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The Ethiopian energy sector and its implications for the SDGs and modeling

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ABSTRACT

The level and mix of energy supply and consumption have substantial roles in shaping the sustainable development pathway of a country. This is particularly important in developing regions where access to modern energy sources remains limited. This paper gives a narrative overview of the energy sector in Ethiopia. It presents the key historical trends and outstanding issues in the energy sector. It also explores the ways through which energy transition could support achieving the Sustainable Development Goals (SDGs) in the country. The review shows that energy supply and consumption in Ethiopia are dominated by bioenergy (88%) and by households (88%), respectively. Electricity barely accounts for 3% of the total energy supply although its generation has increased by more than four times between 2004/05 and 2018/19. Furthermore, the dominance of bioenergy source and households demand is projected to continue until the middle of the century. This study identifies research gaps, particularly, in terms of linking the energy sector with the rest of the economy and the environment using multi-sectoral economic models. Such advanced modeling is constrained by the lack of centrally coordinated energy data source among others. Creating an open platform that facilitates information exchange between energy planning institutions and academic researchers could be a crucial step in this regard.

1. Introduction

The energy mix has important implications as access to energy in shaping the sustainable development pathways of a given economy [1,106]. It is particularly important in countries like Ethiopia which heavily relies on solid biomass energy. Ethiopia has one of the lowest per capita energy supply and consumption [2,3]. About 56% of the total population have no access to any form of electricity [82]. About 95% of the electricity comes from hydropower [4]. Petroleum fuels are entirely imported and make up 10 to 14% of the spending for imports [4]. More than 90% of the households use solid biomass fuels for cooking [5,6]. These and other features reveal that Ethiopia lacks a modern, flexible, reliable, and affordable energy system that could withstand its fast-growing energy demand due to high growth rates of population, urbanization, and industrialization [7,8]. The existing energy system impinges on the quality of the environment in several ways. About 46% of the total greenhouse gases (GHG) emission from the land use change and forestry (LUCF) sector attributes to forest degradation due to fuelwood consumption [9]. Indoor air pollution is responsible to about 65,000 premature deaths [10] and nearly 5% of the national burden of disease [11]. The existing energy system is also susceptible to exogenous factors such as climate variability and oil price changes. Hydropower dams on transboundary rivers may aggravate the geopolitical concerns arising from the downstream countries [12–14]. The expansion of some of the energy sources (e.g., hydropower, biodiesel) may compete for agricultural resources (e.g., water, land) whereas other anticipated energy resources (e.g., domestic fossil fuel reserves) may induce further negative externalities on the environment.

Against this backdrop, Ethiopia urgently needs an energy transition that substantially raises the per capita energy supply while at the same time diversifying the energy portfolio. Energy transition in Ethiopia can be regarded as a subnational, national, regional, and global agenda. It is a subnational agenda as serving most rural Ethiopians depending on smallholder agriculture [15,16] requires deploying decentralized energy systems [17]. Energy transition is also a national macroeconomic issue. Firstly, reliable, and affordable modern energy supply is critically needed to realize the country's much-anticipated structural transformation leading to a middle-income status by 2025 [7,18]. Secondly, the energy sector accounts for 15 to 18% of the external public debts [19] while oil imports absorb more than 75% of the merchandise export earnings [4]. The energy transition in Ethiopia is also a regional and continental subject. First, Ethiopia is exporting electricity to its neighbors [4,20] thereby fostering regional economic integration [8,9]. Second, hydropower dams being built on transboundary rivers require regional cooperation on water management and use [13,14,21]. Energy transition is also one of the major topics in Ethiopia's international develop-

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ment and trade cooperation as it is linked with climate finance, loans and grants, foreign direct investment, and knowledge and technology transfers [19,22,82].

As such, for a meaningful policy impact, energy research in Ethiopia should aim to assess the implications of alternative energy pathways for the macroeconomy as well as for the environment. The existing literature is however both small and fragmented. What is available focuses overwhelmingly on the consumption of a specific fuel by a specific demand sector often excluding the interaction among different energy types and demand sectors as well as the feedbacks between energy and the macroeconomy. Overview studies that present the whole energy system in a unified frame are lacking. Such studies could depict the linkages of the energy sector with other economic sectors to inform energy policy formulation and implementation, and the choice of energy modeling approaches appropriate for the country's context.

This paper attempts to fill this gap. It gives a narrative overview of the Ethiopian energy system by compiling information on the country's energy statistics (resources, demand, and supply), and energy-economy modeling from academic and gray literature. First, it synthesizes the available evidence from peer-reviewed articles as well as from statistical, technical, project, and policy reports by relevant government agencies, funding or implementing international organizations. Second, it explores the possible ways through which energy transition could support the Sustainable Development Goals (SDGs) in Ethiopia. Finally, it identifies some outstanding research gaps that future research should consider in modeling the Ethiopian energy system.

This study contributes to the broader scientific and policy discourse on energy transition in developing countries [23–26], and to the growing literature on the interlinkages between energy and SDGs [27–30].

The remainder of the paper is structured as follows. Section 2 gives an overview of the energy sector in Ethiopia. Section 3 highlights how the energy transition contributes to achieving the SDGs in Ethiopia. Section 4 discusses the main gaps and the outlooks in modeling the Ethiopian energy sector followed by the conclusions in Section 5.

2. Overview of the energy sector

2.1. Energy resources

Ethiopia is endowed with various energy resources. These include hydropower, geothermal, solar, wind, biomass (fuelwood and agricultural wastes), fossil fuel reserves (natural gas, oil shale, and coal), and biofuels (ethanol and biodiesel) [8]. Ethiopia has an estimated hydropower potential of 45 GW, and unexploited reserves of natural gas (113 billion m^3), coal (300 million tons), and oil shale (253 million tons) [82,94]. The country has enormous potential in solar energy [31] which could support privatizing and decentralizing the electric power sector through off-grid and mini-grid technologies [17,82]. The increasing number of sugar factories [32,33] and the vast land suitable for growing feedstocks [34,35] represent considerable resource potentials for biofuels [8] which could serve as alternative fuels for transport and cooking services. With 77% of agricultural households raising cattle, there is a substantial potential for biogas fuel that could substitute several solid biomass fuels in up to 3.5 million rural households [36–38]. Table. 1 presents the summary of various indigenous energy resources in Ethiopia.

Endowments of such diverse indigenous energy resources represent ample opportunities to transit into clean and green energy sources. Nevertheless, as depicted in Table. 1, the energy resources remain largely unexploited mainly due to financial and technical constraints [8]. The two bioenergy sources, i.e., fuelwood and agricultural wastes are relatively exploited.

Table 1
Indigenous energy resources in Ethiopia [82].

Resource	Unit	Exploitable Reserve	Exploited Percent
Hydropower	GW	45	< 10
Solar	kWh/m^2/day	5.5	< 1
Wind power	GW	1350	< 1
Wind speed	m/s	> 6.5	–
Geothermal	GW	7	< 1
Woody bimass	Million tons	1120	50
Agricultural wastes	Million tons	15–20	30
Natural gas	Billion m^3	113	0
Coal	Million tons	300	0
Oil shale	Million tons	253	0

Notes: The exploitable reserve and exploited percent for agricultural wastes presented here are most widely cited figures. Nevertheless, this author believes that these estimates are rather outdated. For example, a recent study shows that the annual potential supply of agricultural wastes (crop residues and dung) is 55.4 million tons, out of which more than 60% is used as fuel [46].

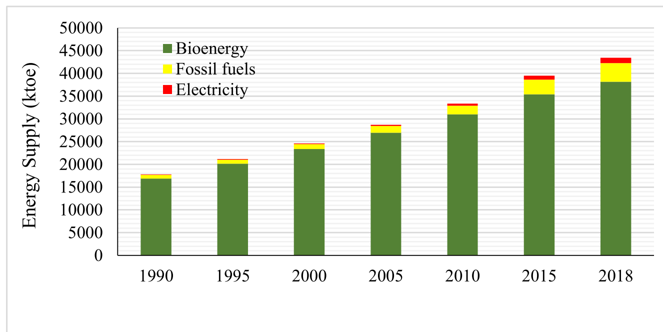

Fig. 1. Trends of energy supply in Ethiopia [2].

2.2. Trends of energy supply and demand

Per capita energy supply and consumption in Ethiopia are among the lowest in the world [2,3]. The per capita primary energy supply is about 0.4 toe compared to the global average of 1.9 toe [2] whereas per capita energy consumption is approximately 0.07 toe [3]. Ethiopia's energy system is also one of the least diversified systems even by the African standard [106]. Approximately 88%, 9.5%, and 2.7% of the total energy supply comes from bioenergy, petroleum, and electricity, respectively [2]. Fig. 1 presents the trends over the past three decades. Although the total energy supply has increased by 144% between 1990 and 2018, the per capita supply change (8%) in the same period was unsatisfactory [2].

In 2018, bioenergy contributed 38,142 ktoe energy of which 99% is consumed by the residential sector [2]. The consumption of fossil fuels, which has increased by 182% since 2005, was 4188 ktoe in 2018 [2]. It is shared among transport (54%), industry (31%), agriculture (4%), residential (2%), and services (2%). The electric power generation has grown by more than four times between 2004/05 and 2018/19 [4]. Fig. 2 depicts that hydropower continues to dominate the Ethiopian power system. The electricity consumption in 2018 is distributed across the residential (46%), services (27%) and industry (26%) [2].

All in all, energy consumption in Ethiopia continues to be dominated by the residential sector which accounts for 95% in 1990 and 88% in 2018 [2]. During the same period, the shares of industry and transport sectors grew, respectively, from 1.3 to 3.7%, and from 1.8 to 5.5% [2]. In contrast, as shown in Table. 2, the share of overall energy consumption in agriculture remains below 0.5% [2]. Agriculture in Ethiopia is virtually all rainfed smallholder that depends on animal and human power [16].

Table 2
Percentage distribution of final energy consumption by demand sector [2].

Year	Industry	Transport	Residential	Services	Agriculture	Others	Total
1990	1.28	1.82	95.26	0.89	0.21	0.54	16,769
1995	1.12	1.81	95.70	0.90	0.12	0.35	20,002
2000	1.27	2.24	95.01	0.97	0.16	0.35	23,391
2005	1.63	2.54	94.16	1.05	0.21	0.41	27,269
2010	2.03	2.82	93.38	1.07	0.24	0.46	31,494
2015	3.20	4.16	90.38	1.31	0.35	0.60	37,117
2018	3.72	5.53	88.19	1.42	0.46	0.69	40,717

Notes: The total consumption figures are in kilo tons of oil equivalent (ktoe). The 'Services' include commercial and public services while 'Others' include non-specified and non-energy uses.

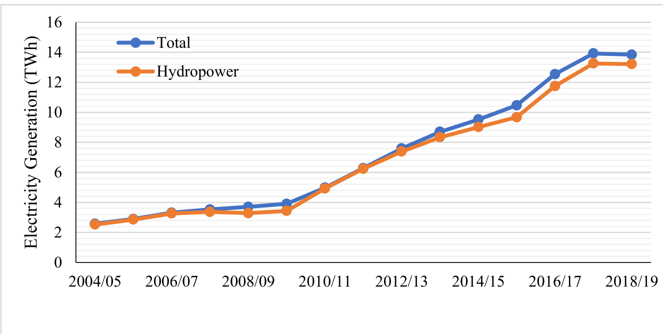

Fig. 2. Total and hydropower electricity generation in Ethiopia [4].

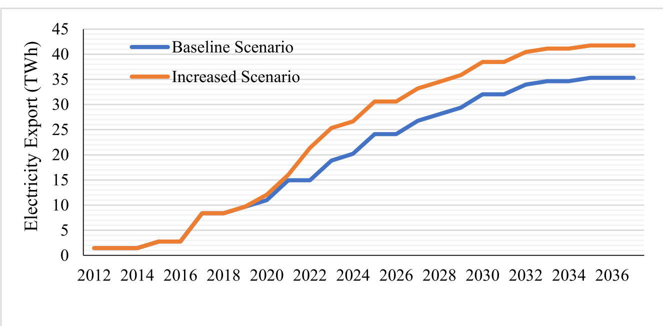

Fig. 3. Forecasted electricity export sales in Ethiopia [94].

A closer look at the energy consumption by demand sectors reveals that the transport (99.8%) and industries (86%) heavily depend on fossil fuels compared to the residential sector that meets 98% of its demand from bioenergy, and the services sector meeting its energy demand from bioenergy (50%), electricity (37%), and fossil fuels (14%) [2]. Foreign (or export) demand for electricity is a recent energy demand sector [82]. Fig. 3 shows, between 2012/13 and 2018/19, Ethiopia exported an average of 895 GWh electricity per year [4]. Electricity export is forecasted to reach to 35,303 GWh per year by 2037 [94].

Only 44% of the households in Ethiopia (33% to grid connections and 11% to off-grid technologies) have access to electricity [5,82]. The available off-grid technologies include solar lantern, solar lighting system, solar home system, mini-grids, and diesel generators which supports only very low-load appliances (e.g., task lighting, phone charging, and radio) in rural areas [5,82]. This could be one of the reasons as to why some studies indicate lower figures for households with access to electricity, for example, 35% in [39]. As such, Fig. 4 demonstrates, about 93% of Ethiopian households use solid biomass fuels for cooking [6]. This contributes to indoor air pollution which is responsible for 5% of the total burden of disease [11] and for about 3 million Disability Adjusted Life Years (DALYs) and 65 thousand deaths in 2016 [10].

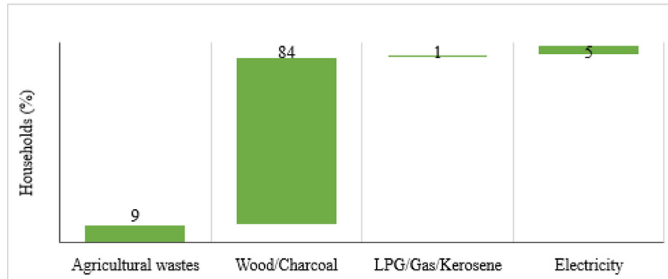

Fig. 4. Percentage distribution of households by cooking fuel type [6].

Table 3
Projected average annual growth rates of total and electricity energy demand in Ethiopia.

Energy	Time-horizon	Growth rate (%)	Source
Total	2000–2030	3.5	ERG [17]
Total	2010–2050	4.1–5.7	Senshaw [41]
Total	2009–2030	4.9	EEA [59]
Total	2012–2030	2.1	Mondal *et al* [44][44]
Electricity	2010–2050	6.0–8.4	Senshaw [41]
Electricity	2012–2030	9.7	Mondal *et al* [44]
Electricity	2012–2037	10.1–14.2	EEP [94]
Electricity	2009–2030	9.5–14.4	EEA [59]

2.3. Projected energy supply and demand

Ethiopia has one of the highest urban population growth rates (4.8%), and its total population is projected to reach 205 million in 2050 [15]. On the other hand, since 2010, Ethiopia has envisaged to become a middle-income country by 2025 [18] which would require annual GDP growth rates of 8–10% between 2015 and 2030 [7]. The projected population and economic dynamics of the country calls for long-term projections of energy demand and supply.

Notwithstanding the differences in the presumed socioeconomic scenarios, policy priorities, time-horizon, and the methods of projections, three main conclusions can be drawn from the small number of studies (summarized in Table. 3) providing long-term energy demand projections.

First, the total energy demand (in particular that of electricity and petroleum fuels) is projected to grow rapidly [41,44,94]. Second, the highest energy demand growth for these two modern energy fuels will come from the industry and transport sectors [41,44]. The energy consumption in these two sectors is projected to significantly increase in both absolute and relative terms [41,44,94] which also mirrors the anticipated structural transformation and urbanization [7]. For instance, the share of electricity consumption by the industries is forecasted to

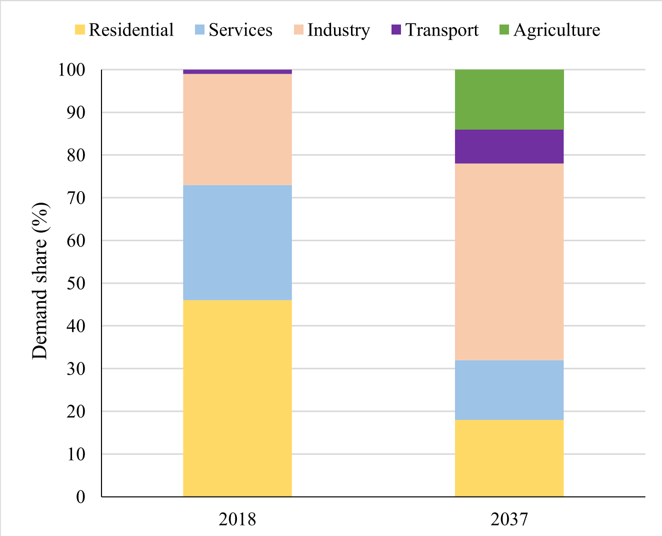

Fig. 5. Percentage distribution of current [2,42] and forecasted [94] electricity by domestic (excluding export) sectors.

increase from its 26–30% share in recent years [2,42] to 46% in 2037 [94]. See also Fig. 5 A notable growth in electricity demand is also expected in the agricultural sector which currently consumes close to zero electricity [94]. Third, all available projections show that the historical trends (households as the main consumer of energy, biomass as the main source of energy, and hydropower as the main source of electricity) will continue until, at least, the middle of the century [41,44,94].

2.4. Key energy sector issues

Energy poverty (or the lack of adequate, affordable, reliable energy sources) remains the main challenge for the Ethiopian energy system [8]. Ethiopia is placed at 101 out of 108 countries in terms of its ability to provide sustainable energy [43] with inadequate per capita electricity consumption (100 kWh/year) even by the sub-Saharan Africa (521 kWh/year) standard [8,42]. Energy poverty in Ethiopia of course reflects the country's population distribution (78% of the population residing in rural areas) and level of economic development (per capita income of approximately US$ 1000) [4].

Energy inefficiency is another outstanding issue in the sector [8]. The efficiency problems are attributed to the poor design of electricity transmission and distribution infrastructure [41], to the obsolete and inefficient industrial and transport technologies [9], and to the households' reliance on inefficient cooking stoves and light bulbs [5,44]. Electricity lost during transmission and distribution was estimated to be approximately 23% in the 2010s [40,41] which is expected to decline but still around 14% in the 2030s [40,94]. Only about 25% of electrified households use efficient lighting bulbs [44]. Tube lamps and compact fluorescent lamps are respectively 30% and 70% more efficient than the incandescent bulbs which are widely used in Ethiopia currently [44]. Likewise, only 18.2% of the households use manufactured cooking stoves [5]. Improved cooking stoves (ICS) could save energy by 20–67% compared to traditional stoves [44].

Energy insecurity, which arises from the lack of diversified energy system, is another major issue. Ethiopia has one of the least diversified energy systems in Africa [43,106]. The country's excessive focus on hydropower is a topic of debate amid the growing climate-related risks and geopolitical concerns [12, 21]. The consumption of fuelwood has already exceeded the sustainable woody biomass yield in 335 out of the 500 districts covered by the Woody Biomass Inventory and Strategic Planning Project in 2000 [45]. Even under improved electrification scenarios, the 201 of the 779 districts and large towns may face biomass resource deficiency by 2030 [46]. International price volatilities represent another source of energy insecurity. Ethiopia depends entirely on imported petroleum fuels while imported technologies account for 60 to 100% of renewable energy project costs [8,44]. Moreover, the expansion of large-scale energy infrastructure projects hinges on a timely availability of international loans [8,19] and grants [38] affecting energy production plans.

Dealing with the foregoing and other energy-related challenges requires strong institutions [8]. Looking at the palpable efforts in terms of energy policy and strategy formulations in the past two decades, one may argue that the Government of Ethiopia recognizes the essential role of the energy sector to achieve the country's economic ambitions [8,9,38]. The existing energy policies are however fragmented and internally inconsistent mainly focusing on the short-term challenges [41]. This could be partly explained by the prevailing limited human, technical, and institutional capacities needed to properly deal with the current and future national and international dynamics relevant to the energy sector [8,47]. For instance, the mandate (and hence providing information) on the status of different energy resources is scattered across different agencies some of which (e.g., sugar factories that could produce electricity and ethanol as co-products) may not even consider themselves as actors in the energy sector. The limited institutional capacity is further complicated by the loss of institutional memories due frequent changes in the names, structures, and mandates of different ministries and agencies relevant to the energy sector. The case of three institutions worth mentioning here. First, energy was once placed under the Ministry of Mines and Energy [47], and later under Ministry of Water and Energy [8]. In the past decade, the latter has restructured itself into "Ministry of Water, Irrigation, and Electricity" and to the "Ministry of Water, Irrigation, and Energy", and then back to the "Ministry of Water and Water" in 2021. Second, since 2013, the power sector reform distributes regulatory, generation, and distribution mandates among the Ethiopian Energy Authority, Ethiopian Electric Power, and Ethiopian Electric Utility, respectively. Third, between 2011 and 2021, the government agency concerned with environmental issues (and thus fuelwood) changed from "Environmental Protection Authority" to the "Ministry of Environment and Forest" to the "Ministry of Environment, Forest and Climate Change", and then to the "Environment, Forest and Climate Change Commission" under the Prime Minister Office, and then very recently renamed back to the "Environmental Protection Authority". Taken together, the country still needs to put remarkable efforts to build its institutional, human, and technological capacities and memories to be able to effectively deal with those outstanding and emerging challenges, and grasp the opportunities to the energy sector in general [8,47].

These energy access, efficiency, security, and institutional issues will be of particular interest in the future considering the increasing size of population [15], anticipated economic growth and structural transformation [7], low level of foreign currency reserves [4], mounting public debts [4,19], and climate change and other global trends with important implications for the energy sector [8].

The climate-energy interaction in Ethiopia deserves special attention due to the dominant role of hydropower in the current and planned energy systems. First, climate change and weather variability could undermine the yearly hydropower generation capacity [48,49], and increase the inter- annual and inter-seasonal variability of electricity production [48]. Run-of-river plants and reservoir plants are in general susceptible to low precipitation (or drought) and to increasing temperature (or evaporation), respectively. Run-of-river power plants accounts for 15% and 30% of installed capacity of the existing and committed hydropower plants, respectively [12,20]. Some recent studies projected that climate change may adversely affect water resources, for example, in Abay and Awash basins [50,51], which together account for 23%, 67%, and 55% of existing, committed, and planned installed hydropower capacity, respectively [12,20]. Second, climate change could intensify the competition between irrigation and hydropower for water resources [40,52].

On the one hand, more irrigation would be needed to offset agricultural productivity losses due to climate change [52]. On the other hand, even without considering climate change, electricity for irrigation is where the country anticipates one of the highest demand growths relative to the current level of consumption [53,94]. Electricity demand forecasts show that the electricity demand from planned large-scale irrigation schemes may increase from zero in 2012 to 12,684 GWh (14% of the total) in 2030 [94]. See also Fig. 3.

The discussion in this section implies that a transition in the country's energy system is critically needed [8,9]. The country is of course striving to increase and diversify its energy supply [8,17]. Transition from traditional to modern fuels [8], and ensuring universal access to electricity by 2025 [82] are at the heart of the current energy policies and strategies. Emphasis has been given to increasing renewable electricity generation capacity and leapfrogging to energy-efficient technologies in transport and industry infrastructure to realize the country's Climate-Resilient Green Economy [9] and Nationally Determined Contribution [22] strategies aiming to mitigate and adapt to climate change.

That being said, however, the country should still need to undertake more concrete actions to tap its vast renewable energy potential from non-hydropower sources. This would help to build a flexible power system that could cope with climate-related risks, and lessen the environmental and geopolitical concerns, the competition between electricity and irrigation for water, and the upfront investment expenses that arise with hydropower plants [12, 21, 49]. More research is needed on the long-term energy mix, supply, and demand projections to underpin energy transition planning and management which is adaptable to the already observed as well as anticipated national and global changes. Energy planning institutions need to regularly incorporate changes affecting the energy system and revise energy demand and supply projections accordingly. For instance, the Ethiopian Power System Expansion Master Plan forecasted the share of industry in total domestic (i.e., excluding export) sales of electricity to grow from 36% in 2012 to 50% in 2015, and then decline to 46% in 2037 [94]. It also predicted that irrigation (agriculture) would begin using electricity in 2015 to account for 4.3% of the total forecasted domestic electricity consumption in the same year [94]. Contrastingly, the latest energy statistics shows that the share of electricity consumption in the industries declined from about 40% in 2014 to less than 30% in 2018 with no consumption reported for agriculture to date [2,42]. This of course might be due to delays in the construction of the hydropower plants [54], and hence industries are experiencing electricity supply shortages [55, 56]. It could also be explained by the fact that the relative shares of irrigated agriculture and manufacturing sectors in the overall economy are not growing as stipulated in the economic plans [7,18]. In any case, it is important to regularly adjust and update the projections as soon as major deviations from initially presumed trajectories are observed, and therefore to continuously strengthen the capacity of energy institutions to be able to do so [8].

3. Linkages between energy transition and the SDGs

Broadly speaking, energy transition involves a change within an energy system, usually to a particular fuel source, technology, or prime mover [57]. Energy transition can also be regarded as energy system change, i.e., a change in the constellation of energy inputs and outputs, involving suppliers, distributors, and end-users along with institutions of regulation, conversion, and trade [58]. In countries like Ethiopia, energy transition is often associated with moving up the energy ladder [59]. In this study, we refer to energy transition as energy system change that involves increasing the per capita energy supply, diversifying the total as well as end user-specific energy sources, and promoting decentralized energy systems that would substantially increase the role of private sector and local actors. Seen in this way, energy transition directly or indirectly underpins almost all of the SDGs [1,82]. Table. 4 tries to establish and explore the linkages between the energy transition and the SDGs in the Ethiopian context.

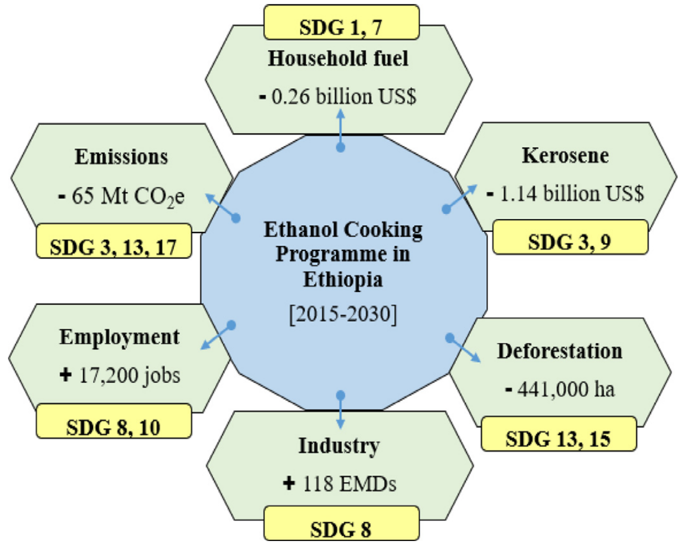

Fig. 6. Expected co-benefits from the Ethanol for Cooking Programme (ECP) in Ethiopia and their linkages with the SDGs. The values are undiscounted aggregate benefits over 15-year time horizon (2015–2030). The Ethanol Micro Distilleries (EMDs) enterprises are assumed to obtain molasses from sugar factories which is abundant currently [84, 32]. Source: Author's illustration based on data from [33].

Despite being small in its scale, the Ethanol for Cooking Programme (ECP) in Ethiopia (2015–2030) provides a good case to illustrate the linkages between energy transition and the SDGs. The ECP estimated that a total of 1,710,988 households (1,406,201 urban and 304,787 rural) will substitute ethanol for firewood, charcoal, or kerosene as cooking fuel between 2015 and 2030 [33]. If the implementation is going as planned, over a period of 15 years, Fig. 6 depicts that the ECP could reduce household energy expenditure (by US$ 0.26 billion), spending on kerosene imports (by US$ 1.14 billion), deforestation (by 441,000 ha), and GHG emissions (by 65 Mt CO_2e) [33].

4. Energy sector modeling: gaps and outlook for future research

4.1. Energy sector modeling: a brief note

Energy sector models provide important insights to policy and decision makers regarding energy demand and supply, least-cost energy technology mix, investment and financial requirements, and the synergies and trade-offs of energy sector development [41,44]. Energy models have become increasingly important when we consider the effects of energy consumption on the environment and climate change [60, 61].

Energy models can be classified on the basis their purpose, sectoral and geographic coverages, model structure, analytical approach, methodology, and time horizon [61]. Irrespective of the criteria or parameter used to classify, all energy models have their own relative strengths and weaknesses [62, 63]. Therefore, in practice, the choice of a model is usually determined by the contexts of the economy being studied, the purpose of the study, and data requirements and availability. Energy models for developing countries should particularly be tailored to their unique structural (energy, geographic, macroeconomic) features [64, 65].

Therefore, the discussions on the basic features of the energy sector (in Section 1), and how its transformation would support various SDGs (in Section 2) seek not only to inform energy sector planning and policy making but also provide a background to stipulate appropriate energy-wide, energy-economy, or energy-economy-environment modeling ap-

Table 4
The linkages between energy transition and the SDGs in Ethiopia.

SDG	SDG Targets	The situation in Ethiopia	How could energy transition support the SDG?	Evidence regarding the linkages
7	*7.1, 7.2, 7.a, 7.b*	• One of the least diversified energy systems in Africa [106] • Solid biomass fuels and electricity accounts for 88% and 3% of energy supply [2] • Low per capita electricity consumption, 100 kWh/year [42] • Only 33% of the households have access to grid connections [82]	• Increase per capita electricity supply • Increase the share of modern, clean, and decentralized energy sources • Improve energy security	• MoWIE [82] • Sterl *et al* [21] • Pappis *et al* [12] • EREDPC [38]
1	*1.2, 1.4*	• The national, rural, and urban poverty headcount ratios in 2015/16 were 23.5%, 25.6%, and 14.8% [83] • Urban unemployment rate is not showing a sign of decline, e.g., 18.7% in 2020 [81]	• Diversify employment opportunities • Broaden tax-base • Improve productivity and competitiveness • Increase farmers' share of agricultural value addition	• Borgstein *et al* [53] • MoWIE [82] • FDRE [9]
2	*2.1, 2.3, 2.4*	• About 37%, 21%, and 7% of children under age 5 are stunted, underweight, and wasted [39] • Using agricultural wastes for fuel compromises soil nutrients [71] • Using dung and crop residues for fuel could forgo about 2% of crop output [45] • Using dung for fuel could reduce agricultural GDP by 7% [85] • Crop residues make a third of animal feed [16]	• Leave agricultural wastes to enrich soil nutrients • Slurry from biogas production as fertilizer • Power for irrigation & food storage facilities • Fishing on hydropower reservoirs, e.g., Tekeze dam	• Negash *et al* [71] • Srivastava *et al* [86] • Jagisso et al [87]
3	*3.4, 3.9*	• Indoor air pollution is responsible for 5% of the total disease burdens [11] • About 3 million DALYs and 65 thousand deaths attributable to indoor air pollution in 2016 [10] • Many health facilities (30% of the hospitals, 72% of the health centers, and 95% of the health posts) have no access to adequate and reliable electricity [82]	• Reduce indoor air pollution & health expenditure • Improve health service quality • Improve nutrition	• Downward *et al* [88]
4	*4.1-4.6*	• About 80% of the rural households uses kerosene lamps, candle, or firewood for lighting [46,89] • Many schools (76% of the primary schools, and 30% of the secondary schools) are not connected to electricity [82] • Children spend considerable time to collect fuelwood [90,47]	• Improve study time & habits of school children • Improve quality of education through reliable electricity to schools	• Lam *et al* [91] • Gaye [92] • Nankhuni and Findeis [93]
5	*5.4*	• Hardly 7% of the households in Ethiopia use electricity for cooking [39] • Women spend considerable time to collect solid biomass fuels [90,47] • Poverty rates are relatively high among female-headed households [82] • Women show less willingness to pay to clean energy sources [5]	• Reduce indoor air pollution & improve women's' health • Improve women's time spent on income generating (productive) activities • Improve women's access to energy to generate extra income	• World Bank [5]
8	*8.1, 8.2, 8.4, 8.6*	• Shortage of electricity is the first major reason for not being fully operational in 24% of the large & medium scale manufacturing industries [55] • Shortage of electricity is the first major reason for not being fully operational in 36% of the small-scale manufacturing industries [56]	• Enhance labor productivity & operational capacities of existing industries • Create new economic & employment opportunities; Reduce petroleum imports • Diversify export portfolio • Dampen the public debts required for energy infrastructure	• Kebede and Heshmati [95] • Borgstein *et al* [53] • Pappis *et al* [12]

(*continued on next page*)

Table 4 (*continued*)

SDG	SDG Targets	The situation in Ethiopia	How could energy transition support the SDG?	Evidence regarding the linkages
9	*9.1, 9.2, 9.4, 9.a*	• Private enterprises are highly encouraged to take part in biogas and biofuel sectors [38] • Expansion of power interconnector infrastructure in the Eastern Africa Power Pool [20] • Ethio-Djibouti Railway using electricity [94] • Lowland regions have limited access to electricity and manufacturing industries [55,56,94] • The power sector is open to Private-Public Partnerships and Independent Power Producers [82]	• Avail affordable & reliable energy (inputs) to industries • Help the renewable energy technology value chain to emerge as an industry by its own	• Negash and Riera [77] • Shete and Rutten [67] • Mondal *et al* [40] • Kruger *et al* [54]
10	*10.1, 10.3, 10.b*	• Poor households heavily depend on biomass fuels and traditional cooking stoves [5] • Only 8.5% of rural households (compared to 93% in urban areas) have access to electricity [6] • Access to electricity varies across administrative units [89,94]	• Affordable energy to poor households • Distributed energy systems to remote villages and pastoralists • Efficient allocation of labor & capital across regions/sectors	• Fried and Lagakosb [96]
11	*11.2, 11.6*	• High urbanization rate [15] • Poor municipal solid waste management practices [97]	• Expand economic activities • Improve productivity • Support urban rail transport (e.g., Addis Ababa) • Municipal waste to energy	• DiBiCoo [98] • Gabisa and Gheewala [75]
12	*12.5, 12.c*	• Most of the molasses from sugar factories is dumped [84] • Petroleum fuel subsidies are common [47]	• Incentive to use molasses to produce ethanol • Electricity co-generation from bagasse	• EAPP [20] • ESC [32]
13	*13.2*	• LUCF sector accounts for 41% of the total GHG emissions in which fuelwood consumption is the single largest driver [22] • Expanding electricity generation from renewable sources of energy, and leapfrogging to modern and energy-efficient technologies are the two (of the four) pillars of the green economy component of the CRGE Strategy [9] • The NDC aims to cut GHG emissions by 68.8% in 2030 compared to the BAU scenario [22]	• Clean transport/cooking fuels (e.g., electricity, biofuel, biogas) • Complement fuel-efficient cooking stoves and electric equipment	• EEP [94] • Mengistu *et al* [99] • Portner *et al* [34] • Mondal *et al* [40]
15	*15.3, 15.5*	• At least, one third of fuelwood comes from unstainable extraction [100]	• Replace biomass fuels • Replace fuel inefficient stoves	• Gaia Association [33] • Wassie and Adaramola [101]
17	*17.3-17-7, 17.9*	• The gross domestic saving (21% of the GDP) falls short of the investment demand (31% of the GDP) [4] • About 55% of the investment to implement the CRGE's green economy plan (2011–2030) is denominated in foreign currency requiring large international capital inflows [9] • Power sector development in line with the CRGE plan requires about US$ 2 billion per annum [9] • About 80% of the US$ 316 billion needed to implement the NDC is expected from international sources [22] • Implementing the NEP between 2019 and 2025 requires US$ 1.33 billion net forex [82]	• Give access to climate finance • Attract FDI & improve trade balance • International loans & grants • Foster regional economic & environmental cooperation	• DEA [102] • Kruger *et al* [54] • Energiekooperation [103] • Lema *et al* [104] • Sterl *et al* [21]

proaches that could accommodate the current and anticipated energy, economic, and environmental conditions in the country. Accordingly, four particular features of the Ethiopian energy system are worth noting.

1. Per capita energy production and consumption is very low. This calls for significant investment in the energy sector which is inherently capital intensive. Given the structural features of the country (i.e., high public debts, trade balance deficits, low saving rates, and low per capita income), the opportunity costs of public investments on the energy sector cannot be ignored.
2. The energy system is susceptible to several exogenous shocks such as to climate variability, international petroleum, and technology price volatilities.
3. The energy system is highly interlinked with the macroeconomy and the environment. It interacts with the environment through fuelwood, soil fertility, hydropower, air pollution, and GHG emissions. It interacts with the macroeconomy through productivity, domestic and foreign investments, foreign currency demand, and trade and fiscal balances.
4. Energy resource varieties, endowments, access, and demand (as represented by population and economic densities) highly vary across geographic and administrative regions of the country. There are, for example, vivid regional variations in using agricultural residues as fuels [46], in the consumption of fuelwood relative to sustainable biomass yields [45], in the feasibility of wind and solar energies [17], and in the distribution of population [69] and economic activities [16,55,56].

These and other features of the energy sector entail both synergies and trade-offs between energy transition and other development goals. On the one hand, as already presented in Table. 4, energy transition in general underpins almost all of the SDGs. On the other hand, however, hydropower and bioenergy crops may compete for agricultural resources such as water, cropland, and pastureland. Ethiopia has an estimated 23.3 and 0.7 million ha of land suitable for growing *jatropha curcas* (for biodiesel) and sugarcane (for bioethanol), respectively [66]. A total of 1.5 million ha of land were leased to 34 investors for biodiesel feedstock production most of which unfortunately ended with bankruptcy [67] but displaced thousands of local smallholder agro-pastoralists, created conflict over water and land resources, and kept thousands of hectares of land out of production [68].As such, to provide a meaningful insight to energy planning and policy formulation, energy research and models for Ethiopia should depict the whole energy system and capture its interactions with the macroeconomy and the environment as much as possible while recognizing the tradability of the sector, and the inter-regional variations. This is however missing in the existing literature.

4.2. Energy research and modeling in Ethiopia: a brief review

The extant energy research in Ethiopia can broadly be classified into micro-, meso-, and macro-level studies. The micro-level studies focus on households' fuelwood consumption [70–72] and electricity [73, 74] using various econometrics techniques. Despite dealing with the detailed aspects of demand, household-level studies cannot capture general policy or market interactions [60]. Meso-level studies in their part focus on a specific energy sources but at national level such as on solid biomass [45,46,75], on biofuels [76, 77, 35], on biogas [36, 37], on solar and wind [78,79,105], electricity [12], and on hydropower [48, 80]. Most of these meso-level studies focus on the supply side. Macro-level studies on the other hand include sector-wide studies that provide long-term supply and demand projections considering multiple fuel types. There are only a few studies that fall in this category. Some of the macro-level studies are summarized in Table. 5 followed by a brief discussion of their important implications for future research and policy making.

Table 5
Summary of selected methods applied in providing long-term energy projections in Ethiopia.

Source	Time-horizon	Method	Focus
EEA [59]	2010–2030	Sector-specific demand equations	Population and economic growths as drivers of future energy demand
EEP [94]	2012–2037	Sector-specific demand equations	Forecasting future electricity demand
ERG [17]	2000–2030	LEAP	Solar and wind energy resource potentials
Senshaw [41]	2010–2050	LEAP	Population and economic growths as drivers of future energy demand
Mondal *et al* [44]	2012–2030	LEAP	Policy priorities (of improved cookstoves, efficient lighting, and universal electrification) as demand drivers
Mondal *et al* [40]	2015–2045	MARKAL	Alternative electricity supply strategies
van der Zwaan *et al* [49]	2010–2050	TIMES-ECN	Prospects for hydropower
Pappis *et al* [12]	2015–2065	OSeMOSYS	Alternative electrification pathways

EEA [59] projects future energy demand using sector-specific demand equations. The report considered economic and population growths as the main drivers assuming constant energy intensity and consumption coefficients. Likewise, EEP [94] forecasts future demand using sector-specific demand equations but focusing only on electricity. Another class of studies applied the Long-range Energy Alternatives Planning (LEAP) accounting model to simulate long-term energy demand under alternative energy policy priorities [44], anticipated economic growth scenarios [41], and solar and wind energy potentials [17]. The third class of studies provides long-term energy supply and demand projections using optimization (or cost minimization) models. Pappis *et al* [12] establishes a soft-link between an Open-Source energy Modelling System (OSeMOSYS) and an Open-Source Spatial Electrification Tool (OnSSET). OSeMOSYS is a whole-system cost-optimization model of the electricity system whereas OnSSET is a geospatial electrification model. Pappis *et al* [12] advances the Ethiopian power system modeling as it considers the spatial dimension of future electricity connections. Mondal *et al* [40] used the MARKet ALlocation (MARKAL) model to assess alternative long-term electricity supply strategies. Van der Zwaan *et al* [49] went a step further particularly focusing on the prospects for the hydropower sector under climate change using the TIMES Integrated Assessment Model of the Energy research centre of the Netherlands (TIAM-ECN) which is essentially a global model.

Previous studies applying energy-wide models are therefore dominated by bottom-up approaches. Most of the studies did not account the regional variations in terms of energy resource potentials and demands. Pappis *et al* [12] is exceptional in this regard although its scope is limited to the residential electricity demand. The feedback effects between energy system and the macroeconomy are scarcely researched. These indirect and induced effects will be significant as energy accounts for 17% of the external public debts [19], and for 12% of import spending [4] whereas imported technology (e.g., transformers, turbines, generators) accounts for at least 60% of the renewable energy project costs [19,40] in a country where foreign currency reserves and public budgets are scarce [4].

4.3. Outlook for future research

Put altogether, energy models for Ethiopia should be able to deal with energy equity, security, and sustainability by gauging the feedback effects, financial and technological constraints, and regional differences as much as possible. Future research particularly using economy-wide models is required to capture the general equilibrium (indirect and induced) effects of energy transition. Such models usually allow assessment of the synergies and the trade-offs of alternative energy pathways. Multi-sectoral economic models such as computable general equilibrium (CGE) models can help to compare alternative development pathways – investment in energy infrastructure against investment in other sectors – in terms of their overall development outcomes. Such models are also suitable to assess the economy-wide effects of parallel developments in the energy and other sectors as they allow simultaneously modeling multiple scenarios and shocks.

Not only in academia but also relevant government agencies should strive to build and possess a variety of in-house and publicly available energy system models. However, the lack of systematic practice of collecting energy statistics in the country [8,59] is one of the major inhibiting factors to developing and applying large-scale energy-economy models. This issue could be resolved by creating and curating a comprehensive national energy database [75, 41]. Coordinating and harmonizing the existing efforts which are scattered across sectors could be a starting point. Accordingly, it is necessary to establish open platforms (and communication protocols) to facilitate information exchange between energy planning institutions, and local (and international) academic institutions working on energy statistics and modeling. This helps to address data limitations while at the same time strengthening the science-policy interface. The need for central coordination is particularly important in light of the current fragmented practices of estimating and reporting energy sources by different agencies, the emergence of decentralized energy resources such as biogas and solar off-grid technologies that are usually operated by household units, and the need to attract more private sector involvement.

5. Conclusions

This paper attempted to give an overview of the Ethiopian energy sector in terms of its resource varieties and potentials, and the historical and projected energy demand and supply mixtures. It then draws on this sector overview to discuss the implications of energy transition for achieving the SDGs, and to identify some prevailing gaps in energy sector modeling.

The per capita energy supply and consumption in Ethiopia are among the lowest in the world. Long-term energy projections show that energy demand in the industry and transport sectors will increase rapidly. It can be argued that the current energy system is unlikely to adequately satisfy the projected energy demand in different sectors. This calls for energy transition to be one of the highest policy priorities in the country. Universal access to electricity especially in rural areas (for households and agricultural activities) could substantially contribute to reduce poverty. The provision of reliable electricity to industries and services could help to realize the long-awaited structural transformation in the country. The potential benefits of energy transition in Ethiopia also transcend boundaries as they entail economic (e.g., electricity) and environmental (e.g., GHG emission reduction) co-benefits to the neighboring countries connected through the Eastern Africa Power Pool (EAPP).

Future research should aim to disaggregate energy supply and demand (by sources, technologies, demand sectors, and regions), to better represent the interactions between energy and the macroeconomy, and to contribute to building a consistent and comprehensive national energy database. Disaggregated energy models give the flexibility to accommodate policy changes related to the SDGs, and to soft-link energy model results with SDG-specific modules.

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Declaration of Competing Interest

The author declares no conflict of interest.

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