is planned to be the period for 100% electricity access. The off-grid supply is designed for remote settlements and villages where grid connectivity is not the least cost solution. The technologies are mainly stand-alone solar systems, but also mini/micro grid network connections expected to be delivered by the private sector.

Tapping and mobilizing private capital and resources is one of the key-components to scale up generation, transmission & distribution capacity, and increase electricity supply. Focusing only on power generation, public private partnerships (PPPs) are typically represented by independent power producers (IPPs), which design, finance, build, operate, maintain and decommission a power generation plant and contract to sell the electricity generated to a publicly owned power utility [Seattle City Light, 2016]. The GoE currently recognized that engagement with the private sector especially with the development of power generation is crucial to meet the country's investment and energy policies and to establish sustainability in infrastructure investment.

In recent years, the GoE is liberalizing the energy sector for private sector participation, specifically to generate significant financial resources and stimulate investment in power generation and transmission. In January 2018, the GoE has passed the comprehensive Public-Private Partnership proclamation that includes the establishment of a legislation and institutional framework for PPPs. Even though the regulator has setup a basic legal framework which invites private players to undertake generation and transmission of power, the energy tariff was one of the main bottlenecks that hampered the engagement of international investors and private power companies.

Last revised in 2006, the average flat rate tariff in Ethiopia was just under 3 US cents per kilowatt hour. Considering currency depreciation due to inflation, the tariff level has been declining in real terms. Less cost of electricity from hydropower and GoE commitment for endowment of the power sector had a big role for the lowest domestic tariff rate in Africa. The generation cost from hydropower is about 9 US cents per kilowatt hour; compared to the above tariff rate, it can be seen that the government makes a significant subsidy for electricity use.

The electricity generation in the country has quintupled from 850 MW to 4,233 MW within just a decade. With such high and fast generation-growth, the government could no longer afford to subsidize electricity generation. Consequently, as part of developing a workable and viable long-term power sector, the tariff-framework revision started in 2017. After long consultation of the draft, new tariff structure has been effected since December 2018. The new tariff structure is planned to be applied gradually with four phases of increment every following year and the tariff after the fourth year is expected to reflect the full cost of service provision (Table 13). However, the adjustment at this time is designed by considering the affordability for the low-income population. Those within a monthly consumption range of up to 50kWh will stay within the old tariff and continues as is.

Table 13 New tariff structure [Source: EEU website]

Tariff amendment		As of Dec. 2018	As of Dec. 2019	As of Dec. 2020	As of Dec. 2021
No.	Tariff category, kWh/month	Birr/kWh			
1	Residential tariff block				
1.1	1st block -Up to 50 kWh	0.273	0.273	0.273	0.273
1.2	2nd block-Up to 100 kWh	0.4591	0.5617	0.6644	0.767
1.3	3rd block-Up to 200 kWh	0.7807	1.0622	1.3436	1.625
1.4	4th block-Up to 300 kWh	0.9125	1.275	1.6375	2
1.5	5th block-Up to 400 kWh	0.975	1.3833	1.7917	2.2
1.6	6th block-Up to 500 kWh	1.0423	1.4965	1.9508	2.405
1.7	7th block-Above 500 kWh	1.141	1.5877	2.0343	2.481
2	General tariff				
2.1	Flat rate	1.0352	1.3982	1.7611	2.124
3	Low Voltage Industry tariff				
3.1	Flat rate	0.8161	1.0544	1.7611	2.124
3.2	Demand charge rate	50	100	150	200
4	Medium Voltage Industry Tariff 15kV & 33kV				
4.1	Flat rate	0.6047	0.8008	0.9969	1.193
4.2	Demand charge rate	36.885	73.77	110.655	147.54
5	High Voltage Industry Tariff, above 66kV				
5.1	Flat rate	0.5174	0.654	0.7911	0.928
5.2	Demand charge rate	21.91	43.82	65.73	87.64
6	Street Light Tariff				
6.1	Flat rate	1.0352	1.3982	1.7611	2.124
7	Bulk Supply Tariff				
7.1	Demand Charge rate per kW	39.2908	78.5815	117.872	157.16
7.2	Generation Tariff, monthly per kWh	0.2218	0.4435	0.6653	0.887

From the above overview, it can be seen that there were few, but major power sector changes conducted within the past few years. However, it is highly questionable whether these reforms are adequate to support the needs arising from the fast-economic growth of the country, regional interconnection and power sector growth in terms of customer size, finance, human capital and technology. The current significant demand increase is because of the new economic developments such as the railway transport, large irrigation projects, industry zones, housing projects and also due to population growth.

3.5.3. Generation: Adequacy of Supply

A literature search [Seattle City Light, 2016; Eduardo and Milligan, 2014; Ogunnubi and Overbye, 2015] on the definition of resource adequacy shows that there is a common understanding on the subject. Resource adequacy (RA) is interpreted as the ability of a utilities' reliable capacity resources (supply, S) to meet the customers' energy or system loads (demand, D) at all hours within the study period. This is shown in equation (1). At any given hour t, a utility desires that, $S_t \geq D_t$ resulting positive RA. The utility is required to have sufficient resources to satisfy forecasted future demand.

$$\mathrm{RA} = \mathrm{S_t} - \mathrm{D_t} \tag{1}$$

The metrics most commonly used to assess resource adequacy measure the expected days in a year that could face a generation shortfall in addition to estimation of the energy shortage. These include loss-of-load probability (LOLP), loss-of-load expectation (LOLE), loss-of-load hours (LOLH), planning reserve margin and expected unserved energy (EUE) [Eduardo and Milligan, 2014; Ogunnubi and Overbye, 2015].

For the study of Ethiopia's near-future resource adequacy, the indices: reserve margin and expected unserved energy are used. These metrics highly depend on the installed capacity, plant capacity factor and peak demand. The data for these parameters has been carefully assessed considering recent developments on power plant constructions and demand trends. The installed capacity growth in the past five years has been significant. This is illustrated in Fig. 7. In comparison to 2013, the installed capacity has more than doubled mainly due to the addition of one hydropower plant: Gilgel gibe-III (1,870 MW) and two windfarms: Ashegoda and Adama-II with installed capacity of 120 MW and 153 MW respectively. This has increased the total installed capacity to 4,233 MW.

Currently, there are many projects that are under development or with signed Power Purchase Agreement (PPA) contracts. Hydropower stations such as GERD (5,150 MW), Koyisha (2,160 MW) and Genale-dawa-III (254MW) are part of the undergoing projects with 86.94%, 52.81% and 21% construction completion status respectively. In addition, Chemoga-yeda (280 MW), Dabus (798 MW), Geba (372 MW), Genale (346 MW), Baro (645 MW), Genji (214 MW) and Wabeshebele (87 MW) are also in the pipeline at their earliest construction stages.

Geothermal power plants which are expected to be operational between 2020 and 2022 are Aluto Langano (70 MW), Corbetti (270 MW) and Tulumoye (500 MW). Biomass plants using sugar factories' residue as a cogeneration, municipal waste or organic matter are also part of the underway projects with a total capacity of 683 MW that are planned to be commissioned by the end of 2021. Two windfarms: Aysha and Assela with installed capacity of 129 MW and 100 MW respectively are expected to be operational by 2020. A number of Photovoltaic (PV) solar plants with total capacity of about 2,000 MW are also expected to be operational before 2022.

Table 14 shows the expected installed capacities for the future six years in comparison to the target set on GTP-II. The corresponding capacities mentioned in the GTP from different sources with a total of 17,208 MW and 63,207 GWh are planned to be realized by the year 2019/20. Assuming timely completion of the ongoing projects according to their respective schedule and considering construction progress of some of the major power plants, the attainable installed capacity and energy production reserve is determined. All power plants are expected to start at full-capacity generation once they are completed except for GERD where early generation of two units (750 MW) is set to start in 2020 followed by 8 units (3,256 MW) in 2023 and the remaining 6 units (2,442 MW) in 2024.

As shown in Fig. 8, the major share of supply is taken by hydropower both on GTP-II plan and implementation; however, there is significant disparity in terms of magnitude between the target and implementation. The investigation shows that it is impossible to meet the target of achieving 17,208 MW installed capacity by 2023/24 let alone 2019/20. This is confirmed by the year 2023 total actual installed capacity data of 5274 MW that is shown in Table 14.

The delay of GERD by five years plays a major role which was originally scheduled to be completed in 2017; but also, other hydro, wind, solar and geothermal projects where there is a significant shortfall. To study the implication of project delays, we used the Planning Reserve Margin (PRM) which is the ability of the projected capacity resources to meet the projected peak demand given by equation (2).

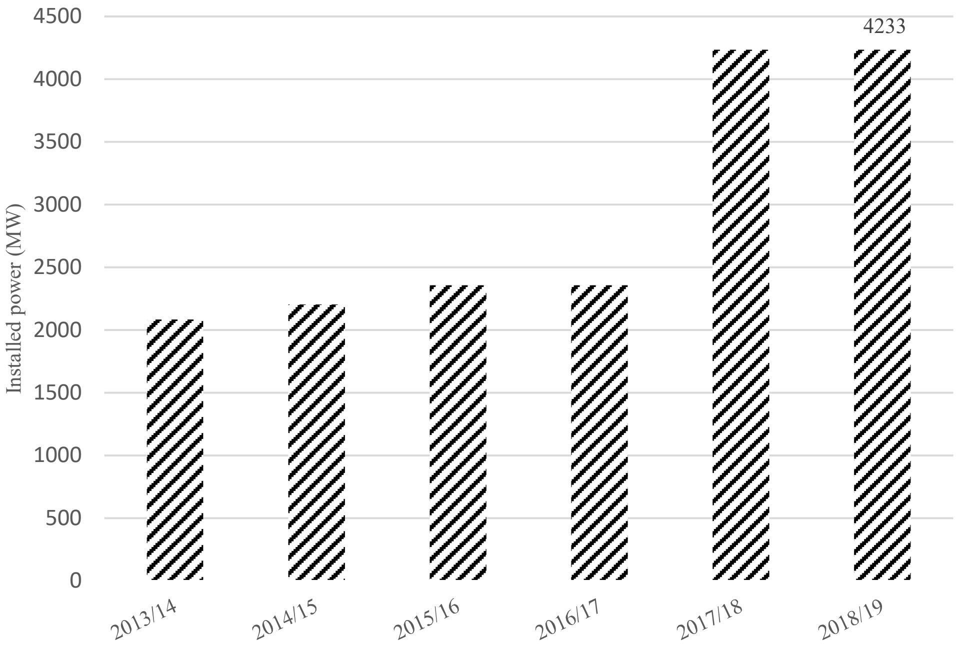
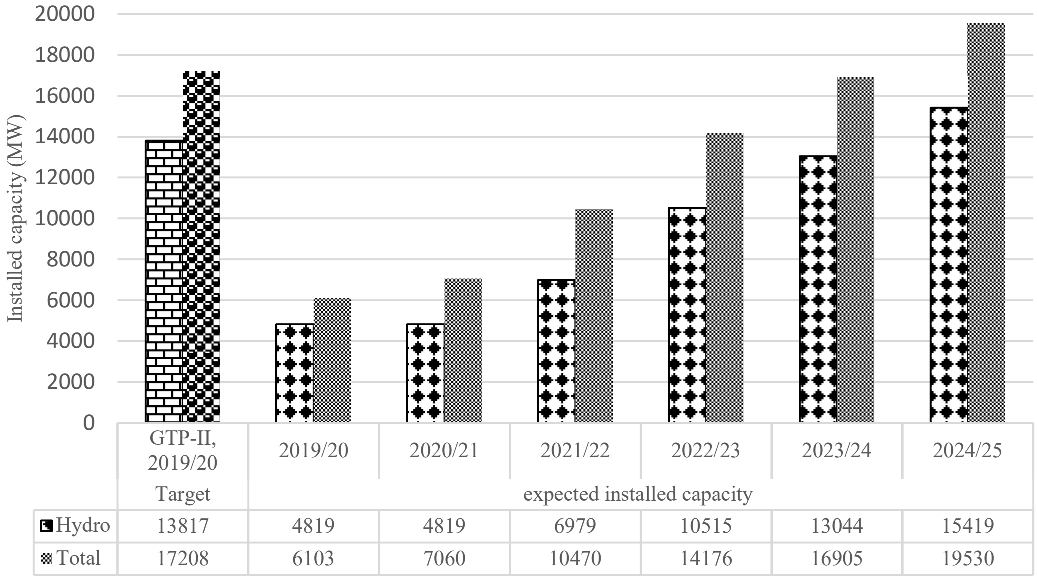


Fig. 7 Installed power capacity in Ethiopia, 2013-2019.



	GTP-II, 2019/20	2019/20	2020/21	2021/22	2022/23	2023/24	2024/25
	Target	expected installed capacity					
◧ Hydro	13817	4819	4819	6979	10515	13044	15419
▩ Total	17208	6103	7060	10470	14176	16905	19530

Fig. 8 GTP target vs. expected installed capacity.

$$\text{PRM} = \frac{\text{Firm Capacity} - \text{Pe} \quad \text{Demand}}{\text{Peak Demand}} \tag{2}$$

The PRM level is given in units of percentage that represents the surplus generating capability above the sustained-peak annual demand. Firm capacity is the fraction of variable renewable energy (VRE) capacity that is guaranteed to meet demand given by equation (3). Where α_i is the capacity credit of power plant/technology i which is considered as "firm"; C_{Pi} is the generating installed capacity of the corresponding power plant.

$$\text{Firm Capacity} = \sum_{i=1}^{n} \alpha_i \times C_{pi} \qquad (3)$$

Dispatchable power technologies (thermal and hydropower using dams) have a value of 100% capacity credit. For VRE (wind and solar), the capacity credit depends on their penetration level and the quality of the resource. Rough estimates of capacity credit for solar and wind in Africa have been used in [Ouedraogo, 2017]. Considering high quality of wind and low share of generating capacity in Ethiopia, we have used 20% for wind power plants. Centralized photovoltaic (PV) plants were given a 5% capacity credit to account for their variability and their sensitivity to cloud cover.

The future annual-peak demand is adapted from robust long-term planning studies conducted on the Ethiopian power system. The Ethiopian Power System Expansion Master Plan (prepared by Parsons Brinckerhoff Consulting) [EPSEMP, 2014] developed in 2014 uses a combination of regression and end- user models to forecast Ethiopia's 25-year electricity demand. The master plan includes peak load forecasting considering domestic demand in various sectors and export projections to neighboring countries. According to this study, the energy demand is forecasted to reach 146,691 GWh by 2037 representing an average growth of 13% per annum from 6,906 GWh in 2012. However, when comparing the forecasted demand with the actual peak demands recorded for the past couple of years, the forecast was very much higher than the actual values indicating that the forecast was too optimistic and need to be revised based on current energy consumption and future development plans. Recently, a new update of the master plan is being developed by United States Agency for International Development (USAID) [GMSP-SIS, 2019]. The study anticipates a 15.2% annual growth rate from 12,540 GWh and 2,148 MW peak demand in 2017 for high scenario forecast considering significant increase in exports as well as estimated improvement in transmission losses.

For the sake of determining the PRM as well as assessing the overall supply adequacy, we have used the forecasted peak demand from the USAID study. The expected installed capacities for the coming years are determined as shown in Table 14 by considering the construction progress of various new power plants. The annual generation from each resource is shown in Table 15, and Fig. 9 depicts the peak demand, installed capacity and corresponding reserve margin for the past and future years while the firm energy production and energy demand are shown in Fig. 10.

Table 14 Installed capacity: GTP target vs. attainable in the near future vs. actual data for the year 2023.

Source Type	**GTP Target, MW**	**Installed Capacity, MW**						
		attainable						***Actual***
	2019/20	***2019/20***	***2020/21***	***2021/22***	***2022/23***	***2023/24***	***2024/25***	***2023***
Hydro	13817	4819	4819	6979	10515	13044	15419	**4819**
Wind	1224	544	544	544	544	544	544	**324**
Geothermal	577	28	78	228	398	598	848	**7**
Biomass and cogen.	781	276	683	683	683	683	683	**25**
Solar	300	350	850	1950	1950	1950	1950	**-**
Gas and others	509	87	87	87	87	87	87	**99**
Total	17208	6104	7060	10470	14176	16905	19530	**5274**

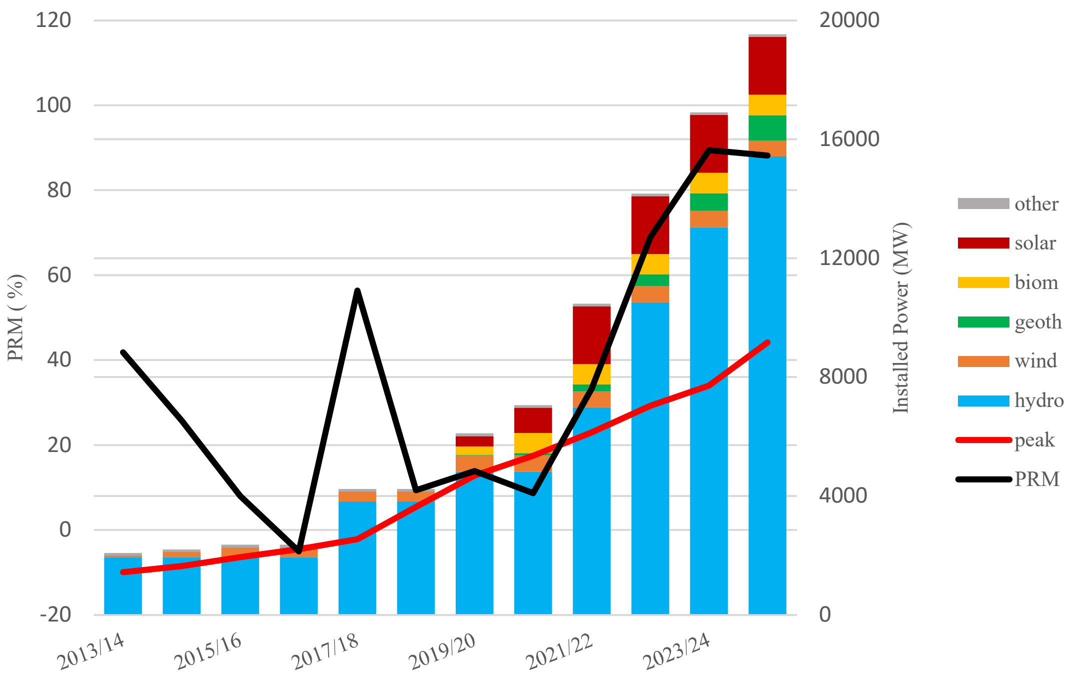


Fig. 9 Planning reserve margin, peak demand and installed capacity.

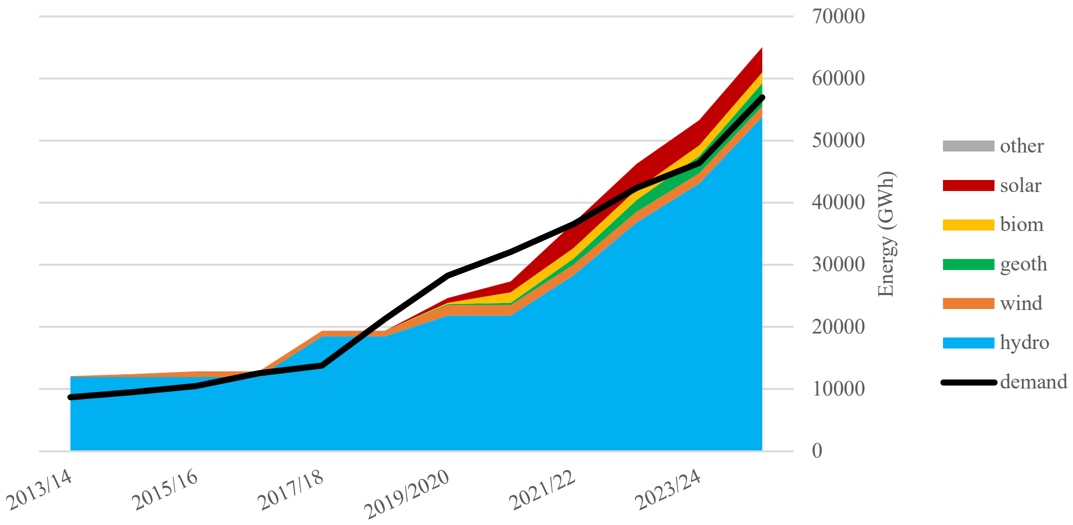


Fig. 10 Firm energy production[1] and energy demand.

([1] Firm energy production is the amount of electric energy guaranteed to be available per year)

Table 15 Annual generation by resource type and ENS

Source Type	**Energy, GWh**											
	2013/14	***2014/15***	***2015/16***	***2016/17***	***2017/18***	***2018/19***	***2019/20***	***2020/21***	***2021/22***	***2022/23***	***2023/24***	***2024/25***
Hydro	11960	11960	11960	11960	18488	18488	21818	21818	28318	36820	43071	53827
Wind	134	449	879	879	879	879	1680	1680	1680	1680	1680	1680
Geothermal	0	0	0	0	0	0	160	364	976	1936	2752	3772
Biomass and cogen.	0	0	0	0	0	0	242	1699	1699	1699	1699	1699
Solar	0	0	0	0	0	0	736	1786	4096	4096	4096	4096
Gas and others	7.55	7.55	7.55	7.55	7.55	7.55	7.55	7.55	7.55	7.55	7.55	7.55
ENS	0	0	0	0	0	1861	3618	4698	0	0	0	0

Due to continuous rise of demand, the PRM had been falling since 2013 with the lowest reserve margin of 8% and -5% in 2015/16 and 2016/17 respectively. This violates the recommended minimum PRM requirement of 10% [Ouedraogo, 2017; Poullikkas, 2015] and 13% [Reimers et al., 2019]. The negative value in 2016/17 indicates that the available resources were not able to meet the peak demand which might have led to load shedding. The margin gets 56% in 2017/18 with the addition of Gilgel gibe-III hydropower plant. In the next three years, the margin is lower than 15%, particularly in 2018/19 and 2020/21 it has a value of 9% which again violates the minimum PRM requirement of 10%. This implies that the available power plants on those years may not be adequate to supply the peak demand. Afterwards, with the addition of GERD and Koyisha hydroelectric station, the PRM is mostly more than 50% meaning the generation firm capacity is very high in comparison to the expected peak demand. It is also evident from the graph that peak demand was steadily but slowly increasing in the past and faster growth is anticipated in the near future.

An evaluation criteria is shown in equation (4) which states that the total firm capacity should always be greater than 110% of the annual peak demand (D_p). This is apparent considering minimum PRM of 10%.

$$\sum_{i=1}^{n} \alpha_i \times C_{pi} \geq (1 + PRM_{min})D_p \tag{4}$$

Using equation (4) as an evaluating criteria, it is seen that the total firm capacity for the years 2015/16, 2016/17, 2018/19 and 2020/21 is less than 110% of the corresponding annual peak demands. Looking also at the energy scenario presented in Fig. 4, the energy demand exceeds the generation reserve for the years from 2018/19 till 2020/21. Equation (5) is used to calculate the Energy Not Supplied (ENS) when the annual energy demand D_i is greater than the expected annual generation G_i of all units existing in the system for the corresponding year i.

$$\mathrm{ENS} = D_i - G_i \tag{5}$$

Consequently, the corresponding ENS for those three years is determined as shown in Table-II which is about 1.8 TWh, 3.6 TWh and 4.7 TWh. This gives a total ENS of 10.1 TWh of energy. This means that the available plants during those years cannot produce adequate energy to supply the huge energy demand of the country. Even though many of the biomass, wind and solar plants will be integrated into the system by then, their lower capacity factor will limit the energy output. The power system expansion master plan used $1,000/MWh as unserved energy cost to see the economic impact of the capacity shortage to the electricity demand. Taking this rate to calculate the unserved energy cost of 10.1 TWh energy would translate into $10.1 billion economical loss. Such amount of money can fully finance two new hydropower stations each with a capacity much more than GERD.

Another important note to be seen from Fig. 9 and Fig. 10 is that the supply mix gets diversified in the coming years. In terms of installed capacity, hydropower penetration reduces from the current 90% to about 79% at the end of 2025. Solar generation is expected to grow to about 2 GW by 2025 followed by geothermal, biomass and wind with roughly 850 MW, 700 MW and 550 MW capacity, respectively. Comparing this with the GTP-II plan of increasing solar to 300 MW and wind to 1.2 GW, there is a significant shortfall in wind capacity whereas much higher capacity in solar.

Finally, it is important to mention that system loss reduction is as important as generation capacity expansion. The losses are currently at 23% which is huge. By implementing projects to cut that in half (reconductoring, adding capacitors and voltage regulators, etc.), the system could see a big increase in supply.

3.6. Discussion

The results of the analysis have shown that it is almost impossible to achieve the GTP-II target of increasing the generation level to 17,208 MW by 2019/20. It is seen that the target is highly likely to be achieved after five years in 2025. It is also seen that the near-future generation reserve is not adequate to supply the increasing energy demand resulting mainly from expansion of electricity access, development of industrial parks, extensive expansion of railway network, extensive agriculture irrigation schemes, new sugar factories and export plan to East African Power Pool (EAPP) countries.

The results presented have important policy and implementation implications. The cost of ENS is huge which has significant impact on the economy of the country. Therefore, corrective measures in terms of revising the existing policies or revamping implementation strategies should be taken as early as possible to continue Ethiopia’s economic ascent through ensuring adequacy of energy supply. Creating a sound and enabling environment for IPP/PPP projects is also essential to obtain and sustain the involvement of the private sector which would contribute a lot particularly with respect to universal access coverage.

The near term anticipated shortages can be mitigated by accelerating the construction of new generation projects with higher capacity factors to cover part of the energy deficit, considering energy import from the regional EAPP, implementing energy efficiency and Demand Side Management (DSM) strategies, improve overall transmission and distribution losses through network rehabilitation and maintenance, encourage Distributed Generation (DG) and small community owned solar and wind generation close to the demand.

4. Long-term evolution of energy and electricity demand forecasting

Energy demand forecasting is the prediction of demand for power and energy into the future and is a fundamental requirement for planning in the energy sector which affects the investment and operational decision of energy projects. It is important to have proper understanding and assessment of the long-term dynamics that determine the evolution of demand. This chapter intends to explore different possible futures and also forecast the long-term energy demand in Ethiopia.

4.1. Literature review

A long-term view spanning decades into the future is necessary to develop and manage complex policy measures that ensure investment and operational decision-making which can lead to sustainable and cost-effective ways of energy supply and demand [McCallum et al, 2019]. To that end, long-term energy demand modeling is crucial in predicting the future energy utilization patterns and trends. It may contribute to strategy formulation and energy policy recommendations with respect to effective utilization of energy resources, improvements in energy efficiency and energy reliability, and emissions reductions [Ouedraogo, 2017].

Policymakers in both developed and developing countries are faced with the question of how the energy sector might evolve in the future with respect to issues ranging from climate change to rural energy access. Accordingly, the use of various modelling frameworks or tools to assess how energy systems can evolve in the future is increasing. The literature provides a list of models and various approaches used to analyse energy demand, policy and planning concerns for the context of developed countries [(McCallum et al, 2019; Adams and Shachmurove, 2008; Baker and Rylatt, 2008; Hong et al, 2019; Jacobson et al, 2017; WWF, 2016; Greenpeace, 2012; World Energy Outlook, 2018]. The most applied tools for long-term forecasting include RAMSES, BALMOREL, LEAP, WASP, MARKAL/TIMES, MESSAGE, PRIMES, HOMER, etc. Some of these approaches have been applied for investigating similar energy policy concerns in developing economies.

Developing countries differ significantly from developed countries and there are a number of characteristics, common to most developing countries, that make the modelling and forecast of their energy systems challenging [Urban et al, 2007; Bhattacharyya and Timilsina, 2009]. The high reliance on traditional energies, shortages and inefficient supply in the modern sector characterized by poor performance of the power sector and limited access, rapid increase in demand for electricity and large share of rural population but rapid urbanization are some of the major challenges witnessed in developing countries. Further, data on prices and supply for traditional energy demand are not always available. In addition, the existence of multiple social and economic barriers to capital flow and technological diffusion, and frequent policy changes makes forecasting in these countries difficult [Pandey R, 2002; Urban et al, 2007; Bhattacharyya and Timilsina, 2009]. Energy demand forecasting relies on many factors and should be able to capture the trends and relationships between the demand and independent economic, technological and demographic variables. It would be feasible to perform short term forecasts through simple mathematical models. However, for long-term forecasting, simple models would not be able to grasp changes and complex interactions of variables such as introduction of new technologies, energy efficient devices and government policies [Qingsong et al, 2010]. In addition, future energy demand projections need to accommodate urbanization and electrification-rates, environmental impact, cost of different fuel sources and, most of all, active demand-side-management policies.

These factors should be carefully considered to understand how the energy demand might evolve in developing countries. However, there are only few studies that have attempted to examine the long-term energy use in a systematic manner within the context of developing countries [Gul and Qureshi, 2012; Kale and Pohekar, 2014; Mondal et al, 2010, 2018]. Even though these studies employed various economic and demographic methods to develop scenarios, analyze their system and design appropriate policies; most of them constrained their scope to the electricity sector and time span of up to 2030. Furthermore, focus is only given to future demand forecasting without considering the specific challenges faced by developing countries as mentioned in the preceding paragraphs.

Even though, a wide range of studies with different aims examined various energy related issues of Ethiopia [Dereje, 2014; Mondal et al, 2017; Hassen et al, 2017; Hassen et al, 2018; Dawit et al, 2019; Tessema et al, 2014; Guta et al, 2015; Gabreyohannes, 2010; Guta, 2012, Samuel et al, 2014; Tadesse, 2018], only a few studies have attempted to assess the long-term energy use development [EPSEMP, 2014; GMSP-SIS, 2019; EEA, 2009; Dereje, 2014; Mondal et al, 2018].

The Ethiopian Power System Expansion Master Plan [EPSEMP, 2014] completed in 2014 was done for Ethiopian Electric Power (EEP) for the period 2013-2037. It uses a macroeconomic multi-variable regression analysis load forecast model and end-user models to determine the 25-year least cost generation and transmission system development plan. Recently, a new update of the master plan was developed [GMSP-SIS, 2019]. It uses regression analysis models and bottom-up sales by considering scenarios (low, base-case and high-growth) and sensitivity forecasts. The Ethiopian energy economy report projected energy demand from 2008 to 2030 by the Ethiopian Economic Policy Research Institute [EEA, 2009]. The report projects demand using energy demand coefficient and macro-economic variables.

The above studies [EPSEMP, 2014; GMSP-SIS, 2019; EEA, 2009] aim to forecast the future energy demand; however, it is important to provide a way of exploring different possible futures that can be meaningful for policy development. In this regard, there are only a few studies that applied energy demand scenario analysis for Ethiopia. [Dereje, 2014] considers business as usual (BAU), moderate shift and advanced shift scenarios of economic development over the period of 2010-2050 to assess sustainable energy system strategies including energy demand projection. [Mondal et al, 2018] forecast sector-wise energy demand up to 2030 by developing three alternative scenarios on improved cookstoves, efficient lighting, and universal electrification. The results mainly suggest that alternative investments can conserve energy and improve environmental sustainability of the country. Even though these two studies attempted to explore the future demand, the developed scenarios did not fully consider the rate-of-change in socio-economy, technological change and future governmental direction.

Considering the identified literature gaps, this chapter aims at seeking answers to these questions.

- What are adequate approaches to capture the specific features of modelling energy demand of developing countries?
- What are the forecasts for the Ethiopian demand and its various sectors, total energy utilization and electricity consumption under different scenarios?
- What is the effect of introducing energy efficiency policies in terms of economic, social and environmental contexts of the country?
- Can Ethiopia meet its ambitious Nationally Determined Contribution (NDC) target of emission reduction?

4.2. Electricity demand trends in Ethiopia

The historical electricity consumption of Ethiopia is presented by grouping customers in representative categories such as domestic, low-voltage (LV) industrial, high-voltage (HV) industrial, public and regional export. All customer groups are connected to the distribution system except the high-voltage industrial customers which are connected to the transmission system. Complete data is available since 2001 with total electricity consumption of 1,388 GWh and it is raised to 10,750 GWh in 2017 with an average growth rate of 13%. The historical consumption distribution by the different customer groups is shown in Fig. 11.

For the considered 17 years, the industrial sector (HV&LV) consumed 36% of the total, domestic sector 35%, commercial sector 22%. The remaining 7% is export to neighboring countries (Djibouti and Sudan) and public loads such as street lighting. The total electricity consumption in the domestic sector was 508 GWh in 2001 and raised to 3,509 GWh in 2017. Such significant rise in domestic power demand in developing countries has been more prominent in contrast to industrialized nations due to high rate of urbanization, growth in population and wealth [Holtedahl et al, 2004]. It is essential to consider these factors when dealing with modeling and electricity demand forecasting of a country like Ethiopia.

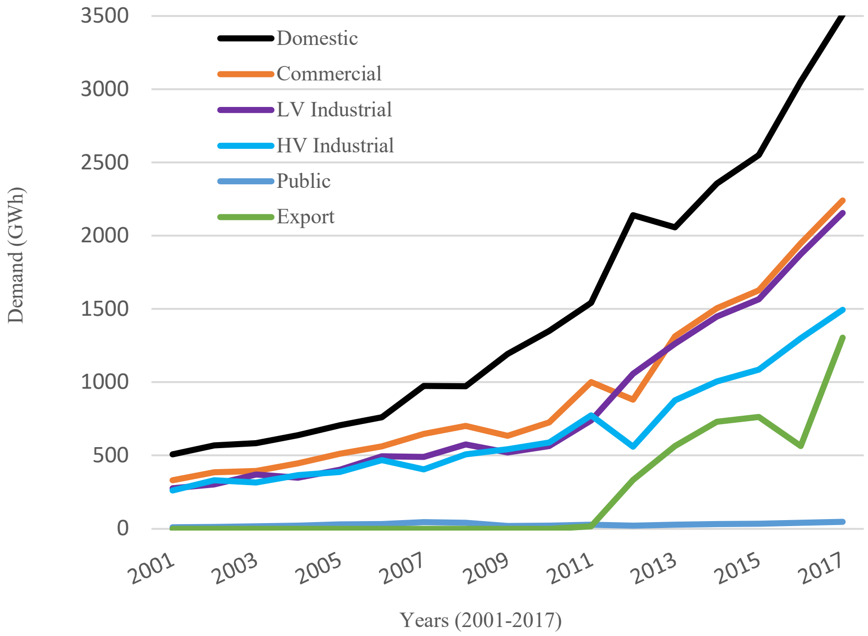


Fig. 11 Historical electrical energy demand trends in various sectors of Ethiopia [Source: GMSP-SIS-2019]

The essential historical data that is needed for modeling has been collected from different sources and is tabulated in Appendix C Table A - 6. According to [CSAE, 2013], the Ethiopian population grew on average by 2.7% every year for the past 17 years. The urban population in 2017 accounted 20.4% of the total population and this number is expected to increase dramatically within the next decades. The per capita income has tripled in the past decade from 267 USD in 2007 to 876 USD in 2017. The Gross Domestic Product (GDP) statistics shows that the share of economic sectors in GDP in Ethiopia since 2001 is mainly from the agriculture and service sector. However, recently the contribution from the industry sector has significantly increased in the past four years.

In 2018, the share of agriculture in the gross domestic product was 34.6%, industry contributed 26.7% and the service sector contributed about 38.7%.

Rural electrification has been very slow until a project called the Universal Electricity Access Program (UEAP) was launched in 2005. Between 2005 and 2015, UEAP has been able to extend the electricity grid to about 6,000 towns and villages and achieving 60% grid coverage in the rural areas [MoWIE, NEP 2.0, 2019]. However, considering the remoteness, large population and sparse density; extension of the grid is technically difficult, inefficient and costly [Dawit et al, 2019]. Currently, only 27% of the rural population gains access to electricity.

Total energy losses due to technical (transmission and distribution components) and non-technical losses are high. Since 2001, it varied between 18 and 27 percent with average estimate of 23 percent. Total system losses have been decreasing over the last two years due to new and better connections for new customers, recent network rehabilitation projects and also partially to the increased amount of exports.

4.3. Methodological approach

Scenarios support the early detection of emerging issues and help policymakers prepare for otherwise surprising developments [UNDP-IEA, 2007]. Accordingly, the energy demand projection is done with two alternative and three policy-driven scenarios in addition to the "business-as-usual" reference scenario.

The development and selection of appropriate scenarios is one of the major considerations in representing the characteristics of the energy systems in developing countries. Failure to represent the features and factors that influence the energy system poses the risk of producing inaccurate results and thereby recommending wrong policies. Accordingly, the scenarios are developed by studying the country's context in terms of energy demand, socio-economy, demography, technological change and future governmental direction in a systematic manner.

Unsustainable use of traditional energy resources in rural areas comprises majority of the population in the country that can significantly contribute to local and global emissions. The approach followed to model this effect is to separately represent urban and rural energy use by analyzing characteristics such as type of resource, energy intensity, penetration level, technology and efficiency. On the other hand, modernization and urbanization of economies leads to life-style changes that causes people to transit to clean fuel technologies such as LPG or electricity which in turn results in rising consumption levels. The relative cost of modern fuels compared to the traditional fuels is also another major factor that determines the transition. This is analyzed by feasible assumptions of urbanization growth rates for future years. Cost analysis of different fuel technologies used for cooking and lighting on the basis of useful energy is also used to project their future penetration.

Characterization of the low electricity access and supply shortage on the energy demand model is also another important issue. This needs the use of appropriate modeling framework that can represent the progress in electrification and energy uses of both urban and rural areas. Furthermore, household energy use in electrified and non-electrified areas should be studied separately by assigning targeted national electrification rates. In the electrified areas, the electricity supply shortage and interruption lead to the use of unsustainable backup solutions. This is represented by analyzing the additional energy use from traditional sources in terms of resource type, energy intensity, penetration level, etc. (as thoroughly discussed in section 4.4).

All these dynamics are specific to developing countries like Ethiopia that are not captured in the models developed for industrially advanced countries.

The energy demand projection is done for different sectors, specifically the electricity demand forecasting is done for various customer categories connected at different stages of the power grid (i.e. different voltage levels). They are categorized as household (HHE_t), HV industry ($HVIE_t$), LV industry ($LVIE_t$), commercial (CME_t), agriculture (AGE_t), transport (TRE_t), public (PBE_t) and export ($EXPE_t$). Demand forecast is made for each of the categories. Then, the total country demand forecast (TED_t) is taken by adding each of the forecasts as shown in equation (6).

$$TED_t = HHE_t + HVIE_t + LVIE_t + CME_t + AGE_t + TRE_t + PBE_t + EXPE_t \qquad (6)$$

Total losses (EL_t) are calculated based on governmental loss reduction targets (TL_t) that is added to the total demand (TED_t).

$$FTED_t = TED_t + EL_t \qquad (7)$$

and

$$EL_t = \left(\frac{TL_t}{1-TL_t}\right) \cdot TED_t \qquad (8)$$

Where EL_t refers to the total transmission and distribution (T&D) losses in year t, TL_t is the T&D losses in terms of percentage of total generation in year t and $FTED_t$ is the final total electricity demand in year t.

The employed demand forecast method is a combination of bottom-up approach and multi-variable regression modeling. Bottom-up consumer level sales forecast is applied to selected customer groups with explicit government plans for new connections and expansions of various projects. In addition, customer applications to the utility company for future supplies and connections to their premises are also included. Such customer groups demand a huge amount of electricity and are usually connected to the transmission system. These customer groups include industrial parks, railway expansion projects, Addis Ababa light-rail project, sugar industry, cement industry, irrigation, steel and metal industry, mining and regional power export.

On the other hand, we have used a multi-variable linear least-square regression modeling for the other sectors such as general HV industry, LV industry, commercial, public and fuel transportation.

$$D_t = B_0 + B_1 \cdot X_{1t} + B_2 \cdot X_{2t} + \cdots + B_n \cdot X_{nt} + B_{n+1} \cdot D_{t-1} \qquad (9)$$

Where D_t - the dependent variable, is the energy demand in the year t, and D_{t-1} is the energy demand in the previous year t-1; B_0,B_1, .., B_{n+1} are the regression weights that are computed in a way that minimize the sum of squared deviations; X_{1t}, X_{2t}, …X_{nt} are the independent variables that potentially impact demand in the specific customer group. These are selected from the entire list of variables such as historical consumption, GDP, per capita income, number of customers and number of households.

The HV industry and LV industry sector use the independent variables: previous year demand (D_{t-1}), number of customers (NC_t) and amount of GDP contribution by the sector (GDP_t).

$$D_t = B_{0in} + B_{1ind} \cdot NC_t + B_{2ind} \cdot GDP_t + B_{3ind} \cdot D_{t-1} \tag{10}$$

The commercial sector demand is dependent on the variables; previous year demand (D_{t-1}), number of customers (NC_t) and per capita income (PI_t).

$$D_t = B_{0com} + B_{1com} \cdot NC_t + B_{2com} \cdot PI_t + B_{3com} \cdot D_{t-1} \tag{11}$$

The transport sector uses the variables: previous year demand, national and sectoral GDP contribution and number of customers. While the public demand is dependent on previous year demand and number of customers.

The forecasts are validated as the best fit by measuring the coefficient of multiple determination (R^2), statistical significance (p-value) and standard error.

The household sector demand forecasting neither uses bottom-up sales forecast nor regression modelling instead it relies on population growth and explicit government strategies and electrification targets. The expected normal growth rates for these variables are entered into the selected modeling tool.

4.4. Model, data and scenarios

Long-range Energy Alternatives Planning (LEAP) is a widely used software tool for energy policy analysis and climate change mitigation assessment. It is an integrated, scenario-based modeling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. The model follows the accounting framework approach to generate consistent view of energy demand based on the physical description of the energy system. Studies using LEAP are diverse in terms of geographical scale, sectoral coverage, and focus of study. This software has been exploited to investigate electricity sector and energy sector of several countries [Dagher et al, 2011; Yophy et al, 2010; Shin et al, 2005; Mondal et al, 2010; Shahinzadeh et al, 2016; Eiswerth et al, 1998]. In particular, it is a widely used tool for energy demand prediction and scenario analysis in developing economies [Gul and Qureshi, 2012; Kale and Pohekar, 2014; Mondal et al, 2018].

Future energy demand in developing countries is highly dependent on the economic and social contexts in addition to new technological innovations. However, these are subject to large uncertainties that are difficult to predict. Therefore, the exploration should be based on scenario-analysis that can be drawn by studying the country's socio-economic context that gives an understanding of the high uncertainties about future energy demand. In addition, sector wise and technological representation of end-uses at a disaggregated level is highly required. This includes rural-urban divide, economic and/or technological transition, informal sector and supply shortage features. In this regard, the most appropriate modeling tool for making the energy analysis is LEAP and the current study, as in the other studies, utilizes this tool to explore and forecast the energy demand up to the year 2050.

The model is also used to estimate the greenhouse gas (GHG) emissions resulting from the use of fossil-fuel within different sectors. Environmental impact is assessed by using the parameter embedded in LEAP's Technology and Environmental Database (TED). It uses the Intergovernmental Panel on Climate Change, IPCC Tier 1 default emission factors to calculate GHG emission from the use of various fuels. This is particularly interesting to policymakers in Ethiopia as the government has bold ambitions under its Nationally Determined Contribution (NDC) to reduce its emissions of 400 $MtCO_2e$ by 64% by the year 2030 [MoWIE, NEP 2.0, 2019].

4.4.1. Model

The energy demand model is primarily structured sector-wise, namely: residential, industrial, commercial, agriculture and transport sector. The data structure for the residential sector follows a bottom-up approach, by using end-use device accounting techniques in LEAP- standard. The residential sector is divided into two main subsectors. i.e. urban and rural. Another division, electrified and non-electrified is also created as shown in the demand model tree in Fig. 12.

It contains four end-use categories including lighting, cooking & baking, refrigeration and other devices (TV, radio, computer, iron, etc.). Data inputs such as population, number and share of households are given to the activity level variable whereas energy consumption data is entered to the final energy intensity variable. The data structure for the remaining sectors is done based on common energy use in different applications or end-uses.

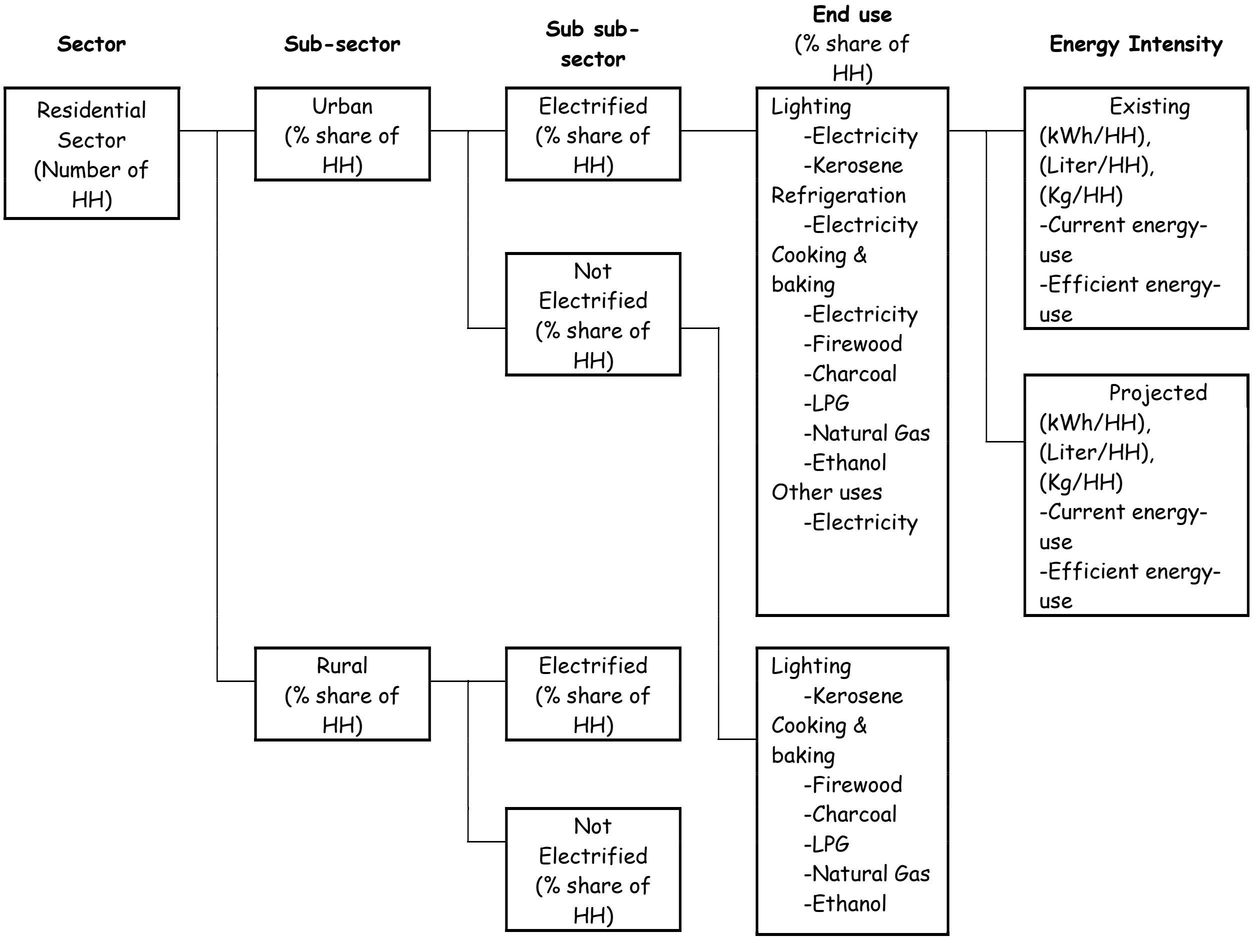


Fig. 12 The developed LEAP energy demand tree for the residential sector of Ethiopia.

4.4.2. Data and key assumptions

4.4.2.1. Key assumptions

Data used in this study is based on extensive data collection, mainly from the electric power sector, including the Ministry of Water, Irrigation and Electricity (MoWIE), Ethiopian Energy Authority (EEA), Ethiopian Electric Power (EEP), Ethiopian Electric Utility (EEU) and National Load Dispatch Center (NLDC). Also, from other sectors such as Central Statistics Agency of Ethiopia (CSAE), National Bank of Ethiopia (NBE), National Planning Commission (NPC), Ethiopian Petroleum Supply Enterprise (EPSE), etc. In addition, necessary local [MoWIE, 2012; NEP 2.0,

2019; CSAE, 2013; NBE, 2016; GTP-II, 2016] and international reports are also used as data sources [World Bank, 2015,2017, 2018; WHO, 2018].

LEAP has four different modules for data input: key assumptions, demand, transformation and resources. Key assumptions include various socio-economic variables such as country population, urban and rural population, households, GDP and other similar data (Appendix C Table A - 7) which affect the level of final energy consumption. The demand module contains the various sectors and customer categories which consume energy such as household, industry, commercial, public and others. In a transformation module, the process of converting primary energy into secondary energy is done and data such as conversion losses are given. Lastly, the resource category includes data for the supply/resource technologies.

In this study, the demand module is sub-categorized into domestic, HV industry, LV Industry, Commercial, Agriculture, Transport, Public and Export. In the transformation module, energy loss data of the power system is given. The demand projection is done for 33 years up to the year 2050 considering 2018 as the first simulation year.

4.4.2.2. Appliance Activity Level and Energy Intensity

The demand data for the domestic sector is entered according to the LEAP demand tree shown in Fig. 12. Accordingly, the major end-use or appliance categories are divided into lighting, cooking & baking, refrigerator and other uses. These appliances have different level of penetration and energy consumption in an average household. The complete data for the year 2017 is shown in Appendix C Table A - 8. Most of the data is extracted from the Energy Access Diagnostic Report Based on the Multi-Tier Framework [World Bank Group, 2018], Application of the World Health Organization Household Energy Assessment Rapid Tool (HEART) Report [WHO, 2018] and [Dresen et al, 2014].

It can be seen that in 2017, 94% of urban households and only 11.7% of the rural households had access to basic electricity. The remaining 6% of urban and 88.3% of rural households had no access to any electricity source and relied on alternative sources mainly kerosene for lighting and wood, charcoal and liquefied petroleum gas (LPG) for cooking and baking.

In addition, to cope with insufficient hours of service and power outages, households use backup solutions for lighting such as candles, torches/flashlights and kerosene lamps. Urban households rely heavily on candles as a back-up solution, while rural households rely more on dry-cell batteries and kerosene lamps. 4.8 percent of urban households and 25.8 percent of rural households use kerosene as a back-up solution [World Bank Group, 2018].

In Ethiopia, 63.3% of households use a three-stone stove as their primary stove, 13.6% use a self-built stove as their primary cooking solution, 18.2% use a manufactured biomass stove, and 4.2% use a clean fuel stove with electricity and LPG. Less than 1% of households use LPG as their primary cooking solution, while 96% of the households use biomass fuels [WHO, 2018; World Bank Group, 2018]. A three-stone stove is a pot balanced on three stones over an open fire. A self-built stove is typically an enclosed stove made using stone, mud, and flat clay that can be slightly more efficient than a three-stone stove. A manufactured biomass stove is typically produced in a factory or by an artisan and usually made of metal and can be considered an improved cookstove. Ethiopian households commonly use injera (traditional Ethiopian bread) and bread baking stoves in addition to regular stoves for cooking (making sauce, tea, coffee, etc.) which consumes between 40% and 65% of the entire household cooking fuel consumption [Dresen et al, 2014].

Urban and rural households use different cooking technologies: 54.3% of urban households use a manufactured stove and 15.3% use a clean fuel stove, while 77% of rural households use a three-stone stove. And 85.4% of rural households use firewood as their primary fuel, while 60.3% of urban households use charcoal [World Bank Group, 2018]. Most households in both urban and rural areas use multiple stove types (i.e. different combination of three-stone stove, self-built, manufactured and clean stove).

According to [World Bank Group, 2018], five different capacity tiers are used to classify the penetration of appliances in urban and rural areas. Medium-load appliances such as refrigerators, freezers and air coolers are assigned in TIER 3 with penetration of 50.5% urban and 5.7% rural grid-connected households. Other-use electrical loads include television, radio, computer, phone charging, etc. are under TIER 1 and 2 which account a penetration of 61.1% in urban households and 75.3% in rural households.

The energy intensity of cooking stoves depends on the cooking technology, fuel type and amount of consumption. Detail data about different cooking stove types is shown in Appendix C Table A - 9. It can be seen that in terms of thermal stove efficiency, electric and ethanol stoves have the highest efficiency of about 60%, followed by LPG (55%), kerosene (42%), charcoal (25%) and firewood (10%). Among the firewood stoves, the manufactured-type has a better efficiency than the self-built and three-stone types. In a study conducted in the field, the fuel saved by the manufactured-type was 22-31% of that with a three-stone fire [Gebregziabher et al, 2018].

Accordingly, by making simple calculations based on daily consumptions, assuming 30% fuel reduction from manufactured-biomass stoves and 10% reduction from self-built stoves; the energy intensity for the different stoves is determined as shown in Appendix C Table A - 8. Energy intensity for injera/ bread baking stove is assumed to be 65% of the total fuel cooking consumption (1057 kg per person) [Dresen et al, 2014].

Table 16 shows the penetration and energy intensity of the electrical appliances applied in LEAP for both urban and rural households. Lighting utilizes 30% of total urban and 42% rural electricity consumption which is calculated to be about 503 kWh and 235 kWh per year per household respectively. Cooking utilizes 35% and 19% of the total consumption. The remaining is consumed by refrigerator and other-use loads. Lighting is assumed to be fully penetrated device as both urban and rural households solely depend on electrical lamps for lighting. Whereas the remaining appliances have partial penetration with electrical stoves accounting only 15.3% urban and 0.6% rural households. The total electricity consumption per household in 2017, is 1676 KWh for urban households and 559 kWh for rural households which is approximately one-third of the urban.

Table 16 Electrical appliance penetration and energy intensity for rural and urban households in 2017

Appliances	Activity Level (% saturation)	Energy Intensity (kWh/HH)
	Urban	
Lighting	100	503
Cooking	15.3	587
Refrigerator	50.5	453
Other uses	61.1	133

Total electricity consumption		1676
Rural		
Lighting	100	235
Cooking	0.6	106
Refrigerator	5.7	168
Other uses	75.3	50
Total electricity consumption		559

4.4.3. Scenarios

In this study, we employ six different scenarios for the projection of the future energy demand. The first one is the business-as-usual (BAU) scenario or reference scenario which assumes continuation of current policies, programs and targets of the government, the two scenarios are alternative scenarios that reflect the uncertainty about future development while the remaining three are policy scenarios. The two alternative scenarios are based on the reference scenario (inherit BAU properties) but with different rate-of-changes in some particular activity such as socio-economy, demography, technological change or future government direction. The three scenarios are policy-driven scenarios that are applied to each of the other scenarios (reference and two alternative scenarios). In the scenarios, population, urbanization, GDP, electrification and other socio-economic factors are set to change. In addition, efficiency improvements from technological advances and demand side management programs are considered to be the main factors for reduction in energy demand over time.

Hence, scenarios of growth in electrification and urbanization (E&U), high economic growth (HEG) and improved energy efficiency (IEE) are designed and their results are mainly compared with the BAU scenario to understand the possible deviation from the normal demand forecast. In addition, their impact on GHG emission is also assessed. We employ the LEAP scenario manager to create and then evaluate alternative scenarios by comparing their energy requirements and environmental impacts. This enables us to see how the energy demand might evolve over time. Below we provide the input data, assumptions and methods used in the reference, alternative and policy scenarios for making the energy demand forecasting.

4.4.3.1. Business as Usual (BAU) Scenario

The BAU/reference scenario is the base of all other scenarios and assumes that historical trends will continue into the future by giving special attention to government policies and strategies. Historical trend of population growth, GDP growth, electrification, urbanization and consumption of energy by sector (as shown in Appendix C Table A - 6) are used to project the future demand. The historical data is of good quality and reliable since it is mainly collected from the Ethiopian electricity sector. In the BAU scenario, it is assumed that the country has no ambition to reduce CO_2 emission and no endeavor to shift to clean fuels. In addition, it is assumed that the current power shortages and interruptions will continue in the future and back-up solutions are necessary. Biofuels such as ethanol and LPG are considered as an important fuel for the last two decades. The energy intensity of electric stoves is assumed to increase by 50% in the year 2040.

Central Statistics Agency of Ethiopia has forecasted the population and urbanization level until the year 2037 [CSAE, 2013] and these rates are used in the BAU scenario. For the remaining years from 2038 up to 2050, the historical trend has been projected with 1.6% (2038-2042) and 1.4% (2043-2050) population growth rates. Similarly, the urbanization level is also targeted to increase from 31.1% in 2037 to 60% in 2050.

In 2017, the government of Ethiopia (GoE) introduced an ambitious program, the National Electrification Program which aims to achieve universal access to electricity nationwide by 2025 [MoWIE, NEP, 2017]. According to this plan, 65% of households are expected to be supplied through grid-connection while the remaining 35% access electricity via off-grid technologies by the end of 2025. Then, by 2030; grid expansion will reach out to 96% of households and only 4% will be supplied via off-grid systems. Accordingly, the BAU scenario is based on this target. However, the progress made in the last two years since the program's launch is slower (40%) compared to the target set (47% total access by 2019). Therefore, considering similar electrification pace, we have only referred the grid-access target (i.e. 65% by 2025 and 96% by 2030) by neglecting the off-grid access target.

Table 17 Assumptions of growth-rates and projected values for different variables under each scenario

Index		[a]Pop'n growth rate	HH size	[b]Urban'n	Urban [c]electr'n	Rural electr'n	Total GDP growth	Per capita income growth	Electric stove [d]pen'n		[e]Total loss
Unit		%	People per HH	%	%	%	%	%	% of urban HH	% of rural HH	%
2020	BAU	2.1	4.7	21.8	96.3	38.0	9.0	9.0	17.1	4.1	21.1
	HEG	2.1	4.7	21.8	96.3	38.0	**11.0**	**11.0**	17.1	4.1	21.1
	E&U	2.1	4.7	**23.0**	96.3	38.0	9.0	9.0	**24.4**	4.1	21.1
	IEE	2.1	4.7	**23.0**	96.3	38.0	9.0	9.0	**24.4**	4.1	**21.3**
2030	BAU	2.0	4.7	27.1	100	96	9.0	9.0	30.0	15.0	17.3
	HEG	2.0	4.7	27.1	100	96	**11.0**	**11.0**	30.0	15.0	17.3
	E&U	2.0	4.7	**33.0**	100	**100**	9.0	9.0	**51.5**	15.0	17.3
	IEE	2.0	4.7	**33.0**	100	**100**	9.0	9.0	**51.5**	15.0	**12.5**
2040	BAU	1.6	4.6	37.8	100	100	7.0	7.0	35.0	30.0	12.5
	HEG	1.6	4.6	37.8	100	100	**8.0**	**9.0**	35.0	30.0	12.5
	E&U	1.6	4.6	**50.0**	100	100	7.0	7.0	**65.0**	**55.0**	12.5
	IEE	1.6	4.6	**50.0**	100	100	7.0	7.0	**65.0**	**55.0**	**9.0**
2050	BAU	1.4	4.6	60.0	100	100	4.0	5.0	40.0	40.0	12.5
	HEG	1.4	4.6	60.0	100	100	**6.0**	**6.0**	40.0	40.0	12.5
	E&U	1.4	4.6	**80.0**	100	100	4.0	5.0	**65.0**	**70.0**	12.5
	IEE	1.4	4.6	**80.0**	100	100	4.0	5.0	**65.0**	**70.0**	**9.0**

[a]population, [b]urbanization, [c]electrification, [d]penetration, [e]Total power system loss

Future GDP growth rate assumptions are based on historical trends, considering IMF predictions and our judgement. Total GDP growth rates of 9%, 7% and 4% are assumed for the years until 2030, 2040 and 2050 respectively. The per capita income growth rate is assumed to be 9% (2018-2030), 7% (2031-2040) and 5% (2041-2050). The reduced growth rate used for later years is associated due to creating a mature and larger economy. Customer growth rate assumptions also depend on historical trends while considering the roles of population growth and grid expansion targets. Customer growth rates of 8%, 6% and 5% for commercial and LV industry, 12%, 8% and 6% for HV industry and 6%,4% and 3% for public load is assumed for the years until 2030, 2040 and 2050 respectively. The summary of all the assumed growth-rates and projected values for the macroeconomic, demographic and other variables for all the scenarios is shown in Table 17. The bold numbers indicate that the value specified for the given scenario is different compared with the assumption in the BAU scenario.

Electricity demand projection is made for 17 industrial parks which have become recently operational, are under construction, or planned to be developed in the long run (see Fig. 13). Feasible operating period and demand level at different years is assumed considering the location, construction time and investment opportunity. In addition, future unidentified industrial parks are also included in the projection. These are expected to be operational from 2030 up to 2050 with increasing consumption.

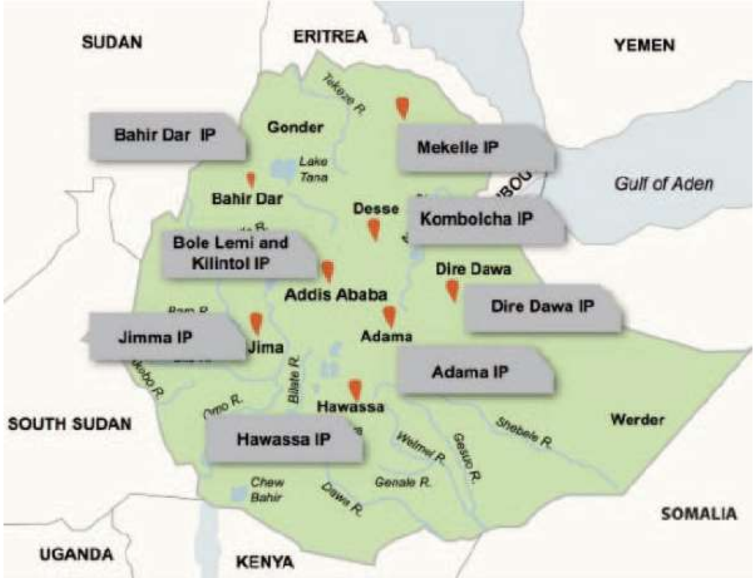


Fig. 13 Existing and planned Industrial Parks [FDRE, MoWIE, 2017]

Considering customer electricity supply requests brought to the utility from cement, mining, steel and metal industries; the energy demand is projected for the future years. Similar approach is followed for agriculture, transport and export sectors. In the transport sector, cross-country railway lines of Ethio-Djibouti, Addis Ababa light railway and 10 other national railways connecting different cities are considered. Reasonable future expansion is also assumed for each of the projects. Increased export of electric power and natural gas to neighboring countries is considered. Electric power export to Sudan and Djibouti has already been started in 2017 with 1.5 TWh and is set to reach 35.3 TWh by 2045. Export of natural gas will start in 2021 with 10 million metric cube and is assumed to increase up to 50 million metric cube and 500 million metric cube by 2030 and 2050 respectively.

Rapid rise of demand for solid fossils is assumed in industry, particularly for cement and steel & metal industries. Complete reliance of fossil-fuel consumption is also assumed in the transport sector which is expected to produce significant growth in diesel, gasoline and jet fuel. The projection is done using regression modeling based on the variables total GDP, service GDP and previous year demand. Increased use of petroleum is also assumed in the agriculture sector for irrigation and other farm activities. Petroleum use in the agriculture and LV industry is set to grow at 9% annual growth rate.

Power loss assumption is based on reduction targets and reviewing the progress made in the past few years. Total loss target is assumed to be continuously reducing from the average historical loss of 23% to 12.5% by 2040 through implementing projects of network rehabilitation, reconductoring, adding capacitors and voltage regulators, etc.

4.4.3.2. High Economic Growth (HEG) Scenario

As mentioned in the introduction, Ethiopia has a big vision of attaining a lower-middle-income country status by 2025 after implementing successive development plans. This has led to remarkable achievements in real GDP growth, infrastructure development and social development which translates into a large demand for energy. The HEG scenario builds up on the BAU/reference scenario by assuming the continuation of high economic growth in the country. Total GDP growth of 11%, 8% and 6% is considered for the years until 2030, 2040 and 2050 respectively. GDP growth by industry is assumed to be 11%, 8% and 5% while the service sector is expected to grow by 10%, 8% and 6%. The agriculture sector GDP growth rate is assumed to be the same with the BAU scenario (i.e. 9%, 8% and 5%). Finally, the per capita income growth rate is targeted to hit 11%, 9% and 6% for the future three decades.

4.4.3.3. Growth in Electrification and Urbanization (E&U) Scenario

The E&U scenario is also based on the BAU scenario but with major difference in country policy and direction. It is assumed that the country has a strong ambition to reduce CO_2 emission through various initiatives. One of those initiatives is to push for a rapid-shift from biomass-based household consumption to clean-fuel based consumption. Biomass-based cooking and injera/bread baking stoves are assumed to significantly reduce their penetration over time. Firewood cooking and baking stoves are targeted to be used in less than 10% and 40% of households by 2045 respectively. With such assumption, electric stoves are expected to penetrate 65% of urban households by 2035 and 70% of rural households by 2045. Such shift to electric stoves and additional new demand is expected to double its energy intensity by

2040. In addition, biofuel-based and natural gas-based cooking stoves are targeted to penetrate 30% of households.

The scenario targets 100% electrification by the end of 2025. In order to reduce the transport sector CO_2 emission, electric vehicles are assumed to be deployed in 2025 with increasing penetration for latter years. 1.1 million electric cars are set to replace fossil-fuel based cars by 2050.

Historically, Ethiopia had a low level of urbanization. However, since 2007, government policies helped the growth of small towns and infrastructure development which increased the tempo of urbanization. In addition, implementation of the GTP with objectives of increasing employment generation in urban areas is likely to result in higher rural to urban migration and thus faster urbanization [CSAE, 2013]. Accordingly, this scenario assumes a faster-urbanization rate of 6% per year which results 80% urban population by the year 2050.

4.4.3.4. Improved Energy Efficiency (IEE) Scenario

Ethiopia has a significant transmission and distribution bottlenecks that limit the delivery of the existing supply from reaching demand centers. Poor reliability, significant transmission and distribution (T&D) loss and low power quality affect the end-use consumers. These capacity, reliability and quality constraints compromise the ability of the electricity sector to support sustained economic growth. Realizing this, the GoE is actively exploring how demand-side management (DSM), energy efficiency and conservation can help lower cost and improve economic growth (EEA, 2019). Accordingly, principal energy efficiency and conservation programs and projects are underway. Some of these include standards and labeling, energy management and auditing, public sector efficiency, technology acceleration, awareness training and accreditation, etc. In the standards and labeling program, minimum energy performance standards are to be developed for the main industrial loads and household appliances. These include electric motors, injera cookers, electric cookers, lighting, refrigerators and freezers, etc.

Therefore, this scenario is a policy-driven scenario that explores the long-term demand evolution by assuming significant efficiency improvements on the electricity sector. The efficiency improvements are applied to each scenario, i.e. the BAU (IEE-1), HEG (IEE-2) and E&U (IEE-3).

Introducing industrial energy audits and industrial efficiency measures on the use of electricity can have the potential to save up to 30% of the electricity consumed in the industry sector by 2040. As a result, progressive efficiency gain is assumed to be effective in the LV industry and HV industry (excluding industrial parks) from the base year until 2040.

Improved lighting standards and DSM programs are expected to reduce the energy intensity of electric lighting in urban households by 1% every year starting from the base year. Similarly, electric stove energy intensity reduction is expected to achieve 0.5% per year. The other assumption is on energy efficiency improvement of refrigerators in urban households with energy intensity reduction of 5% in 2020 and 20% in 2040.

A program to install efficient street lighting systems could also reduce electricity consumed in the public sector. The use of efficient light emitting diodes (LEDs) with proper controlling and monitoring system can reduce the electricity consumption by 60% compared to the conventional street lighting system. The program is assumed to start in 2018 and by the end of 2030 all streetlights in the country are expected to meet the new requirement.

Regarding T&D loss, the government is expected to implement network rehabilitation, reconductoring, adding capacitors and voltage regulators, etc. that result in power quality and system efficiency improvement. Accordingly, the total power loss is targeted to reduce to 12.5% by 2030 and down to 9% by 2035.

4.5. Result and analysis

4.5.1. Demand projection

The final energy demand, fuel consumption and GHG emission are derived for each of the scenarios and end-use categories. Projected final energy consumption for each of the scenarios is shown in Appendix C Table A - 10. The projected demand for the BAU scenario is about 2,950 PJ by 2030 and 4,900 PJ by 2050, a growth of 90% and 215% compared to the demand in the year 2017. Fig. 14 shows the projected energy demand by sector. The domestic sector has the highest share with 2,273 PJ in 2030 and 2,844 PJ in 2050 accounting for 77% and 58% of the total demand respectively. It displays a sharp increase until 2040 and remains at a saturation level afterwards. The transport sector is the second major energy demanding sector, showing a significant increase in the last two decades. It accounts 25% of the total energy demand in 2050. The HV industry, LV industry and other sectors are expected to gradually increase their demand over time.

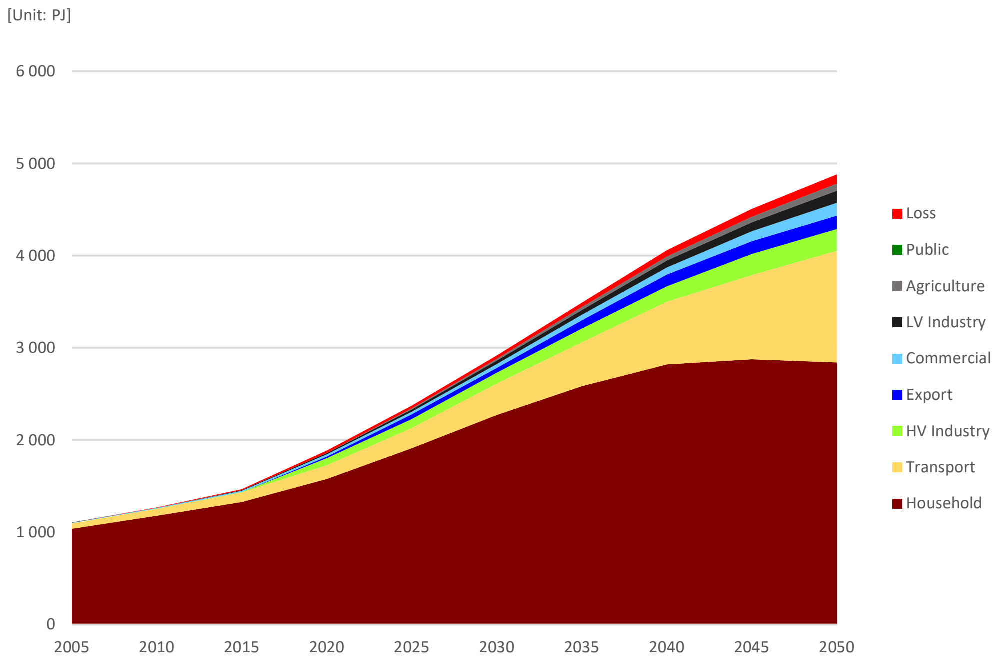


Fig. 14 Final energy demand under BAU

Fig. 15 shows the household sector total energy consumption by end-use under the BAU scenario. Cooking is the major end-use that takes highest energy demand in both electrified and non-electrified urban and rural areas. This is due to the high energy intensity and high penetration of biomass-based cooking in both rural and urban areas. In the last period of: 2040-2050, urbanization causes declining cooking energy demand trend in rural areas.

The transport sector energy consumption projection is shown in Fig. 16 with increasing fossil-fuel demand both in road and air transportation.

Fig. 17 shows the high-voltage industry energy consumption pattern by sector with the cement industry drawing the highest demand and general industry, steel and metal industry, industrial parks following in respective order.

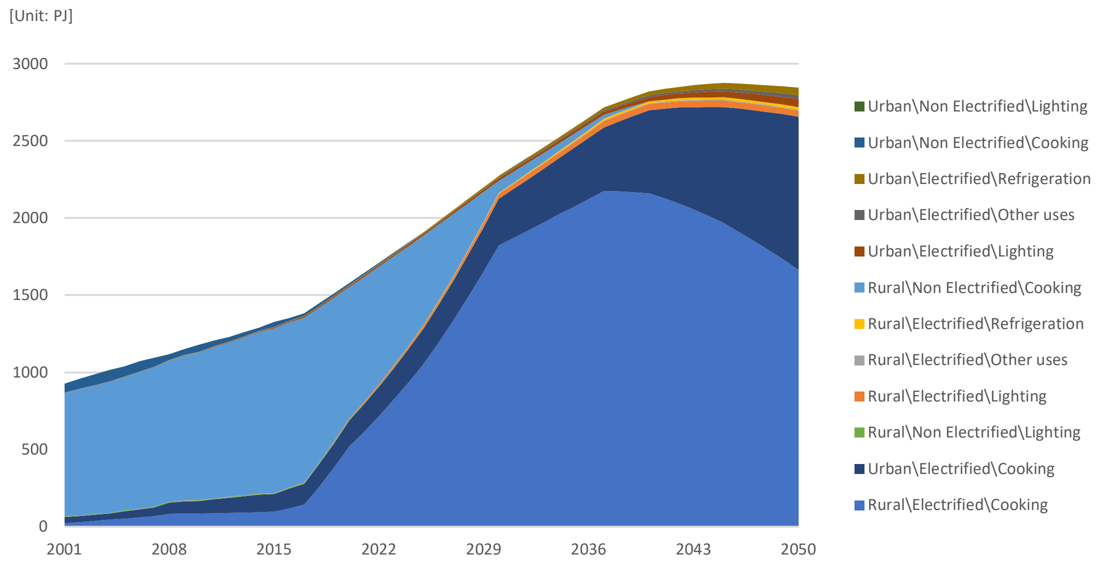


Fig. 15 Household sector total energy consumption by end use under BAU

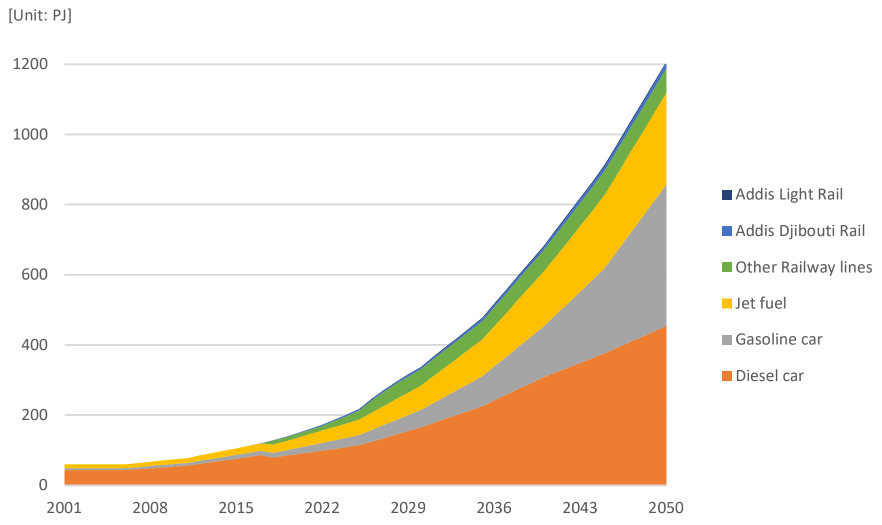


Fig. 16 Transport sector total energy consumption by end use under BAU

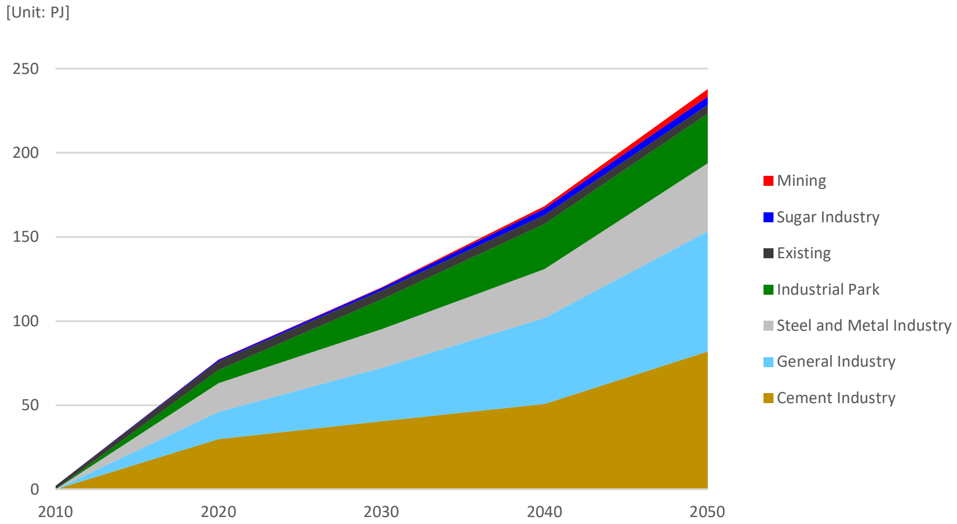


Fig. 17 HV industry sector total energy consumption by end use under BAU

4.5.2. Comparison of demand under various scenarios

A comparison of the scenarios shows that the energy demand is highest for the HEG & IEE-2 scenarios followed by BAU & IEE-1 and E&U & IEE-3 scenarios (Fig. 18). There is a huge difference between E&U vs. BAU and IEE-3 vs. BAU scenario. The HEG scenario is based on the BAU scenario and it assumes a higher economic growth-rate which incurs additional energy demand. The final demand is expected to reach about 5,255 PJ by 2050. Assumption of total GDP growth rates of 11%, 8% and 6% for the future three decades results in demand increase by 7% compared to the BAU scenario in 2050. On the other hand, the energy demand reduces by 42% in E&U scenario and by 46% in IEE-3 scenario.

In the case of electricity demand, the result shows that highest demand is expected for E&U scenario since more electricity-based end-uses are utilized (Fig. 19). In 2050, the total electricity demand under the E&U scenario is expected to reach 292 TWh while HEG demands 289 TWh and BAU consumes 262 TWh. The total energy saving under the IEE scenarios is estimated to be about 43 TWh (IEE-1), 63 TWh (IEE-2) and 56 TWh (IEE-3) in 2050. Technology improvement and DSM activities account 28%, 19% and 41% of the energy saving in IEE-1, IEE-2 and IEE-3 respectively. Industrial energy audit and efficiency measures contribute to 41% (IEE-1), 55% (IEE-2) and 31% (IEE-3) of the total saving while network loss reduction has a share of 30%, 25% and 27% with the same order. The remaining 0.5-1% is due to technology improvement in streetlights.

Fig. *20* shows sector-wise electricity demand projection under the policy-driven scenarios (IEE-1, IEE-2 & IEE-3). It can be seen that the household sector has the highest share of demand. In 2050, the household sector is anticipated to consume about 23%, 22% & 25% of the total electricity demand in IEE-1, IEE-2 and IEE-3 respectively. IEE-2 didn't have much effect on the household consumption share compared to its applied HEG scenario (i.e. both 22%). Whereas IEE-1 & IEE-3 have reduced the share by 1% & 3% compared to BAU (24%) & E&U (28%) scenarios respectively. This implies that the policy-driven measures applied to E&U scenario (IEE-3) have stronger impact on household consumption compared to the others (IEE-1 & IEE-2).

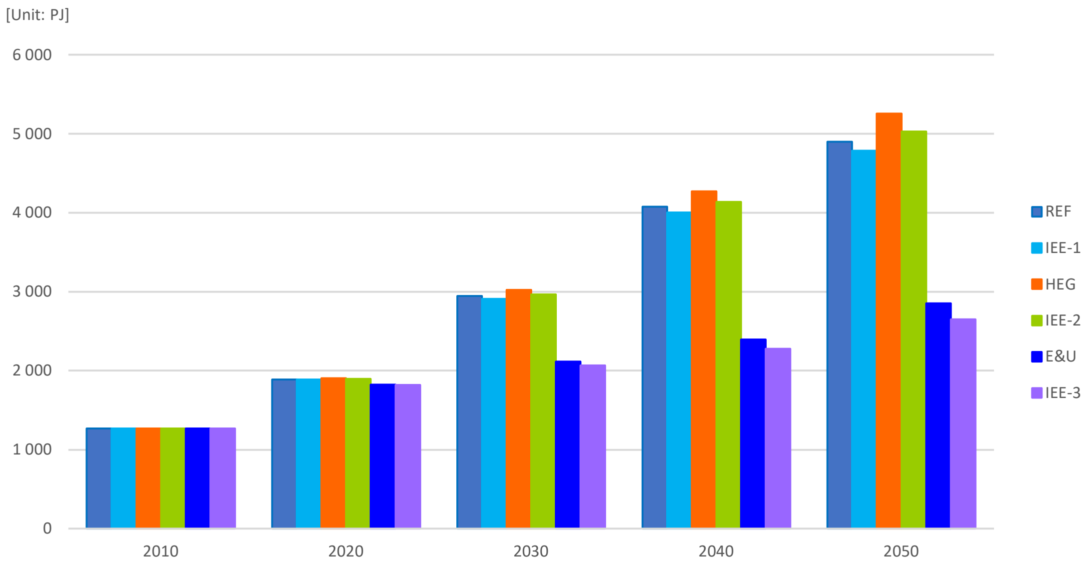


Fig. 18 Total energy demand for all scenarios

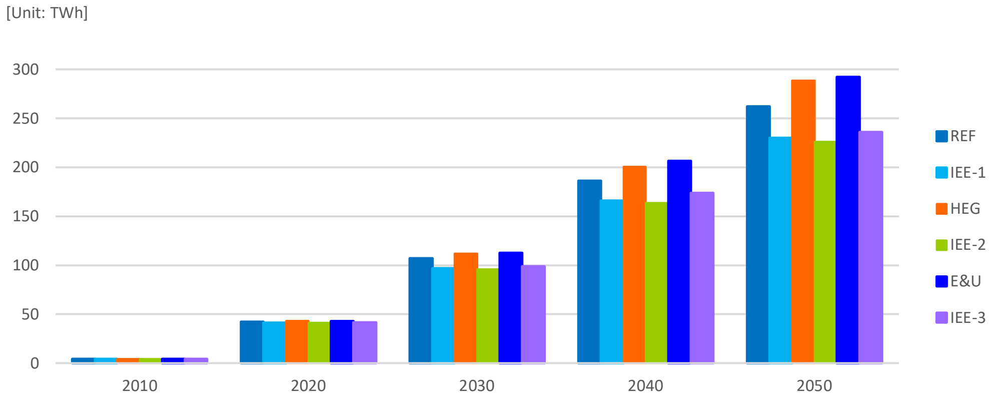


Fig. 19 Electricity demand for all scenarios

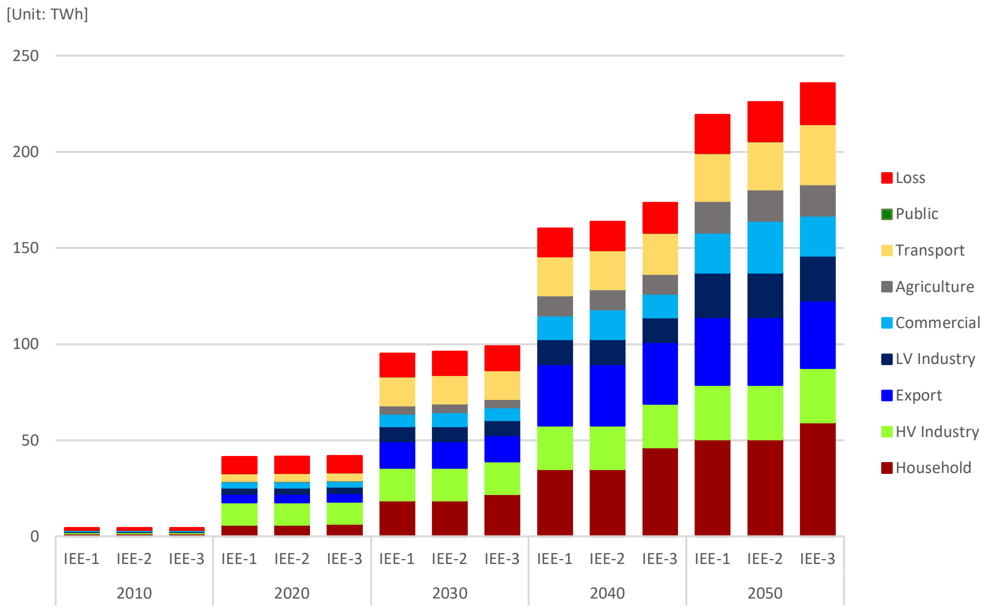


Fig. 20 Electricity demand under policy-driven scenarios

4.5.3. Fuel consumption

Fuel consumption is dominated by wood, accounting 73% of the total fuel consumption by 2030 and 51% by 2050 (Fig. 21). This is mainly driven by the household fuel consumption (Fig. *22*) where 94% of total fuel consumption in 2030 (88% rural and 12% urban) and 86% in 2050 (66% rural and 34% urban) is from wood. Our analysis also shows that the use of traditional biomass will keep on increasing until 2040 under the BAU and HEG scenarios. On the contrary, for the E&U & IEE-3 scenarios, biomass use is expected to reach its peak in 2022 and then decline from 2023 onward. From Fig. 21, it can be seen that electricity demand is expected to increase drastically from 107 TWh (13% of total fuel consumption) in 2030 to 262 TWh (19% of total fuel consumption) in 2050. Fossil fuels like diesel, gasoline and jet kerosene will also see an increasing consumption due to rise in number of fossil-fuel-based road transportation and aviation expansion.

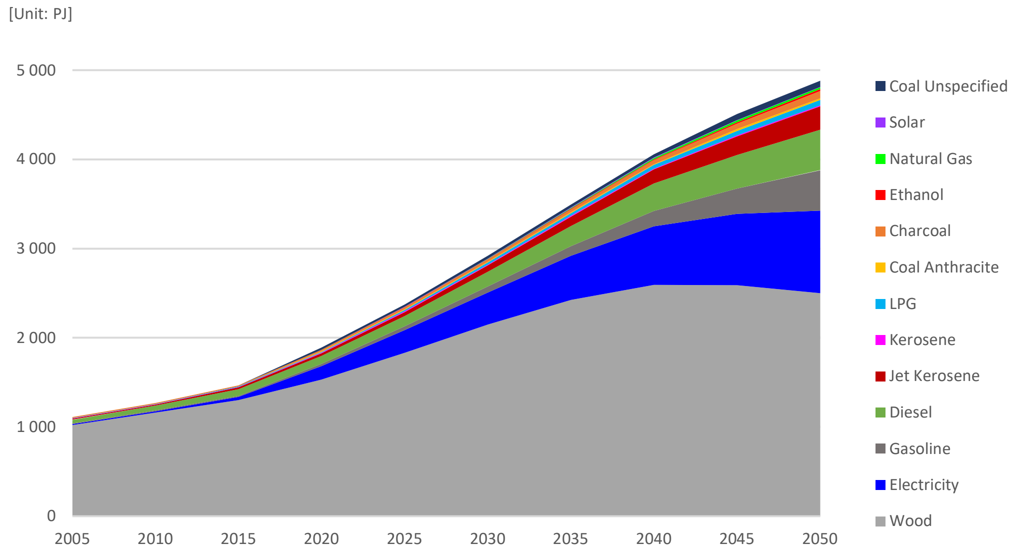


Fig. 21 BAU fuel consumption

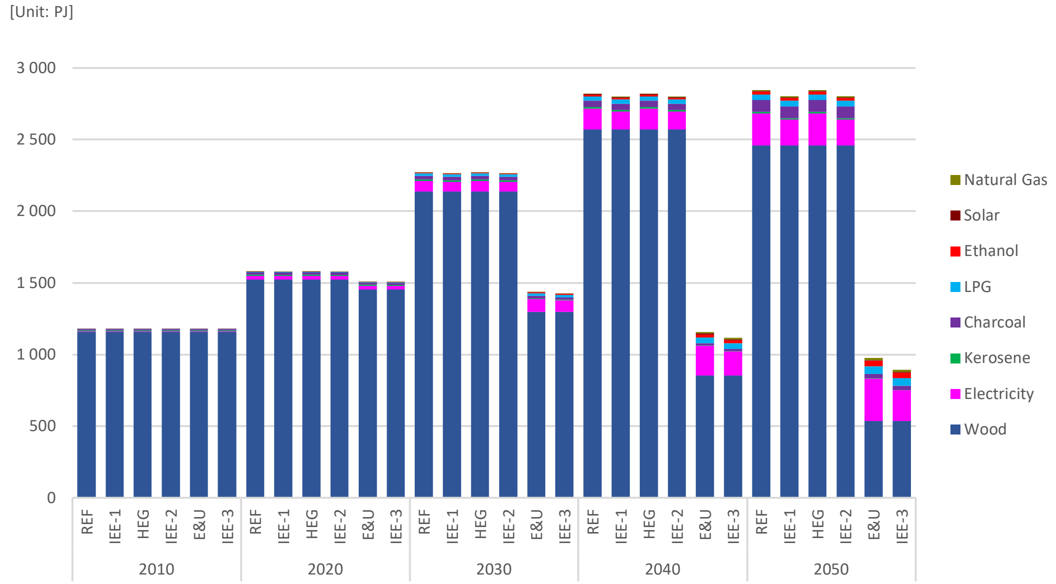


Fig. 22 Household fuel consumption under all scenarios

Fig. *22* shows that the fuel consumption in E&U scenario is entirely different from BAU & HEG scenario. In 2050, the total fuel consumption in E&U scenario is less by more than 65% than the other two scenarios. In addition, the penetration of electricity increases accounting 30% of the total fuel consumption while wood consumption takes about 55%.

4.5.4. Greenhouse gas emissions

It is observed that under the BAU scenario in 2030, biogenic carbon dioxide emission reaches 122 million-ton CO_2e, 30 million-ton non-biogenic CO_2e and about 11 million-ton non-CO_2 emission (Fig. 23 and Fig. 24). Biogenic carbon dioxide emissions are defined as emissions from a stationary source directly resulting from the combustion of biologically based materials, mainly from biomass burning while non-biogenic CO_2 emissions are from the use of transportation fossil-fuels. In this study, biogenic CO_2 emissions are not treated as "carbon neutral" despite the fact that the country is taking various initiatives to tackle deforestation by planting many trees. The large amount of carbon released into the atmosphere due to burning biomass may take decades for the new forests to draw back the same amount of carbon out of the air. This shows that the process has the potential to become "carbon neutral" over very long-time scales but not in the short term where world leaders are working towards potentially reducing the global carbon emissions in the coming decade.

In addition, there are also other small non-CO_2 GHG emissions like carbon monoxide, methane, non-methane organic compounds, nitrogen oxides, nitrous oxide, etc. (Fig. 23).

Biogenic carbon dioxide emissions are expected to further increase from 122 $MtCO_2e$ in 2030 to 160 $MtCO_2e$ in 2040 and slowly reduce for the remaining years. On the other hand, non-biogenic carbon dioxide emissions keep on increasing by more than a fourfold from 30 $MtCO_2e$ in 2030 to 106 $MtCO_2e$ in 2050. This shows that the transport sector heavily relies on fossil-fuel and could be a potential target to reduce CO_2 emission in the long-run.

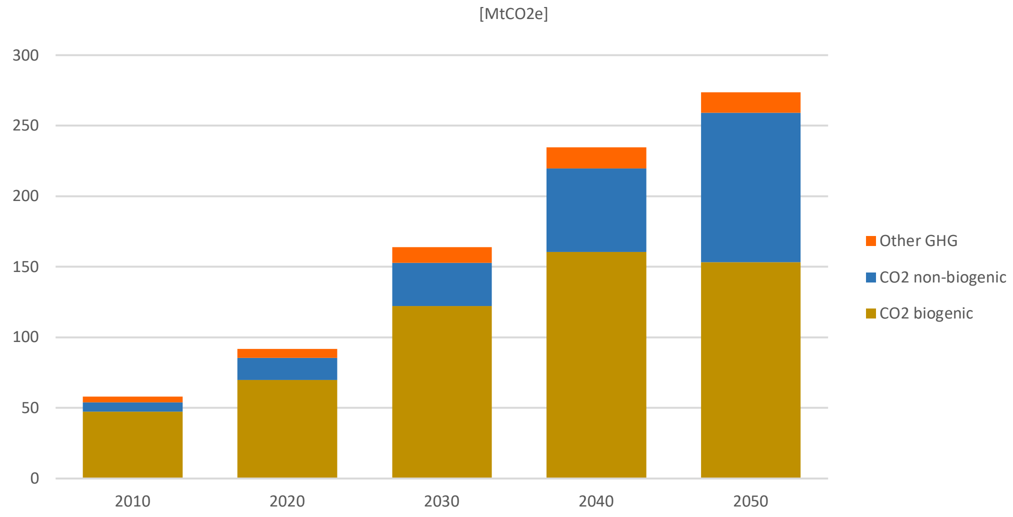


Fig. 23 Total GHG under BAU scenario

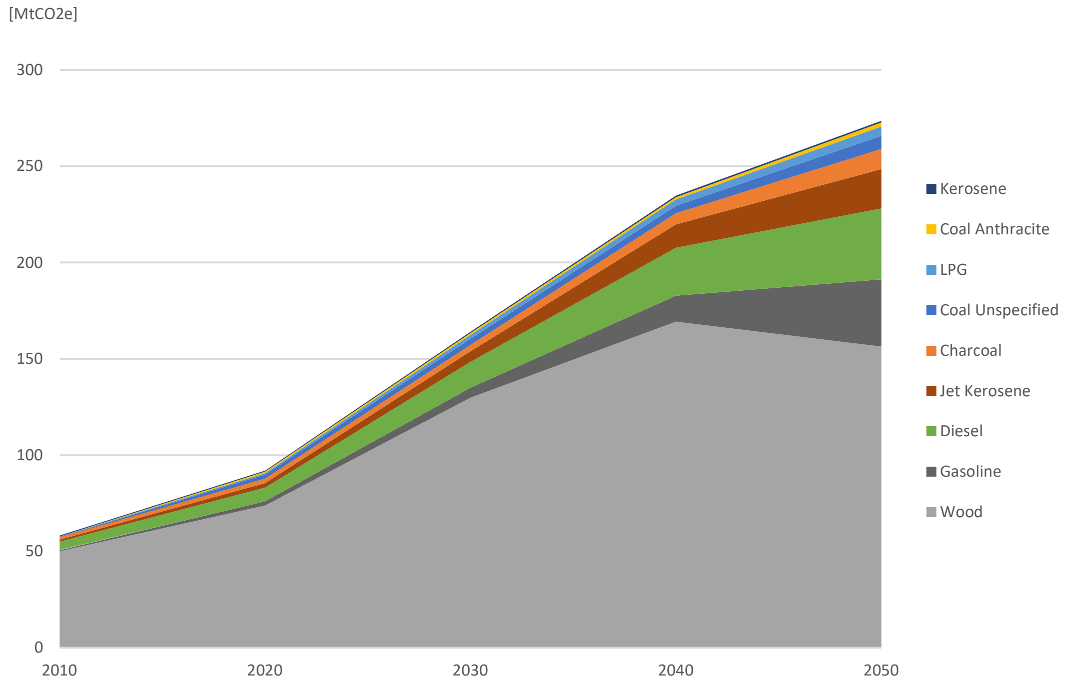


Fig. 24 Total GHG emission by fuel under BAU scenario

There is a huge difference on the total emission levels of the different scenarios. As can be seen from Fig. 25, BAU & IEE-1 and HEG & IEE-2 scenarios emit much higher than E&U & IEE-3 scenarios. BAU scenario's total GHG emission in 2050 is estimated to reach 274 MtCO$_2$e and HEG scenario releases about 295 MtCO$_2$e. This is a significant level of emission that can have a serious implication on the environment and human health. On the other hand, E&U & IEE-3 scenario emission is only projected to be 111 MtCO$_2$e. This is mainly due to the policy-driven shift from biomass-based household appliances to clean biofuel and electric-based appliances. Fig. 25 also shows that the policy-driven scenarios do not have any impact on the GHG emission as the policies are implemented on the electricity sector with no emission.

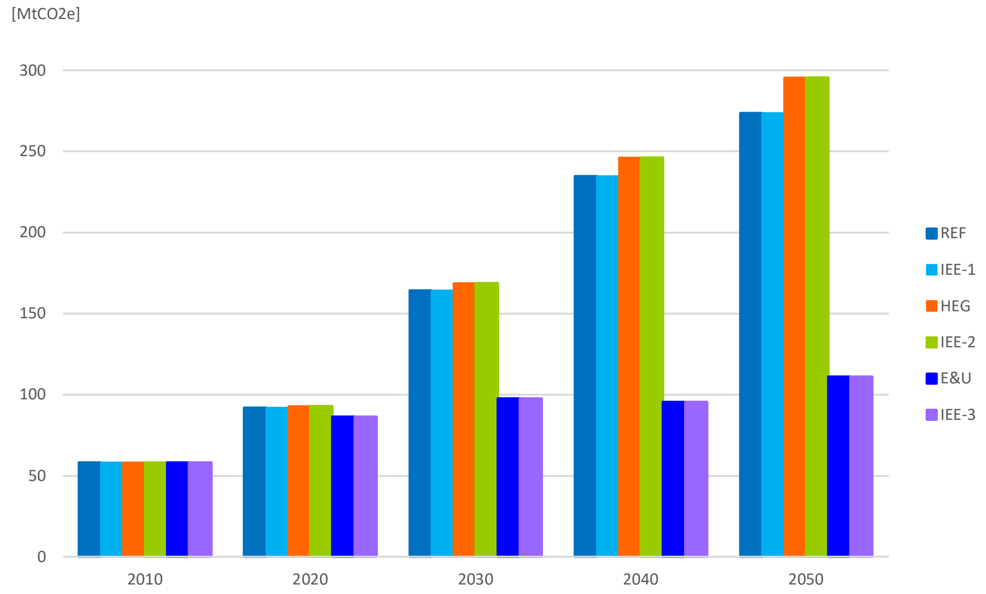


Fig. 25 Total GHG emission for all scenarios

4.6. Discussion

This study has investigated the evolution of the future (2018-2050) energy demand, with the specific Ethiopian context. The existing challenges and dynamics that are specific to the country and to other less developed countries in general are identified and reflected on the model to have a better representation of the energy system. These include unsustainable use of traditional energy sources, high population growth, modernization and urbanization, low electricity access and supply shortage, high system loss, etc. Then, the effect of such factors on the energy demand forecasting was studied through scenario analysis in a modeling software. The scenarios are deliberately chosen by looking at plausible future trends aimed to spur action by underscoring the impacts on the future of the policy decisions made today.

LEAP modeling framework was used as a tool for analysis as it relies on scenario approach to develop the possible paths of the energy system evolution. It also follows a bottom-up forecasting approach that is suitable to developing countries that captures the prevalence of informal economic activities and reliance on traditional and non-marketed fuels to a large extent. The study is based on extensive and detailed dataset to simulate the six different scenarios, business-as-usual, high economic growth, growth in electrification & urbanization and improved energy efficiency (IEE-1, IEE-2 and IEE-3). Each of the scenarios consider certain assumptions. The business-as-usual scenario assumes continuation of current and historical trends. High economic growth scenario builds on the business-as-usual scenario hoping that the country registers a high economic growth in the future. The improved energy efficiency scenario calls for various measures to minimize power loss and ultimately increase energy saving. Growth in electrification and urbanization scenario considers fast growth in electrification and urbanization. It also pushes for a major policy-shift to change the biomass-based household energy demand to clean-fuel based demand. This transition will be accelerated by increasing access and affordability of clean fuels such as LPG and electricity to rural areas.

In the BAU scenario, the total energy demand is expected to reach 2,950 PJ and 4,900 PJ by 2030 and 2050 respectively. There is only one study [Dereje, 2014] that forecasted the demand till 2050 for Ethiopia making the present study the second. [Dereje, 2014] estimates the total energy demand in its BAU scenario to reach 2,934 PJ and 6,553 PJ by the years 2030 and 2050 respectively. (Mondal et al, 2018) projects the energy demand from 2012-2030 and expects 2,120 PJ in 2030. The 2030 projected demand results of [Dereje, 2014] are similar to ours while [Mondal et al, 2018]) anticipates much lower value. This is mainly because the useful energy demand for baking (injera, bread, etc.) which accounts about 65% of the entire cooking fuel consumption is not represented in the energy use by households. In our study, cooking and baking appliances have different data structures with corresponding activity level and energy intensity.

Compared to the present study, [Dereje, 2014] projected much higher demand for all the sectors in 2050. It uses a top-down approach assuming a constant average GDP growth rate of 7% for the years from 2006 to 2050. Our study draws a feasible assumption of reduced GDP growth rates of 9%, 7% and 4% over the years 2018-2030, 2031-2040 and 2041-2050 respectively. It also uses multi-variable regression and bottom-up model that are more accurate and reliable.

Total electricity demand forecast in 2030 by earlier Ethiopian Power System Expansion Master Plan Study [EPSEMP, 2014] and updated Master Plan [GMSP-SIS, 2019] for the base-case scenarios are 106 TWh and 71 TWh respectively. Our result is much similar to [EPSEMP, 2014] with total projected electricity demand of 107 TWh. However, by using various energy efficiency improvement measures, it is shown that it is possible to reduce the total consumption to 95 TWh by 2030. The main reason for the difference is assumption of the operation period for various planned projects in industry and transport sectors. The present study assumes the capacity and operation period of future industrial parks and railway lines considering the latest developments and government plans. In addition, export plan assumption is also different. In 2030, [EPSEMP, 2014] assumes a much larger increase in exports of around 32 TWh compared to 16 TWh in the updated one and 14 TWh in the present study.

As the expectations to demand growth are different from country to country, comparison of the electricity demand projection to other countries needs careful consideration of country status in terms of forecasting methodology, their status and growth rates of demography, economy and socio-economic activities. The master plan study of modeling the power systems of the EAPP member countries [EAPP, 2014] in BALMOREL explores their electricity demand forecasts till the year 2040. From our analysis, Ethiopia's projected electric demand is expected to reach about 200 TWh by 2040; while Egypt expects a demand of about 750 TWh, Kenya's demand increases up to 127 TWh, Libya - 126TWh, DRC - 70 TWh, Tanzania - 56 TWh and Sudan - 54 TWh for the same period.

Aligned with the Paris Agreement on mitigation of climate change, the GoE has bold ambitions under its Nationally Determined Contribution (NDC), as it intends to reduce its emissions of 400 $MtCO_2e$ down to 145 $MtCO_2e$ by 2030. The emission reduction of 255 $MtCO_2e$ is expected to be achieved from agriculture (90 $MtCO_2e$), forestry (130 $MtCO_2e$), industry (20$MtCO_2e$), transport (10 $MtCO_2e$) and buildings (5 $MtCO_2e$). In addition, reduction of 19 $MtCO_2e$ is also achieved through regional power export from clean generation technologies.

Our results show how much GHG emission (mainly biogenic and non-biogenic CO_2) is expected in the long run from each fuel used in different demand sectors. In 2030, the total emission amounts to about 165 $MtCO_{2e}$, and when including the contribution from other sectors that are not included in this study, it will be much higher. This shows that it is not possible for Ethiopia to meet the NDC target under the BAU scenario. However, the E&U & IEE-3 scenarios have the ability to cut the emission by more than 40% compared to BAU. This can help Ethiopia revamp implementation strategies for hitting the emission reduction target in 2030 and also plan further targets in later periods.

5. Long-term modeling and analyses of optimum generation scenarios

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 [Ouedraogo, 2017].

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. 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 variable demand.

5.1. Literature review

Several studies have examined issues of power generation expansion in developing countries of Africa, Asia and Latin America. In this regard, the OSeMOSYS and LEAP modelling framework have been applied in various settings to assess the future energy sector. 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 [Rady et al., 2018]. 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 [Dhakouani et al., 2017]. 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 [Awopone and Zobaa, 2017]. 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

[Ouedraogo, 2017]. 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 [Kumar, 2016]. 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 [Yophy et al., 2010].

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 [Marong et al., 2018]. 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 [Dountio et al., 2016]. 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 [Das et al., 2018]. 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 [Ruijven et al., 2012].

Even though the above studies have attempted to assess the long-term energy development with models and approaches that are considered to be applicable within the context of the countries, they have not been fully successful in providing independent assessments of alternative technologies and policy choices that can be essential for developing countries in addressing their particular needs and constraints. In this regard, Dawit et al. [Dawit et al., 2020] present a comparative overview of the most commonly used modelling tools in terms of their applicability to developing countries where unique features such as traditional energy consumption, informal economy, urban-rural divide, low electrification, supply shortage, data and skill needs should be considered. These features should be reflected while developing energy supply and demand models, particularly the feasibility of including new technologies to the existing system. Nowadays, electricity supply can be provided by either centralized grid-based means, or by decentralized methods; and detailed analysis are 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.

At the national level, 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 [EPSEMP, 2014] 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 [GMSP-SIS, 2019] 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 aim to forecast the future electricity supply without providing alternative possible futures that can be meaningful for policy development. In this regard, Dereje [Dereje, 2014] considers 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. In addition, Mondal et al. [Mondel et al., 2017] present an assessment of alternative, long-term energy supply strategies using the MARKAL energy system model. The results show 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. Even though the studies of Dereje and Mondal et al. 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.

The overall objective of this chapter 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 find optimal (least-cost) power generation and capacity mixes to meet future electricity demand subject to certain policy scenarios that may impose technical constraints, economic realities, and environmental targets. The specific objective is to provide independent assessments of alternative technologies and policy choices that are essential for developing countries in addressing their particular needs and constraints. The study further explores practical strategies for overcoming problems of electricity access, security, sustainability, and affordability.

5.2. Methodology

In the methodological aspect, 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 main methodological contributions of this paper. Moreover, contextual representation of the electricity system on RES diagram, feasibility of both grid-extension and off-grid supply options, feasibility of 100% renewable and intermittent resource (solar and wind) target are investigated as discussed below. An overview of the methodology used is outlined in Fig. A - 1 of the Appendix D which is discussed further in detail below.

5.2.1. Context and model development

The choice of the appropriate modelling framework depends on the kind of insights the country model is intended to provide and should therefore start from an assessment of the context, the challenges, and the policy questions to be answered [Dhakouani et al., 2017]. Long-term energy modelling tools that aim to provide insights into investment and infrastructure needs, usually with a cost-optimization perspective include long-established MESSAGE, MARKAL and TIMES, or recent open-source alternatives to them, such as Balmorel and OSeMOSYS [Gardumi et al, 2019]. Each of these tools have their own features and selection of the appropriate modelling tool depends on the level of use of the features for a particular application. Thereby, MESSAGE, TIMES and OSeMOSYS have been widely used optimization models that are applied in different countries. As discussed in chapter-2, 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 such as 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 [Dawit et al., 2020]. 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 urban-rural divide, being an open-source and easy to use optimization modelling framework. For this reason, OSeMOSYS is chosen to make the electricity supply analysis in Ethiopia within a time period between 2018 and 2050.

In the current study, a soft-linking approach is adopted by coupling two independently developed models. 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 shown in chapter 4). 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. Moreover, sensitivity analysis is conducted on the results found from the model by identifying the underlying factors that affect the output. This will provide crucial information regarding the effects of changes in critical inputs and assumptions.

As in most long-term optimization models, OSeMOSYS in its standard configuration assumes a perfect foresight and perfect competition on energy markets [Howells et al., 2011]. This means that full information is available for cost trends, demand projection, efficiency of power plants, etc. and the optimization is done for all time periods simultaneously. 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, and Iran [Rady et al., 2018; Dhakouani et al., 2017; Awopone et al., 2017; Markus et al., 2016; Eshraghi et al., 2016; Mondal et al., 2010], and thus its functionality has been tested in large models in the past.

5.2.2. Optimization mechanism and logic

The least-cost power generation and capacity mixes will be 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 Equations (12) and (13) 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. Subscripts r,t and y represent the region or country modelled, technology representing a type of power plant and the year in time horizon, 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.

$$\text{Minimise} \sum_{r,t,y} \text{TotalDiscountedCost}_{r,t,y} \tag{12}$$

$$\begin{aligned}\forall_{y,t,r}\text{: TotalDiscountedCost}_{r,t,y} &= \text{DiscountedOperatingCost}_{r,t,y} + \text{DiscountedCapitalInvestment}_{r,t,y} \\ &+ \text{DiscountedTechnologyEmissionsPenalty}_{r,t,y} \\ &- \text{DiscountedSalvageValue}_{r,t,y}{}^{1}\end{aligned} \tag{13}$$

Capital costs are discounted back to the first/base year (eq 14) and operating costs are discounted to the middle of each year assuming uneven spread of variable costs over the course of a year (eq 15).

$$\begin{cases}\text{DiscountedCapitalInvestment}_{r,t,y} = \dfrac{\text{CapitalCost}_{r,t,y} \times \text{NewCapacity}_{r,t,y}}{(1 + \text{DiscountRate})^{(y-\min(y))}} & (14) \\ \text{DiscountedOperatingCost}_{r,t,y} = \dfrac{\text{OperatingCost}_{r,t,y}}{(1 + \text{DiscountRate})^{(y-\min(y)+0.5)}} & (15)\end{cases}$$

Where the operating cost is given by:

$$\begin{aligned}\text{OperatingCost}_{r,t,y} &= \left(\text{TotalCapacityAnnual}_{r,t,y} \times \text{FixedCost}_{r,t,y}\right) \\ &+ \left(\sum_{m} \text{TotalAnnualTechnologyActivityByMode}_{r,t,m,y} \times \text{VariableCost}_{r,t,m,y}\right)\end{aligned} \tag{16}$$

---

[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.*

$$\left\{\text{DiscountedTechnologyEmissionsPenalty}_{r,t,y} = \frac{\text{AnnualTechnologyEmissionsPenalty}_{r,t,y}}{(1+\text{DiscountRate})^{(y-\min(y)+0.5)}}\right. \quad (17)$$

Where the annual technology emission penalty is given by the following:

$$\sum_{e} \text{AnnualTechnologyEmission}_{r,t,e,y} \times \text{EmissionsPenalty}_{r,e,y} = \text{AnnualTechnologyEmissionsPenalty}_{r,t,y} \quad (18)$$

$$\left\{\text{DiscountedSalvageValue}_{r,t,y} = \frac{\text{SalvageValue}_{r,t,y}}{(1+\text{DiscountRate})^{(1+\max(y)-\min(y))}}\right. \quad (19)$$

The salvage value is calculated using the sinking fund method as shown in eq. (20).

$$\text{SalvageValue}_{r,t,y} = \text{CapitalCost}_{r,t,y} \times \text{NewCapacity}_{r,t,y}.\left(1 - \left(\frac{\left((1+\text{DiscountRate})^{\max(y)-y+1}\right)-1}{\left((1+\text{DiscountRate})^{\text{OperationalLife}_{r,t}}\right)-1}\right)\right) \quad (20)$$

- **Constraints**

The 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, iii) energy balance in each time slice and year.

The capacity adequacy constraints are shown in eq. (21) and (22). Total capacity of each technology for each year based on existing capacity from before the model period (*ResidualCapacity*), *AccumulatedNewCapacity* during the modelling period, and *NewCapacity* installed in each year are calculated. It is then ensured that this Capacity is sufficient to meet the *RateOfTotalActivity* in each TimeSlice and Year.

$$\text{s.t.}\begin{cases} \text{TotalCapacityAnnual}_{r,t,y} = \text{AccumulatedNewCapacity}_{r,t,y} + \text{ResidualCapacity}_{r,t,y} \\ \text{RateOfTotalActivity}_{r,t,l,y} = \sum_{m} \text{RateOfActivity}_{r,l,t,m,y} \\ \text{RateOfTotalActivity}_{r,t,l,y} \\ \leq \text{TotalCapacityAnnual}_{r,t,y} \times \text{CapacityFactor}_{r,t,l,y} \times \text{CapacityToActivityUnit}_{r,t} \end{cases} \quad (21)$$

Eq. (22) ensures that adequate capacity of technologies is present to at least meet the average annual demand.

$$\text{s.t.}\left\{\begin{aligned} &\sum_{l}\text{RateOfTotalActivity}_{r,t,l,y}\times\text{YearSplit}_{l,y}\\ &\quad\leq\sum_{l}\begin{matrix}\text{TotalCapacityAnnual}_{r,t,y}\times\text{CapacityFactor}_{r,t,l,y}\times\text{YearSplit}_{l,y}\\ \times\,\text{AvailabilityFactor}_{r,t,y}\times\text{CapacityToActivityUnit}_{r,t}\end{matrix}\end{aligned}\right. \tag{22}$$

The energy balance constraint is shown in eq. (23). It ensures that demand for each commodity is met in each TimeSlice.

$$\text{s.t.}\left\{\begin{aligned} &\text{RateOfProductionByTechnology}_{r,l,t,f,y}\\ &\quad=\sum_{m}\text{RateOfActivity}_{r,l,t,m,y}\times\text{OutputActivityRatio}_{r,t,f,m,y}\\ &\text{RateOfProduction}_{r,l,f,y}=\sum_{t}\text{RateOfProductionByTechnology}_{r,l,t,f,y}\\ &\text{RateOfUseByTechnology}_{r,l,t,f,y}=\sum_{m}\text{RateOfActivity}_{r,l,t,m,y}\times\text{InputActivityRatio}_{r,t,f,m,y}\\ &\text{RateOfUse}_{r,l,f,y}=\sum_{t}\text{RateOfUseByTechnology}_{r,l,t,f,y}\\ &\text{Production}_{r,l,f,y}=\text{RateOfProduction}_{r,l,f,y}\times\text{YearSplit}_{l,y}\\ &\text{Use}_{r,l,f,y}=\text{RateOfUse}_{r,l,f,y}\times\text{YearSplit}_{l,y}\\ &\text{RateOfDemand}_{r,l,f,y}=\frac{\text{SpecifiedAnnualDemand}_{r,f,y}\times\text{SpecifiedDemandProfile}_{r,f,l,y}}{\text{YearSplit}_{l,y}}\\ &\text{Demand}_{r,l,f,y}=\text{RateOfDemand}_{r,l,f,y}\times\text{YearSplit}_{l,y}\\ &\text{Production}_{r,l,f,y}\geq\text{Demand}_{r,l,f,y}+\text{Use}_{r,l,f,y}\\ &\sum_{l}\text{Production}_{r,l,f,y}=\text{ProductionAnnual}_{r,f,y}\\ &\sum_{l}\text{Use}_{r,l,f,y}=\text{UseAnnual}_{r,f,y}\\ &\text{ProductionAnnual}_{r,f,y}\ \geq\ \text{UseAnnual}_{r,f,y}+\text{AccumulatedAnnualDemand}_{r,f,y}\end{aligned}\right. \tag{23}$$

Accounting equations used to generate specific intermediate variables: *ProductionByTechnology*,*UseBytechnology*,*TotalAnnualTechnologyActivityByMode*, and *ModelPeriodCostByRegion* are shown in eq. (24).

$$s.t.\begin{cases} \text{ProductionByTechnology}_{\text{r,l,t,f,y}} \\ \quad = \text{RateOfProductionByTechnology}_{\text{r,l,t,f,y}} \times \text{YearSplit}_{\text{l,y}} \\ \text{UseByTechnology}_{\text{r,l,t,f,y}} = \text{RateOfUseByTechnology}_{\text{r,l,t,f,y}} \times \text{YearSplit}_{\text{l,y}} \\ \sum_{\text{y}} \text{TotalDiscountedCost}_{\text{r,y}} = \text{ModelPeroidCostByRegion}_{\text{r}} \end{cases} \tag{24}$$

Eq. (25) calculates the total discounted system cost for each technology over the entire model period that is minimized in the model's objective function.

$$\text{s.t.}\left\{\sum_{\text{t}} \text{TotalDiscountedCostByTechnology}_{\text{r,t,y}} = \text{TotalDiscountedCost}_{\text{r,y}}\right. \tag{25}$$

Eq. (26) ensures that capacity of each technology in each year is greater than and less than the user-defined parameters *TotalAnnualMinCapacityInvestment* and *TotalAnnualMaxCapacityInvestment* respectively.

$$\text{s.t.}\begin{cases} \text{TotalCapacityAnnual}_{\text{r,t,y}} \leq \text{TotalAnnualMaxCapacity}_{\text{r,t,y}} \\ \text{TotalCapacityAnnual}_{\text{r,t,y}} \geq \text{TotalAnnualMinCapacity}_{\text{r,t,y}} \end{cases} \tag{26}$$

The new capacity constraints are shown in eq. (27) that ensure the new capacity of each technology installed in each year is greater than and less than the user-defined parameters *TotalAnnualMinCapacityInvestment* and T*otalAnnualMax Capacity Investment* respectively.

$$\text{s.t.}\begin{cases} \text{NewCapacity}_{\text{r,t,y}} \leq \text{TotalAnnualMaxCapacityInvestment}_{\text{r,t,y}} \\ \text{NewCapacity}_{\text{r,t,y}} \geq \text{TotalAnnualMinCapacityInvestment}_{\text{r,t,y}} \end{cases} \tag{27}$$

Eq. (28) ensures the total activity of each technology over each year is greater than and less than the user-defined parameters *TotalTechnology AnnualActivityLowerLimit* and *Total Technology Annual Activity Upper Limit* respectively.

$$\text{s.t.}\begin{cases} \sum_{\text{l}} \text{RateofTotalActivity}_{\text{r,t,l,y}}.\text{YearSplit}_{\text{l,y}} = \text{TotalTechnologyAnnualActivity}_{\text{r,t,y}} \\ \text{TotalTechnologyAnnualActivity}_{\text{r,t,y}} \leq \text{TotalTechnologyAnnualActivityUpperLimit}_{\text{r,t,y}} \\ \text{TotalTechnologyAnnualActivity}_{\text{r,t,y}} \geq \text{TotalTechnologyAnnualActivityLowerLimit}_{\text{r,t,y}} \end{cases} \tag{28}$$

Eq. (29) ensures that sufficient reserve capacity of specific technologies is installed such that the user-defined ReserveMargin is maintained.

$$\text{s.t.}\begin{cases} \text{TotalCapacityInReserveMargin}_{r,y} = \\ \sum_{t} \text{TotalCapacityAnnual}_{r,t,y}.\text{ReserveMarginTagtechnology}_{r,t,y}.\text{CapacityToActivityUnit}_{r,t} \\ \text{DemandNeedingReserveMargin}_{r,l,y} = \\ \sum_{f} \text{RateOfProduction}_{r,l,f,y}.\text{ReserveMarginTagFuel}_{r,f,y} \end{cases} \tag{29}$$

Emission constraints are accounted in eq. (30) with the calculation of the annual and model period emissions from each technology and for each type of emission. It also calculates the total associated emission penalties, if any. Finally, it ensures that emissions are maintained before stipulated limits that may be defined for each year and/or the entire model period.

$$\text{s.t.}\begin{cases} \text{AnnualEmissions}_{r,e,y} = \sum_{t} \text{AnnualTechnologyEmission}_{r,t,e,y} \\ \sum_{y} \text{AnnualEmissions}_{r,e,y} = \\ \text{ModelPeriodEmissions}_{r,e} - \text{ModelPeriodExogenousEmission}_{r,e} \\ \text{AnnualEmissions}_{r,e,y} + \text{AnnualExogenousEmission}_{r,e,y} \leq \\ \text{AnnualEmissionLimit}_{r,e,y} \\ \text{ModelPeriodEmissions}_{r,e} \leq \text{ModelPeriodEmissionLimit}_{r,e} \end{cases} \tag{30}$$

5.2.3. Reference Energy System

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 flow from primary energy supply, via energy conversion technology to the products/services that satisfies the demands. The RES-diagram developed with the context of Ethiopia which later will be the basis of the OSeMOSYS model is shown in*Fig. 26.* 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. They take many forms, including nuclear energy, fossil energy 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 diesel). The country has very large exploitable reserves of renewable and clean energy resources (see Table 5) while it relies on imported fuels for nuclear and diesel energy.

- Power generation technologies

Power generation technologies convert the primary sources into electricity. Two types of supply technologies are considered: centralized grid-based and decentralized off-grid methods. The 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 18).

Hydropower plants are classified as large-scale (>100MW), medium-scale (20-100MW) and small-scale (<20MW). 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 [GMSP-SIS, 2019].

- Transmission and distribution infrastructures

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 split into different sectors such as industry, agriculture, services, residential and transport. Moreover, power export to neighbouring countries is also represented as a final demand.

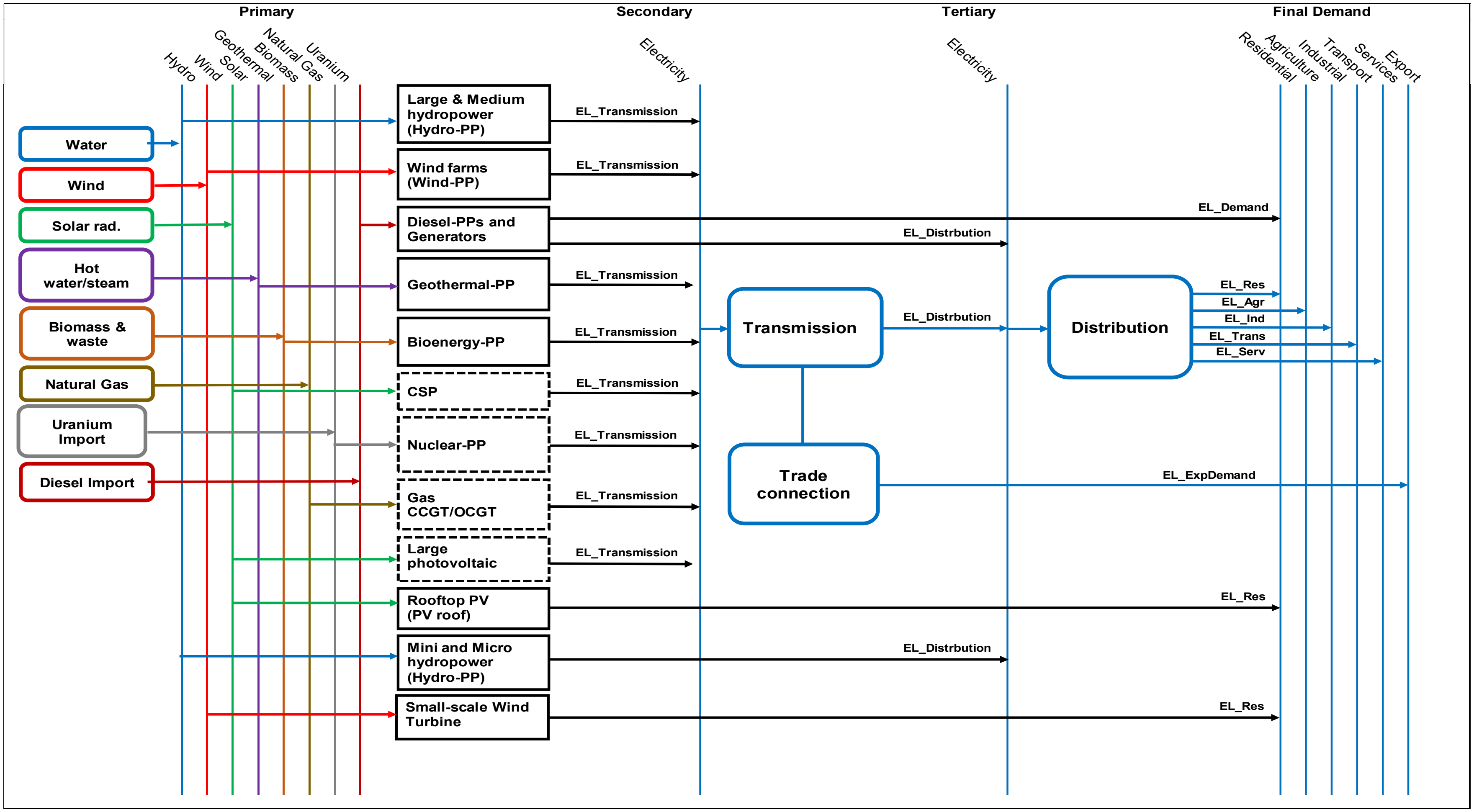


Fig. 26 The reference energy system (RES) of Ethiopian electricity sector

Table 18 Techno-economic input parameters of various power generation technologies in OSeMOSYS

[Ouedraogo, 2017; EPSEMP, 2014; GMSP-SIS, 2019; MoWIE, 2012; EEP, 2018/19; MoWIE, 2017; ECRGES,2011; Taliotis et al, 2016; Handayani et al., 2019; Hossain et al., 2019; IRENA, 2017; IRENA-IEA, 2017; Ayodele et al., 2013; Sustainable energy handbook, 2016; Mondal et al., 2020; Hayward et al., 2011; IEA-ETSAP, 2010; IEA-ETSAPP, 2013; IRENA, 2020; IEA-ETSAP, 2010; IEA-ETSAP, 2014; Zelalem, 2016; IEA, 2019; Jakhrani et al., 2012; Guta et al., 2015; IRENA, 2013; Dawit et al., 2021; Guta et al., 2015; Mekonnen et al., 2015; Partha et al., 2018]

	Input parameter [a]									
	Capital cost	Fixed cost	Variable cost	Capacity factor	Availability factor	Capacity credit	Efficiency	Life cycle	CO_2 emission	NO_x emission
Unit	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 [EPSEMP, 2014]										
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.

5.3. Application

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

5.3.1. Model

The OSeMOSYS model is based on the Ethiopian RES shown in *Fig. 26*. It makes the 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 [Mondal et al., 2010; Dagher et al., 2011; Shin et al., 2005; Shahinzadeh et al., 2016; Eiswerth et al., 1998]. In particular, it is a widely used tool for energy demand prediction and scenario analysis in developing economies [Mondal et al., 2018; Gul et al., 2012; Kale and Pohekar, 2014]. Both the OSeMOSYS and LEAP model consider a spatial scope of a single region in a time horizon between 2018 and 2050.

5.3.2. 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 [EPSEMP, 2014; GMSP-SIS, 2019; MoWIE, 2012; EEP, 2018/19; MoWIE, 2017; ECRGES, 2011] but also from international studies and reports [Ouedraogo, 2017; Taliotis et al, 2016; Handayani et al., 2019; Hossain et al., 2019; IRENA, 2017; IRENA-IEA, 2017; Ayodele et al., 2013; Sustainable energy handbook, 2016; Mondal et al., 2020; Hayward et al., 2011; IEA-ETSAP, 2010; IEA-ETSAPP, 2013; IRENA, 2020; IEA-ETSAP, 2010; IEA-ETSAP, 2014; Zelalem, 2016; IEA, 2019; Jakhrani et al., 2012; Guta et al., 2015; IRENA, 2013; Dawit et al., 2021; Guta et al., 2015; Mekonnen et al., 2015; Partha et al., 2018]. Table 18 and Table 19 summarize the main input data and key assumptions for making the OSeMOSYS 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 labour costs, which in turn makes hydropower investment costs for developing countries to be much lower than in industrialized countries. Consequently, after considering the context and referring local studies, a specific investment cost of 2000 USD/kW, 2400 USD/KW and 3533 USD/kW are used for large, medium and small-scale plants respectively (see Table 18).

Table 19 Model setup, electricity demand and key assumptions [Ouedraogo, 2017; IRENA, 2017; Dhakouani, 2017; GMSP-SIS, 2019; Mondal et al., 2018; Dawit et al., 2019; Kale et al., 2014; Handayani et al., 2019; Mondal et al., 2020]

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 (SeeTable 20)
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%

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 [IRENA, 2017]. 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 1kWh 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 5238USD/kW to 3650USD/kW to 2555USD/kW).

The investment cost of biomass power plants falls to 2750USD/kW by 2030 from 3333USD/kW in 2020 [IEA-ETSAP, 2011]. Geothermal power plant installed costs are highly site sensitive due to the reservoir quality, the type of power plant and number of wells [IRENA, 2020]. In the past decade, geothermal capital cost didn't show visible reduction. On the contrary, it increased from 2588USD/kW in 2010 to 3916USD/kW in 2019. Considering these, a very slow cost reduction to 3100USD/kW is taken by 2030. Waste incineration plant is considered to show a 3% capital cost fall in ten years. Other technologies like 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 Table 18 and 10% discount rate.

Reserve margin (RM) is the amount of firm electricity generation capacity minus the system's maximum annual demand as a ratio of maximum annual demand [Ouedraogo, 2017]. An evaluation criterion is shown in eq. (31) 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 literature on Sub-Saharan African countries use a reserve margin constraint of below 10% [Ouedraogo, 2017; IRENA, 2017; Dawit et al., 2019; IRENA, 2013]. Given the importance of having sufficient firm capacity to system reliability, an average reserve capacity of 10% is considered as reasonable in this study.

$$\sum_{i=1}^{n} \alpha_i \times C_{pi} \quad \geq (1 + RM_{min})D_p \qquad (31)$$

The LEAP electricity demand projection which was discussed in Chapter-4 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 20. It is evident that the country expects a strongly increasing electricity demand in the future three decades. A comparison of the scenarios shows that, highest demand is expected for 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 demands 253 TWh and BAU consumes 229 TWh. The total energy saving under the IEE scenario is 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.

Table 20 Electricity demand projections in LEAP-BAU scenario, 2018-2050.

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**

In the context of the country, where variable sources account a negligible part of the power system, time slices are defined primarily according to the variability of demand (according to the seasonality of river, 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 hours that make up a year are broken down into time blocks or time slices that capture seasonal, weekly and daily variations. In this study, 6 time-slices are used in which the year is sub-divided into two seasons as dry (September-May) and rainy (June-August) season. The 24-hour 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).

5.3.3. Scenarios

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 selected by considering the country's context in terms of electricity access, future governmental direction, and technological change.

- 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 [MoWIE, 2019; ECRGES, 2011]. 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. 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, both grid and off-grid systems will serve their respective demand with 65%/35% household share (see Table 21).

Table 21 Household electricity access and demand projection-ref scenario, 2018-2050

	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

- 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.

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

- 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 [Guta et al., 2015; Mekonnen et al., 2015]. 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 40GW. 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.

- 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 favorable to both customers and utility through peak shaving, valley filling, load shifting, strategic load reduction and growth, etc. [Das et al., 2018]. Some of the mechanisms include standards and labeling, energy management and auditing, technology improvement, etc. 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 taken for other home appliances. Replacement of streetlights with efficient light emitting diodes (LEDs) with smart control can also reduce the electricity consumption by 60%.

From the supply side, Ethiopia has a significant transmission and distribution (T&D) losses that affect the reliability and quality of service provided to customers. The government is expected to implement network rehabilitation that result in power quality and system efficiency improvement. Accordingly, this scenario considers a total power loss reduction from the average historical loss of 23% to 12.5% by 2030 and down to 9% by 2035.

5.4. Optimization results and analysis

Each of the developed scenarios described above are compared in terms of composition of electricity generation, energy resource diversity, economic cost and emissions.

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

Fig. 27 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 Fig. 28 to Fig. 31) 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.

Looking at the electricity generation mix, the transition from a hydro-dominated source to diversified sources is slow. In all the scenarios, the OSeMOSYS 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 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. 32 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. 27-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 the next section, this capacity reduction has resulted in a significant financial saving by avoiding unnecessary future power plant investments.

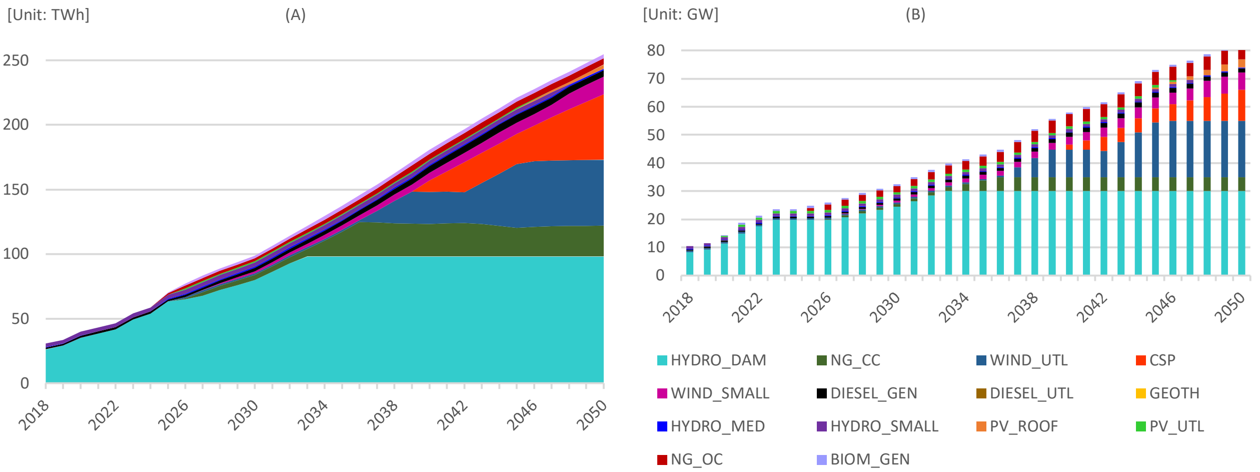


Fig. 27 Electricity generation mix (A) and installed capacity (B) under the reference scenario

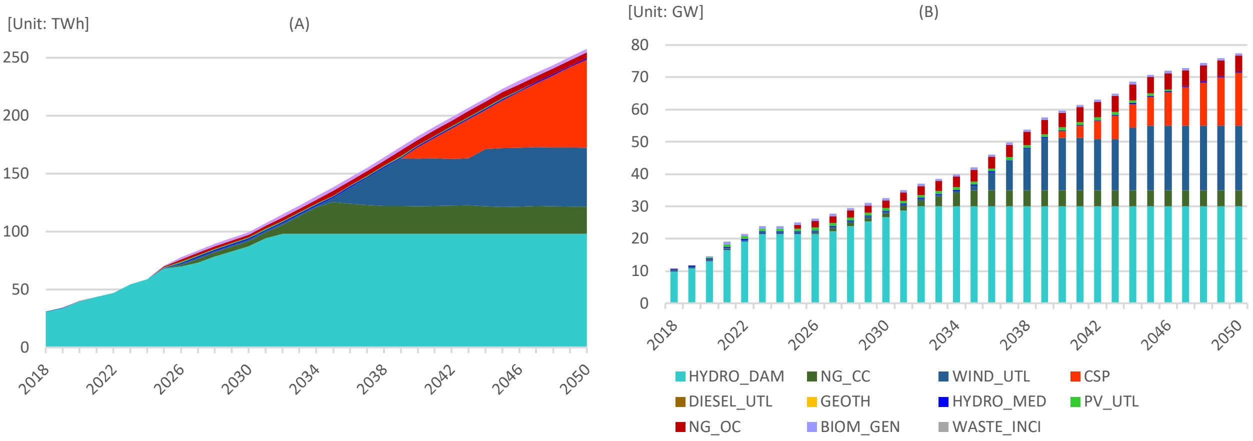


Fig. 28 Electricity generation mix (A) and installed capacity (B) under the grid extension scenario

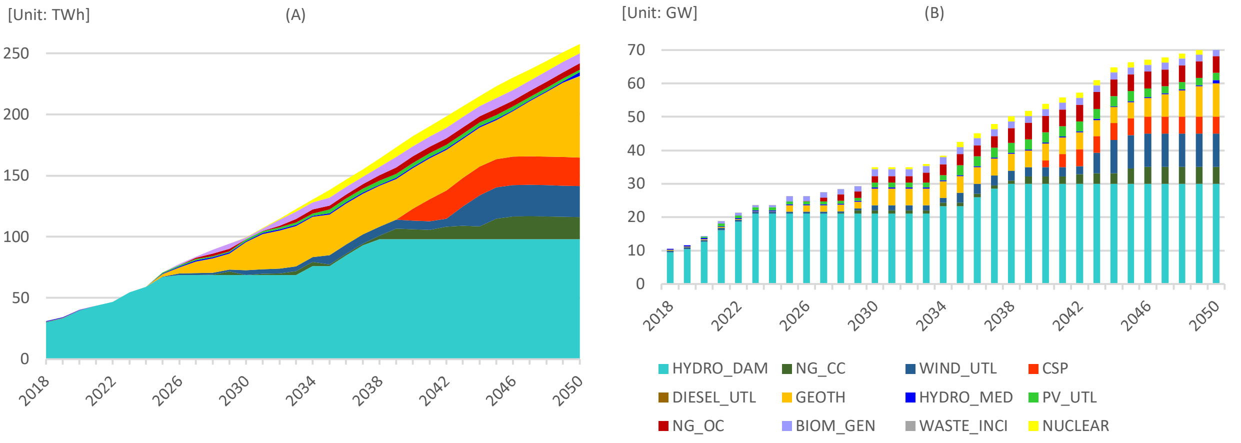


Fig. 29 Electricity generation mix (A) and installed capacity (B) under the multiple resource mix scenario

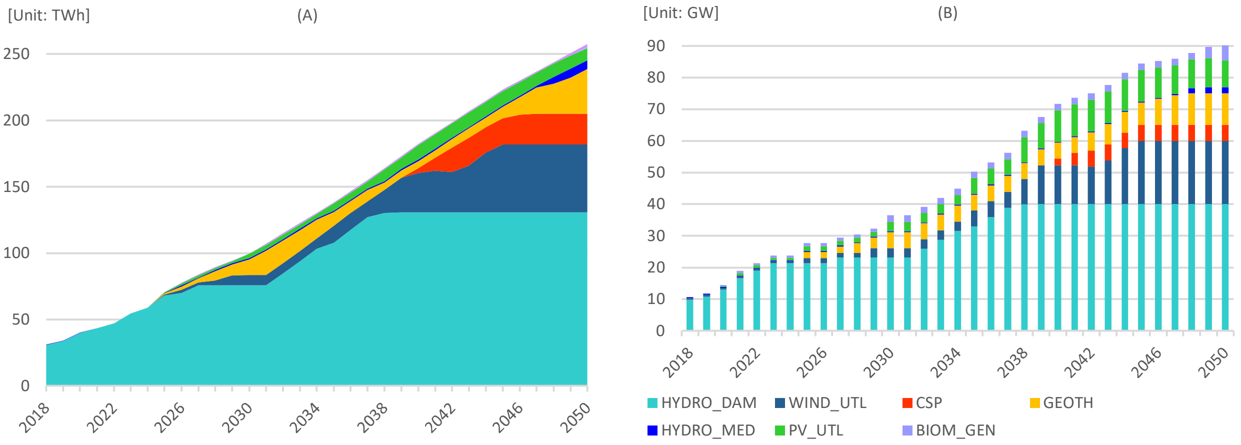


Fig. 30 Electricity generation mix (A) and installed capacity (B) under the intermittent resource target scenario

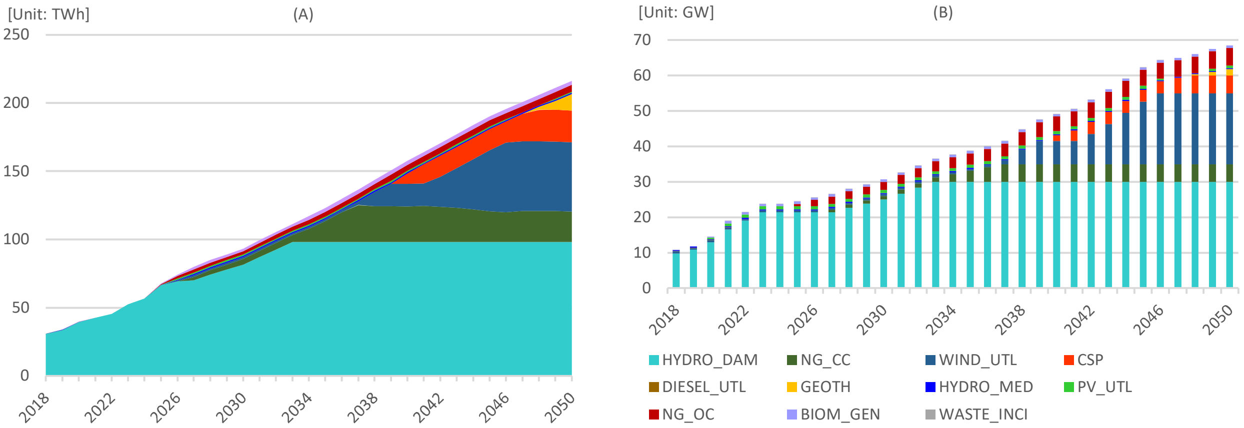


Fig. 31 Electricity generation mix (A) and installed capacity (B) under the improved efficiency scenario

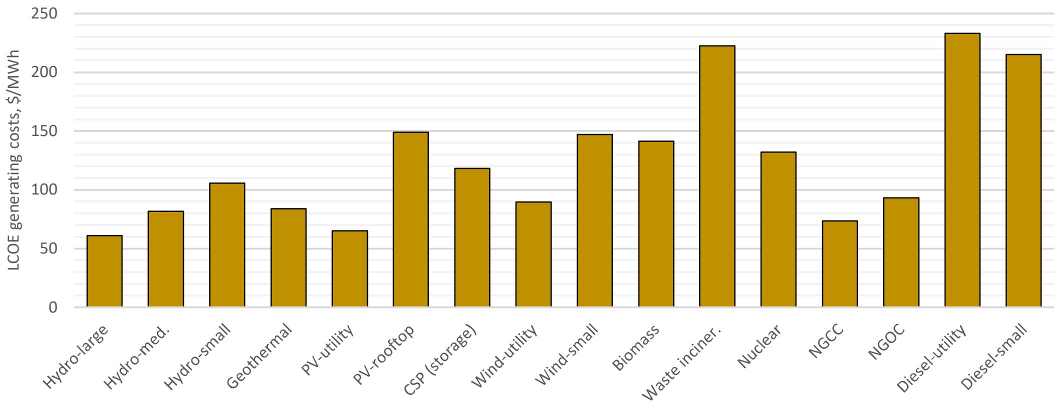


Fig. 32 Levelized cost of electricity (LCOE) for various technologies

5.4.2. Economic cost

Fig. 33 (subplot a) shows the total (MUSD) and unit discounted cost of 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 for 14%, 12% & 5% respectively.

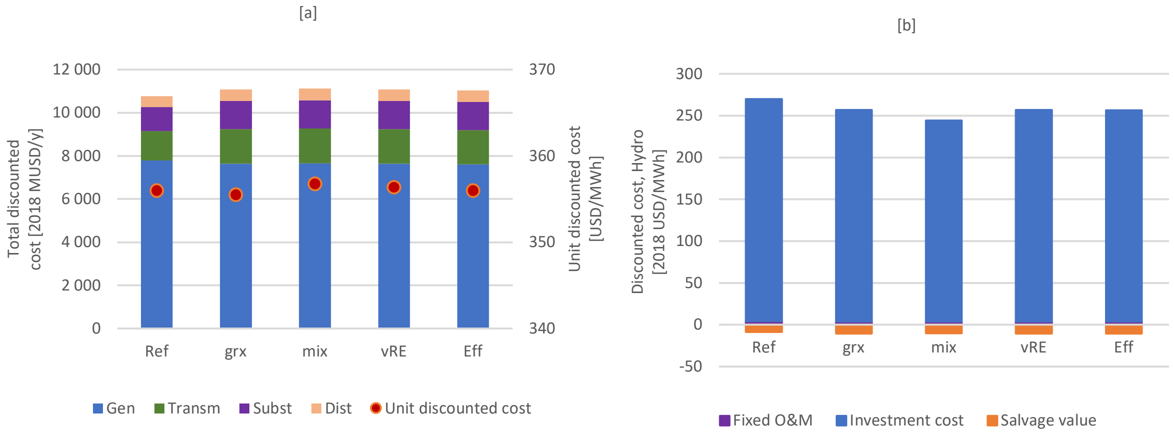


Fig. 33 Total and unit discounted costs (a) and discounted cost of hydropower technology (b)

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 is higher by about 9% while the Eff scenario 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. 33 (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.

5.4.3. 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 (see Appendix D, Fig. A - 7 Annual emissions under the grx scenario). NO_x emissions are also negligible. These low-level CO_2 and NO_x emissions are mainly generated from the natural gas power plants.

5.4.4. Model validation

In order to verify that the OSeMOSYS model is performing as expected, the energy balance of the output is checked according to the RES developed for Ethiopia (see *Fig. 26*). 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.

5.4.5. Sensitivity analysis

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

5.4.5.1. 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 22 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” [Gusano and Kirkengen, 2016]. In addition, the OSeMOSYS discounted equations (refer Eq. 12 & 13) also justify this result.

The effect of the discount rate on choice of technologies and energy-mix is shown in Fig. 34 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.

Table 22 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	8,898
grx	12,605	12,188	11,086	10,265	9,078
mix	12,605	12,188	11,125	10,329	9,213
vRE	12,605	12,188	11,086	10,265	9,078
Eff	12,564	12,149	11,050	10,232	9,049

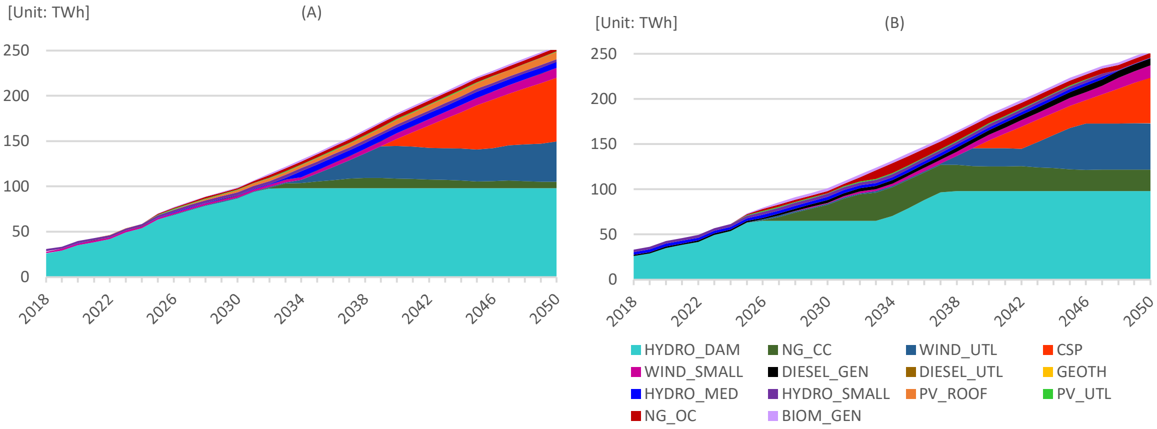


Fig. 34 Electricity generation mix under the reference scenario with a 5% (A) and 15% (B) discount rates

5.4.5.2. Electricity generation sensitivity to increased hydro capital cost

Increased capital costs of hydro will change the shape of the energy-mix as demonstrated in Fig. 35 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 hydro, keeping only the residual capacity.

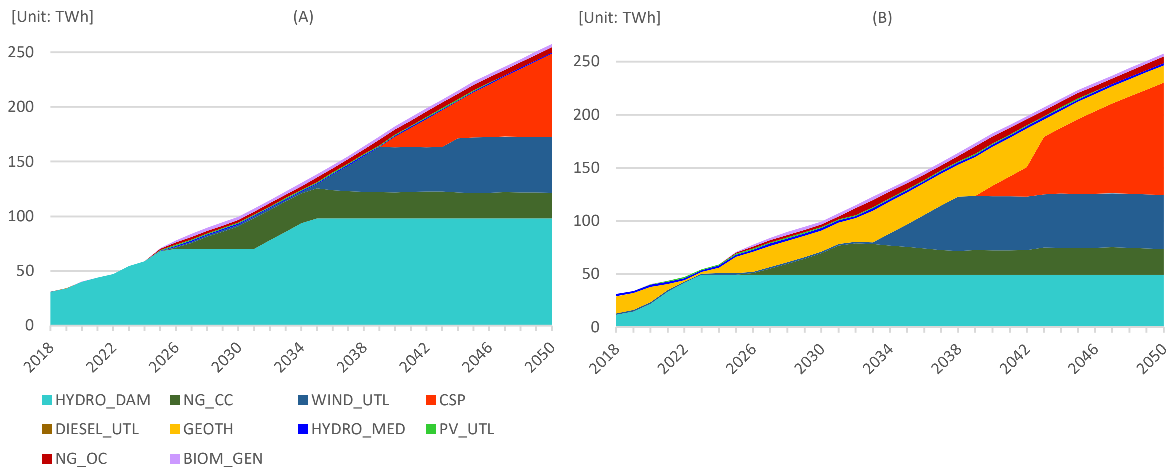


Fig. 35 Electricity generation mix under grid extension scenario with a capital cost increase by 20% (A) and 50% (B)

5.4.5.3. Electricity generation sensitivity with no thermal storage of CSP

Avoiding the thermal storage of CSP will mainly change the value of the parameters: capital cost, capacity factor and capacity credit. The capital cost is changed from the original values of 5238USD/kW in 2020 to 2910USD/kW, 3650USD/kW in 2030 to 2037USD/kW, and 2555USD/kW in 2040 to 1426USD/kW. The original capacity factor of 63% is changed into 35% which is only applicable for the time slices DD and RD while zero values are entered for the remaining time slices: DN, DP, RN and RP. This will drastically decrease the availability and annual production of the technology that is similar to utility-scale PV plants. The capacity credit is also reduced to 5% which significantly lowers its contribution to the reserve supply.

Fig. 36 shows the model outputs of the electricity generation mix and corresponding total annual installed capacity without considering the thermal storage of CSP. It can be seen that 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.

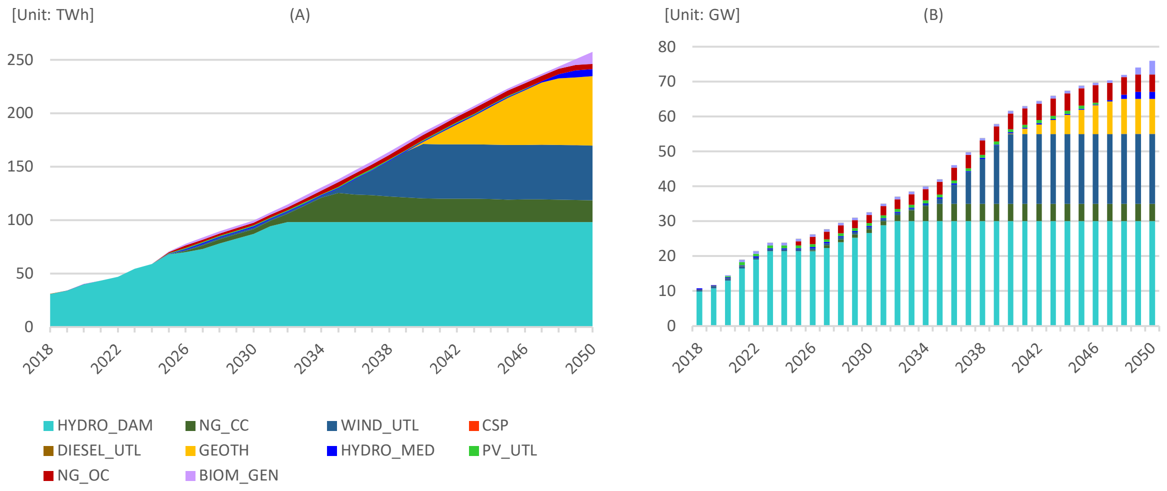


Fig. 36 Electricity generation mix (A) and installed capacity (B) under grid extension scenario with no thermal storage of CSP

5.5. Discussion

This study aims to provide a better representation of the electricity system of developing countries while considering their unique features and characteristics. It tries to identify the potential pathways of the future power generation sector taking Ethiopia as a case study. Five scenarios were employed, 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 assess alternative development pathways of Ethiopia’s future electricity system from 2018 to 2050. The scenarios represent alternative technologies, policy choices and practical strategies that can address issues of electricity access, security, sustainability, and affordability.

Even though there is a similar approach of using OSeMOSYS and LEAP in [Rady et al., 2018; Ouedraogo, 2017; Dhakouani et al., 2017; Awopone and Zobaa, 2017; Kumar, 2016; Yophy et al., 2010; Mondal et al., 2018], their methodologies are different compared to the current study. Considering the unique features and specific characteristics of energy and electricity systems in developing countries (as discussed in section 2.3), a better representation of the electricity system is needed in both the supply and demand models. In this regard, none of the above studies fully address these features in their models.

In the present study, the methodology used to determine the optimal supply mix alternatives of the future power system of Ethiopia is by soft-linking a simulation modeling tool to an optimization modeling tool. The motivation for this soft-linking is driven by the fact that one specific modeling tool cannot incorporate all the specific characteristics of developing countries and better system representation of the supply and demand-sides can be achieved by drawing on the strengths of additional modeling tools. LEAP is a simulation-based modeling framework which is used for demand forecasting and energy system analysis. It is also used to analyze the energy demand evolution of the country by considering major scenarios that detect emerging issues and plausible trends. 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 studied in making the projection of the energy demand. Few of these aspects are reflected in [Mondal et al., 2018] that attempts to forecast the future demand of Ethiopia using the LEAP framework. However, that assessment is 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 is constrained up to 2030.

On the other hand, we used the OSeMOSYS framework as an optimization model to find the minimum electricity generation costs for given constraints. The projected energy demand outputs of the LEAP model for various scenarios and sectors are extracted for multiple target years which are then given as input to the demand parameters of the OSeMOSYS model. 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, [Marong et al., 2018] considers 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 supplying the non-electrified remote-rural areas through assessment of grid-extension and/or off-grid systems options.

Technology learning and investment cost reduction aspects are included in [Marong et al., 2018; Das et al., 2018; Mondal et al., 2017; Handayani et al., 2019] and high system losses are represented in [Ouedraogo, 2017; Awopone and Zobaa, 2017; marong et al., 2018; Mondal et al., 2017], while in the current study and model, all these, declining cost with technology learning, high system losses and future policy-driven energy savings, are 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. These factors are important in improving the data quality which would have some impact on capacity, generation, technology mix, and costs.

Proper understanding and modelling of all these unique characteristics and context of developing countries is crucial to prevent inaccurate analysis and the prescription of wrong policies.

Comparison of the findings with other studies is only limited to some aspects due to discrepancy of followed approaches and considered scenarios. Considering the first period 2018-2030 and second period 2031-2045, similar results of hydro dominance are estimated with the electricity mix outputs in [GMSP-SIS, 2019] and [Mondal et al., 2017]. The least-cost optimization model employed in [Mondal et al., 2017] also finds greater investment in hydro and wind power technologies while solar PV, geothermal and combined gas plants contribute to a limited extent. However, CSP is not selected by the 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, [Mondal et al., 2017] anticipates a much lower value of the energy demand and annual electricity production. In the best-case scenario, the electricity production grows from 11 TWh in 2015-170 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) is used to estimate electricity demand till 2045. The present study draws a feasible assumption of reduced gross domestic product (GDP) growth rates of 9%, 7% and 4% over the years 2018-2030, 2031-2040 and 2041-2050 respectively. It also uses multi-variable regression and disaggregated model that represents the useful energy demand in all sectors. 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.

When modelling energy systems with high variable resources, models need to capture the variability of supply by accounting intra-annual temporal resolution. Having low level of temporal detail or temporal mismatch may cause a period when too much variable resource (VRE) is produced, which could lead to its being curtailed, or to a period of no production, which other capacity would be required to cover. Moreover, insufficient capture of the variability of supply could lead to a sub-optimal or inadequate capacity mix, as the costs linked with periods of VRE over or under-production are insufficiently represented, and the need for flexibility in the system may be underestimated [IRENA, 2017]. In this regard, the vRE scenario which targets 40% share of variable generation can be more applicable by increasing the model's temporal resolution. However, temporal resolution can be increased only to a limited extent because a model's computational time exponentially increases as the task becomes more complex particularly with the use of long planning horizon of 30 years plus.

Furthermore, increasing a model's resolution of time requires detailed and quality datasets which are not readily available in developing countries like Ethiopia.

6. Reflections on the selected approaches and methods

This chapter provides a brief and critical reflection of the followed approaches and methods as well as the main choices made during the course of this study.

6.1. Capturing unique features of developing countries

Our research has highlighted the importance of better system representation through capturing the specific features of developing countries. These are: (i) supply shortage (ii) low electrification (iii) poor performance of power sector (iv) high T&D loss (v) dominance of traditional fuels (vi) urban-rural difference (vii) informal economy (viii) economic transition (ix) inadequate use of subsidies (x) data need (xi) skill requirement and (xii) upfront financial cost. This can be achieved by selection of the most appropriate modeling tool, use of disaggregated analysis during model development and design of plausible scenarios. In this regard, our soft-linking approach of coupling LEAP and OSeMOSYS has captured most of these features. However, assessment of some of the features – i.e. informal sector, poor performance of power sector and inadequate use of subsidies are not sufficiently represented mainly due to limitation of modeling tool capability and lack of data.

6.2. Single-region Vs multi-region model

The OSeMOSYS-based supply optimization model is developed considering a spatial scope of a single-region. This means that the electrified and unelectrified areas are modelled within the same region by differentiating them through creating ad hoc fuels and technologies for each of them. Centralized powerplants will inject produced power to the transmission system which is part of the grid system while distributed and small-scale technologies will supply the distribution system or directly to the end-users, as part of the off-grid system or back-up supply. In the case of grid-extension, centralized technologies are allowed to contribute while distributed technologies are constrained not to contribute to the demand. i.e. The total country demand is supplied with centralized/large-scale powerplants. On the other hand, in the case of off-grid supply, distributed technologies are allowed to contribute to the off-grid demand by constraining centralized technologies only to contribute to the grid-demand.

The other approach is to divide the country into two or more sub-regions, allowing the spatial distribution of resources, demand and investment to be reflected in the model. Electrified (e.q. urban) and unelectrified (e.q. rural) areas within the country can be represented by separate supply-demand balances for the respective regions, including trade with other regions. Each region will have separate fuels, technologies, T&D infrastructure and demand. It is then possible to make comparison and feasibility assessment of centralized (grid-extension) and decentralized (off-grid) systems and understand the optimization of when to connect them and at what cost. However, in this study we used the single-region model approach mainly because it is more efficient and convenient from a computational point of view.

6.3. Driver-based demand projections

As explained in the previous sections, the energy demand is critical in driving the OSeMOSYS based supply-optimization model and its projection is done outside the model. Driver-based demand projections are calculated for end-use and customer categories, namely, industry, household, commercial, agriculture, transport, public and export.

A combination of bottom-up forecasts and multi-variable regression modeling is employed to make the forecast. The multi variable regression is advantageous in that a number of variables other than the GDP can be included. Historical consumption, GDP, per capita income, number of customers and number of households are the considered drivers whose evolution with time will determine the energy demand projections. The rate-of-change of these driving factors can incorporate the effects of changes in population, urbanization, agricultural growth, structure of GDP, pattern of industrial growth, etc. and they are changed between different scenarios.

Other techniques such as artificial neural networks (ANN), Markov chain, time series, fuzzy logic and autoregressive integrated moving average (ARIMA) are extensively used in the literature to forecast future energy demands. However, the general purpose of the demand projection in this study is exploring the future by relying on scenario analysis. This means that being a long-term demand forecasting, the predictions are not required to be as accurate as the short one. As a result, a less robust prediction is done avoiding the use of sophisticated tools.

6.4. Techno-economic assumptions

Techno-economic assumptions play a crucial role in the least-cost generation optimization model by determining which of the existing and future technologies should be included and by how much capacity. All the technologies are defined by techno parameters such as performance (efficiency, availability factor, capacity factor, residual capacity, operational life, etc.), production targets, reserve margin, etc. while economic parameters include investment costs, fixed and variable operation and maintenance cost.

The investment cost of certain technologies such as solar PV, wind, biomass, CSP and geothermal are assumed to change over time to account for technology learning. All these parameters are considered when developing the optimization model, particularly giving more attention to the relative costs of different technologies (as opposed to trying to use correct absolute costs). Furthermore, the techno-economic data used in this research strongly considers the country's context in terms of resource availability, technology maturity, government plan, construction period and labor cost. Therefore, our techno-economic assumptions are better suited to represent the reality which enhances the credibility of the optimization model and results of capacity, generation, technology mix and costs.

6.5. Model projection uncertainties and validation

Even though models are designed to best represent the real system by taking large sets of data, there will always be uncertainties about the future. The model developer is required to make its own estimates and assumptions to simplify the reality by disregarding certain aspects that are not critical. This is especially true for models dealing with future situations. Those estimates and assumptions may or may not turn out to be valid under certain circumstances.

Similarly, our long-term supply-demand model also includes many choices and assumptions about socio-economic and technological progress, future costs, future demand, policies, government commitment, future people's behavior, etc.

Lundqvist and Mattson (2002) explore the approaches on how to measure the uncertainties and validation accuracies in their transport model. They propose four types of validation criteria: *practical, theoretical, internal and external* validation. Although supply-demand models are different as they are more general compared to sector-specific transport models, these criteria can be applicable to our model as well to a certain extent. However, it should be noted that the validation of models is not the focus of this dissertation.

Practical validation involves how the system design corresponds to the scope of intended policy analysis and how well the system is represented. *Theoretical validation* is the extent of which theoretical foundation of the model describe the 'causal relationships' of the analyzed system and which theoretical foundation it is based: partial or general equilibrium, optimization, dynamic or static? And how well this corresponds to the studied system. *Internal validation* involves goodness-of-fit measures, parameters of the right sign and right magnitude and sensitivity tests. *External validation* is the ability of the model to predict the future and reproduce independent data.

In this regard, uncertainties are dealt in our model in the following ways. 1) Energy balance (practical and external validation), 2) RES diagram (practical validation) 3) level of disaggregation (practical validation), 4) soft-linking (practical and theoretical validation) 5) consistency (internal validation), 6) comparison with other literature (external validation), 7) sensitivity analysis (internal validation), 8) measuring of goodness-of-fit and error (internal validation).

As discussed in section 5.4.4. the energy balance of the OSeMOSYS model output is checked considering the developed RES diagram. The produced electric energy is supposed to show reduction in value from generation to transmission and all the way to final demand because of T&D losses. This pattern has been confirmed for all the scenarios and years. The RES diagram is also developed considering the context of the country in terms of resource availability, technology options, future system extensions, sectoral demands, power trade, etc. which validates the high degree of system representation.

Sector wise and technological representation of supply and end-uses at a disaggregated level in terms of centralized vs decentralized systems, rural-urban divide, economic and/or technological transition, informal sector and supply shortage features are employed in our soft-linked supply-demand optimization models. This again is important in enhancing the accuracy of system representation and making essential policy analysis.

The developed OSeMOSYS model is an LP-based optimization that finds the least-cost way of meeting the demand. This means that the techno-economic data input plays a key role in the selection and comparison of all possible combinations. However, certain values and estimations can differ between different sources and researches. In such a case, it is more important to be consistent when developing the model and give more weight to relative difference of parameters than having the absolute values correct. That is the approach followed in taking the input data which is expected to improve the data quality and model outputs.

Comparison of the model outputs and findings with other studies is also another way of checking how well the model is performing. The results are not expected to be similar, but a substantial difference needs to be scrutinized and explained. In this regard, even though there are not many studies, we made comparison of the projections with few studies who worked on similar supply-demand aspects (see section 4.6 and 5.5). Discrepancies in methods and results are justified and discussed in detail.

As part of internal validation process, sensitivity analysis is carried out on the results of the model by identifying the underlying factors that affect the output (see section 5.4.5). This provides crucial information regarding the effects of changes in critical inputs and assumptions. Accordingly, the results of the OSeMOSYS model are analyzed by varying the discount rates, capital cost of hydro and availability of CSP storage. Our soft-linked supply-demand model also employs multiple alternative scenarios that cover a broad range of uncertainties and policy options considering the context of the country.

The results of the multi-variable regression demand forecasts are validated as the best fit by measuring the coefficient of multiple determination (R^2), statistical significance (p-value) and standard error. Only those regressions which have high R^2 values (indicating good correlation), and with coefficients of reasonable magnitude and sign, and low p-values are used for forecasting.

7. Conclusions

This chapter summarizes the main contributions and conclusions of this PhD dissertation and provides suggestions for further research.

7.1. Summary and conclusions

7.1.1. Demand modeling

In this study, six demand scenarios were assessed to represent the alternative development pathways of Ethiopia's energy future from 2018 to 2050. The comparative analysis between evaluated scenarios shows that energy demand will significantly increase for the BAU and the HEG scenarios mainly due to population growth and economic development but much more moderately for the E&U scenario due to faster electrification and urbanization that can replace biomass-based consumption. The electricity demand increases strongly for BAU but even more for HEG and E&U. This is due to high rate of urbanization, electrification and economic development. The scenario independent strong increase shows the need for new capacity additions. The result of the policy scenarios (IEE-1, IEE-2 and IEE-3) shows that while the application of the energy efficiency policies and measures would only have a minor impact of the energy demand, their impact on the electricity demand is large, and that the application of such policies is a very important measure to combat supply-demand mismatch causing power shortages and blackouts. Further, it is interesting to note that the electricity demand development is very similar for the three policy scenarios both with regards to overall demand and sector-specific demands. The electricity demand is increasing strongly in all sectors.

In all the years, the household sector takes the highest share of energy demand followed by the transport sector. It is seen that it is possible to potentially reduce the household sector consumption by rapidly shifting from biomass-based energy consumption to clean-fuel (biofuel and electric)-based consumption. However, such technology transitions are not automatic and require state intervention through appropriate policy-development. In this regard, the current very low electricity access rate in rural areas should improve in the near future. Moreover, better service reliability and good power quality is also an important requirement to minimize the use of biomass and fossil fuel-based backup solutions during interruptions and power outages. This in turn requires a good power system planning.

The energy demand evolution under the BAU and HEG scenarios show that the household sector and other sectors will heavily rely on biomass and fossil-fuels that lead to significant CO_2 emission. On the other hand, E&U and IEE-3 scenarios result a much lower energy demand that can reduce significant CO_2 emission. This implies that it is possible for Ethiopia to potentially reduce its biomass dependency and CO_2 emission by setting the right policies and implementing various strategies. It is also shown that electricity efficiency improvements are crucial for controlling the evolution of the electricity demand through proper energy policies. Considerable energy can be saved by implementing policy-driven efficiency measures through technology improvement, DSM activities, industrial energy audit and network loss reduction. The Ethiopian government has already started to explore several measures including standards and labeling, energy management and auditing, public sector efficiency, technology acceleration, awareness training and accreditation, etc. To ensure the effectiveness of these programs in achieving electricity efficiency improvements, the government should focus on long-term policies and strategies that can have significant impact on the future electricity sector.

The analysis also showed that the transport sector will see an increasing and heavy reliance on imported fossil-fuels in the long-run. This is true despite the assumption of intensive electric vehicle deployment in the last decade. This means that it takes many more years beyond 2050 to potentially replace the existing/future penetrating fossil-fuel-based vehicles. Therefore, the government is required to work on new policy measures that can speed up the transition to electric vehicles and encourage their adoption through various means.

Overall, the scenario analysis and forecasting results of this study could potentially have important implications for energy planners and policymakers in fostering a long-term energy strategy, systems planning, financing and development of new generation capacity to meet the projected demand in energy and electricity. The presented scenarios set clear targeted vision that could be fully or partially adopted by policymakers in all underdeveloped countries for the purpose of determining future supply mixes, minimizing system costs, social & economic benefits, emission reductions, improve service reliability, etc. The developed LEAP energy demand model considered the unique features and characteristics of developing countries which resulted in a better system representation compared to earlier studies. The model could be used by other interested academicians and energy-planners to further study the future energy demand by modifying the existing scenarios or drawing additional new scenarios with an entirely different assumption. In addition, someone could also explore by conducting sensitivity analysis on how scenario results would change on critical assumptions.

7.1.2. Supply modeling

In the supply modeling, a soft-linking approach of coupling two modelling frameworks was adopted while considering the unique features and context of developing countries. The open-source long-term energy modelling framework - OSeMOSYS was used to analyze the long-term capacity expansion of the electricity supply system while the future energy demand was analyzed in the LEAP framework. The work in this study shows that the soft-linking methodology of LEAP based simulation and OSeMOSYS based optimization model provides a useful method to have better system representation that prevents inaccurate analysis and the prescription of wrong policies.

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 and low economic cost of the technologies compared to others. This results in a slow transition of the historically hydro-dominated source to 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 favorable 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. 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 [Gusano & Kirkengen, 2016], the sensitivity results in general show that higher discount rates favor expansion of natural gas power plants while lower discount rates lead to increased utilization of CSP, medium-scale hydropower plant and rooftop solar PVs. Moreover, it is shown that increased capital cost of hydro results in reduction of the share of hydro and replacement with other competitive sources. The sensitivity results also showed that CSP without storage is not competitive in the context of Ethiopia.

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 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 neighboring 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 also 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.

7.2. Possible limitations of the research and future work

There are some limitations of our research that point to topics to be addressed in the future. The model and analysis consider a spatial scope of a single-region and did not consider the disaggregation of the country on socio-economic status (level or urbanization, size, economic structure, human resources, etc.) or climate conditions by region. A detailed disaggregated analysis may provide better insight into sector wise regional climate impact. This is especially evident for the fossil-fuel based transport sector that has the potential to reduce the significant CO_2 emission in the country. In addition, a disaggregated analysis may provide better insight into sector wise regional energy assessments with regard to electricity access, sustainability, security and affordability. Another limitation with regards to the demand modeling is that it does not consider seasonal fluctuations. Even though the study is long-term, concerned with the general evolution of energy demand in the next three decades, someone may be interested to see the future seasonal behavior of the energy consumption. However, we do not expect these limitations to change the analysis and results.

Increasing the model resolution in time and space is important at representing the operation of the power system, particularly with large-scale deployment of wind and solar sources to the grid as it poses challenges by introducing variability on the generation side. Unlike conventional sources, variable renewable energy resources are non-dispatchable and inflexible. This makes it very difficult for power system operators to keep the balance between supply and demand. In this regard, accounting the intra-annual variability of VRE supply and load, and the resulting flexibility requirements and relevant technical characteristics of dispatchable plants becomes quite essential. Therefore, assessment of the best applicable ways to increase the effective variation management strategies (VMS) along with design of the electricity system to tackle the varying or inflexible generation problems could be taken as an interesting topic for future research.

The use of high time and geographical resolution in operational models of developing countries should also be accompanied by other modelling improvements. Our study showed that the existing standard global modelling tools inadequately capture the characteristics of developing countries with a huge need for improvement. As a result, interested modeling framework developers and institutions could either improve the existing modeling tools or develop new advanced solutions to effectively represent the energy system of developing countries and capture all their features.

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Appendices

Appendix A: Published articles

Paper-I

2019 IEEE PES/IAS PowerAfrica

Assessment of Resource Adequacy in Power Sector Reforms of Ethiopia

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Abstract—**Recently, the government of Ethiopia has been shaking up the power industry by introducing reforms with the hope of increasing electricity access, ensuring resource adequacy, stimulating private investment and guaranteeing financial sustainability of the sector. Restructuring of utility, liberalizing energy market, tariff revision, targeting universal access, and export market are some of the sea changes undertaken by the government. The expected return from these reforms is very high, sometimes to a level that it looks too good to be true. The study thus evaluates the effectiveness of the reforms by assessing the future generation adequacy in contrast to the growing electricity demand. An analytical method to calculate resource planning indices such as reserve margin and expected unserved energy is used. The results show that the Ethiopian power system will face about 10 TWh energy shortage in the near-future. The study begins by providing an overview of the power sector and the recent reform activities with their intentions and goals. The result of the study could be important as input for making policy-adjustments and/or revamping implementation strategies.**

Index Terms—power sector reform, generation, resource adequacy, installed capacity, peak demand.

I. INTRODUCTION

a) Overview of Ethiopian power sector

Ethiopia is one of the most suitable nations in Africa for tapping renewable energy resources. It has a high potential for solar, wind, and hydropower in addition to geothermal and bioenergy as alternative source. The country has the potential to generate more than 45,000 MW from its boundary and trans-boundary rivers, an astounding 1,350 GW from wind and 10,000 MW from geothermal energy resources [1],[2]. Since the country is located near the equator, its solar resource is obviously of significant potential. The annual average daily radiation reaching the ground is estimated to be 5.5 kWh/m^2/day [1],[3].

Under the Paris agreement countries have committed to realize substantial GHG emission reduction in the short term (COP-21, 2015) and stay below the 2 °C average atmospheric temperature increase [4]. Ethiopia has significantly bold ambitions under its Nationally Determined Contribution (NDC), as it intends to reduce its emissions of 400 MtCO$_2$e by 64% by the year 2030, implying a reduction of 255 MtCO$_2$e down to 145 MtCO$_2$e [1],[5]. All sources of renewable energy would have huge contributions to Ethiopia's green energy development, as the government intends to achieve the middle-income status by 2025 [1]. But, the country's renewable energy potential is still largely untapped.

The interconnected system (ICS) consists of 13 hydro, six diesel standbys, one geothermal and three wind farm plants with installed capacities of 3,814 MW, 87 MW, 7.5 MW and 324 MW, respectively, implying a total of 4,233 MW national generating capacity. The generation is dominated by hydropower accounting for some 90% of the total generation. A number of hydropower plants are also under construction including the Grand Ethiopian Renaissance Dam, GERD (6,450 MW). The government's aim is to achieve 17,208 MW installed capacity by 2020. According to the second Growth and Transformation Plan (GTP-II), that is guiding the overall development endeavors of the country; in year 2020, 13,817 MW is planned to be generated from hydropower; 1,224 MW from wind, 300 MW from solar, 577 MW geothermal, 257 MW from biomass and the remaining from waste, gas and sugar-factory cogeneration [6].

b) Electricity access

The country has managed to achieve universal electricity access to almost all urban areas, while access to electricity in rural areas is still very limited although expanding at a rapid pace. About 80% of the population resides in rural areas, largely relying on traditional biomass energy sources for cooking and heating. The current access rate is 29% rural and 85% urban population which translates to about 40% total electricity access with per capita consumption of 0.04 kW [7]. The majority of the supply is through the national grid, which accounts to about 28% and the remaining 12% is via off-grid access.

The first rural electrification project, launched in 1999/2000, resulted in electrification of 667 towns [1]. It mainly focused on extending the network to major towns and small towns (commonly called 'Woreda') located close to substations or existing distribution lines. However, in 2005, a more ambitious endeavor called the Universal Electricity Access Program (UEAP) was launched that aimed to promote socioeconomic development of rural areas in the country by expanding the electricity network.

Between 2005 and 2015, UEAP has been able to spread out the electricity grid to about 6,000 towns and villages and achieve 60% grid coverage (geographical access) in the rural areas [1]. The program also showcased the social and economic impact of electricity through creating business opportunities, improving health and education service as well as improving life style. But, considering the remoteness, large population and sparse density; extension of the grid is technically difficult, inefficient and costly.

II. ELECTRICITY REFORM ACTIVITIES AND ITS CHALLENGES

Many literature have shown that the driving force behind power sector reforms in developing countries is the poor technical and financial performance of their electricity industry. The main technical problems are lags in generation capacity and high transmission and distribution (T&D) losses. Whereas, the financial problems are reflected by low-debt coverage, insufficient cash for new investments and subsidized prices [8],[9]. Ethiopia has faced both technical and financial problems. Technical problems in which rotational load shedding has been in practice due to insufficient generation and high T&D losses accounting for 23% [6] against a world average of 9% [10], frequent interruption and poor power quality were the prevalent characteristics of the grid network. Lack of the provision of adequate and reliable electricity has also been the bottleneck for accelerating the government's major economic plan on growth of manufacturing industry. On top of solving all these problems, finding a way to boost the low-electricity access was a big assignment of the government. In order to deal with this crisis, the Government of Ethiopia (GoE) committed itself to embark on reforming the power sector.

The reform began in 2013 by restructuring the utility: Ethiopian Electric Power Corporation (EEPCo), which used to be fully state-owned and vertically-integrated enterprise was in charge of generating, transmitting, distributing and selling electricity throughout Ethiopia. EEPCo has been split into two separate public enterprises, Ethiopian Electric Power and Ethiopian Electric Utility (EEP and EEU), each with a very different business, technical focus, and accountability for operation and results. EEP is responsible for generation, transmission and wholesale of electricity nation-wide and export the balance whereas EEU is engaged in power distribution, sales, and customer services. In addition, the Ethiopian Energy Authority (EEA) has also been established as the sector regulator.

In 2017, the GoE introduced an ambitious program, the National Electrification Program (NEP) with a theme 'Light to All' which aims to achieve universal access of electricity nationwide by 2025. The program is designed mainly to consider least-cost grid connection rollout strategy from both grid and off-grid supply that is based on spatial distribution of households. In 2016, 7.6 million households were settled proximately to the existing low voltage (LV) network of EEU, while the other 8 million households (assuming average 5.5 persons per household) were not proximate and could not be supplied by LV lines and required higher voltage levels [1]. To provide urgent connection, the plan is to connect 4.5 million of the proximate households by 2022 through extending short LV service drops and metering which requires less investment while the other 5.4 million customers (3.1 million proximate and 2.3 million non-proximate customers) by 2025 through extending medium and high voltage lines. In addition, the remaining 5.7 million households are planned to be supplied with off-grid systems. These accounts for some 65% grid-connection and 35% off-grid supply by 2025 which is planned to be the period for 100% electricity access. The off-grid supply is designed for remote settlements and villages where grid connectivity is not the least cost solution. The technologies are mainly stand-alone solar systems, but also mini/micro grid network connections expected to be delivered by the private sector.

Tapping and mobilizing private capital and resources is one of the key-components to scale up generation, transmission & distribution capacity, and increase electricity supply. Focusing only on power generation, public private partnerships (PPPs) are typically represented by independent power producers (IPPs), which design, finance, build, operate, maintain and decommission a power generation plant and contract to sell the electricity generated to a publicly owned power utility [11]. The GoE currently recognized that engagement with the private sector especially with the development of power generation is crucial to meet the country's investment and energy policies and to establish sustainability in infrastructure investment.

In recent years, the GoE is liberalizing the energy sector for private sector participation, specifically to generate significant financial resources and stimulate investment in power generation and transmission. In January 2018, the GoE has passed the comprehensive Public-Private Partnership proclamation that includes the establishment of a legislation and institutional framework for PPPs. Even though the regulator has setup a basic legal framework which invites private players to undertake generation and transmission of power, the energy tariff was one of the main bottle-necks that hampered the engagement of international investors and private power companies.

Last revised in 2006, the average flat rate tariff in Ethiopia was just under 3 US cents per kilowatt hour. Considering currency depreciation due to inflation, the tariff level has been declining in real terms. Less cost of electricity from hydropower and GoE commitment for endowment of the power sector had a big role for the lowest domestic tariff rate in Africa. The generation cost from hydropower is about 9 US cents per kilowatt hour; compared to the above tariff rate, it can be seen that the government makes a significant subsidy for electricity use.

The electricity generation in the country has quintupled from 850 MW to 4,233 MW within just a decade. With such high and fast generation-growth, the government could no longer afford to subsidize electricity generation. Consequently, as part of developing a workable and viable long-term power sector, the tariff-framework revision started in 2017. After long consultation of the draft, new tariff structure has been effected since December, 2018. The new tariff structure is planned to be applied gradually with four phases of increment every following year and the tariff after the fourth year is expected to reflect the full cost of service provision. However, the adjustment at this time is designed by considering the affordability for the low-income population. Those within a monthly consumption range of up to 50kWh will stay within the old tariff and continues as is.

From the above overview, it can be seen that there were few, but major power sector changes conducted within the past few years. However, it is highly questionable whether these reforms are adequate to support the needs arising from the fast-economic growth of the country, regional interconnection and power sector growth in terms of customer size, finance, human capital and technology. The current significant demand increase is because of the new economic developments such as the railway transport, large irrigation projects, industry zones, housing projects and also due to population growth.

III. GENERATION: ADEQUACY OF SUPPLY

A literature search [12],[13],[14] on the definition of resource adequacy shows that there is a common understanding on the subject. Resource adequacy (RA) is interpreted as the ability of a utilities' reliable capacity resources (supply, S) to meet the customers' energy or system loads (demand, D) at all hours within the study period. This is shown in (1). At any given hour t, a utility desires that, $S_t \geq D_t$ resulting positive RA. The utility is required to have sufficient resources to satisfy forecasted future demand.

$$\mathrm{RA} = \mathrm{S_t} - \mathrm{D_t} \qquad (1)$$

The metrics most commonly used to assess resource adequacy measure the expected days in a year that could face a generation shortfall in addition to estimation of the energy shortage. These include loss-of-load probability (LOLP), loss-of-load expectation (LOLE), loss-of-load hours (LOLH), planning reserve margin and expected unserved energy (EUE)[13],[14].

For the study of Ethiopia's near-future resource adequacy, the indices: reserve margin and expected unserved energy are used. These metrics highly depend on the installed capacity, plant capacity factor and peak demand. The data for these parameters has been carefully assessed considering recent developments on power plant constructions and demand trends. The installed capacity growth in the past five years has been significant. This is illustrated in Fig. 1. In comparison to 2013, the installed capacity has more than doubled mainly due to the addition of one hydropower plant: Gilgel gibe-III (1,870 MW) and two wind-farms: Ashegoda and Adama-II with installed capacity of 120 MW and 153 MW respectively. This has increased the total installed capacity to 4,233 MW.

Currently, there are many projects that are under development or with signed Power Purchase Agreement (PPA) contracts. Hydropower stations such as GERD (6,450 MW), Koyisha (2,160 MW) and Genale-dawa-III (254MW) are part of the undergoing projects with 58%, 96% and 21% construction completion status respectively. In addition, Chemoga-yeda (280 MW), Dabus (798 MW), Geba (372 MW), Genale (346 MW), Baro (645 MW), Genji (214 MW) and Wabeshebele (87 MW) are also in the pipeline at their earliest construction stages.

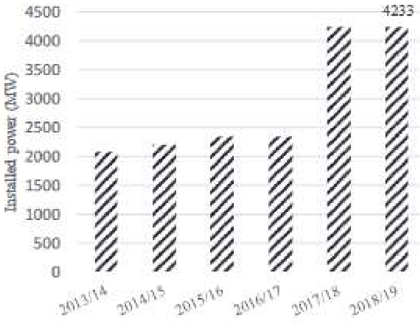
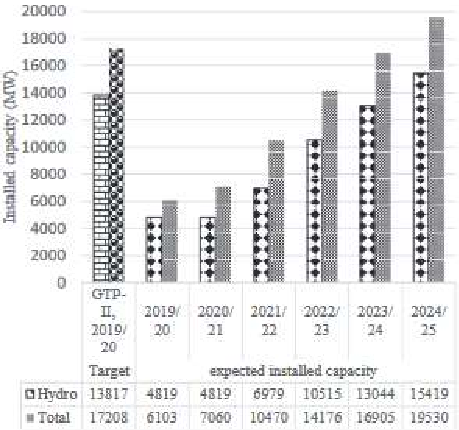


Fig. 1. Installed power capacity in Ethiopia, 2013-2019.

Geothermal power plants which are expected to be operational between 2020 and 2022 are Aluto Langano (70 MW), Corbetti (270 MW) and Tulumoye (500 MW). Biomass plants using sugar factories' residue as a cogeneration, municipal waste or organic matter are also part of the underway projects with a total capacity of 683 MW that are planned to be commissioned by the end of 2021. Two wind-farms: Aysha and Assela with installed capacity of 129 MW and 100 MW respectively are expected to be operational by 2020. A number of Photovoltaic (PV) solar plants with total capacity of about 2,000 MW are also expected to be operational before 2022.

Table-I shows the expected installed capacities for the future six years in comparison to the target set on GTP-II. The corresponding capacities mentioned in the GTP from different sources with a total of 17,208 MW and 63,207 GWh are planned to be realized by the year 2019/20. Assuming timely completion of the ongoing projects according to their respective schedule and considering construction progress of some of the major power plants, the attainable installed capacity and energy production reserve is determined. All power plants are expected to start at full-capacity generation once they are completed except for GERD where early generation of two units (750 MW) is set to start in 2020 followed by 8 units (3,256 MW) in 2023 and the remaining 6 units (2,442 MW) in 2024.

As shown in Fig. 2, the major share of supply is taken by hydropower both on GTP-II plan and implementation; however, there is significant disparity in terms of magnitude between the target and implementation. The investigation shows that it is impossible to meet the target of achieving 17,208 MW installed capacity by 2023/24 let alone 2019/20. The delay of GERD by five years plays a major role which was originally scheduled to be completed in 2017; but also other hydro, wind, solar and geothermal projects where there is a significant shortfall. To study the implication of project delays, we used the Planning Reserve Margin (PRM) which is the ability of the projected capacity resources to meet the projected peak demand given by (2).



	GTP-II, 2019/20	2019/20	2020/21	2021/22	2022/23	2023/24	2024/25
	Target	expected installed capacity					
▢ Hydro	13817	4819	4819	6979	10515	13044	15419
▨ Total	17208	6103	7060	10470	14176	16905	19530

Fig. 2. GTP target Vs. expected installed capacity.

$$\mathrm{PRM} = \frac{\text{Firm Capacity} - \text{Peak Demand}}{\text{Peak Demand}} \tag{2}$$

The PRM level is given in units of percentage that represents the surplus generating capability above the sustained-peak annual demand. Firm capacity is the fraction of variable renewable energy (VRE) capacity that is guaranteed to meet demand given by (3). Where α_i is the capacity credit of power plant/technology i which is considered as "firm"; C_{Pi} is the generating installed capacity of the corresponding power plant.

$$\text{Firm Capacity} = \sum_{i=1}^{n} \alpha_i \times C_{pi} \tag{3}$$

Dispatchable power technologies (thermal and hydropower using dams) have a value of 100% capacity credit. For VRE (wind and solar), the capacity credit depends on their penetration level and the quality of the resource. Rough estimates of capacity credit for solar and wind in Africa have been used in [15]. Considering high quality of wind and low share of generating capacity in Ethiopia, we have used 20% for wind power plants. Centralized photovoltaic (PV) plants were given a 5% capacity credit to account for their variability and their sensitivity to cloud cover.

The future annual-peak demand is adapted from robust long-term planning studies conducted on the Ethiopian power system. The Ethiopian Power System Expansion Master Plan (prepared by Parsons Brinckerhoff Consulting) [16] developed in 2014 uses a combination of regression and end-user models to forecast Ethiopia's 25-year electricity demand. The master plan includes peak load forecasting considering domestic demand in various sectors and export projections to neighboring countries. According to this study, the energy demand is forecasted to reach 146,691 GWh by 2037 representing an average growth of 13% per annum from 6,906 GWh in 2012. However, when comparing the forecasted demand with the actual peak demands recorded for the past couple of years, the forecast was very much higher than the actual values indicating that the forecast was too optimistic and need to be revised based on current energy consumption and future development plans. Recently, a new update of the master plan is being developed by United States Agency for International Development (USAID) [17]. The study anticipates a 15.2% annual growth rate from 12,540 GWh and 2,148 MW peak demand in 2017 for high scenario forecast considering significant increase in exports as well as estimated improvement in transmission losses.

For the sake of determining the PRM as well as assessing the overall supply adequacy, we have used the forecasted peak demand from the USAID study. The expected installed capacities for the coming years are determined as shown in Table-I by considering the construction progress of various new power plants. The annual generation from each resource is shown in Table-II, and Fig. 3 depicts the peak demand, installed capacity and corresponding reserve margin for the past and future years while the firm energy production and energy demand are shown in Fig. 4.

TABLE I. INSTALLED CAPACITY: GTP TARGET VS. ATTAINABLE IN THE NEAR FUTURE

Source Type	GTP Target, MW	Installed Capacity, MW					
	2019/20	*2019/20*	*2020/21*	*2021/22*	*2022/23*	*2023/24*	*2024/25*
Hydro	13817	4819	4819	6979	10515	13044	15419
Wind	1224	544	544	544	544	544	544
Geothermal	577	28	78	228	398	598	848
Biomass and cogen.	781	276	683	683	683	683	683
Solar	300	350	850	1950	1950	1950	1950
Gas and others	509	87	87	87	87	87	87
Total	17208	6104	7060	10470	14176	16905	19530

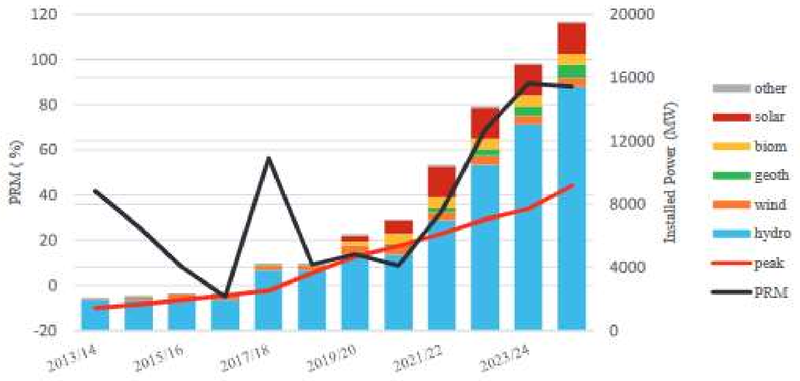


Fig. 3. Planning reserve margin, peak demand and installed capacity.

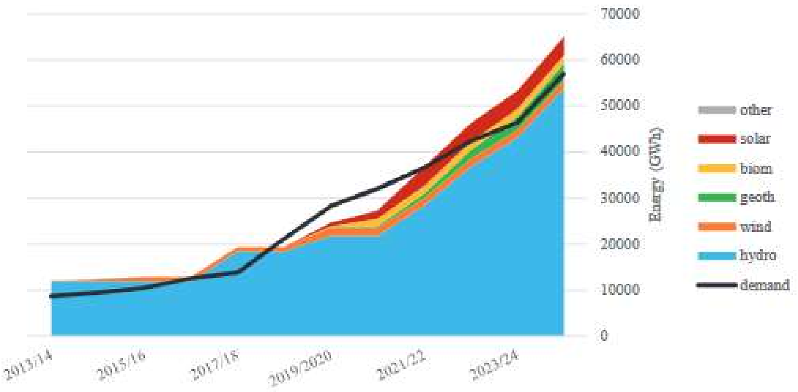


Fig. 4. Firm energy production[1] and energy demand.

([1]Firm energy production is the amount of electric energy guaranteed to be available per year)

TABLE II. ANNUAL GENERATION BY RESOURCE TYPE AND ENS

Source Type	Energy, GWh											
	2013/14	*2014/15*	*2015/16*	*2016/17*	*2017/18*	*2018/19*	*2019/20*	*2020/21*	*2021/22*	*2022/23*	*2023/24*	*2024/25*
Hydro	11960	11960	11960	11960	18488	18488	21818	21818	28318	36820	43071	53827
Wind	134	449	879	879	879	879	1680	1680	1680	1680	1680	1680
Geothermal	0	0	0	0	0	0	160	364	976	1936	2752	3772
Biomass and cogen.	0	0	0	0	0	0	242	1699	1699	1699	1699	1699
Solar	0	0	0	0	0	0	736	1786	4096	4096	4096	4096
Gas and others	7.55	7.55	7.55	7.55	7.55	7.55	7.55	7.55	7.55	7.55	7.55	7.55
ENS	0	0	0	0	0	1861	3618	4698	0	0	0	0

Due to continuous rise of demand, the PRM had been falling since 2013 with the lowest reserve margin of 8% and -5% in 2015/16 and 2016/17 respectively. This violates the recommended minimum PRM requirement of 10% [15],[18] and 13% [19]. The negative value in 2016/17 indicates that the available resources were not able to meet the peak demand which might have led to load shedding. The margin gets 56% in 2017/18 with the addition of Gilgel gibe-III hydropower plant. In the next three years, the margin is lower than 15%, particularly in 2018/19 and 2020/21 it has a value of 9% which again violates the minimum PRM requirement of 10%. This implies that the available power plants on those years may not be adequate to supply the peak demand. Afterwards, with the addition of GERD and Koyisha hydroelectric station, the PRM is mostly more than 50% meaning the generation firm capacity is very high in comparison to the expected peak demand. It is also evident from the graph that peak demand was steadily but slowly increasing in the past and faster growth is anticipated in the near-future.

An evaluation criteria is shown in (4) which states that the total firm capacity should always be greater than 110% of the annual peak demand (D_p). This is apparent considering minimum PRM of 10%.

$$\sum_{i=1}^{n} \alpha_i \times C_{pi} \geq (1 + PRM_{min})D_p \tag{4}$$

Using (4) as an evaluating criteria, it is seen that the total firm capacity for the years 2015/16, 2016/17, 2018/19 and 2020/21 is less than 110% of the corresponding annual peak demands.

Looking also at the energy scenario presented in Fig. 4, the energy demand exceeds the generation reserve for the years from 2018/19 till 2020/21. Equation (5) is used to calculate the Energy Not Supplied (ENS) when the annual energy demand D_i is greater than the expected annual generation G_i of all units existing in the system for the corresponding year i.

$$\text{ENS} = D_i - G_i \tag{5}$$

Consequently, the corresponding ENS for those three years is determined as shown in Table-II which is about 1.8 TWh, 3.6 TWh and 4.7 TWh. This gives a total ENS of 10.1 TWh of energy. This means that the available plants during those years cannot produce adequate energy to supply the huge energy demand of the country. Even though many of the biomass, wind and solar plants will be integrated into the system by then, their lower capacity factor will limit the energy output.

The power system expansion master plan used $1,000/MWh as unserved energy cost to see the economic impact of the capacity shortage to the electricity demand. Taking this rate to calculate the unserved energy cost of 10.1 TWh energy would translate into $10.1 billion economical loss. Such amount of money can fully finance two new hydropower stations each with a capacity much more than GERD.

Another important note to be seen from Fig. 3 and 4 is that the supply mix gets diversified in the coming years. In terms of installed capacity, hydropower penetration reduces from the current 90% to about 79% at the end of 2025. Solar generation is expected to grow to about 2 GW by 2025 followed by geothermal, biomass and wind with roughly 850 MW, 700 MW and 550 MW capacity, respectively. Comparing this with the GTP-II plan of increasing solar to 300 MW and wind to 1.2 GW, there is a significant shortfall in wind capacity whereas much higher capacity in solar.

Finally, it is important to mention that system loss reduction is as important as generation capacity expansion. The losses are currently at 23% which is huge. By implementing projects to cut that in half (reconductoring, adding capacitors and voltage regulators, etc.), the system could see a big increase in supply.

IV. DISCUSSION

The results of the analysis have shown that it is almost impossible to achieve the GTP-II target of increasing the generation level to 17,208 MW by 2019/20. It is seen that the target is highly likely to be achieved after five years in 2025. It is also seen that the near-future generation reserve is not adequate to supply the increasing energy demand resulting mainly from expansion of electricity access, development of industrial parks, extensive expansion of railway network, extensive agriculture irrigation schemes, new sugar factories and export plan to East African Power Pool (EAPP) countries.

The results presented in this study have important policy and implementation implications. The cost of ENS is huge which has significant impact on the economy of the country. Therefore, corrective measures in terms of revising the existing policies or revamping implementation strategies should be taken as early as possible to continue Ethiopia's economic ascent through ensuring adequacy of energy supply. Creating a sound and enabling environment for IPP/PPP projects is also essential to obtain and sustain the involvement of the private sector which would contribute a lot particularly with regard to universal access coverage.

The near term anticipated shortages can be mitigated by accelerating the construction of new generation projects with higher capacity factors to cover part of the energy deficit, considering energy import from the regional EAPP, implementing energy efficiency and Demand Side Management (DSM) strategies, improve overall transmission and distribution losses through network rehabilitation and maintenance, encourage Distributed Generation (DG) and small community owned solar and wind generation close to the demand.

V. CONCLUSION AND FUTURE WORK

In this paper we have assessed the supply adequacy as part of a wider investigation on power sector reforms in Ethiopia. Reforms play a substantial role to meet Ethiopia's rising demand for energy by breaking the "business-as-usual" trajectory of the past. However, the reforms did not keep pace with the fast-economic growth of the country, regional interconnection, grid-access and increasing population growth which implicate that there is still a strong possibility for introducing further reforms.

In line with the long-term generation expansion plan, the optimal selection of various energy sources and proportion of supply mixes is also very important to avoid reliance on hydropower and mitigate intermittency. In addition, considering the varying nature of solar and wind resources, the optimal and applicable variation management strategies should be identified. As a future work, all of these need a scientific study to come-up with overall energy system planning and appropriate policy to guide through the planning to achieve its goals.

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Paper-II

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Energy System Modeling Tools: Review and Comparison in the Context of Developing Countries

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Abstract—**Given the fact that there are a wide variety of models that are available for analysing energy systems, it is important to develop a comparative overview of the models in terms of several criteria, particularly their applicability to developing countries where unique features such as 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. This paper presents a review and comparison of the most commonly used modeling tools for analysing energy and electricity system. It reviews the available literature and follows a systematic approach of classifying the alternative models that can serve as a guidance to select the most appropriate analytical tool, mainly when dealing with energy modeling and analysis for developing countries.**

Keywords—comparison of models, developing countries, energy system models, model criteria.

I. INTRODUCTION

The energy system is defined as a system that comprises all components related to the production, conversion, delivery and use of energy [1]. Modeling being a non-physical entity and a simplified representation of reality, it has been a tool for analysing energy systems or sub-systems since the mid-1970s [2],[3]. The increasing availability of computers and the rise in environmental awareness due to climate change and the oil crisis saw the introduction of energy models [4]-[6]. A wide-variety of models were developed to better understand the present and future demand-supply interactions, energy and environment interactions, energy-economy interactions and to predict the functioning and performance of individual components or overall system behavior by making national energy planning. More recently, global warming, energy security and economic competitiveness have become the most significant topics for decision makers and planners. As a result, they are increasingly relying on various assessments to answer different questions, introduce appropriate policies and set the right national targets. In this regard, computer-based modeling tools are at the core of energy planning that can perform a comprehensive analysis.

The models initially built were mostly for industrialized countries, and as such, their application to the developing countries was based on the assumption related to the developed country's situation [7],[8]. Furthermore, it was assumed that the future developmental projections would be similar to the historical projections of developed countries, which in reality is not the same [9]. The choice of the appropriate modelling framework depends on the kind of insights the country model is intended to provide and should therefore start from an assessment of the context, the challenges and the policy questions to be answered [10].

In this paper, we review the available literature on energy system modeling tools, propose classification criteria that can serve as guidance in selecting the most appropriate analytical tool, mainly when dealing with energy modeling and analysis for developing countries. The remaining sections are organized as follows: Section II presents the energy system planning models which are divided into three parts as a) model classifications, b) developing country context and c) comparison of modeling tools, and Section III provides the summary and conclusions.

II. ENERGY SYSTEM PLANNING MODELS

A. Classification of Models

Over the past four decades, a large number of energy models have been developed that vary considerably and it is important to have a certain classification scheme that provides insight to the differences and similarities between the models and thus facilitate the selection of the proper tool for proper application. The classification may be based up on the use of several criteria. A wide variety of literature have established several ways of categorizing the models [2], [3], [11]- [20].

Reference [11] has identified four different purposes for generally grouping models. These are power system analysis tools, operation decision support tools, investment decision support tools and scenario modeling tools. Reference [12] used two criteria to categorize different types of planning models: scope of the model and methodology. Reference [2] used four important criteria to categorize energy planning models: the modeling approach, methodology, modeling technology and the spatial dimension. Reference [14] proposed nine criteria to classify models for energy planning: purposes of energy models, model structure, analytical approach, underlying methodology, mathematical approach, geographical coverage, sectoral coverage, time horizon and data requirements. Reference [15] and [16] presented a thorough discussion on the two contrasting modeling types: the bottom-up engineering approach and the top-down macroeconomic approach.

Reference [17] categorized energy planning models, optimization models, simulation models and computer-assisted tools. Reference [18] suggested an alternative classification based on methodology adopted (bottom-up vs top-down), spatial coverage, sectoral coverage and temporal coverage. Reference [19] classified planning models into optimization models, decentralized energy models, energy supply/demand driven models based on neural networks. Reference [3] and [20] used a set of attributes such as approach (top-down simulation, bottom-up optimization/accounting), spatial focus (global, regional, national, local), sector (macro-economy, energy) and time (short, medium or long-term).

Considering the research results mentioned above as a springboard, we have come up with a more comprehensive and extended classification that is important with regard to the comparison of models as follows. (i) purpose (ii) model scope (iii) analytical approach (iv) methodology (v) mathematical approach (vi) geographical/spatial coverage (vii) sectoral coverage and (viii) time horizon. Category (i) is selected from [11], category (ii) is selected from [12] and categories (iii) up to (viii) are referred from [2], [3], [14]-[18], [20]. Each of these classification criteria is briefly discussed below.

i. Purpose

The purpose relates to the general objective of the modeling tool which can fit into the following categories: power system analysis tools, operation decision support, investment decision support and scenario-based tools.

ii. Model Scope

The scope or coverage of planning models determines the endogenous interactions, type of questions that can be addressed, level of detail and complexity of executing the model [21]. In this regard, there are four major types of long-term planning models. These are: integrated assessment models, energy-economy models, energy-system models and power-system planning models.

iii. Analytical Approach

With the aim of meeting the demand in an economical fashion, energy models generally follow two contrasting modeling/ analytical approaches; a top-down and a bottom-up approach. The bottom-up modeling approach or often referred to as the engineering approach is based on detail technological and engineering descriptions of the energy system. Energy demand is typically provided exogenously, and the models analyze how the given energy demand should be fulfilled in a cost-optimal fashion [15]. On the other hand, the top-down modeling approach follows an aggregated view and macroeconomic relationships [16]. The influence of prices and markets is believed to have more impact than the technical characteristics of the energy sector.

iv. Methodology

The commonly used methodologies for the development of energy and electricity models are grouped into three main categories; optimization, simulation and equilibrium methods.

Optimization models are used to balance demand and supply by optimizing energy investment decisions such as capacity and choice of technology alternatives. The outcome represents the best solution usually the least-cost path, while meeting a set of operative constraints. Simulation models are descriptive models that simulate an energy system based on specified equations and characteristics. Such models are often bottom-up models, with a detailed technological description [11]. Equilibrium models are used to study the energy sector as part of the whole economy and focus on interrelations between the energy sector and the rest of the economy [14].

v. Mathematical Approach

The mathematical approach refers to the mathematical techniques that are used to represent the complex correlations between different variables and components of the energy system. Accordingly, commonly applied mathematical techniques include linear programming, mixed integer programming and dynamic programming. In addition, most recent studies are using fuzzy programming or stochastic and interval programming methods to deal with uncertainties in the energy systems such as energy demand, price market and learning rate of technologies [22].

vi. Geographical/Spatial Coverage

The geographical coverage refers to the spatial area or space where the analysis is taking place. The relationships between energy and society take different forms across space, as energy policies are pursued in different local, national, regional and global settings [23]. Emerging problems are often requiring geo-referencing to certain spatial scales [24]. Tools that capture the spatial dimension of energy systems are essential for the development of spatially inclusive and comprehensive energy demand supply analyses. This is particularly important for developing countries which are investigating different electrification options including grid extension, mini-grid and stand-alone systems [25].

vii. Sectoral Coverage

Sectoral coverage refers to the scope and focus of the model with regard to fuel type, technology, economy, class of customer, etc. Based on this division, models can be classified, into sub-sectoral, sectoral, and economy wide models [26].

viii. Time Horizon

The time horizon is simply the timeframe in consideration under the study. It is very common to classify models into short-term, medium-term, and long-term. However, there is no explicit definition of the exact timeframe for each of them. In this paper, we consider a short-term time horizon to be 1 year or less; medium-term, between 1 and 15 years; and long-term to be over 15 years.

B. Modeling Tools for Developing Countries

The energy systems of industrialized countries are characterized by a constant match of supply and demand, low losses of transmission and distribution, universal access to electricity, predominance of modern energy carriers, similar structural premises in urban and rural areas, adequate financing and investment decisions, adequate subsidies and profit-making utility companies in developed economies with a low extent of informal economies [9]. To the contrary, the energy and the electricity system of developing countries differ from industrialized countries.

Adopting global tools without incorporating the inherent characteristics of developing countries could lead to inaccurate analysis and policy prescriptions. As a result, the analytical tools used for modeling should be able to capture the specific features of developing countries. Few literature have attempted to identify the specific features and unique characteristics of developing countries compared to the developed countries. Reference [9] indicated three specific features: poor performance of the power sector and traditional fuels, the transition from traditional to modern economies, and structural deficiency in society, economy and energy systems. Reference [20] pointed out that the existence of inequity and poverty, the dominance of traditional life styles and markets in rural areas, transitions of populations from traditional to modern markets, the existence of multiple social and economic barriers to capital flow and technology diffusion, and the radical nature of policy changes being witnessed in energy sector cause developing countries' energy system entirely different from that of developed countries.

Other studies [3],[16] have attempted to investigate the use of existing energy models with regard to incorporating the above unique features of developing countries. Reference [3] suggests that most of the existing models inadequately capture the developing country characteristics and that the problem is more pronounced with econometric and optimization models than with accounting models. However, many routine applications of standard models are found in the developing countries, which raises concerns about the accuracy and policy implications of such analyses. Reference [16] presented that the top-down approaches are not suitable for developing countries as they rely on per capita demand which are not applicable to developing countries with the fact that there is unequal electricity access. In addition, most of the tools can not consider the informal economy in their analysis. As a result, [16] also concludes that most energy analytical tools do not incorporate the inherent characteristics of developing countries. However, similar to [3]; [16] suggests that the accounting-based bottom-up models are suitable to simulate dynamic transition and forecasting in developing countries.

Considering the characteristics of the energy systems and economies of developing countries identified in the above studies, we use the following ten specific features to evaluate the suitability of energy models to developing countries. These are: (i) supply shortage (ii) performance of power sector (iii) traditional fuels (iv) urban-rural divide (v) informal economy (vi) economic transition (vii) subsidies (viii) data need (ix) skill requirement and (x) upfront financial cost.

C. Comparison of Modeling Tools

A number of modeling tools are available that are systematically used to analyse the energy and electricity system. In this section, the comparative overview of selected models is presented. They essentially cover global models which are frequently used for policy analysis in the energy sector. These include Open Source Energy Modeling System (OSeMOSYS), MARKet Allocation (MARKAL), Integrated MARKAL-Energy Flow Optimization Modeling System (TIMES), Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE), Modular Energy System Analysis and Planning Environment (MESAP), EnergyPLAN, Long-range Energy Alternatives Planning System (LEAP) and Renewable Energy Scenario Generation (RESGEN).

Table-I shows the comparison of the models considering the eight classification criteria presented in the previous Section. It can be seen that each tool has its own feature and selection of the appropriate modeling tool depends on the level of use of the features for a particular application. Table-II shows the model comparison based on the ten main characteristics of developing countries' energy systems and economies. And Table-III presents the comparison of different modeling approaches based on the following: a modeling approach, geographical, technological and activity coverage, level of disaggregation, data and skill needs, portability, price and non-price policy capabilities, rural energy capabilities, energy shortage, informal sector, subsidies, rural-urban divide and economic transition.

From the comparative overviews, it is observed that most of the models are not suitable for developing country contexts as they do not explicitly cover the essential features of developing countries. But, models like LEAP appear to be more suitable as such tools are scenario-based and are better suited to capture rural-urban divide, economic transition, informal sector and energy shortage features. LEAP has been used to investigate the energy system and analyze energy policies in different countries including India, Pakistan, Africa and others [27]-[30]. From Table-III, it can also be seen that the bottom-up accounting type framework appear to be more appropriate to developing country contexts because of their flexibility, limited skill requirement, ability to capture rural-urban differences, traditional and modern energies and also can account non-monetary transactions [3],[9],[31],[32]. Among the bottom-up optimization models, OSeMOSYS is an open-source energy model, which has an accessible, easy to use and freely modifiable code. This makes it particularly interesting to developing countries that are avoiding costly models and are looking tools with less skill requirement. OSeMOSYS has been used as a long-term optimization model in many countries such as Tunisia, Egypt, Ghana, Saudi Arabia and Iran [10], [33]-[36].

TABLE I. COMPARISON OF SELECTED ENERGY MODELS BASED ON THE EIGHT CLASSIFICATION CRITERIA

Criteria	**OSeMOSYS**	**MARKAL/TIMES**	**MESSAGE**	**MESAP**	**EnergyPLAN**	**LEAP**
Purpose	Investment decision, scenario	Investment decision, scenario	Investment decision, scenario	Scenario	Scenario, investment decision, operational decision	Scenario
Model scope	Energy-system	Energy-system	IAM, Energy-economy	Energy-system	Energy-system	Energy-system
Analytical approach	Bottom-up	Bottom-up	Bottom-up	Bottom-up	Bottom-up	Bottom-up
Methodology	Optimization	Optimization	Optimization	Simulation, econometric	Simulation, optimization	Simulation, econometric
Mathematical approach	LP, MIP	LP, DP	DP	LP, DP	Analytical programming	N/A
Geographical/ spatial coverage	Local, national, regional	Local, national	Local, national	Local, national	Local, national, regional	All
Sectoral coverage	Energy	Energy	Energy	All	Energy	All
Time horizon	Medium, long-term	Medium, long-term	Short, medium, long-term	Short, medium-term	Short, medium-term	Medium, long-term

TABLE II. COMPARISON OF SPECIFIC MODELS BASED ON MAIN CHARACTERISTICS OF DEVELOPING COUNTRIES' ENERGY SYSTEMS AND ECONOMIES

Criteria	OSeMOSYS	MARKAL/TIMES	MESSAGE	MESAP	RESGEN	LEAP
Supply shortage	Not explicitly	Not explicitly	Not explicitly	Not known	Not explicitly	Possible explicitly
Performance of power sector	Not possible	Not possible	Not possible	Not possible	Not possible	Implicitly modeled
Traditional fuels	Possible	Possible	Possible	Possible	Possible	Possible
Urban-rural divide	Possible	Possible and covered	Not explicitly	Not known	Possible but not covered usually	Possible and covered usually
Informal economy	Not possible	Not possible	Not possible	Not possible	Not possible	Possible
Economic transition	Not possible	Can be covered	Possible and covered	Not known	Not covered	Usually covered through scenarios
Subsidies	Not explicitly	Possible but normally ignored	Not explicitly	Not known	Difficult	Not considered explicitly
Data need	Extensive but can work with limited data	Extensive	Extensive	Extensive	Variable, limited to extensive	Extensive but can work with limited data
Skill requirement	Limited to High	Very high	High	High to very high	Limited	Limited
Upfront financial cost	Free, open-source	Commercial	Free for academic and IAEA members	Commercial	Commercial	Free for developing countries

TABLE III. COMPARISON OF MODELS BY MODELING APPROACHES [3]

Criteria	Bottom-up, optimization	Bottom-up, accounting	Top-down, econometric	Hybrid	Electricity Planning
Geographical coverage	Local to global, but mostly national	National but can be regional	National	National or global	National
Activity coverage	Energy system, environment, trading	Energy system and environment	Energy system, environment	Energy system, environment and energy trading	Electricity system and environment
Level of disaggregation	High	High	varied	High	Not applicable
Technology coverage	Extensive	Extensive but usually predefined	Variable but normally limited	Extensive but usually predefined	Extensive
Data need	Extensive	Extensive but can work with limited data	High	High to extensive	Extensive
Skill requirement	Very high	High	Very high	Very high	Very high
Capability to analyse price-induced policies	High	Does not exist	High	Normally available	Available
Capability to analyse non-price policies	Good	Very good	Very good	Very good	Good
Rural energy	Possible but normally limited	Possible	Possible but normally limited	Possible but normally limited	Difficult
New technology addition	Possible	Possible	Difficult	Possible but often limited	Possible
Informal sector	Difficult	Possible	Difficult	Possible	Difficult
Time horizon	Medium to long-term	Medium to long-term	Short, Medium or long-term	Medium to long-term	Medium to long term
Computing requirement	Requires commercial LP solvers	Not demanding	Econometric software required	Could require commercial software	Requires commercial or licensed software

III. SUMMARY AND CONCLUSION

In this paper, a comparative review of frequently-used models are presented with the aim of selecting a suitable tool for various applications; particularly, assessing whether the available tools are suitable for developing countries. Accordingly, we provide a guideline to select the appropriate analytical tool based on eight classification criteria. In addition, the specific features of developing countries that need to be considered during tool selection and modeling are also identified.

The review suggested that proper understanding of the unique characteristics and context of developing countries is crucial to prevent inaccurate analysis and the prescription of wrong policies. It is also shown that most of the standard energy models inadequately capture the developing country characteristics.

The comparison of the features of different types of energy system models shows that the bottom-up accounting type framework appears to be more appropriate for developing country contexts because of their detailed technical representation, flexibility, capture rural-urban differences, traditional and modern energies, can account for non-monetary transactions and informal sector activities.

The model comparison showed that LEAP and OSeMOSYS are more suitable and have some attractive features to developing and emerging countries. LEAP is a scenario-based, demand-supply model that can capture rural-urban divide, economic transition, informal sector and energy shortage features. OSeMOSYS is also a scenario-based, bottom-up, flexible, open-source and easy to use optimization modeling framework. Developing economies may have the limitation of resource, data availability and technical capability. In this regard and in terms of capturing some of the other specific features of developing countries, such modeling tools can support the short to long-term planning in developing countries. However, in order to effectively address all the characteristics of developing countries' energy systems and economies, we either believe that the existing models need to be improved or new tools should be developed.

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Paper-III

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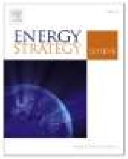

Long-term evolution of energy and electricity demand forecasting: The case of Ethiopia

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ABSTRACT

Long-term energy demand forecasting is crucial for any country, in particular for developing countries with rapid developments of energy needs. This study focuses on Ethiopia, a country with a highly increasing energy demand resulting mainly from the currently low share of electricity access, rapid development of industrial parks, extensive expansion of the railway network, extensive irrigation schemes for agriculture, new cement and sugar factories, housing projects, power export plan to neighboring countries, etc. These all are on top of the 2.7% average population growth. In this study, the Long-range Energy Alternatives Planning System (LEAP) is used to explore different possible futures and also to forecast the long-term energy requirements in Ethiopia. The planning period is 33 years from 2018 to 2050. The study employs six different scenarios to unfold the future evolution. The developed scenarios are Business-As-Usual (BAU), Growth in Electrification and Urbanization (E&U), High Economic Growth (HEG) and three policy-driven, Improved Energy Efficiency (IEE-1, IEE-2 and IEE-3) scenarios. The pathways represented by these scenarios can show the maximum expected rise in demand under different drivers and the best-case energy saving opportunities. The model is also used to estimate the associated greenhouse gas (GHG) emissions.

1. Introduction

Long-term view spanning decades into the future is necessary to develop and manage complex policy measures that ensure investment and operational decision-making which can lead to sustainable and cost-effective ways of energy supply and demand [1]. To that end, long-term energy demand modeling is crucial in predicting the future energy utilization patterns and trends. It may contribute to strategy formulation and energy policy recommendations with respect to effective utilization of energy resources, improvements in energy efficiency and energy reliability, and emissions reductions [2].

Policymakers in both the developed and developing countries are faced with a question of how the energy sector might evolve in the future with respect to issues ranging from climate change to rural energy access. Accordingly, the use of various modelling frameworks or tools to assess how energy systems can evolve in the future is increasing. The literature provides a list of models and various approaches used to analyze energy demand, policy and planning concerns for the context of developed countries [1–9]. The most applied tools for long-term forecasting include RAMSES, BALMOREL, LEAP, WASP, MARKAL/TIMES, MESSAGE, PRIMES, HOMER, etc. Some of these approaches have been applied for investigating similar energy policy concerns in developing economies.

Developing countries differ significantly from developed countries and there are a number of characteristics, common to most developing countries, that make the modeling and forecast of their energy systems challenging [10,11]. The high reliance on traditional energies, shortages and inefficient supply in the modern sector characterized by poor performance of the power sector and limited access, rapid increase in demand for electricity and large share of rural population but rapid urbanization are some of the major challenges witnessed in developing countries. Data on prices and supply for traditional energy demand are not always available. Furthermore, the existence of multiple social and economic barriers to capital flow and technological diffusion, and frequent policy changes makes forecasting in these countries difficult [10–12]. Energy demand forecasting relies on many factors and should be able to capture the trends and relationships between the demand and independent economic, technological and demographic variables. It could be easier to perform short term forecasts through simple mathematical models. However, for the long-term forecasting, simple models

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would not be able to grasp changes and complex interactions of variables such as introduction of new technologies, energy efficient devices and government policies [13]. Additionally, future energy demand projections need to accommodate urbanization and electrification rates, environmental impacts, cost of different fuel sources and, most of all, active demand-side-management policies.

These factors should be carefully considered to understand how the energy demand might evolve in developing countries. However, there are only few studies that have attempted to examine the long-term energy use in a systematic manner within the context of developing countries [14–17]. Even though these studies employed various economic and demographic methods to develop scenarios, analyze their system and design appropriate policies; most of them constrained their scope to the electricity sector and a time span of up to 2030. Furthermore, focus is only given to future demand forecasting without considering the specific challenges faced by developing countries as mentioned in the preceding paragraphs.

In light of the mentioned, our paper focuses on Ethiopia for a number of reasons. Ethiopia is the second most populous country in Africa after Nigeria with a population of over 100 million. About eighty percent of the population resides in rural areas largely relying on traditional biomass energy resources for cooking and heating. 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 current access rate is 27% for rural and 96% for urban population, which translates to about 40% total access with per capita consumption of 143 kWh. Most rural customers gain access through off-grid solutions [18].

Even though, a wide range of studies with different aims examined various energy related issues of Ethiopia [19–29], only a few studies have attempted to assess the long-term energy use development [17,19,30–32].

The Ethiopian Power System Expansion Master Plan [30], completed in 2014, was done for Ethiopian Electric Power (EEP) for the period 2013–2037. It uses a macroeconomic multi-variable regression analysis load forecast model and end-user models to determine a 25-year least cost generation and transmission system development plan. Recently, a new update of the master plan was developed [31]. It uses regression analysis models and bottom-up sales by considering scenarios (low, base-case and high-growth) and sensitivity forecasts. The Ethiopian energy economy report projected the energy demand from 2008 to 2030 by the Ethiopian Economic Policy Research Institute [32]. The report projects the demand using energy demand coefficients and macro-economic variables.

The above studies [30–32] aim to forecast the future energy demand; however, it is important to provide a way of exploring different possible futures that can be meaningful for policy development. In this regard, there are only a few studies that applied energy demand scenario analysis for Ethiopia [19]. considers business as usual (BAU), moderate shift and advanced shift scenarios of economic development over the period of 2010–2050 to assess sustainable energy system strategies including energy demand projections [17]. forecasted sector-wise energy demand up to 2030 by developing three alternative scenarios on improved cookstoves, efficient lighting, and universal electrification. The results mainly suggest that alternative investments can conserve energy and improve environmental sustainability of the country. Even though these two studies attempted to explore the future demand, the developed scenarios did not fully consider the rate-of-change in socio-economy, technological change and future governmental direction.

Considering the identified literature gaps, this paper aims at seeking answers to these questions:

- What are adequate approaches to capture the specific features of modeling energy demand of developing countries?
- What are the forecasts for the Ethiopian demand and its various sectors, total energy utilization and electricity consumption under different scenarios?
- What is the effect of introducing energy efficiency policies in terms of economic, social and environmental contexts of the country?

The structure of the article is as follows. In Section 2 we provide an overview about Ethiopia, its energy sector and electricity demand trends. Section 3 discusses the research methodology and approaches followed. Section 4 describes the model, data and scenarios in detail. Section 5 presents the main findings of our study with its analysis. Finally, Section 6 discusses the main conclusions and policy implications of the study.

2. Country overview

2.1. Overview of the energy sector in Ethiopia

Over the past decade, Ethiopia has been one of the fastest growing economies in the world with annual rate of economic growth averaging 10.3% over the 2005/06–2015/16 period [33]. The country has a vision of becoming a lower-middle-income country by 2025 after implementing three successive five-year development plans referred to as the Growth and Transformation Plan (GTP). The main objective is to eradicate poverty in a relatively short period of time by implementing broad-based development policies to enhance growth [34,35]. This development is translating into a large demand for energy in urban and rural areas.

The highest increase in demand for energy is envisaged to come from developing countries where, growing population, rapid urbanization, rise in living standard and income are prevailing [36]. In this regard, Ethiopia can be taken as the best example and representative for studying the context and characterization of the energy system in developing countries. Moreover, most of the challenges mentioned in the introduction are faced by the country.

The primary source of energy in Ethiopia is biomass, which accounts for 91% of energy consumed, petroleum supplies about 7% and electricity only 2% of total energy use [17,37]. In about 95% of Ethiopian households, cooking is done with polluting fuels and technologies and the proportion is almost 100% in rural areas [38]. Different studies [17,25,27,37–39] show that the national energy balance is dominated by a heavy reliance on firewood, crop residues and dung.

Ethiopia has a high potential for solar, wind and hydropower in addition to geothermal and bioenergy. However, the country's renewable energy potential is largely untapped. The power generation is dominated by hydropower accounting for some 90% of the total. The interconnected system (ICS) 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 [40].

Currently, Ethiopia is facing a serious energy shortage enforcing electricity load shedding in all consumer categories. Electricity shortage is prevailing due to lags in power plant construction and increase in demand [23].

2.2. Electricity demand trends

The country's historical electricity consumption is presented by grouping customers in representative categories such as domestic, low-voltage (LV) industrial, high-voltage (HV) industrial, public and regional export. All customer groups are connected to the distribution system except the high-voltage industrial customers which are connected to the transmission system. Complete data is available since 2001 with total electricity consumption of 1388 GWh and it is raised to 10,750 GWh in 2017 with an average growth rate of 13%. The historical consumption distribution by the different customer groups is shown in

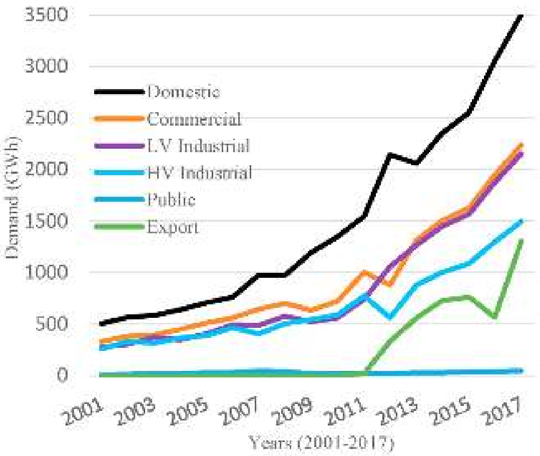

Fig. 1. Historical electrical energy demand trends in various sectors of Ethiopia [31].

Fig. 1.

For the considered 17 years, the industrial sector (HV&LV) consumed 36% of the total, the domestic sector 35%, and the commercial sector 22%. The remaining 7% is export to neighboring countries (Djibouti and Sudan) and public loads such as street lighting. The total electricity consumption in the domestic sector was 508 GWh in 2001 and raised to 3509 GWh in 2017. Such significant rise in domestic power demand in developing countries has been more prominent in contrast to industrialized nations due to the high rate of urbanization, growth in population and wealth [41,42]. It is essential to consider these factors when dealing with modeling and electricity demand forecasting of a country like Ethiopia.

3. Methodological approach

Scenarios support the early detection of emerging issues and help policymakers prepare for otherwise surprising developments [43]. Accordingly, the energy demand projection is done with two alternative and three policy-driven scenarios in addition to the "business-as-usual" reference scenario.

The development and selection of appropriate scenarios is one of the major considerations in representing the characteristics of the energy systems in developing countries. Failure to represent the features and factors that influence the energy system poses the risk of producing inaccurate results and thereby recommending wrong policies. Accordingly, the scenarios are developed by studying the country's context in terms of energy demand, socio-economy, demography, technological change and future governmental direction in a systematic manner.

The energy demand projection is done for different sectors. Specifically, the electricity demand forecasting is done for various customer categories connected at different stages of the power grid (i.e. different voltage levels). They are categorized as household (HHE_t), HV industry ($HVIE_t$), LV industry ($LVIE_t$), commercial (CME_t), agriculture (AGE_t), transport (TRE_t), public (PBE_t) and export ($EXPE_t$). A demand forecast is made for each of the categories. Then, the total country demand forecast (TED_t) is taken by adding each of the forecasts as shown in equation (1).

$$TED_t = HHE_t + HVIE_t + LVIE_t + CME_t + AGE_t + TRE_t + PBE_t + EXPE_t \tag{1}$$

Total losses (EL_t) are calculated based on governmental loss reduction targets (TL_t) that is added to the total demand (TED_t).

$$FTED_t = TED_t + EL_t \tag{2}$$

and

$$EL_t = \left(\frac{TL_t}{1 - TL_t}\right) \cdot TED_t \tag{3}$$

where EL_t refers to the total transmission and distribution (T&D) losses in year t, TL_t is the T&D losses in terms of percentage of total generation in year t and $FTED_t$ is the final total electricity demand in year t.

The employed demand forecast method is a combination of bottom-up approach and multi-variable regression modeling. Bottom-up consumer level sales forecast is applied to selected customer groups with explicit government plans for new connections and expansions of various projects. In addition, customer applications to the utility company for future supplies and connections to their premises are also included. Such customer groups demand a huge amount of electricity and are usually connected to the transmission system. These customer groups include industrial parks, railway expansion projects, Addis Ababa light-rail project, sugar industry, cement industry, irrigation, steel and metal industry, mining and regional power export.

On the other hand, we used a multi-variable linear least-square regression modeling for the other sectors such as general HV industry, LV industry, commercial, public and fuel transportation.

$$D_t = B_0 + B_1 \cdot X_{1t} + B_2 \cdot X_{2t} + \cdots + B_n \cdot X_{nt} + B_{n+1} \cdot D_{t-1} \tag{4}$$

where D_t - the dependent variable, is the energy demand in the year t, and D_{t-1} is the energy demand in the previous year t-1; $B_0, B_1, \ldots, B_{n+1}$ are the regression weights that are computed in a way that minimize the sum of squared deviations; $X_{1t}, X_{2t}, \ldots X_{nt}$ are the independent variables that potentially impact demand in the specific customer group. These are selected from the entire list of variables such as historical consumption, GDP, per capita income, number of customers and number of households.

4. Model, data and scenarios

Long-range Energy Alternatives Planning System (LEAP) model is a widely used software tool for energy policy analysis and climate change mitigation assessment. It is an integrated, scenario-based modeling tool that can be used to track energy consumption, production and resource extraction in all sectors of an economy. The model follows the accounting framework approach to generate a consistent view of energy demand based on the physical description of the energy system. Studies using LEAP are diverse in terms of geographical scale, sectoral coverage, and focus of study. This software has been exploited to investigate electricity sector and energy sector of several countries [16,44–48]. In particular, it is a widely used tool for energy demand prediction and scenario analysis in developing economies [14,15,17].

Future energy demand in developing countries is highly dependent on the economic and social contexts in addition to new technological innovations. However, these are subject to large uncertainties that are difficult to predict. Therefore, the exploration should be based on scenario-analysis that can be drawn by studying the country's socio-economic context that gives an understanding of the high uncertainties of the future energy demand. In addition, sector wise and technological representation of end-uses at a disaggregated level is highly required. This includes the rural-urban divide, economic and/or technological transitions, the informal sector and supply shortage features. In this regard, LEAP is an appropriate modeling tool for making energy analysis and the current study, as other studies, utilizes this tool to explore and forecast the energy demand up to the year 2050.

4.1. Model

The energy demand model is primarily structured sector-wise, namely: residential, industrial, commercial, agriculture and transport sector. The data structure for the residential sector follows a bottom-up approach, by using end-use device accounting techniques in LEAP-standard. The residential sector is divided into two main subsectors. i.e. urban and rural. Another division, electrified and non-electrified is also created as shown in the demand model tree in Fig. 2. It contains four end-use categories including lighting, cooking & baking, refrigeration and other devices (TV, radio, computer, iron, etc.). Data inputs such as population, number and share of households are given to the activity level variable whereas energy consumption data is entered to the final energy intensity variable. The data structure for the remaining sectors is done based on common energy use in different applications or end-uses.

4.2. Data and key assumptions

4.2.1. Key assumptions

Data used in this study is based on extensive data collection, mainly from the electric power sector, including the Ministry of Water, Irrigation and Electricity (MoWIE), Ethiopian Energy Authority (EEA), Ethiopian Electric Power (EEP), Ethiopian Electric Utility (EEU) and National Load Dispatch Center (NLDC) but also from other sectors: Central Statistics Agency of Ethiopia (CSAE), National Bank of Ethiopia (NBE), National Planning Commission (NPC) and Ethiopian Petroleum Supply Enterprise (EPSE). In addition, necessary local [18,35,37,42,49] and international reports are also used as data sources [33,34,38,50].

LEAP has four different modules for data input: key assumptions, demand, transformation and resources. Key assumptions include various socio-economic variables such as country population, urban and rural population, households, GDP and other similar data which affect the level of final energy consumption. The demand module contains the various sectors and customer categories which consume energy such as household, industry, commercial, public and others. In the transformation module, the process of converting primary energy into secondary energy is done and data such as conversion losses are given. Lastly, the resource category includes data for the supply/resource technologies.

In this study, the demand module is sub-categorized into domestic, HV industry, LV Industry, Commercial, Agriculture, Transport, Public and Export. In the transformation module, energy loss data of the power system is given. The demand projection is done for 33 years up to the year 2050 considering 2018 as the first simulation year.

4.2.2. Appliance activity level and energy intensity

The demand data for the domestic sector is entered according to the LEAP demand tree shown in Fig. 2. Accordingly, the major end-use or appliance categories are divided into lighting, cooking & baking, refrigerator and other-uses. These appliances have different level of penetration and energy consumption in an average household.

It can be seen that in 2017, 94% of urban households and only 11.7% of the rural households had access to basic electricity. The remaining 6% of urban and 88.3% of rural households had no access to any electricity source and relied on alternative sources mainly kerosene for lighting and wood, charcoal and liquefied petroleum gas (LPG) for cooking and baking.

In addition, to cope with insufficient hours of service and power outages, households use backup solutions for lighting such as candles, torches/flashlights and kerosene lamps. Urban households rely heavily on candles as a back-up solution, while rural households rely more on dry-cell batteries and kerosene lamps. 4.8% of urban households and 25.8% of rural households use kerosene as a back-up solution [51].

In Ethiopia, 63.3% of households use a three-stone stove as their primary stove, 13.6% use a self-built stove as their primary cooking solution, 18.2% use a manufactured biomass stove, and 4.2% use a clean fuel stove with electricity and LPG. Less than 1% of households use LPG as their primary cooking solution, while 96% of the households use biomass fuels [38,51]. A three-stone stove is a pot balanced on three stones over an open fire. A self-built stove is typically an enclosed stove made using stone, mud, and flat clay that can be slightly more efficient than a three-stone stove. A manufactured biomass stove is typically produced in a factory or by an artisan and usually made of metal and can be considered an improved cookstove. Ethiopian households commonly use injera (traditional Ethiopian bread) and bread baking stoves in addition to regular stoves for cooking (making sauce, tea, coffee, etc.) which consumes between 40% and 65% of the entire household cooking fuel consumption [52].

Urban and rural households use different cooking technologies: 54.3% of urban households use a manufactured stove and 15.3% use a clean fuel stove, while 77% of rural households use a three-stone stove. And 85.4% of rural households use firewood as their primary fuel, while 60.3% of urban households use charcoal [51]. Most households in both urban and rural areas use multiple stove types (i.e. different combination of three-stone stove, self-built, manufactured and clean stove).

According to Ref. [51], five different capacity tiers are used to

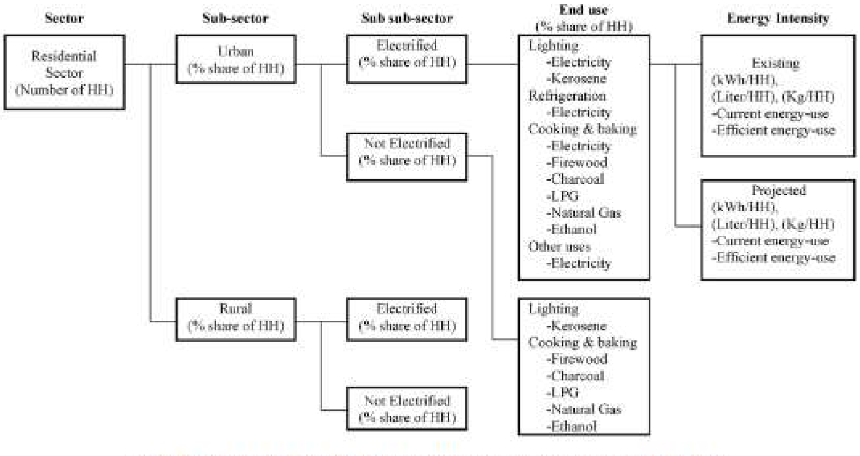

Fig. 2. The developed LEAP energy demand tree for the residential sector of Ethiopia.

classify the penetration of appliances in urban and rural areas. Medium-load appliances such as refrigerators, freezers and air coolers are assigned in TIER 3 with penetration of 50.5% urban and 5.7% rural grid-connected households. Other-use electrical loads include television, radio, computer, phone charging, etc. Are under TIER 1 and 2 which account a penetration of 61.1% in urban households and 75.3% in rural households.

The energy intensity of cooking stoves depends on the cooking technology, fuel type and amount of consumption. In terms of thermal stove efficiency, electric and ethanol stoves have the highest efficiency of about 60%, followed by LPG (55%), kerosene (42%), charcoal (25%) and firewood (10%) [53]. Among the firewood stoves, the manufactured-type has a better efficiency than the self-built and three-stone types. In a study conducted in the field, the fuel saved by the manufactured-type was 22–31% of that with a three-stone fire [54].

Accordingly, by making simple calculations based on daily consumptions, assuming 30% fuel reduction from manufactured-biomass stoves and 10% reduction from self-built stoves; the energy intensity for the different stoves is determined. Energy intensity for injera/bread baking stove is assumed to be 65% of the total fuel cooking consumption (1057 kg per person) [52].

Table 1 shows the penetration and energy intensity of the electrical appliances applied in LEAP for both urban and rural households. Lighting utilizes 30% of total urban and 42% rural electricity consumption which is calculated to be about 503 kWh and 235 kWh per year per household respectively. Cooking utilizes 35% and 19% of the total consumption. The remaining is consumed by refrigerator and other-use loads. Lighting is assumed to be fully penetrated device as both urban and rural households solely depend on electrical lamps for lighting. Whereas the remaining appliances have partial penetration with electrical stoves accounting only 15.3% urban and 0.6% rural households. The total electricity consumption per household in 2017, is 1676 KWh for urban households and 559 kWh for rural households which is approximately one-third of the urban.

4.3. Scenarios

In this study, we employ six different scenarios for the projection of the future energy demand. One is a business-*as*-usual (BAU) scenario or reference scenario which assumes continuation of current policies, programs and targets of the government, two scenarios are alternative scenarios reflecting the uncertainty about future development and the remaining three are policy scenarios. The two alternative scenarios are based on the reference scenario (inherit BAU properties) but with different rate-of-changes of some particular activities such as socio-economy, demography, technological change and future government direction. The three policy scenarios are policy-driven scenarios that are applied to each of the other scenarios (reference and two alternative scenarios). In the scenarios, population, urbanization, GDP, electrification and other socio-economic factors are set to change. In addition, efficiency improvements from technological advances and demand side management programs are considered to be the main factors for reduction in energy demand over time.

Table 1
Electrical appliance penetration and average energy intensity for electrified urban and rural households in 2017.

Appliances	Activity Level (% saturation)	Energy Intensity (kWh/HH)
Urban		
Lighting	100	503
Cooking	15.3	587
Refrigerator	50.5	453
Other uses	61.1	133
Total electricity consumption		1676
Rural		
Lighting	100	235
Cooking	0.6	106
Refrigerator	5.7	168
Other uses	75.3	50
Total electricity consumption		559

Hence, scenarios of growth in electrification and urbanization (E&U), high economic growth (HEG) and improved energy efficiency (IEE) are designed and their results are mainly compared with the BAU scenario to understand possible deviations from the normal demand forecast. In addition, their impact on GHG emissions is also assessed. We employ the LEAP scenario manager to create and then evaluate the alternative scenarios by comparing their energy requirements and environmental impacts. This enables us to see how the energy demand might evolve over time. Below we provide the input data, assumptions and methods used in the reference, alternative and policy scenarios for making the energy demand forecasting.

4.3.1. Business as usual (BAU) scenario

The BAU/reference scenario is the base of all other scenarios and assumes that historical trends will continue into the future by giving special attention to government policies and strategies. Historical trends of population growth, GDP growth, electrification, urbanization and consumption of energy by sector are used to project the future demand. In the BAU scenario, it is assumed that the country has no ambition to reduce CO_2 emission and no endeavor to shift to clean fuels. In addition, it is assumed that the current power shortages and interruptions will continue in the future and back-up solutions are necessary. Biofuels such as ethanol and LPG are considered as an important fuel for the last two decades. The energy intensity of electric stoves is assumed to increase by 50% in the year 2040.

The Central Statistics Agency of Ethiopia has forecasted the population and urbanization levels until the year 2037 [42] and these levels are used in the BAU scenario. For the remaining years from 2038 up to 2050, the historical trend has been projected with 1.6% (2038–2042) and 1.4% (2043–2050) population growth rates. Similarly, the urbanization level is targeted to increase from 31.1% in 2037 to 60% in 2050.

In 2017, the government of Ethiopia (GoE) introduced an ambitious program, the National Electrification Program which aims to achieve universal access to electricity nationwide by 2025 [55]. According to this plan, 65% of households are expected to be supplied through grid-connection and the remaining 35% via off-grid technologies by the end of 2025. Then, by 2030; grid expansion will reach out to 96% of households and only 4% will be supplied via off-grid systems. Accordingly, the BAU scenario is based on this target. However, the progress made in the last two years since the program's launch is slower (40%) compared to the target set (47% total access by 2019). Therefore, considering a similar electrification pace, we have only applied the grid-access target (i.e. 65% by 2025 and 96% by 2030) by neglecting the off-grid access target.

Future GDP growth rate assumptions are based on historical trends, considering IMF predictions and our judgement. Total GDP growth rates of 9%, 7% and 4% are assumed for the years until 2030, 2040 and 2050 respectively. The per capita income growth rate is assumed to be 9% (2018–2030), 7% (2031–2040) and 5% (2041–2050). The reduced growth rate used for later years is associated due to creating a mature and larger economy. Customer growth rate assumptions also depend on historical trends while considering the roles of population growth and grid expansion targets. Customer growth rates of 8%, 6% and 5% for commercial and LV industry, 12%, 8% and 6% for HV industry and 6%,4% and 3% for public load is assumed for the years until 2030, 2040 and 2050 respectively. The summary of all the assumed growth-rates and projected values for the macroeconomic, demographic and other variables for all the scenarios is shown in Table 2.

Electricity demand projections are made for 17 industrial parks which recently have become operational, are under construction, or

Table 2

Assumptions of growth-rates and projected values for different variables under each scenario.

Index		[a]Pop'n growth rate	HH size	[b]Urban'n	Urban [c]electr'n	Rural electr'n	Total GDP growth	Per capita income growth	Electric stove [d]pen'n		[e]Total loss
Unit		%	People per HH	%	%	%	%	%	% of urban HH	% of rural HH	%
2020	BAU	2.1	4.7	21.8	96.3	38.0	9.0	9.0	17.1	4.1	21.1
	HEG	2.1	4.7	21.8	96.3	38.0	**11.0**	**11.0**	17.1	4.1	21.1
	E&U	2.1	4.7	**23.0**	96.3	38.0	9.0	9.0	**24.4**	4.1	21.1
	IEE	2.1	4.7	**23.0**	96.3	38.0	9.0	9.0	**24.4**	4.1	**21.3**
2030	BAU	2.0	4.7	27.1	100	96	9.0	9.0	30.0	15.0	17.3
	HEG	2.0	4.7	27.1	100	96	**11.0**	**11.0**	30.0	15.0	17.3
	E&U	2.0	4.7	**33.0**	100	**100**	9.0	9.0	**51.5**	15.0	17.3
	IEE	2.0	4.7	**33.0**	100	**100**	9.0	9.0	**51.5**	15.0	**12.5**
2040	BAU	1.6	4.6	37.8	100	100	7.0	7.0	35.0	30.0	12.5
	HEG	1.6	4.6	37.8	100	100	**8.0**	**9.0**	35.0	30.0	12.5
	E&U	1.6	4.6	**50.0**	100	100	7.0	7.0	**65.0**	**55.0**	12.5
	IEE	1.6	4.6	**50.0**	100	100	7.0	7.0	**65.0**	**55.0**	**9.0**
2050	BAU	1.4	4.6	60.0	100	100	4.0	5.0	40.0	40.0	12.5
	HEG	1.4	4.6	60.0	100	100	**6.0**	**6.0**	40.0	40.0	12.5
	E&U	1.4	4.6	**80.0**	100	100	4.0	5.0	**65.0**	**70.0**	12.5
	IEE	1.4	4.6	**80.0**	100	100	4.0	5.0	**65.0**	**70.0**	**9.0**

The bold numbers indicate that the value specified for the given scenario is different compared with the assumption in the BAU scenario.

[a] Population.

[b] Urbanization.

[c] Electrification.

[d] Penetration.

[e] Total power system loss.

planned to be developed in the long-run. Feasible operating periods and demand levels at different years are assumed considering the location, construction time and investment opportunity. In addition, future unidentified industrial parks are also included in the projection. These are expected to be operational from 2030 up to 2050 with increasing consumption.

Considering customer electricity supply requests brought to the utility from cement, mining, steel and metal industries, the energy demand is projected for the future years. A similar approach is followed for the agriculture, transport and export sectors. In the transport sector, the cross-country railway lines of Ethio-Djibouti, Addis Ababa light railway and 10 other national railways connecting.

different cities are considered. Reasonable future expansions are assumed for each of the projects. Increased export of electric power and natural gas to neighboring countries is considered. Electric power export to Sudan and Djibouti has already been started in 2017 with 1.5 TWh and is set to reach 35.3 TWh by 2045. Export of natural gas will start in 2021 with 10 million metric cube and is assumed to increase up to 50 million metric cube and 500 million metric cube by 2030 and 2050 respectively.

A rapid rise of demand for solid fossils is assumed in industry, particularly for cement and steel & metal industries. Complete reliance on fossil-fuel consumption is also assumed in the transport sector which is expected to produce significant growth of diesel, gasoline and jet fuel demands. The projection is done using regression modeling based on the variables total GDP, service GDP and previous year demand. Increased use of petroleum is also assumed in the agriculture sector for irrigation and other farm activities. Petroleum use in the agriculture and LV industry is set to grow at 9% annual growth rate.

Power loss assumptions are based on reduction targets and by reviewing the progress made in the past few years. The total loss target is assumed to be continuously reducing from the average historical loss of 23%–12.5% by 2040 through implementing projects of network rehabilitation, reconductoring, adding capacitors and voltage regulators, etc.

4.3.2. *High economic growth (HEG) scenario*

As mentioned in the introduction, Ethiopia has a big vision of attaining lower-middle-income country status by 2025 after implementing successive development plans. This has led to remarkable achievements in real GDP growth, infrastructure development and social development which translates into a large demand for energy. The HEG scenario builds up on the BAU/reference scenario by assuming the continuation of high economic growth in the country. Total GDP growth of 11%, 8% and 6% is considered for the years until 2030, 2040 and 2050 respectively. The GDP growth by industry is assumed to be 11%, 8% and 5% while the service sector is expected to grow by 10%, 8% and 6%. The agriculture sector GDP growth rate is assumed to be the same as in the BAU scenario (i.e. 9%, 8% and 5%). Finally, the per capita income growth rate is targeted to hit 11%, 9% and 6% for the future three decades.

4.3.3. *Growth in electrification and urbanization (E&U) scenario*

The E&U scenario is also based on the BAU scenario but with major differences in country policy and direction. It is assumed that the country has a strong ambition to reduce CO_2 emissions through various initiatives. One of these initiatives is to push for a rapid-shift from biomass-based household consumption to clean-fuel based consumption. Biomass-based cooking and injera/bread baking stoves are assumed to significantly reduce their penetration over time. Firewood cooking and baking stoves are targeted to be used in less than 10% and 40%, respectively, of households by 2045. Instead, electric stoves are expected to penetrate 65% of urban households by 2035 and 70% of rural households by 2045. With such a shift to electric stoves and the future additional new demand, the energy intensity is expected to double by 2040. In addition, biofuel-based and natural gas-based cooking stoves are targeted to penetrate 30% of households.

The scenario targets 100% electrification by the end of 2025. In order to reduce the transport sector CO_2 emissions, electric vehicles are assumed to be deployed in 2025 with increasing penetration for later years. 1.1 million electric cars are set to replace fossil-fuel based cars by 2050.

Historically, Ethiopia had a low level of urbanization. However, since 2007, government policies helped the growth of small towns and infrastructure development which increased the tempo of urbanization. In addition, implementation of the GTP with objectives of increasing employment generation in urban areas is likely to result in higher rural to urban migration and thus faster urbanization [42]. Accordingly, this scenario assumes a faster-urbanization rate of 6% per year resulting in

80% urban population by the year 2050.

4.3.4. Improved energy efficiency (IEE) scenario

Ethiopia has significant transmission and distribution bottlenecks that limit the delivery of the existing supply from reaching demand centers. Poor reliability, significant transmission and distribution (T&D) losses and low power quality affect the end-use consumers. These capacity, reliability and quality constraints compromise the ability of the electricity sector to support sustained economic growth. Realizing this, the GoE is actively exploring how demand-side management (DSM), energy efficiency and conservation can help lower cost and improve economic growth [56]. Accordingly, principal energy efficiency and conservation programs and projects are underway. Some of these include standards and labeling, energy management and auditing, public sector efficiency, technology acceleration, awareness training and accreditation, etc. In the standards and labeling program, minimum energy performance standards are to be developed for the main industrial loads and household appliances. These include electric motors, injera cookers, electric cookers, lighting, refrigerators and freezers, etc.

Therefore, this scenario is a policy-driven scenario that explores the long-term demand evolution by assuming significant efficiency improvements in the electricity sector. The efficiency improvements are applied to each scenario; i.e. the BAU (IEE-1), HEG (IEE-2) and E&U (IEE-3).

Introducing industrial energy audits and industrial efficiency measures on the use of electricity can have the potential to save up to 30% of the electricity consumed in the industry sector by 2040. As a result, progressive efficiency gains are assumed to be effective in the LV industry and HV industry (excluding industrial parks) from the base year until 2040.

Improved lighting standards and DSM programs are expected to reduce the energy intensity of electric lighting in urban households by 1% every year starting from the base year. Similarly, electric stove energy intensity reductions are expected to achieve 0.5% per year. The other assumption is on energy efficiency improvement of refrigerators in urban households with energy intensity reduction of 5% in 2020 and 20% in 2040.

A program to install efficient street lighting systems could also reduce electricity consumed in the public sector. The use of efficient light emitting diodes (LEDs) with proper controlling and monitoring system can reduce the electricity consumption by 60% compared to the conventional street lighting system. The program is assumed to start in 2018 and by the end of 2030 all streetlights in the country are expected to meet the new requirement.

Regarding T&D losses, the government is expected to implement network rehabilitation, reconductoring, adding capacitors and voltage regulators, etc. that result in power quality and system efficiency improvements. Accordingly, the total power loss is targeted to reduce to 12.5% by 2030 and to 9% by 2035.

5. Result and analysis

5.1. Demand projection

The final energy demand, fuel consumption and GHG emissions are derived for each of the scenarios and end-use categories. The projected demand for the BAU scenario is about 2950 PJ by 2030 and 4900 PJ by 2050, a growth of 90% and 215% compared to the demand in the year 2017. Fig. 3 shows the projected energy demand by sector. The domestic sector has the highest share with 2273 PJ in 2030 and 2844 PJ in 2050 accounting for 77% and 58% of the total demand respectively. It displays a sharp increase until 2040 and remains at a saturation level afterwards. The transport sector is the second major energy demanding sector, showing a significant increase in the last two decades. It accounts for 25% of the total energy demand in 2050. The HV industry, LV industry and other sectors are expected to gradually increase their demand over time.

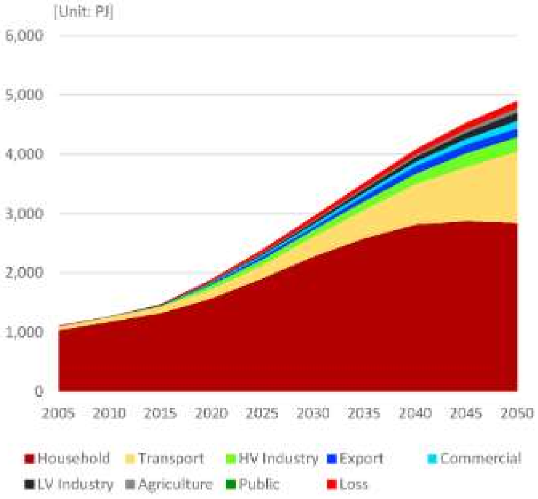

Fig. 3. Final energy demand under BAU.

5.2. Comparison of demand under various scenarios

A comparison of the scenarios shows that the energy demand is highest for the HEG & IEE-2 scenarios followed by the BAU & IEE-1 and E&U & IEE-3 scenarios (see Fig. 4). There is a huge difference between E&U vs. BAU and IEE-3 vs. BAU. The HEG scenario is based on the BAU scenario but assumes a higher economic growth-rate which incurs additional energy demand. The final demand is expected to reach about 5255 PJ by 2050. Assumption of total GDP growth rates of 11%, 8% and 6% for the future three decades results in demand increase by 7% compared to the BAU scenario in 2050. On the other hand, the energy demand reduces by 42% in E&U scenario and by 46% in IEE-3 scenario.

In the case of electricity demand, the result shows that the highest

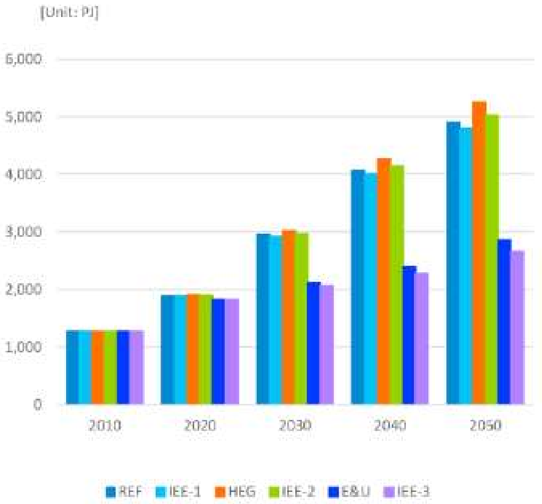

Fig. 4. Total energy demand for all scenarios.

demand is expected for the E&U scenario since more electricity-based end-uses are utilized (Fig. 5). In 2050, the total electricity demand under the E&U scenario is expected to reach 292 TWh while HEG demands 289 TWh and BAU consumes 262 TWh. The total energy saving under the IEE scenarios is estimated to be about 43 TWh (IEE-1), 63 TWh (IEE-2) and 56 TWh (IEE-3) in 2050. Technology improvement and DSM activities account 28%, 19% and 41% of the energy saving in IEE-1, IEE-2 and IEE-3, respectively. Industrial energy audit and efficiency measures contribute to 41% (IEE-1), 55% (IEE-2) and 31% (IEE-3) of the total savings while network loss reduction contribute to 30%, 25% and 27%, respectively. The remaining 0.5–1% is due to technology improvement in streetlights.

Fig. 6 shows sector-wise electricity demand projections under the policy-driven scenarios (IEE-1, IEE-2 & IEE-3). It can be seen that the household sector demand is strongly increasing and in 2050 the household sector is anticipated to consume about 23%, 22% & 25% of the total electricity demand in IEE-1, IEE-2 and IEE-3, respectively.

IEE-2 does not have much effect on the household consumption share compared to HEG (i.e. both 22%) while IEE-1 & IEE-3 reduce the share by 1% & 3% compared to BAU (24%) & E&U (28%), respectively. This implies that the policy-driven measures applied to E&U scenario (IEE-3) have stronger impact on household consumption compared to the others (IEE-1 & IEE-2).

5.3. Fuel consumption

The fuel consumption is dominated by wood, accounting for 73% of the total fuel consumption by 2030 and 51% by 2050 (Fig. 7). This is mainly due to the household fuel consumption (Fig. 8) where 94% of total fuel consumption in 2030 (88% rural and 12% urban) and 86% in 2050 (66% rural and 34% urban) is from wood. Our analysis also shows that the use of traditional biomass will continue increasing until 2040 under the BAU and HEG scenarios. On the contrary, for the E&U & IEE-3 scenarios, biomass use is expected to reach its peak in 2022 and then decline from 2023. From Fig. 7, it can be seen that the electricity demand is expected to increase drastically from 107 TWh (13% of total fuel consumption) in 2030 to 262 TWh (19% of total fuel consumption) in 2050. Fossil fuels like diesel, gasoline and jet kerosene will also see an increasing consumption due to expansion of fossil-fuel-based road transportation and aviation.

Fig. 8 shows that the household fuel consumption in the E&U scenario is entirely different from the BAU & HEG scenarios. In 2050, the total fuel consumption in E&U is more than 65% lower than in the other two scenarios. In addition, in E&U, the penetration of electricity increases strongly, to 30% of the total fuel consumption while wood share is about 55%.

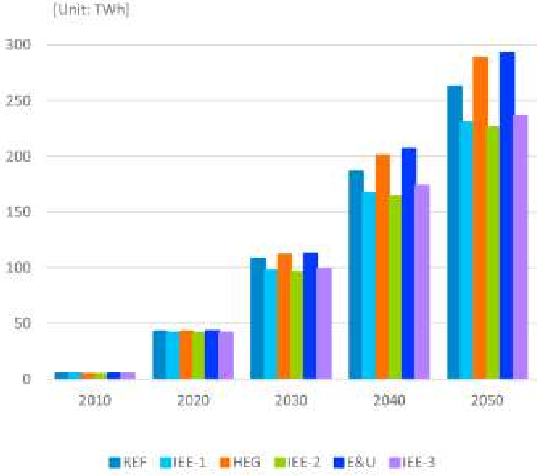

Fig. 5. Electricity demand for all scenarios.

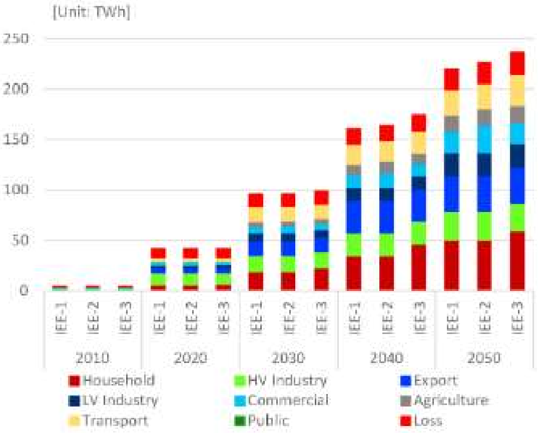

Fig. 6. Electricity demand under policy-driven scenarios.

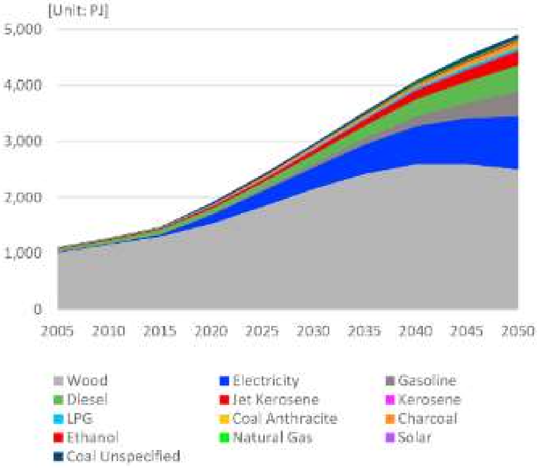

Fig. 7. BAU fuel consumption.

5.4. Greenhouse gas emissions

It is observed that under the BAU scenario in 2030, biogenic carbon dioxide emissions reach 122 million-ton CO_2e, 30 million-ton non-biogenic CO_2e and about 11 million-ton non-CO_2 (Fig. 9 and Fig. 10). Biogenic carbon dioxide emissions are defined as emissions from a stationary source directly resulting from the combustion of biologically based materials, mainly from biomass burning while non-biogenic CO_2 emissions are from the use of transportation fossil-fuels. In this study, biogenic CO_2 emissions are not treated as "carbon neutral" despite the fact that the country is taking various initiatives to tackle deforestation by planting many trees. Regrowth is not sufficient and the large amount of carbon released into the atmosphere due to burning of biomass may take decades for new forests to absorb. This shows that the process has

Fig. 8. Household fuel consumption under all scenarios.

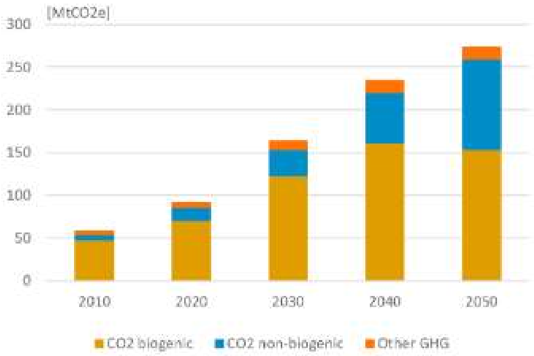

Fig. 9. Total GHG emission under BAU scenario.

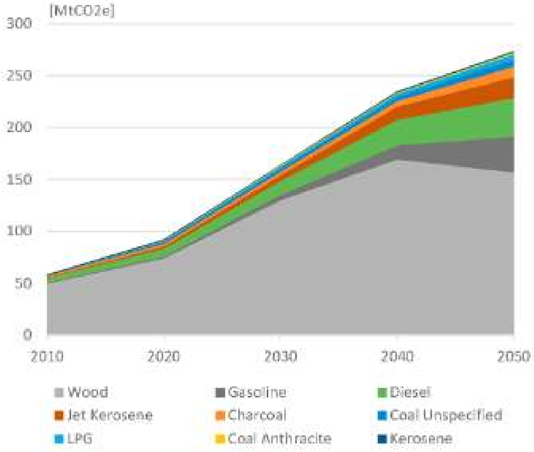

Fig. 10. Total GHG emission by fuel under BAU scenario.

the potential to become "carbon neutral" only over very long-time scales but not in the short term.

In addition, there are also other small non-CO_2 GHG emissions like carbon monoxide, methane, non-methane organic compounds, nitrogen oxides, nitrous oxide, etc. (see Fig. 9).

Biogenic carbon dioxide emissions are expected to further increase from 122 $MtCO_2e$ in 2030 to 160 $MtCO_2e$ in 2040 and then slowly decrease. On the other hand, non-biogenic carbon dioxide emissions keep on increasing by more than a fourfold from 30 $MtCO_2e$ in 2030 to 106 $MtCO_2e$ in 2050. This shows that the transport sector heavily relies on fossil-fuel and could be a potential target to reduce CO_2 emission in the long-run.

There is a large difference of total GHG emissions between the different scenarios. As can be seen from Fig. 11, in the BAU & IEE-1 and HEG & IEE-2 scenarios, emissions are much higher than in the E&U & IEE-3 scenarios. The BAU scenario's total GHG emissions in 2050 are estimated to reach 274 $MtCO_2e$ and the HEG scenario releases about 295 $MtCO_2e$. On the other hand, the E&U & IEE-3 scenario emissions are only projected to be 111 $MtCO_2e$. This difference is mainly due to the policy-driven shift from biomass-based household appliances to clean biofuel and electric-based appliances. Fig. 11 also shows that there is no impact from policy in the policy-driven scenarios on the GHG emission since the policies are implemented on the electricity sector with no emissions.

6. Conclusion and policy implications

In this study, six scenarios are assessed to represent the alternative development pathways of Ethiopia's energy future from 2018 to 2050. The comparative analysis between evaluated scenarios shows that the energy demand will significantly increase for the BAU and the HEG scenarios mainly due to population growth and economic development but much more moderately for the E&U scenario due to faster electrification and urbanization resulting in lower biomass-based consumption. The electricity demand increases strongly for BAU but even more for HEG and E&U. This is due to high rate of urbanization, electrification and economic development. The scenario independent strong increase shows the need for new capacity additions. The result of the policy scenarios (IEE-1, IEE-2 and IEE-3) shows that while the application of energy efficiency policies and measures would only have a minor impact on the energy demand, their impact on the electricity demand is large, and that the application of such policies is a very important measure to combat supply-demand mismatch causing power shortages and blackouts. Further, it is interesting to note that the electricity demand development is very similar for the three policy scenarios both with regard to overall demand and sector-specific demands. The electricity

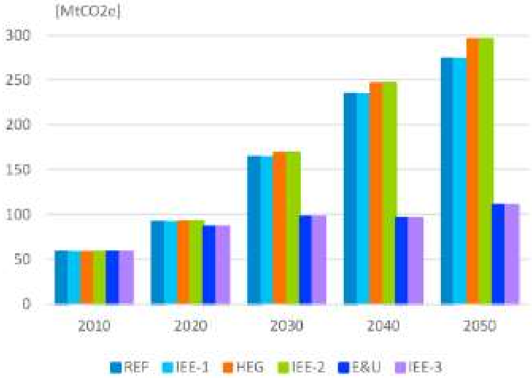

Fig. 11. Total GHG emission for all scenarios.

demand is increasing strongly in all sectors.

In all the years, the household sector accounts for the highest share of the energy demand followed by the transport sector. It is seen that it is possible to potentially reduce the household sector consumption by rapidly shifting from biomass-based energy consumption to clean-fuel (biofuel and electric)-based consumption. However, such technology transitions are not automatic and require state intervention through appropriate policy-development. In this regard, the current very low electricity access rate in rural areas should improve in the near future. Moreover, better service reliability and good power quality is also an important requirement to minimize the use of biomass and fossil fuel-based backup solutions during interruptions and power outages. This in turn requires good power system planning.

The energy demand evolution under the BAU and HEG scenarios show that the household sector and other sectors will heavily rely on biomass and fossil-fuels that lead to significant CO_2 emission. On the other hand, the E&U and IEE-3 scenarios result in a much lower energy demand resulting in significant reduction of CO_2 emissions. This implies that it is possible for Ethiopia to potentially reduce its biomass dependency and CO_2 emission by setting the right policies and implementing various strategies. It is also shown that electricity efficiency improvements are crucial for controlling the evolution of the electricity demand through proper energy policies. Considerable energy can be saved by implementing policy-driven efficiency measures through technology improvement, DSM activities, industrial energy audit and network loss reduction. The Ethiopian government has already started to explore several measures including standards and labeling, energy management and auditing, public sector efficiency, technology acceleration, awareness training and accreditation, etc. To ensure the effectiveness of these programs in achieving electricity efficiency improvements, the government should focus on long-term policies and strategies that can have significant impact on the future electricity sector.

Authorship statement

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.

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Paper-IV

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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.g. 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.

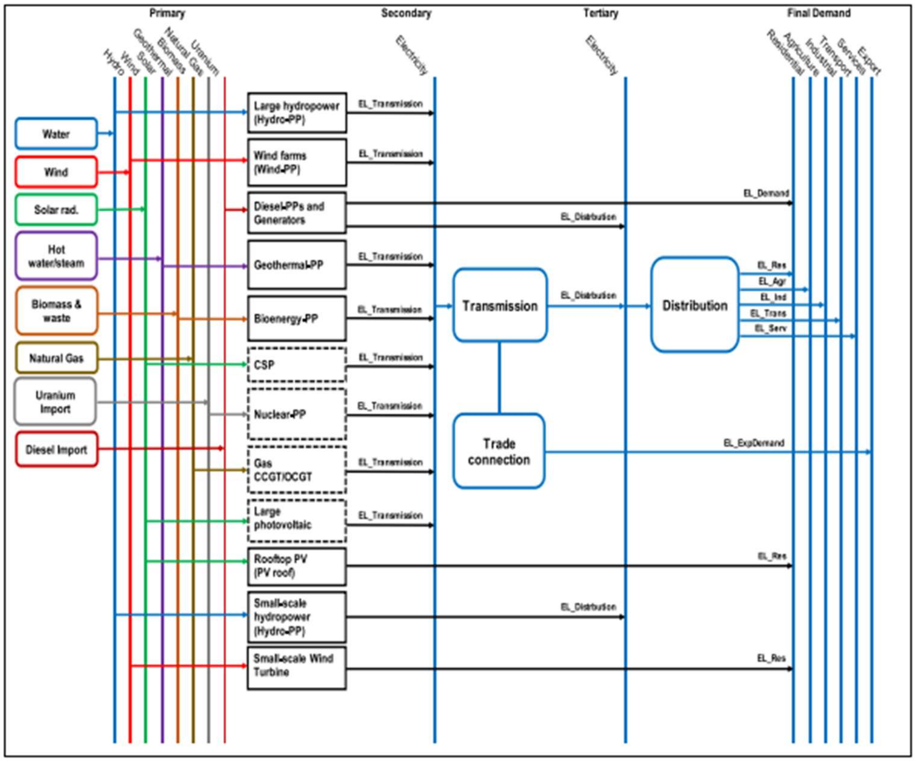

Fig. 1. The reference energy system (RES) of Ethiopian electricity sector.

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%

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.

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**

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

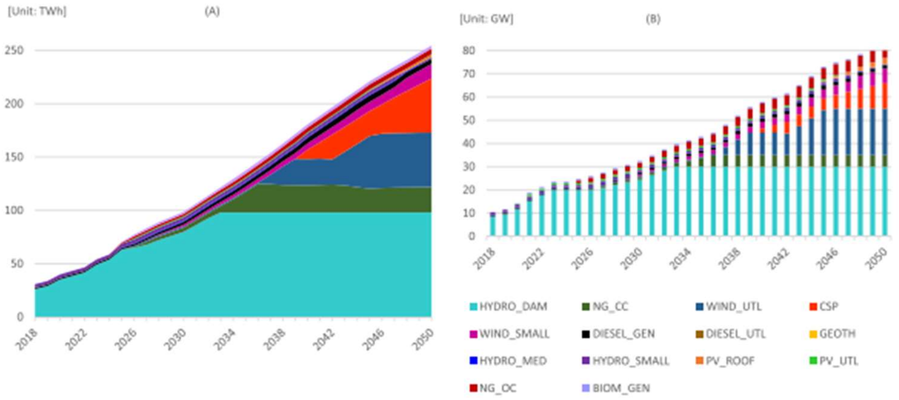

Fig. 2. Electricity generation mix (A) and installed capacity (B) under the reference scenario.

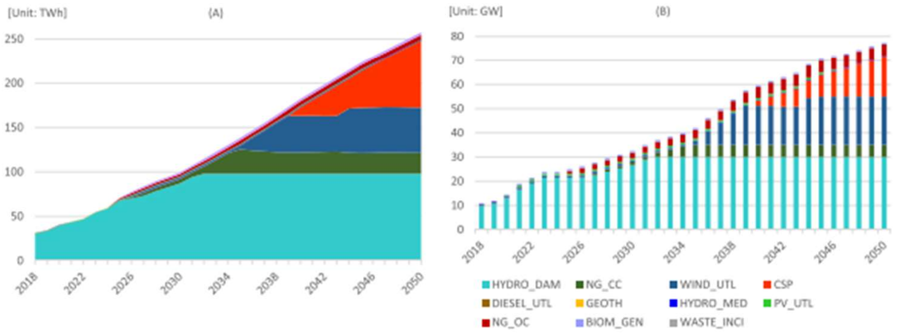

Fig. 3. Electricity generation mix (A) and installed capacity (B) under the grid extension scenario.

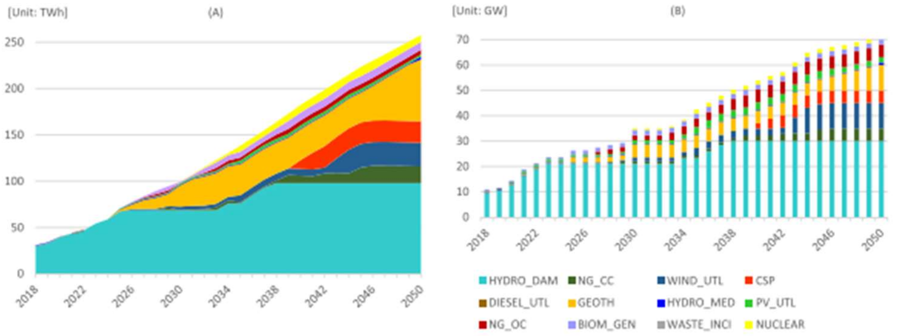

Fig. 4. Electricity generation mix (A) and installed capacity (B) under the multiple resource mix scenario.

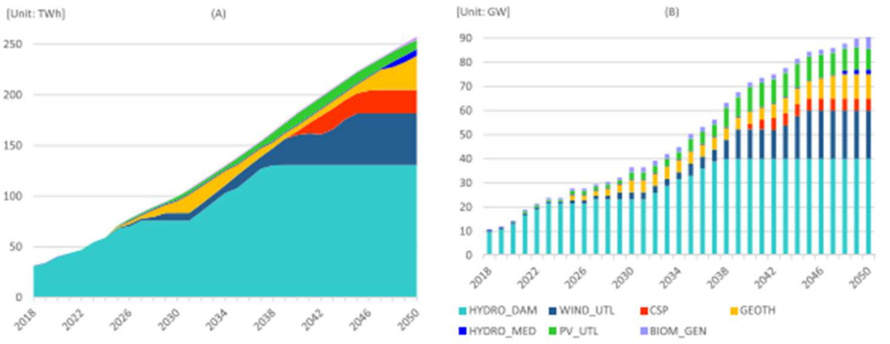

Fig. 5. Electricity generation mix (A) and installed capacity (B) under the intermittent resource target scenario.

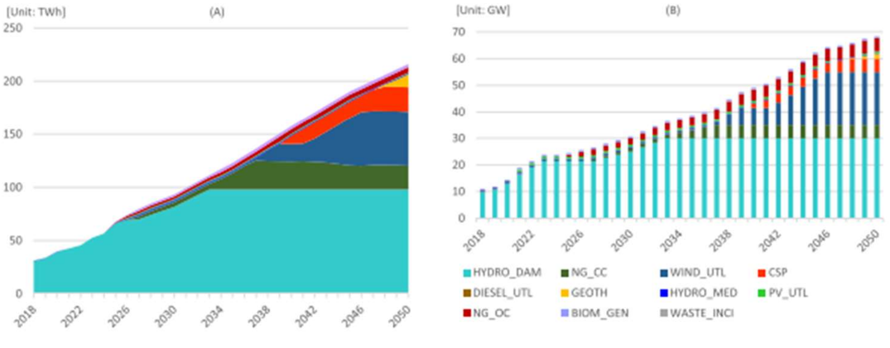

Fig. 6. Electricity generation mix (A) and installed capacity (B) under the improved efficiency scenario.

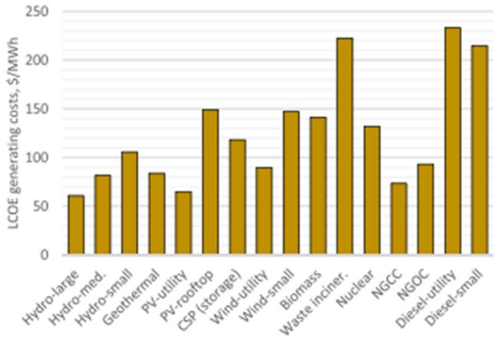

Fig. 7. Levelized cost of electricity (LCOE) for modelled technologies.

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

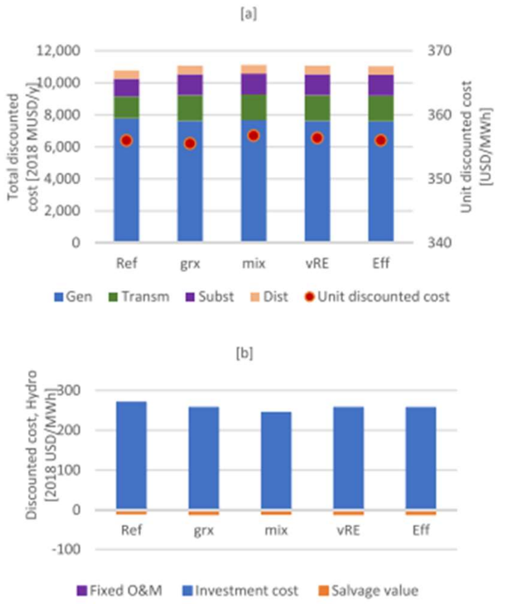

Fig. 8. Total and unit discounted costs (a) and discounted cost of hydropower technology (b).

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

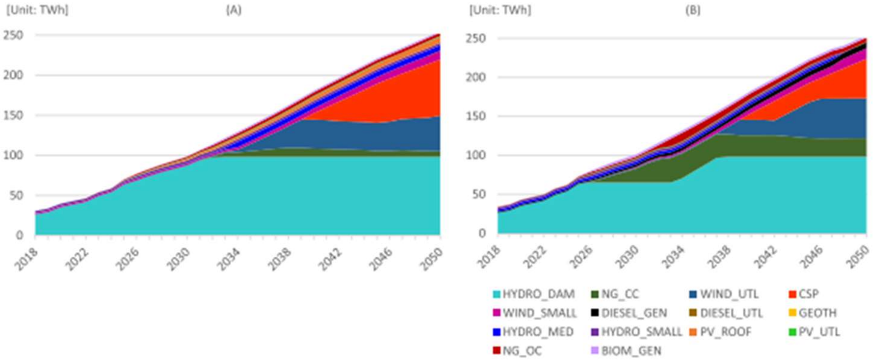

Fig. 9. Electricity generation mix under the reference scenario with a 5% (A) and 15% (B) discount rates.

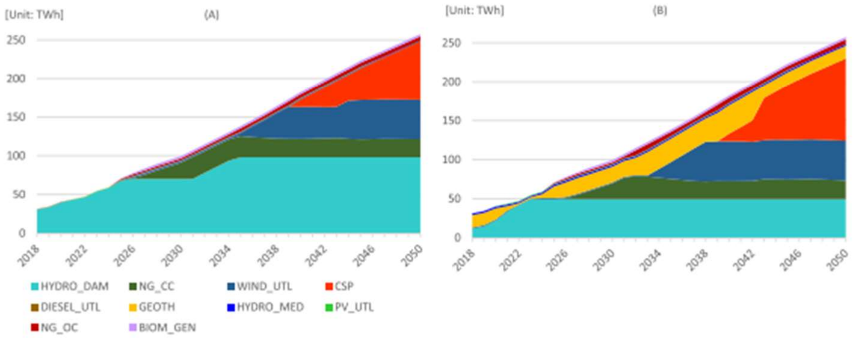

Fig. 10. Electricity generation mix under grid extension scenario with a capital cost increase by 20% (A) and 50% (B).

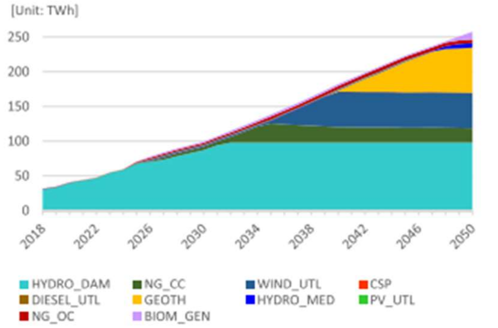

Fig. 11. Electricity generation mix under grid extension scenario with no thermal storage of CSP.

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 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

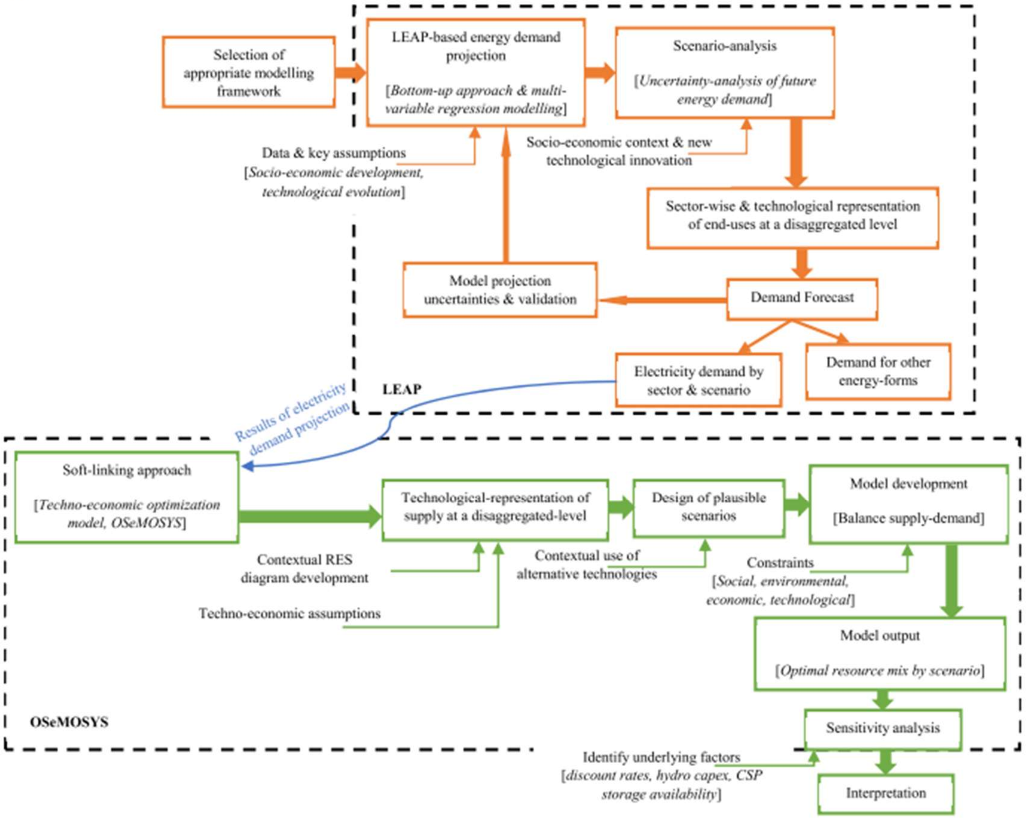

Fig. A1. Overview of the methodology used to explore the potential pathways of the future power supply and demand evolution in Ethiopia.

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Appendix B: Modeling tools

Table A - 1 Comparison of models by modelling approaches [Bhattacharyya and Timilsina, 2010]

Criteria	Bottom-up, optimization	Bottom-up, accounting	Top-down, econometric	Hybrid	Electricity Planning
Geographical coverage	Local to global, but mostly national	National but can be regional	National	National or global	National
Activity coverage	Energy system, environment, trading	Energy system and environment	Energy system, environment	Energy system, environment and energy trading	Electricity system and environment
Level of disaggregation	High	High	varied	High	Not applicable
Technology coverage	Extensive	Extensive but usually predefined	Variable but normally limited	Extensive but usually predefined	Extensive
Data need	Extensive	Extensive but can work with limited data	High	High to extensive	Extensive
Skill requirement	Very high	High	Very high	Very high	Very high
Capability to analyse price-induced policies	High	Does not exist	High	Normally available	Available
Capability to analyse non-price policies	Good	Very good	Very good	Very good	Good
Rural energy	Possible but normally limited	Possible	Possible but normally limited	Possible but normally limited	Difficult
New technology addition	Possible	Possible	Difficult	Possible but often limited	Possible
Informal sector	Difficult	Possible	Difficult	Possible	Difficult
Time horizon	Medium to long-term	Medium to long-term	Short, Medium or long-term	Medium to long-term	Medium to long term
Computing requirement	High end, requires commercial LP solvers	Not demanding	Econometric software required	Could require commercial software	Requires commercial or licensed software

i. MESAP PlaNet

Mesap (Modular Energy System Analysis and Planning Environment) is an energy-system analysis toolbox, and PlaNet (Planning Network) is a linear network module for Mesap that is designed to analyse and simulate energy demand, supply, costs and environmental impacts for local, regional and global energy-systems. It was originally developed by the Institute for Energy Economics and the Rational Use of Energy (IER) at the University of Stuttgart in 1997.

Energy systems are represented in Mesap in a standardized form as a diagram of commodities and transformation processes that is called the Reference Energy System (RES). Mesap PlaNet calculates energy and emission balances for any kind of RES. A detailed cost calculation determines the specific production cost of all commodities in the RES based on the annuity of investment cost and the fixed and variable O&M cost [MESAP]. The model uses a technology-oriented modelling approach where several competitive technologies that supply energy services are represented by parallel processes. All thermal generation, renewable, storage and conversion, and transport technologies are considered in the simulation. The simulation is carried out in a user-specified time-step which ranges from one minute to multiple years, and the total time-period is unlimited.

ii. LEAP

LEAP, the Long-range Energy Alternatives Planning System is a software tool that is used for energy policy analysis and climate change mitigation assessment developed by the Stockholm Environment Institute. It is usually used to analyse national energy systems. LEAP functions use an annual time-step and the time horizon can extend from 20 up to 50 years. LEAP supports bottom-up, end-use accounting techniques as well as top-down macroeconomic modeling [LEAP, 2009]. On the supply side, LEAP provides a range of accounting and simulation methodologies for modeling electric sector generation and capacity expansion planning. On the demand side, LEAP supports the representation of various sectors in a detailed, disaggregated level. LEAP is designed with the concept of scenario analysis. Scenarios are the possible alternatives that represent how an energy system might evolve over time. Accordingly, it is important for policy makers and planners to create and evaluate potential scenarios by comparing their energy requirements, their social costs and benefits and their environmental impacts. Usually the alternative scenarios are compared with the reference or business-as-usual scenario. LEAP displays its results as charts, tables and maps which are user-defined and can be exported to Excel or PowerPoint: these include fuel demands, costs, unit productions, GHG emissions, air-pollutants and more.

iii. MESSAGE

MESSAGE (Model for Energy Supply Strategy Alternatives and their General Environmental Impact) has been developed by the International Institute for Applied Systems Analysis (IIASA) in Austria. It provides a flexible framework for the comprehensive assessment of major energy challenges including analyzing climate change policies, developing scenarios, planning medium to long-term energy systems. It uses a 5- or 10-year time-step to simulate a maximum of 120 years [MESSAGE]. The scenario analysis in MESSAGE is used to describe future uncertainties and develop robust technology strategies with its investment requirements. The model’s principal results are the estimation of global and regional, multi-sectoral climate mitigation strategies instead of climate targets. It allows determining cost-effective portfolios of GHG emission limitation and reduction measures. Typical scenario outputs of the model provide information on the utilization of domestic resources, energy imports, and exports and trade-related monetary flows, investment requirements, the types of production or conversion technologies selected, pollutant emissions as well as temporal trajectories for primary, secondary, final and useful energy [IIASA, 2019].

iv. EnergyPLAN

The EnergyPLAN model is a computer model designed for energy systems analysis. It is developed and maintained by the Sustainable Energy Planning Research Group at Aalborg University, Denmark. It is a deterministic model which optimizes the operation of a given energy system on the basis of inputs and outputs defined by the user. General inputs are demands, renewable energy sources, energy station capacities, costs and a number of optional different regulation strategies emphasizing import/export and excess electricity production. Outputs are energy balances, annual productions, fuel consumption, import/export of electricity, and total costs. The main purpose of EnergyPLAN model is to analyse the energy, environmental and economic impact of various energy strategies [EnergyPLAN]. EnergyPLAN simulates the operation of national energy systems on an hourly basis, including the electricity, heating, industry and transport sectors.

v. MARKAL/TIMES

MARKet Allocation (MARKAL) is a generic model tailored by the input data to represent the evolution over a period of usually 40 to 50 years of a specific energy system at the national, regional or community level. It was developed by the Energy Technology Systems Analysis Programme (ETSAP) of the International Energy Agency (IEA). TIMES (The Integrated MARKAL-EFOM System) is a successor of MARKAL that combines technical engineering approach and an economic approach. It is a technology rich, bottom-up model generator which uses linear programming to produce a least-cost energy system, optimized according to a number of user constraints, over a medium to long-term horizon [Loulou et al., 2004]. The entire energy system can be modelled by representing it as a network, from resource extraction, through energy transformation and end-se devices, to demand for useful energy services. All thermal, renewable, storage and conversion and transportation technologies can be simulated by the model. Many different energy networks or Reference Energy Systems (RES) are feasible for each time period. MARKAL/TIMES finds the “best” RES for each time period by selecting the set of options that minimizes total discounted system cost or the total discounted surplus over the entire planning horizon, within the limits of all imposed policy and physical constraints.

vi. OSeMOSYS

OseMOSYS: The Open-Source Energy Modelling System is a full-fledged system optimization model that is designed to inform the development of local, national and multi-regional energy strategies. It was developed in collaboration with a range of institutions in 2008. OseMOSYS computes the energy supply mix by minimizing the total discounted costs under the constraint of meeting the demand every year and in every time step of the case under study [KTH-dESA, 2018]. Similar to the other tools, it can cover all or individual energy sectors, including heat, electricity and transport and it has a user-defined spatial and temporal domain and scale. The energy demands can be met through a range of technologies which have certain techno-economic characteristics and draw on a set of resources. In addition, desired policy scenarios can impose certain technical, economic and environmental constraints. OseMOSYS is a deterministic, linear optimization, long-term modeling framework. However, mixed integer programming may also be applied for certain functions.

Table A - 2 Comparison of bottom-up models [Bhattacharyya and Timilsina, 2010]

Criteria	RESGEN	EFOM	MARKAL	TIMES	MESAP	LEAP
Approach	Optimization	Linear optimization	Linear optimization	Optimization	Optimization	Accounting
Geographical coverage	Regional and national	Country or multi-country	Country or multi-country	Local, regional, national or multi-country	National	Local to national to global
Activity coverage	Energy system	Energy system	Energy system	Energy system and energy trading	Energy system	Energy system and environment
Level of disaggregation	Pre-defined	User-defined	User defined	User defined	Pre-defined sector structure	Sector structure pre-defined
Technology coverage	Good	Extensive	Extensive	Extensive	Extensive	Menu of options
Data need	Variable, limited to extensive	Extensive	Extensive	Extensive	Extensive	Extensive but can work with limited data
Skill requirement	Limited	High	High to very high	Very high	High to very high	Limited
Portability to another country	Difficult	Difficult	Difficult	Difficult	Difficult	Difficult
Documentation	Limited	Good	Extensive	Good	Good	Extensive
Capability to analyse price-induced policies	Exists	Exists	Exists	Exists	Exists	Does not exist
Capability to analyse non-price policies	Good	Very good	Very good	Very good	Good	Very good
Rural energy	Possible	Possible	Possible	Possible	Not known	Possible
Informal sector	Not possible	Not possible	Not possible	Not possible	Not possible	Possible
New technology addition	Difficult	Possible	Possible	Possible	Possible	Possible
Energy shortage	Not explicitly	Not explicitly	Not explicitly	Not explicitly	Not known	Possible explicitly
Subsidies	Difficult	Possible but often ignored	Possible but normally ignored	Possible but normally ignored	Not known	Not considered explicitly
Rural-urban divide	Possible but not covered usually	Possible but not covered usually	Possible and covered	Possible and covered	Not known	Possible and covered usually
Economic transition	Not covered	Not covered	Not covered	Can be covered	Not known	Usually covered through scenarios

Table A - 3 Comparison of hybrid models [Bhattacharyya and Timilsina, 2010]

Criteria	NEMS	POLES	WEM	SAGE
Approach	Optimization	Accounting	Accounting	Optimization
Geographical coverage	Country	Global but regional and country specific studies possible	Global but regional and country specific studies possible	Global but regional and country specific studies possible
Activity coverage	Energy system	Energy system	Energy system	Energy system and energy trading
Level of disaggregation	Pre-defined	Pre-defined	Pre-defined	Pre-defined
Technology coverage	Extensive but pre-defined	Extensive but pre-defined	Extensive but pre-defined	Extensive but pre-defined
Data needed	Extensive	Extensive	Extensive	Extensive
Skill requirement	Very high	High to very high	High to very high	Very high
Portability to another country	Difficult	Difficult	Difficult	Difficult
Documentation	Extensive	Limited	Good	Extensive
Capability to analyze price-induced policies	Good	Good	-	Good
Capability to analyze non-price policies	Good	Very good	Very good	Good
Rural energy	Possible and covered in a limited way	Possible but not included	Possible and included in a limited way in recent version	Possible but not included
Informal sector	Difficult and not included	Possible but not included	Possible but not included	Not included
New technology addition	Possible but difficult	Possible but difficult	Possible but difficult	Possible but difficult
Rural-urban divide	Possible and considered	Possible but not considered	Possible and included in the recent version	Possible but not considered
Economic transition	Not applicable	Considered implicitly	Considered implicitly	Considered implicitly

Table A - 4 Comparison of various energy models based on the eight classification ways

Criteria	OSeMOSYS	MARKAL/TIMES	MESSAGE	MESAP PlaNet	EnergyPLAN	LEAP
Purpose	Investment decision, scenario	Investment decision, scenario	Investment decision, scenario	Scenario	Scenario, investment decision, operational decision	Scenario
Model scope	Energy-system	Energy-system	IAM, Energy-economy	Energy-system	Energy-system	Energy-system
Analytical approach	Bottom-up	Bottom-up	Bottom-up	Bottom-up	Bottom-up	Bottom-up
Methodology	Optimization	Optimization	Optimization	Simulation, econometric	Simulation, optimization	Simulation, econometric
Mathematical approach	LP, MIP	LP, DP	DP	LP, DP	Analytical programming	N/A

Geographical /spatial coverage	Local, national, regional	Local, national	Local, national	Local, national	Local, national, regional	All
Sectoral coverage	Energy	Energy	Energy	All	Energy	All
Time horizon	Medium, long-term	Medium, long-term	Short, medium, long-term	Short, medium-term	Short, medium-term	Medium, long-term

Table A - 5 Unique features and possible tools for developing countries [Irsyad et al., 2017]

Criteria	Sub-criteria	1	2	3	4	5	6	7	8
Analysis purposes	To determine best options	X			X			X	X
	To determine economic impacts of a policy			X		X	X		X
	To estimate environmental impacts of a policy	X	X	X		X	X	X	X
	To understand energy mix impacts of a policy	X	X			X	X		X
Developing country issues	Rural electrification/energy access equity	X	X		X	X	X	X	X
	Data availability and analysis capability	X	X	X	X	X	X		
	Informal economy								
	Income inequality			X	X		X		X
	Affordability issue for green energy	X	X		X		X	X	X
	Traditional energy	X	X	X	X	X	X	X	X
	Free tools	X	X	X	X	X	X	X	X
1: Optimization model, 2: Simulation model, 3:Top-down model, 4:Multi-criteria decision analysis, 5: System dynamics, 6: Agent-based model, 7: Life cycle thinking, 8: Hybrid tool, x: Common features.									

Appendix C: Demand model

Table A - 6 Historical data input in LEAP

Index	Unit	2001	2003	2006	2009	2012	2015	2017
Population	Million	61.9	65.6	71.7	77.9	84	90.7	95.2
Population growth rate	Percent	-	3.0	3.0	2.8	2.4	2.5	2.5
Household size	People per HH	4.85	4.84	4.81	4.79	4.77	4.75	4.73
No. of households	Million	12.8	13.6	14.9	16.3	17.6	19.1	20.1
GDP								
Agriculture	Million USD	4448	4184	7742	15100	18570	24829	28995
Industry	Million USD	739	911	1518	3108	4965	9614	20672
Service	Million USD	2898	3379	5753	13659	19778	30132	30938
Total	Billion USD	8.1	8.5	15.0	31.9	43.3	64.6	80.6
Per capita Income	USD	131	131	215	415	524	725	876
Urban population	Percent	14.9	15.3	15.9	16.9	18.2	19.4	20.4
Electrification	% of HH	2.7	4.3	6.3	8.1	8.3	8.3	11.7
Total loss	Percent	27	21	23	25	26	26	23
Total loss	GWh	391	347	523	751	1252	1837	1719
Number of customers								
Domestic	Thousand	511.8	572	820.5	1216.3	1450.3	1648.5	2093.1
LV Industrial	Thousand	7.9	8.2	11.4	18.1	21.7	25	34.5
HV Industrial	Customers	91	93	131	169	142	94	315
Commercial	Thousand	75.8	83.8	114.3	162.2	209.2	258.9	317.2
Public	Connections	917	1139	1782	2635	3036	3307	3600
Electricity demand								
Domestic	GWh	508	584	760	1193	2140	2549	3509
HV Industrial	GWh	262	314	468	543	560	1086	1495
LV Industrial	GWh	276	370	494	520	1057	1565	2155
Commercial	GWh	332	394	562	633	881	1628	2240
Public	GWh	10	17	32	19	20	34	47
Export	GWh	-	-	-	-	332	762	1305
Transport, Rail	GWh	-	-	-	-	-	-	62

Table A - 7 Key assumptions

Index	Unit	2001	2005	2010	2015	2025	2030	2035	2040	2045	2050
Population	Million	61.9	69.6	79.9	90.7	114.1	126	137.8	149.5	160.8	172.4
Household size	People per HH	4.85	4.82	4.78	4.75	4.71	4.68	4.67	4.64	4.63	4.6
Rural household	% of HH	85.1	84.3	82.7	80.6	75.6	72.9	70.1	62.2	51.1	40
Total GDP growth	%	7.4	12.6	10.4	10.4	9	9	7	7	4	4
Industry GDP growth	%	-	9.3	12.6	19.9	10	10	7	7	7	7
Service GDP growth	%	-	12.4	12.9	11.1	9	9	8	8	4	4
Agriculture GDP growth	%	-	13.5	7.6	6.4	9	9	8	8	5	5
Electric car penetration	'000 vehicles	-	-	-	-	1	10	30	150	300	1100

*Population figures for 2001-2037 are from CSAE (2013) whereas the projections for 2038-2050 are estimations based on previous growth rate trend.

Table A - 8 Household appliance activity level and energy intensity in 2017.

Sub-sector	Sub-sub sector	End-use	Fuel source/ appliance type	Activity Level		Energy Intensity	
				Unit	Value	Unit	Value
Urban (20.4%)	Electrified (94%)	Lighting	Electricity	% saturation of households	100	kWh/HH	503
			Kerosene		5.1	Liter/HH	18
		Cooking	Electricity		16.3	kWh/HH	587
			Wood (self-build)		13.6	Kg/HH	783
			Wood (manufactured)		54.3	Kg/HH	609
			Charcoal		60.3	Kg/HH	181
			LPG		1	Kg/HH	52.5
			Wood (Injera/bread)		100	Kg/HH	1614.57
		Refrigerator	Electricity		50.5	kWh/HH	453
		Other uses	Electricity		61.1	kWh/HH	133
	Total urban electricity consumption per household					kWh	1676
	Non-Electrified (6%)	Lighting	Kerosene	% saturation of households	4.8	Liter/HH	36
		Cooking	Wood (self-build)		13.6	Kg/HH	1566
			Wood (manufactured)		54.3	Kg/HH	1218
			Charcoal		60.3	Kg/HH	362
			LPG		1	Kg/HH	105
			Wood (Injera/bread)		100	Kg/HH	3229.14
Rural (79.6%)	Electrified (11.68%)	Lighting	Electricity	% saturation of households	100	kWh/HH	235
			Kerosene		25.8	Liter/HH	18
		Cooking	Electricity		5.1	kWh/HH	106
			Wood (self-build)		14.4	Kg/HH	1566
			Wood (manufactured)		6.7	Kg/HH	1218
			Wood (three-stone)		77	Kg/HH	1740
			LPG		1	Kg/HH	105
			Wood (Injera/bread)		100	Kg/HH	3229.14
		Refrigerator	Electricity		5.7	kWh/HH	168
		Other uses	Electricity		75.3	kWh/HH	50
	Total rural electricity consumption per household					kWh	559
	Non-Electrified	Lighting	Kerosene		32.6	Liter/HH	36
		Cooking	Wood (self-build)		14.4	Kg/HH	1566

(88.32%)	Wood (manufactured)	% saturation of households	6.7	Kg/HH	1218
	Wood (three-stone)		77	Kg/HH	1740
	LPG		1	Kg/HH	105
	Solar		0.09	kWh/HH	450
	Wood (Injera/bread)		100	Kg/HH	3229.14

Table A - 9 Relative cost of cooking on the basis of useful energy (October 2014 prices).

Source: Gaia Association, (2014)

Fuel type	Firewood	Charcoal	Kerosene	LPG	Electricity	Ethanol
	Kg	Kg	L	Kg	kWh	L
Price (ETB/unit)	1	8.7	16	43.8	0.567	13.99
Energy content (MJ/unit)	15	29	35.3	45.2	3.6	24
Price of stove (ETB/unit)	0	70	90	460	450	1035
Life of stove (years)	0	4	5	10	10	10
Thermal efficiency of stove (%)	10	25	42	55	60	60
Annualized capital cost (CFR @ 10%)	-	22.1	23.7	73.2	73.2	168.4
Fuel cost (ETB/year)	1740	3152	2816	4598	685	2535
Total expenditure per year (ETB)	1740	3154	2840	4671	758	2704
Total expenditure per month (ETB)	145	263	237	389	63	225
Index (firewood=1)	1.00	1.81	1.63	2.68	0.43	1.55
Rank	2	5	4	6	1	3

*LPG: liquefied petroleum gas, ETB: Ethiopian birr, CFR: capital financing requirement

Table A - 10 LEAP model energy demand projection

Fuel type		Final energy consumption (PJ)							
	2017	2030				2050			
		BAU	E&U	HEG	IEE-3	BAU	E&U	HEG	IEE-3
Total	1,551.7	2,947.3	2,115.0	3021.0	2,066.0	4,899.8	2,854.7	5,254.9	2,651.5
Household	1,383.1	2,273.0	1,439.0	2,273.0	1,428.5	2,844.4	977.3	2,844.4	894.1
-Electricity	14.5	74.1	90.0	74.1	79.5	224.9	296.8	224.9	213.6
-Natural Gas	-	1.2	2.9	1.2	2.9	6.5	17.3	6.5	17.3
-Kerosene	6.5	8.7	2.9	8.7	2.9	10.3	0.6	10.3	0.6
-LPG	0.9	18.0	18.0	18.0	18.0	39.1	54.0	39.1	54.0
-Wood	1,347.5	2,137.5	1,298.4	2,137.5	1,298.4	2,457.4	535.5	2,457.4	535.5
-Charcoal	13.7	26.7	17.4	26.7	17.4	82.3	31.3	82.3	31.3
-Ethanol	.	3.5	6.4	3.5	6.4	19.1	38.1	19.1	38.1
-Solar	0.0	3.3	2.9	3.3	2.9	4.9	3.6	4.9	3.6
HV Industry	5.4	120.1	120.1	132.5	112.7	237.9	237.9	277.9	209.3
-Electricity	5.4	67.8	67.8	69.1	60.4	130.3	130.3	142.2	101.6
-Gasoline	-	12.1	12.1	14.5	12.1	20.8	20.8	23.1	20.8
-Coal Anthracite	-	9.4	9.4	9.4	9.4	20.9	20.9	20.9	20.9
-Coal Unspecified	-	30.8	30.8	39.6	30.8	65.9	65.9	91.6	65.9
LV Industry	7.8	36.6	36.6	47.9	31.1	134.2	134.2	205.5	98.4
-Electricity	7.8	33.9	33.9	44.0	28.4	119.1	119.1	168.5	83.3

-Gasoline	-	2.7	2.7	3.8	2.7	15.1	15.1	37.0	15.1
Commercial	17.3	43.1	43.1	48.8	43.1	138.0	138.0	183.0	138.0
-Electricity	8.1	23.3	23.3	26.5	23.3	74.6	74.6	96.7	74.6
-LPG	3.2	6.7	6.7	7.6	6.7	21.6	21.6	29.4	21.6
-Wood	6.1	13.0	13.0	14.7	13.0	41.8	41.8	56.9	41.8
Agriculture	0.9	18.6	18.6	19.3	18.6	74.2	74.2	86.6	74.2
-Electricity	-	15.9	15.9	15.9	15.9	59.1	59.1	59.1	59.1
-Gasoline	0.9	2.7	2.7	3.4	2.7	15.1	15.1	27.5	15.1
Transport	120.0	337.7	336.0	376.4	336.0	1,208.0	1,016.5	1,375.5	1,016.5
-Electricity	0.2	53.8	54.0	53.8	54.0	89.7	112.5	89.7	112.5
-Gasoline	12.2	49.7	48.9	50.1	48.9	403.1	309.9	347.7	309.9
-Jet Kerosene	21.5	69.6	69.6	75.6	69.6	261.1	261.1	330.8	261.1
-Diesel	86.1	164.6	163.5	196.9	163..5	454.1	333.0	607.3	333.0
Public	0.2	0.4	0.4	0.4	0.1	1.1	1.1	1.1	0.4
-Electricity	0.2	0.4	0.4	0.4	0.1	1.1	1.1	1.1	0.4
Export	5.5	51.3	51.3	53.1	51.3	144.2	144.2	151.0	144.2
-Electricity	5.5	49.6	49.6	49.6	49.6	127.1	127.1	127.1	127.1
-Natural Gas	-	1.7	1.7	3.4	1.7	17.1	17.1	23.9	17.1
Loss	11.5	66.6	69.9	69.6	44.5	118.0	131.5	129.9	76.4
-Electricity	11.5	66.6	69.9	69.6	44.5	118.0	131.5	129.9	76.4

Appendix D: Supply model

Table A - 11 Residual capacities of various sources (GW)

Year	Biomass	Diesel-Util.	Geoth	Hydro-Dam	Hydro-Med.	Hydro-small	PV-Util.	Waste-Inci	Wind-Util.
2013		0.087	0.0075	1.6444	0.2936	0.00012			0.051
2014		0.087	0.0075	1.6444	0.2936	0.00012			0.171
2015		0.087	0.0075	1.6444	0.2936	0.00012			0.324
2016		0.087	0.0075	1.6444	0.2936	0.00012			0.544
2017		0.087	0.0075	3.5214	0.2936	0.00012			0.544
2018		0.087	0.0075	3.5214	0.2936	0.00012			0.544
2019		0.087	0.0075	4.5254	0.2936	0.00012			0.544
2020	0.276	0.087	0.0075	6.6854	0.2936	0.00012	0.35		0.544
2021	0.683	0.087	0.0075	10.221	0.2936	0.00012	0.85	0.025	0.544
2022	0.683			12.75	0.2936	0.00012	0.85	0.025	0.544
2023	0.683			15.125	0.2936	0.00012	0.85	0.025	0.544
2024	0.683			15.125	0.2936	0.00012	0.85	0.025	0.544
2025	0.683			15.125	0.2936	0.00012	0.85	0.025	0.544
2026	0.683			15.125	0.2936	0.00012	0.85	0.025	0.544
2027	0.683			15.125	0.2936	0.00012	0.85	0.025	0.544
2028	0.683			15.125	0.2936	0.00012	0.85	0.025	0.544
2029	0.683			15.125	0.2936	0.00012	0.85	0.025	0.544
2030	0.683			15.125	0.2936	0.00012	0.85	0.025	0.544
2031	0.683			15.125	0.2936	0.00012	0.85	0.025	0.544
2032	0.683			15.125	0.2936	0.00012	0.85	0.025	0.544
2033	0.683			15.125	0.2936	0.00012	0.85	0.025	0.544
2034	0.683			15.125	0.2936	0.00012	0.85	0.025	0.544
2035	0.683			15.125	0.2936	0.00012	0.85	0.025	0.544
2036	0.683			15.125	0.2936	0.00012	0.85	0.025	0.544
2037	0.683			15.125	0.2936	0.00012	0.85	0.025	0.544
2038	0.683			15.125	0.2936	0.00012	0.85	0.025	0.493
2039	0.683			15.125	0.2936	0.00012	0.85	0.025	0.372
2040	0.683			15.125	0.2936	0.00012	0.85	0.025	0.372
2041	0.683			15.125	0.2936	0.00012	0.85	0.025	0.372
2042	0.683			15.125	0.2936	0.00012	0.85	0.025	
2043	0.683			15.125	0.2936	0.00012	0.85	0.025	
2044	0.683			15.125	0.2936	0.00012	0.85	0.025	
2045	0.683			15.125	0.2936	0.00012	0.85	0.025	
2046	0.683			15.125	0.2936	0.00012	0.5	0.025	
2047	0.683			15.125	0.2936	0.00012			
2048	0.683			15.125	0.2936	0.00012			
2049	0.683			15.125	0.2936	0.00012			
2050	0.683			15.125	0.2936	0.00012			

Table A - 12 Total annual maximum capacity under ref scenario (GW)

Year	Diesel-Util.	Geoth	Hydro-Dam	Hydro-Med.	Hydro-small	NGCC	NGOC	Wind-Util.
2018	0.087	10	30	2	1	0	0	20
2019	0.087	10	30	2	1	0	0	20
2020	0.087	10	30	2	1	0	0	20
2021	0.087	10	30	2	1	0	0	20
2022	0.087	10	30	2	1	5	5	20
2023	0.087	10	30	2	1	5	5	20
2024	0.087	10	30	2	1	5	5	20
2025	0.087	10	30	2	1	5	5	20
2026	0.087	10	30	2	1	5	5	20
2027	0.087	10	30	2	1	5	5	20
2028	0.087	10	30	2	1	5	5	20
2029	0.087	10	30	2	1	5	5	20
2030	0.087	10	30	2	1	5	5	20
2031	0.087	10	30	2	1	5	5	20
2032	0.087	10	30	2	1	5	5	20
2033	0.087	10	30	2	1	5	5	20
2034	0.087	10	30	2	1	5	5	20
2035	0.087	10	30	2	1	5	5	20
2036	0.087	10	30	2	1	5	5	20
2037	0.087	10	30	2	1	5	5	20
2038	0.087	10	30	2	1	5	5	20
2039	0.087	10	30	2	1	5	5	20
2040	0.087	10	30	2	1	5	5	20
2041	0.087	10	30	2	1	5	5	20
2042	0.087	10	30	2	1	5	5	20
2043	0.087	10	30	2	1	5	5	20
2044	0.087	10	30	2	1	5	5	20
2045	0.087	10	30	2	1	5	5	20
2046	0.087	10	30	2	1	5	5	20
2047	0.087	10	30	2	1	5	5	20
2048	0.087	10	30	2	1	5	5	20
2049	0.087	10	30	2	1	5	5	20
2050	0.087	10	30	2	1	5	5	20

Table A - 13 Total annual maximum capacity under grx and Eff scenarios (GW)

Year	Diesel-Gen	Diesel-Util.	Geoth	Hydro-Dam	Hydro-Med.	Hydro-small	NGCC	NGOC	PV-Roof	Wind-small	Wind-Util.
2018	0	0.087	10	30	2	0	0	0	0	0	20
2019	0	0.087	10	30	2	0	0	0	0	0	20
2020	0	0.087	10	30	2	0	0	0	0	0	20
2021	0	0.087	10	30	2	0	0	0	0	0	20
2022	0	0.087	10	30	2	0	5	5	0	0	20
2023	0	0.087	10	30	2	0	5	5	0	0	20
2024	0	0.087	10	30	2	0	5	5	0	0	20
2025	0	0.087	10	30	2	0	5	5	0	0	20
2026	0	0.087	10	30	2	0	5	5	0	0	20
2027	0	0.087	10	30	2	0	5	5	0	0	20
2028	0	0.087	10	30	2	0	5	5	0	0	20
2029	0	0.087	10	30	2	0	5	5	0	0	20
2030	0	0.087	10	30	2	0	5	5	0	0	20
2031	0	0.087	10	30	2	0	5	5	0	0	20
2032	0	0.087	10	30	2	0	5	5	0	0	20
2033	0	0.087	10	30	2	0	5	5	0	0	20
2034	0	0.087	10	30	2	0	5	5	0	0	20
2035	0	0.087	10	30	2	0	5	5	0	0	20
2036	0	0.087	10	30	2	0	5	5	0	0	20
2037	0	0.087	10	30	2	0	5	5	0	0	20
2038	0	0.087	10	30	2	0	5	5	0	0	20
2039	0	0.087	10	30	2	0	5	5	0	0	20
2040	0	0.087	10	30	2	0	5	5	0	0	20
2041	0	0.087	10	30	2	0	5	5	0	0	20
2042	0	0.087	10	30	2	0	5	5	0	0	20
2043	0	0.087	10	30	2	0	5	5	0	0	20
2044	0	0.087	10	30	2	0	5	5	0	0	20
2045	0	0.087	10	30	2	0	5	5	0	0	20
2046	0	0.087	10	30	2	0	5	5	0	0	20
2047	0	0.087	10	30	2	0	5	5	0	0	20
2048	0	0.087	10	30	2	0	5	5	0	0	20
2049	0	0.087	10	30	2	0	5	5	0	0	20
2050	0	0.087	10	30	2	0	5	5	0	0	20

Table A - 14 Total annual minimum capacity under mix scenario (GW).

Year	Biomass	Geoth	NGCC	NGOC	Nuclear	PV-Util.	Wind-Util.	Waste-Inci
2018								
2019								
2020								
2021								
2022								
2023								
2024								
2025	1.5	2						
2026								
2027								
2028								
2029								
2030	2	5	1	0.5	0.5	1.5	1.5	0.1
2031								
2032								
2033								
2034								
2035					1.5	3	3	
2036								
2037								
2038								
2039								
2040								
2041								
2042								
2043								
2044								
2045								
2046								
2047								
2048								
2049								
2050								

Table A - 15 Total annual maximum capacity under mix scenario (GW)

Year	CSP	Diesel -Gen	Diesel -Util.	Geoth	Hydro -Dam	Hydro -Med.	Hydro-small	NGCC	NGOC	Nuclear	Wind-small	Wind-Util.	Waste-Inci.
2018	5	0	0.087	10	30	2	0	0	0	0	0	10	0.5
2019	5	0	0.087	10	30	2	0	0	0	0	0	10	0.5
2020	5	0	0.087	10	30	2	0	0	0	0	0	10	0.5
2021	5	0	0.087	10	30	2	0	0	0	0	0	10	0.5
2022	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2023	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2024	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2025	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2026	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2027	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2028	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2029	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2030	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2031	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2032	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2033	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2034	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2035	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2036	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2037	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2038	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2039	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2040	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2041	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2042	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2043	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2044	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2045	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2046	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2047	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2048	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2049	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5
2050	5	0	0.087	10	30	2	0	5	5	5	0	10	0.5

Table A - 16 Total annual maximum capacity under vRE scenario (GW)

Year	CSP	Diesel -Gen	Diesel -Util.	Geoth	Hydro -Dam	Hydro -Med.	Hydro-small	NGCC	NGOC	PV-roof	Wind-small	Wind-Util.	Waste-Inci.
2018	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2019	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2020	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2021	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2022	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2023	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2024	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2025	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2026	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2027	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2028	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2029	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2030	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2031	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2032	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2033	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2034	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2035	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2036	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2037	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2038	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2039	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2040	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2041	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2042	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2043	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2044	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2045	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2046	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2047	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2048	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2049	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5
2050	5	0	0.087	10	40	2	0	0	0	0	0	20	0.5

Table A - 17 Total annual minimum capacity under vRE scenario (GW)

Year	Biomass	Geoth	NGCC	NGOC	Nuclear	PV-Util.	Wind-Util.	Waste-Inci
2018								
2019								
2020								
2021								
2022								
2023								
2024								
2025	1.5	2				1.5	1.5	
2026								
2027								
2028								
2029								
2030	2	5				3	3	
2031								
2032								
2033								
2034								
2035						5	5	
2036								
2037								
2038						8	8	
2039								
2040						10	10	
2041								
2042								
2043								
2044								
2045								
2046								
2047								
2048								
2049								
2050								

Table A - 18 Evaluation of LCOE for different technologies

Basic technology characterization								
Technology	Hydro-large	Hydro-med.	Hydro-small	Geoth	PV-util.	PV-roof.	CSP (storage)	Wind-util.
Technical data								
Efficiency (%)	-	-	-	-	-	-	-	-
Fuel	-	-	-	-	-	-	-	-
Load factor (%)	41	41	46	80	25	25	63	30
Operational lifetime (years)	80	50	30	25	25	25	25	25
Economic data								
Investment cost ($/kW)	2000	2400	3533	4000	1100	2770	5238	1700
Fixed O&M cost ($/kW/yr)	18	50	50	88.8	21	21	67.3	46
Variable O&M cost excl. fuel ($/MWh)	0.1	0.36	0.36	8.4	-	-	1.5	0.8
Fuel costs ($/GJ)	-	-	-	-	-	-	-	-
Fuel costs ($/MWh)	-	-	-	-	-	-	-	-
Interest/discount rate	10% per year							
Calculation of LCOE								
Annuity factor $(\frac{(r(1+r)^n)}{(((1+r)^n)-1)})$	0.100	0.101	0.106	0.110	0.110	0.110	0.110	0.110
Investment	0.056	0.067	0.093	0.063	0.055	0.139	0.105	0.071
Fix O&M	0.005	0.014	0.012	0.013	0.010	0.010	0.012	0.018
Variable O&M	0.000	0.000	0.000	0.008	0.000	0.000	0.002	0.001
Fuel cost	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
LCOE $/kWh	0.061	0.082	0.106	0.084	0.065	0.149	0.118	0.090
LCOE $/MWh	**60.824**	**81.678**	**105.774**	**83.953**	**64.925**	**148.934**	**118.25**	**89.569**
Basic technology characterization								
Technology	Wind-small	Biomass	Waste incin.	Nuclear	NGCC	NGOC	Diesel-util.	Diesel-small
Technical data								

Efficiency (%)	-	38	34	33	55	36	35	35
Fuel	-	Biomass	Municipal waste	Uranium	Natural gas	Natural gas	Diesel	Diesel
Load factor (%)	30	50	50	85	80	80	80	80
Operational lifetime (years)	20	30	25	40	25	30	25	20
Economic data								
Investment cost ($/kW)	2900	3333	7900	4500	1100	700	1600	692
Fixed O&M cost ($/kW/yr)	46	75.6	75.6	164	24	17	60	27.6
Variable O&M cost excl. fuel ($/MWh)	-	6.5	6.5	20	2.6	3.5	6	6
Fuel costs ($/GJ)		3.89	-	2.59	7.66	7.66	18.8	18.8
Fuel costs ($/MWh)		14.01	-	9.33	27.59	27.59	67.72	67.72
Interest/discount rate	10% per year							
Calculation of LCOE								
Annuity factor $(\frac{(r(1+r)^n)}{(((1+r)^n)-1)})$	0.117	0.106	0.110	0.102	0.110	0.106	0.110	0.117
Investment	0.130	0.081	0.199	0.062	0.017	0.011	0.025	0.012
Fix O&M	0.018	0.017	0.017	0.022	0.003	0.002	0.009	0.004
Variable O&M	0.000	0.007	0.007	0.020	0.003	0.004	0.006	0.006
Fuel cost	0.000	0.037	0.000	0.028	0.050	0.077	0.193	0.193
LCOE $/kWh	0.147	0.141	0.222	0.132	0.073	0.093	0.233	0.215
LCOE $/MWh	**147.12**	**141.351**	**222.465**	**132.099**	**73.481**	**93.161**	**233.2**	**215.02**

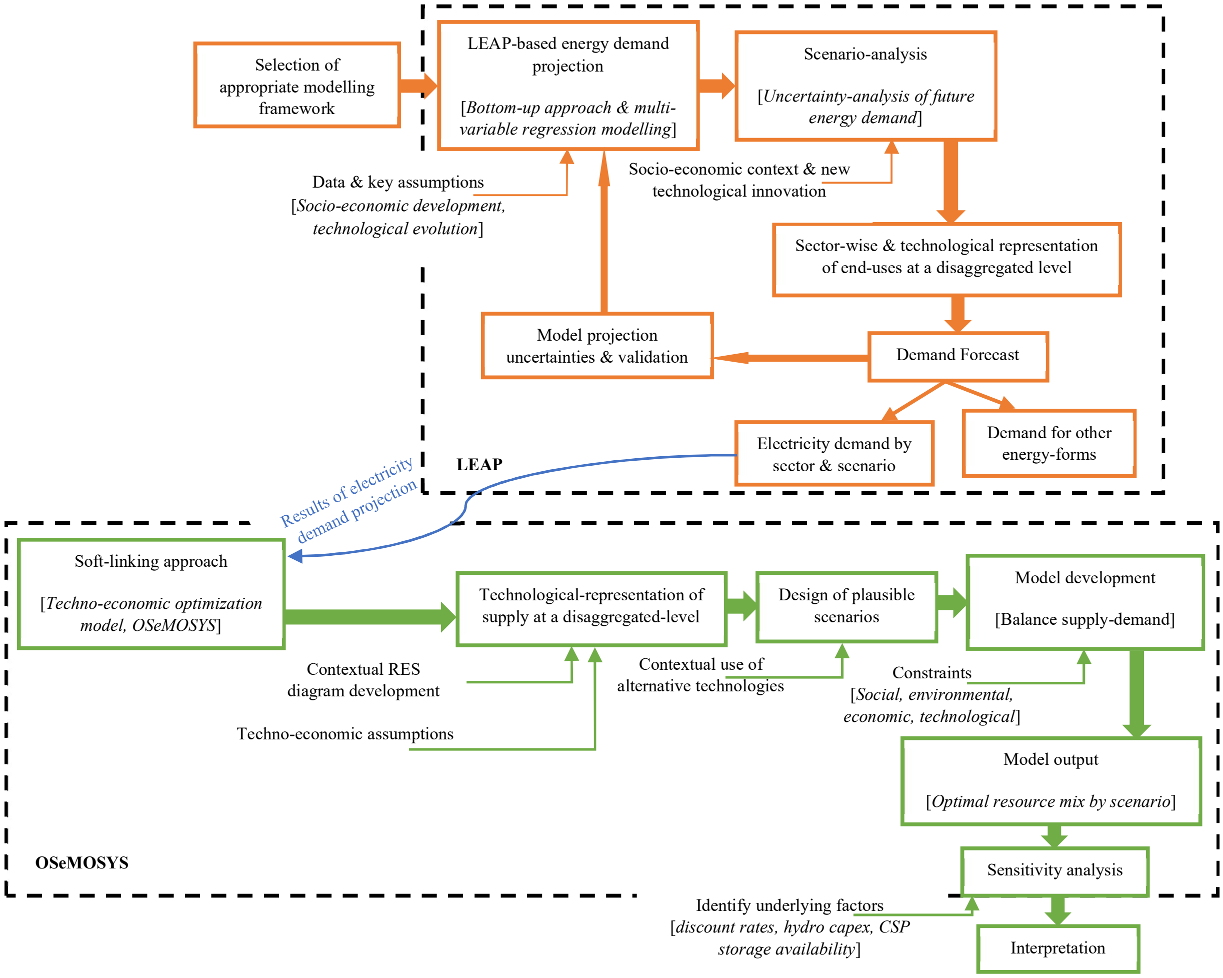

Fig. A - 1 Overview of the methodology used to explore the potential pathways of the future power supply and demand evolution in Ethiopia.

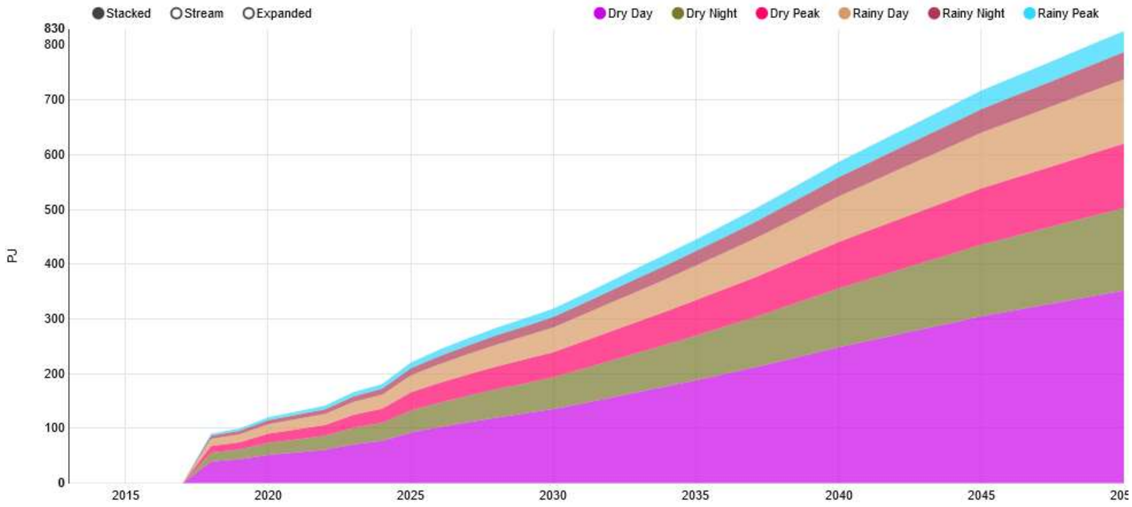

Fig. A - 2 Demand by time slice under ref scenario

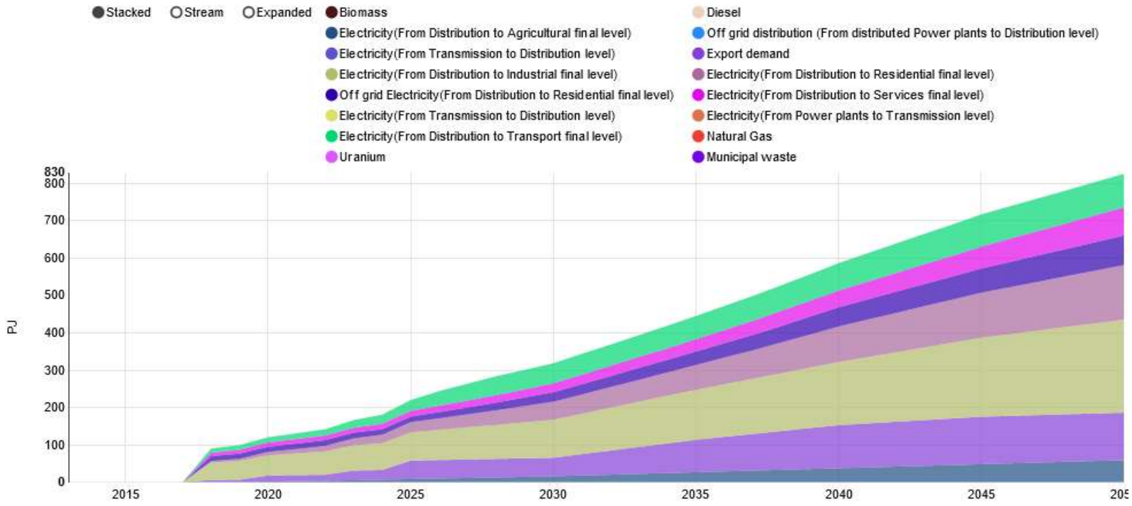

Fig. A - 3 Demand by fuel under ref scenario

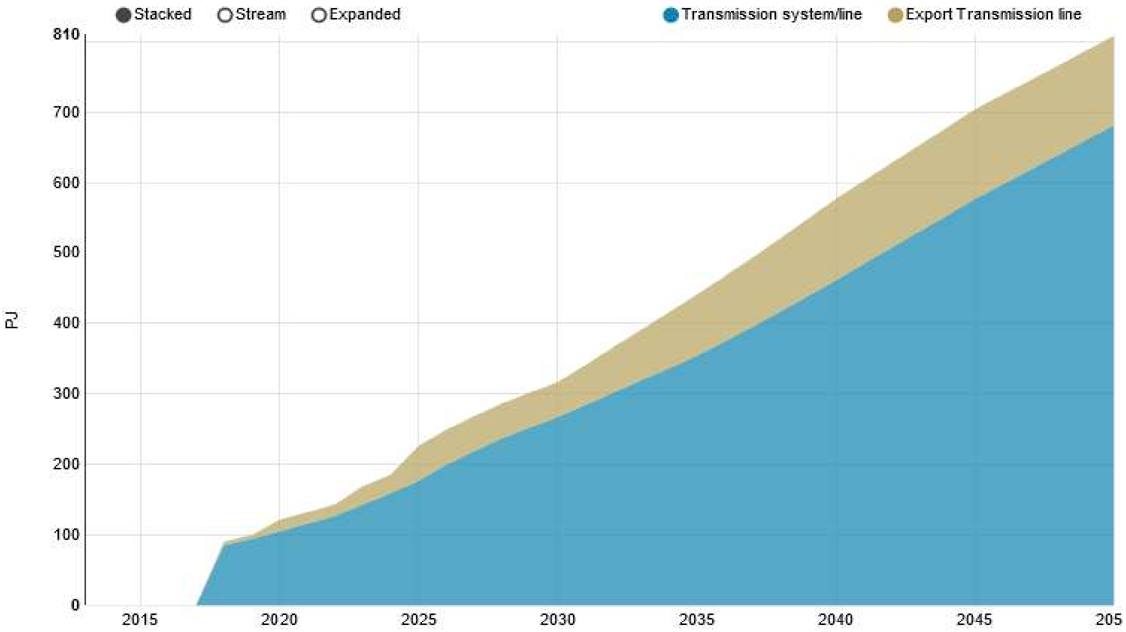

Fig. A - 4 Annual transported energy with the transmission system under the ref scenario

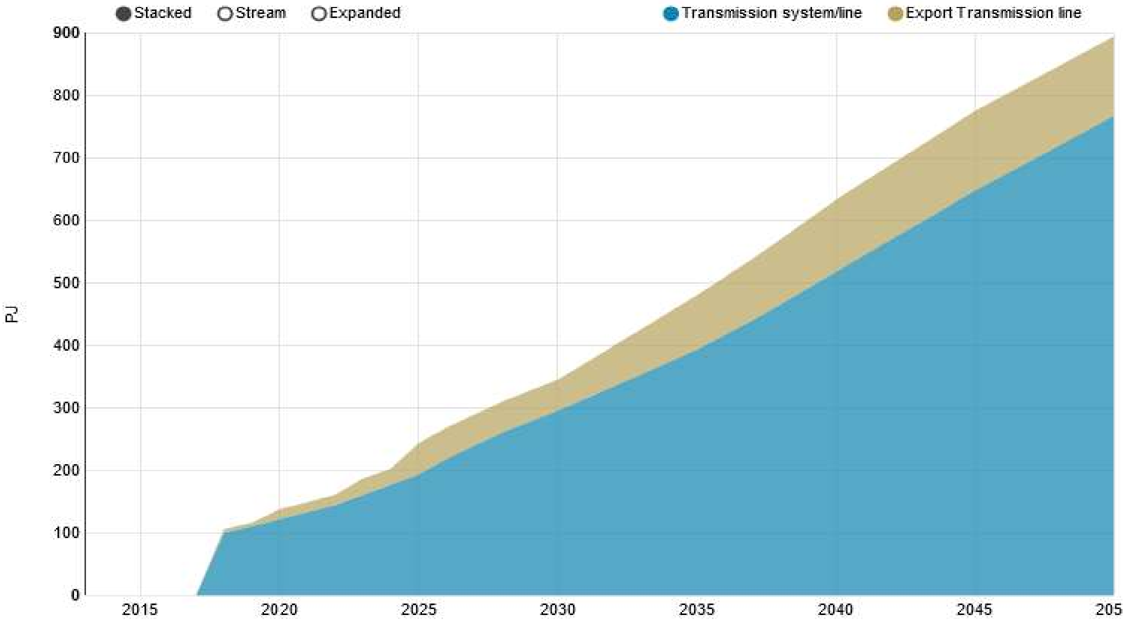

Fig. A - 5 Annual transported energy with the transmission system under the grx scenario

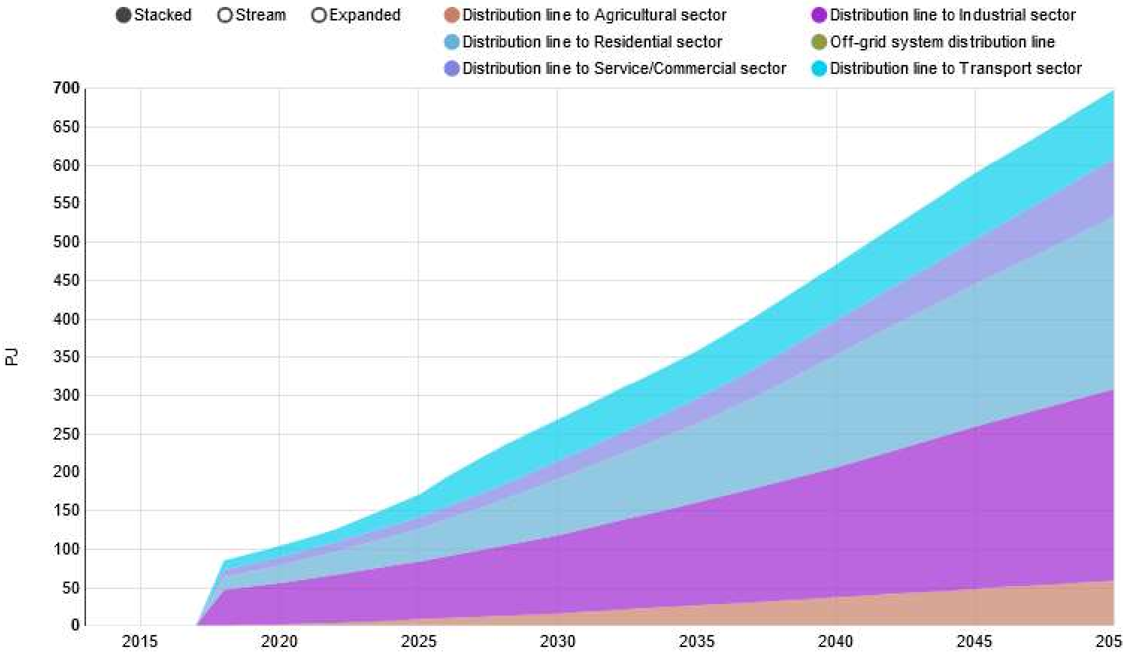

Fig. A - 6 Annual transported energy with the distribution system under the grx scenario

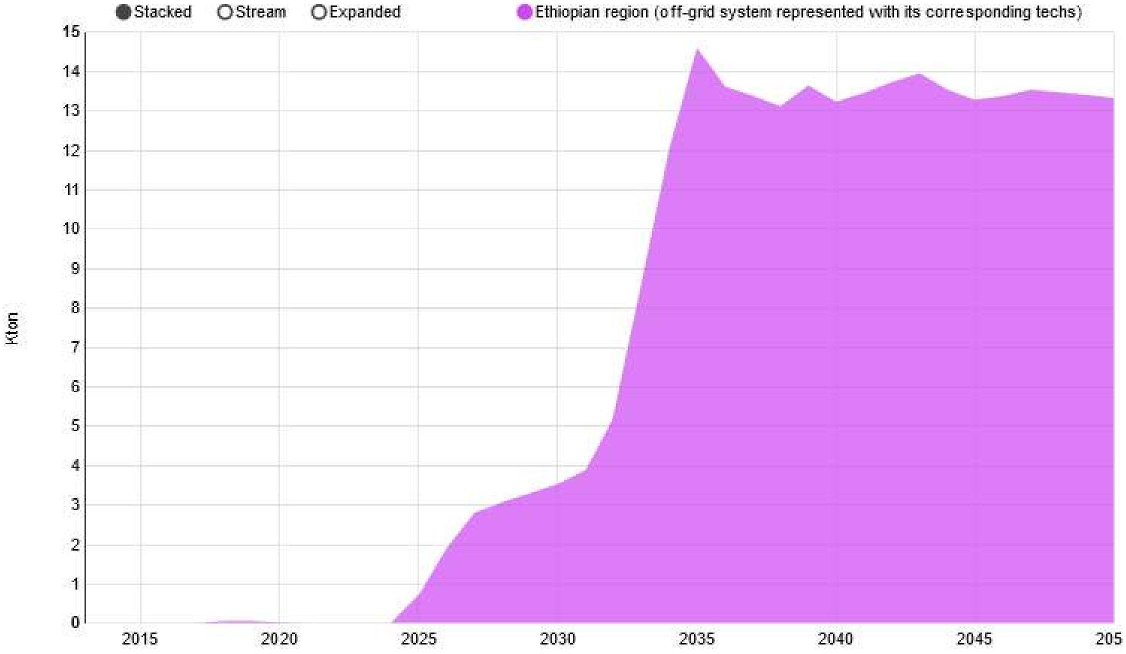

Fig. A - 7 Annual emissions under the grx scenario

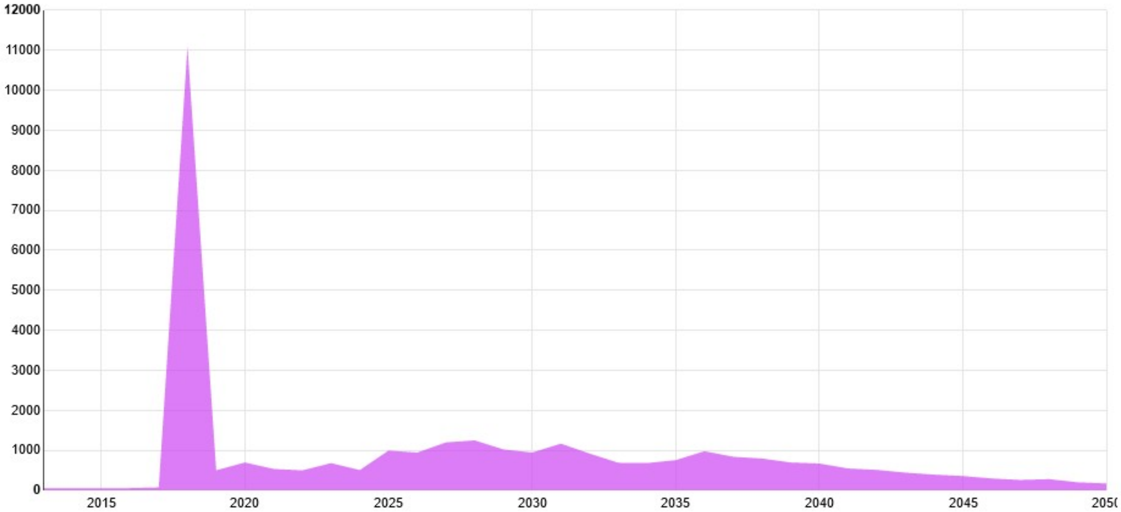

Fig. A - 8 Total discounted cost (Million USD) for the grx scenario

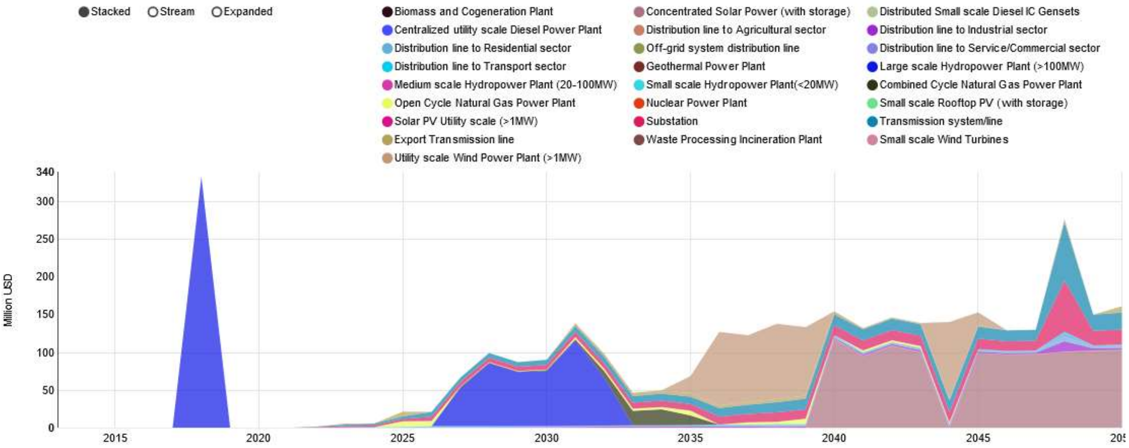

Fig. A - 9 Discounted Salvage Value under the grx scenario

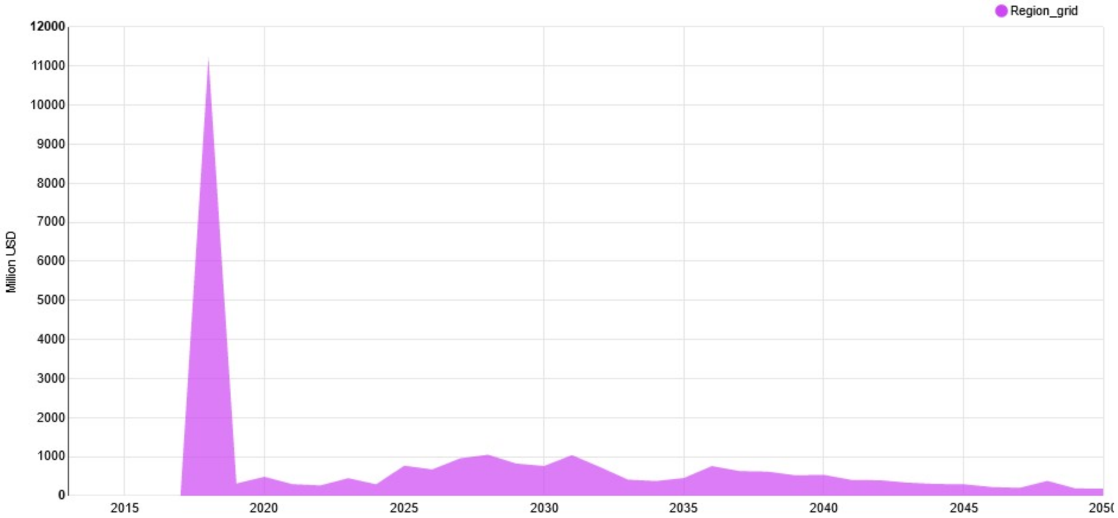

Fig. A - 10 Discounted capital investment (Million USD) for the grx scenario

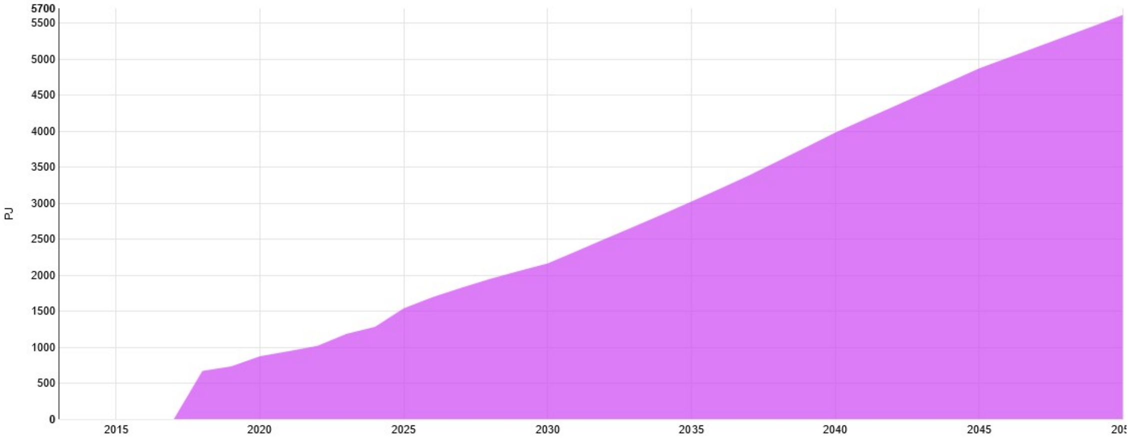

Fig. A - 11 Demand needing reserve margin (PJ) under the grx scenario

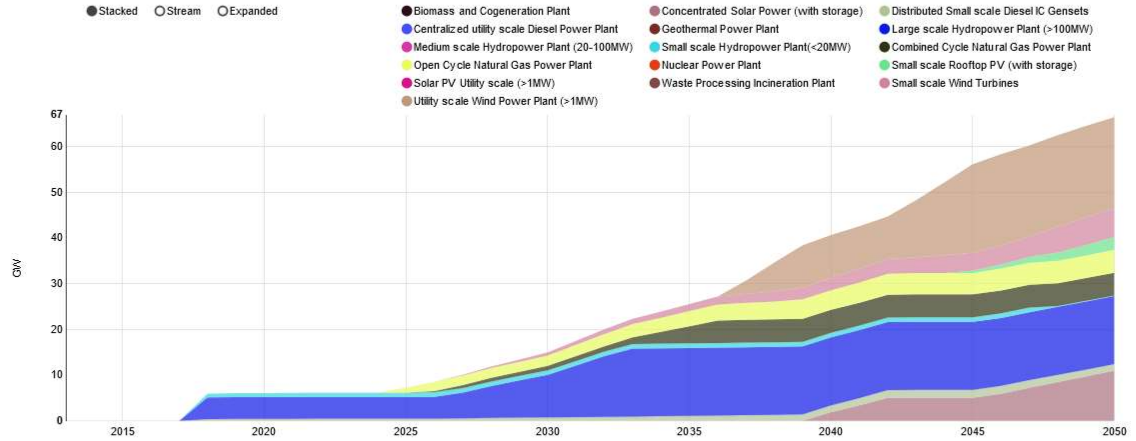

Fig. A - 12 Accumulated new capacity (GW) for ref scenario

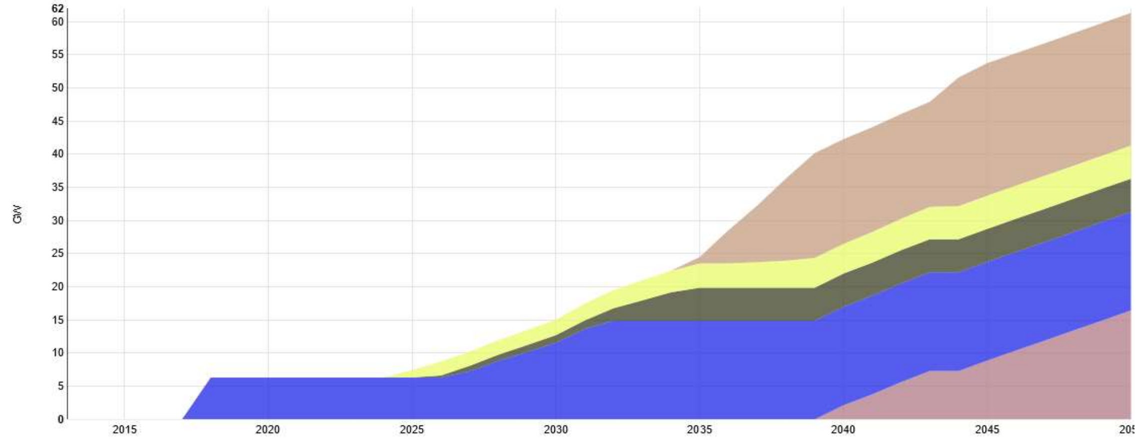

Fig. A - 13 Accumulated new capacity (GW) for grx scenario

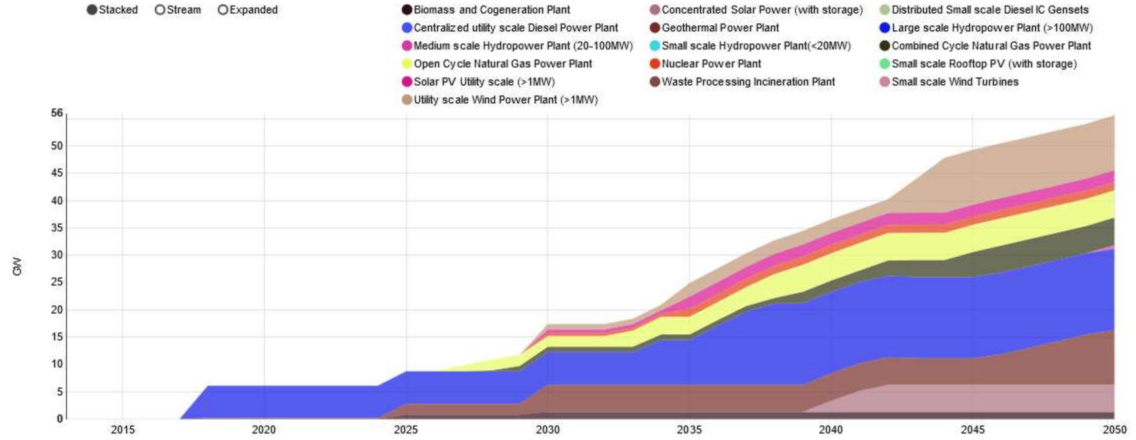

Fig. A - 14 Accumulated new capacity (GW) for mix scenario

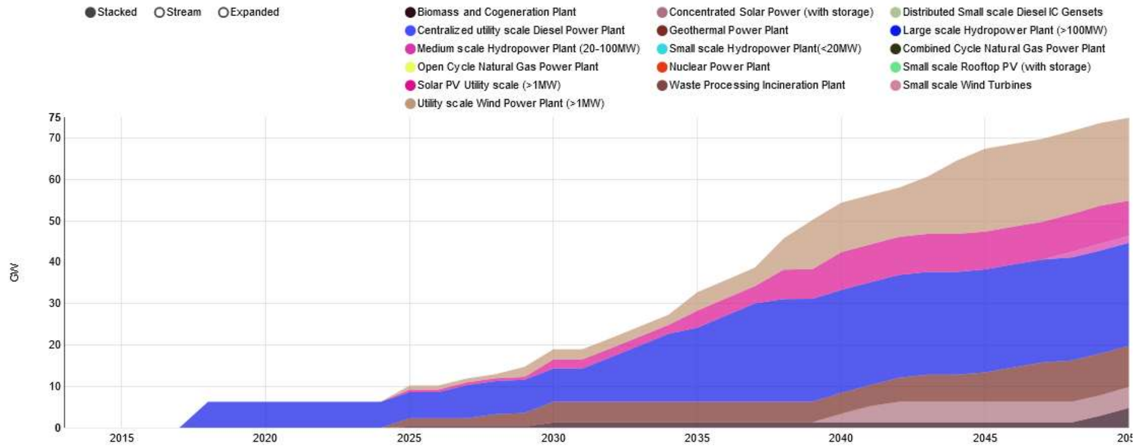

Fig. A - 15 Accumulated new capacity (GW) for vRE scenario

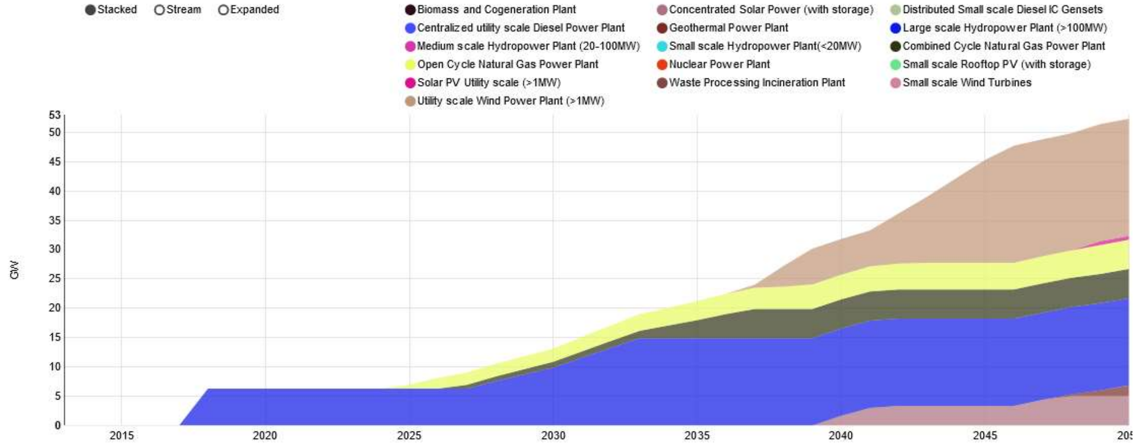

Fig. A - 16 Accumulated new capacity (GW) for Eff scenario

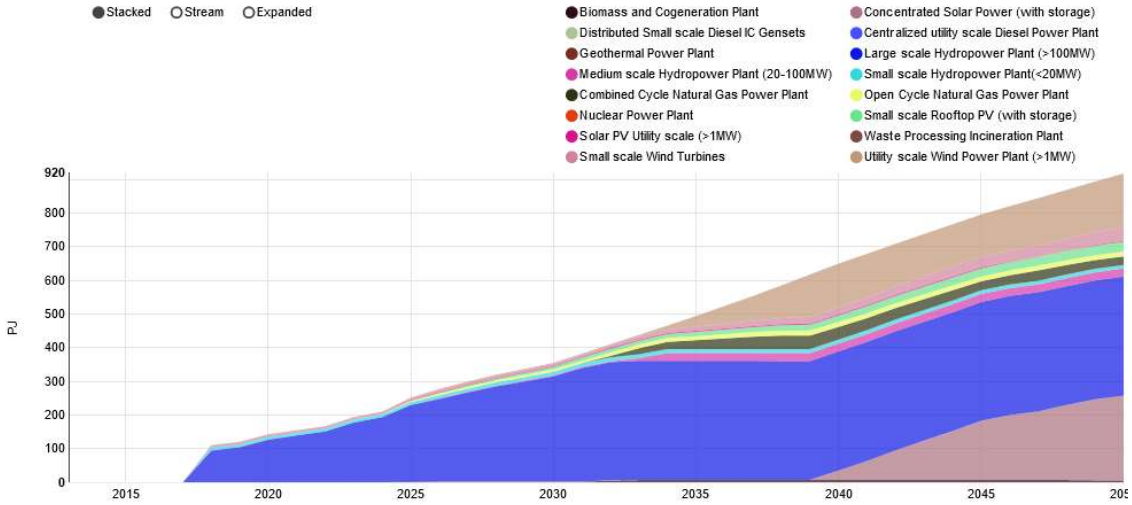

Fig. A - 17 Energy mix under ref scenario with a 5% discount-rate.

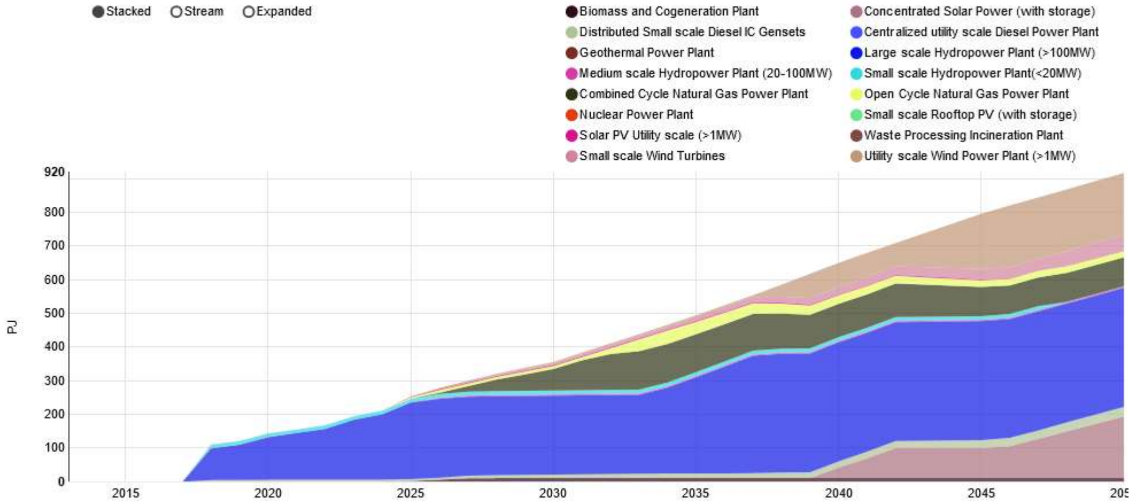

Fig. A - 18 Energy mix under ref scenario with a 15% discount-rate

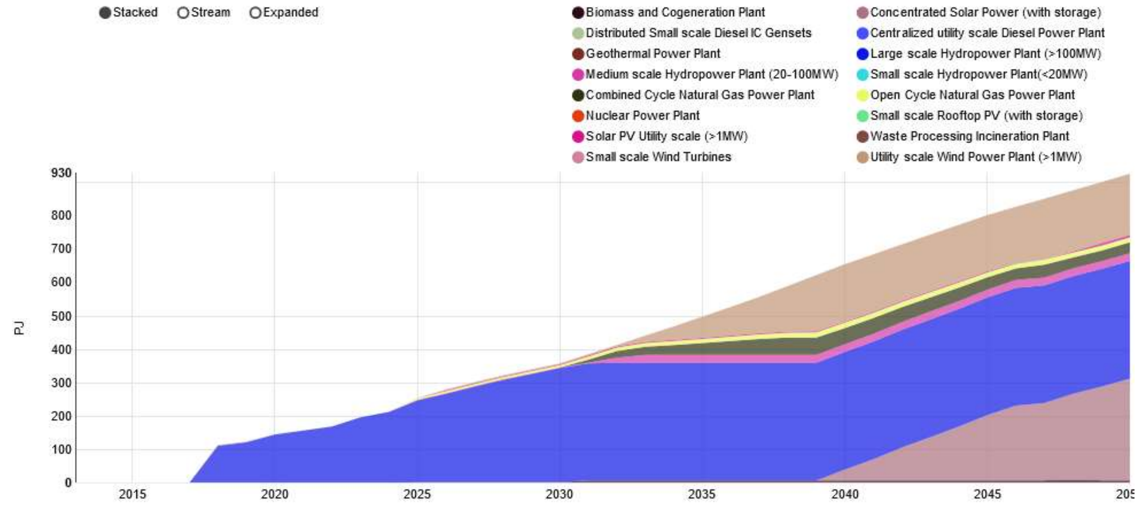

Fig. A - 19 Energy mix under grx scenario with a 5% discount-rate

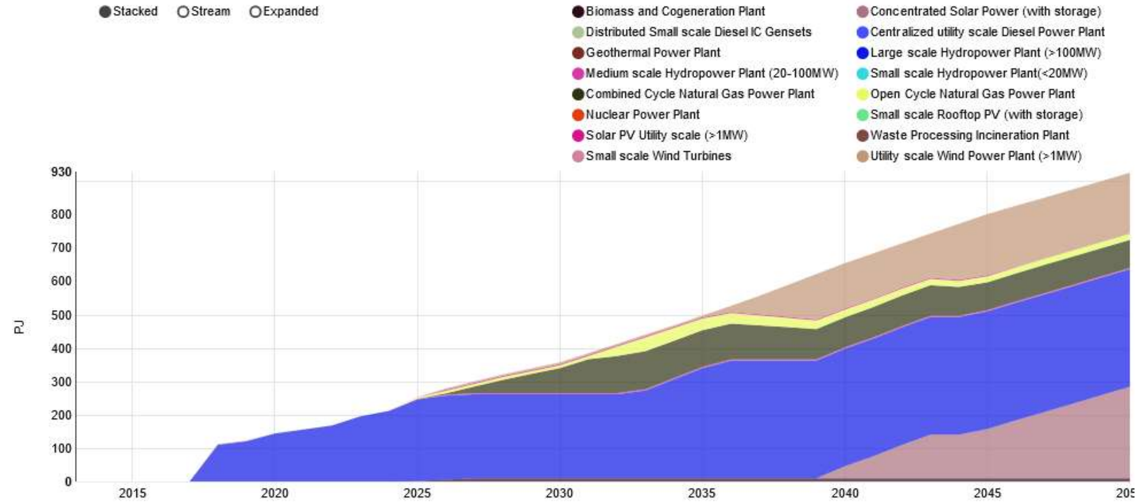

Fig. A - 20 Energy mix under grx scenario with a 15% discount-rate

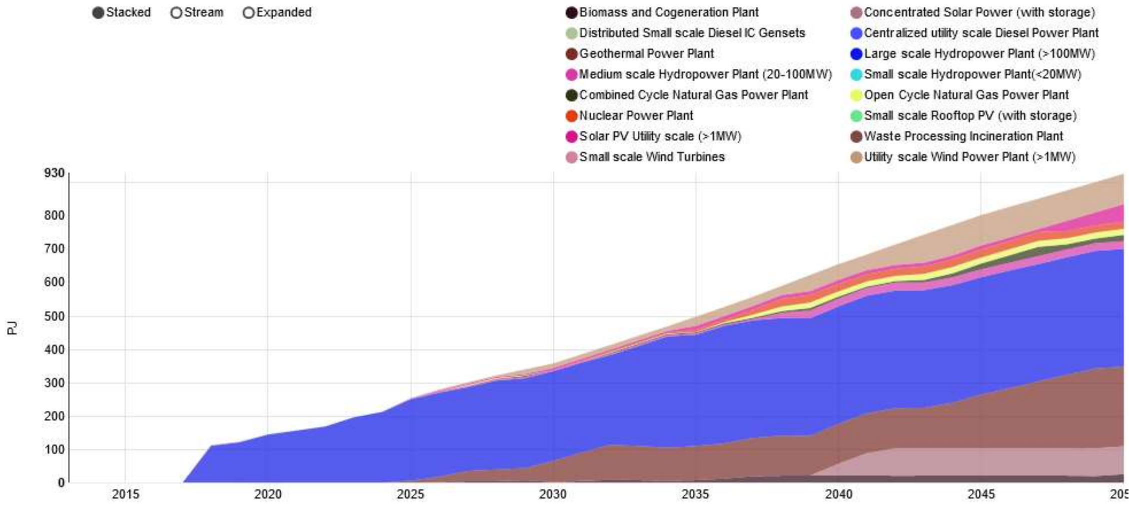

Fig. A - 21 Energy mix under mix scenario with a 5% discount-rate

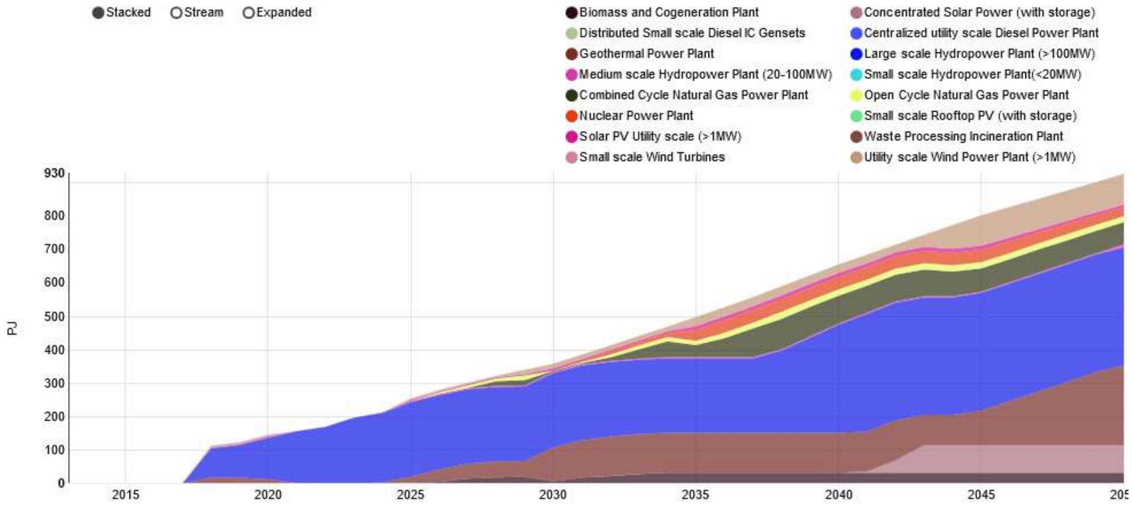

Fig. A - 22 Energy mix under mix scenario with a 15% discount-rate

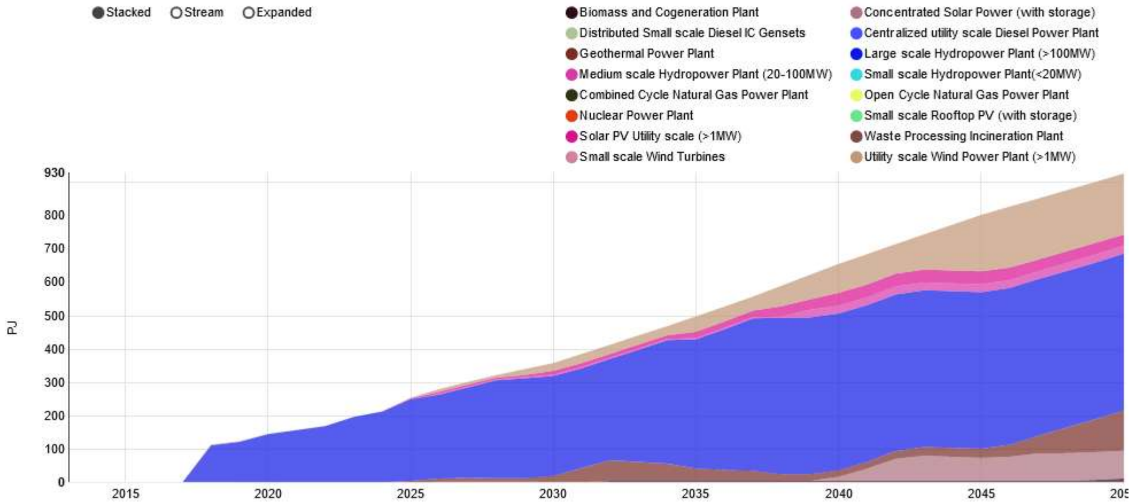

Fig. A - 23 Energy mix under vRE scenario with a 5% discount-rate

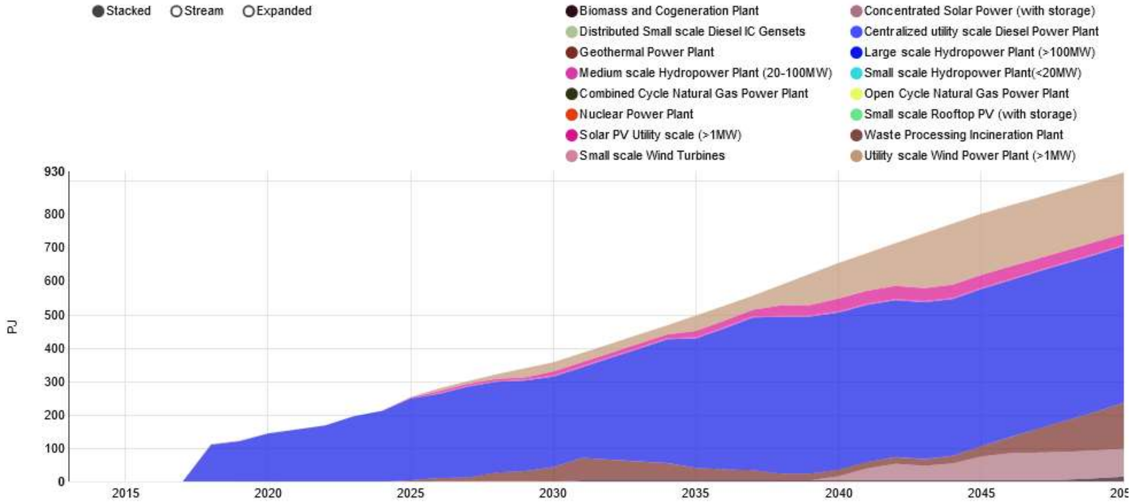

Fig. A - 24 Energy mix under vRE scenario with a 155 discount-rate

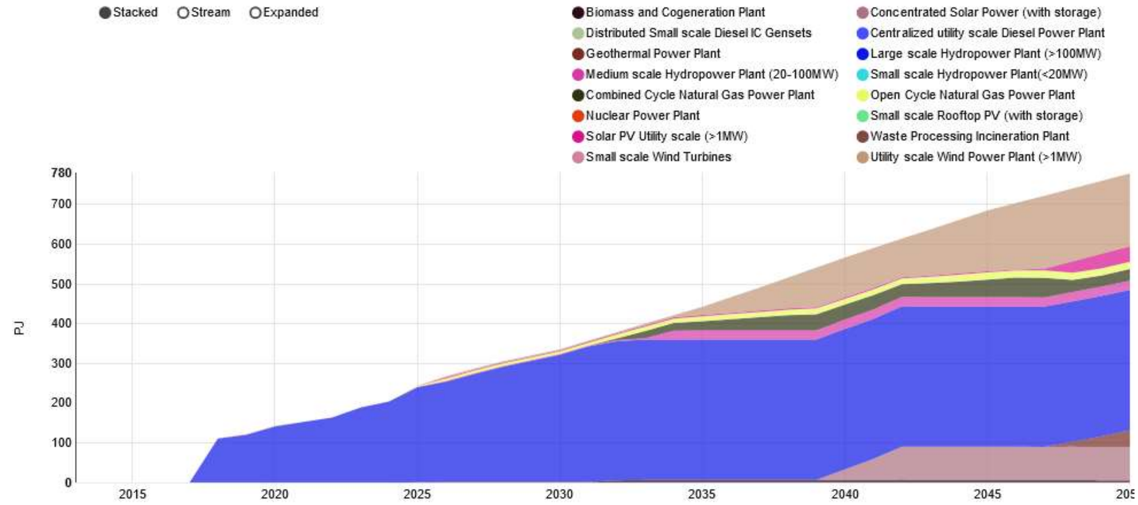

Fig. A - 25 Energy mix under Eff scenario with a 5% discount-rate

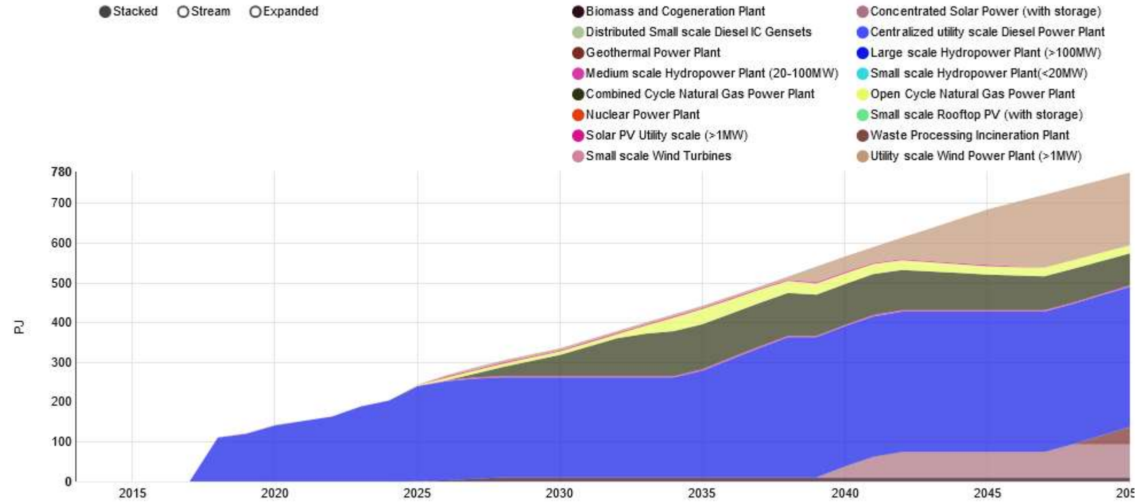

Fig. A - 26 Energy mix under Eff scenario with a 15% discount-rate

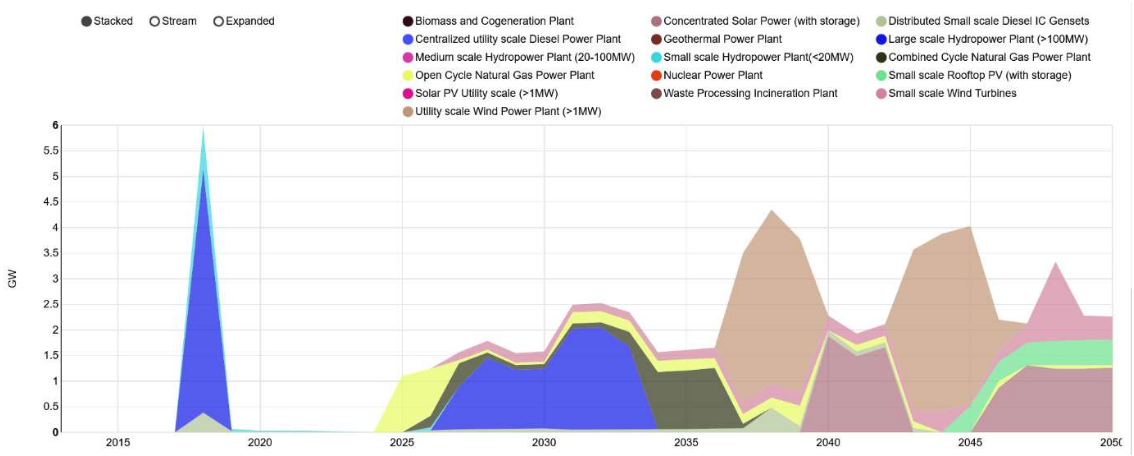

Fig. A - 27 New capacity under the ref scenario

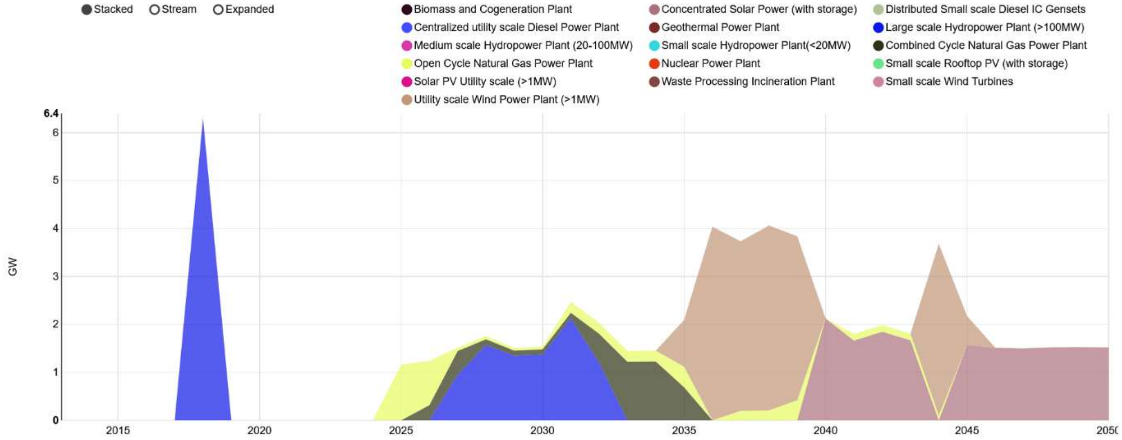

Fig. A - 28 New capacity under the grx scenario

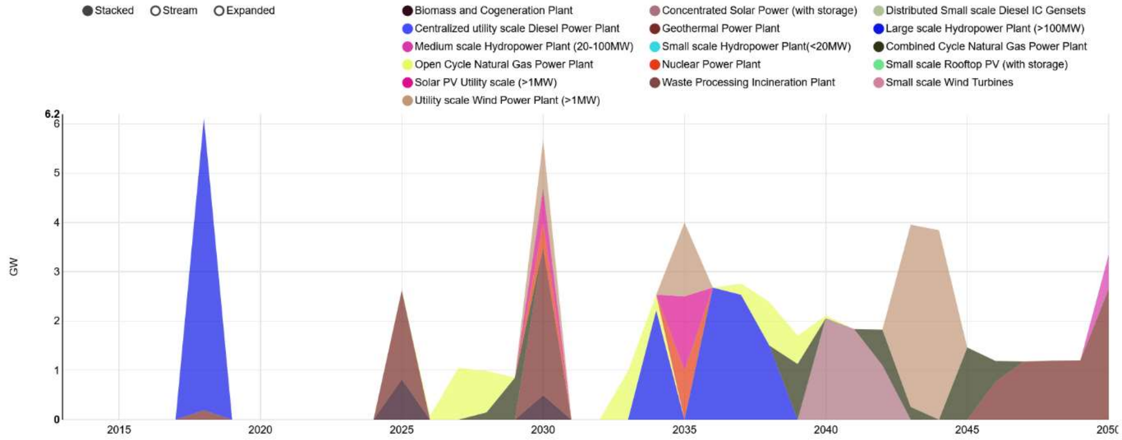

Fig. A - 29 New capacity under the mix scenario

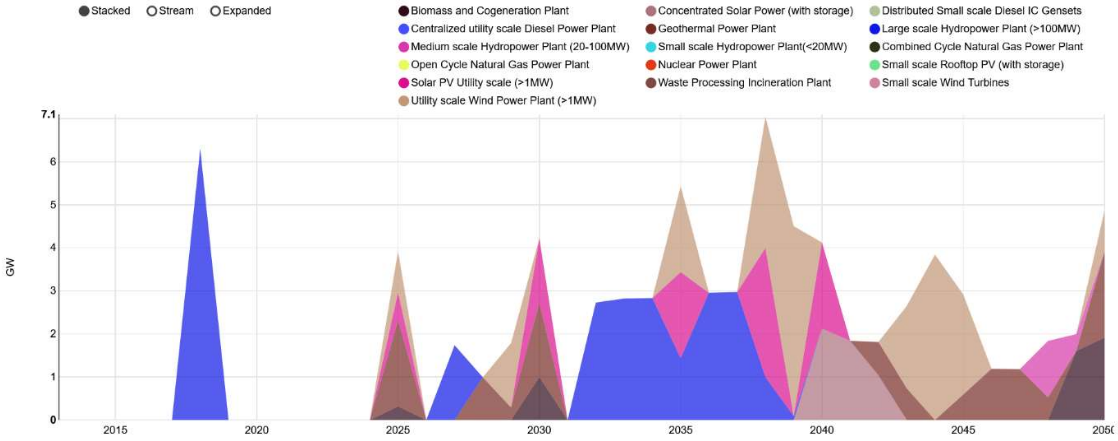

Fig. A - 30 New capacity under the vRE scenario

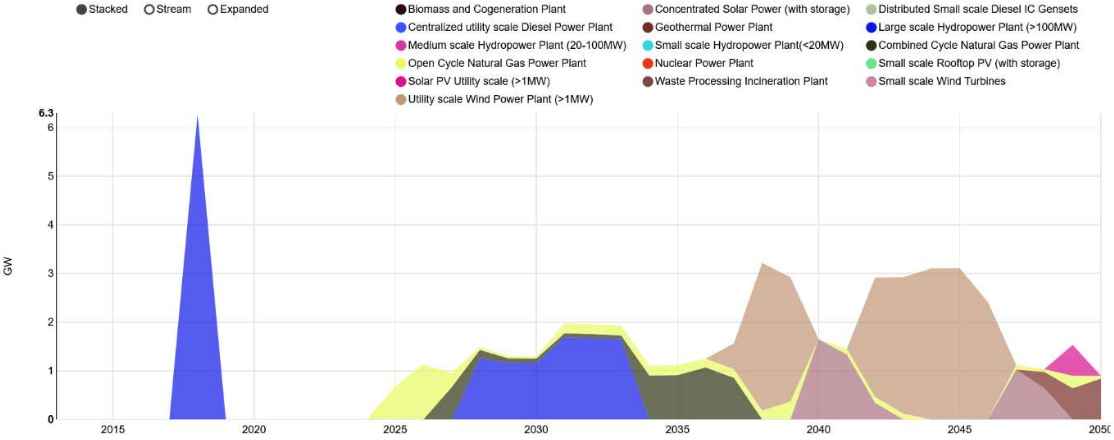

Fig. A - 31 New capacity under the Eff scenario

Short Curriculum

Dawit Habtu Gebremeskel

Education:

2015	M.Sc. in Electrical Power and Energy Engineering, Addis Ababa Institute of Technology (AAiT), Addis Ababa University (AAU).
2011	B.Sc. in Electrical Power Engineering, AAiT, AAU.

Work Experience:

2012-Present	Lecturer in AAiT, School of Electrical and Computer Engineering (SECE), Electrical Power division (Taught courses: power system, power system planning, Power system automation, Hydropower Engineering, Electrical Installation).
2015-Present	Research assistant in AAiT, SECE, Participated in several local and international research projects (energy efficiency, renewable energy, appliance labeling, energy efficient lighting, community energy, power reliability, energy audit, etc.).
2012-2018	Test Engineer in AAiT, SECE, Working on high-voltage tests for different power system equipment.
2014-Present	Consulting Engineer in different projects (new headquarter building of Commercial Bank of Ethiopia, Electrical Power Supply Reliability Study for Yara Dallol Potash Project, Grand Ethiopian Renaissance Dam, Ethiopian Electric utility Excellence Center, etc.)

List of Publications:

I. Dawit H. Gebremeskel, Getachew Bekele, Erik O. Ahlgren, Assessment of resource adequacy in power sector reforms of Ethiopia, 2019 IEEE PES/IAS PowerAfrica, Abuja, Nigeria, 2019, pp. 81-86.

II. Dawit H. Gebremeskel, Getachew Bekele, Erik O. Ahlgren, Energy System modeling tools: Review and comparison in the context of developing countries, 2020 IEEE PES/IAS PowerAfrica, Nairobi, Kenya, 2020.

III. Dawit H. Gebremeskel, Getachew Bekele, Erik O. Ahlgren, Long-term evolution of energy and electricity demand forecasting: The case of Ethiopia, Energy Strategy Reviews, Vol. 36(2021) 100671.

IV. Dawit H. Gebremeskel, Getachew Bekele, Erik O. Ahlgren, Long-term electricity supply modelling in the context of developing countries: The OSeMOSYS-LEAP soft-linking approach for Ethiopia, Energy Strategy Reviews, Vol. 45 (2023) 101045.

V. Dawit H. Gebremeskel, Getachew Biru Worku, Study on power distribution network automation to mitigate power outages, Journal of Ethiopian Engineers and Architects, Zede, ISSN: 0514-6216, 2017; Vol. 35: pp. 38-46.

VI. Dawit H. Gebremeskel, Interaction between distributed generation and the Addis Ababa distribution network, Journal of the Ethiopian Society of Electrical Engineers, 2013, 7th scientific conference on Electrical Engineering, CEE-2013.