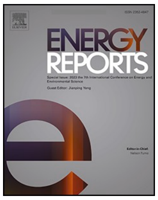
Energy Reports 11 (2024) 165–178

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr



Research paper

The impacts of the informal economy, climate migration, and rising temperatures on energy system planning

M. Yazdanie [a,*], P.B. Frimpong [b], J.B. Dramani [b], K. Orehounig [a,c]

[a] *Urban Energy Systems Laboratory, Empa, Dübendorf, Switzerland*
[b] *Department of Economics, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana*
[c] *Vienna University of Technology, Vienna, Austria*

ARTICLE INFO

Keywords:
Informal economy
Climate migration
Global warming
Urban energy systems
Optimization modeling
Developing countries

ABSTRACT

This study aims to investigate the impacts of the informal economy, climate migration and temperature changes on energy demand and long-term urban energy system planning. The elasticity of energy demand to changes in the size of the informal sector, urban population and mean temperature is estimated for the case study city of Accra, Ghana. Elasticities are then applied to estimate energy demand under different Shared Socioeconomic Pathways (SSPs). An energy system optimization model analyzes SSP impacts on energy planning. Accra's energy demand is found to be most elastic to climate change-induced migration and rising temperatures; for example, energy demand is up to 43% higher in 2050 in a worst-case scenario compared to the base case. These factors will exacerbate the city's ability to meet its sustainability targets and manage informal sector growth. Photovoltaics, waste CCP and decarbonization of the transportation sector through electrification are found to be critical solution pathways for Accra to meet rising demand while supporting sustainability objectives. However, significant local distribution grid upgrades are required to support these technologies' rollout. Overall, this work demonstrates the importance and value of incorporating climate migration, rising temperature and informal sector analysis in energy planning models and decision-making processes, particularly in low and middle-income countries that are the most vulnerable to climate change. Although the approach is demonstrated on Accra, it can be applied at other scales and scopes globally.

1. Introduction

Developing countries face distinct challenges to energy planning which are often overlooked in conventional energy system modeling analyses. Such challenges include the impacts of the informal sector, suppressed energy demand, and power sector failures on energy systems and planning. Climate change impacts on energy planning and resilience also require attention in energy models, particularly in the context of underprepared developing countries which will experience more devastating impacts, particularly in coastal, arid and hot regions (IPCC, 2022; Nath and Behera, 2011; Yi, 2022).

This work investigates the impacts of three factors in the context of urban energy planning. The factors of interest that play a particularly significant role in our case study area are the impacts of changes in 1) the informal economy, 2) urban migration due to climate change, and 3) rising temperatures due to global warming.

The informal economy refers to a range of economic activities that are not regulated, state-protected, or accounted for in official GDP figures. A large part of economies in developing countries are informal. Approximately 90 countries worldwide (i.e., almost half of the world's nations) have an informal economy over 30% in size as a percentage of their national GDP (World Economics, 2023). Given its unofficial nature, the impacts of the informal economy on energy demand, both in general and with respect to formal economic transitions, are challenging to capture and quantify.

Climate change also brings significant challenges to urban energy planning. The IPCC has delineated climate change scenarios according to different Shared Socioeconomic Pathways (SSPs) in its Sixth Assessment Report (IPCC, 2021a). These scenarios include projections regarding climate change-induced urban migration, as populations

---

Abbreviations: AC, air conditioner; BEV, battery-electric vehicle; CCP, combined cycle plant; elec, electricity; Gen, Generator; ICEV, Internal combustion engine vehicle; PV, photovoltaic; Stnd, Standalone (PV).

[*] Corresponding author.

E-mail address: mashael.yazdanie@empa.ch (M. Yazdanie).

https://doi.org/10.1016/j.egyr.2023.11.041
Received 9 June 2023; Received in revised form 13 October 2023; Accepted 16 November 2023

move from rural to urban areas in search of job opportunities and improved resource access. The UNHCR estimates that 21.5 million people have been displaced annually since 2008 due to weather-related extreme climate events (UNHCR, 2016). At this rate, another 1.2 billion people will be displaced by 2050 (Institute for Economics and Peace, 2020). Thus, countries and cities should anticipate significant population fluxes in the coming decades.

Rising temperatures under climate change also impact energy demand; for example, due to increased cooling demand. Van Ruijven et al. estimate that national energy demand will increase by up to 58% in worst-case climate scenarios (van Ruijven et al., 2019). Demand is expected to rise by over 25% in tropical regions, as well as in southern Europe, China and the USA (van Ruijven et al., 2019).

As in the case of many national energy planning evaluations and reports, both in developed and developing countries, Ghana's national planning strategy lacks a detailed evaluation of informal economic and climate change impacts on energy planning (Essandoh-Yeddu, 2006; Ministry of Energy, Ghana, 2010, 2022). These challenges exacerbate energy planning for long-term resilience, particularly at an urban scale. Cities such as Accra acknowledge these challenges, but local assessments lack quantitative evaluation of their impacts on urban planning (Accra Metropolitan Assembly (AMA), 2019a). Literature also emphasizes the importance of considering informality and climate change impacts in energy planning, while acknowledging their under representation in conventional modeling approaches, particularly in the context of developing countries (Bhattacharyya and Timilsina, 2010; Neshat et al., 2014; Urban et al., 2007; van Ruijven et al., 2008).

Thus, the objective of this work is to develop a methodological framework using energy system optimization models to investigate the impacts of the informal economy, climate change-induced urban migration, and rising temperatures on urban energy demand and long-term sustainable and resilient energy strategy planning. The study aims to understand the relative importance of considering these factors, which are unique to local environments and often overlooked, in conventional assessment approaches.

Using the case study area of Accra, Ghana, the elasticity of energy demand to changes in these three factors is determined, and this information is used to develop scenarios that follow the SSPs in the IPCC Sixth Assessment Report (IPCC, 2021a). The developed scenarios are subsequently evaluated using an energy planning optimization model for Accra built using an open-source optimization framework (OSeMOSYS). The performance of each SSP scenario is compared to a base case scenario (i.e., which does not consider the evaluated factors) to determine the local impacts of each factor on long-term energy system capacity and operational planning.

The paper is structured as follows: background information regarding the case study area, SSP scenarios, and state-of-the-art approaches in the field is presented in Section 2. The methodology section (3) then presents our approach to estimating energy demand and demand elasticity, followed by scenario development and modeling. Results and analytical insights corresponding to each of these areas are presented in the remaining sections of the study (Section 4, 5 and 6).

2. Background

The background section first introduces the case study area (§2.1). This is followed by an overview of the SSPs under investigation (§2.2). Finally, section 2.3 presents a literature review of current approaches to investigate and model the energy planning impacts of our three factors of interest.

2.1. Case study area: Accra

Accra is a city of approximately 2.5 million inhabitants (World Population Review, 2022). It is committed to long-term sustainable planning under the C40 Cities and Global Covenant of Mayors for Climate and Energy frameworks (C40 Cities, 2020; Global Covenant of Mayors for Climate and Energy, 2022).

Accra outlines several challenges to its resilience planning (Accra Metropolitan Assembly (AMA), 2019c, 2019a). Climatically, Accra faces ongoing threats due to increasing temperatures, flooding and rising sea levels. The average temperature of Accra has already increased by 1 °C compared to 1960, with projections estimating that this could rise to 2 °C by 2050 (Accra Metropolitan Assembly (AMA), 2019a). Rising temperatures exacerbate and intensify urban heat island effects and increase the frequency of heatwaves. By 2050, the city may experience a sea level rise of 20 cm, corresponding to 150 m of coastline loss (Accra Metropolitan Assembly (AMA), 2019a).

Socially and economically, Accra employs approximately 80% of its population in the informal sector (Accra Metropolitan Assembly (AMA), 2019c). Walking rates are also high, with approximately 50% of trips done by walking. Thus, rising temperatures impact mobility and present a risk to vulnerable citizen groups, such as the elderly (Accra Metropolitan Assembly (AMA), 2019a).

Our case study focuses on the Accra metropolitan area, which utilized approximately 6 TWh of energy in 2015 (Accra Metropolitan Assembly (AMA), 2019b). The majority of local energy consumption is allocated to transportation fuels (~60%), followed by national grid electricity imports (~25%; largely used in the industrial sector), and cooking fuels (~15%; mainly charcoal, wood and LPG used in the residential sector).

Accra also has significant local renewable energy resource potential. Solar PV installations, consisting of rooftop PV, standalone, and minigrid systems, are estimated at a total potential of approximately 4 GW in the long term (which corresponds to approximately 4 TWh for a capacity factor of 11%). The waste energy resource potential (from municipal solid waste collection) is estimated to be approximately 4 TWh as well. Approximately 70% of all solid waste is collected formally (Accra Metropolitan Assembly (AMA), 2019c). Accra aims to capitalize on solar and waste renewable energy resource potentials, as described in its climate action plan (Accra Metropolitan Assembly (AMA), 2019a).

2.2. Shared socioeconomic pathways

There are five distinct pathways for future socioeconomic developments upon which the SSPs have been developed. These scenarios are developed to enhance climate change research and policy analysis, and are applied in the IPCC Sixth Assessment Report (IPCC, 2023). They are also developed to cover a range of combinations of challenges to mitigation and adaptation to climate change, as detailed in (Riahi et al., 2017).

The five distinct pathways representing different combinations of socioeconomic development trajectories and challenges to climate change adaptation and mitigation are also summarized well in (O'Neill et al., 2017). In SSP1, a reduction in inequality, considerable income growth, strong institutional development, and CO_2 emission reductions lead to low socio-economic challenges to both climate change adaptation and mitigation. SSP2 is commonly referred to as a middle-of-the-road scenario, which presents intermediate challenges to both adaptation and mitigation. There are significant challenges to both mitigation and adaptation in SSP3, which result from slow growth in income and technological change, weak institutions, and inadequate investment in human capital. In SSP4, there is high inequality across and within countries. SSP4 presents a scenario in which mitigation would be tolerable, but adaptation would be quite difficult for the population with relatively low education and inadequate access to effective institutions. Finally, SSP5 is characterized by high economic growth driven by fossil-fuel dependency and high CO_2 emissions. Adaptation challenges are low, but mitigation challenges remain high.

SSPs are distinguished by radiative forcing levels (in W/m^2) by 2100. The higher the radiative forcing, the greater the global warming potential (detailed further in section 3.4.1). The IPCC Sixth Assessment

Report, and this study, utilize SSP1–2.6, SSP2–4.5, SSP3–7.0 and SSP5–8.5 scenario storylines.

The IPCC has developed long-term climate models for each of the SSPs, including temperature, precipitation, population density, and other indicators. This data is readily available via IPCC's Interactive Atlas (IPCC, 2021b). The IPCC SSP data sets applied in this study are also detailed further in section 3.4.

2.3. The informal economy, climate change and energy system modeling

2.3.1. Impacts of informality, rising temperatures and migration on energy demand

Economists gave the concept of informal economy attention after it was first introduced and coined by Hart (Hart, 1973). Hart describes the informal economy as all economic activities that are conducted outside the confines of bureaucratic private and public institutions (Hart, 2008). Ihrig and Moe, on the other hand, define the informal economy as the sector that undertakes production legally but is unregulated (Ihrig and Moe, 2004). The sector employs more labor-intensive methods of production relative to capital-intensive methods, applies an insignificant amount of technology, and produces on a small scale to avoid governmental regulations (Basbay et al., 2016). Thus, it is unable to benefit from economies-of-scale, but enjoys low operational labor costs since firms do not have to pay employees minimum wages, severance packages or social security, unlike in the formal economy. Even though the informal economy is less capital intensive, (Akpan et al., 2013) argue that the establishment, development and growth of micro, informal enterprises are dependent on energy access.

To the extent that the informal economy is less capital- and technology-intensive, but requires a minimal amount of energy to grow, two major contrasting views have been proposed regarding its response to energy consumption. On one hand, Basbay et al. argue that since high energy consumption is associated with high capital-intensity production and technology, a large informal economy has a high prospect of being associated with low energy consumption, ceteris paribus (Basbay et al., 2016). On the other hand, Egger and Winner suggest that a huge informal economy can offer an advantage to multinational firms to pay bribes to easily establish their businesses and promote the inflow of foreign direct investment (FDI) (Egger and Winner, 2005). Since multinational firms are characterized by high capital intensity and technology, an increase in their inflow is expected to cause high energy consumption, ceteris paribus. This implies that a large informal economy can lead to high energy consumption in the long run. The consequences are that low energy consumption among informal firms has the potential to reduce economic activity and this can lead to reduced tax revenue generation. On the other hand, high energy consumption due to the presence of many formal firms can induce increased economic activities which promotes high tax revenue generation for an economy.

Climate change is expected to increase the incidence and severity of people's exposure to high temperatures, predominantly in highly urbanized areas (Romitti and Sue Wing, 2022). Increasing ambient temperatures are anticipated to cause high energy demand in both the hot and cold seasons across many sectors of the economy, particularly in countries within the tropics (B. J. van Ruijven et al., 2019). Higher temperatures will cause inhabitants to utilize coping strategies, such as increased air conditioning. Both peak and total electricity demand have risen in recent years in Accra, causing an increasing demand for space cooling as a coping strategy to the high incidence and severity of temperatures (Asante and Amuakwa-Mensah, 2015). Increasing temperatures in Accra have equally caused significant disasters, physical damages and economic losses affecting about 100,000 individuals (Asibey et al., 2022). Climate shocks can cause a higher percentage of people in Accra to fall into poverty by reducing the income of poor households by up to 40% in 2050 (World Bank Group, 2022a), which also increases the size of the informal sector. The negative effect of climate change on Accra demands fashioning an urban planning policy that includes resilience to climate change and transitioning to a greener economy, applying both public and private sector investments.

In addition, climate change will hurt agricultural production and, thus, rural income and subsistence, causing rural-urban migration in Sub-Saharan Africa. According to the World Bank Group, Sub-Saharan Africa is likely to witness about 86 million of rural-urban migration by 2050 induced by climate change (Clement et al., 2021). Massive and frequent migration will increase urban energy demand (e.g., increased transportation demand in Accra) and related CO_2 emissions. In 2015, the total number of registered vehicles in Ghana was estimated to be about 1,952,564, of which 60% were located in the Greater Accra Region (Musah et al., 2020). This is partly driven by rapid population growth and urbanization in Ghana. In addition, rapid urbanization has led to a massive increase in domestic appliance ownership (Gyamfi et al., 2018).

Climate migration implies urbanization in the context of metropolitan Accra. Hence, the term climate migration can be considered as synonymous with urbanization throughout this study. Similarly, historical urbanization impacts on Accra are assumed to be applicable to local climate migration trends as well.

2.3.2. Energy system optimization modeling

Although the informal economic sector is estimated to be larger than 30% of the economy in almost half of the world's countries (World Economics, 2023), the informal sector tends to be neglected in most energy planning models and analyses, including models based on LEAP, MARKAL/TIMES, MESSAGE, and RETScreen. This analytical gap is recognized as an area for further research and development by multiple experts in the field (Bhattacharyya and Timilsina, 2010; Neshat et al., 2014; Urban et al., 2007; B. van Ruijven et al., 2008). A handful of studies currently attempt to address this issue.

Riva et al. (2019) include the informal sector in energy planning models by linking bottom-up energy demand projections in rural India with an energy optimization model in OSeMOSYS. The authors conclude that the integration of these models, including informal activity, is vital for more reliable long-term energy capacity investment planning (Riva et al., 2019). Sassi et al. (2010) also attempt to address economic issues in their modeling framework. However, consideration of the informal sector remains largely untreated in the majority of energy system models.

Energy system optimization models are used to evaluate energy transition pathways under climate scenarios from the national to the local scale; for example, in (Emodi et al., 2019; Prina et al., 2020; Ramachandran and Turton, 2014; Yazdanie et al., 2017). The impacts of climate change effects and adaptation planning for energy systems, such as in (de Lucena et al., 2010), are less commonly addressed in deterministic optimization modeling frameworks. However, stochastic optimization approaches have been applied in various studies to evaluate the impacts of climate change and extreme events on energy systems (Guerra et al., 2019; Liu et al., 2022; Perera et al., 2020).

To the best of the authors' knowledge, few, if any, studies disentangle and separately treat climate change effects, such as climate migration and rising temperatures, on energy system planning in the domain of energy optimization models. At the time of writing, few studies also evaluate the impacts of the IPCC Sixth Assessment Report's SSP scenarios on urban energy planning. Most energy models in this domain also focus on developed, rather than developing countries, especially in low- and middle-income countries. Thus, this work attempts to ameliorate some of these research gaps.

3. Methodology and data

3.1. Conceptual framework

The methodological approach in this study is summarized graphically in Fig. 1, which consists of four overarching processes. The figure also provides the corresponding section numbers that detail the theory/

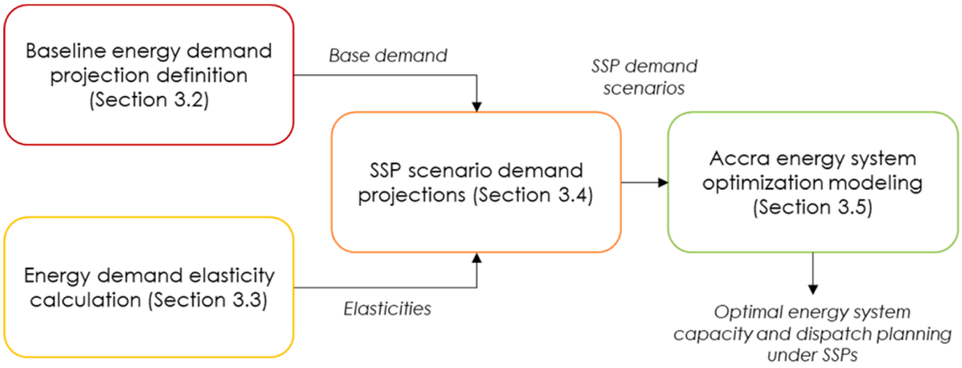


Fig. 1. Conceptual framework for analysis.

equations in each stage.

In the first stage (detailed in Section 3.2), a baseline energy demand projection is calculated using a regression model, which does not consider any of the three factors of interest (i.e., the informal economy, population size, and temperature). In parallel, the elasticity of energy demand to changes in the three factors is calculated using the two-step least-squares estimation principle (detailed in Section 3.3).

The base profile and demand elasticity outputs of these processes are then applied to define demand projections for each of the SSP scenarios until 2050 (Section 3.4). These SSP scenarios are then applied to a least-cost optimization model of the Accra energy system (Section 3.5) to evaluate the impacts of the informal economy, climate migration, and rising temperature on energy system capacity and operational planning.

3.2. Base energy demand projection

Baseline energy demand is projected using a regression-based energy demand model. The key outcome variable in this model is energy demand. The analysis is at the urban land-use sectoral level; that is, total energy demand is examined for the residential, service, industry and transport sectors of the economy. Historical energy demand data is used on an annual basis for the period 2000–2020. Data for other regressors is obtained within the same period to gain a coherent estimation of the demand model. Energy demand (*ED*) in sector *i* at time *t* is assumed to depend on Gross Domestic Product (*GDP*), crude oil energy price (*PRICE*) and population (*POP*). Its regression specification, following (Mauleón, 2022), is expressed as:

$$ED_t^i = \alpha^i + \beta_1^i GDP + \beta_2^i POP + \beta_3^i PRICE + \varepsilon_t^i \tag{1}$$

where ε_t^i is the error term, α^i is the constant term in each sector's demand function, and $\beta_j^i (j = 1, 2, 3)$ are the slope coefficients measuring the effect of each of the independent variables on energy demand. The energy demand is forecasted for each sector $(\widehat{ED_t^i})$ out-of-sample to 2030 following the energy demand projection by the Ghana Energy Commission in their Strategic National Energy Plan (Energy Commission, 2021). A polynomial curve fitting model is then estimated and projected to 2050:

$$\widehat{ED_t^i} = \gamma^i + \gamma_1^i time + \gamma_2^i time^2 + \epsilon_t^i \tag{2}$$

where *time* is the key regressor of interest in this specification, γ_s are the polynomial curve fit coefficients, and ϵ_t^i is the error term (Zhang and Zhou, 2018).

Energy demand data was only available at a national level at the time of the study. Therefore, it is assumed that national-level trends are applicable at the urban scale. This is a reasonable assumption given that Accra is the largest city in Ghana, driving over 30% of national energy demand (GridCo, 2020) and almost 40% of the national GDP (UNECA, 2021).

3.3. Energy demand elasticity

To determine energy demand elasticities, the baseline model is modified to include the informal economy and temperature variables. The energy price, population size and national income are indexed to a base year of 2020. The model is obtained using the two-step least-squares estimation principle as follows (Lin and Zeng, 2013):

$$ED_t^i = \Gamma \left(\frac{PRICE_t^i}{PRICE_0^i}\right)^{\alpha} \left(\frac{GDP_t^i}{GDP_0^i}\right)^{\beta} \left(\frac{POP_t^i}{POP_0^i}\right)^{\gamma} \left(INFORMAL_t^i\right)^{\delta} \left(TEMP_t^i\right)^{\theta} e^{\varepsilon_t^i} \tag{3}$$

where the variables are as previously defined, except *INFORMAL* and *TEMP*, which are informal economy and temperature, respectively; *t* is time; 0 is the initial value corresponding to a base year; α is the price elasticity; β is the income elasticity; γ is the elasticity of population; δ is the elasticity of the informal economy; θ is the temperature elasticity; and Γ is a constant.

Data on historical mean temperature was acquired from the Climate Change Knowledge Portal for Development Practitioners and Policy Makers, a database maintained and published by the Word Bank Group (World Bank Group, 2021). Historical population growth for Ghana was obtained from the World Development Indicators published by the World Bank (World Bank Group, 2022b). Data on the informal economy of Ghana was obtained from (Dramani et al., 2022), who estimated the size of the informal economy of Ghana between the period 1971–2019 (see Fig. 2). It is important to note that obtaining consistent time series data on population growth and informal economy data for Accra was

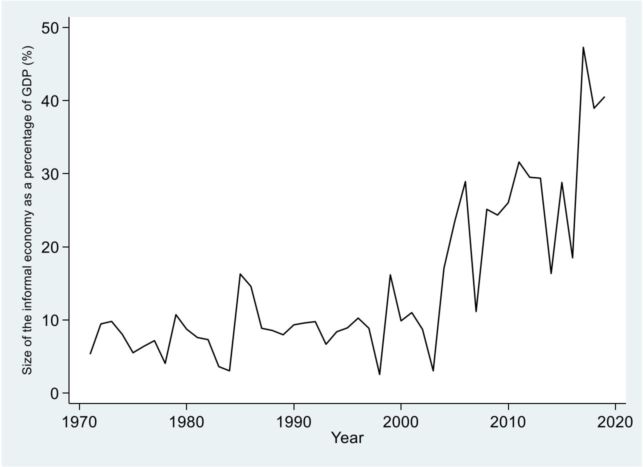


Fig. 2. Size of the informal economy of Ghana for the period 1971–2019; Source: (Dramani et al., 2022).

constrained. However, mean temperature data could be obtained at subnational levels. Other variables, such as GDP and energy prices are assumed to affect every subnational area and, hence, using them to proxy the situation in Accra is quite innocuous. Given that a significant share of Ghana's economic activities takes place in the capital region, for which Accra is the main city, and given that disaggregated data on most of the key variables in our model are lacking, the economy-wide elasticity of energy demand with respect to the variables in Eq. (3) can serve as a reasonable approximation for Accra.

3.4. Long-term scenario development

3.4.1. SSP scenario parameters and objectives

Long-term scenarios are defined based on SSP projections regarding urban population growth and mean temperature change for Accra. Informal sector changes are also prescribed for each scenario based on historical trends and SSP storylines.

3.4.1.1. Population growth. A base population trend is projected for Accra based on historical data (Macrotrends LLC, 2022). Future population growth due to climate migration is based on IPCC SSP scenario projections (IPCC, 2021b). Table 1 illustrates population density in each SSP scenario in the medium term (IPCC, 2021b). Population growth is assumed to reach these SSP values by 2050 in our modeling scenarios.

3.4.1.2. Temperature increase. Table 2 provides the mean temperature from 2020 to 2050 for each SSP scenario (World Bank Group, 2021). Relative changes are considered when applying derived energy demand elasticities.

3.4.1.3. Informal economic growth. SSP scenarios do not address informal economic growth directly. However, suitable informal economic growth rates have been assigned to each SSP scenario based on historical trends in Ghana (Fig. 2) and the development storylines of each SSP scenario. The informal economic trend in each scenario is summarized below.

SSP1 and SSP5: these scenarios assume coordinated and cooperative efforts to stimulate local economic growth and development. Therefore, the informal economic sector is assumed to shrink by 10% by 2050 compared to the current size in these scenarios. This figure is selected based on historical trends and development patterns in Ghana.

SSP2: This scenario assumes development trends in line with today. Therefore, the relative size of the informal sector is assumed to be the same in 2050 as today.

SSP3: This scenario assumes poor local development which exacerbates existing issues. A relative increase in the informal economic sector of 20% is assumed compared to the current economy, based on trends in historical volatility.

3.4.1.4. Optimization objectives. Objective functions are adapted based on SSP scenario storylines. SSP1 assumes cooperation from the international to the local scale to minimize CO_2 emission reductions; therefore, CO_2 emissions are minimized in the SSP1 objective function. SSP2 aims for a balance between cost and CO_2 emission minimization; therefore, this is formulated as a cost minimization objective along with a constraint to reduce CO_2 emissions by at least half of the maximum possible reduction value (i.e., given by CO_2 emission minimization). SSP3 assumes a lack of coordinated cooperation, and SSP5 does not seek to constrain emissions; therefore, both of these scenarios apply a cost-minimization objective only.

Table 1
Projected population density (persons/km^2) in Accra in the medium term (2041–2060) by SSP scenario (IPCC, 2021b).

SSP1-2.6	2351.7
SSP2–4.5	2441.0
SSP3–7.0	2522.4
SSP5–8.5	2309.8

Table 2
Projected mean temperature (°C) by year and SSP scenario (World Bank Group, 2021).

	2020	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
SSP 1–2.6	27.24	27.35	27.47	27.57	27.61	27.71	27.80
SSP 2–4.5	27.24	27.34	27.40	27.54	27.70	27.82	27.92
SSP 3–7.0	27.24	27.30	27.37	27.54	27.68	27.83	28.00
SSP 5–8.5	27.24	27.33	27.49	27.57	27.80	27.98	28.22

3.4.2. Calculating final energy demand

The energy demand increase relative to the base scenario is calculated for each SSP scenario to determine the total final energy demand. Total final demand is approximated in each year, for each SSP scenario, based on the demand elasticity as follows:

$$D_{y,s} = \sum_{f \in FACTORS, c \in SECTORS} \varepsilon_{f,c} \Delta x_{f,y,s} B_{c,y} + B_{c,y}$$

$$\forall y \in YEAR, \forall s \in SSP$$

Where:

D_y is the total demand in year y for scenario s.

$\varepsilon_{f,c}$ is the demand elasticity of factor f in urban land-use sector c.

$\Delta x_{f,y,s}$ is the percentage change of factor f in year y for scenario s compared to the base year value.

$B_{c,y}$ is the base energy demand for urban land-use sector c in year y.

YEAR is the set of modeled years.

SSP is the set of SSP scenarios under consideration.

FACTORS is the set of factors under consideration (i.e., informal economy, temperature, and population).

SECTORS is the set of urban land-use sectors under consideration.

3.5. Energy system modeling

This study utilizes an energy system model of Accra which was built using the open-source OSeMOSYS framework (OSeMOSYS, 2020; Yazdanie, 2023b). It is a linear programming, deterministic optimization model, in which all energy system components and energy carriers are represented. Cost and/or carbon emissions can be minimized as objective functions. Key model outputs include optimal capacity investment and operation by technology over the modeling time horizon.

The Accra OSeMOSYS model has a time horizon of 2020–2050, implemented in 5-year time steps. The sub-annual time resolution is a representative 24-hour day (i.e., 24 hourly time slices). The model represents the four main urban land-use sectors of Accra: residential, services/commercial, industry and transportation. The final or end-use energy demands accounted for are electricity, cooling, cooking, lighting and transportation. Energy carriers available as imports to the model are electricity from the national grid, diesel, gasoline, LPG, charcoal and wood.

A range of energy technologies are available as possible investment options in the model. This set of technologies was selected in consultation with local stakeholders. Technology options include:

1. waste incineration power plant
2. biomass (waste) CCP (combined cycle plant)
3. wind turbines
4. PV (rooftop grid-connected and standalone (stnd) systems with batteries; mini-grid with battery storage in industry; and grid-connected utility-scale PV)
5. generators (diesel/gasoline)

6. air conditioners (ACs)
7. stoves (charcoal/wood/LPG/electric)
8. light bulbs (CFL/LED)
9. internal combustion engine vehicles (ICEVs) (gasoline/diesel)
10. battery electric vehicles (BEVs)

Accra has significant potential for local renewable energy resources, such as waste and solar energy. The waste-based energy potential (i.e., from municipal solid waste) is estimated to be 4.1 TWh in the base year; this value is assumed to scale with population growth in future modeling years. The total PV installation potential is assumed to be up to 4 GW in the long term (i.e., until 2050), and up to 300 MW of wind turbines can also be installed to meet local demand.

The energy system model structure, including all current and future technology investment options, as well as energy carrier flows, is illustrated in Fig. 3. All SSP scenarios are evaluated using this model. Further information on the base Accra energy system model and inputs is given in (Yazdanie, 2023b). The open-source model code is available online (Yazdanie, 2023a).

All CO_2 emissions are accounted for in the model. Standardized combustion emissions factors are applied for fuels based on (Engineering ToolBox, 2009). Grey emissions associated with the national grid electricity mix are approximately 406 t-CO_2/GWh_{el} (Accra Metropolitan Assembly (AMA), 2019b).

4. Results and discussion

4.1. Base energy demand projection

Fig. 4 presents base demand projections for the residential, service, industrial and transportation sector in Ghana. Fig. 4(a) presents the residential and transportation sectors, while Fig. 4(b) presents the service and industrial sectors. The trends indicate that the transportation sector is growing rapidly compared to all the other sectors. Starting from the year 2000, residential sector energy demand was almost twice that of the transport sector in Ghana. However, by 2020, energy demand by the transportation sector overtook the residential sector. Projections indicate that transportation demand will continue to rise until 2050 as, indeed, the growth of vehicles in Ghana has increased tremendously over the last few decades. Aside from the increase in the number of vehicles, there has also been increased migration to and from cities in the recent past, and this is expected to increase further. Hence, by 2050, transport energy demand is expected to grow by a factor of approximately two relative to residential energy demand. Similarly, there has been rapid growth in the industrial and service sectors, for which demand is also expected to continue to rise until 2050.

4.2. Demand elasticity

Table 3 presents the energy demand elasticities by factor and sector. Energy demand responds positively to temperature and urbanization in all sectors except the informal economy. Again, the degree of

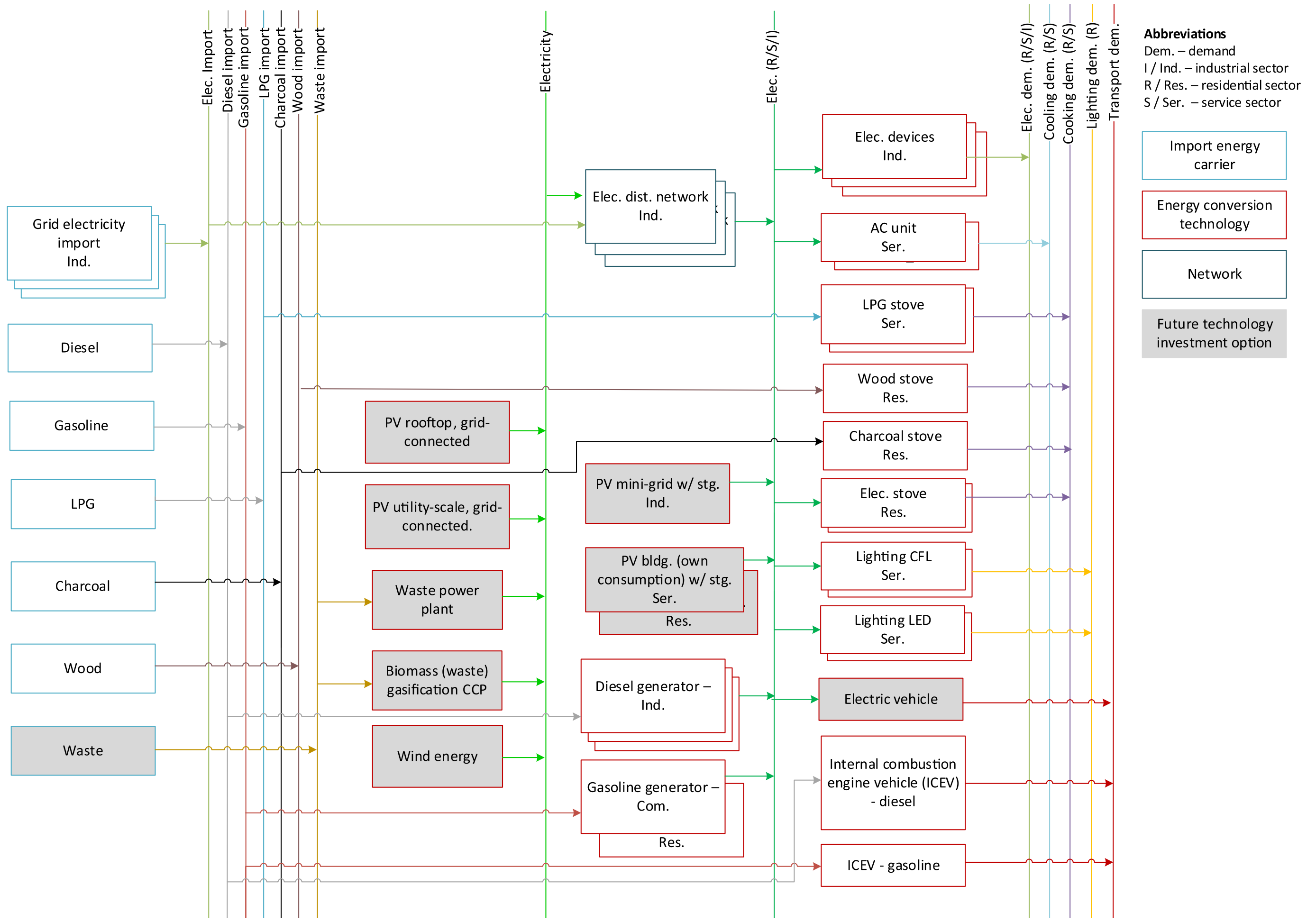


Fig. 3. Accra energy system model structure; based on
Source: (Yazdanie, 2023b).

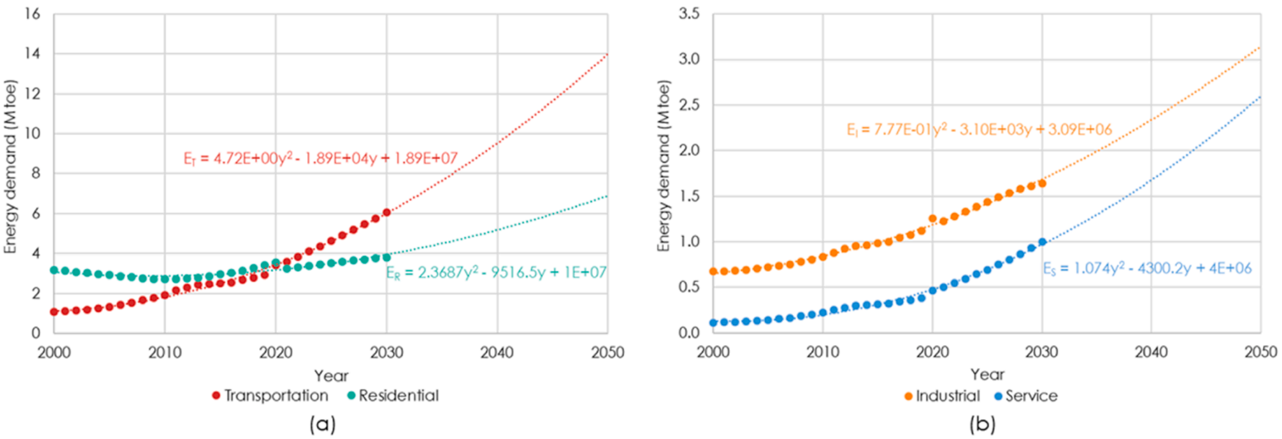


Fig. 4. National energy demand projections across transportation and residential sectors (a), and industrial and service sectors (b).

Table 3
Energy demand elasticities by factor and sector.

Factor	Sector			
	Residential	*Industrial*	*Service*	*Transportation*
Informal economy	-0.025	-0.049	-0.014	-0.047
Mean temperature	2.593	1.865	7.159	3.339
Urbanization	1.538	4.066	3.841	5.061

responsiveness (i.e., the magnitude) is low concerning the informal sector compared to temperature and urbanization. For example, a 1% change in temperature induces a 2.6% change in residential energy demand. Energy demand is inelastic to informal economic changes in all sectors.

The low sensitivity of energy demand to informal economic changes is explained by several factors. First, a low elasticity figure indicates that there may not be a large discrepancy between energy use intensity in the informal and formal sectors in Ghana. This result will vary from country to country depending on the economy; however, Ghana has the lowest primary energy intensity (in MJ/GDP) compared to its neighboring countries (e.g., less than half that of Nigeria, Benin and Togo) (World Bank Group, 2022b). At the same time, it is also plausible that the observed magnitude of elasticity is low due to data issues. The unofficial use of charcoal, electricity, biomass, and LPG is not fully accounted for in official data sets; thus, the data is not able to fully capture informal energy demand consumption and dynamics. This highlights a broader issue; government support is needed to collect more reliable data in the informal sector in order to understand its behavior and implications for energy planning.

The sensitivity of energy demand to temperature changes appears to be high in all sectors. The service sector's energy demand, however, appears to be more sensitive to temperature changes compared to other sectors. This is likely due to the increased availability and use of air conditioners in this sector during working hours. Even when there are power outages, a significant number of firms within the service sector use generators, which consume significant petroleum energy to keep businesses in operation. The transportation sector also shows a high sensitivity to temperature changes, as more people shift from walking to using motorized transportation and air conditioning in hot weather.

Energy demand also responds strongly to increased urbanization, as a larger population demands more energy. Urban development in Ghana has also seen some remarkable improvements over the years. Such developments, vis-à-vis the development phase of Ghana, require significant energy, often via low-efficiency conversion pathways. Consequently, increased urbanization tends to result in high demand for energy across sectors. However, the residential sector exhibits a lower demand elasticity to urbanization compared to other land-use sectors. This indicates comparatively low energy use-intensity in this sector, which is also likely associated with suppressed energy demand (i.e., energy demand which is not met due to issues such as energy affordability and access). This observation makes sense in light of the relatively low wealth of the residential sector compared to others as well. As noted earlier, climate change-induced migration to Accra implies urbanization; thus, this demand elasticity factor is applied in the following analysis of climate migration under SSPs.

4.3. Energy demand under informal economy and climate changes

The total energy demand projection under each SSP scenario (i.e., under different given changes in temperature, urban population, and the informal sector) is illustrated in Fig. 5. Fig. 6 breaks down the net change in energy demand by each contributing factor and sector in the year 2050.

The observed increase in energy demand across scenarios is primarily driven by urban population growth due to climate change, followed by rising temperatures. The smallest impact factor driving change is the informal economic sector, owing to its low demand elasticity.

SSP3 presents the highest demand of any considered scenario due to poor local development and climate change. High urban migration rates and a temperature increase result in 43% higher total demand in 2050 than compared to the base case in the same year. This value is also 32% higher compared to the best-case climate change scenario considered (SSP1) in 2050. SSP2 presents a similar trend, albeit with lower urban migration and rising mean temperature rates.

SSP5 and SSP1 present apparently similar total energy demand trends in Fig. 5; however, a breakdown of factor contributions (Fig. 6)

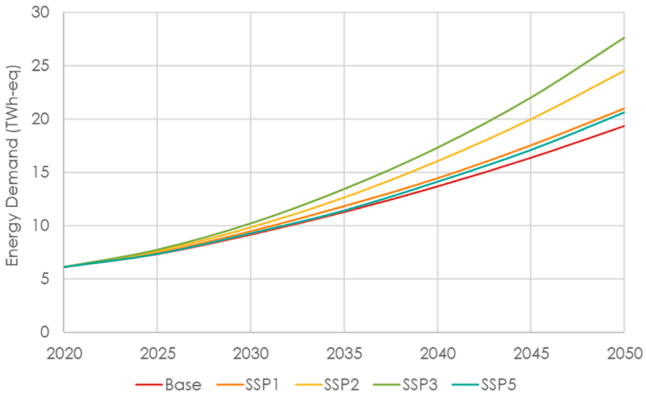


Fig. 5. Total energy demand across scenarios.

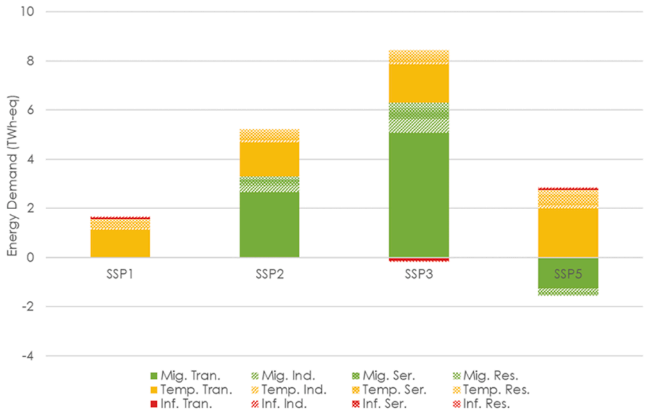


Fig. 6. Change in energy demand relative to base case by sector and factor in 2050 across SSP scenarios.

reveals further insight into this observation. SSP5 experiences a 75% increase in energy demand due to rising temperatures compared to SSP1; however, it also undergoes a reduction in urban population by 2050 due to strong local development compared to the base case scenario. Due to the high sensitivity of energy demand to population change, this negative effect counterbalances the high demand due to the rising temperatures.

The transportation sector, which constitutes the highest share of energy demand in Accra, contributes the most to observed demand increases, followed by industry. This indicates that decarbonization efforts should focus on these sectors to meet sustainability targets in Accra. As mentioned previously, since over half of all trips are walked in Accra, rising temperatures push people to switch to motorized transport for comfort where possible. Rising temperatures also contribute to urban migration, particularly from northern areas towards southern urban hubs, such as Accra, and from rural to urban areas. Such a rapidly growing population further exacerbates the demand for transport fuels, as illustrated by the highly elastic transport demand response determined for Ghana.

4.4. Accra energy planning impacts

Energy modeling results for energy supply, capacity planning and CO_2 emissions are presented in the following sections. Detailed results are given for the base case, SSP1 and SSP3 scenarios, as these scenarios capture demand envelope boundaries. Summary comparative results are presented for all scenarios as well.

4.4.1. Energy supply

Energy supply for local generation technologies across the modeling horizon is illustrated in Fig. 7 for the base case, SSP1 and SSP3 scenarios. Fig. 8 presents the local generation mix for all scenarios in 2050. The transportation demand met by different vehicle types across the modeling horizon for the base case, SSP1 and SSP3 scenarios is depicted in Fig. 9 as well. Finally, Fig. 10 depicts total energy imports for the entire modeling period for all scenarios.

Across all scenarios, Accra is able to meet most of its non-transportation energy demands through local renewable energy generation technologies, such as waste CCP and various PV technologies.

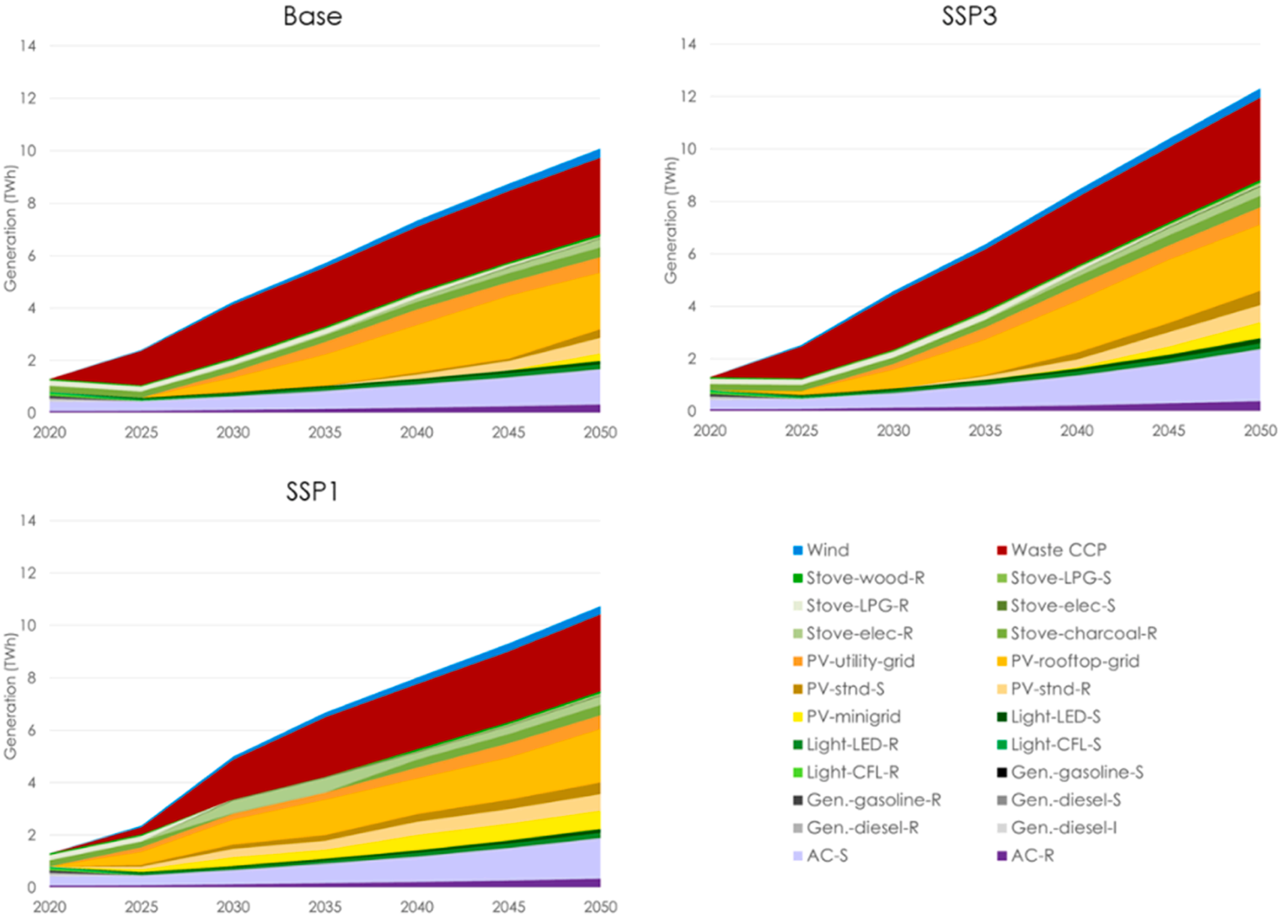


Fig. 7. Local generation to meet (non-transportation) energy demand across technologies from 2020 to 2050 in base case, SSP1 and SSP3 scenarios. Legend sector descriptions: I-industry, S-service, R-residential.

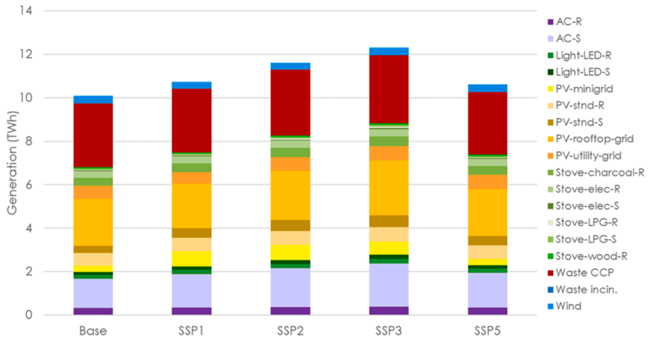


Fig. 8. Generation output across technologies and scenario in 2050. Legend sector descriptions: I-industry, S-service, R-residential.

Accra is uniquely positioned to achieve this, as its electricity demand is relatively low, especially compared to industrialized cities.

As Fig. 7 illustrates, SSP1 has the earliest and heaviest investment in renewable energy technologies (PV and waste CCP) in order to minimize emissions. It is also the only scenario to achieve 100% electrification in the transport sector in 2050 (compared to 56% BEVs in the base case scenario; see Fig. 9). This is associated with high electricity demand, which is largely met through grid imports in SSP1.

SSP1 demands the highest total electricity grid imports of any scenario; however, it also has the lowest total energy imports (see Fig. 10). SSP1 presents the most efficient system of any scenario, largely due to high-efficiency transportation. Hence, although SSP1 and SSP5 have similar total energy demands, SSP1 requires 15% lower total energy imports than SSP5. The high-efficiency, low-carbon system design of SSP1 comes at a total system cost which is approximately 25% greater than that of SSP5 (and 20% higher than the base case scenario).

Diesel and waste dominate energy imports across all scenarios, with only SSP1 minimizing its use of diesel by achieving zero diesel imports by the year 2050. This has important implications for energy planning, both with respect to the benefits of capitalizing on available local energy resources (e.g., waste and PV), and the drawbacks of overreliance on fossil fuels for transportation (e.g., diesel) in Accra (i.e., regarding energy security, CO_2 emissions and significant fuel import requirements).

SSP3 demands the largest total energy imports of all scenarios. These are approximately 40% greater than SSP1, and 20% greater than the base case scenario. The base scenario underestimates local generation planning and total energy imports in all scenarios (with the exception of SSP1 with respect to total imports). These differences are significant and

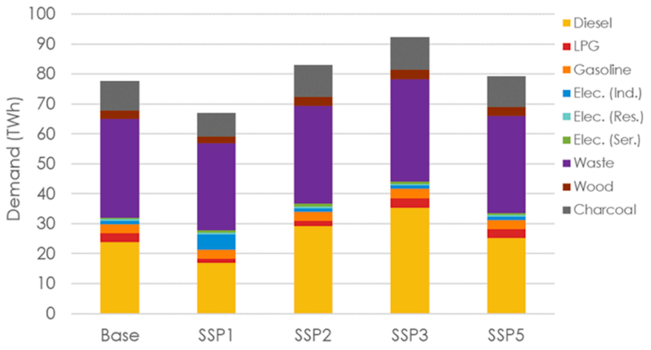


Fig. 10. Energy carrier imports from 2020 to 2050 across scenarios.

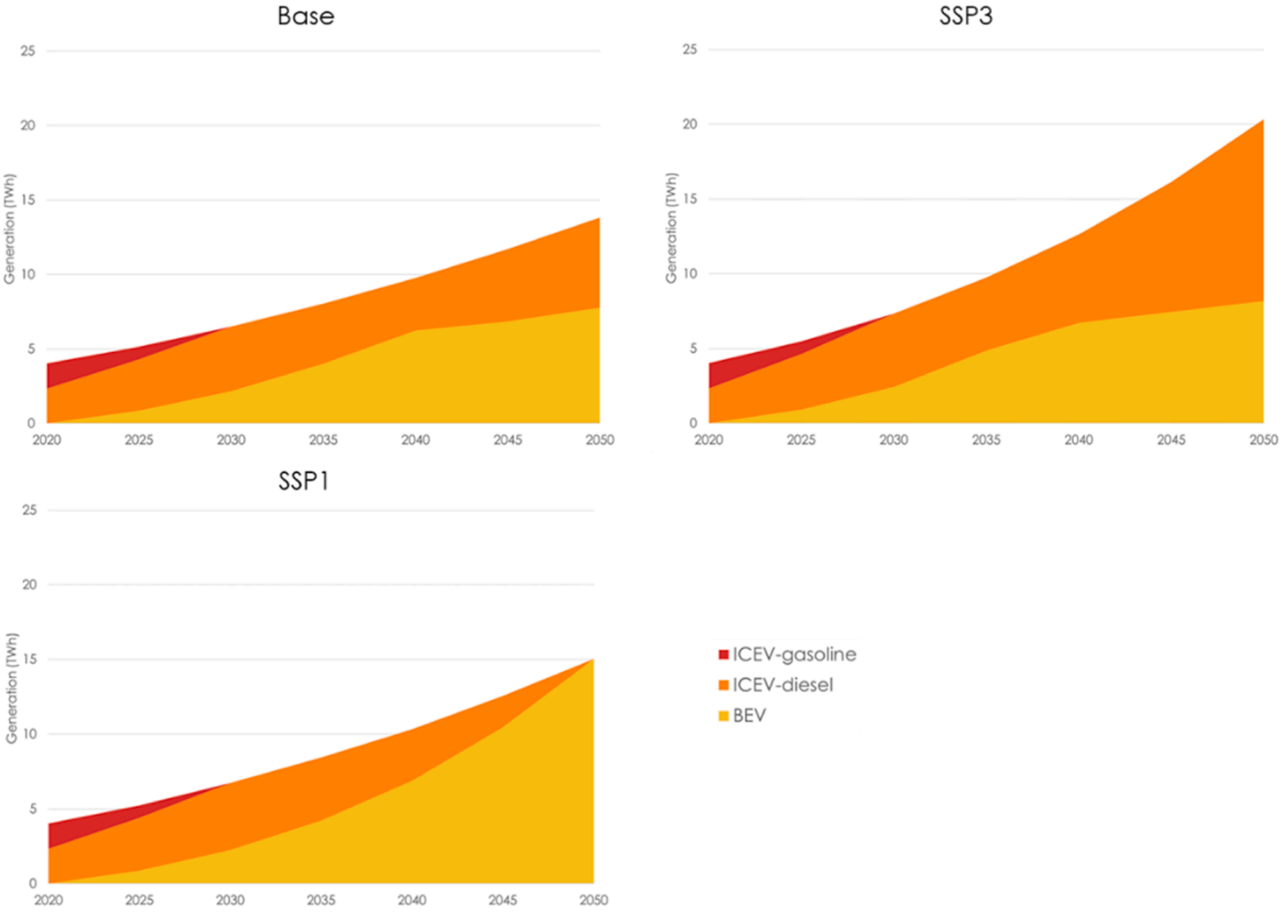


Fig. 9. Transportation demand met by vehicle type from 2020 to 2050 in base case, SSP1 and SSP3 scenarios.

illustrate the importance of considering climate change impacts on urban energy planning, and their implications. For example, local planning efforts should ensure that infrastructure (e.g., distribution networks) will be able to support higher local generation loads than in the base case scenario which neglects climate change impacts.

4.4.2. Capacity

Fig. 11 depicts optimal technology capacity installations for the base case, SSP1 and SSP3 scenarios across the modeling horizon, while Fig. 12 compares installed capacities across all scenarios in 2050.

The main local technology investments across all scenarios are PV, followed by waste CCP and AC technologies. All SSP scenarios demand higher capacity investments than the base case scenario, ranging from 4% higher total investments in 2050 in SSP5 to 16% greater investments in SSP3 compared to the base case. This further illustrates the need to consider climate change-driven urban migration and rising temperatures in long-term energy technology capacity planning.

SSP1 has the largest and most aggressive rollout of PV technologies. Under its carbon minimization target, SSP1 deploys PV at the maximum permissible rate beyond 2030, achieving the maximum total PV potential of 4 GW by 2040.

SSP3 has the highest total capacity installation of all scenarios in order to absorb drastic changes in urban population and temperature. The installed AC capacity is 42% higher in this scenario compared to the base case. With its high cooking energy demand, Accra will also install a 21% higher stove capacity in this scenario compared to the base case. Waste energy will have a significant role to play in a high climate migration scenario such as SSP3. With an increased waste resource potential due to a growing population, the SSP3 case optimally plans for a 13% larger waste CCP plant, and 7% higher total generation compared to the base scenario. This illustrates the vital role that waste energy conversion has to play in Accra's sustainable and climate-resilient energy future. The city should prepare itself to effectively scale up its collection capabilities and utilization of waste resources, which can help it absorb the shock of increased demand due to a rapidly growing

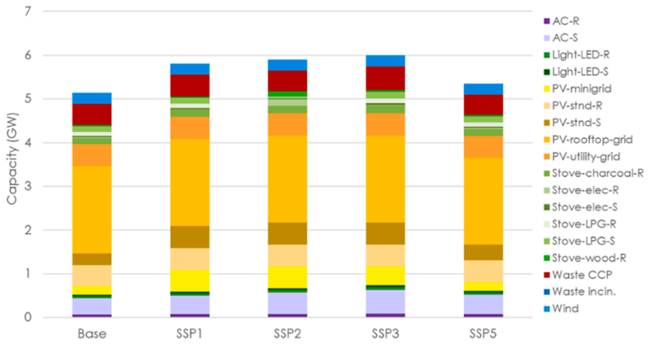


Fig. 12. Technology capacity installation in 2050 across scenarios.

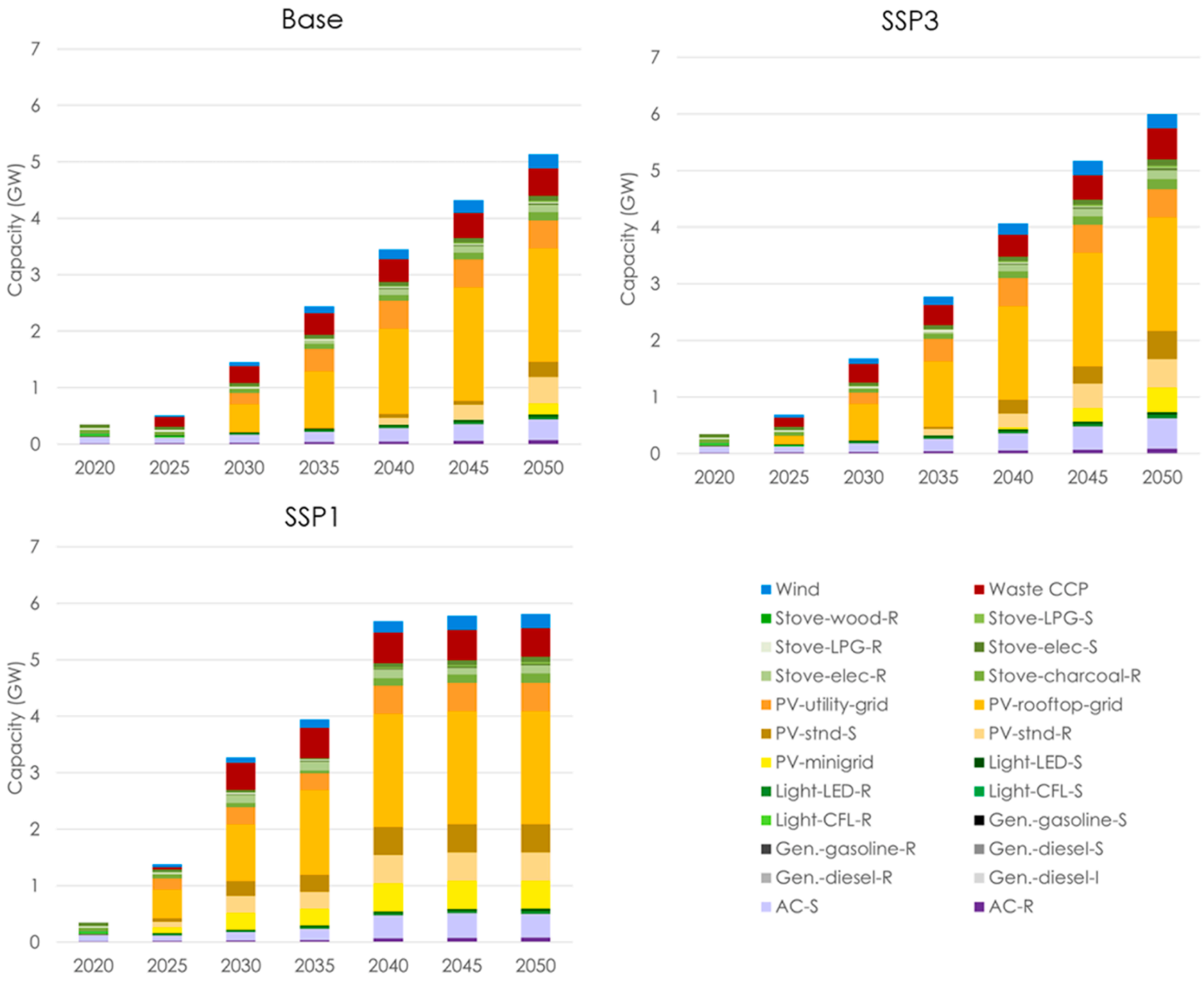


Fig. 11. Technology capacity installation from 2020 to 2050 in base case, SSP1 and SSP3 scenarios.

population.

The significantly higher energy demand and capacity planning needs of SSP3 also have implications for long-term local infrastructure planning. The size of the distribution grid in SSP3 is 25% larger than that of the base case by 2050. This has important financial and power system planning implications for the city.

4.4.3. CO2 emissions

CO2 emissions are presented for the base, SSP1 and SSP3 scenarios across the modeling horizon in Fig. 13. Fig. 14 illustrates total emissions across all scenarios.

CO_2 emissions are mainly driven by the combustion of transportation fuels (i.e., diesel), emphasizing the need for Accra to focus decarbonization efforts in this sector. SSP1 replaces diesel with grid electricity for BEVs, which plays a crucial role in its total emission reduction performance. SSP1 emissions gradually increase after 2040, as transportation demand rises and local generation from carbon emissions-free renewable energy can no longer meet rising electricity demand due to BEVs (i.e., grid imports increase). It is important to note that emissions performance in this scenario depends on the grid emissions factor, which is assumed will not worsen compared to Ghana’s current national energy mix by 2050.

SSP1, therefore, presents the lowest total emissions of any scenario. Despite increasing temperatures and demand compared to the base scenario, SSP1 still achieves 5% lower overall emissions compared to the base case scenario. This emphasizes the importance of high-efficiency technology adoption in Accra to tackle increased demand under climate change.

SSP3 presents the highest total emissions, which are almost 40% greater than that of the base case scenario. Emissions are driven by diesel combustion for transportation, resulting from increased demand due to a growing population under rising temperatures. In 2050, emissions are almost 50% greater in SSP3 compared to 2020; while in the base case scenario, these emissions are 25% lower. This is a radical difference that highlights the challenges Accra will face in achieving its emission reduction and sustainability goals under local climate change impacts, especially urban migration effects. It further emphasizes the importance of maximizing the rollout of local renewable energy technologies, such as PV and waste, and vehicle fleet electrification to mitigate CO_2 emissions.

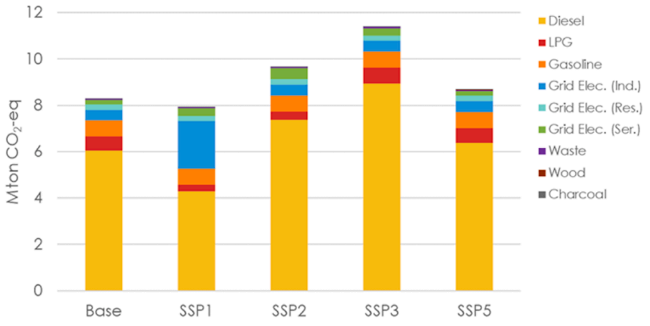


Fig. 14. Total CO_2 emissions by energy carrier from 2020 to 2050 across scenarios.

5. Limitations and future work

The findings of this work are limited by some factors. One limitation is concerning data sets. As discussed in section 3.3, the result that energy

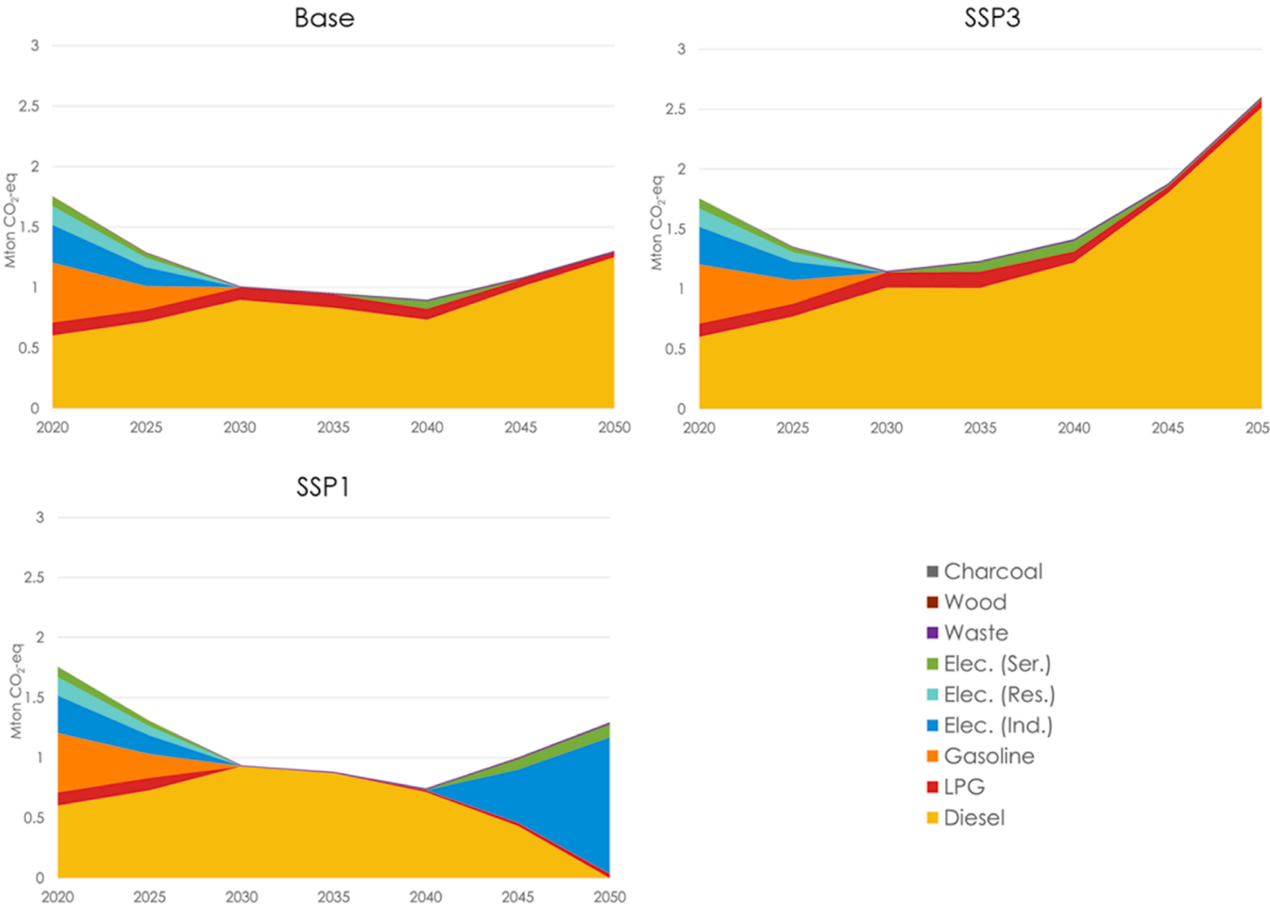


Fig. 13. CO_2 emissions by energy carrier from 2020 to 2050 in base, SSP1 and SSP3 scenarios.

demand is relatively inelastic to changes in the informal sector may be a result of data underestimating the consumption of informal energy resources (e.g., informally collected and sold firewood and charcoal). Further data set investigation, collection and improvement would enable us to draw stronger informal sector elasticity conclusions. This outcome vitally illustrates data issues in this domain and the need for governmental institutes to intervene to improve data collection in the informal sector. This is essential to better understand and plan for changing energy demands driven by changes in the informal (and formal) sector size.

Further detailing of energy consumption data sets by end-use application can also enable further refinement of demand elasticity by end-use type (e.g., electricity demand for cooling compared to other end uses). Higher resolution data sets could improve the accuracy of cooling demand impacts due to rising temperatures, which may currently be underestimated due to supply-side data aggregation. The use of Accra-specific data (rather than national data as a proxy in some cases) would also improve model accuracy.

The scope of this study is limited to a relatively small set of climate change impacts on Accra. Further studies would benefit from the evaluation of additional impacts (e.g., rising sea levels, precipitation changes and flooding events) and their interactions with socioeconomic and energy systems.

The present scenarios are defined by elasticity values which are based on historical data. This means that the dynamics of future climate change events and their interactions with the present system are not yet captured in data sets. This indicates that this study's findings may be conservative estimates of informal economy, climate migration, and temperature change impacts on Accra's energy system. Demand elasticity should continually be reevaluated as new data becomes available.

6. Conclusions

This study presents an approach to evaluate the impacts of the informal economy, climate change-driven urban migration, and rising temperatures on energy planning using optimization models. Conventional energy system optimization models typically neglect or underevaluate these factors, which are prominent issues in most developing countries and cities worldwide. Our approach focuses on long-term scenario design based on derived demand elasticities by sector for each evaluated factor. Scenario performance is then compared using an energy system optimization model, demonstrated for Accra.

Energy demand in Accra is found to be highly sensitive to changes in population (i.e., urban migration) and rising temperatures, particularly in transportation and service sectors. Energy demand appears to have a comparatively low sensitivity to changes in the informal economic sector in Ghana, which is a reasonable result considering the low primary energy intensity of the formal sector (e.g., compared to other developing African countries). However, it is also plausible that elasticities to changes in the informal sector are being underestimated due to data issues, signaling the need for authorities to develop better informal sector data collection programs to enable cities to better understand and plan for changes in informal sector growth. The authors argue that considering informality in energy planning remains important due to its sheer size and persistence in many developing nations, such as Ghana, particularly in nations with comparatively high energy use-intensity in the formal sector (i.e., energy use-intensity differences between the informal and formal sectors are expected to drive higher demand elasticities). Rapid urbanization due to climate migration will also affect informal sector growth if cities are unprepared to accommodate this influx.

The application of demand elasticities to climate change scenario conditions in Accra results in total energy demand projections which are up to 43% higher than the base case scenario (i.e., which neglects informal sector and climate change effects) in 2050. This stresses the importance of considering climate migration, temperature and informal sector impacts in long-term energy planning assessments and decision-making processes. Without their consideration, urban energy plans are likely to underestimate climate change-induced energy system stresses, for which they may be grossly underprepared.

Energy system modeling results indicate that Accra should brace itself for increased urban migration and rising temperatures due to climate change, as these factors have significant impacts on optimal energy planning. Increased energy demand induced by these effects challenges Accra's ability to meet its sustainability and CO_2 emission reduction targets. Thus, PV and waste CCP installations have a particularly important role to play in meeting this growing urban energy demand while simultaneously tackling sustainability objectives. Accra should focus energy planning efforts on efficient waste resource capture and utilization; this will support its absorption of a growing population's energy demand, which can partly be met by the increased waste resource they yield.

Accra must also ensure that local distribution infrastructure can handle increased demand and PV installations. In the SSP3 scenario, for example, the distribution grid is 25% larger in 2050 compared to the base case scenario. AC unit installations are also over 40% higher in SSP3 compared to the base case to meet rising cooling demands.

In addition to rolling out PV and waste energy conversion technologies, Accra should focus decarbonization efforts in its transportation sector since this is Accra's largest energy demand sector, which is also highly sensitive to urban migration and temperature changes. Therefore, to meet sustainability and emission reduction goals in the long term, Accra must decarbonize transportation (e.g., through fleet electrification).

The proposed methodology has been demonstrated for Accra, but it can be applied on city- and larger scales worldwide. It is vital to consider these factors, especially climate migration and rising temperatures in cities, in order to build resilient energy systems in the long-term.

CRediT authorship contribution statement

Mashael Yazdanie: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Visualization, Writing – original draft, Writing – review & editing. **Prince Boakye Frimpong:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **John Bosco Dramani:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Kristina Orehounig:** Conceptualization, Funding acquisition, Project administration, Supervision.

Declaration of Competing Interest

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

Data Availability

Data will be made available on request.

Acknowledgements

This work was supported by the Swiss National Science Foundation (SNF) (grant number IZSTZ0_193649). We also thank The Brew-Hammond Energy Center at the Kwame Nkrumah University of Science and Technology for their support in preparing cost data for the Accra model.

References

Accra Metropolitan Assembly (AMA). (2019a). *Accra Climate Action Plan*. Sustainability and Resilience Office of the Mayor.

Accra Metropolitan Assembly (AMA). (2019b). *Accra Greenhouse Gas Inventory for the Year 2015* . Sustainability and Resilience Office of the Mayor.

Accra Metropolitan Assembly (AMA). (2019c). *Accra Resilience Strategy—Accra Metropolitan Assembly—100 Resilient Cities*. 〈https://ama.gov.gh/documents/Accra-Resilience-Strategy.pdf〉.

Akpan, U., Essien, M., Isihak, S., 2013. The impact of rural electrification on rural micro-enterprises in Niger Delta. Niger. *Energy Sustain. Dev.* 17, 504–509.

Asante, F.A., Amuakwa-Mensah, F., 2015. Climate Change and Variability in Ghana: Stocktaking. *Clim.*, *3*(1), Artic. 1. https://doi.org/10.3390/cli3010078.

Asibey, M.O., Mintah, F., Adutwum, I.O., Wireko-Gyebi, R.S., Tagnan, J.N., Yevugah, L. L., Agyeman, K.O., Abdul-Salam, A.J., 2022. Beyond rhetoric: Urban planning-climate change resilience conundrum in Accra, Ghana. Cities 131, 103950. https://doi.org/10.1016/j.cities.2022.103950.

Basbay, M.M., Elgin, C., Torul, O., 2016. Energy Consumption and the Size of the Informal Economy. Econ.: Open-Access, Open-Assess. E-J. https://doi.org/10.5018/economics-ejournal.ja.2016-14.

Bhattacharyya, S.C., Timilsina, G.R., 2010. A review of energy system models. Int. J. Energy Sect. Manag. 4 (4), 494–518. https://doi.org/10.1108/17506221011092742.

C40 Cities. (2020). *Accra City Snapshot*. 〈https://www.c40.org/cities/accra〉.

Clement, V., Rigaud, K.K., E Sherbinin, A., Jones, B., Adamo, S., Schewe, J., Sadiq, N., & Shabalat, E. (2021). *Groundswell Part 2: Acting on Internal Climate Migration*. 〈https://openknowledge.worldbank.org/handle/10986/36248〉.

de Lucena, A.F.P., Schaeffer, R., Szklo, A.S., 2010. Least-cost adaptation options for global climate change impacts on the Brazilian electric power system. Glob. Environ. Change 20 (2), 342–350. https://doi.org/10.1016/j.gloenvcha.2010.01.004.

Dramani, J.B., Frimpong, P.B., Ofori-Mensah, K.A., 2022. Modelling the informal sector and energy consumption in Ghana. Soc. Sci. Humanit. Open 6 (1), 100354. https://doi.org/10.1016/j.ssaho.2022.100354.

Egger, P., Winner, H., 2005. Evidence on corruption as an incentive for foreign direct investment. Eur. J. Political Econ. 21 (4), 932–952. https://doi.org/10.1016/j.ejpoleco.2005.01.002.

Emodi, N.V., Chaiechi, T., Alam Beg, A.B.M.R., 2019. Are emission reduction policies effective under climate change conditions? A backcasting and exploratory scenario approach using the LEAP-OSeMOSYS Model. Appl. Energy 236, 1183–1217. https://doi.org/10.1016/j.apenergy.2018.12.045.

Energy Commission. (2021). *National Energy Statistics 2021* . 〈http://energycom.gov.gh/files/National%20Energy%20Statistics%202021.pdf〉.

Engineering ToolBox. (2009). *Combustion of Fuels—Carbon Dioxide Emission*.

Essandoh-Yeddu, J. (2006). *Strategic National Energy Plan*. Energy Commission. 〈http://www.energycom.gov.gh/files/snep/MAIN%20REPORT%20final%20PD.pdf〉.

Global Covenant of Mayors for Climate and Energy. (2022). *City Dashboard: Accra*. Global Covenant of Mayors. 〈https://www.globalcovenantofmayors.org/cities/sub-saharan-africa/ghana/accra/〉.

GridCo. (2020). *BSP Peak Demand Data*.

Guerra, O.J., Tejada, D.A., Reklaitis, G.V., 2019. Climate change impacts and adaptation strategies for a hydro-dominated power system via stochastic optimization. Appl. Energy 233–234, 584–598. https://doi.org/10.1016/j.apenergy.2018.10.045.

Gyamfi, S., Amankwah Diawuo, F., Nyarko Kumi, E., Sika, F., Modjinou, M., 2018. The energy efficiency situation in Ghana. Renew. Sustain. Energy Rev. 82, 1415–1423. https://doi.org/10.1016/j.rser.2017.05.007.

Hart, K., 1973. Informal income opportunities and urban employment in Ghana. J. Mod. Afr. Stud. 11 (1). Article 1. JSTOR.

Hart, K., 2008. Informal economy. In: Macmillan, P. (Ed.), The New Palgrave Dictionary of Economics. Palgrave Macmillan UK, pp. 1–4. 〈https://doi.org/10.1057/978-1-349-95121-5_804-2〉.

Ihrig, J., Moe, K.S., 2004. Lurking in the shadows: the informal sector and government policy. J. Dev. Econ. 73 (2), 541–557. https://doi.org/10.1016/j.jdeveco.2003.04.004.

Institute for Economics & Peace. (2020). *Over one billion people at threat of being displaced by 2050 due to environmental change, conflict and civil unrest*. 〈https://www.economicsandpeace.org/wp-content/uploads/2020/09/Ecological-Threat-Register-Press-Release-27.08-FINAL.pdf〉.

IPCC, 2021a. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. 〈https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Citation.pdf〉.

IPCC, 2022. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. 〈https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/〉.

IPCC. (2021b). *IPCC Working Group I AR6: Interactive Atlas*. 〈https://interactive-atlas.ipcc.ch/〉.

IPCC. (2023). *IPCC Sixth Assessment Report*. 〈https://www.ipcc.ch/assessment-report/ar6/〉.

Lin, C.-Y.C., Zeng, J. (Jean), 2013. The elasticity of demand for gasoline in China. Energy Policy 59, 189–197. https://doi.org/10.1016/j.enpol.2013.03.020.

Liu, Z., Li, L., Wang, S., Wang, X., 2022. Optimal design of low-carbon energy systems towards sustainable cities under climate change scenarios. J. Clean. Prod. 366, 132933 https://doi.org/10.1016/j.jclepro.2022.132933.

Macrotrends, L.L.C., 2022. Accra, Ghana Metro Area Popul. *1950–2022*. 〈https://www.macrotrends.net/cities/21107/accra/population〉.

Mauleón, I., 2022. A statistical model to forecast and simulate energy demand in the long-run. Smart Energy 7, 100084. https://doi.org/10.1016/j.segy.2022.100084.

Ministry of Energy, Ghana. (2010). *National Energy Policy*. 〈https://www.climate-laws.org/geographies/ghana/policies/the-national-energy-policy〉.

Ministry of Energy, Ghana. (2022). *National Energy Transition Framework*. 〈https://www.energymin.gov.gh/sites/default/files/2022–11/National%20Energy%20Transition%20Framework%20Abridged%20Version.pdf〉.

Musah, B.I., Peng, L., Xu, Y., 2020. Urban Congestion and Pollution: A Quest for Cogent Solutions for Accra City. IOP Conf. Ser.: Earth Environ. Sci. 435 (1), 012026 https://doi.org/10.1088/1755-1315/435/1/012026.

Nath, P.K., Behera, B., 2011. A critical review of impact of and adaptation to climate change in developed and developing economies. Environ., Dev. Sustain. 13 (1), 141–162. https://doi.org/10.1007/s10668-010-9253-9.

Neshat, N., Amin-Naseri, M.R., Danesh, F., 2014. Energy models: Methods and characteristics. J. Energy South. Afr. 25 (4), 101–111.

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Change 42, 169–180. https://doi.org/10.1016/j.gloenvcha.2015.01.004.

OSeMOSYS. (2020). *OSeMOSYS - Open Source Energy Modelling System*. 〈http://www.osemosys.org/〉.

Perera, A.T.D., Nik, V.M., Chen, D., Scartezzini, J.-L., Hong, T., 2020. Quantifying the impacts of climate change and extreme climate events on energy systems. Article 2 Nat. Energy 5 (2). https://doi.org/10.1038/s41560-020-0558-0.

Prina, M.G., Manzolini, G., Moser, D., Vaccaro, R., Sparber, W., 2020. Multi-Objective Optimization Model EPLANopt for Energy Transition Analysis and Comparison with Climate-Change Scenarios. Energies 13 (12), 3255. https://doi.org/10.3390/en13123255.

Ramachandran, K., Turton, H., 2014. Switzerland Energy Transition Scenarios – Development and Application of the Swiss TIMES Energy System Model (STEM). Swiss Federal Office of Energy,.

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Tavoni, M., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Glob. Environ. Change 42, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009.

Riva, F., Gardumi, F., Tognollo, A., Colombo, E., 2019. Soft-linking energy demand and optimisation models for local long-term electricity planning: An application to rural India. Energy 166, 32–46. https://doi.org/10.1016/J.ENERGY.2018.10.067.

Romitti, Y., Sue Wing, I., 2022. Heterogeneous climate change impacts on electricity demand in world cities circa mid-century. *Sci. Rep.*, *12*(1), Artic. 1. https://doi.org/10.1038/s41598-022-07922-w.

Sassi, O., Crassous, R., Hourcade, J.C., Gitz, V., Waisman, H., Guivarch, C., 2010. IMACLIM-R: A modelling framework to simulate sustainable development pathways. Int. J. Glob. Environ. Issues 10 (1/2), 5. https://doi.org/10.1504/IJGENVI.2010.030566.

UNECA. (2021). *New study shows Accra generates one-third of Ghana's GDP | United Nations Economic Commission for Africa*. 〈https://uneca.org/stories/new-study-shows-accra-generates-one-third-of-ghana%E2%80%99s-gdp〉.

UNHCR. (2016). *Frequently asked questions on climate change and disaster displacement*. UNHCR. 〈https://www.unhcr.org/news/latest/2016/11/581f52dc4/frequently-asked-questions-climate-change-disaster-displacement.html〉.

Urban, F., Benders, R.M.J., Moll, H.C., 2007. Modelling energy systems for developing countries. Energy Policy 35 (6), 3473–3482. https://doi.org/10.1016/J.ENPOL.2006.12.025.

van Ruijven, B., Urban, F., Benders, R.M.J., Moll, H.C., van der Sluijs, J.P., de Vries, B., van Vuuren, D.P., 2008. Modeling Energy and Development: An Evaluation of Models and Concepts. World Dev. 36 (12), 2801–2821. https://doi.org/10.1016/j.worlddev.2008.01.011.

van Ruijven, B.J., De Cian, E., Sue Wing, I., 2019. Amplification of future energy demand growth due to climate change. *Nat. Commun.*, *10*(1), Artic. 1. https://doi.org/10.1038/s41467-019-10399-3.

World Bank Group. (2022a). *Ghana Country Climate and Development Report*. 〈http://hdl.handle.net/10986/38209〉.

World Bank Group. (2022b). *World Development Indicators DataBank*. 〈https://databank.worldbank.org/source/world-development-indicators〉.

World Bank Group. (2021). *Climate Change Knowledge Portal*. 〈https://climateknowledgeportal.worldbank.org/download-data〉.

World Economics. (2023). *Informal Economy Sizes*. World Economics. 〈https://www.worldeconomics.com/Informal-Economy/default.aspx〉.

World Population Review. (2022). *Accra Population*. 〈https://worldpopulationreview.com/world-cities/accra-population〉.

Yazdanie, M., 2023b. Resilient energy system analysis and planning using optimization models. Energy Clim. Change 4, 100097. https://doi.org/10.1016/j.egycc.2023.100097.

Yazdanie, M., Densing, M., Wokaun, A., 2017. Cost optimal urban energy systems planning in the context of national energy policies: A case study for the city of Basel. Energy Policy 110, 176–190. https://doi.org/10.1016/j.enpol.2017.08.009.

Yazdanie, M. (2023a). Accra OSeMOSYS Base Model [dataset]. Google Drive. https://drive.google.com/drive/folders/1AYyoUevoE2go3AJ0nFGy7dzkRCQFpD8J?usp=sharing.

Yi, B.L. (2022). Coastal cities seen unprepared as IPCC flags climate risk hotspots. *Reuters*. ⟨https://www.reuters.com/business/cop/coastal-cities-seen-unprepared-ipcc-flags-climate-risk-hotspots-2022–02-28/⟩.

Zhang, X., Zhou, W., 2018. Forecast of China's natural gas consumption using mathematical models. Energy Sources, Part B: Econ., Plan., Policy 13 (4), 246–250. https://doi.org/10.1080/15567249.2013.863410.