Heliyon 10 (2024) e25364

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Electricity demand analysis and forecasting: The case of GADA special economic zone

Meskerem Tadesse Gebre [a,*], Junseok Hwang [b], Getachew Biru [c]

[a] Department of Technology and Innovation Management, Adama Science and Technology University (ASTU), Adama, Ethiopia
[b] Seoul National University (SNU), Technology management, Economic and Policy Program Korea, South Korea
[c] Addis Ababa institute of Technology (AAiT), Addis Ababa, Ethiopia

ARTICLE INFO

Keywords:
GADA special economic zone (GSEZ)
Long-range energy alternatives planning (LEAP)
Power demand forecasting
Ethiopia
Energy consumption
Demand analysis

ABSTRACT

Ethiopia is a country in East Africa experiencing significant economic growth in recent years, with an increasing electricity demand. Ensuring sustainable and efficient energy for newly developed industries and economic zones is crucial. In this study, a 15-year electric power demand forecast for the new economic zone under construction is conducted. The electrical power demand forecast is done for the year 2025–2040 by using bottom-up forecasting approach for three different scenarios. Long-range Energy Alternatives Planning (LEAP) system software is used to analyze residential, industrial, and general business sector electric power demand. The analysis of the assessed scenario shows that the economic zone's electric power demand increases by 52.2 % from the base year 2025–2040 for the baseline scenario, due to anticipated rapid urbanization, growth in population, economic expansion, and anticipated political stability. Compared to the baseline scenario, the total power demand shows a growth of 68 % from the forecast year (2025) to 2040 for the aggressive scenario, which ensures sustainable and efficient energy options that can draw businesses from both domestic and international baselines. In contrast, the total power demand in the conservative scenario shows a growth of 30.3 % from the base year (2025) to 2040. This reduction in demand compared to the two scenarios indicates a reflection of how much electricity power demand could be if certain development conditions failed to be realized in the economy. In general, both results show a rapid increase in power demand compared to the base year. To address this increasing demand, a supply-side demand analysis can be done for reference and aggressive scenarios. The analysis result indicated that by 2040, supply-side demand from the national grid will increase by 93.5 % and 175.9 % for reference and aggressive scenarios, respectively, compared to the base year 2025 demand. Due to the huge gap between the supply and demand in the country, onsite off-grid generation can be considered to cover 25 % of the demand in the economic zone. Hence, with the support of off-grid generation, the demand from the national grid was reduced to 45 % and 107 % for reference and aggressive scenarios with the support of onsite generation. Hence, this research clearly shows that there is a serious need for large scale electricity generation and distribution planning and preparation to meet the continually increasing electric power demand in a sustainable manner to accommodate the growth and change required to develop the modern economic zones in the country.

* Corresponding author.
E-mail addresses: meskerem.tadesse@astu.edu.et (M.T. Gebre), junhwang@snu.ac.kr (J. Hwang), gbiru@yahoo.co.uk (G. Biru).

https://doi.org/10.1016/j.heliyon.2024.e25364
Received 18 August 2023; Received in revised form 29 December 2023; Accepted 25 January 2024
Available online 1 February 2024

1. Introduction

Energy is well known to play a significant role in the economic and social advancement of every economy in the world [1]. Due to industrialization and globalization, the demand for energy has been rising steadily for decades. As indicated in Ref. [2], there is a good chance that between 2015 and 2035, global economic growth will increase by almost 30 %. Hence the prediction of energy demand should, target optimizing the energy system communications, which enables us to get valuable information for scheduling the energy supply system [3]. Therefore, it was crucial is to anticipate and model long-term energy demand in future energy use and design. In addition to making recommendations for energy policy, it also helps with production planning, grid management, trading, efficient energy use, and reliability and efficiency improvement [4].

Ethiopia, a nation in East Africa, experienced rapid economic growth in recent years, which increased the country's industrial activity and electricity demand [5]. However, like many other developing countries, Ethiopia has been facing significant challenges in ensuring reliable and sustainable power supply for its citizens [6]. Despite the country's abundant renewable energy resources and significant investment in the reliability of power systems and expanded access to electricity. The issue of power system reliability has been caused by a number of factors, and in recent years, issues related to the reliability of power systems have persisted in the power sector. These problems include frequent power outages, load shedding, voltage fluctuations, lack of redundancy in the power grid, and limited access to electricity. Only 51.1 % of the population had access to electricity in 2020, with rates even lower in rural areas, according to a World Bank progress report. The report also noted a critical need for improvements to the country's power system infrastructure, including insufficient generation capacity, weak transmission systems, broken equipment, and high electricity demand. These challenges are compounded by the country's rapidly growing population and economy, which are putting increasing pressure on the power sector [7].

The industrial sector in Ethiopia also faces several power system challenges, like frequent and long-lasting power outages, voltage fluctuations, harmonic distortion, and low energy efficiency. As indicated in Ref. [8] numerous factors, including load changes, equipment malfunctions, and lightning strikes, cause voltage fluctuations. Harmonic distortion is also another challenge that occurs when non-linear loads, such as variable-speed drives and computers, inject harmonics into the power system. This can cause overheating of transformers and motors, which leads to equipment failure and downtime. Harmonic distortion can also cause interference with communication systems and other sensitive equipment [9]. T. G. Tilla [10] underscored that power quality issues like voltage sags, surges, interruptions, and harmonic distortion are also other problems for the economic zone and industries, since these issues lead to equipment damage, production downtime, and increased maintenance costs. Undoubtedly, a lot of industrial and economic zones use a lot of energy, necessitating a steady and effective supply system. Consequently, enhancing energy efficiency can aid in decreasing costs and the impact on the environment. M. A. H. Monda et al. [11] argued that common strategies for improving energy efficiency include, implementing energy-efficient equipment, optimizing processes, and improving energy management. Hence, power demand forecasting plays a critical role in addressing those challenges related to electricity demand in industrial or economic zones.

Accurate demand forecasting enables power system operators to anticipate energy consumption patterns and plan accordingly, ensuring that there is sufficient supply to meet demand. This is particularly important in industrial or economic zones where energy demand can be highly variable and difficult to predict. By using effective forecasting techniques, operators can make more informed decisions about when to generate or purchase electricity, how much to produce, and how to distribute it. This can help reduce costs, improve energy efficiency, and ensure a reliable and stable power supply for businesses and consumers. Studies have shown that accurate electricity demand forecasting can lead to significant economic benefits, such as increased operational efficiency, reduced interruptions, and improved customer satisfaction [12]. It can also help with the integration of renewable energy sources, which are very variable and need careful planning to ensure a consistent supply of energy [13].

Forecasting is a crucial planning tool because it can increase the constancy of management decisions [14]. Planning for efficient and secure operation of the power distribution systems includes forecasting the consumption load as well. There are three categories of studies on energy consumption in the literature, as stated in Ref. [15]: long-term, mid-term, and short-term. For resource management and development investments, long-term prediction is frequently used [16]. Whereas mid-term and short-term forecasting are usually applied for planning the power production resources and scheduling and analyzing the distribution networks, respectively. The forecasted load in the mid-term and long-term is commonly used as an important reference value in policy formulation associated with national economic and economic development strategies [17].

Forecasting is crucial for predicting future electric loads based on historical energy consumption trends [18]. It is dependent on a variety of variables that can identify patterns and connections between demand and separate economic, technological, and demographic variables. Therefore, accurate future energy forecasting is necessary for effective planning of energy distribution in order to balance energy supply and demand in the industry. Just as underestimating energy consumption leads to power outages, which have a detrimental effect on the economy and daily life of society and result in consumer dissatisfaction, overestimating energy demand could lead to the waste of human and financial resources [18]. Selecting an appropriate model for future energy consumption forecasts based on nonlinear data is one of the issues facing' the production and distribution of power [19].

In most of the underdeveloped countries, energy demand has increased over the past decade with growth in population and development in the economy and industry [20]. However, traditional energy dependence, inefficient supply, inefficient system performance, restricted access, and rapid urbanization present challenges for countries like Ethiopia when attempting to forecast energy demand [21]. Ethiopia is a country among the fastest-growing economies, with an average annual rate of economic growth of 10.3 % over the 2005/06–2015/16 period [22]. Therefore, with the increasing population size and rapid urbanization needs, a detailed energy demand forecast and analysis for the newly developed industries and economic zones is critical.

In countries like Ethiopia with inefficient distribution systems, the main goal of predicting power demand for industries and economic zones is primarily to accurately predict future electricity consumption patterns. This aids in efficiently planning and managing power generation, distribution, and consumption in order to maximize operational efficiency. By accurately forecasting power demand, the economic zone or end-users can understand when and how much electricity will be needed. This enables them to optimize their operations, schedule production processes, and allocate resources effectively. It is also used to avoid disruptions, since accurate power demand forecasting allows end-users to avoid power shortages or blackouts. By ensuring a sufficient power supply, it can prevent disruptions in production processes, minimize downtime, and maintain a smooth workflow. In addition, accurate power demand forecasting helps optimize energy usage of the economic zone, leading to energy savings and cost reduction. By identifying low-demand periods, users can schedule energy-intensive processes or machinery during off-peak hours when electricity rates are lower. In addition, reliable power demand forecasts assist end-users in planning their long-term infrastructure requirements and investments. Thus, this study aims to forecast and analyze the future power demand and supply needed for the newly constructed Economic Zone (GSEZ) for the coming 15 years. It also aims to lay the groundwork for generation planning which includes the current power system challenges and shortage, to address the community's need. This study also gives an insight into automating the grid system with smart grid technology in the new economic zone.

2. Materials and methods

2.1. Description of the site

The study was conducted in the GSEZ, which is currently under construction and located between Modjo and Adama towns in central Ethiopia indicated in, located 38 miles southeast of Ethiopia's capital, Addis Ababa, with a latitude of 80 39′N and a longitude of 3905E' at an elevation between 1788 and 1825 m above sea level. It covers an area of about 23,639.93 ha. Fig. 1 indicated the map location of the economic zone between ADDIS and ADMA city.

The site construction of the economic zone has four phases. The first phase is the startup phase, which covers 3150.80 ha; the second phase, called the short-term phase, covers 5056.37 ha. Similarly, the third phase is the medium-term phase, which covers 7416.33 ha, and the fourth phase is called the long-term phase, which covers 8067.05 ha of the catchment area. As per the GSEZ working document, the first phase (phase I) will incorporate the development of short-term functions, which are production and manufacturing functions, agro-processing and value-chain development functions, and free trade functions. The second phase (phase II) of the construction is supposed to develop medium- and long-term functions such as transport networking functions, production service functions, scientific and technological innovation functions, and urban living service functions. Table 1 indicates the overall stages and planned implementation period of the economic zone.

2.1.1. Energy resource potential for the study area

Ethiopia is currently experiencing encouraging economic growth, but in order to sustain it, the energy supply will need to be rapidly increased. Almost all of Ethiopia's current energy production is hydroelectric. According to World Bank data on electricity access, only 28.9 % of urban residents had access to electricity in 2012. This percentage increased to 29 % in 2015. The World Bank report [23], released in 2018, estimates that 45 % of the urban population has access to electricity and is connected to the national grid. However, there are significant regional differences regarding access to electricity, with urban areas having much higher rates of access than rural areas [24]. With the government's goal of achieving universal access to electricity by 2025, Ethiopia has made significant strides in increasing access to electricity in recent years [25]. The government has developed and put into effect a number of policies and programs aimed at expanding the national grid and promoting off-grid solutions like solar and wind power. It is a fact that Ethiopia is gifted with huge renewable energy resources like hydro, wind, geothermal, solar, and bioenergy.

According to Awoldie Yalew in Ref. [26], the estimated potential for hydro, wind, geothermal, and solar energy is, (45,000 MW, 1035 GW, 7000 MW, and 5.2 kWh/ m^2) respectively. However, the country has still used a very small amount of its potential. Currently, Ethiopian Electric Power possesses 20 power plants, as shown in Table 2, thereby generating a total of 4228 MW of

Fig. 1. Location of GSEZ between Modjo and Adama city.

Table 1
Overall stage of GSEZ.

No	Stage/phase	Implementation period in year	from	Proposed area to be developed/he	% share
1	Phase I (startup)	5–10	2021–2025	3150.8	13.3
2	Phase II (short term)	10–20	2026–2030	5056.37	21.3
3	Phase III (Medium term)	20–50	2030–2050	7416.18	31.3
4	Phase IV(Long term)	>50	After 2050	8064.99	34.1
	Total			23688.34	100

Source: GSEZ working document

electricity nationwide. Among the 20 power plants, 14 are hydroelectric, with a total installed capacity of 3810 MW. The remaining plants include wind plants with an installed capacity of 324 MW on aggregate and 87 MW and 7.3 MW generated from diesel and geothermal plants, respectively. Table 2 shows the existing power generation plants and their capacities.

There are several electric power potentials around GADA in the vicinity of the Special Economic Zone (GSEZ). KOKA hydropower, Adama I and II wind power, Awash II and III hydropower, and the Aluto-Langano geothermal plant. These resources are found in the vicinity of Modjo substation, Fig. 2, indicated the current existing power infrastructure around the GSEZ which offers an opportunity for future system expansion and automation on the substation. Among the identified nearby energy resources, wind and solar power alternatives are identified as the two main electric power alternatives to generate onsite off-grid power for the new economic zone.

2.2. Methods and approaches

The study is focused on analyzing and forecasting the power demand in GSEZ from the supply and consumer sides. The Long-range Energy Alternatives Planning (LEAP) model is used to analyze the supply and demand pathway and to forecast the power demand for the newly constructed economic zone, it identifies factors that impact the power demand pathway of the model in the proposed scenarios. Choosing and creating suitable scenarios is a crucial aspect of accurately describing the characteristics of the power system in developing nations [27]. Neglecting to accurately represent the future and influencing factors of the energy system has the potential to generate inaccurate outcomes and suggest misguided policies. In order to understand how the economic zone in a particular country will develop, scenarios are consequently created by analyzing various factors in a structured manner. In order to develop a comprehensive understanding of the context, this analysis looks at the energy requirements, socioeconomic development priorities, technological advancement, and future governmental policy [28].

Long-term forecasting is essential for proactive policy development and supply expansion. It also demonstrates how much the adoption of new technologies affects demand [29]. In this study, a quantitative methodology is used to forecast a long-term power demand over 15 years. A power demand forecast is made for various loads in the sector; the sectoral category is directly taken from the GSEZ working document. Based on the number of households, the residential sector is classified into three sub-sectors (high-density, mid-density, and low-density). This classification considers the population density and the living standards of the residence. The high dens are the residences where the most populated residents in the economic zone are expected to live and take the most shares, followed by the mid-dens and low-dens, where residents with a high living standard are expected to live. Based on the load demand, the industrial sector is also classified under heavy load, medium load, and light load that are connected to the power grid at various voltage

Table 2
Power generation plant and its capacity.

Power plant	Generation location	Generation Capacity in MW
Hydro	Aba Samuel	6.6
	Gilgal gibe III	1870
	Beles	460
	Gilgal gibe II	420
	Tekeze	300
	Gilgal gibe I	184
	Melka wakena	153
	Fincha	134
	Amerti Neshi	95
	Tis abayII	73
	koka	43.2
	Awash II	32
	Awash III	32
	Tis abay	14.4
Wind	Adama II	153
	Ashegoda	120
	Adama I	51
Geothermal	Aluto Geotermal	7.3
Diesel		104
Total		4244

Source [41].

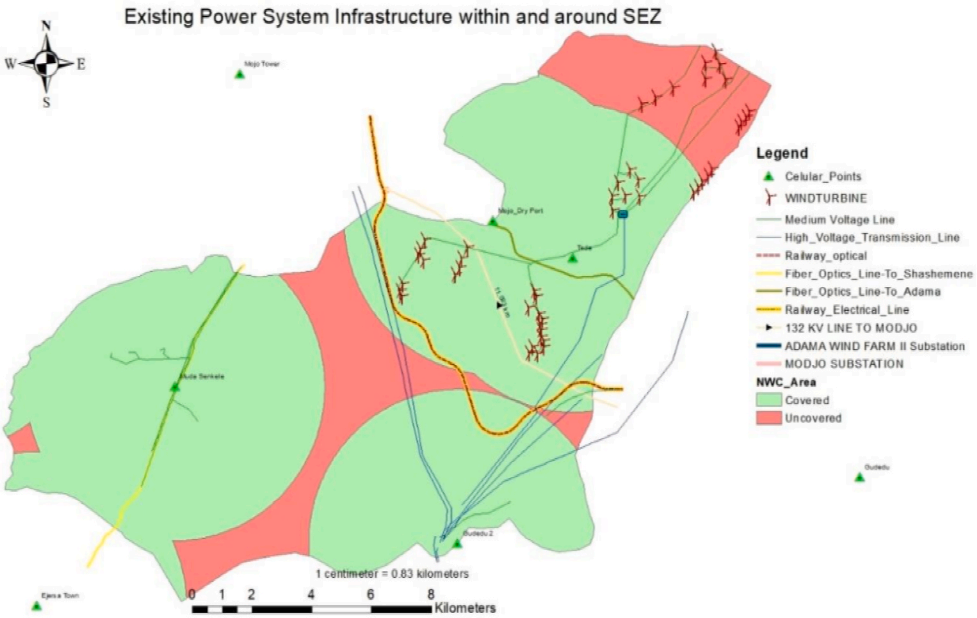

Fig. 2. Existing power infrastructure within the GSEZ area. (Source GSEZ document).

levels, as shown in Fig. 3.Thus, a demand forecast is made for the residential (REt), industrial (IEt), and general business sectors (GBEt), counting transport, service, commercial, recreational, free trade, and administration. Here, the sectors power demand are represented as residential power demand (RPD_t), Industrial power demand (IPD_t), and General business sector power demand ($GBPD_t$), counting transport, service, commercial, recreational, free trade, and administration. Hence, the total forecasted electric power ($TEPD_t$) is determined by adding each of the forecasts in the given sectors as given in equation (1).

$$TEPD_t = TRPD_t + TBPD_t \tag{1}$$

$$TRPD_t = HDPD_t + MDPD_t + LDPD_t \tag{2}$$

$$TBPD_t = TIPD_t + GBPD_t \tag{3}$$

$$TIPD_t = HIPD_t + MIPD_t + LIPD_t \tag{4}$$

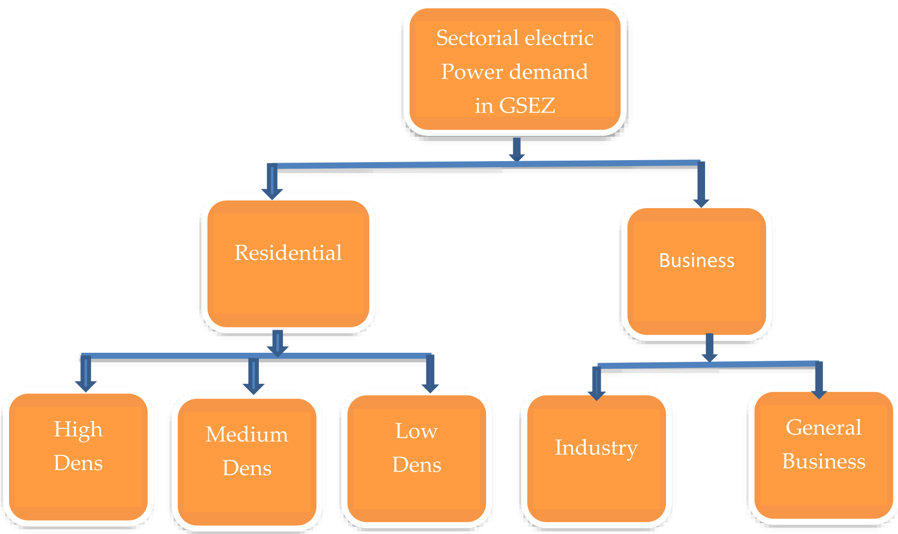

Fig. 3. Overall GSEZ Power demand classifications.

Where, $TEPD_t$ is the total power demand in a year t, $TRPD_t$, in equation (2), indicates the summation of the HD, MD, and LD residential power demand in a year t, $TBPD_t$, is the total business sector electric power demand indicated in equation (3). $HDPD_t$, the high density power demand, $MDPD_t$, is the medium density power demand, $LDPD_t$, the low density power demand. The total industrial power demand indicated in equation (4) is the summation of $HIPD_t$, is heavy industrial power demand, $MIPD_t$ medium industrial power demand, and $LIPD_t$, light industrial load demand at the year t. The total transmission and distribution losses should be taken into account when creating the forecast model, and evaluated in accordance with governmental loss reduction targets, and added to the overall power demand. Thus the final power demand is the summation of the total power demand plus the total distribution loss given in equation (5).

$$FPD_t = TPD_t + TDL_t \tag{5}$$

According to Swan and Ugursal [30], top-down and bottom-up methodological approaches are considered for modelling residential power demand. The top-down approach regards the residential sector as a consumer of energy without considering the distinct behavior of end-users, whereas the bottom-up approach assumes energy consumption estimation by considering a comparative range of techno-economic factors. Bottom-up forecasting is a method of estimating a power demand that determines the future performance of a company applied to specific customer groups in the model [31]. For this specific study, a simulation-based bottom-up model is employed to study the power demand by the sectors. The residential model explicitly includes the representation of various alternative appliances, such as cooking devices, lighting fixtures, refrigerators, and other similar appliances. The model also accounts for a collective representation of all appliances that are not individually modeled.

2.2.1. Bottom-up forecasting approach

Bottom-up forecasting is a widely used method for forecasting power for both sides (supply and demand), which involves making individual forecasts for each customer or group of customers and aggregating the results to get the total forecast for the sectors. The paper [32] gives a comprehensive overview of different methods and models used in bottom-up forecasting, including data-driven techniques and simulation-based approaches. In the residential sector, for example, bottom-up forecasting involves estimating the power consumption of individual households based on factors such as the number of residents, the size of the home, and the types of appliances used. In the industrial sector, the method might involve analyzing the power consumption patterns of individual factories and plants and using this information to estimate the overall demand.

Article [33] describes an approach of bottom-up forecasting for industrial power demand, which involves analyzing historical data on the energy usage patterns of individual factories and estimating future demand based on expected changes in production levels and other factors. In the business sector, bottom-up forecasting might involve analyzing the energy usage patterns of individual offices, stores, or other commercial buildings to estimate the overall demand. F. L. C. Silva et al. [34] describes a bottom-up forecasting method that takes data from end-use devices in commercial buildings to estimate overall power demand. This method is found to be effective in accurately predicting demand and identifying potential areas for improvements of energy efficiency. Hence bottom-up forecasting can be a highly effective method for accurately predicting power demand in different sectors, as it considers the unique characteristics and needs of each customer or group of customers [35]. A bottom-up method is a detailed approach to forecasting power demand that involves analyzing the energy consumption patterns of individual consumers and aggregating them to estimate the total energy demand for a specific area. Here's how the bottom-up method works.

A. **Data collection**: The first step in the bottom-up approach is to collecting data on power consumption patterns from individual consumers, such as households, commercial buildings, and industrial plants. Such data can be obtained through surveys, energy audits, or smart meter readings.
B. **Categorization:** The second step in the bottom-up approach is categorization. Here the collated data is then categorized by consumer type, consumption level, and other relevant factors, such as time of day, day of the week, year, and season etc.
C. **Analysis and modeling**: The categorized data is analyzed and modeled to identify patterns and trends in energy consumption for each consumer type and location. This can involve statistical analyses, such as regression analysis, time-series analysis, and cluster analysis.
D. **Aggregation**: once the analysis and modeling have been accomplished, the consumed data for each consumer type and location is aggregated to guess the total energy need for the specific area being forecasted. This can be done by adding up the energy consumption for each consumer type and location or by using a more sophisticated modeling approach, such as a geographic information system (GIS) or a network flow model.
E. **Validation and refinement**: the last step in bottom-up modeling approach, where the forecasted energy demand is validated against historical data and refined based on any discrepancies or changes in consumer behavior or other factors that may affect energy consumption patterns.

2.2.2. Power demand forecasting model, data and scenarios

There are different software tools applied to predict long-term power demand forecasting. Among them,

LEAP, the Long-range Energy Alternatives Planning System, is a software tool applied for power demand.

Forecasting and analysis [36]. An integrated modeling tool called LEAP is used to keep track of energy production, consumption, and resource extraction across the entire economy [37–39]. According to Ref. [40], LEAP is a widely used modelling tool for predicting energy demand and conducting scenario analysis in developing economies. Additionally, it showed how heavily social, economic, and new technological innovations influence power demand in developing nations. The investigation should use a scenario analysis that can be developed by studying the country's socioeconomic context and gives an understanding of the high uncertainties of future power demand because demand prediction is subject to uncertainties that are challenging to predict. Additionally, it is imperative that end users are represented technologically and sector-wise at a disaggregated level [41]. It also includes distinctions between residential and industrial classes, economic and technological changes, and supply shortage characteristics [42]. In this regard, LEAP is a suitable modelling tool for conducting analyses of power demand. Therefore, this study made use of this tool to investigate and project the GSEZ's energy needs through the year 2040.

2.2.2.1. Power demand forecasting model. Fig. 5 illustrates the developed Power Demand Model for various sectors. In the model, the sectoral demand is categorized mainly as residential and business sectors. The first sector is the residential sector, which integrates three sub-sectors classified as high-dens, medium-dens, and low-dens as per the working document classification. Each residential sub-sector is also classified under four end-used categories, i.e., cooking, lighting, refrigeration, and other devices that represent an aggregate of all appliances not explicitly modeled. (e.g., air conditioning, dish and cloth washing/drying, TVs, iron, etc.).

The second largest sector is the business sector, which includes the industrial and general business sub-sectors in GSEZ. As per the working document, the industrial sub-sector also has three different categories per its required voltage level, called the heavy load industry, the medium load industry, and the light load industry. The other sub-sector is the general business sector, which includes (transport, commercial, service, recreational, administration, and free trade). According to the GSEZ feasibility study document, 166 MW of yearly power should be shared between the three sectors in the base year. Here, the residential sector shared 23.7 MW in the base year. According to the GSEZ working document, this power will be shared among the three sub-sectors called high-dens, medium-dens, and low-dens shares: 45 %, 35 %, and 20 % of the total residential yearly power share of (10.7 MW, 8.3 MW, and 4.7 MW) per household respectively. The industrial sector is the high-power consuming sector which shares 57.8 % of total power in 2025, which equals 96 MW. This power is shared with the industrial sub-sectors called heavy-load, medium-load, and light-load industries, with a share of 45 %, 35 %, and 20 % of the total demand equals 43.2 MW, 33.6 MW and 19.2 MW, respectively. The General Business sector is the largest next to the industrial sector in GSEZ, which shares 27.9 % of the total estimated power of 46.3 MW in the base year shared along the unspecified sub-sectors.

For this specific study, an end-used device accounting technique in LEAP was applied with a bottom-up data structure approach. Data inputs like population size, the share of households, and the load given to the activity level variable of the LEAP software have been subsumed. Energy consumption data feed to the final energy intensity variable of the LEAP modeling tool. The data input structure for the industrial and general business sectors considers the number of companies and employees who joined the economic zone in the base year and the load shared across sectors entered to the appliance level of the LEAP software based on different applications or end-users.

2.2.2.2. Supply-side demand model. Due to a lack of integrated power system planning and an unbalanced supply and demand for energy, Ethiopia is now experiencing an electrical crisis. In this study, the Long-range Energy Alternatives Planning System (LEAP) is used to develop GSEZ supply-side demand for the period 2025–2040. For the supply-side analysis, two scenarios (reference and aggressive) are considered to depict the future supply pathways and provide insight. Fig. 4 illustrates the developed model for supply-side demand analysis. For this specific study, the national grid and onsite off-grid generation alternatives (wind and solar) are proposed to address sectoral power demand in a sustainable way. Based on the estimated demand in the working document, the study model considers that 75 % of the total demand will be supplied from the national grid, and the remaining 25 % will be covered by off-grid stand-alone generation alternatives as shown in Fig. 6. To do so, appropriate supply forecasting will be needed to evaluate the

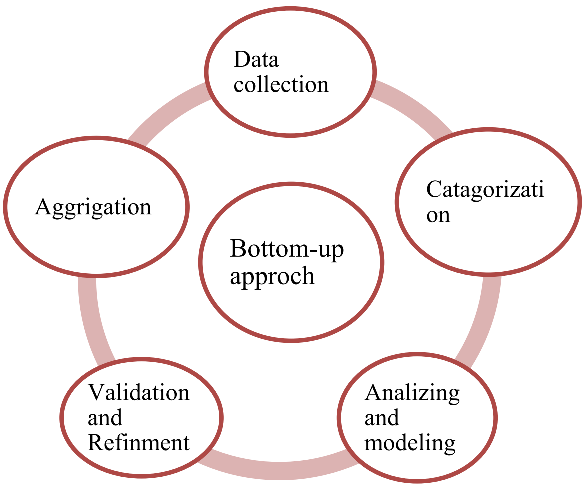

Fig. 4. Basic steps in bottom-up method approach.

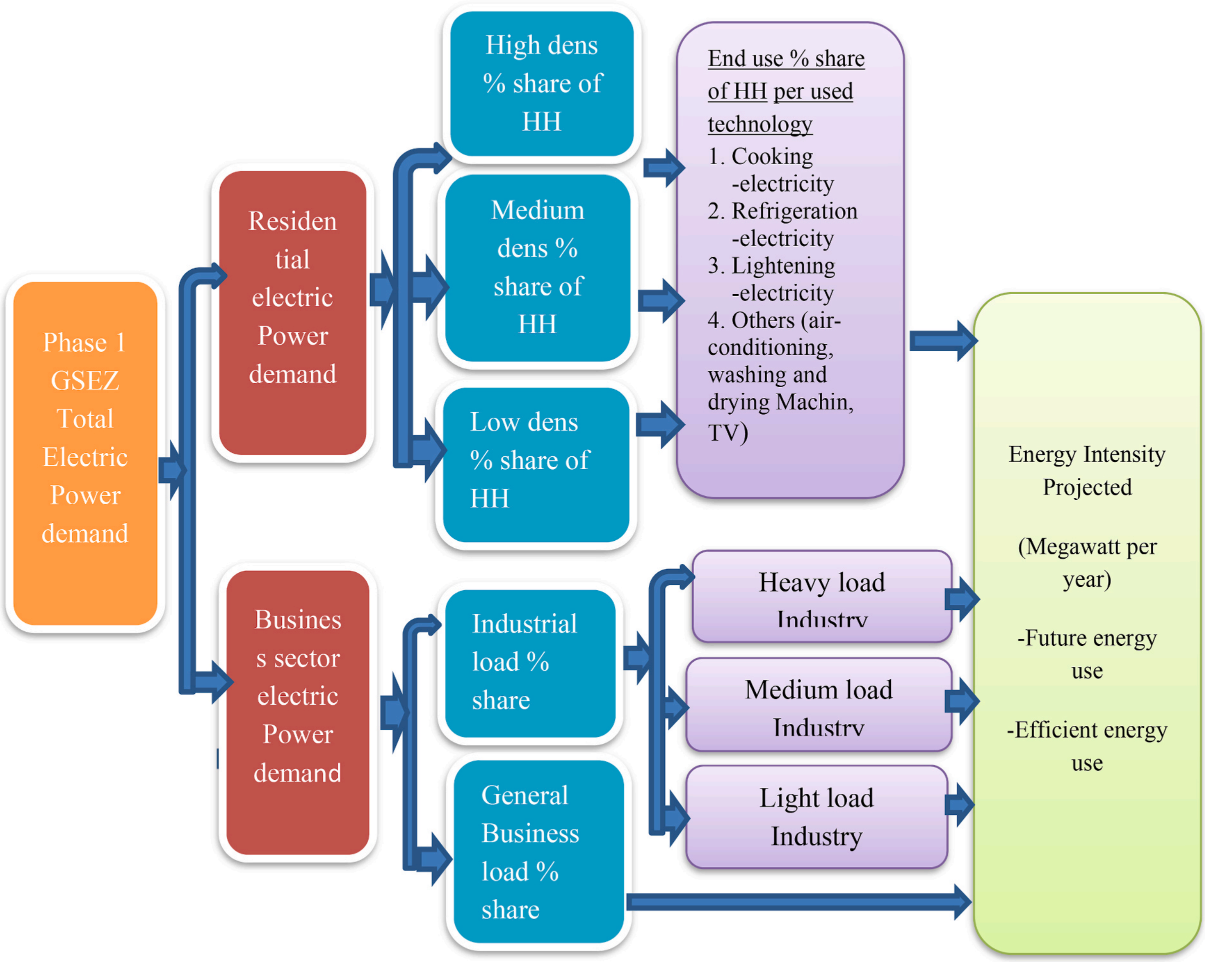

Fig. 5. The developed LEAP energy demand tree for the all sectors in GSEZ.

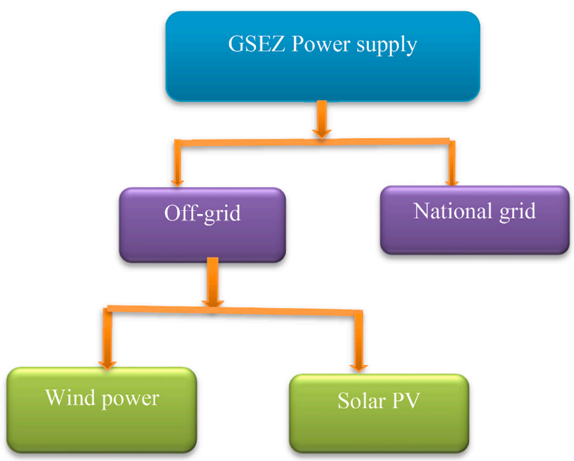

Fig. 6. GSEZ supply-side demand model developed in LEAP software.

economic zone's future supply pathway in line with the increasing demand for the supply needed. Fig. 6, shows the supply-side demand model of GSEZ developed in LEAP software.

2.2.2.3. Data collection. Since the GSEZ is a new economic zone under construction, it is not easy to get historical data on energy consumption in the GSEZ. However, as per the working document, historical data related to the formation of companies and industrial parks is taken from basis throughout the country and used as a basis for the feasibility study of the document. For this specific study, the sectoral power consumption data was taken from GSEZ working documents. The Ministry of Water, Irrigation, and Electricity (MoWIE), the Ethiopian Energy Authority (EEA), Ethiopian Electric Power (EEP), Ethiopian Electric Utility (EEU), and the National Load Dispatch Centre (NLDC), as well as other sectors like the Central Statistics Agency of Ethiopia (CSAE), the National Bank of Ethiopia (NBE), and other significant national and international sources, were used to collect additional significant data [43].

2.2.2.3.1. Key assumptions. The Leap software applied in this study contains four modules, which were used for data inputs: key assumptions, demand, transformation, and resources. Numerous socioeconomic factors that influence the level of final energy consumption are included in the module for the key assumption, including the population in the economic zone, the number of tents (company), the number of households, GDP, and other comparable information [44]. The demand module also contains the various sectors and customer categories called residential, industrial, and general business (GB). For this specific study, from the 7 million estimated population of all phases in GSEZ, 20 % are expected to join the economic zone in the start-up phase. The average household size is also estimated based on an average household size estimate in Ethiopia, which is estimated at 4.7 persons per household [45,46]. As per the working document, 0.2 million households are estimated to live in the GSEZ at the start-up (phase 1). Additionally, 60 companies with 600 employees are expected to join the industrial sector in the base year. For this specific study, end-used device accounting techniques in LEAP will be applied with a bottom-up data structure approach, and the estimated data added to the demand module of LEAP modeling software. In this study, the economic zone's demand is projected over a 15-year period, from the year 2025 through the year 2040, with 2025 serving as the first forecast year.

2.2.2.3.2. Appliance activity level and energy intensity for the first phase. In this specific study, an appliance activity level indicates the level that shows how much residential, industrial, and general business sectors share electric power for the given specific period. In this case, the LEAP software's activity level variable receives data input such as population size, the percentage of households, and annual GDP. Here the historical data for population growth, the percentage of households and the annual GDP are taken from the MFMOD database, World Bank WDI and GEM databases, IMF shown in Table 3.

Energy intensity is a gauge of an economy's energy inefficiency, calculated as energy units per unit of GDP. The energy intensity section is where the data on the energy consumption of each sector is analyzed and assessed. The consumption data for the startup year (2025) for the residential, industrial, and general business sectors are thus displayed in Table 4.

According to the LEAP demand tree depicted in Fig. 5, the necessary information on the domestic, industrial, and general business sectors is entered. In light of this, the primary end-uses or appliance categories for the residential sector are divided into a variety of appliance categories (cooking, lighting, refrigeration, and others) with varying degrees of penetration and energy consumption in a typical household. The estimated total power demand for the startup phase (phase I), according to the GSEZ feasibility study document, is 166 MW. This power will be shared across the residential, industrial, and general business sectors. Here the residential sector shares 23.7 MW of the total load for activities like cooking, lighting, refrigeration, and other household activities (air conditioning, dishes, cloth washing and drying, TV, iron, etc.). The residential sector in the economic zone, is further classified into three different sub-sectors, namely high dens (HD), medium dens (MD), and low dens (LD). The power demand estimate across sectors can be done, based on factors affecting the total power consumption. These factors include the population size, GDP, system efficiency, the type of technology used, and the economic level of the household in the sector, etc. Owing to the fact that high-dens has the highest population density, followed by medium-dens and low-dens sub-sectors, the high-dens residential sector's power consumption is estimated. It is evident that households in Ethiopia do not use electricity exclusively for cooking. Hence, natural gas, charcoal, and LPG stoves are also used for cooking and baking. However for lighting, refrigeration, and other electronic household devices (air-conditioning, dish-washing/drying, cloth washing/drying, ironing, TV, etc.), use 100 % electricity.

2.2.2.4. Demand forecast scenarios. The power demand needed in each category varies with various factors and decisions. To capture this variance, it is necessary to consider appropriate scenarios that consider facts and realities potentially expected to occur in the economic zone [47]. These are the country's political situation, access to electric power, technological advancement, reliability

Table 3
Growth indicators from (2011–2021) in Ethiopia.

Selected indicator	Average 00–15	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18	2018/19	2019/20E	2020/21E
GDP growth (annual %)	9.0	8.6	10.6	10.3	10.4	8.0	10.1	7.7	9.0	6.1	2.3
GDP per capita growth (annual %, real)	6.0	5.6	7.5	7.2	7.4	5.1	7.2	4.9	6.2	3.4	−0.2
Population, total (millions)	82.5	92.7	95.4	98.1	100.8	103.6	106.4	109.2	112.1	115.0	117.9
Population Growth (annual %)	2.8	2.9	2.9	2.8	2.8	2.7	2.7	2.7	2.6	2.6	2.5

Sources: MFMOD Database, World Bank WDI and GEM databases, IMF

Table 4
Sectoral category and power demand for base year (2025) estimate taken from GSEZ working document.

No	GSEZ Sectoral demand category	Sub-sector category	Demand for base(start-up) year in MW	% share
1	Residential power demand/HH		23.7	100 %
		High dens	10.5	45
		Medium dens	8.2	35
		Low dens	4.7	20
2	Industrial power demand/tent		96	100 %
		Heavy load industry	42.2	45
		Medium load industry	33.6	35
		Light load industry	19.2	20
3	General business power demand		46.3	100 %

enhancement through smart-grid options, population size, etc. Here the scenarios are based on development recommendations and policy direction indication. They also show what demand would be if certain conditions occur and fail to happen. In this study, three scenarios are identified, where one is the reference (baseline), and the other two alternatives (aggressive and conservative) scenarios that are considered for the forecasting of the GSEZ's future energy demand in GSEZ.

2.2.2.4.1. Baseline scenario. The Baseline Scenario is the reference scenario used as a base for the others in the study. The baseline scenario assumes that the Special Economic Zone (SEZ) is designed and operated as planned, with all required infrastructure. Additionally, it takes into account backup decisions like smart-grid options and privately generated on-site renewable power. It also assumes the current power shortages and interruptions, which may likely persist in the future. For this analysis, future GDP growth rates are predicted using historical trends [48], taking into account forecasts from the IMF and GSEZ documents. For 2030, 2035, and 2040, respectively, the estimated growth rates of the total GDP of 7 %, 9 %, and 4 % are predicated. According to the document, the estimated rates of per capita income growth will be 7 % in 2025–2030, 9 % in 2031–2035, and 5 % in 2036–2040. As a result of the larger economy, the slower growth rate used for later years is related to saturation. For the years until 2030, 2035, and 2040, respectively, the customer growth rate assumptions for the light load industry are 5 %, 7 %, and 4 %; for the medium load industry, 8 %, 7 %, and 5 %; for the heavy load industry, 12 %, 8 %, and 6 %; and for general business, 6 %, 4 %, and 3 % are estimated for the year 2030, 2035, and 2040, respectively. Here, household energy consumption decreases as the energy efficiency improves. This fact makes it evident that electricity will be the best choice for household activities since it is cheap and efficient compared to other energy alternatives. Here, the analysis is done for 15 years with an assumed population annual growth rate of 4 % in the GSEZ working document. Fig. 7 shows the total power demand for all sectors in the baseline scenario.

2.2.2.4.2. Aggressive scenario. The aggressive scenario is one of the two alternative scenarios, which assumes conducive and attractive economic conditions in Ethiopia, particularly at GSEZ. It also assumes best practice in the design, development and operations of the infrastructure. Based on the working document, the scenario assumes a 6 % growth rate in the economic zone that indicates a continuous power demand increment in the sector. It also considers the SEZ will generate onsite off-grid renewable energy and smart grid technology options for improving system reliability. The aggressive scenario assumes the growth rate in GDP, customer, and per-capital income are increased by 2 % about the baseline scenario and 6 % from the first year of the forecast. Fig. 8 below indicates the total power demand required under the aggressive scenario.

2.2.2.4.3. Conservative scenario. The conservative scenario is the second alternative scenario, which gives a realistic reflection of existing facts. It indicates the uncertainty about future demand in the SEZ. It also shows what could happen if the assumptions in the reference (baseline) scenario (political stability, technological advancement, onsite renewable energy generation, smart grid technology, etc.) failed to be satisfied. The rate of population growth is predicted to be 2 %. For this scenario, the rate of growth in GDP, customer, and per capita income is reduced by 2 % compared to the base line. Fig. 9 below shows the power demand forecast for the

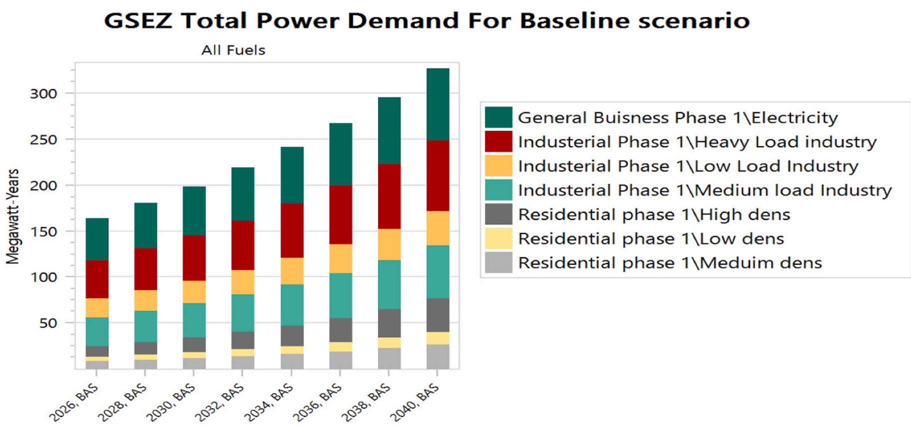

Fig. 7. GSEZ power demand forecast for baseline scenario for phase 1.

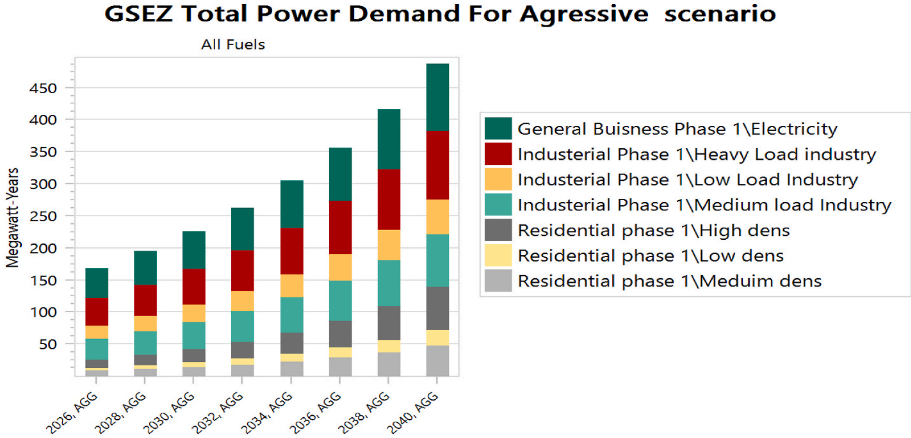

Fig. 8. GSEZ electric power demand forecast for aggressive scenario for phase1.

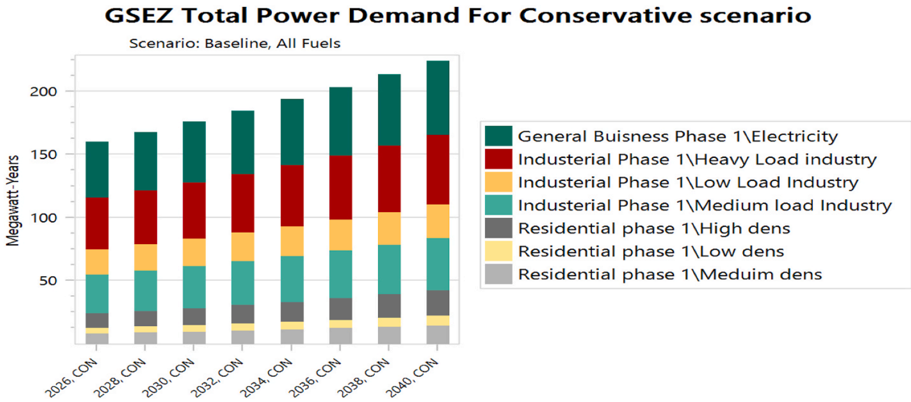

Fig. 9. GSEZ electric power demand forecast for conservative scenarios for phase1.

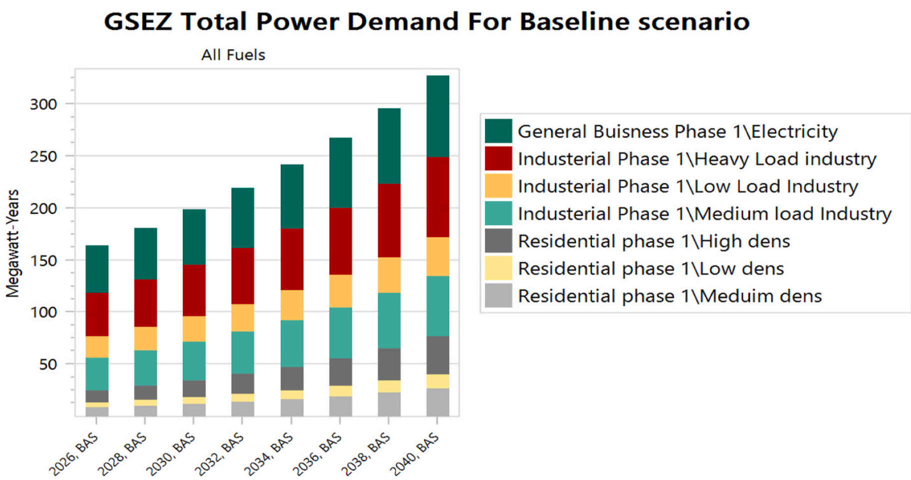

Fig. 10. Phase1 GSEZ power demand forecasted for baseline scenario.

conservative scenarios in GSEZ.

3. Result and discussion

3.1. Demand prediction

3.1.1. Demand prediction under baseline scenario

This study provides a 15-year prediction for the GSEZ electricity consumption using 2025 as the base year. To evaluate the sectoral demand, three scenarios are considered, and the electric power demand for each scenario and end-user categories has been described. The analysis results for the baseline scenario show a 156 MW demand in the base year (2025), which increased by 52.2 % by 2040 to 327. Fig. 10 displays the estimated energy demand by sector for the baseline scenarios with the given category.

The study's findings, in Table 5, indicate that demand for all sectors (residential, industrial, and general companies) climbed gradually during the anticipated year.

3.1.1.1. Industrial load forecast under baseline scenario. The industrial sector has the largest share in the baseline scenario, contributing 111.3 MW in 2030 and 172 MW in 2040, or 34 % and 52.6 % of the total electric demand. The analysis result indicated the heavy load industry is the highest load-consuming sub-sector, followed by the medium load and light load industries shown in Table 6. Like other sectors in the baseline scenario, the industrial sector shows continuous growth in demand for the specified years in the analysis. Fig. 11 below shows the industrial load demand forecast in MW/year for the baseline scenario.

3.1.1.2. General business load forecast under baseline scenario. The second high-demand sector under the baseline scenario is the General Business sector with a share of 64 MW in 2030 and 78 MW in 2040, which account for 10.6 % and 16 % of the total energy demand in 2030 and 2040, respectively. It shows a continuum of demand growth like other sectors in the baseline scenario. The general business sector includes commercial, transport, service, and free trade in the economic zone. Fig. 12 shows, the power demand for the general business sector for the baseline scenario. Table 7 below also shows the analysis result of the general business sector under the baseline scenario.

3.1.1.3. Residential power demand forecast under baseline scenario. The residential sector is the third-highest consumer of electricity in the economic zone. The analysis result indicated that residential sector demand increased by 69.8 % from 23.4 MW in the base year to 77.2 MW in 2040. This growth is comparable to the population density in the economic zone and is consistent with what is anticipated there. Here, a continuous increment in demand is observed for all sub-sectors in the baseline scenario. As a result, we see that the high-density residential sub-sector shares the maximum power among the residential sub-sectors, followed by the medium-density and light-density sub-sectors, which indicates that as the population size increases, the power demand also increases. Fig. 13 and Table 8, indicate the residential power demand forecasted under the baseline scenario.

3.1.2. Demand prediction under the aggressive scenario

The aggressive scenario is one of the two alternative scenarios which share maximum power in the sector. In the aggressive scenario, the total forecasted power in the base year (2025) is 156 MW. The aggressive scenario is one of the two alternative scenarios that share maximum power in the sector. In the aggressive scenario, the total forecasted power in the base year (2025) is 156 MW and is projected to be 487 MW by 2040, with a growth of 68 % compared to the demand in the forecast year (2025), as shown in Table 7. Under the aggressive scenario, the demand shows a continuous increment. It indicates the growth is due to assumptions like economic development, technological advancement, reliable power alternative, smart grid technology, political stability to attract foreign companies, and aggressive marketing in the economic zone. Table 9 and Fig. 14 show the total power demand forecast under the aggressive scenario.

3.1.2.1. Industrial load demand under an aggressive scenario. According to the analysis's findings for the aggressive scenario, the industrial sector accounts for the largest percentage of the economic zone's overall power. The forecasted power demand reaches 125 MW in 2030 and 243.3 MW in 2040, accounting for 25.7 % and 49.9 % of the total electric demand for the years 2030 and 2040, respectively. Fig. 15 and Table 10 show the industrial load demand forecasted for the aggressive scenario.

3.1.2.2. General business load demand forecast under aggressive scenario. The power demand forecasted for the general business sector can be seen in Fig. 16. From the analysis results, one can conclude the general business sector is the second power-consuming sector

Table 5
Total Power demand forecast for baseline scenario.

Branch	2025 BAS	2030 BAS	2035 BAS	2040 BAS	Total
Residential phase 1	23.4	34.8	51.8	77.2	187.2
Industrial phase 1	89.5	111.3	138.4	172.0	511.2
General business phase 1	43.3	52.7	64.1	78.0	238.1
Total	156.2	198.8	254.3	327.1	936.5

Table 6
Industrial load forecast under baseline scenario in.

Branch	2025 BAS	2030 BAS	2035 BAS	2040 BAS	TOTAL
Heavy load industry	40.0	49.7	61.7	76.5	227.9
Low load industry	19.5	24.3	30.3	37.8	112.0
Medium load industry\Electricity	30.0	37.3	46.4	57.6	171.3
Total	89.5	111.3	138.4	172.0	511.2

Source (LEAP result).

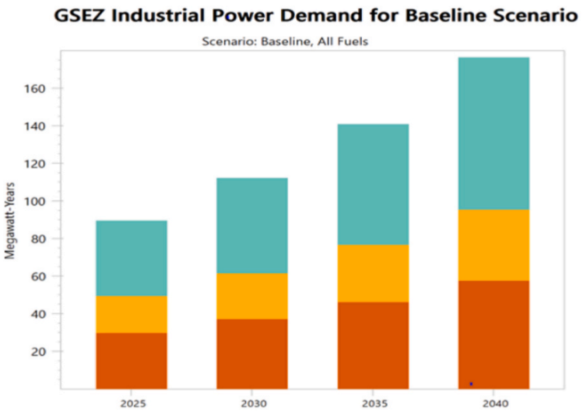

Fig. 11. Phase1 GSEZ industrial load demand forecasted for baseline scenario.

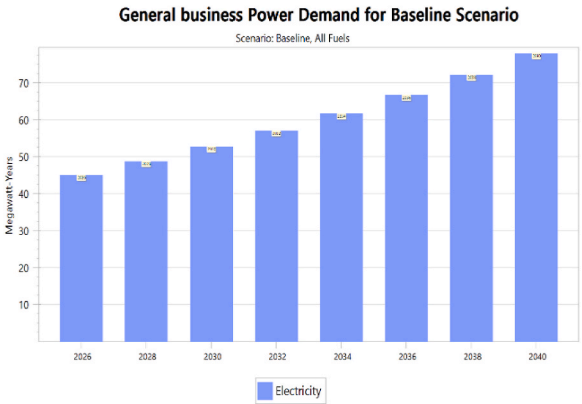

Fig. 12. General business power demand for baseline scenario.

Table 7
General Business load forecast under baseline scenario.

Branch	BAS 2025	BAS 2030	BAS 2035	BAS 2040	TOTAL
Electricity	19.5	24.3	30.3	37.8	112.0
Total	19.5	24.3	30.3	37.8	112.0

Source (LEAP result)

which shares 57.9 MW in 2030 and 103.8 MW in 2040, accounting for 19.9 % and 21.3 % of the total electric power demand respectively. Table 11 below shows the anticipated general business power demand under the aggressive scenario. The outcome demonstrates that as long as conditions in SEZ proceed as expected, the annual power demand will continue to rise.

3.1.2.3. Residential load demand forecast under aggressive scenario. The residential sector in the aggressive scenario shares 42.5 MW and 140Mw of the total power demand for the years 2030 and 2040, respectively, which accounts for 8.7 % and 28.7 % for the years

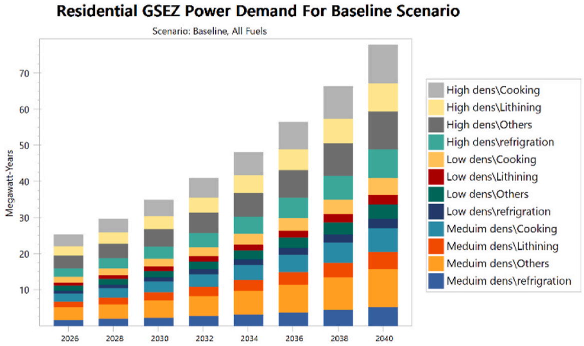

Fig. 13. GSEZ Residential power demand forecasted for baseline scenario.

Table 8
Residential power demand forecast under baseline scenario.

Branch	BAS 2025	BAS 2030	BAS 2035	BAS 2040	TOTAL
High dens	110.0	16.4	24.4	36.5	88.3
Medium dens	8.2	12.1	18.0	26.8	65.2
Low dens	4.3	6.3	9.3	13.8	33.7
Total	23.4	34.8	51.8	77.2	187.2

Table 9
Total GSEZ power demand under aggressive scenario.

Branch	AGG 2025	AGG 2030	AGG 2035	AGG 2040	TOTAL
Residential phase 1	23.4	42.5	77.1	140.0	283.0
Industrial phase 1	89.5	125.1	174.6	243.3	632.5
General business phase 1	43.3	57.9	77.5	103.8	282.6
Total	156.2	225.5	329.3	487.1	1198.

Source: (LEAP analysis result)

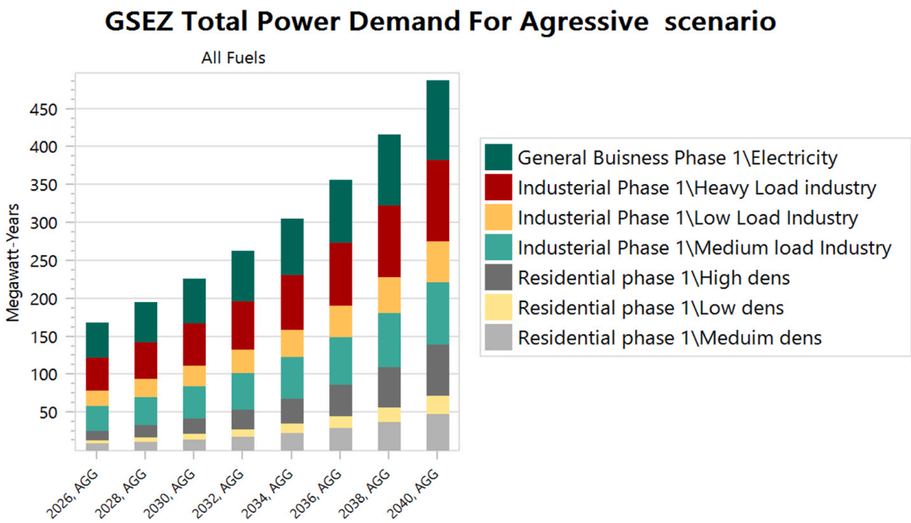

Fig. 14. Total power demand forecasted for aggressive scenario.

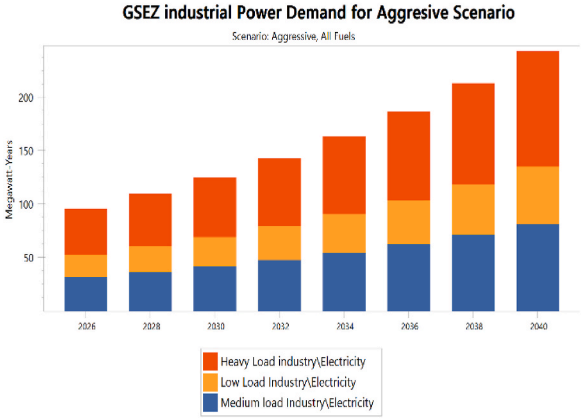

Fig. 15. The general industrial load forecasted.

Table 10
Industrial load demand forecast under aggressive scenario.

Branch	AGG 2025	AGG 2030	AGG 2035	AGG 2040	TOTAL
HL-industry	40.0	55.8	77.6	107.8	281.2
ML-Industry	30.0	41.9	58.5	81.5	211.9
LL-Industry	19.5	27.4	38.5	53.9	139.4
Total	89.5	125.1	174.6	243.3	632.5

Source: (LEAP analysis result)

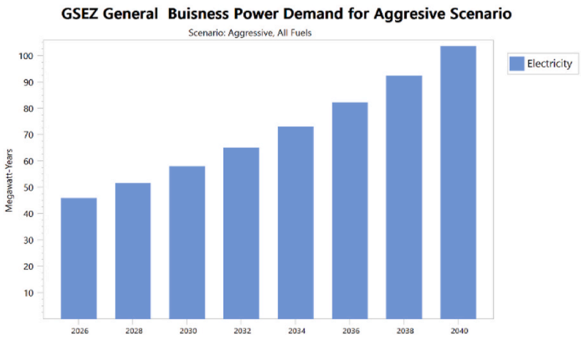

Fig. 16. General Business Power Demand forecasted.

Table 11
Forecasted demand for General Business sector.

Branch	AGG 2025	AGG 2030	AGG 2035	AGG 2040	TOTAL
Electricity	43.3	57.8	77.5	103.8	282.6
Total	43.3	57.9	77.5	103.8	282.6

2030 and 2040. The result shows that among household activities, cooking shares the maximum power demand, followed by refrigeration and lighting. The unspecified household appliances (dish and cloth washing, ironing, TV, air conditioning, etc.) consume 100 % electricity, unlike cooking that uses natural gas stoves, charcoal stoves, and wood stoves for cooking in all sub-sectors (high-dens, mid-dens, and low-dens) in the category shown in Fig. 17 and Table 12 below.

3.1.3. Demand prediction under the conservative scenario

The conservative scenario is the second alternate scenario, and it shares 156 MW of the total power in the base year (2025), increasing to 223.9 MW by 2040, representing a growth of 30.3 % from the base year (2025) (see Fig. 18). In the conservative scenario, the predicted demand for all sectors differs slightly from the base year (2025). This scenario shows what demand will be, if the assumptions are against the expectations.

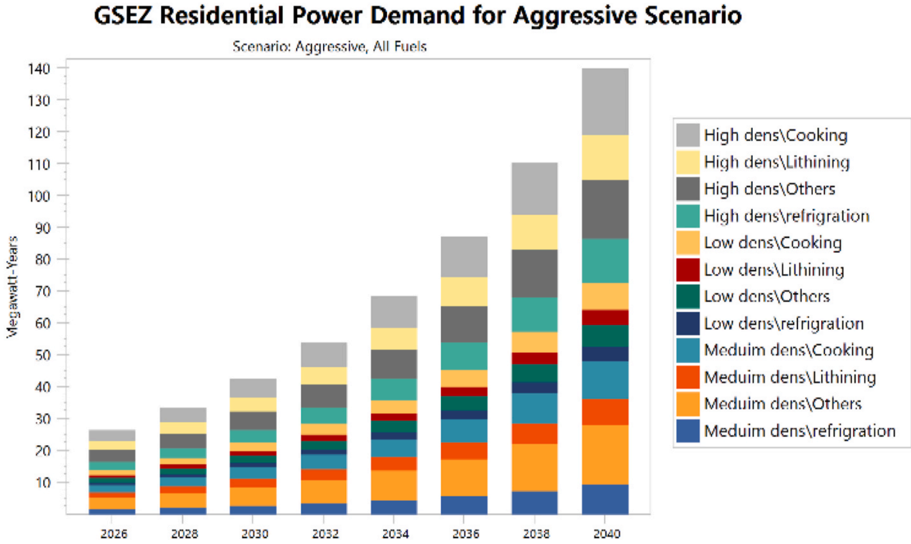

Fig. 17. Total power demand forecasted for residential sector.

Table 12
Residential power demand under aggressive scenario.

Branch	AGG 2025	AGG 2030	AGG 2035	AGG 2040	TOTAL
High dens	11.0	20.1	36.8	67.5	135.3
Medium dens	8.2	14.7	26.6	47.9	97.4
Low dens	4.3	7.6	13.7	24.7	50.3
Total	23.4	42.5	77.1	140.0	283.0

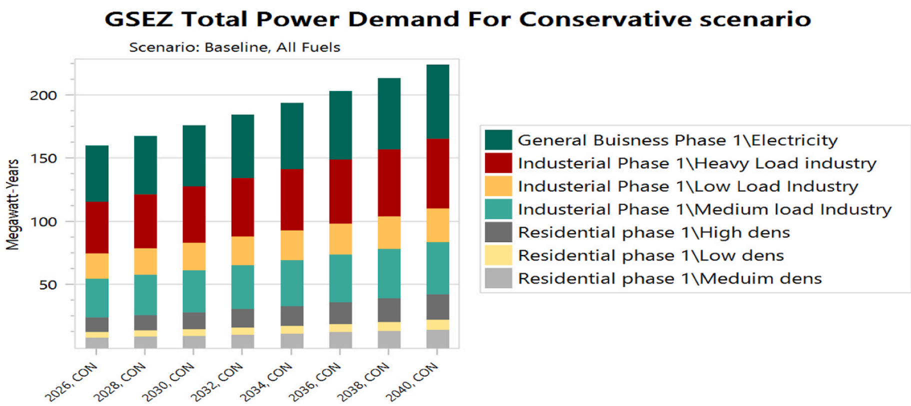

Fig. 18. Total Power forecasted for the Conservative scenario.

Table 13
Projected demand under the conservative scenario.

Branch	2025 CON	2030 CON	2035 CON	2040 CON	TOTAL
General Business	43.3	47.8	52.8	58.3	202.2
HL- Industry	40.0	44.5	49.5	55.0	189.0
LL- Industry	19.5	21.7	24.1	26.8	92.0
ML-Industry	30.0	33.3	37.1	41.2	141.6
Residential-HD	11.0	13.4	16.4	20.0	60.8
Residential -LD	4.3	5.2	6.3	7.7	23.5
Residential -MD	8.2	10.0	12.2	14.9	45.2
Total	156.2	175.9	198.3	223.9	754.3

Table 13 shows that the projected electric power under conservative scenario of all sectors in GSEZ.

3.2. Comparison of demand under various scenarios

The analysis result depicts the power demand under various scenarios. In evaluating the results under all scenarios, the power demand is high in the aggressive, followed by the baseline and conservative. A conservative scenario is a scenario wherein less power can be required. Fig. 19 shows the total sectoral power demand in GSEZ.

3.2.1. Forecasted residential demand analysis under all scenarios

In the sector-wise electricity demand projections under the baseline scenario, we see that the residential sector demand keeps increasing continuously. The analysis result shows the residential sector demands less power when compared to the sectors in the economic zone. This is because, in the first phase of operation, a limited number of households in the startup phase can join the GSEZ due to the uncertainty related to startups, like the availability of schools, hospitals, recreational areas, and other infrastructures in the economic zone. In evaluating the residential sector, huge variations can be seen in the three scenarios. (See Fig. 20). The result indicates that, in 2030, the total residential power will be a share of 34.8 MW, 28.6 MW, and 42.5 MW, for the bassline, conservative and aggressive scenarios, respectively. The residential sector also has a share of 77.2 MW, 42.7 MM, and 140 MW in 2040. The result shows a growth of 69.7 % for baseline, 45.4 % for conservative, and 83.2 % for aggressive scenarios compared to the forecast year (2025). In this investigation, the sub-sectoral power demand growth rate shows a continuous increment for baseline and aggressive scenarios in the given years. However, the demand growth rate shows less in the conservative.

Table 14 below shows the residential sector power demand in mega-watt per year of high-dens, medium-dens, and low-dens sub-sectors. Table 14 shows the industrial load forecast of the sub-sectors in GSEZ.

3.2.2. Forecasted industrial load demand analysis under all scenarios

The other category is the business sector, which includes the industrial and general business subsectors. For the aggressive scenario, the industrial sector is a sector that shares the maximum power (49.9 %) of the total electric power demand forecasted for 2040. The increase in power demand is related to the assumptions made such as reliable and stable power, development of smart grid technology, political stability, availability of infrastructures, and aggressive market in the economic zone with multi-functional foreign companies joining the sector. In the base year (2025), 60 companies with 900 employees will join the industrial sector. In the analysis model, 70 % of industry loads will use electricity, and 30 % of it may be covered by other energy alternatives. In the analysis, the industrial sector shows a continuous increment in demand for all scenarios except the conservative. Fig. 21 shows forecasted electric demand in the industrial sector.

The evaluation in the industrial sector, shows a maximum variation in demand between the aggressive, conservative, and the baseline scenarios shown in Fig. 21. The analysis indicated that, for the year 2030, industrial load shared 125 MW for aggressive, 111.3 MW for baseline, and 99.5 MW for conservative scenarios, and in 2040, the industrial load demand share will be 172 MW for the baseline, 243 MW for, aggressive, and 123 MW for a conservative shown in Table 15 with a growth of 48 %, 63 %, and 27 % respectively which shows an increment in demand compared to the base year (2025).

3.2.3. Forecasted general business load demand analysis under all scenarios

The third sector is the general business sector, which includes the commercial, transport, service and free trade share of demand. The analysis result indicated in 2030 shows the sectors predicted to share 57.9 MW, 52.7 MW, and 47.8 MW for aggressive, baseline and conservative scenarios respectively, whereas in 2040, the demand is forecasted to be 103.8 MW, 78 MW, and 58.3 MW for aggressive, baseline and conservative respectively. In comparison to the base year in the analysis, it shows a growth of 44.2 %, 32.4 %,

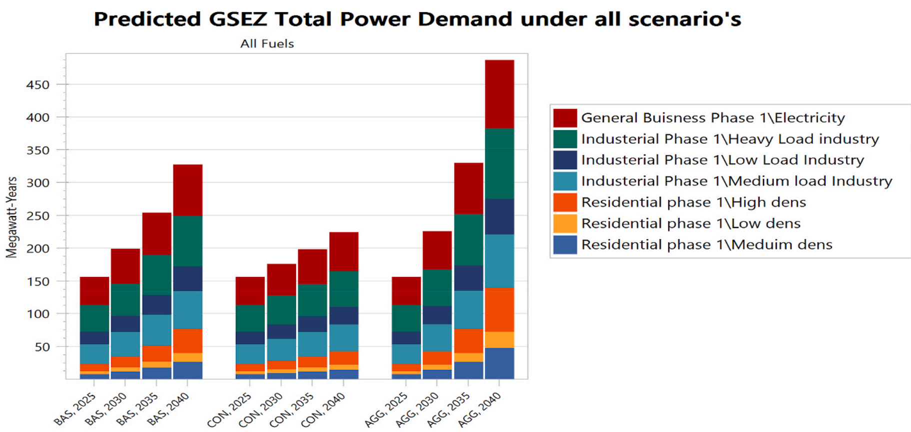

Fig. 19. Total power demand forecasted under all scenarios.

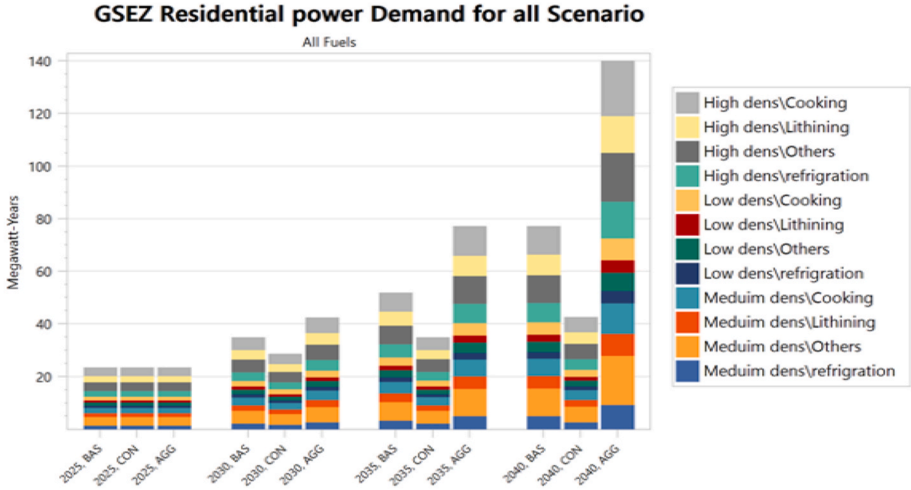

Fig. 20. Residential power demand under all scenarios.

Table 14
Forecasted residential Power demand under all scenarios.

Branch	BAS 2025	BAS 2030	BAS 2035	BAS 2040	CON 2025	CON 2030	CON 2035	CON 2040	AGG 2025	AGG 2030	AGG 2035	AGG 2040	TOTAL
High dens	11.0	16.4	24.4	36.5	11.0	13.4	16.4	20.0	11.0	20.1	36.8	67.5	284.4
Medium dens	8.2	12.1	18.0	26.8	8.2	10.0	12.2	14.9	8.2	14.7	26.6	47.9	207.8
Low dens	4.3	6.3	9.3	13.8	4.3	5.2	6.3	7.7	4.3	7.6	13.7	24.7	107.5
Total	23.4	34.8	51.8	77.2	23.4	28.6	34.9	42.7	23.4	42.5	77.1	140.0	599.8

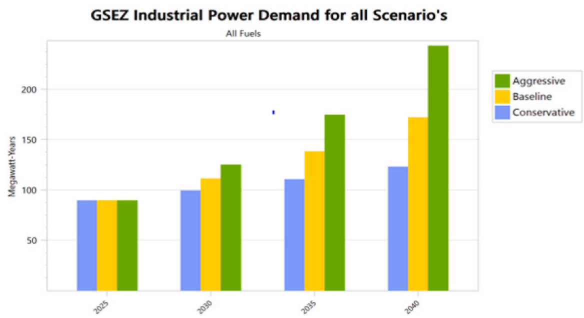

Fig. 21. Load forecast for the industry sector under all scenarios in MW/Y.

Table 15
Forecasted load for industry sub-sectors under all scenarios.

Branch	2025 BAS	2025 CON	2025 AGG	2030 BAS	2030 CON	2030 AGG	2035 BAS	2035 CON	2035 AGG	2040 BAS	2040 CON	2040 AGG	TOTAL
HL-industry Electricity	40.0	40.0	40.0	49.7	44.5	55.8	61.7	49.5	77.6	76.5	55.0	107.8.	698.1
L L-Industry Electricity	19.5	19.5	19.5	24.3	21.7	27.4	30.3	24.1	38.5	37.8	26.8	53.9	343.4
ML-Industry Electricity	30.0	30.0	30.0	37.3	33.3	41.9	46.4	37.1	58.5	57.6	41.2	81.5	524.8
Total	89.5	89.5	89.5	111.3	99.5	125.1	138.4	110.6	174.6	172	123	243.3	1566.3

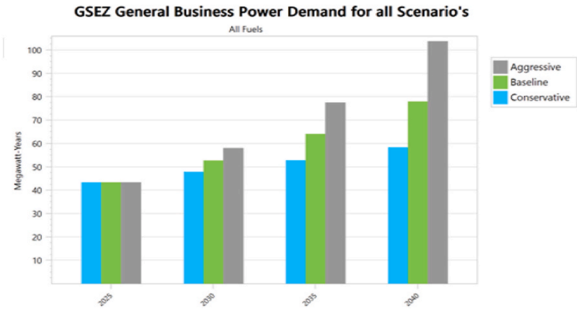

Fig. 22. The general business power demand forecasted under all scenarios.

Table 16
General Business Forecasted power in MW per year.

Branch	BAS 2025	BAS 2030	BAS 2035	BAS 2040	CON 2025	CON 2030	CON 2035	CON 2040	AGG 2025	AGG 2030	AGG 2035	AGG 2040	TOTAL
Electricity	43.3	52.7	64.1	78.0	43.3	47.8	52.8	58.3	43.3	57.9	77.5	103.8	722.8
Total	43.3	52.7	64.1	78.0	43.3	47.8	52.8	58.3	43.3	57.9	77.5	103.8	722.8

and 18 % for aggressive, baseline and conservative scenarios respectively. Fig. 22 shows the power demand for each predicted year.

The power demand forecasted for the general business sector also shows variations for the three scenarios. Compared to the baseline scenario in the same year shown in Table 16 and Fig. 22, the power demand in the conservative scenario in 2040 decreases by 67 %. Thus, the scenario reflects the uncertainty surrounding future development in the SEZ and provides a realistic depiction of what the demand would look like if certain development conditions were not to materialize.

3.3. *Supply-side demand prediction*

In order to assess the demand for electricity supply in the economic zone for the anticipated year, this study considers two scenarios to validate the supply-side demand model in the LEAP software based on information from the GSEZ working document. Additionally, to assess if off-grid generation is required to meet the rising power demand for economic zone sectors in both scenarios. The analysis can be done in two cases. The first case is the case where the national grid is the only alternative to supply the economic zone shown in Fig. 23. In this analysis, it is indicated that, in the year 2040, supply-side demand from the national grid will increase by 93.5 % and 175.9 % for reference and aggressive scenarios, respectively, compared to the base year 2025 demand shown in table.

Here, the national grid is expected to cover 100 % of the supply needed. Here, the analysis results indicate that the demand for electric power in the study area shows a continuous increment, which requires a proportional supply increment. To address this gap in demand, increasing supply capacity and substation expansion will be required. However, the current power supply situation in the

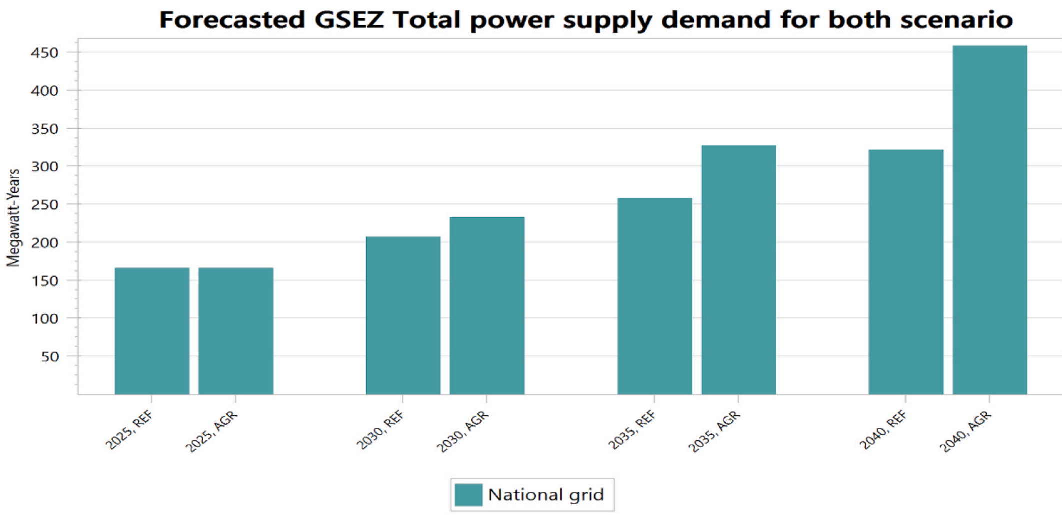

Fig. 23. Forecasted supply-side demand under all scenarios.

Table 17
Forecasted supply-side demand under all scenarios.

Branch	2025, REF	2025, AGR	2030, REF	2030, AGR	2035, REF	2035, AGR	2040, REF	2040, AGR
National grid	166.0	166.0	206.9	232.8	257.8	326.5	321.3	458.0
Total	166.0	166.0	206.9	232.8	257.8	326.5	321.3	458.0

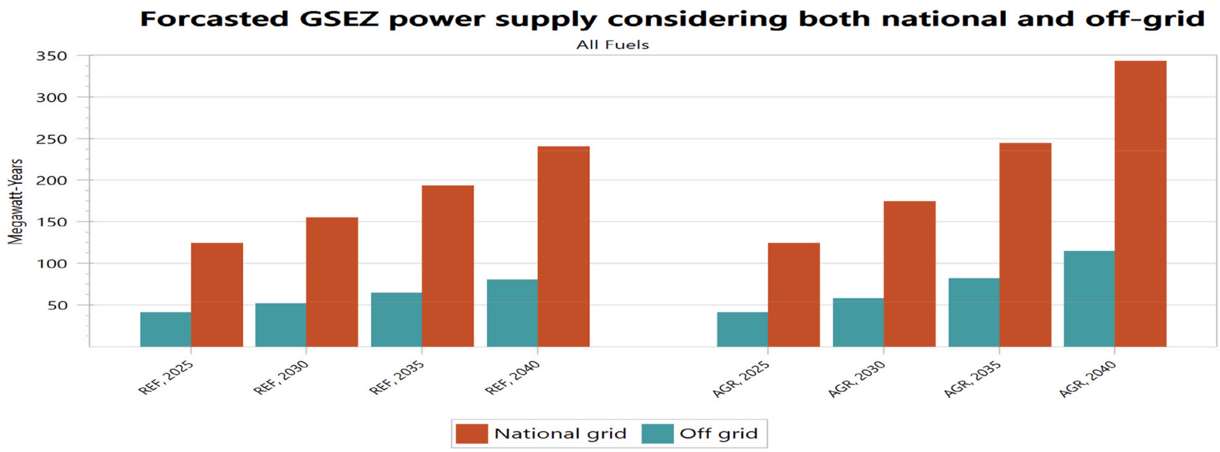

Fig. 24. Forecasted supply-side demand for hybrid generation under all scenario.

country indicates the economic zone will require onsite off-grid generation to support the national grid and ensure a sustainable supply system in the economic zone. Table 17 indicated the forecasted supply-side demand under all scenario.

The second case is the case where hybrid supply alternatives are considered to cover the increasing demand in the economic zone. Here, off-grid power alternatives from wind and solar power generation can be considered to cover the 25 % of the demand in the economic zone, and the rest is covered by the national grid, as shown in Fig. 24.

The analysis results indicate that by 2040, 240.9 MW and 343.5 MW of power will be required from the national grid for the reference and aggressive scenarios, respectively. At the same time, by 2040, 80.3 MW and 114.5 MW of electric power will be needed from the off-grid generation, which will support 25 % of the total demand in 2040, as shown in Fig. 24 and Table 18 below.

4. Conclusion and policy indication

Ethiopia is one of the developing countries struggling to alleviate poverty and create job opportunities for the huge human labor the country has through the recently established industrial parks and currently constructed economic zones in the country. The nation's energy industry is regarded as one of the driving forces in achieving this goal. Having a dependable, sustainable, and efficient energy choice is necessary to attract foreign investors to the nation's businesses. One of the largest economic zones now under construction, GSEZ, is a focus of this study in order to estimate its power needs. In this study, a power demand forecast and analysis can be done to evaluate the supply and demand pathway of the newly constructed economic zone in Ethiopia. In this study, a 15-year electric power demand forecast for the new economic zone under construction is conducted. To show the future development path for the GADA Special Economic Zone (GSEZ) sectoral power demand from 2025 to 2040, the bottom-up forecasting method is used with three scenarios. To evaluate supply-side demand, two scenarios can be considered. The analysis result of the evaluated scenarios reveals that the sectoral power demand shows a continuous increment. Compared to the base year, by 2040, the baseline and aggressive scenarios show growth of 52.2 % and 68 %, respectively, which indicates the conditions in the economic zone go as expected. The conservative scenario, on the other hand, depicts a small change in demand by 2040, showing a 30.3 % increment from the forecast year. The conservative scenario is the one that gives a realistic reflection of what demand could be if certain development conditions fail to be realized in the economic zone. These facts may be related to political instability in the country, a lack of reliable power alternatives, a lack of infrastructure in the economic zone, and a failure to implement smart grid technology for the new city. To ensure the

Table 18
Forecasted supply-side demand for hybrid generation under all scenario.

Branch	**2025 REF**	2025, AGR	2030, REF	2030, AGR	2035, REF	2035, AGR	2040, REF	2040, AGR
National grid	124.5	124.5	155.1	174.6	193.3	244.9	240.9	343.5
Off grid	41.5	41.5	51.7	58.2	64.4	81.6	80.3	114.5
Total	166.0	166.0	206.9	232.8	257.8	326.5	321.3	458.0

availability of sustainable and cost-effective power options that can draw in foreign business in the economic zone, it is estimated that proportional supply-side interventions will be required. To narrow the gap between supply and demand in the country, this study considers onsite off-grid generation alternatives for the economic zone to cover 25 % of the total demand. It is believed that the study has several contributions and policy implications. Firstly, it can help industries and the economic zone plan their production schedules, optimize their energy consumption, and reduce their energy costs. Accurate forecasting enables them to identify periods of high demand and adjust their operations accordingly, which can help them avoid peak electricity charges and reduce their overall energy bills. This can lead to increased profitability and competitiveness in the market. Secondly, effective power demand forecasting can help policymakers make informed decisions about energy infrastructure investments and energy policies. With accurate forecasting, new energy infrastructure can be developed and existing networks can be expanded by understanding trends in future energy demand. It can also aid in the creation of efficient energy policies that promote renewable energy sources and energy efficiency. Thirdly, accurate forecasting of power demand can help with the grid integration of renewable energy sources. Since renewable energy sources like wind and solar are so unstable, careful planning is necessary to maintain a steady power supply. Generally, accurate forecasting can help to design and develop renewable energy and allow operators to adjust their energy production accordingly. Overall, effective power demand forecasting can provide numerous benefits for the industry and policymakers, including increased profitability, informed decision-making, and sustainable energy planning. Having the above stated contribution, the study has also the following limitations.

➢ Data availability and quality: Accurate power demand forecasting requires access to comprehensive and reliable data on factors such as weather conditions, economic indicators, and energy consumption patterns. However, since the economic zone is under construction, there is no historical consumption data, leading to less accurate forecasts.
➢ Assumptions and simplifications: Forecasting models often require making assumptions and simplifications to represent the complex nature of power demand. These assumptions, such as linearity, stationarity, or independence of variables, may not fully capture the intricacies of demand behavior, leading to potential forecasting errors.
➢ Accuracy: Power demand forecasting relies on historical data and mathematical models to predict future demand. However, unexpected events such as extreme weather, changes in consumer behavior, or major infrastructure disruptions may lead to inaccurate forecasts.

Data availability statement

Data associated with this study is included in article/supp. Material/referenced in article.

CRediT authorship contribution statement

Meskerem Tadesse Gebre: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation. **Junseok Hwang:** Writing – review & editing, Supervision, Software, Methodology, Conceptualization. **Getachew Biru:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

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

References

[1] I. Vera, L. Langlois, Energy indicators for sustainable development, Energy 32 (6) (2007) 875–882.
[2] J. Huang, Y. Tang, S. Chen, Energy demand forecasting: combining cointegration analysis and artificial intelligence algorithm, Math. Probl Eng. 2018 (2018) 1–13.
[3] X. Wang, A. Palazoglu, N.H. El-Farra, Operational optimization and demand response of hybrid renewable energy systems, Appl. Energy 143 (Apr. 2015) 324–335, https://doi.org/10.1016/j.apenergy.2015.01.004.
[4] N. P. Commission, Growth and Transformation Plan II (GTP II) (2015/16-2019/20), Fed. Democr. Repub, Ethiop. Addis Ababa, 2016. Volume I: Main Text.
[5] G. Tiruye, et al., Opportunities and challenges of renewable energy production in Ethiopia, Sustainability 13 (2021), https://doi.org/10.3390/su131810381.
[6] Sustainable Development Goals (SDG) Target 6.2 in Ethiopia: Challenges and Opportunities." https://www.scirp.org/journal/paperinformation.aspx?paperid=109145 (accessed May 25, 2023).
[7] Y. Kifle, B. Khan, P. Singh, Assessment and enhancement of distribution system reliability by renewable energy sources and energy storage, J. Green Eng. 8 (3) (2018) 219–262, https://doi.org/10.13052/jge1904-4720.832.
[8] (PDF) Mitigation of Voltage Fluctuation in Power Distribution System Using D-STATCOM." https://www.researchgate.net/publication/303845431_Mitigation_of_Voltage_Fluctuation_in_Power_Distribution_System_Using_D-STATCOM (accessed May 10, 2023).
[9] Impact of Total Harmonic Distortion in SWIPT Enabled Wireless Communication Networks IEEE Conference Publication IEEE Xplore." https://ieeexplore.ieee.org/abstract/document/9588824 (accessed May 11, 2023).
[10] T. G. Tella, "An Investigation on Factories Power Quality (Harmonic) Problems So that to Protect Equipment's Damaging at the Distribution Network (Case Study: Maa-Garment, Mekelle, Ethiopia)".
[11] M.A.H. Mondal, E. Bryan, C. Ringler, D. Mekonnen, M. Rosegrant, Ethiopian energy status and demand scenarios: prospects to improve energy efficiency and mitigate GHG emissions, Energy 149 (Apr. 2018) 161–172, https://doi.org/10.1016/j.energy.2018.02.067.
[12] H. Hu, L. Wang, L. Peng, Y.-R. Zeng, Effective energy consumption forecasting using enhanced bagged echo state network, Energy 193 (2020) 116778, https://doi.org/10.1016/j.energy.2019.116778.
[13] Simulating the Annual Energy Yield of a Rotationally Asymmetrical Optical Concentrator IEEE Conference Publication IEEE Xplore." https://ieeexplore.ieee.org/abstract/document/8533197/(accessed May 11, 2023).

[14] G. Beyene, The Challenges and Prospects of Electricity Access in Ethiopia, PhD Thesis, master's thesis, 2018.
[15] N.S. Ouedraogo, Africa energy future: alternative scenarios and their implications for sustainable development strategies, Energy Pol. 106 (2017) 457–471.
[16] G. Gebreyohans, N.K. Saxena, A. Kumar, Long-term electrical load forecasting of Wolaita Sodo Town, Ethiopia using hybrid model approaches, in: 2018 IEEE 8th Power India International Conference (PIICON), IEEE, 2018, pp. 1–6.
[17] R.V. Klyuev, et al., Methods of forecasting electric energy consumption: a literature review, Energies 15 (23) (2022) 8919.
[18] I. Ghalehkhondabi, E. Ardjmand, G.R. Weckman, W.A. Young, An overview of energy demand forecasting methods published in 2005–2015, Energy Syst 8 (2017) 411–447.
[19] Q. Feng, S. Qian, "Research on power load forecasting model of economic development zone based on neural network,", Energy Rep. 7 (2021) 1447–1452.
[20] N. An, W. Zhao, J. Wang, D. Shang, E. Zhao, Using multi-output feedforward neural network with empirical mode decomposition based signal filtering for electricity demand forecasting, Energy 49 (2013) 279–288.
[21] Modelling energy demand of developing countries, Are the specific features adequately captured? ScienceDirect. 38 (4) (2010) 1979–1990. https://www.sciencedirect.com/science/article/abs/pii/S030142150900929X. (Accessed 5 December 2023).
[22] W. Bank, Ethiopia Economic Update: the Inescapable Manufacturing-Services Nexus, World Bank, 2018.
[23] World bank report on access to electricity in ethiopia pdf - Google Search." https://www.google.com/search?.
[24] F.F. Nerini, O. Broad, D. Mentis, M. Welsch, M. Bazilian, M. Howells, A cost comparison of technology approaches for improving access to electricity services, Energy 95 (2016) 255–265.
[25] I. Pappis, et al., Influence of electrification pathways in the electricity sector of Ethiopia—policy implications linking spatial electrification analysis and medium to long-term energy planning, Energies 14 (4) (2021) 1209.
[26] K. Kavaklioglu, H. Ceylan, H.K. Ozturk, O.E. Canyurt, Modeling and prediction of Turkey's electricity consumption using artificial neural networks, Energy Convers. Manag. 50 (11) (2009) 2719–2727.
[27] T. Nakata, D. Silva, M. Rodionov, Application of energy system models for designing a low-carbon society, Prog. Energy Combust. Sci. 37 (4) (2011) 462–502.
[28] L.G. Swan, V.I. Ugursal, Modeling of end-use energy consumption in the residential sector: a review of modeling techniques, Renew. Sustain. Energy Rev. 13 (8) (2009) 1819–1835.
[29] F. Urban, R.M.J. Benders, H.C. Moll, Modelling energy systems for developing countries, Energy Pol. 35 (6) (2007) 3473–3482.
[30] L.G. Swan, V.I. Ugursal, Modeling of end-use energy consumption in the residential sector: a review of modeling techniques, Renew. Sustain. Energy Rev. 13 (8) (Oct. 2009) 1819–1835, https://doi.org/10.1016/j.rser.2008.09.033.
[31] C. Ye, Y. Ding, P. Wang, Z. Lin, A data-driven bottom-up approach for spatial and temporal electric load forecasting, IEEE Trans. Power Syst. 34 (3) (May 2019) 1966–1979, https://doi.org/10.1109/TPWRS.2018.2889995.
[32] S.C. Bhattacharyya, G.R. Timilsina, Energy Demand Models for Policy Formulation: a Comparative Study of Energy Demand Models, World Bank Policy Res. Work. Pap., 2009 no. 4866.
[33] T. Fleiter, et al., A methodology for bottom-up modelling of energy transitions in the industry sector: the FORECAST model, Energy Strategy Rev. 22 (2018) 237–254.
[34] F.L.C. Silva, R.C. Souza, F.L. Cyrino Oliveira, P.M. Lourenco, R.F. Calili, A bottom-up methodology for long term electricity consumption forecasting of an industrial sector - application to pulp and paper sector in Brazil, Energy 144 (Feb. 2018) 1107–1118, https://doi.org/10.1016/j.energy.2017.12.078.
[35] R. Ghedamsi, et al., Modeling and forecasting energy consumption for residential buildings in Algeria using bottom-up approach, Energy Build. 121 (Jun. 2016) 309–317, https://doi.org/10.1016/j.enbuild.2015.12.030.
[36] H. Shahinzadeh, S.H. Fathi, A. Hasanalizadeh-Khosroshahi, Long-term energy planning in Iran using LEAP scenario: using combined heat and power (CHP), in: 2016 Iranian Conference on Renewable Energy & Distributed Generation (ICREDG), IEEE, 2016, pp. 32–37.
[37] Y.-H. Jin, S.-P. Jin, X.-H. Wang, An analysis of energy consumption and GHG emissions reduction for hubei using the LEAP model, in: New Energy and Sustainable Development: Proceedings of 2016 International Conference on New Energy and Sustainable Development (NESD 2016), World Scientific, 2017, pp. 34–43.
[38] M. Azam, J. Othman, R.A. Begum, S.M.S. Abdullah, N.G.M. Nor, "Energy consumption and emission projection for the road transport sector in Malaysia: an application of the LEAP model,", Environ. Dev. Sustain. 18 (2016) 1027–1047.
[39] F. Kemausuor, I. Nygaard, G. Mackenzie, "Prospects for bioenergy use in Ghana using long-range energy alternatives planning model,", Energy 93 (2015) 672–682.
[40] Energy system analysis with a focus on future energy demand projections, The case of Norway, ScienceDirect 272 (2023) 127107. https://www.sciencedirect.com/science/article/pii/S0360544223005017. (Accessed 20 May 2023).
[41] Long-term energy planning and demand forecast in remote areas of developing countries, Classification of case studies and insights from a modelling perspective, ScienceDirect 20 (2018) 71–89. https://www.sciencedirect.com/science/article/abs/pii/S2211467X18300099. (Accessed 20 May 2023).
[42] D.A. Senshaw, Modeling and Analysis of Long-Term Energy Scenarios for Sustainable Strategies of Ethiopia, 2014.
[43] Long-term evolution of energy and electricity demand forecasting, The case of Ethiopia, ScienceDirect 36 (2021) 100671. https://www.sciencedirect.com/science/article/pii/S2211467X21000572. (Accessed 20 May 2023).
[44] G.E. Beyene, A. Kumie, R. Edwards, K. Troncoso, Opportunities for Transition to Clean Household Energy in Ethiopia: Application of the Household Energy Assessment Rapid Tool, HEART), 2018.
[45] Y.A. Mekonnen, Population forecasting for design of water supply system in Injibara Town, Amhara Region, Ethiopia, Population 10 (10) (2018).
[46] A. Kidane, A. Hailemariam, Mortality, fertility and population projection of famine affected regions of Ethiopia, in: Workshop on Famine Experience and Resettlement in Ethiopia, IDR, Addis Abeba (Ethiopia), 1989, 29-30 Dec 1988.
[47] R.V. Kale, S.D. Pohekar, Electricity demand and supply scenarios for Maharashtra (India) for 2030: an application of long range energy alternatives planning, Energy Pol. 72 (2014) 1–13.
[48] J. Charmes, The Contribution of Informal Sector to GDP in Developing Countries: Assessment, Estimates, Methods, Orientations for the Future, 2000. Geneva.