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Projecting Ethiopia's energy future to 2060: scenario analysis of demand, electrification, and GHG emissions using the LEAP model

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Abstract

Despite Ethiopia's abundant renewable energy resources, the country continues to face challenges in balancing growing energy demand and ensuring equitable access to modern energy services and climate goals. This study employs the Long-range Energy Alternatives Planning System (LEAP) to project Ethiopia's energy pathways from 2022 to 2060 under the Business-As-Usual, Universal Electrification and Efficiency, High Economic Growth, and High Urbanisation Growth scenarios. The model incorporates historical demand data, socioeconomic trends, electrification levels, and appliance penetration, particularly cooking, baking and lighting technologies.

Results show significant increases in energy demand across all scenarios, with the household sector showing the largest absolute growth. Energy demand is projected to reach 6478 PJ and 6960 PJ by 2060, under the BAU and HEG scenarios, respectively. Conversely, the UEE scenario predicts a slower growth in demand, limiting it to 5660 PJ due to energy efficiency interventions. GHG emissions are expected to rise from 40.7 MtCO2e in 2022 to 214 MtCO2e under BAU and 232.5 MtCO2e under HEG by 2060, underscoring the climate trade-offs of growth pathways. These findings underscore the importance of scenario-based planning for strategic energy and climate policy. The study highlights the need for robust demand-side interventions and targeted electrification strategies aligned with Ethiopia's sustainable development and climate goals.

Keywords LEAP model, Ethiopia energy pathways, Energy demand, Sustainable energy transitions, Scenario analysis, GHG emissions mitigation, Urbanisation-energy nexus

Introduction

Ethiopia faces two major energy challenges: limited access to modern energy services and a heavy dependence on traditional biomass to meet growing energy demand. Despite rapid economic growth, annual GDP growth ranging from 6.7% to 10.8% between 2010 and 2022 (World Bank, 2024), sustaining this growth lagged, with traditional biomass still providing 86.1% of the country's total energy demand in 2022 (MoWE, 2024).

The continued use of traditional biomass alarms both indoor air pollution and deforestation. Although electrification has improved, but remains uneven. National electrification stood at 44%, with 33% of the population connected to the grid and 11% served by off-grid solutions in 2018 (MOWIE, 2019). Access has increased to 52% in 2021, largely through off-grid expansion (MoWE, 2024). Yet, only 26.7% of rural residents had electricity compared to 96.2% of urban residents (MoWE, 2024). The National Sustainable Energy Development Strategy (N-SEDS) aims to raise rural access to 72.3% and urban access to 96.2% by 2030 (MoWE, 2024). Yet, at

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the current pace of electrification, achieving this target appears highly challenging.

As the most populous country in East Africa, Ethiopia's population growth, urbanisation, and industrialization, drive the rising energy demand, reaching 1811 PJ in 2022 (Tahiru et al., 2023). Meeting this growing energy demand and supporting continued economic development will require substantial investment in the energy sector (FDRE, 2015), to position Ethiopia as the regional energy exporter beyond universal electrification. Scenario-based modelling can inform the goals by projection energy demand tailored to its unique context. To inform the goals and support long-term energy planning, modelling tools have long been used globally (Bai et al., 2024; Ouedraogo, 2017). However, Ethiopia lacks an institutionalised modelling framework capable of producing long-term, scenario-based projections tailored to its context. In Ethiopia's Power System Expansion Master Plan used regression analysis and scenario-based forecasting (Gebremeskel et al., 2021); the Ethiopian Economic Association (2009) employed macroeconomic variables and energy demand coefficients to project energy needs from 2008 to 2030; the National Sustainable Energy Development Strategy projected demand through 2030 based on demographic and industrial trends (MoWE, 2024), while the Ethiopian Electric Power uses econometric analysis to correlate electricity demand with GDP (EEP, 2024).

Several studies have applied LEAP or similar tools in Ethiopia: Yalew (Yalew, 2022) summarised projections from LEAP and compared them with other projections using other methods (e.g., MARKAL, TIMES, or OSeMOSYS), whereas Gebremeskel et al. (Gebremeskel et al., 2021) used LEAP to highlight how urbanization, economic growth, and policy interventions shape electricity demand and underscore the importance of long-term forecasting. Similarly, Eludoyin et al. (Eludoyin, et al., 2021) applied a mixed-methods approach with LEAP to analyse residential electricity demand. Mondal et al. (Mondal et al., 2018a) focused on short-term energy efficiency gains, while Hailu et al. (Hailu et al., 2024) used regression analysis to project demand through 2052 across multiple economic growth scenarios. The Balmoral model, used in the 2022 Ethiopian Energy Outlook, emphasizes technical and economic analysis but lacks focus on key policy scenarios (Lastname, et al., 2022a).

Despite this progress, gaps remain in Ethiopia's energy modelling efforts. Existing literature tends to disaggregate energy demand by broad sectors: industry, agriculture, transport, and services, without incorporating regional or household-level dynamics, overlooks sub-national trends such as urbanization patterns and household growth, and relies on short- to medium-term horizons. Notably, most prior research has been tied to the NEP goal of achieving 100% electrification by 2030, often assuming similar progress rates for rural and urban areas and relying on outdated policy frameworks, whereas, National Sustainable Energy Development Strategy (N-SEDS, 2024–2030) targets 96.2% electrification in urban and 72.3% in rural areas by 2030 (MoWE, 2024).

Ethiopia's sectoral electricity demand underscores emerging pressure. In 2023, total electricity demand was 12,233 GWh (EEP, 2024). Similarly, the domestic sector's energy consumption surged from 508 GWh in 2001 to 6023 GWh in 2023, comprising 39.40% of the total demand. The low voltage (LV) industry demand increased from 276 GWh in 2001 to 2510 GWh in 2023 (EEP, 2024), signalling an expanding small-scale industry.

This paper addresses these gaps by aligning with the N-SEDS targets and offering a more contextually relevant four-demand scenarios incorporating urbanization, economic growth, and efficiency measures. Additionally, a novel contribution of this study is the incorporation of electric cooking and baking appliances, significant electricity loads in the household sector, and lighting efficiency improvement measures into the modelling process. Methodologically, using LEAP, we provide long-term scenario-based pathways from 2022–2060 to support the transition toward sustainable energy development.

Methodology

This section outlines the modelling framework, data sources, assumptions, and structure used to project Ethiopia's long-term energy demand from 2022 to 2060 using the Long-range Energy Alternatives Planning (LEAP) system.

Modelling framework

The LEAP model, developed by the Stockholm Environment Institute (Charles Heaps & "LEAP, 2024), was employed to simulate Ethiopia's future energy demand and associated greenhouse gas (GHG) emissions under four alternative scenarios: Business-As-Usual (BAU), Universal Electrification and Efficiency (UEE), High Urbanization Growth (HUG), and High Economic Growth (HEG). For long-term energy planning and policy analysis, several modelling tools are available, such as LEAP, Balmorel, MARKAL/TIMES, PRIMES, and MESSAGE. Each has a unique advantage and limitations.

MARKAL/TIMES offers flexible time slicing for detailed optimisation studies, high temporal and techno-economic detail (Connolly et al., 2010); however, intensive data requirements and suitability for household-level demand studies are its limitations. PRIMES is suitable for simulating policies within an equilibrium framework and detailed policy modelling (Ringkjøb et al., 2018). It has restrictions of complexity, flexibility for incorporating fine-grained sectoral or household data, and a lack of global transparency. MESSAGE offers techno-economic detail and includes modules for demand elasticity (Huppmann et al., 2019) (Painuly, 2022); however, less suited for national-level policy scenario development in data-constrained contexts and is primarily designed for large-scale studies (Connolly et al., 2010). Balmorel is a bottom-up, partial equilibrium energy systems model for optimizing electricity and combined heat and power systems for hourly electricity dispatch and market analysis, and is not intended to capture household-level energy dynamics (Liegl et al., 2023; Wiese et al., 2018).

LEAP, in contrast, is relatively a user-friendly that can be handled by different analysts, and well suited for national, local, and multi-regional energy projections and strategy development (Akpahou et al., 2024; Amir et al., 2022; Ates, 2015; Charles Heaps & "LEAP, 2024; Gebremeskel et al., 2021; Mondal et al., 2018b; Ringkjøb et al., 2018; Sadri et al., 2014; Subramanyam et al., 2017) (Gómez et al., 2016; Manzini et al., 2001; Yophy et al., 2011). It also enables users to define energy-intensive units and calculate energy flow for each technology(Mondal et al., 2010; Suganthi & Samuel, 2012). Key limitations of LEAP are its lack of detailed market modelling and economic optimization, reliance on user input data, and limited spatial/temporal resolution, making it less applicable for grid-level studies compared to TIMES or Balmorel (Bhattacharyya & Timilsina, 2009; Charles Heaps & "LEAP, 2024; Connolly et al., 2010)). Furthermore, LEAP does not capture the rebound effect, in which an improved efficiency may increase consumption due to behavioural or economic response, potentially exaggerating demand saving (Sorrell, 2007). Despite its limitations, its adaptability and scenario-based approach, and incorporation of novel technologies make it suitable for Ethiopia's long-term energy planning.

The LEAP model consists of two main modules: (1) The core assumption module serves as the central data center, storing key data like Population growth, Economic indicators, and household size. (2) The demand module covers household, industrial, transportation, agricultural, commercial, and public service sectors. Non-energy uses, like petrochemical processes, are not considered in this study.

Data sources

The model integrates both primary and secondary data sources. Primary sources include structured data collection from unpublished documents of institutions such as the Ministry of Water and Energy (MoWE, 2024), Ethiopian Electric Power (EEP) (EEP & "Input, 2024) and GiZ, Ethiopia (GFA Consulting Group, 2021), and expert consultations. Secondary sources were drawn from authoritative databases and reports such as UN World Population Prospects (2022) (United Nations & World Population Prospects, 2022,), UN-Habitat (2022) (UN-Habitat and World Cities Report 2022), World Bank Group (World Bank Group, 2020),, the International Energy Agency Ethiopia Energy Outlook(IEA, 2023), Central Statistics Agency (Central Statistical Agency, 2012), World Bank (World Bank 2021), IMF (IMF, 2025), MECS (Lastname, et al., 2022b), Ministry of Finance and Economic Development (MoFED) reports ("Ethiopia - Country Strategy Paper, 2022), Ministry of Water, Irrigation and Energy (MoWIE) energy balances (MoWIE, 2017), and National Electrification Program (MOWIE, 2019), and offline national energy strategy documents.

Key input data included:

- Population and household growth trends
- Urban–rural electrification rates
- Sectoral energy demand patterns
- Appliance energy intensities and penetration rates
- Urbanisation and economic growth projections

Model structure and assumptions

Ethiopian energy demand module is developed within the LEAP framework, structured around five main sectors: household (HH), industry, transport, commercial and public services, and agriculture. Within the household sector, further distinctions are made between urban and rural households. These are then broken down into sub-categories based on electrification status (i.e., percentage of electrified vs. non-electrified households). At the end-use level, energy demand is categorised by activities such as lighting, cooking, baking, refrigeration, and other uses. These are linked to specific end-use devices (both existing and energy-efficient models) and the types of fuels consumed (e.g., electricity, biomass, etc.).

Energy demand for each sector or sub-sector is calculated using energy intensity values and the specific fuel types consumed by each device. In terms of cooking and baking technologies, rural and urban households rely on a range of stove types. According to Gebremeskel et al. (Gebremeskel et al., 2021), 55% of households use traditional three-stone stoves, 19% use self-built stoves, 22% use manufactured biomass stoves, and only 4% use clean stoves, categorised based on their method of construction (Gebremeskel et al., 2021). Biomass remains a major energy source, used by 96.3% of rural households and 43.5% of urban households (Porridge, 2024). Energy intensity for cooking and baking has been estimated using data from the Ethiopian Biomass Energy Strategy

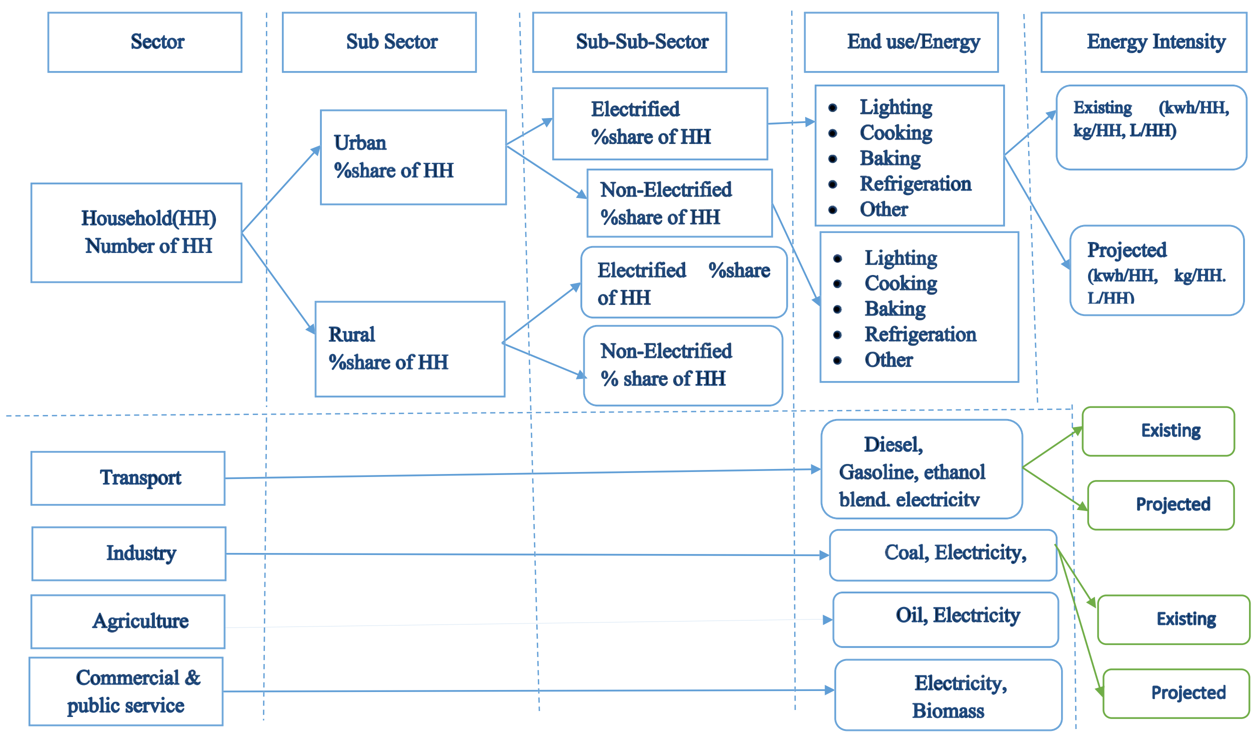

Fig. 1 The developed energy demand tree framework for the Ethiopia LEAP model

(Geissler et al., 2013) and the Ethiopian Energy Balance Sheets (MOWIE, 2019). Based on average annual biomass demand, biomass use for cooking and baking is estimated at 2200 kg per year for electrified households and 3400 kg per year for non-electrified households.

Key assumptions include:

- Electrification targets aligned with N-SEDS (96.2% urban and 72.3% rural by 2030)
- Incremental adoption of efficient lighting, cooking, and baking appliances
- Gradual urbanisation and household growth
- Sector-specific growth rates for energy demand (e.g., industrial sector at 8–9% per year)

Shown in Fig. 1 is the LEAP model's demand tree structure, representing how data inputs cascade from national indicators down to device-level energy demand.

In both urban and rural electrified households, the use of electric appliances such as electric stoves (for baking and cooking), lighting bulbs, refrigerators, and other devices (including televisions, radios, PCs, mobile phones, and coffee makers) remains relatively limited. According to Gebremeskel et al.(Gebremeskel et al., 2021), refrigerator ownership stands at 50.5% among urban households and only 5.7% among rural households. Gebremeskel et al.(Gebremeskel et al., 2021), also reported that other electrical devices have a penetration rate of 61.1% in urban areas (number of households that own the device) and 75.3% own the device in rural areas. While the penetration of other electrical devices is greater in rural areas than urban households, the

Table 1 Estimated typical average energy intensity and penetration level of activities for electrified urban and rural households (Gebremeskel et al., 2021; Padam et al., 2018)

Indicators	Penetration Level (%)	Energy Intensity (KWh/Y/HH)
Urban		
Lighting	100	370
Baking	15.3	400
Cooking	15.3	510
Refrigeration	50.5	305
Other devices	61.1	120
Total		**1705**
Rural		
Lighting	100	200
Baking	0.6	225
Cooking	0.6	300
Refrigeration	5.7	160
Other devices	75.3	50
Total		**935**

Bold indicates total values for the urban and rural households

Table 2 Key features and assumptions of the Ethiopian LEAP model for all scenarios (Akpahou et al., 2024; CSA, 2013; Gebremeskel et al., 2021; mohammed jemal Abdurahman, 2017; Mondal et al., 2018a; MoWE, 2024; Tahiru et al., 2023; UN, 2024; World Bank 2021) (IMF, 2025; Macrotrends 2025)

Key assumptions/indicators	2030	BaU			UEE				HUG				HEG			
		2040	2050	2060	2030	2040	2050	2060	2030	2040	2050	2060	2030	2040	2050	2060
Households Growth rate (%/year)	2.75	2.7	2	1.9	2.75	2.7	2	1.9	2.75	2.9	3	3	2.75	2.7	2	1.9
Urbanization rate (%)	31	43	56	63	31	43	56	63	34	46	58	65	31	43	56	63
Urban electrification rate (%)	96.2	100	100	100	100	100	100	100	96.2	100	100	100	96.2	100	100	100
Rural electrification rate (%)	72.3	96.2	100	100	72.3	100	100	100	72.3	100	100	100	72.3	96.2	100	100
Per capita income growth (%/year)	7	7	5	5	7	7	5	4	7	7	5	4	9	8	7	6
Industry growth rate (%)	8	8	9	9	8	8	9	9	8	8	9	9	7	9	10	11
Agriculture growth rate (%/year)	9	9	9	10	9	9	9	10	9	9	9	10	9	9	10	11
Efficient lighting penetration (% of households)	30	50	65	80	30	60	70	90	30	50	65	85	30	65	90	100
Electric cooking stove and baking Electric mitad penetration level (% of urban HH)	35.5	56	65	70	35.5	60	70	80	35.5	56	70	80	35.5	56	80	90
Electric cooking stove and baking, Electric mitad penetration level (% of rural HH)	3	15	35	45	3	20	40	50	3	15	35	55	3	25	45	70

annual energy demand per household per year is much less in rural areas (50Kwh/year/household) than in urban households (120 kWh/year/household). Kerosene is still used as a backup source for lighting in some households, with 4.8% of urban and 25.8% of rural households relying on it.

Despite electrification, the use of clean cooking fuels, particularly electricity, remains low. According to several sources (Gebremeskel et al., 2021; Lastname, et al., 2022b; MoWE, 2024), only 15% of electrified urban households and 0.6% of rural households use electricity for cooking, indicating limited penetration of electric cooking. Nevertheless, nearly all electrified households in both urban and rural areas use electricity for lighting. Table 1 provides estimated energy intensities for lighting, cooking, baking, refrigeration, and other uses, reflecting electricity demand in both urban and rural settings.

Cooking practices in Ethiopian households also influence electricity demand patterns. Most households tend to cook at similar times, leading to peak electricity usage in the early morning, midday, and evening. Richard et al. (Lastname, et al., 2022b) noted that 30–50% of electric stoves are turned on during these periods, contributing to significant demand surges. The average annual household electricity demand is estimated at 1705 kWh in urban areas and 935 kWh in rural areas. Cooking alone accounts for roughly 30% of total electricity use in both urban and rural homes. As shown in Table 1, the energy intensity of refrigerators is estimated at 305 kWh per year for urban households and 160 kWh per year for rural households.

Table 2 presents the key assumptions underlying all projections in the Ethiopian LEAP model are summarised based on several critical features for all scenarios. It serves as a foundational input parameter that drive the LEAP model. These include household characteristics, urban and rural electrification rates, the pace of urbanization, the penetration of electric cooking and baking technologies, and other relevant factors influencing final energy demand.

Scenario development

Four scenarios analyse varying electrification, urbanisation, efficiency, appliance adoption, and economic growth ("THE INESCAPABLE MANUFACTURING-SERVICES NEXUS: Exploring the potential", 2019; MoPD, 2023; MoWE, 2024). Table 2 summarises the key assumptions for all scenarios, while Table 3 is the complement of Table 2.

Business-as-usual (BAU)

Policy context: We explicitly note that the BAU scenario projects Ethiopia's energy demand from 2022 to 2060, under the assumption of no significant policy interventions.

Key motivators: Population growth from 123.38 million (2022) to 205 million (2060), urbanisation to 63%, electrification reaches 100% in urban and rural areas by 2040–2060, and urban electric cooking and baking reaches 70% by 2060.

Energy implications: The dominance of biomass continues in rural areas; electricity demand grows moderately. Cooking and lighting appliance adoption increases gradually in urban households. The risks of inaction are emphasised by the ongoing urban and rural inequities, increasing pressure on the supply, and reliance on biomass. Table 4 presents the BAU drivers projection from 2022 to 2060, allowing readers to observe the scale of change.

Universal electrification and efficiency (UEE)

Policy context: The UEE scenario reflects an ambitious policy-driven pathway in line with Ethiopia's Long-Term Low Emission and Climate Resilient Development Strategy (LTS, 2020–2050) (MoPD, 2023) and the National Sustainable Energy Development Strategy (N-SEDS, 2024–2030) (MoWE, 2024).

Key motivators: The rapid adoption of energy-efficient technologies (LEDs, electric cooking and baking stoves), and similarly, the universal electrification of urban areas by 2030 and rural regions by 2040. It also emphasises the deployment of energy efficiency policy measures, including transport (deployment of 1.5 million electric vehicles by 2060).

Energy implications: Increases electricity demand and energy efficiency while decreasing energy poverty and reliance on biomass.

High economic growth (HEG) scenarios

Policy context: HEG scenario highlights how a rapid economic growth trajectory affects energy demand, consistent with achieving lower-middle-income status.

Key motivators: High GDP growth peaking at 9% in 2030, per capita incomes, industrial growth reaching 11% by 2060, and driving energy demand.

Energy implications: Significant rise in industrial and residential energy use; increased demand for fuel for vehicles and appliances. The use of clean cooking is growing, but biomass is still prevalent in rural regions, although 90% of urban and 70% rural by 2060 will adopt electric cooking technologies, leading to the need for supportive policies. HEG indicates that sustainable energy transition by itself cannot be achieved with economic growth alone without proactive policies.

Table 3 Descriptive summary of scenario drivers, policy context, and energy implications

Scenario	Key driver	Policy context	Implication for energy demand
Business as Usual (BAU)	Historical trends	No significant policy interventions	Rising energy demand, continued reliance on biomass, and pressure on the electricity supply
Universal electrification and efficiency (UEE)	Electrification & efficiency	Aggressive policy-led electrification and technology adoption	Accelerated clean energy adoption, reduced energy poverty, improved efficiency
High economic growth (HEG)	Rapid GDP & industrial growth	Strong economic development	Higher energy demand from industry and households, increased appliance ownership
High urbanisation growth (HUG)	Fast urbanization	Accelerated rural-to-urban migration	Urban infrastructure growth drives electricity and appliance demand

Table 4 Projections for the BAU scenario (2022–2060) for Ethiopia's LEAP model

Indicator	2022	2060	Change
Households (million)	26.7	63.1	+136% (2022–2060)
Urbanization (%)	22.7	63	+177% (2022–2060)
Urban electrification (%)	96	100	+4% (2030–2040)
Rural electrification (%)	27	100	+270% (2022–2060)
Per capita income growth ($)	1,074	1,800	+67.7% (2022–2060)
Industry share of GDP (%)	22.72	36	+58.5% (2022–2060)
Agriculture share of GDP (%)	37.64	55.3	+46.9% (2022–2060)
Efficient lighting (% of households)	25	80	+220% (2022–2060)
Urban electric cooking (% of urban HH)	15	70	+367% (2022–2060)
Rural electric cooking (% of rural HH)	0.9	45	+4900% (2022–2060)

High urbanisation growth (HUG) scenario

Policy context: The HUG scenario explores the effect of accelerated rural-to-urban migration and infrastructure growth. This scenario anticipates faster urbanisation than BAU, consistent with the United Nations urbanisation forecast (United Nations Department of Economic & Social Affairs Population Division, World Urbanization Prospects, 2018).

Key motivators: Urban infrastructure expansion and city growth are the main drivers of the fast urbanization growth, than BAU, which is expected to reach 65% by 2060.

Energy implications: Increased adoption of LED lighting, electric cooking and baking, electrification, and efficiency measures are important to improve supply pressure, as shown in Table 2.

Modelling process

Final energy demand in LEAP is calculated by multiplying sector-specific activity levels by energy intensity per end-use technology. The LEAP model computed total final energy demand and associated GHG emissions for each year from 2022 to 2060. This study is designed as a demand-driven analysis at the sectoral level, using LEAP's end-use accounting framework to project total final energy demand and GHG emissions. Final energy demand is estimated by combining sector specific activity-levels with energy intensities over multi-decade horizons. This study does not include energy generation/supply side modelling, as LEAP is applied solely for final energy demand projections (Akpahou et al., 2024; Charles Heaps & "LEAP, 2024; Chughtai et al., 2024; Villamizar-Villamizar et al., 2023; Windarta et al., 2018). This ensures that, results are consistent with demand side factors presented in Sects. 2.3–2.4. Validation was conducted by benchmarking 2022 base-year estimates against actual national energy statistics (MoWE, 2024). Results were cross-compared with prior studies to ensure consistency and robustness, including (Boke et al., 2022; Gebremeskel et al., 2021; KTH, 2018; MoWE, 2024; Senshaw, 2014).

Activity levels in the Ethiopian LEAP model indicate the drivers of energy demand, such as GDP by sector, population size, urbanisation rates, household growth, and electrification rates, per-capita income, technology and appliance adoption. These activity levels were derived from historical data (Sect. 2.2) and are integrated hierarchically across sectors (household, transport, industry, agriculture, commercial) and sub-sectors (urban/rural, electrified/non-electrified), linked to energy intensities (e.g., kWh/household, kg/household). In the Ethiopian LEAP model, future activity levels were extrapolated using specific assumptions linked to GDP, population growth, urbanisation, and household numbers and sectoral shares.

Key projections, summarised in The risks of inaction are emphasised by the ongoing urban and rural inequities, increasing pressure on the supply, and reliance on biomass. Table 4 presents the BAU drivers projection from 2022 to 2060, allowing readers to observe the scale of change.

Table 4, highlight significant changes from the 2022 base year to 2060. According to UN World Population Prospects (United Nations & World Population Prospects, 2022), for example, the Ethiopian population is expected to increase by 66%, from 123.38 million in 2022 to 205 million in 2060, with an annual growth rate of 2.4% in 2030 and by 0.95% in 2060. Similarly, as to the UN-Habitat forecasts (UN-Habitat and World Cities Report 2022), the relative proportion of urbanisation rises by 177%, from 22.7% in 2022 to 63% in 2060. The Ethiopian household has projected from 26.7 million in 2022 to 63.1 million in 2060, which increase of 136%. Linked to the National Sustainable Energy Development Strategy document (MoWE, 2024), rural electrification increases by 270% from 27% in 2022 to 100% by 2060, while urban electrification increases by 4% from 96% in 2022 to 100% by 2040. Linked to GDP growth averaging 7.5% through 2040 and 7% through 2060, per capita income rises by 67.7%, from $1,074 in 2022 to $1800 in 2060, World Bank (World Bank 2021), IMF (IMF, 2025) and MoFED data ("Ethiopia - Country Strategy Paper, 2022). Similarly, according to World Bank and MoFED data, the industry shares of GDP increase by 58.5% from 22.72% in 2022 to 36% in 2060, and agriculture's share increases by 46.9% from 37.64% to 55.3%. Energy intensity (MJ/$) is expected to decline by 23% from 5.2 MJ/$ in 2022 (IEA & "World, 2024) to 4 MJ/$ by 2060, reflecting the adoption of efficiency measures such as LEDs and electric cooking.

Result analysis

This section presents the results of Ethiopia's energy demand projections under four scenarios: Business-As-Usual (BAU), Universal Electrification and Efficiency (UEE), High Economic Growth (HEG), and High Urbanisation Growth (HUG) modelled from 2022 to 2060 using the LEAP framework.

Energy demand trends under the BAU scenario

Under BAU, total final energy demand is projected to increase substantially from 1811 PJ in 2022 to 6,478 PJ by 2060. This translates to a compound annual growth rate of approximately 3.37%, reflecting steady population growth, household formation, and urbanisation.

Temporal energy demand milestones

Under the BAU scenario, the demand milestones across the projection period are 2030: 2348 PJ, 2040: 3192 PJ, 2050: 4439 PJ, and 2060: 6478 PJ. This trajectory reflects early electrification and infrastructure growth driven by urban expansion and increasing appliance penetration gains, with biomass still dominant in rural areas.

We compared our energy demand projections for Ethiopia with those of other studies. The Ministry of Water and Energy (2024) (MoWE, 2024) projected 2258.7 PJ by 2030, Gebremesekle et al. (2021) (Gebremeskel et al.,

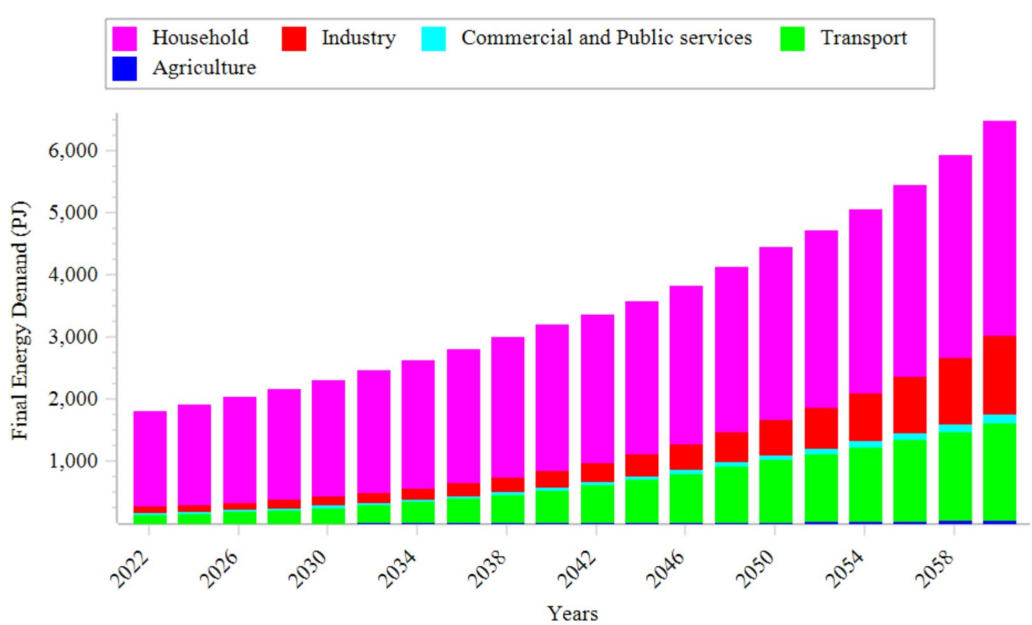

Fig. 2 Final energy demand under the BAU scenario from 2022 to 2060

2021) projected 2950 PJ by 2030, and our model estimated 2,348 PJ by 2030 under the BAU scenarios. Similarly, Senshaw (2014) (Senshaw, 2014) and Gebremesekle et al. (2021) projected to reach 6553 PJ, 4900 PJ by 2050, respectively, whereas our model projected to reach 4439 PJ by 2050. Despite variations due to updated data on GDP, population growth, and electrification, our business-as-usual energy projection aligns with these studies.

Sectoral contributions

Under the BAU scenario in Fig. 2, the household Sector drives the largest absolute increase in energy use of 1918 PJ, driven by increased household numbers, partial electrification, and continued reliance on traditional biomass for cooking, baking and heating. The transport sector adds approximately 1432 PJ, with demand for diesel and gasoline due to increasing mobility and limited penetration of electric vehicles. The industrial sector grows by 1148 PJ, reflecting moderate industrial expansion, particularly in manufacturing and construction. Energy intensity remains relatively high due to the slow uptake of efficiency technologies. Agricultural, commercial, and public service experience steady but comparatively smaller growth. It is mainly for irrigation, refrigeration, service delivery, and lighting, especially in expanding urban centres.

The BAU scenario demonstrates the risks of inaction: although access improves incrementally, energy efficiency gains are limited, and traditional biomass continues to dominate household energy use. The steep rise in energy demand underscores the potential strain on Ethiopia's energy infrastructure and the need for long-term planning. Without significant intervention, this pathway perpetuates regional inequalities in energy access. The BAU scenario illustrates Ethiopia's likely energy future if current trends continue without bold policy changes. While access to energy improves gradually, the absence of transformative efficiency measures and clean energy transitions leads to substantial increases in energy demand, especially in households and transport. These results highlight the urgency of proactive, integrated energy planning to ensure a sustainable and equitable future.

Energy demand trends under the HEG scenario

The High Economic Growth (HEG) scenario explores the energy implications of Ethiopia's ambition to achieve rapid, sustained economic expansion. This scenario builds on the BAU baseline but incorporates higher GDP and income growth rates, increased industrial activity, and greater demand for goods and services, all of which significantly elevate energy requirements across all sectors.

Temporal energy demand milestones

Under the HEG scenario, final energy demand is projected to grow from 1811 PJ in 2022 to 6,960 PJ by 2060, marking the highest total demand among all four modelled scenarios. This represents a compound annual

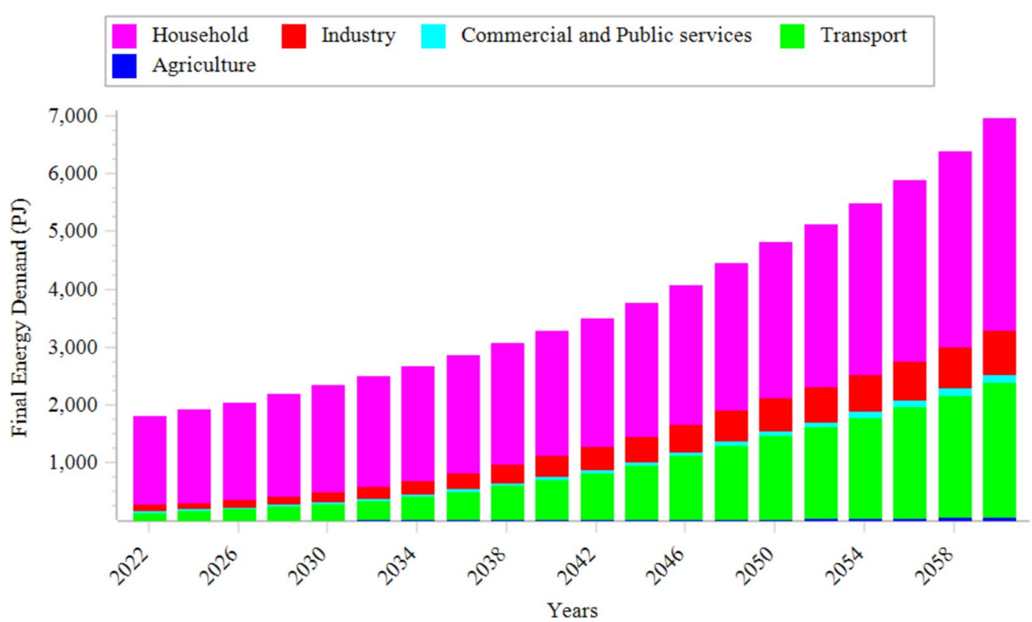

Fig. 3 Final energy demand under the HEG scenario from 2022 to 2060

growth rate (CAGR) of approximately 3.46%, slightly higher than BAU, but with more energy-intensive drivers. The demand milestones across the projection period are 2030: 2347 PJ, 2040: 3281 PJ, 2050: 4814 PJ, and 2060: 6960 PJ. This trajectory reflects the influence of higher income levels, increased industrial output, urban lifestyle shifts, and broader economic modernisation.

Sectoral contributions

As the modelling result under the HEG in Fig. 3 indicates, the sectoral contribution to energy demand growth. The Industrial Sector experiences the largest proportional increase in demand, driven by accelerated manufacturing, construction, and industrial park expansion. Growth in industrial electricity and fossil fuel use reflects limited efficiency improvements. The household sector energy demand rises as households acquire more appliances and shift to modern fuels. While electrification expands, traditional biomass remains significant in rural areas. Appliance ownership increases with income, driving higher per capita electricity use. The transport sector shows substantial demand growth, largely from increased vehicle ownership, freight logistics, and air travel. The uptake of electric vehicles remains limited, and diesel and gasoline dominate the fuel mix. The commercial, agricultural, and public services sectors also expand significantly in line with economic growth and urbanization. Demand for electricity, especially in commercial cooling, lighting, and irrigation systems, increases rapidly.

Compared to the BAU scenario, the HEG pathway adds approximately 482 PJ more energy demand by 2060, highlighting the energy intensity of unmitigated economic growth. The rising affluence and urbanization embedded in this scenario drive both electricity and fossil fuel demand sharply upward. Without deliberate policy to decouple economic growth from energy intensity, Ethiopia risks locking into an inefficient and carbon-intensive development model. The HEG scenario underscores the challenge of balancing robust economic growth with sustainable energy use. While it reflects Ethiopia's national development aspirations, it also illustrates the energy and environmental costs of growth without strong efficiency measures. This scenario reinforces the importance of integrating energy efficiency, clean technologies, and sustainable transport policies into the country's economic transformation agenda to manage future demand responsibly.

Energy demand trends under the HUG scenario

Temporal energy demand milestones

Under the HUG scenario depicted in . Figure 4, Ethiopia's total energy demand is projected to grow significantly, reaching 2274 PJ in 2030, 3125 PJ in 2040, 4467 PJ in 2050, and 6609 PJ by 2060, as illustrated in **Error! Reference source not found.**. This represents an approximate 265% increase over the 38 years from 2022 to 2060, underscoring the strong upward trajectory in national energy demand driven by rapid urbanization.

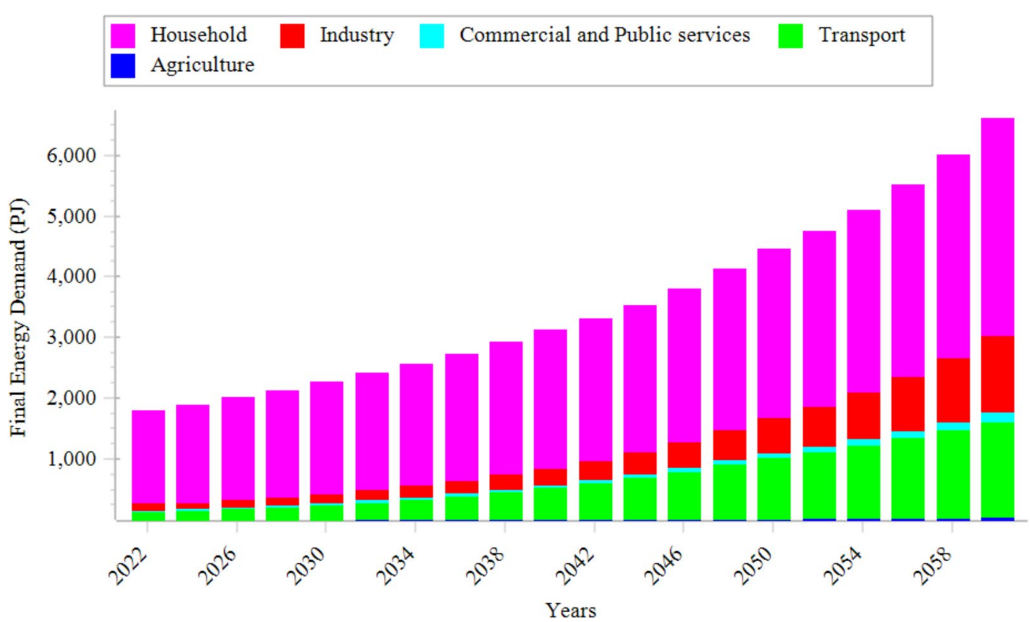

Fig. 4 Final energy demand under the HUG scenario from 2022 to 2060

This substantial rise is largely attributed to the transformation of Ethiopia's demographic and economic landscape through mass urbanization. As urban populations grow, so does energy demand across residential, industrial, transport, and service sectors. Urban expansion entails higher demand for lighting, cooking, and appliance use in households; powering electric vehicles and mass transit systems; and supporting civic facilities and infrastructure. Additionally, rising household incomes and improved living standards are expected to amplify energy use, particularly for appliances and other lifestyle-related demand.

Sectoral contributions

In the HUG scenario, the household sector demonstrates steady growth in energy demand, reaching 1830 PJ in 2030, 2262 PJ in 2040, 2781 PJ in 2050, and 3564.7 PJ by 2060 an increase of approximately 134% from 2022 levels. This reflects the increasing electrification of urban households, growing appliance ownership, and the alignment of household energy use with urban lifestyles. As urban living becomes the norm, energy demand in this sector is expected to continue its upward trend.

Energy demand in the transport sector shows one of the most dramatic increases, rising from 135.7 PJ in 2022 to 250 PJ in 2030, 528 PJ in 2040, 1011 PJ in 2050, and 1576 PJ by 2060. This nearly 12-fold growth reflects the expansion of transportation networks, increased vehicle ownership, and the development of public transit systems to accommodate growing urban populations. Energy use in this sector will span private and public transport, freight systems, and associated infrastructure.

The industrial sector is projected to experience a significant surge in energy demand under HUG, growing from 147.7 PJ in 2030 to 1262.7 PJ by 2060. Intermediate growth benchmarks include 273 PJ in 2040 and 567 PJ in 2050. This sharp increase corresponds with the scaling up of manufacturing and industrial activities, as urbanization drives economic diversification and industrialization. Higher production volumes and increased energy intensity of operations contribute to this trend.

Energy demand in the commercial and public services sector is also expected to grow substantially, from 31.4 PJ in 2022 to 153.7 PJ by 2060 a cumulative increase of approximately 389%. This sector's growth is driven by expanding commercial activities, rising demand for retail and office space, and greater energy needs in public institutions such as hospitals, schools, and administrative buildings.

Although starting from a lower base, the agriculture sector exhibits the fastest relative growth in energy demand, rising from 5.6 PJ in 2022 to 51.8 PJ by 2060, marking an approximate 824% increase. This surge is fuelled by the mechanisation of farming practices, the development of cold chains, the expansion of irrigation systems, and increased integration of agriculture into urban food supply networks. As agricultural practices modernise in response to urban demand, energy use in this sector is expected to continue rising.

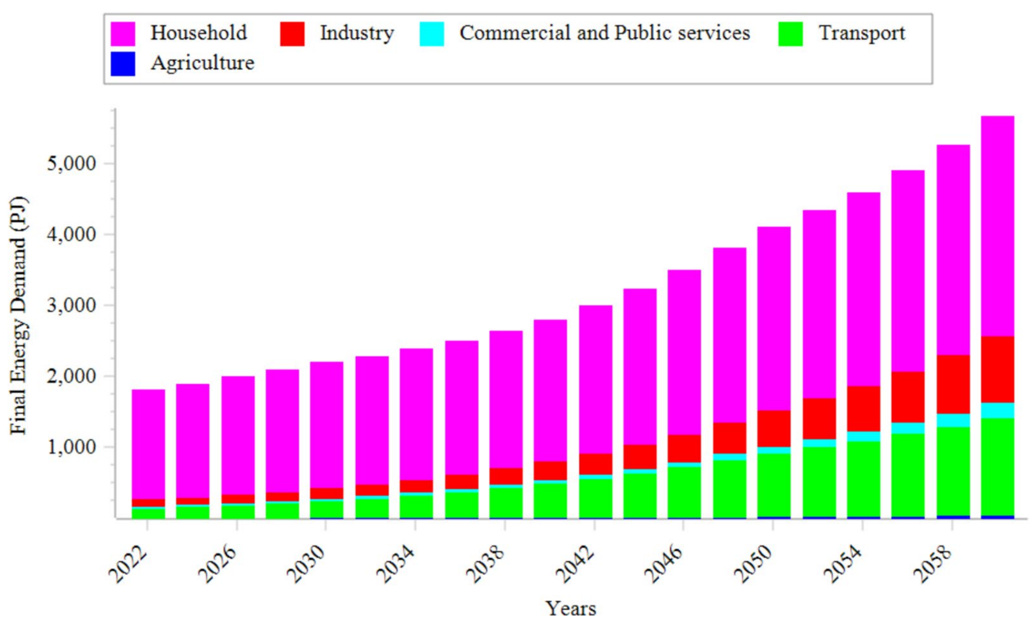

Fig. 5 Final energy demand under the UEE scenario from 2022 to 2060

Energy demand trends under the UEE scenario

Temporal energy demand milestones

Under the Universal Electrification and Efficiency (UEE) scenario where Ethiopia achieves full electrification while implementing widespread energy efficiency measures total energy demand is projected to rise from a base level of 1500 PJ in 2022 to 2194 PJ in 2030, 2795 PJ in 2040, 4102 PJ in 2050, and 5660 PJ by 2060, as shown in Fig. 5. This reflects a near tripling of national energy demand over the period, driven by expanded electricity access, urbanization, and gradual improvements in living standards tempered by strong efficiency measures across sectors.

Sectoral contributions

The household sector, which accounts for a major share of national energy use, is projected to grow steadily, reaching 1763 PJ in 2030, 1989 PJ in 2040, 2571 PJ in 2050, and 2940 PJ by 2060. This growth is shaped by increased electrification of homes and greater use of appliances, balanced by the adoption of energy-efficient technologies such as improved lighting and low-wattage devices.

In the transport sector, energy demand is expected to more than triple from 2022 levels, reaching 1,368 PJ by 2060. This substantial increase results from expanded public and private transportation systems, urban mobility demand, and greater freight movement associated with economic growth. However, energy efficiency strategies, including fuel economy improvements and electrified transport, help to moderate this growth.

The industrial sector, a key driver of economic transformation, is also set to expand considerably. Energy demand is expected to rise from 231 PJ in 2030 to 481 PJ in 2040, 901 PJ in 2050, and 1368 PJ by 2060, representing nearly a 200% increase over the period. This

Table 5 Comparison of final energy demand relative to BAU scenario (2060) and key drivers

Sector	HEG vs BAU	HUG vs BAU	UEE vs BAU	Key driver
Household	+6.6%	6%	− 10%	adoption of electric cooking and baking technologies, and other appliance ownership, electrification, income growth, urbanization
Transport	49%	0.50%	− 13%	Economic growth, transportation system/motorization, urbanisation, EV adoption
Industry	− 26%	0%	− 40%	Energy efficiency measures, cleaner technology adoption
Agriculture	10%	2%	− 5%	Mechanization, irrigation, rural electrification

Although agriculture remains the smallest sector in terms of absolute energy demand, it exhibits notable relative growth across all scenarios. In the HEG scenario, demand increases from 9 PJ in 2030 to 57 PJ by 2060, achieving a 10% increase over BAU driven by enhanced mechanisation, cold storage development, expanded irrigation systems, and broader rural electrification

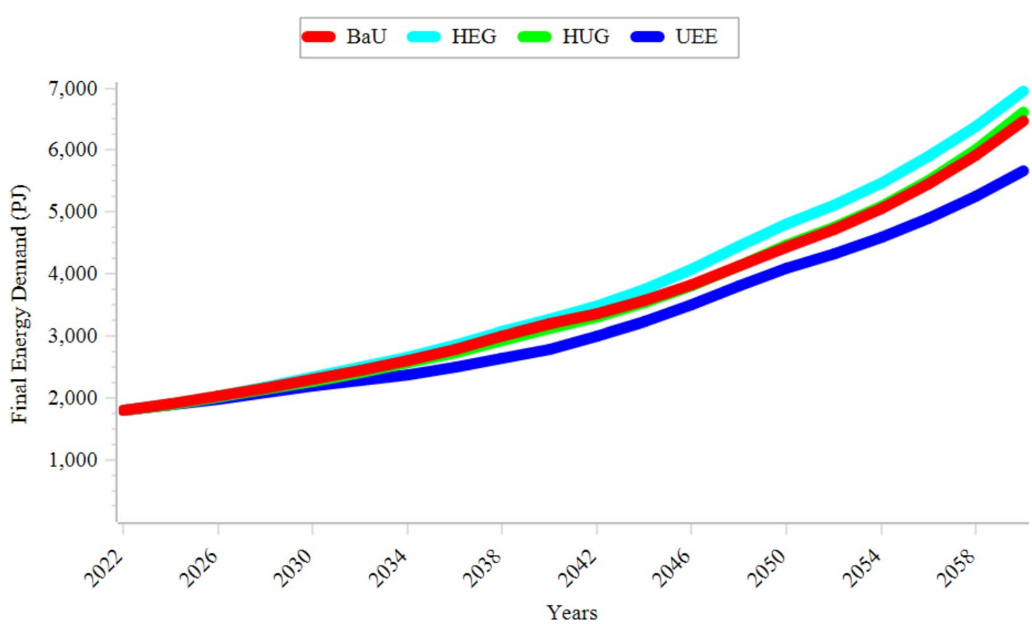

Fig. 6 Temporal total energy demand comparison for all scenarios between 2022 to 2060

reflects the sector's evolution toward greater production capacity, mechanisation, and industrial diversification, complemented by cleaner and more efficient production processes.

Although starting from a small base, the agriculture sector is also expected to experience notable growth, reaching 48 PJ by 2060 a 200% increase from 2022 levels. This rise is linked to enhanced mechanisation, irrigation, cold storage, and integration into urban food supply chains as the sector modernises alongside urban expansion.

The commercial and public services sector is projected to grow to 227 PJ by 2060, fuelled by the development of urban infrastructure and expanding energy needs of institutions such as schools, health facilities, administrative centres, and retail spaces.

Comparative analysis of the scenarios

This section compares Ethiopia's projected total final energy demand and greenhouse gas emissions across the four scenarios, focusing on the factors that differentiate demand development. Detailed sectoral projection comparisons are summarized in Table 5 and Fig. 6.

Total energy demand trajectories

The trends displayed in Fig. 6 present the total energy demand comparison trajectory by scenarios from 2022 to 2060. The average annual growth rate shows HEG: 3.46%, HUG: 3.40%, BAU: 3.37%, and UEE: 3.11% (lowest). The HEG and HUG scenarios both result in faster growth than BAU, with the key drivers of difference including economic growth driving higher energy consumption in HEG, accelerated urbanization driving HUG to increase households and infrastructure expansion, while UEE mitigates demand growth via energy efficiency and clean cooking adoption.

Sectoral dynamics

The trends displayed in Fig. 7 and Table 5 present the total energy demand comparison by sector for all scenarios.

The household sector sees robust energy demand growth. The HEG scenario consistently records the highest demand, rising from 1847 PJ in 2030 to 3661 PJ in 2060, a 6.6% increase over the BAU scenario, fuelled by too high appliance ownership, rapid income growth, electrification, urbanization, adoption of electric cooking and baking technologies and other appliance ownership, as shown in Table 5. The BAU scenario also shows substantial growth, from 1864 PJ in 2030 to 3443 PJ in 2060. On the other hand, the UEE scenario grows more modestly, from 1764 PJ to 3084 PJ, achieving a 10% reduction below BAU due to the deployment of energy-efficient measures like cooking, baking technologies, and other appliances.

The transport sector shows a significant increase from 285 PJ in 2030 to 2338 PJ in 2060 under the HEG scenario, a 49% increase over the BAU scenario. Both HUG and BAU follow similar trends, reaching around 1576 PJ and 1568 PJ by 2060, respectively, with HUG showing an increase of 0.5% energy demand, compared to BAU, due to urbanisation's little effect without substantial economic growth. Conversely, the UEE

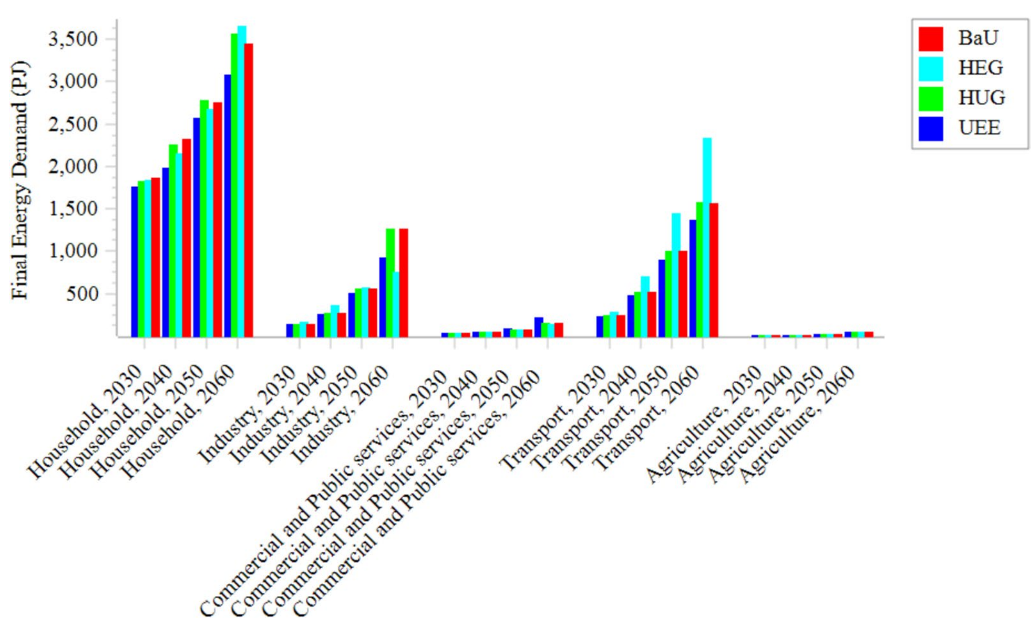

Fig. 7 Total energy demand comparison by sector for all scenarios between 2030 to 2060

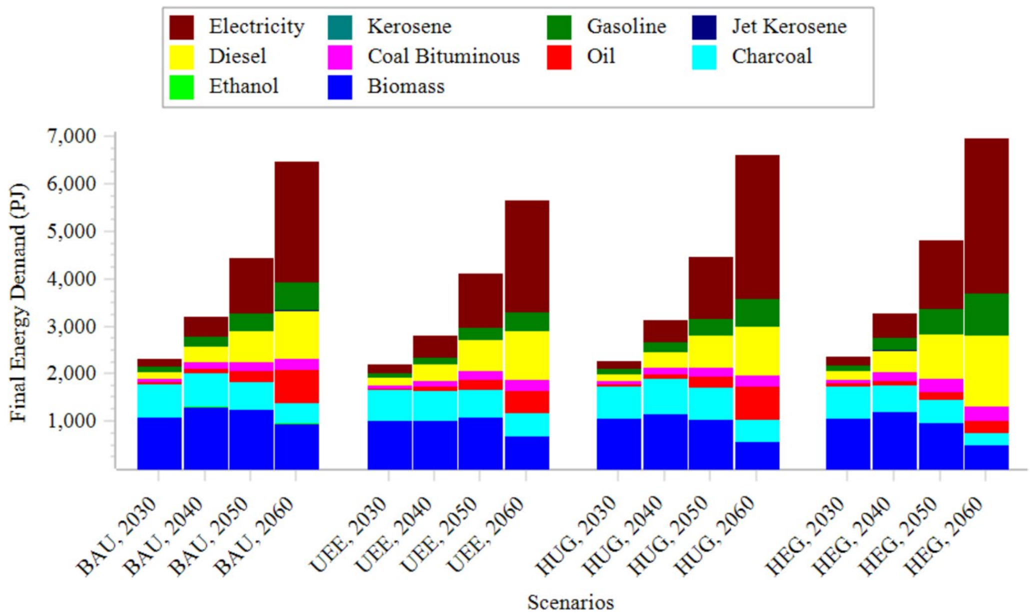

Fig. 8 Total energy by fuel comparison for all scenarios between 2022 and 2060

Table 6 Comparison of final energy demand by fuel type across scenarios with respect to BAU and key drivers (2060)

Fuel	HEG vs BAU	HUG vs BAU	UEE vs BAU	Key driver
Electricity	2%	36%	12%	Electrification, urbanization, appliance adoption, EVs
Biomass	2%	−10%	−33%	Clean cooking adoption, fuel-switching, policy
Diesel	25%	1%	−15%	Industrial growth, transport expansion, EV adoption
Gasoline	30%	2%	−15%	Vehicle use, economic growth, EV adoption
Jet fuel	28%	2%	−12%	Air transport growth, efficiency measures

scenario grows modestly, rising from 238 PJ to 1369 PJ, achieving a 13% reduction below BAU with the deployment of efficiency measures and widespread electric vehicle adoption.

The industrial sector's energy demand shows significant variation across scenarios. Under BAU and HUG, demand grows from 148 PJ in 2030 to 1263 PJ by 2060, due to structural transformation, increased output, and rising industrialisation. The HEG scenario projects a peak demand of 932 PJ, reflecting a 26% reduction compared to the BAU scenario, due to efficiency measures and system modernization. On the other hand, the UEE scenario follows a more gradual trajectory, reaching 761 PJ by 2060, achieving a 40% reduction in energy demand from the BAU scenario through advanced technologies, wide spread EV adoption and the industrial sector's efficiency gains.

Total energy demand by fuel type

Understanding how the fuel mix changes under different pathways is critical for assessing sustainability, infrastructure needs, and emissions impacts. Figure 8 and Table 6 illustrates the relative shares and absolute demand of key fuels, including biomass, electricity, diesel, gasoline, kerosene, jet fuel, coal, and ethanol.

Electricity

Electricity demand grows rapidly in all scenarios, reflecting expanding access, appliance adoption, and urbanization. However, the scale of growth differs based on policy interventions. With the UEE scenario, electricity demand increases more than 13-fold, from 165 PJ in 2022 to 2351 PJ in 2060, achieving 12% above BAU. This reflects universal electrification, widespread use of efficient lighting, electric cooking and baking appliances, and moderate EV uptake. The adoption of electric cooking and baking technologies accounts for approximately 1551 PJ from the total energy demand of 1887 PJ in 2060, which is the largest driver of household electricity increase in this scenario. This trend implies their contribution is similar to the other scenarios. The HUG scenario shows the highest electricity demand at 3010 PJ by 2060, achieving 36% more than BAU, driven by dense urban populations and increased electrified infrastructure, and moderate adoption of electric appliances. However, the HEG and BAU scenarios exhibit more modest growth (to ~ 2100–2200 PJ), with a roughly 2% difference from the BAU scenario, with slower adoption of electric cooking and baking technologies and continued reliance on biomass in rural areas. This surge underscores the need for large-scale investment in generation, transmission, and demand-side management to support a reliable and clean electricity system.

Biomass

Within the BAU and HEG, biomass remains the dominant fuel, though its share of total demand declines from ~ 63% in 2030 to ~ 39% in 2060, reflecting slow shifts toward modern energy. However, at the UEE, biomass use falls sharply due to aggressive deployment of electric cooking and baking appliances, which replace traditional biomass use in households. Compared with the BAU, HEG is achieving a 33% faster reduction in biomass use. The HUG scenario shows a steady decline (10% below the BAU scenario by 2060) in biomass, as urbanisation drives fuel-switching in cities, but informal settlements and peri-urban areas retain biomass dependence. The persistence of biomass in all but the UEE scenario highlights the importance of policies targeting clean cooking solutions and behavioural change.

Fossil fuels (diesel, gasoline, jet fuel)

Demand for fossil fuels, especially in transport and industry, remains high in all scenarios except UEE. HEG sees the highest fossil fuel use, with diesel rising to 1017 PJ and gasoline to 389 PJ by 2060, showing a 25% above BAU for diesel, and 30% more than the BAU for gasoline, driven by industrial growth, increased freight transport, and personal vehicle use. BAU and HUG show steady growth in diesel and gasoline use (2% difference from BAU), reflecting limited penetration of electric mobility. In the UEE, moderating fossil fuel demand reflects a 15% less than the BAU, through the gradual introduction of electric vehicles and energy efficiency measures, though fossil fuels still play a substantial role in transport and industrial operations.

Greenhouse gas (GHG) emissions analysis

As a developing country, Ethiopia's rapid industrialisation and economic growth drive greenhouse gas (GHG) emissions. including carbon dioxide, methane (combustion and biogenic) and Nitrous oxide. As illustrated in Fig. 9, this study projects that GHG emissions will rise significantly from 40.7 Mmtonnes of CO_2 equivalent ($MmtCO_2e$) in 2022 to 214 $MmtCO_2e$ by 2060 under the BAU scenario.

This finding aligns with the 2016 Addis Ababa GHG Emissions Inventory Report, which reported a 50%

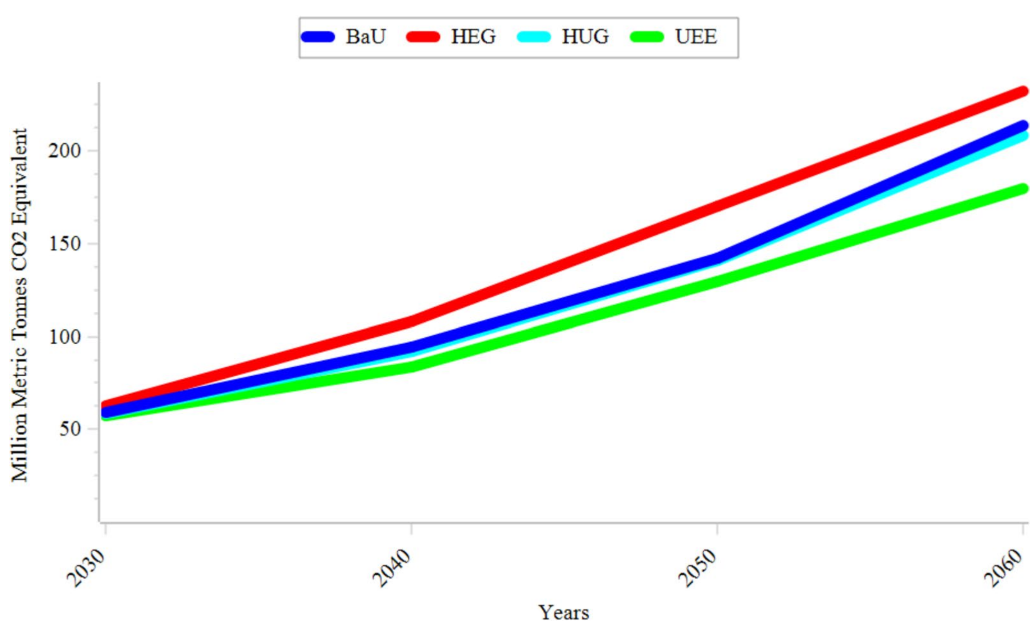

Fig. 9 Total GHG emissions for all scenarios

Table 7 Comparison of final energy demand and GHG emissions

	2030	2030	2040	2040	2050	2050	2060	2060		
Scenario	Energy (PJ)	Emissions ($MmtCO_2e$)	Energy (PJ)	Emissions ($MmtCO_2e$)	Energy (PJ)	Emissions ($MmtCO_2e$)	Energy (PJ)	Emissions ($MmtCO_2e$)	Total energy (PJ)	Total emissions ($MmtCO_2e$)
BAU	2308.40	59.2	3192.70	94.2	4438.90	142.2	6478.70	213.9	16,418.60	509.5
HEG	2347.50	62.7	3281.00	108.1	4814.30	170.2	6960.20	232.5	17,403.00	573.4
HUG	2274.00	58.4	3125.90	92.2	4467.00	140.7	6609.10	208.3	16,476.00	499.6
UEE	2194.10	57.3	2795.40	83.5	4102.40	129.5	5660.10	180	14,751.90	450.3
Total	9123.90	237.6	12,395.00	378	17,822.60	582.6	25,708.00	834.6	65,049.50	2032.80

increase in emissions between 2012 and 2016, primarily from the transport and waste sectors (Nnene et al., 2023). Consistent with past studies (Etensa et al., 2025; Hailu et al., 2024; IEA, 2022; Nnene et al., 2023) identify industrialization, economic development, and urbanisation as the primary drivers of future energy demand and GHG emissions in Ethiopia, this study confirms that those conclusions the resulting emission explicitly to the energy sector remains the leading contributor, as indicated by IPCC guidelines (IPCC, 2006a, 2006b). Ethiopia's Climate Resilient Green Economy (CRGE) strategy is positioned to play a critical role in reducing emissions by promoting clean biofuels and electricity over traditional biomass for household appliances (MoPD, 2023). This underscores the urgent need for continued research and comprehensive environmental policy measures to support sustainable development and mitigate environmental degradation in Ethiopia.

Consolidated summary of final energy demand and emissions across scenarios

A consolidated summary of final energy demand and GHG emissions for the milestone years 2030, 2040, 2050, and 2060 for all scenarios is depicted in Table 7. It also presents the cumulative totals of final energy demand and emissions. The HEG scenario reflects the highest final energy demand and emission level of 6960PJ and 232.5 $MmtCO2e$, by 2060, respectively. The BAU scenario exhibits a final energy demand and emission value of 6478.7PJ and 213.9 $MmtCO2e$, respectively, while UEE shows the lowest energy demand of 5660PJ and emission level of 180.0 $MmtCO2e$ by 2060. Though the UEE scenario shows minimum energy demand and emission levels with efficiency gains and electrification, it still shows significant growth in demand.

Policy implications

The scenario analysis presented in this study offers a robust foundation for guiding Ethiopia's long-term energy policy.

General policies

Universal and equitable electrification as a national priority: To achieve near-universal electricity access with a strong focus on rural and marginalised communities, all stakeholders should scale up both grid extension and off-grid solutions (e.g., mini-grids, solar home systems) tailored to geographic and economic contexts; prioritise investments in last-mile infrastructure and grid stabilisation, guided by the National Sustainable Energy Development Strategy (N-SEDS) and incorporate gender-responsive electrification strategies to ensure inclusive energy access, particularly for women and vulnerable groups.

Fast-tracking efficient and clean technology adoption: Promote large-scale adoption of electric cooking, baking and lighting through targeted subsidies, concessional financing, and results-based incentives. Establish mandatory appliance efficiency standards, labelling schemes, and import regulations to raise market quality. Implement programs to phase out traditional biomass use, focusing on improved stoves, modern bioenergy solutions, and fuel-switching policies. Additionally, support forest conservation and reforestation efforts as part of an integrated biomass reduction strategy.

Decarbonising the transport and industry sector: Develop a national electric mobility strategy with investments in EV charging infrastructure and public transport electrification (buses, rail), incentives for local EV assembly and battery manufacturing, and urban mobility planning with non-motorised transport infrastructure. Additionally, institutionalise energy audits and offer grants for energy efficiency retrofits and provide tax incentives for clean production technologies and green industrial zones. Encourage industrial fuel-switching and renewable heat technologies (e.g., solar thermal) in the industrial sector.

Mainstreaming energy modelling for strategic planning: It is important to integrate LEAP and other tools to develop evidence-based plans by mandating the use of LEAP and similar tools in all national and regional energy plans to ensure data-driven decisions. Establish a dedicated inter-ministerial modelling and monitoring unit to track energy-climate targets.

Managing demand and promoting smart demand: Introduce time-of-use pricing and demand response programs to shift peak loads and optimize generation capacity. Deploy smart grid technologies, including smart meters, predictive analytics, and decentralized energy systems. Provide incentives for household and commercial users to adopt low-demand practices and technologies through demand side management strategies.

Managing urbanization with integrated planning: Develop green, resilient urban energy systems by investing in electric mass transit, energy-efficient buildings (via updated building codes), and urban solar and district energy networks. Additionally, Implement transit-oriented development and city-level energy planning frameworks.

Scenario-specific insights for policy action

- **Business-as-usual (BAU)**:

  Highlights risks of inaction: rising GHGs, unsustainable biomass dependence, and economic vulnerability.
  Urges immediate and transformative interventions to avoid carbon lock-in.

- **High economic growth (HEG)**:

  Signals the need for synchronised energy and industrial policy to manage demand and emissions.
  Emphasizes efficiency, clean electrification, and green industrialization as essential complements to growth.

- **Universal electrification & efficiency (UEE)**:

  Demonstrates the benefits of access-driven and efficiency-focused planning.
  Encourages scaling of clean cooking, appliance efficiency, and inclusive energy access programs.

- **High urban growth (HUG)**:

  Reveals both opportunity and risk in urban expansion.
  Underlines the urgency of integrated urban–energy strategies to guide cities toward low-carbon futures.

By addressing these policy implications holistically, Ethiopia can leverage its demographic dividend, renewable energy potential, and development momentum to build a resilient, equitable, and sustainable energy future by 2060.

Limitations and future scope

This paper employs LEAP for comprehensive energy demand projection, but faces limitations. First, results are susceptible to data uncertainties due to limited historical data availability. Second, inherent uncertainties exist in long-term estimates, as little deviations in economic, demographic and technological considerations can lead to variations in outcomes with time. Third, although LEAP enables policy-driven scenario analysis, it does not account for behavioural, political, and financial factors that may hinder energy sector reforms. Furthermore, only indirect representation of socio-cultural factors like household preferences and income restrictions affecting the adoption of electric cooking and baking technologies, and other appliances is indirectly represented.

To improve the robustness of the alternative energy demand projections, future research could soft linking LEAP with Balmorel, TIMES or MESSAGE, integrating uncertainty and sensitivity analyses could address these problems.

Conclusion

This study presents a comprehensive long-term energy demand analysis for Ethiopia using the LEAP modelling framework, projecting trends from 2022 to 2060 across four distinct development scenarios: Business-As-Usual (BAU), Universal Electrification and Efficiency (UEE), High Economic Growth (HEG), and High Urbanization Growth (HUG). The results highlight a sharp increase in energy demand across all sectors, particularly in the household and transport sectors, driven by population growth, urbanization, and economic transformation. Without targeted interventions, energy demand could nearly quadruple by 2060, accompanied by a significant rise in greenhouse gas emissions. However, the UEE scenario demonstrates that Ethiopia could reduce its total energy demand by over 18% and emissions by 28% compared to the HEG pathway primarily through improved electrification, efficient end-use technologies, and structural shifts away from traditional biomass.

These findings underscore the critical importance of scenario-based planning and the institutionalization of energy modelling tools like LEAP in national policy development. The study also reinforces the need for integrated, demand-side strategies that align with Ethiopia's climate goals, energy access targets, and sustainable development vision. To support Ethiopia's energy transition, policymakers should prioritize investments in:

- Universal access to clean electricity, especially in rural areas,
- Deployment of energy-efficient appliances, including those for cooking and baking,
- Urban infrastructure and electrified transport systems,
- Capacity building for data-driven energy planning

By leveraging robust modelling tools and embracing transformative energy policies, Ethiopia can chart a sustainable and inclusive energy future that supports economic development, improves livelihoods, and mitigates environmental impacts.

Competing interest

The authors declare no competing interests.

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Author contributions
STB: Writing original draft, Software, review and editing, Conceptualization, Methodology, Data Curation, Formal analysis, Validation, Visualization. MGG: Writing-original draft, review & editing, visualization, Data Curation, and Validation. AHM: Data collection, Data Curation, review & editing.

Data availability
No datasets were generated or analysed during the current study.

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