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Energy efficiency impact on urban residential's electricity consumption and carbon dioxide reduction: a case study of Lomé, Togo

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Abstract Urban areas' energy consumption accounts for almost three fourths the global energy use with 70% of the related emissions. Therefore, cities play a meaningful role in decoupling economic growth from greenhouse gases (GHGs) emissions. This study presents a system dynamic approach to model the energy efficiency impact on the Togolese capital city's residential electricity consumption and carbon dioxide emissions reduction. The time spans from 2000 to 2050. An assessment of household appliances, such as lighting, refrigeration, cooling, and ventilation, was conducted along with monitoring electricity consumption of used and newly bought televisions, refrigerators, and freezers. Then, using Stella software, Lomé's residential electricity consumption model was built based on the following variables: (1) population, (2) the number of existing households with access to electricity, (3) new homes having access to electricity, and (4) per capita electricity consumption. The model was calibrated and validated using data for the years 2000 to 2016. Afterward, this previous knowledge was used to evaluate three efficient energy policies: 1) business-as-usual scenario, 2) new policies scenario, and 3) sensitivity scenario. Lomé's households present a predominantly low efficient appliances percentage. Therefore, the study found that substituting inefficient electric appliances with new and efficient models can lead Togo to substantial energy savings and reduce CO_2 emissions of about 680 GWh and 350 kt in the horizon of 2050, respectively. Additionally, the findings of this study could stimulate policymakers to audit other sectors to implement related energy efficiency policies and/or set up corresponding energy management strategies in neighboring emerging countries.

Keywords Carbon dioxide · Energy efficiency · Electricity consumption · Residential sector · System dynamics

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Introduction

The world's urban areas' primary energy use accounted for 75%, with 70% of energy-related

carbon dioxide (CO2) emissions in 2021 (IEA, 2021). Cities, therefore, represent the primary source of CO2 emissions (Moretto et al., 2018). By 2050, two thirds of the world's population will live in urban areas, and the corresponding energy demand will grow up two thirds of the current global energy demand, especially in emerging and developing economies, according to the analysis of Energy Technology Perspectives. To transition to the future sustainable energy system, decoupling economic growth from greenhouse gas (GHG) emissions is a step that cannot be overlooked. Energy efficiency is the most critical "arrow in the quiver" to achieve this paradigm shift (IEA, 2015). As a fact, energy efficiency is one of the most cost-effective ways to support the transition to a low carbon economy, prompt further investment opportunities, and create growth and employment (EU, 2016). Cities have a meaningful role in this regard because sustainable urban energy systems can decouple gross domestic product (GDP), energy, and CO2 emissions. Cities will represent 70% of the cost-effective CO2 abatement potential by 2050 (IEA/ETP, 2014). In 2014, energy efficiency improvements by the member countries of the International Energy Agency (IEA) since 1990 have avoided a cumulative 10.2 billion tons of CO2 emissions (IEA, 2015).

After the industry, the Togolese residential sector is the second-largest energy consumer, accounting for 31.51% (ARSE, 2019; Ntagungira, 2015). The country's electrical appliance market is flooded with used and low-efficiency appliances imported from Europe and the United States of America (USA) as noted by (Gyamfi et al., 2017; Akinbani, 2009; Kenfack et al., 2017). Unfortunately, this sad reality is the trend in most developing countries. Therefore, because of the low and middle-income status of the residents, as reported in (BTI, 2016), the number of households that can afford aged household appliances is expected to increase. As a result, many consumers affording inefficient appliances will put an additional burden on the electricity demand. Meanwhile, Togo is heavily dependent on electricity importation (Ntagungira, 2015), and the electricity demand grows on average 8% per year (MEF, 2014). The energy demand is projected to be more than double in 2022 years; thus, an additional power need of 200 MW is needed to meet the country's ever-growing population and ongoing development (MEF, 2014). It is, therefore, essential to

implement new power generation strategies in Togo. These new measures should primarily be directed to clean and renewable energy sources. Hence, the country must urgently set up energy efficiency measures in various sectors, such as agriculture, industry, and residential. The aforementioned new measures should consider the technology progress because the technology has a positive impact on the energy efficiency of African countries (Ohene-Asare et al., 2020). Improving energy efficiency, wherever possible, is vital; it should be set as a country's top priority by ensuring long-term cost savings by reducing environmental impacts (IEA, 2017). Interestingly, energy efficiency benefits are multiple (IEA, 2014). It is a strategy that requires very little to zero investment. It remains a means of energy savings that every country possesses in abundance and the quickest and cheapest way of addressing energy security and environmental challenges (IEA, 2015). It is then vital to improving EE measures wherever possible (IEA, 2017) to set one of the bases for promoting renewable energy that can offset CO2 emissions and mitigate the effects of climate adversities (Busu, 2019). Lomé, the capital city of Togo, was used as a case study to assess the potential of EE and estimate its impact on long-term electricity consumption with the corresponding reduction of carbon dioxide emissions and the rebound effect that might be offset. In this endeavor, households can reduce electricity use and save costs by choosing more efficient appliances and adopting energy-saving habits (National Climate Change Secretariat, 2016). This study attempts to point out the necessity of improving the efficient use of energy, a required step for promoting renewable energy, in developing countries in general and in Togo particularly in order to harvest the benefits related to. The research objectives of this paper are:

1) to assess the current electricity demand in the Lomé's residential area,
2) to predict the long-term electricity demand trends in Lomé (2030–2050),
3) to assess the type of appliances commonly used in Lomé,
4) to evaluate the total electricity consumption in Lomé, and finally
5) to estimate the city's subsequent CO_2 reductions by the horizon 2050 under efficient scenarios.

Consequently, an attempt was made to answer the following three questions:

a) What are the energy demand patterns in the Lomé's residential sector?
b) How will Lomé's residential electricity consumption trends evolve by the horizon of 2050? and
c) What will be the decrease in residential energy consumption and the subsequent CO_2 emissions if efficient appliances (lighting, refrigeration, heating, cooling, ventilation, etc.) are implemented by the horizon of 2050?

The following sub-section discusses the literature on electricity demand estimation and energy efficiency. Section 2 presents the methodology and data collection. Section 3 presents and discusses the results. Finally, Sect. 4 concludes the paper by summarizing the main findings of the research and the recommendations.

Literature review

Tackling climate change from the demand side will help achieve higher sustainability goals, such as saving energy means and natural resources, reducing carbon emissions, and saving extraction and transportation costs (Development, 2011). More energy-efficient technologies can improve supply security by reducing future energy-supply demands and associated GHG emissions (Schock et al., 2007). Several works have been conducted in West Africa and beyond on energy efficiency and energy conservation in the residential sector. For example, opportunities and challenges to electrical energy conservation and CO2 emissions reduction in Nigeria's building sector were analyzed, using Model for Analysis of Demand for Energy by (Akinbani, 2009). They have stated that the promotion of compact fluorescent lamps (CFL) and better energy-efficient fans and air conditioners would help in reducing both electric lighting and cooling energy. Furthermore, these same authors estimated the reduction of end-use electricity to be at least 10% leading ultimately to a reduction in greenhouse gas emissions in the country.

S. Gyamfi et al. (2017) have conducted a study on three household appliances regarding Ghana's current energy efficiency status. Conclusively, their study indicated that the energy efficiency measures of the Ghanaian government, especially in the replacement of incandescent lamps with CFLs, made substantial electricity savings, which in turn offset the national electricity peak demand by 200-240 MW. This study also pointed out that standard and labeling programs made for the air conditioners provided a demand savings of 250 MW. Moreover, the study has stated that the EE program was one of the most cost-effective means of meeting energy needs.

A similar study was conducted by (Yuan et al., 2016). Results showed that energy conservation actions in the Chinese power sector could reduce 240 Mtce of primary energy consumption with 590 Mt of related CO2 emissions avoided in 2020. In the United Kingdom (UK) in 2012, research was conducted on efficient appliances using surveys, electricity consumption monitoring, and old appliances replacement (Leach, 2012). The study's objective was to find the contribution of appliance replacement and consumer behavior on reducing energy use. After analyzing the results, they found that new appliances offer substantial energy savings with the existing state of technology. In that order, the fridge and freezer replacement with new and smart items typically yielded energy savings of 47 to 66% for each.

The energy efficiency in Africa remains unclear and difficult to implement (Amowine et al., 2019). This fact is partly attributable to widespread poverty. Measuring aggregate electricity savings from the diffusion of more efficient lighting technologies has been of interest to J. Moral-Carcedo & J. Pérez-García (2021). Their study has shown that replacing incandescent and halogen light bulbs with more efficient lighting technologies could save 251 GWh in Spain (Moral-Carcedo & Pérez-García, 2021). Many authors have used different methods to model electricity consumption, CO2 emissions, and the determinant of electricity demand across the World. These methods varied from econometric methods to system dynamics. Interestingly, an Autoregressive Distributed Lag (ARDL) approach was utilized to predict the Namibian residential and aggregate electricity demand (Vita et al., 2005). They found that the energy consumption is positively dependent to GDP variation and negatively dependent to variation in price and air temperature. Nowadays, it is hard to imagine any economic prosperity without access to a reliable and resilient electricity system. For this reason, a

thorough investigation of the nexus—between electricity consumption and economic growth in Bahrain—was conducted (Hamdi et al., 2014). The output of Hamdi et al.'s work had shown that the economic growth is dependent on electricity consumption and vice versa. This fact was confirmed by Hamdi et al. (2014). Their study showed that economic growth strictly depends on the amount and availability of electricity. The reverse is also true because access to a reliable and continuous energy supply leads to social wellbeing and economic growth. According to De Vita, G., an increase in income intuitively leads to a significant rise in households' electricity demands. In contrast, increasing the electricity price/ kWh only discourages residents from consuming more electricity. In 2011 the Nigerian urban residential energy demand was modeled using economic and system dynamics (Kayode et al., 2011). The results concluded that power generation and real disposable income mostly affected residential household electricity demand. A long-term energy planning was modeled based on system dynamics in Niger, with population, per capita electricity consumption, and industrial sectors as critical components (Moumouni et al., 2014). This study shed additional light on the West African existing literature.

A two-part model was employed in order to shed light on the determinants of household electricity consumption in South Africa (Ye et al., 2018). The finding of the latter authors revealed that household income and electricity price were the major determinants of electricity consumption and once the household income increases, the electricity demand increases as well. From the above studies, one can notice that households' electricity consumption depends on the 1) household size, 2) gross income, 3) price of electricity, and 4) per capita electricity consumption.

Some studies were equally conducted outside the African continent, where authors utilized a system dynamics approach. One of the most relevant was conducted in Latin America (Colombia) to comprehensively model residential energy efficiency and management using system dynamics (Dyner et al., 1995). They concluded that SD was appropriate for integrated planning and management problems related to EE issues. In Taiwan, the residential electricity demand was modeled utilizing an error correction model (Holtedahl & Joutz, 2004). This study

found that the demand for electricity in the residential sector was a function of household disposable income, population growth, price of electricity, and degree of urbanization. Similarly, Beijing's urban energy consumption and CO_2 emissions were adequately modeled using system dynamics (Feng et al., 2013). The authors have found that electricity use per capita was highly correlated with the stock of electrical appliances and GDP. The lifestyle of any households is influenced by the its income level that affect the electricity consumption(Sukarno et al., 2017). Other determinants such as buildings factors, weather, head of the household gender affect the residential electricity consumption (Besagni & Borgarello, 2018; Brounen et al., 2012; Esmaeilimoakher et al., 2016; Harold et al., 2015; Kavousian et al., 2013; Lee & Song, 2022).

The present study utilizes the system dynamics approach based on the following key parameters: population, continuous population growth, households with access to electricity, per capita electricity consumption, and energy efficiency measures. The impacts of the latter factor were assessed through various scenarios. However, this work did not consider the household income because the economy in Togo, as in most developing countries, is predominantly informal and therefore remains complex to evaluate. Nonetheless, the per capita electricity consumption revealed an idea of the per capita GDP of a country (Wolde-Rufael, 2006). To date, we are unaware of any such works that have attempted to comprehensively model the efficient energy consumption in the residential sector of Togo. Therefore, this study attempts to comprehensively model the efficient electric consumption in the Lomé's residential sector using system dynamics modeling.

Methods

The methodology adopted in the study consisted of an integrated approach, which utilized the following tools: 1) system dynamics (SD) modeling, 2) a survey, and 3) an experiment for accuracy. The electricity consumption is dynamic and requires a robust method to model its inherent complexities accurately. SD is suitable for performing such work on Stella software as an approach to understanding the nonlinear behavior of dynamic systems. SD is the most

effective approach that 1) can provide a better and more informative models than other approach, 2) can provide more reliable forecasts than other statistical models, and 2) offers a means to determining more robust sensitivities and scenarios (J.M. Lyneis, 2000; Suryani et al., 2010).

Stella is a powerful system thinking tool that helps visualize and understand complex problems (Allender et al., 2015; Apostolopoulos et al., 2017; Belue et al., 2012; Dangerfield, 2016; Forrester, 1969, 2007; Maksimovic et al., 1997; Smit et al., 2019). The necessity of collecting information related to households' appliances and light bulbs has called for a survey. The implementation of the survey aimed to set up a reference database on light bulbs and household electric

appliances on Lomé. As it was concerned, the experiment has been used as a supplement to collect on-ground knowledge on the electricity consumption of new brands against second-hand electric appliances under Lomé's weather conditions (Fig. 1). The rest of the methods presented the:

1. Conceptual framework.
2. Study area.
3. Historical data.
4. Description of system dynamics.
5. Survey and the experiments.
6. SD model of the Lomé an electricity consumption.
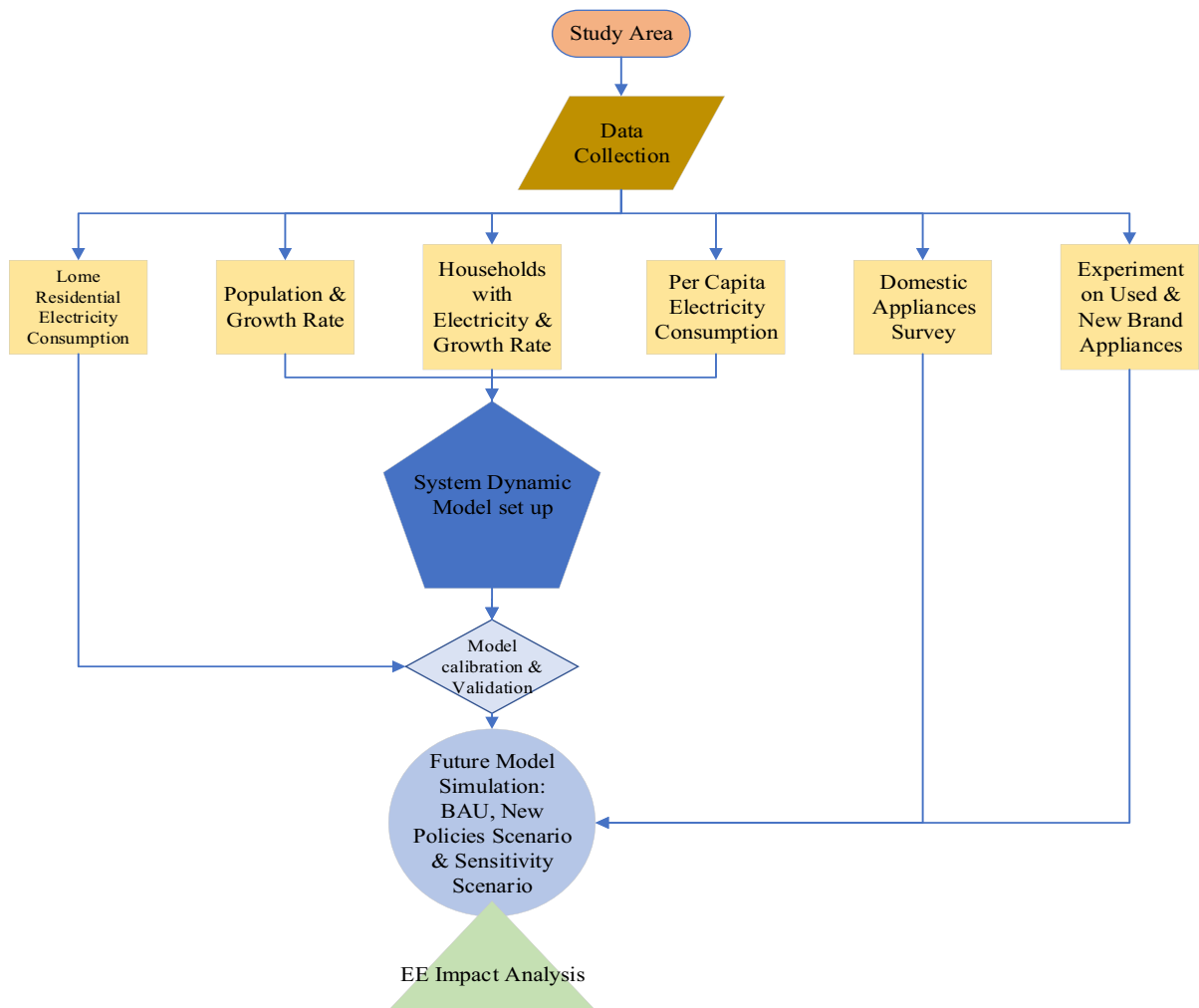7. Specific mathematical formulations and scenarios.

Fig. 1 Flow chart

Conceptual framework

Study area presentation

Lomé, the capital of Togo, is the largest city in the country. It has a population of 1,754,589 inhabitants. Located in the Gulf of Guinea (West Africa), Lomé is an administrative and industrial center. It hosts the biggest government's offices in the country, with an administrative area spanning over some 333km2. This area is comprised of 8 administrative subdivisions. Lomé is situated between 6° 08′ 14″ N and 1° 12′ 45″ E. In 2008, the national annual electric consumption was 110 MW. From the latter, Lomé's consumption alone accounted for 80 to 85 MW (PNUD-Togo, 2012), i.e., between 72% and 77.3%. Like other capital cities in emerging countries, Lomé is rapidly transforming, including rapid population and construction growth. Subsequent automobile traffic is equally intensified with residents expressing their needs to attain self-satisfaction by possessing various goods.

Along with the socio-economic development, Lomé has witnessed a significant increase in energy consumption and related carbon dioxide emissions in the last two decades. It is worth mentioning that Lomé is the most representative town in Togo, experiencing rapid urbanization and economic growth, increasing changes in technology, lifestyle, societal transformation, and rising electricity consumption and greenhouse gas (GHG) emissions. For the reasons mentioned above, Lomé was chosen as a case study to dynamically model its energy efficiency potentials. Additionally, the long-term impact of efficient electricity consumption in the urban residential sector was proposed and estimated. System dynamics modeling was adopted to assess the urban energy consumption and, subsequently, the CO_2 emissions.

Historical data

The number of electrified households per year in Lomé is the total yearly number of clients supplied by the utility company (CEET). The above data were collected with the corresponding electricity consumption from the same electricity company, viz., CEET, for 2000 to 2016. The number of electrified households in the city progressed due to rapid population growth, unprecedented urbanization growth, and increasing economic growth. The clients in Lomé were 343,543 in 2016, representing 65.50% of the company's total clients in that same year. The household size was estimated as five inhabitants per dwelling. It is also worthy of note to specify that 83.64%, on average, of the clients subscribed to a low voltage (0.4 kV) in the city represented the share of households with access to electricity. Furthermore, the related electrification rate of the aforementioned houses in the capital city was 92.47%. In contrast, the electrification rate of the whole country was 35.81%, according to the utility company. Households' electricity consumption in Lomé accounts for 80% of the total electricity consumption of low voltage in the city.

Additional parameters were needed to effectively predict the actual behavior of the country in terms of energy consumption, economic growth, and environmental impacts. First, Togo's fractional death rate was estimated at https://doi.org/10.60/1000 according to the General Population and Housing Census (GPHC) done in 2010 by INSEED. Second, as the model period extends from 2000 to 2050, the fractional birth rate 39.30/1000 of 2000 (Factfish, 2016) was chosen as a benchmark. Third, the population of the country estimated at 5,400,000 inhabitants (UNIDO, 2009) was selected as a base for our analysis. According to the World Bank report in 2012 and (Euromonitor, 2014), the number of inhabitants per household is estimated at five on average, as stated earlier. In 2000, the per capita electricity consumption was estimated at 120kWh, on average, according to the data of Word Bank for the past sixteen years.

System dynamics (SD) approach

System dynamics is a powerful method utilized in solving real-life problems. SD, a computer-aided approach, is used to gain insight from dynamic, complex, and policy-resistant situations. SD is increasingly used to design more successful policies in companies and public policy settings (Sterman, 2000). Modeling is inherently creative and iterative. Yet, all successful modelers follow a disciplined process that involves the following sequence: 1) articulating the problem to be addressed, 2) formulating a dynamic hypothesis or theory about the causes of the problem, 3) formulating a simulation model to test the dynamic hypothesis, 4) testing the model until the users are

satisfied and it is suitable for their purpose, and 5) designing and evaluating policies for improvement (Sterman, 2000).

Regarding these steps, J. D. Sterman argued that any previous step could yield insights that potentially lead to the revisions of actions performed earlier. The details and background theory can be found in the System Thinking and Modeling for a Complex World of J. D. Sterman (Sterman, 2000). In addition, SD uses four fundamental building blocks: 1) stocks or accumulators, 2) flows (inflow or input and outflow or output), 3) converters, and 4) connectors, as explained in (Martin, 1997). Stock and flow structures are ubiquitous in organizations of all kinds and their concept is fundamental in disciplines ranging from humanities, engineering, sciences, accounting to medical sciences. Hence, Fig. 2 presents the aforementioned basic building blocks. More specifically, stocks (quantities) are represented as rectangles that can be seen as tangible and intangible. According to the nature of the flows, stocks could fluctuate, viz., increase or decrease. The former parameters (flows) are labeled as inflow/input when adding to the stock and outflow/output when draining the stock. The converters are the circles, while the connectors are the curved lines with arrows.

As stated above, stocks are accumulations, collecting whatever flows into them and net of whatever flows out. Flow are variables that directly change the stocks. For instance, they can increase the stocks through births or decrease them through deaths. Connectors connect model elements, while Converters convey transforming variables. The software Stella produces finite difference equations that describe the graphical model and allows users to select a numerical analysis method and apply it to any complex system. Before running a model, users may also specify a time step and runtime for the simulation. Stella can output data in graphical or tabular forms (Lindfield, 1992). Stella runs one window at a time, meaning that only one model runs at any given moment.

Lomé's electricity consumption system dynamic model

The model developed for Lomé's electricity consumption is a replication of the models as in (Amega et al., 2021; Moumouni et al., 2014) but modified. Many variables, such as population, various appliances, and the number of households, driven by the evolving per capita electricity consumption, were constantly re-shaping the Lomé a residential electricity demand sector. Two different time horizons were considered to fit the purpose of this study: the near future, 2030, and far future, 2050. In light of the objectives of the study, a model was built based on the above variables, including the number of households having access to Electricity. These houses were named Lomé Electricity Consumption System Dynamic with Population and Households having access to Electricity (LECSD-PHAE). The latter variable was presented in Fig. 3.

The model was calibrated and validated with the past households' electricity consumption data of Lomé for the period ranging from 2000 to 2016, with a coefficient of correlation being set at 0.992. Figure 4 shows the model and the curve of the historical and the simulated electricity consumption. Interestingly, the past energy consumption and the simulation closely matched each other.

FBR and FDR were, respectively, the fractional rates of birth and death expressed in percentage, while the Unknown was an eventual event that could increase the number of deaths in the country. The population of Lomé was approximately 25% that of the country.

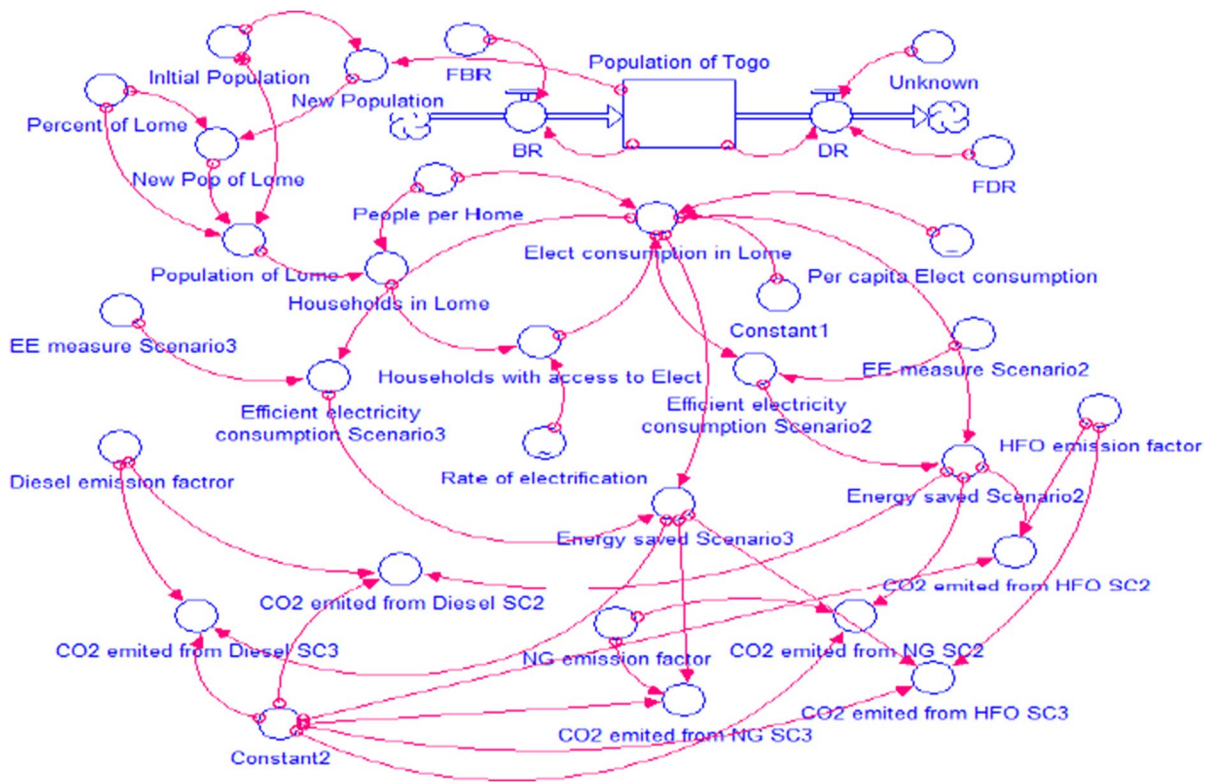**Fig. 2** A simple Stella model, adapted from (Richmond et al., 1987, pp. 85–97)
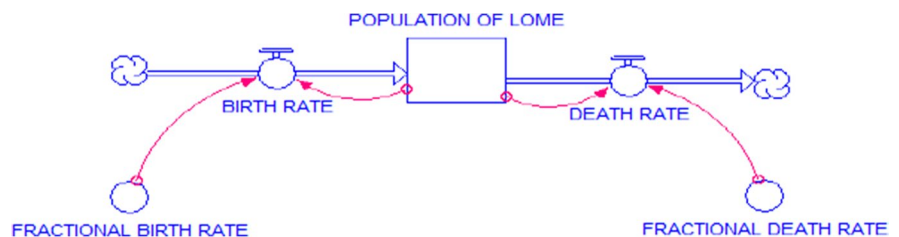
Fig. 3 Model of LECSDPHAE (Source: Authors)

Specific mathematical formulations

Behind the model is another interface displaying all the equations that help understand the theory deeply.

This section presents the mathematical functions to the long-term electricity consumption in Lomé's residential sector.

Fig. 4 Validation of LECS-DPHAE model
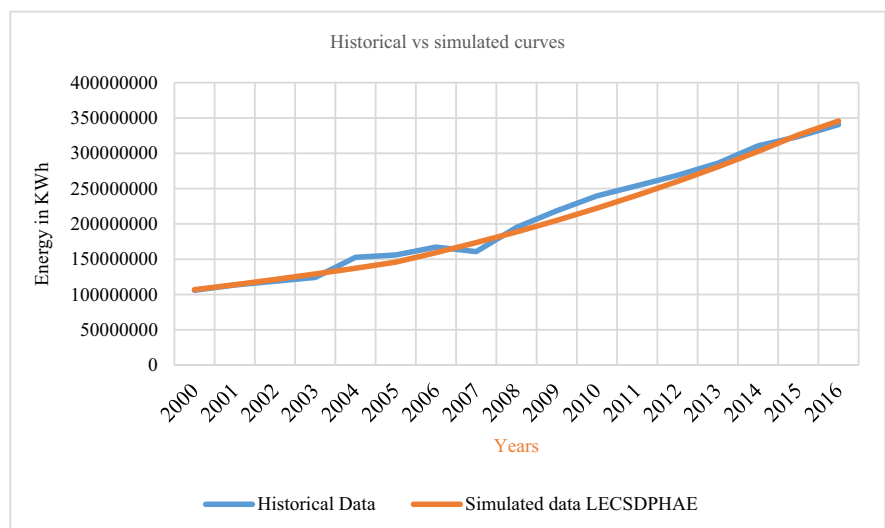
Population

The inflows to the population consisted of births, while deaths were the outflows. The latter flows decreased or balanced the "population." Based on the abovementioned dynamics, at any instant (*t*), the population can be estimated utilizing Eq. (1). The estimation of the population was the same for the two models.

$$Pop(t) = Pop(t - dt) + (BR - DR) \cdot dt \qquad (1)$$

where,

Pop　(*t*) is the population of Togo at time, "*t*,"

Pop　(*t—dt)* is the population at previous time step,

BR　is the number of births in time, *dt*,

DR　is the number of deaths in time, *dt* and.

Unknown represents actually anything or any situation could decrease and increase the population. It may be floods, earthquakes, droughts and famines, wars or any other event.

New population and population of Lomé

It is imperative to model the existing population accurately and model the new population during the upcoming years. This scheme will enable us to project, as accurately as possible, the future electricity consumption in Lomé. These new percent populations of the country and the capital city were estimated through Eqs. (2) and (3), in that order. However, Eq. (4) is the formula used to estimate the actual population of Lomé.

$$NPT = Pop(t) - \text{InItial\_Population} \qquad (2)$$

$$New_{PopofLome} = NPT \cdot \text{Percent\_of\_Lome} \qquad (3)$$

$$PL = \text{Pop}(t) \cdot \text{Percent}_{of_{Lome}} \qquad (4)$$

where *NPT* and *PL* are, respectively, the new populations of Togo and population of Lomé.

Number of households in Lomé

The number of households in Lomé is expressed as the population of Lomé over the number of people per household. According to the World Bank, Eq. (5) can be mathematically utilized to compute the homes needed for this study.

$$\text{HouseholdsinLome} = \frac{PL}{PPH} \qquad (5)$$

where *PPH* was the number of people per home.

Electricity consumption in Lomé

This model mathematically calculated the electricity consumption in Lomé as the product of the per capita electricity consumption by people per household by the households having access to electricity by a constant, as shown in Eq. (6). In addition, the household electricity access was expressed as the number of households in Lomé times the rate of electrification, as presented by Eq. (7). This formulation was adopted because the company in charge of energy in Togo estimated the rate of electrification as the ratio of the number of households having access to electricity over the total number of homes. The constant in Eq. (8) was introduced as a correction coefficient. Overall, the rate of electrification was increasing due to the country's energy policy targets to improve and increase access to electricity in the country and especially in the cities.

$$ECL = PCEC \cdot \text{People\_per\_Home} \cdot HAE \cdot \text{Constant1} \qquad (6)$$

$$HAE = HL \cdot RE \qquad (7)$$

$$\text{Constant1} = e^{\frac{1}{5.5}} \qquad (8)$$

where,

ECL　is the electricity consumption in Lomé,

HAE　is the number of households with access to electricity,

HL and *RE*　are the numbers of households in Lomé, the rate of electrification, respectively and.

PCEC   is the per capita electricity consumption in Togo closely dependent on the GDP per capita as expressed in equation:

$$PCEC = GDP_{perCapita} * 0.4279 + 26.2808 \qquad (9)$$

Over the time PCEC is expressed as:

PCEC = GRAPH(TIME)

    (2000, 121),

    (2005, 128), (2010, 146),

    (2015, 160), (2020, 169),

    (2025, 192), (2030, 199), (2035, 211),

    (2040, 225), (2045, 240), (2050, 250)

Electricity saved

The electricity economy was set as a clear target at the heart of energy efficiency policy scenarios. As a result, under the two types of efficiency scenarios, the electricity saved was quantified by the ratio of the product of electricity consumption times the energy efficiency over 100, as expressed in Eq. (10). The saved energy can also be estimated as electricity consumption minus efficient energy consumption under scenarios (Eq. 11).

$$Energy_{Saved-Scenario} = Electricity_{Consumption} \cdot \frac{EE_{Measure-Scenario}}{100} \qquad (10)$$

$$Efficient_{Elect-Consumption-Scenario} = Electricity_{Consumption} - Energy_{Saved-Scenario} \qquad (11)$$

$$EE_{measure-scenario2} = 4.4\% \qquad (12)$$

$$EE_{mearure-scenario3} = 28.2\% \qquad (13)$$

Reduction of carbon dioxide emissions

In this study, CO_2 emissions were considered as direct consequences, i.e., products of various fuel combustions, of the stationary combustibles. To that end, Eqs. (14) to (19) were formulated in this model and various scenario were run to estimate the emissions. Moreover, emissions of CO_2, solely based on scenarios 2 and 3, related to electricity production were computed for fuels, such as natural gas, diesel, and heavy fuel oil.

$$CO2_{(NG)-Scenario2} = \frac{Energy_{Saved-Scenario2}}{Constant \cdot \lambda_1} \qquad (14)$$

where λ_1 is the natural gas (NG) emissions factor. The actual value of λ_1 is 56.1.

$$CO2_{(Diesel)-Scenario2} = \frac{Energy_{Saved-Scenario2}}{Constant \cdot \lambda_2} \qquad (15)$$

where λ_2 stands for the diesel emission factor. The actual value of λ_2 is 74.1

$$CO2_{(HFO)-scenario2} = \frac{Energy_{Saved-Scenario2}}{Constant \cdot \lambda_3} \qquad (16)$$

where λ_3 represents the heavy fuel oil (HFO) emission factor. The actual value of λ_3 is 77.4.

$$CO2_{(NG)-Scenario3} = \frac{Energy_{Saved-Scenario3}}{Constant \cdot \lambda_1} \qquad (17)$$

$$CO2_{(Diesel)-Scenario3} = \frac{Energy_{Saved-Scenario3}}{Constant \cdot \lambda_2} \qquad (18)$$

$$CO2_{(HFO)-Scenario3} = \frac{Energy_{Saved-Scenario3}}{Constant \cdot \lambda_3} \qquad (19)$$

The value of the constant appearing in Eqs. (14)–(19) is 277777.78. It gives the conversion from Terajoules (Tj) to Kilowatt-hour(kWh).

These equations were based on TIER 1 approach, which was a method used by IEA to estimate greenhouse gas emissions from stationary combustions. The method assumes that a fuel used for each activity will result in the entering of the carbon it contains in atmosphere in the short and long term. Hence, the emissions can be expressed by Eq. (20) as

$$Emissions_{(GHG, Fuel)} = Fuel\ consumption \cdot Emission\ Factor_{(GHG, Fuel)} \qquad (20)$$

Although fuel consumption was the amount of fuel combusted, this study signified the amount of fuel that could be reduced in the context of energy efficiency and policy promotions. The emission factor was the default emission factor of carbon content.

Survey and experiments

There was no available data on Lomé's residential sector appliances revealing their brands, nominal powers,

and usage time per day. Also, there was no evidence if the appliances were bought new or used, and the corresponding electricity consumption was missing. A survey questionnaire was purposely formulated to collect such vital information for this study. The collected data were appended to this article. The survey was conducted on a random representative sample of 242 households in Lomé with access to electricity to collect the necessary information on the appliances. These collected data covered the following:

1. different electric devices,
2. light bulbs in the households,
3. conditions (used or new) at the time of purchase,
4. rated power,
5. hours of operation per day, and
6. rebound effect.

In addition, several experiments were conducted over a month on three different appliances, viz., TV, refrigerator, and freezers. A brand-new appliance and used one were considered for each type. An electricity meter (SIAME) was connected to each of the aforementioned appliances to monitor/measure the electricity consumption.

Scenarios

The scenarios are based on the situation whereby the minimum efficiency performance standards (MEPS) and energy labels are set up in the country. MEPS and energy labels are key policies to induce the promotion of energy efficient appliances and lights equipment that could help to reduce the accumulative residential electricity consumption and the CO2 reductions as well as the peak, to meet energy efficiency and climate policy and favor the low income households (Bertoldi et al., 2006; Ezeamama, 2020; Isabirye et al., 2012a, 2012b; Karali et al., 2020; McNeil et al., 2019; Nogueira et al., 2015; Palkowski et al., 2019; Sakah et al., 2019; Schleich et al., 2021; Siderius & Nakagami, 2013; Tziogas et al., 2021; Yilmaz et al., 2020; Zhou et al., 2011).

Scenario 1

This scenario was run as the "Business-As-Usual (BAU)." Under the BAU, we simply maintained the status quo, as there were no new energy efficiency policies implemented yet in the capital city, Lomé.

Scenario 2

Scenario 2 dealt with the introduction of efficient appliances in some households. There were no more incandescent bulbs and second-hand appliances, such as TVs, refrigerators, and freezers in all the Lomé's households. The percentage of introduction is respectively 2.4%, 34.71%, 6.20%, and 5.79%. It is worth pointing the following:

1. More stars on the Energy Rating Label is equivalent to a more energy-efficient appliance,
2. Efficient appliances consume less energy to achieve the same performance as would similar devices with the same capacity, and
3. More energy-efficient will cost to run.
4. Incandescent bulbs were all replaced by new and energy-efficient LED light fixtures. Also, their characteristics were chosen to be of higher and updated efficient power ratings. Similarly, the used TVs, refrigerators, and freezers were replaced by brand-new models. Equation (21) was used to compute the yearly electricity consumption (*YEC*).

$$YEC = P \cdot H \cdot \frac{365}{1000} \tag{21}$$

where *P* represents the mean power of the appliance in watt, *H* represents the number of operating hours per day, 365 is the number of days in a year, and the constant 1000 takes care of the conversion from Wh to kWh.

Based on the sample, the annual electricity consumption of lamps was estimated at 15,489.140 kWh. Then, under scenario 2, the yearly electricity consumption became 14,718.260 kWh, thus reducing 771 kWh. Also, according to the results, replacing used appliances with new or relatively new ones saved on an annual basis up to 3024 kWh on TVs, 1605 kWh on refrigerators, and 1498 kWh on the freezers. Without any assumption, all sample appliances' total yearly electricity consumption was estimated at 158,454.67 kWh. Therefore, the total electricity saved was 6898 kWh, representing an electricity reduction of 4.4% for the sample.

Scenario 3

This scenario represented the sensitivity test, where all the households were hypothetically equipped with efficient appliances only. In other words, neither incandescent bulbs nor used appliances were used in Lomé's households. Moreover, this scenario considered technological advancement: all Lomé's market appliances had high-efficiency ratings and followed the characteristics of Tables 1, 2, 3, 4, and 5. The electricity saved was the sum of electricity saved in the scenario2 and the electricity saved when using more efficient appliances. The total energy savings were 6898 kWh and 37,773 kWh, which represented the electricity saved based on the above assumptions. As a result, the total electricity saved was 44.76

MWh, representing 28.2% of electricity reduction (Amega et al., 2020).

Results and discussions

This section is dedicated to the research results and the discussion of their true meanings. The domestic appliances in Lomé's residential sector have been assessed and presented. Also, the knowledge gained from the experiment was successfully disclosed and could be utilized by the local utility companies and lawmakers for quality assurance. Further, the electricity demand in the above sector has been assessed and analyzed under the different scenarios, and the corresponding electricity savings have been estimated.

Table 1 Characteristics of selected efficient TVs

Brands	N		Hour	Mean	Median	Min. P(W)	Max P(W)
	Valid	Missing					
LG	46	196	5	157.83	195	40	250
Samsung	39	203	6	120.49	110	40	220
Philipps	31	211	7	110.58	110	45	250
Sony	19	224	4	97.56	110	40	190
President	3	239	6	95	110	40	135
Gruding	7	235	4	109.29	110	60	155
NASCO	1	241	0	110	110	110	110
BEKO	1	240	3	67.5	67.5	40	95
SHARP	35	209	5	101.91	90	45	195
Other TVs	54	188	6	108.52	110	35	250

Table 2 Characteristics of selected efficient AC units

Brands	*N*		Mean Hours	Mean	Median	Min P(W)	Max P(W)
	Valid	Missing					
ROYAL AIR	4	238	2	1987.5	1875	1200	3000
SHARP	2	240	1	1522.5	1522.5	1145	1900
ICE CRIME	1	241	1	1850	1850	1850	1850
CLIMY	1	241	1	2015	2015	2015	2015

Table 3 Characteristics of selected efficient refrigerators

Brands	*N*		Hour	Mean	Median	Min P(W)	Max P(W)
	Valid	Missing					
LG	12	230	8	115.42	120	65	120
BEKO	5	237	6	76	65	65	120
NASCO	4	238	9	92.5	92.5	65	120
Other refrigerators	20	222	10	117.25	120	65	150

Table 4 Characteristics of selected efficient brewers

Brands	N		Hours	Mean	Median	Min P(W)	Max P(W)
	Valid	Missing					
BINATONE	22	220	4	66.14	75	45	75
PRESIDENT	1	241	3	55	55	55	55
NEON	6	236	3	69.17	65	45	100
SHARP	3	239	4	75	75	50	100
Other Brewers	10	232	6	64.5	57.5	45	100

Table 5 Characteristics of selected efficient fans

Brands	N		Hours	Mean	Median	Min P(W)	Max P(W)
	Valid	Missing					
BINATONE	88	154	5	56.99	50	40	100
BRUDER	15	227	4	47.67	45	45	55
PRESIDENT	6	236	4	55.83	50	40	100
NEON	9	233	4	77.78	90	45	100
Other fans	44	198	6	51.7	50	30	100

Finally, the reduction of CO_2 emissions under the policies scenarios has also been presented and discussed.

Lomé residential sector appliances assessment

Lomé, the capital city of Togo, like the other regional capitals, is overflowed with various appliances in the residential sector. The main characteristics of the appliances are 1) low quality, 2) low-efficiency ratings, hap-hazardous, cheap. Most of the items found in Lomé's housing sector are numerous lamps and appliances like televisions, air conditioners, brewers, fans, freezers, refrigerators, and electric cookers, as presented in Table 6. It can be pointed out based on the survey result that in Lomé there are five categories of socio-economic households: 1) houses with light fixtures only, 2) houses with light fixtures and television; 3) houses with light, television and ventilator; 4) houses with light, television, ventilator and/or brewer, and refrigerator and/or freezer; and 5) houses with light, television, ventilator and/or brewer, refrigerator and /or freezer, air conditioner and electric cooker.

The annual electricity consumption per each type of appliance is estimated with their respective percentage shown in Fig. 5. It can be observed that the drivers of the residential electricity consumption in Lomé are television (38.39%), cooling (38.12%) (freezers, refrigeration and AC), ventilation (13.59%) (ventilators and brewers), and lamps (9.78%) irrespective of the brands. Televisions and cooling appliances are the most significant drivers.

Knowledge gained from the experiments

The electricity consumption of the appliances mainly depended on their condition, i.e., brand new, relatively new, or used. The latter consumed more electricity than the brand-new one because of its low energy-efficiency ratings. In addition, this difference in the electricity consumption was primarily exacerbated by the aging factor rather than any difference in nominal power. Since the experiments were conducted on refrigerator-freezers, the difference in electricity consumption related to refrigerator-freezers could exclusively be applicable to refrigerators or freezers. Secondhand TV's consumption was 47.43Wh while the new brand appliance consumed 28.2Wh per day. On the other hand, the used refrigerator-freezers electricity consumption was 2717.33Wh per day, and the brand-new ones were estimated at 2424.67Wh per. The difference in electricity consumption between the two categories of TV was found to be 34,666Wh per year, while between refrigerator-freezers, it was 106,823Wh per year. The electricity price varies according to the level of the consumption in the country. If the consumption is between 0 and 40 kWh, the
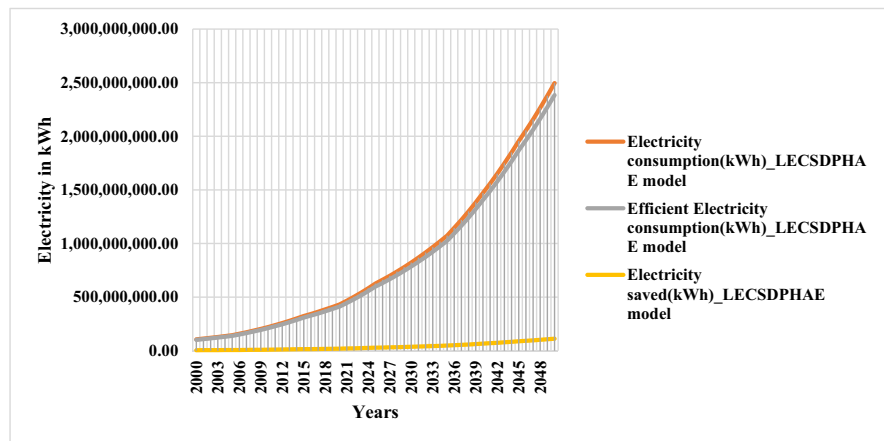
Table 6 Assessment of the residential appliances

Households appliances	Percentage (%)	Mean rated power (W)	Mean usage time per day
Lamps			
Fluorescent	49.7	16	6
Neon	34.9	22	7
LED	11.8	8	6
Incandescent	2.4	52	6
Televisions			
LG	19.6	193.63	5
Samsung	16.6	120.49	6
Sharp	14.9	101.91	5
Philips	13.2	127.1	7
Sony	8.1	97.56	5
President	1.3	95	6
Grunding	3	109.29	4
Beko	0.4	67.5	3
Non-Specified	23	118	6
Air conditioner			
Royal Air	3.3	2196.25	2
Sharp		1522.5	1
Ice Crime		1850	1
Climy		2015	1
Brewers			
Binatone	17.8	66.14	4
Sharp		55	4
Neon		78.33	3
President		78.33	3
Other		68.1	6
Ventilators/fans			
Binatone	66.94	63.86	5
Bruder		47.67	4
President		65	4
Neon		85.56	4
Non-Specified		53.33	6
Freezers			
LG	16.9	184.5	7
Beko		201.67	7
Nasco		184	4
Sharp		498.38	4
Non-Specified		211.73	12
Refrigerators			
LG	18.6	171.67	8
Beko		112	6
Nasco		122.5	9
Non-Specified		134	10

Table 6 (continued)

Households appliances	Percentage (%)	Mean rated power (W)	Mean usage time per day
Electric cooker			
Fides	1.7	Not known	1
Studio		Not known	1
LG		Not known	1
Mielle		350	1

Fig. 5 Percentage of electricity consumption per appliances

The electricity demand was a function of the number of current households with access to electricity and the newly built houses having access to electricity. A growth of households having access to electricity burdens the electricity consumption in Lomé's

price is 63F CFA/kWh (0.10USD). If the consumption is between 41–200 kWh, the price is 84F CFA/kWh (0.14USD). The difference in electricity consumption between the two TV is equivalent to 2,184F CFA (3.76USD) in a year. The difference in consumption between the refrigerators-freezers is equivalent to 9,973F CFA (15.48USD) in a year. Togo is known as low income country, therefore, a saving of the amount of money mention above is significant for a typical household in Lome in a long run. In term of consumption, these differences imply that the time of their usage would be extended in the corresponding households and may result in a positive impact on cooling, conservation of food and watching TV for more information.

Assessment of Lomé's near (2030) and far (2050) futures residential electricity demands

residential sector in the past and the future. Based on the model, in 2030 and 2050, the population of Lomé will be, respectively, 2,839,793 and 4,991,338 inhabitants. The electricity consumption, if all things being considered, would be 828G Wh in 2030 and 2,513G Wh in 2050, with respective 457,240 and 1,105,834 households having access to electricity.

Energy efficiency scenarios

Scenario 1

Again, we started this set of runs with the Business-As-Usual (BAU) under energy-efficiency scenarios. Under the BAU, the general trends were described in Fig. 4 because no new energy efficiency policies have been implemented yet.

Scenario 2

This scenario was based on the hypothesis that some households were using efficient appliances meaning that incandescent bulbs (2.4%), second-hand TV (34.71%), second-hand refrigerators (6.20%) and

second-hand freezers (5.79%) were replaced by efficient ones. The usage of efficient lamps and the elimination of secondhand appliances were paramount to reducing electricity consumption in the city. Under this scenario, electricity savings were more outstanding than 4.4% of the annual electricity consumption. Therefore, the electricity consumption varied from 350G Wh in 2018 to 792 GWh in 2030; these figures then increased to at least 2,403 GWh in 2050, as portrayed in Fig. 6.

Scenario 3

Similar to the analysis performed in Sect. 4.3, this scenario tested the sensitivity of the designed system. The reduction in electricity consumption was more important than in scenario (2), 28.2%. The electricity consumption increased from 279 GWh in 2018 to 595

GWh in 2030; it then increased to and to 1,805 GWh in 2050, as portrayed in Fig. 7.

The comparative analysis of the electricity saved under the two scenarios mentioned above under presented in Fig. 8.

Electricity saved

The simulation results from scenarios 2 and 3 revealed substantial electricity savings through the years due to the dramatic energy efficiency measures introduced in the models. In scenario 2, for instance, viz., 2030 and 2050, the reduction in electricity consumption was expected to become 37 GWh and 110 GWh, in that order. The energy savings during the "far future" were more than 197% of what they were in the "near future". These savings would assist the country in achieving its long-term economic goals.

Fig. 6 Electricity consumption, efficient electricity consumption, and electricity saved (Scenario 2), where the acronym LECSDPHAE stands for Lomé Electricity Consumption System Dynamic with Population and Households Having Access to Electricity
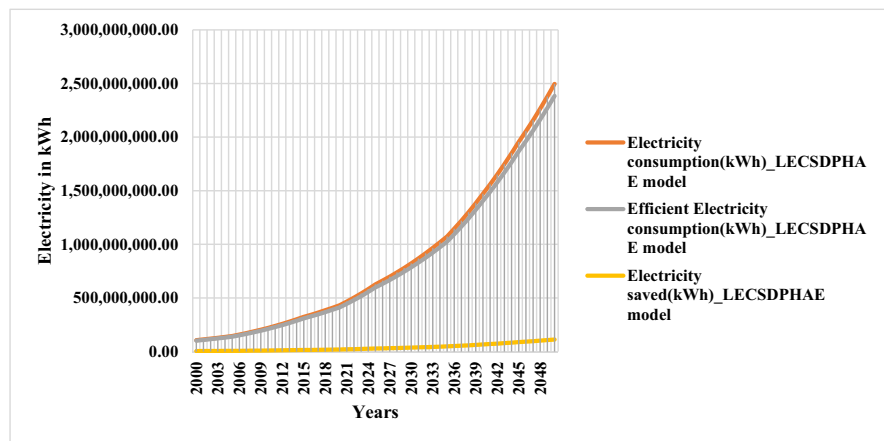

Fig. 7 Electricity consumption, efficient electricity consumption. and electricity saved (Scenario 3), where the acronym LECSDPHAE represents Lomé Electricity Consumption System Dynamic with Population and Households Having Access to Electricity
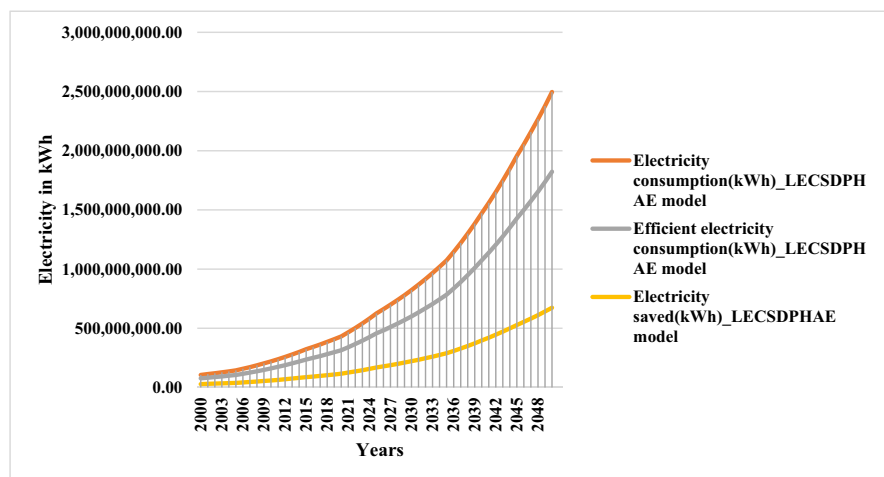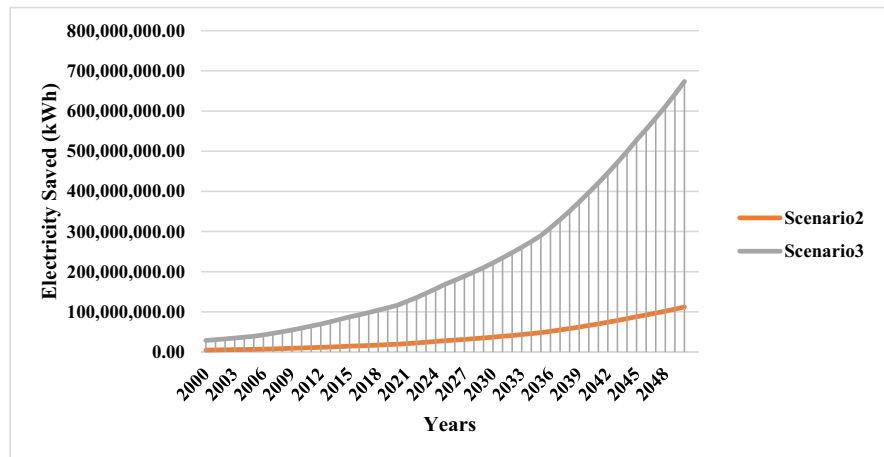
Fig. 8 Comparison of electricity savings under scenarios 2 and 3

Thus, 339 GWh of energy was projected to be saved from 2018 to 2030. Furthermore, the savings were even more pronounced if the time span was extended by twenty more years. The savings are estimated to be 1,734GWh from 2018 to 2050.

In a like manner, scenario 3 was succinctly run for 2030 and 2050, respectively. In that order, the reduction in electricity consumption was expected to be 234 GWh and 709 GWh. From 2018 to 2030, the total energy saved was estimated to be 2,171 GWh, while the forecasted energy reduction in horizon 2050 was 11,110GWh. These projected savings in the "far future" were equivalent to a 400% increase than the "near future." As indicated by the results, a potential of energy efficiency could be found in Lomé's residential sector, representing energy that would otherwise be wasted. Therefore, good energy management was needed to lower barriers to this low-cost energy source (Abrardi, 2018; Cagno et al., 2015; Cooremans & Schönenberger, 2019; Schützenhofer, 2021).

Carbon dioxide reduction

Energy efficiency is defined as one of the ways to reduce greenhouse gas (GHG) emissions. Although there is an open lack of consensus among scientists, GHG emissions are the most noticeable causes of Global Warming (GW). In contrast, scientists, lawmakers, and other nongovernmental organizations unanimously agreed upon the consequences of GW.

Promoting energy-efficient appliances through subsidies and incentives will undoubtedly lead to a tremendous reduction of GHG. Electricity consumed in Togo comes from various sources, such as hydropower plants, thermal plants, and Contour Global, a local contractor. An assumption in energy savings from thermal plants and Contour Global would have a tremendous impact on the national GHG emissions. Therefore, the following analysis focuses on reducing carbon dioxide emissions associated with electricity production from Diesel, heavy fuel oil, and NG. The implementation of energy efficiency policies stated in scenario (2) could help to reduce CO_2 emissions up to 1) 7,362 tones from NG; 2) 9,724 tones from Diesel; and 3) 10,157 tones from HFO by 2030. Similarly, the reductions were projected to be: 1) 22,333 tones from NG; 2) 29,499 tones from Diesel, and 3) 30,813 tones from HFO by 2050, as shown in Fig. 9. Alternatively, the implementation of energy efficiency measures as formulated in scenario (3) could help to reduce CO_2 emissions up to 1) 65,096 tones from HFO; 2) 47,182 tones from NG; and 3) 62,320 tones from Diesel by 2030. Also, the reductions associated with NG, Diesel, and HFO were estimated to be, respectively, 143,137 tones, 189,063 tones, and 197,483 tones, as presented in Fig. 10. The comparative analysis of the emissions mentioned above under the two scenarios is presented in Fig. 11. This result highlighted the importance of educating people, as suggested by (Kempton et al., 2008), to use efficient appliances and elaborate enough on implementing EE labels. Finally, renewable energy should also be promoted through good policies (rebates, subsidies, and incentives) and practices.

Analysis of rebound effect

Concerning the question: "Would you purchase other appliances if it has been enacted that only efficient appliances enter the Lomé's market?" 65.70% of the households surveyed randomly responded positively by "Yes." The analysis of the responses revealed an increase in the number of purchased appliances. The proportions are presented in Fig. 12. Based on the increasing usage of appliances, if only efficient appliances were accepted in the Togolese market, there would have been an annual efficiency increase of

Fig. 9 Carbon dioxide reductions (Scenario 2), where the acronym LECSDPHAE was already defined above
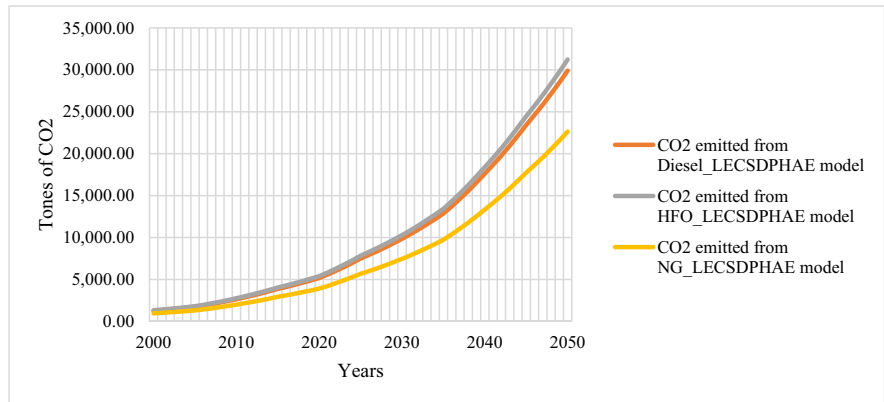
Fig. 10 Carbon dioxide reductions (Scenario 3)
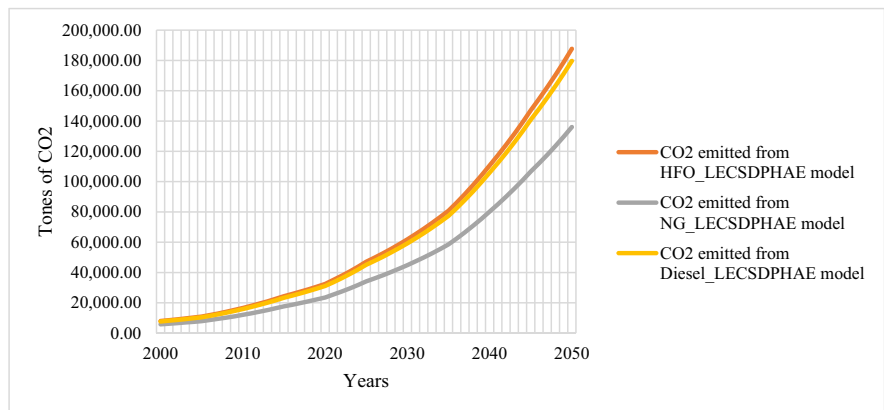
Fig. 11 Comparison of reductions in CO2 emissions under scenarios 2 & 3
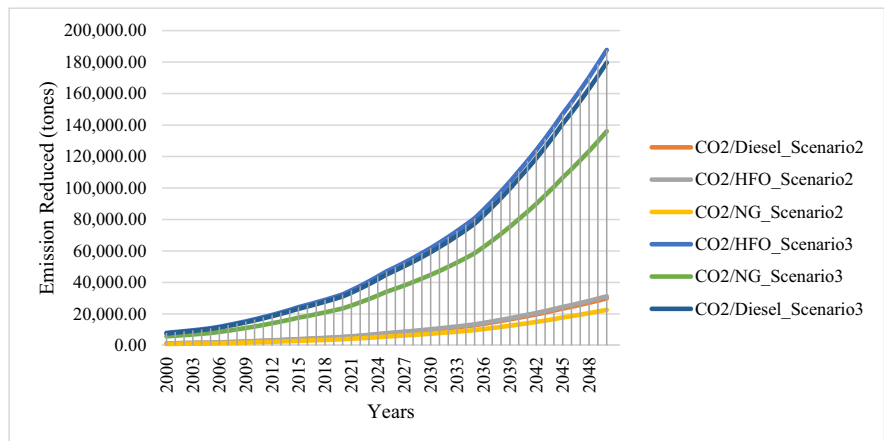
34.93% in the residential sector. Additionally, Fig. 13 presents the percentage of electricity consumption per appliance. The latter percentage represents the rebound effect that would not exist if there were no efficient measures on electricity use. The study exposed the difficulties in meeting the basic energy demands for a majority of households in great detail. It can also be inferred from the results that improving energy-efficient policies would tremendously improve the quality of life. Had the outcomes been different, the country would have to produce or look for additional energy to improve the well-being of its residents. The good news is that implementing efficient measures would constitute an additional more minor

cost source of energy for the country. These measures altogether could alleviate the population's need for energy.

Conclusions and policy recommendations

The main objective of this study was to assess the potential of energy efficiency and its impact on electricity consumption in the Lomé's residential sector. Lomé is the capital city of Togo. Also, the corresponding reduction of CO_2 emissions by 2050 under different energy efficiency scenarios was investigated. To attain this objective, several

Fig. 12 Increase in appliances usage due to rebound effect
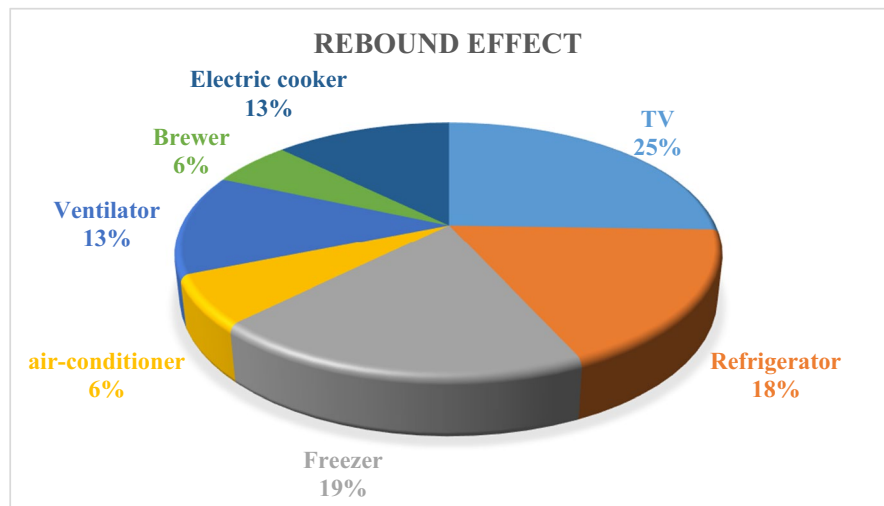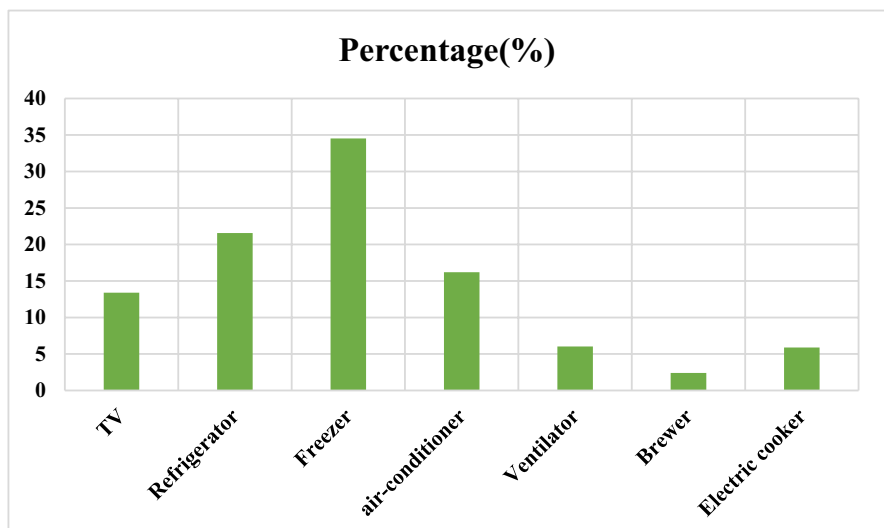

Fig. 13 Percentage of increase of electricity consumption per type of appliance

approaches and assumptions were implemented. First, a random 242 sample households were surveyed to assess appliances and light fixtures in Lomé. It was found that numerous light fixtures and appliances were used in Lomé's residential sector with power power-efficiency ratings. The most common light fixtures revealed through this study were 1) fluorescent lamps (49.7%), 2) neon lamps (34.9%), 3) led lamps (8%), and 4) incandescent bulbs (2.4%). Moreover, the proportion of the most frequent household appliances found was as follows: 1) televisions (TV) (97.1%), 2) fans (66.94%), 3) refrigerators (18.6%), 4) brewers (17.8%), 5) freezers (16.9%), 6) air conditioner (3.3%), and 7) electric cookers (1.7%). Second, an experiment was set up and carried out on two appliances, TV and refrigerator-freezers, to estimate the difference in electricity consumption between used and brand-new appliances for a whole month. The results showed that used televisions consumed 0.24Wh more than the newly bought TVs, while the used refrigerator-freezers consumed 12Wh more than the brand-new appliances. Finally, a system dynamic, SD, modeling was developed to investigate the residential electricity consumption of Lomé. This SD model (LECSDPHAE) had the population, houses with access to electricity, number of households having access to electricity, and per capita electricity consumption as variables. The model was calibrated and validated using raw data for the past 16 years (2000–2016). Therefore, Lomé's household electricity consumption could be simulated from the present to the near (the year30) and the far future (2050). In addition to the above variables, household appliances' efficiency effects data were utilized in this research. Hence, we tested three energy-efficiency policy scenarios:

1. business-as-usual (bau),
2. a proposed energy-efficiency policy. This introduced policy banned incandescent light bulbs and used appliances in Lomé, and finally
3. an extreme (sensitivity) case specified that only household appliances fitting a specific margin of rated power were accepted in Lomé.

The latter scenario included the assumption made in scenario (2). The related percent of electricity reduction due to the energy-efficient policy is 4.4%

and 28.2% under scenarios (2) and (3), respectively. As a result, the following can be found:

a) The population in Lomé under the current birth rate will be close to 3 million in 2030 and 5 million in 2050.
b) Regarding the growing households having access to electricity, electricity consumption will be close to 830 GWh in 2030 and 2.5 TWh in 2050.
c) Under scenario (2), the predicted electricity savings would be close to 40 TWh in 2030 and 115 GWh in 2050. Under scenario (3), it was predicted that the electricity savings would be 225 GWh in 2030 and 680 GWh in 2050.
d) Under the optimal conditions, the economy on electricity under these scenarios may imply a significant reduction in CO2 emissions. It should be pointed out that the expected electricity savings would be undermined by any expensive utilization of NG, diesel fuel, and heavy fuel oil (HFO) as the main combustible in the country.
e) Under scenario (2), the reduction in CO_2 was predicted to be 22.2 kt from NG, 29.3 kt from Diesel fuel, and 30.6 kt from HFO in 2030. The reductions then became 180.6 kt from NG, 238.5 kt from Diesel fuel, and 249.2 kt from HFO in 2050.
f) Under scenario (3), the expected reduction of CO_2 emissions was foreseen to be 82.13 kt from HFO, 59.53 kt from NG, and 78.63 kt from Diesel fuel in 2030. In 2050, these reductions would be for NG, Diesel fuel, and HFO 180.60 kt, 238.5 kt, and 249.2 kt, respectively.

At the end of this research, we recommend:

1) setting up and implementing large-scale energy efficiency policy measures,
2) A QR code-based efficiency standard program at all the ports of entry to the country,
3) A QR code-based efficiency labeling program at all the ports of entry to the country,
4) A ban on import of used and low energy-efficiency rating appliances,
5) A national and regional market transformation, and finally
6) To essentially educate the people on energy conversion, conservation, and sustainable development.

In order to reach more conclusive insights, the present and future weather parameters, such as temperature and heatwaves, could be considered. The latter variables were absent in estimating the electricity consumption; thus, their actual impacts could not be highlighted.

Declarations

Conflict of interest The authors declare no competing interests.

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