Modelling residential electricity demand in Ethiopia: a mixed methods approach

This study explored potential pathways for residential electricity demand growth in Ethiopia to 2065, and the potential impacts of Minimum Energy Performance Standards (MEPS) on appliances using a mixed method that combined expert elicitation with bottom-up energy demand modelling. The judgements of 16 local experts were elicited on the possible futures of the drivers of residential electricity demand. Insights suggest a potential 30% in cumulative savings on residential electricity demand between 2017 and 2065 from fully implemented standards for household appliances by 2030. Supplementary analysis of the government's efficient technology plans was conducted with the use of multiple scenarios. Our analysis points to the useful prioritisation of effective standards implementation, over speed.

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Modelling residential electricity demand in Ethiopia: a mixed methods approach

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1. Introduction

We sought to explore pathways for Ethiopia's electricity system to 2065 under a project entitled 'PATHWAYS' with the use of open-source energy system models, and to develop local capacity to use and build on those models for the country's energy planning and policy decision support. In this technical report, we present quantitative analysis conducted by University College London (UCL) and Policy Studies Institute (PSI) to explore potential pathways for residential electricity demand growth in Ethiopia to 2065, and the potential impacts of Minimum Energy Performance Standards (MEPS) on appliances using a mixed method that combined expert elicitation with bottom-up energy demand modelling.

Under Agenda 2063, African leaders set out a plan for the continent to realise a prosperous future by the year 2063 [1]. Key aims of the masterplan such as inclusive social and economic development will need to be energised by major transformations in the continent's energy sector. The transformations required are particularly extensive in Sub-Saharan Africa (SSA), which consists of many of the world's poorest countries. According to the International Energy Agency (IEA), the achievement of Agenda 2063 in full will require an increase in electricity provision for SSA countries (outside of South Africa) from less than 200TWh in 2018 to almost 1,500TWh in 2040; with the residential sector accounting for almost half of this demand. Absent savings from energy efficiency, the IEA estimates that the 2040 figure could reach close to 2,000TWh [2].

Ethiopia is one such SSA country, with major ambitions for growth and articulated targets to electrify that growth. The country has its own ambitious near term national targets to become a middle-income country by 2025 [3], [4], and to electrify all of its population by the same year [5]; up from a 2018 level of only 45% [6]. Sustained development of the country's electricity sector to energise growth through to 2063 will benefit from long term planning.

Modelled scenarios of future electricity demand and supply pathways can be valuable tools for long term electricity planning and policy decision-making, to safeguard sustainable futures. A number of studies using various methods and tools have modelled energy scenario pathways for Ethiopia. Examples include the exploration of short term demand pathways covering energy sources including and beyond electricity [7], medium term electricity supply pathways [8], short term examinations of electricity supply and demand [9], long term electricity supply pathways [10], and the IEA's whole energy system exploration for Ethiopia's energy outlook [11], to name a few.

Depending on the aims and objectives of the modelling exercise and resource availability, demand sectors can often be treated with limited detail, despite the significance of some sectors on the whole system, both in terms of share of demand and thus supply needs, but also in opportunities for savings. Further to the potential significance of SSA's residential sector earlier referenced from the IEA, efficiency gains in residential appliances present important opportunities for the savings possible by 2040 [2].

Detailed treatment of the residential sector in modelled scenarios, for example in a way that disaggregates demand across household appliances, can enable the assessment of technological developments and policies on resulting demand and supply. Studies that adopt such a strategy typically limit the scope of the model to explore demand only or to a specific demand sector (e.g. residential) due to the level of detail required [12]–[14]. The benefit of this is they can either form part of a suite of models that inform futures planning, or can have their outputs incorporated into whole systems models.

To add to its growing suite of energy models for decision support, Ethiopia will benefit from a model that gives detailed attention to the long-term future of its residential electricity demand, which hitherto does not exist. Such a model will support energy efficiency efforts led by the national energy regulator, Ethiopian Energy Authority (EEA). This study aims to fill this gap by developing such a model for Ethiopia, where future scenarios were informed by insights from country experts. It answers the primary question: how might Ethiopia's residential electricity demand progress through to the year 2065?

The rest of this paper is structured as follows. Section 2 presents a background to residential electricity demand in Ethiopia. Section 3 gives a detailed description of the methodology behind the model developed. Section 4 presents the results from the scenarios explored in the model and discusses the insights obtained. Section 5 concludes the study, and highlights areas for further development of the model.

1. Background

Ethiopia is Africa's second most populous nation with 117.9 million people in 2021 [15]. Of these, 79% live in rural areas, where access to electricity stands at 43.8% primarily through off-grid sources, and in urban areas access levels have reached 96.9% primarily from the grid [16]. In 2018, the residential sector accounted for 46% of total electricity demand in the country. The sector dominates energy consumption in the country through wood fuel consumption (Figure 1), but this study will only consider electricity consumption. Under the country's National Electrification Program (NEP 2.0), it aims to achieve 100% electrification by 2025, where 75% of the population would be served by the grid, with the remainder having off-grid access; before bringing service from the grid to 96% of the population by 2030 [5].

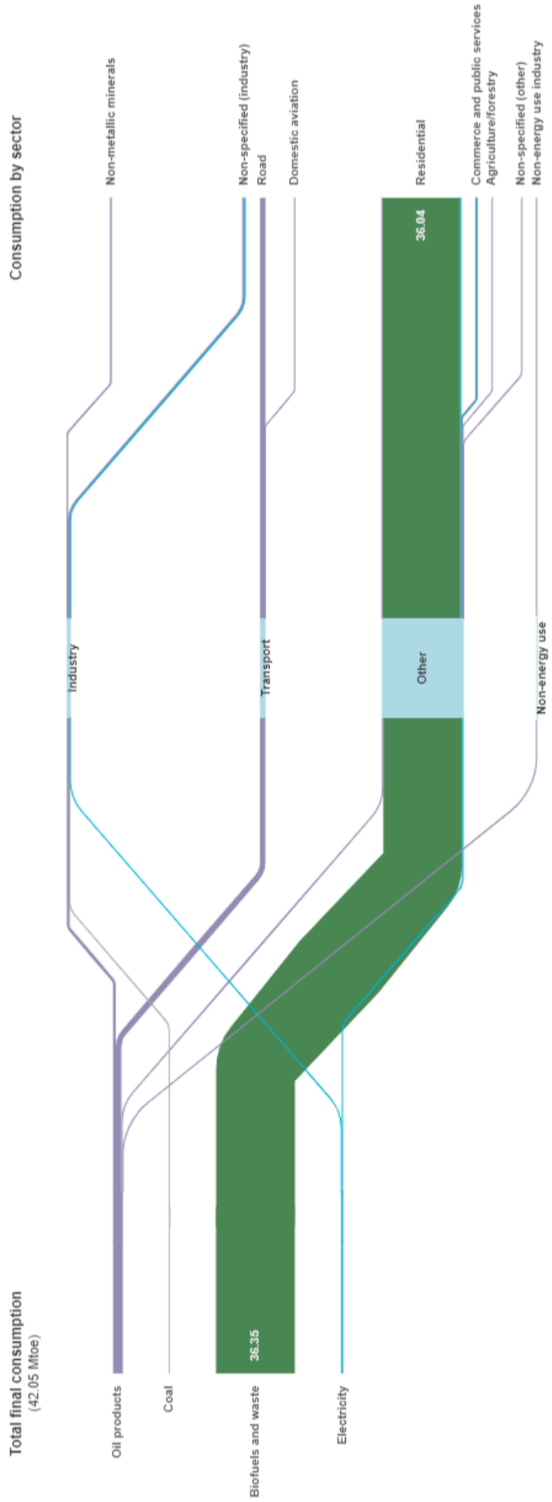

Figure 1. Ethiopia final energy consumption, 2019 (source: IEA [17])

Ethiopia is currently undergoing a reform of its power sector, which includes incremental upward revisions of its tariff regime since 2018 to a level that is reflective of costs, following years of supressed tariffs. These revisions are producing changes in residential consumer demand and behaviour [18], [19], [53].

In the country's residential sector, electricity is typically demanded for services such as lighting, mobile phone charging, television services, and refrigeration [16]. To a lesser extent, and particularly among those receiving grid electricity services, electricity is used for cooking, baking, computing, and other room, bathroom and kitchen appliances (see Padam et al. [16], CSA and World Bank [20]). The majority of appliances used to meet to these services in the Ethiopian market are imported from regions such as the Europe, North America, and Asia [21]. Local manufacturing capability exists primarily only for the injera mitad and cookstoves [21].

The Ethiopian government has embarked on an energy efficiency and conservation programme that covers areas of awareness, building codes, and technology standards, to support reform activities principally in the area of cost reduction to various stakeholders [21]. The development of minimum energy performance standards for residential electric appliances form part of these efforts, with anticipated savings between 2019 and 2030 for services such as lighting and injera baking[1] [22]. This work provides insight that can inform and update these activities, with further analyses on the potential savings over the above period, and beyond.

Mondal et al. [7] explored demand pathways for Ethiopia in the case of lighting efficiency, and separately in a case of improved biomass cookstoves. This study focusses on electricity demand using a dynamic model to explore residential electricity demand pathways for the country, and potential efficiency effects from a wider array of residential appliances relevant to the Ethiopian context.

2. Materials and Methods

This work formed part of a broader project to support the development of Ethiopia's energy models for long term planning, within which a participatory stakeholder workshop was undertaken to develop qualitative narratives about the future Ethiopia's energy sector (see Tomei et al. [23] and Usher et al. [24]). The scenarios that emerged from that process form the basis of the pathways explored in this study, namely: the Business as Usual (BAU), Ambition (AMB), and Slow Down (SLO) scenarios. These are further discussed in Section 4.

3.1. Residential electricity demand model for Ethiopia

The bottom-up residential electricity demand model developed for Ethiopia in this study made use of the Low Emissions Analysis Platform (LEAP) [25]. LEAP is a flexible open-source tool that can be used to model energy systems from resource extraction through to end-use technology consumption; catering to a wide range of modelling objectives, methodologies, and data availability. The modelling approach adopted in this study using LEAP, is adapted from a methodology developed by the Lawrence Berkeley National Laboratory (LBNL) for their Bottom-up Energy Analysis (BUENAS) tool [26]. Further details of the methodology as applied in this study can be found in **Error! Reference source not found.**.

The modelling framework has three main analytical steps:

1. The use of pooled cross-sectional data for a range of countries to estimate regression models for residential energy service (e.g., lighting, refrigeration) diffusion and their drivers, which is used to project changes in service diffusion under scenario assumed changes in drivers, to be used as input data to LEAP;
2. An endogenous stock analysis in LEAP that calculates the share of appliances (efficient or otherwise) used to meet each service in each model year, based on the stock of appliance types in the market, a characterisation of appliance lifetimes, their survival profiles, and the vintage of existing appliances in the base year of the model; and
3. Estimated unit energy consumption (UEC) for each appliance, to be used as input data to LEAP.

The total residential electricity demand in the country in each year of the model is the summed product of UEC and activity (number of households using an appliance to meet a service), for every appliance used by each household in the country.

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[1] Injera is the common staple food in Ethiopia made from an indigenous grain called 'teff'. Traditionally this 60cm sourdough pancake is baked on a clay griddle, called a '*mitad*' placed on three stones above an open fire.

The BUENAS methodological framework is adapted in this work in two main ways: 1) the addition of expert elicitation to obtain best available local expert judgements about the future of uncertain drivers of service demand, as quantitative inputs to the model; and 2) the disaggregation of the residential model structure into urban and rural categories. Figure 2 provides an illustration of the adapted modelling framework, and Figure 3 illustrates the structure of the model developed in LEAP.

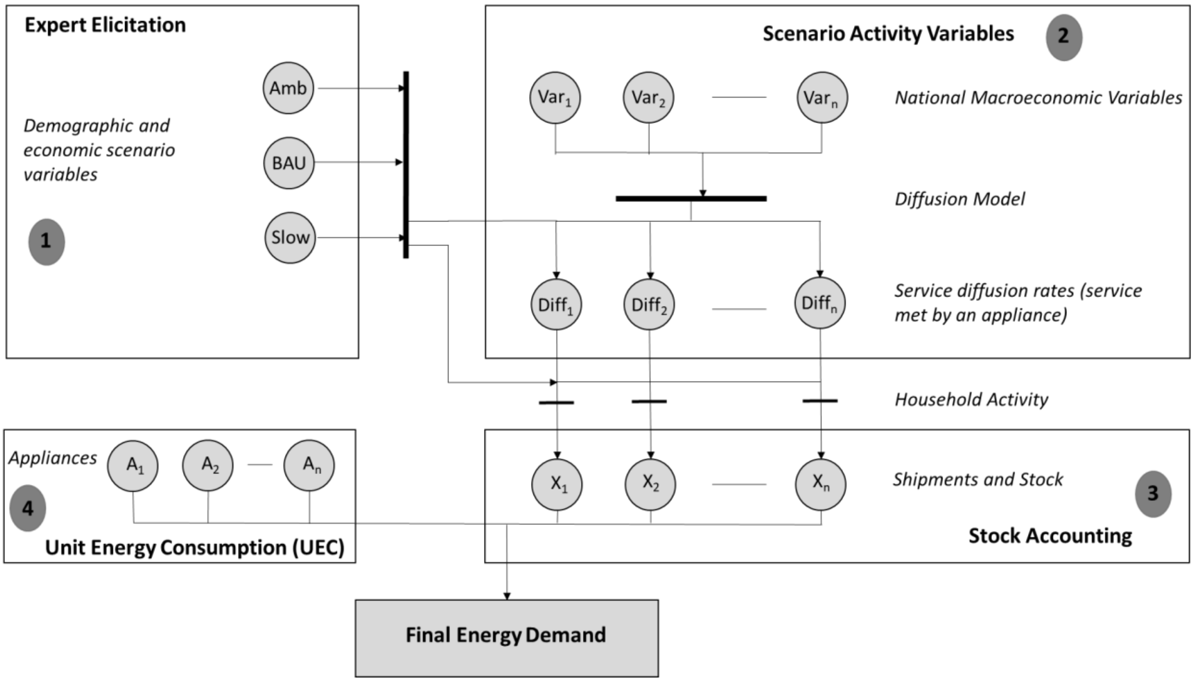


Figure 2. Modelling framework (adapted from McNeil, Letschert and de la Rue du Can [27])

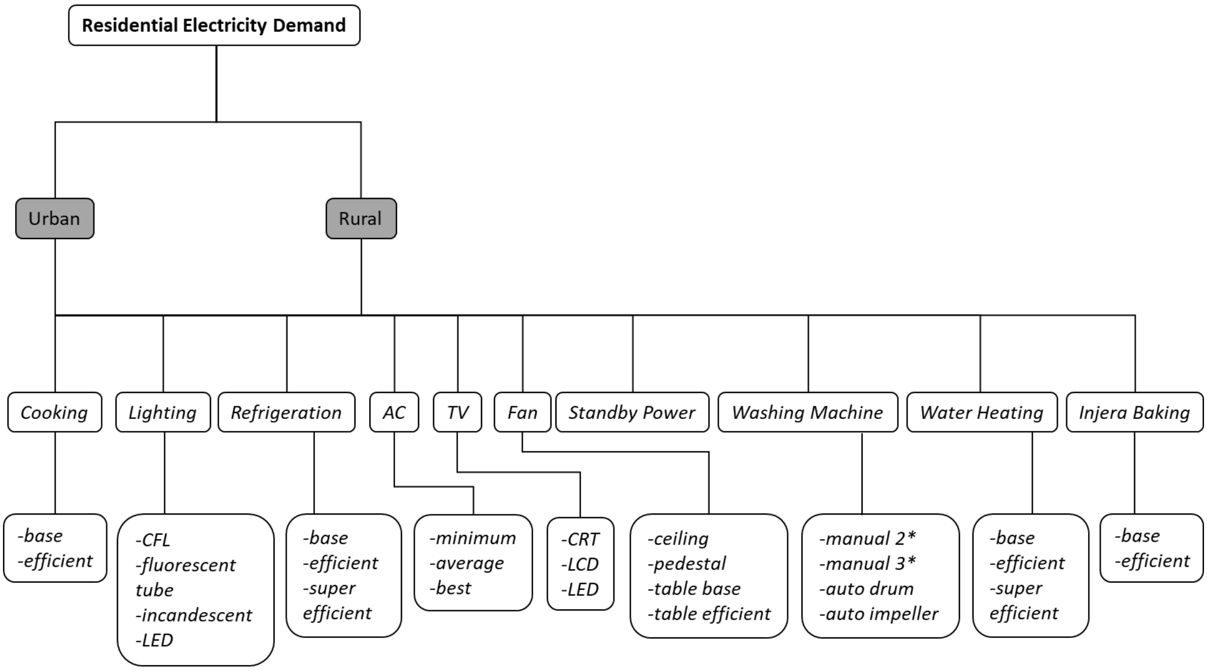


Figure 3. Model structure

Most recent data from the Central Statistics Agency of Ethiopia (CSA), the EEA, and the World Bank, among others, have been used to build this model with a 2017 base year. Key sources include Ethiopia's energy access survey, based on the World Bank's Multi-tier Framework [16] and the Living Standard Measurement Study (LSMS) Ethiopia Socioeconomic Survey 2016 and 2019 [20], [28]. The full range of data sources can be found in **Error! Reference source not found.**.

Due to the nature of electricity delivery and sales in Ethiopia – including estimated billing practices – it was impractical for this study to access measured data from utilities on consumption specific to Ethiopia's *residential sector* alone, by which the model could be validated. Nevertheless, comparison can be made with official estimates for the sector. In the base year of the bottom-up model (2017), residential electricity demand is accounted to 5,180GWh, or 445ktoe. According to IEA data – which is collated, in part, using official reporting from Ethiopia's Ministry of Water Irrigation and Energy (MoWIE) – 2017 residential electricity consumption in Ethiopia was 353ktoe [17]. The difference between the model's estimated demand and official consumption estimates can, in part, be explained by power outages i.e., unmet demand. Power outages in Ethiopia are such that the total electricity demanded by households are not fully met by available supply, and thus reflected in consumption statistics. The model developed is based on demand according to appliance ownership, not consumption, and therefore does not account for power outages.

3.2. Expert Elicitation

Among the range of approached to model electricity demand is the use of input variables (drivers) on which projections are based. Some of these input variables include GDP (or other income metrics), electrification rate, population, urbanisation and more. Future estimates of these variables are uncertain, and typically based on the views of authoritative resources (e.g., IEA projections), individual modeler assumptions, or derived explicitly from other model outputs. In this study, we derived estimates about key uncertain variables used in the scenario projections, by engaging with 16 Ethiopian subject experts in a specific process of elicitation.

Elicitation is the process of capturing expert knowledge about one or more uncertain quantities in the form of a probability distribution [29]. Subject experts from academia, government, industry and others were asked to provide their beliefs about the plausible value range of each driver of household electricity demand in Ethiopia by 2060, and the likelihood of the values across the range considered. In order to ensure the scientific soundness of the process, the protocol adopted was in line with standard practices and was based on the Sheffield Elicitation Framework (SHELF) (see Oakley and O'Hagan [30]).

The elicitation protocol was piloted with four locally-based experts in August 2019, where the selected drivers relevant to the Ethiopian context were also refined and finalised. The 16 elicitation interviews were undertaken between December 2019 and January 2020. Following a review of the literature, a preliminary set of electricity demand drivers (uncertain variables) were selected; giving close attention to household appliance ownership, and the capabilities of the methodological framework adopted. These drivers were refined and confirmed after consultation with Ethiopian experts during the pilot interviews. We limited the final number of variables to four, as interviews took between 1 and 1.5 hours to complete. The selected uncertain variables can be found in **Error! Reference source not found.**.

Table 1: Elicited drivers of electricity demand

Uncertain variable	Unit
Avg. annual GDP growth in Ethiopia 2017-2060	Avg. annual % change
Avg. annual population growth in Ethiopia 2017-2060	Avg. annual % change
Urban proportion of Ethiopia population in 2060	% of total population
Avg. Ethiopian household size in 2060	Number of persons (#)

3.3. Limitations

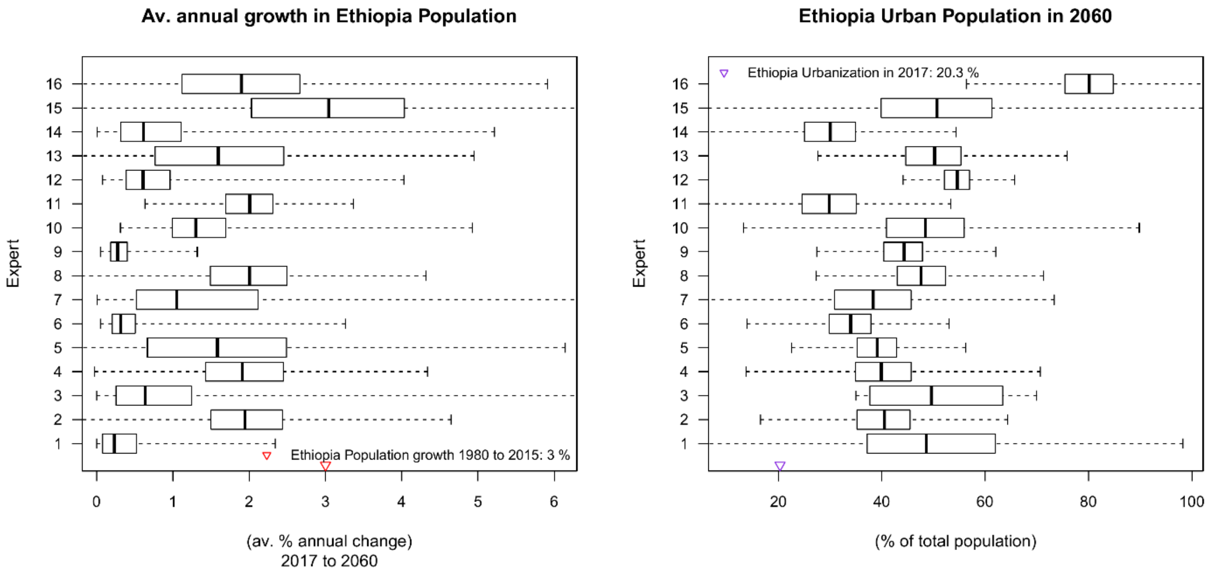
The main limitation of the model developed is in the area of data. Some of the steps in the modelling framework will benefit from more readily available and timely data. The model uses international estimates for average appliance lifetimes (see **Error! Reference source not found.**), which tend to be longer than lifetimes experienced locally, for a range of reasons including unstable power supply. Recent studies have undertaken surveys that obtain local appliance lifetimes [31]. The import of adjusted lifetimes is higher when undertaking cost analyses, which this study does not include. Similarly, data on imported household appliances was not readily available nor regularly updated (see Kärkkäinen and Tyynismaa [32]). A Strengthening of country open access energy data will greatly enable analyses such as this.

Historical data from various countries was used for the service diffusion projections in urban and rural Ethiopia. This exposes the analyses to the risk of inappropriate relationship attribution through differences in time and space. Future developments in technology and buildings can impact service diffusion requirements and possible saturation levels. Similarly, correlations between demand drivers and service diffusion that were true for other countries may not be true for the Ethiopian context. The use of relationships across multiple countries formed part of the steps to treat potential risks inherent in the BUENAS framework, but it is important to acknowledge such risks cannot be mitigated in their entirety. Importantly, the projections obtained in this study are simply assumptions about possible futures, which across the scenarios explored, cover reasonable possibilities of future service diffusion in Ethiopia's residential sector. They are not intended to be forecasts and should not be treated as such.

4. Results and Discussion

4.1. Elicited judgements for residential electricity demand drivers

Figure 4 presents examples of the range of expert beliefs for the interested variables (demand drivers). There are a range of approaches that can be used to interpret the range of expert beliefs for use as model inputs. With the interviewing of experts individually – as was undertaken in this study – the beliefs of the experts can be aggregated mathematically via a range of techniques including a linear pooling of their judgements either as an average, by applying weights for bias or correlation (see Cooke [33], and Usher and Strachan [34] for examples). Alternatively, the diversity of expert opinions, that is their judgements and reasoning, can be explored without seeking to combine their individual judgements [35], [36].



(a) (b)

Figure 4. Elicited judgements from Ethiopian experts on: (**a**) population; and (**b**) urbanisation
[1] Visuals produced using code developed by Usher and Strachan [34].

Given that a range of scenarios, and thus driver pathways would be explored in this work, which were also being shaped by narratives developed under Usher et al. [24], it was useful and necessary not to pool expert judgements. Instead we examined the range of expert judgements and their rationales, in accordance with the scenario narratives, with guidance from existing forecasts for each driver (see Fouré et al. [37], UNDESA [38], and UNDESA [39]), to intuitively attribute future values for each driver under each scenario. Under this process, we considered observed changes in other economies, and also accounted for co-evolution of the four drivers, to avoid scenario inconsistencies. For example, a scenario with lower GDP growth over 2017-2065 than another, would be consistent with empirical evidence if it also maintained a higher growth in population than the respective other.

4.1.1. The scenarios

As previously mentioned, three scenarios were considered: Business as Usual (BAU), Ambition (AMB), and Slow Down (SLO). Their final pathways, which were used to project service diffusion, are illustrated in Figure 5. Each scenario’s pathway is described below.

In the BAU scenario, Ethiopia's GDP and population growth were assumed such that the country's per capita GDP reaches a level commensurate with today's typical lower-middle-income country by the early 2040s and that of an upper-middle income country by the model end year. Over the model timeline, Ethiopia obtains double-digit annual GDP growth in approximately only half a dozen years and averages 7.89% growth between 2015 and 2065. The UN forecasts Ethiopia's population grows at a yearly average of 2.03% between 2016 and 2050 [38]. Our BAU scenario's annual growth rates are not too dissimilar to this, slowing down only marginally quicker than UN projections, with a 2015 to 2065 annual average of 1.75%. Finally, we assume urbanization and average household size to reach 56.3% and 2.98 respectively, in 2065.

In SLO, Ethiopia's annual GDP growth falls as low as 3% within the decade leading up to 2030, together with a second slow down for half a decade leading up to 2040. Following those turbulent periods, only modest growth is experienced, with levels rarely exceeding 7%. Over the model timeline, the country is assumed to grow only as the average low-income country has, with average annual GDP growth of 5.45%. Population growth is a lot faster in the SLO scenario, with a yearly average of 2.27% over the model timeline. It highlights a continued demand for larger households in a society with fewer socio-economic improvements in scenario indicators relative to present circumstances, only achieving an annual growth rate that is akin to that of a lower-middle-income country by the end of the model timeline. By 2065, the country's urban population only reaches 36% and the size of the average household is 4.15. It is assumed that the country only sees the type of urbanization changes that India observed in the 40 years to 2018, before growing marginally faster between 2060 and 2065.

In AMB, the country experiences double-digit in annual GDP growth over 2021-2030, before it mirrors growth in the BAU through to 2065. Per capita GDP reaches a level commensurate with today’s lower-middle-income country by mid-2030s, and that of an upper-middle income country by mid-2050s. By 2060, it’s per capita GDP is around the level of Brazil’s in 2017. Population growth closely follows the BAU, and urbanization and average household sizes reach 65.3% and 2.9 respectively, in 2065.

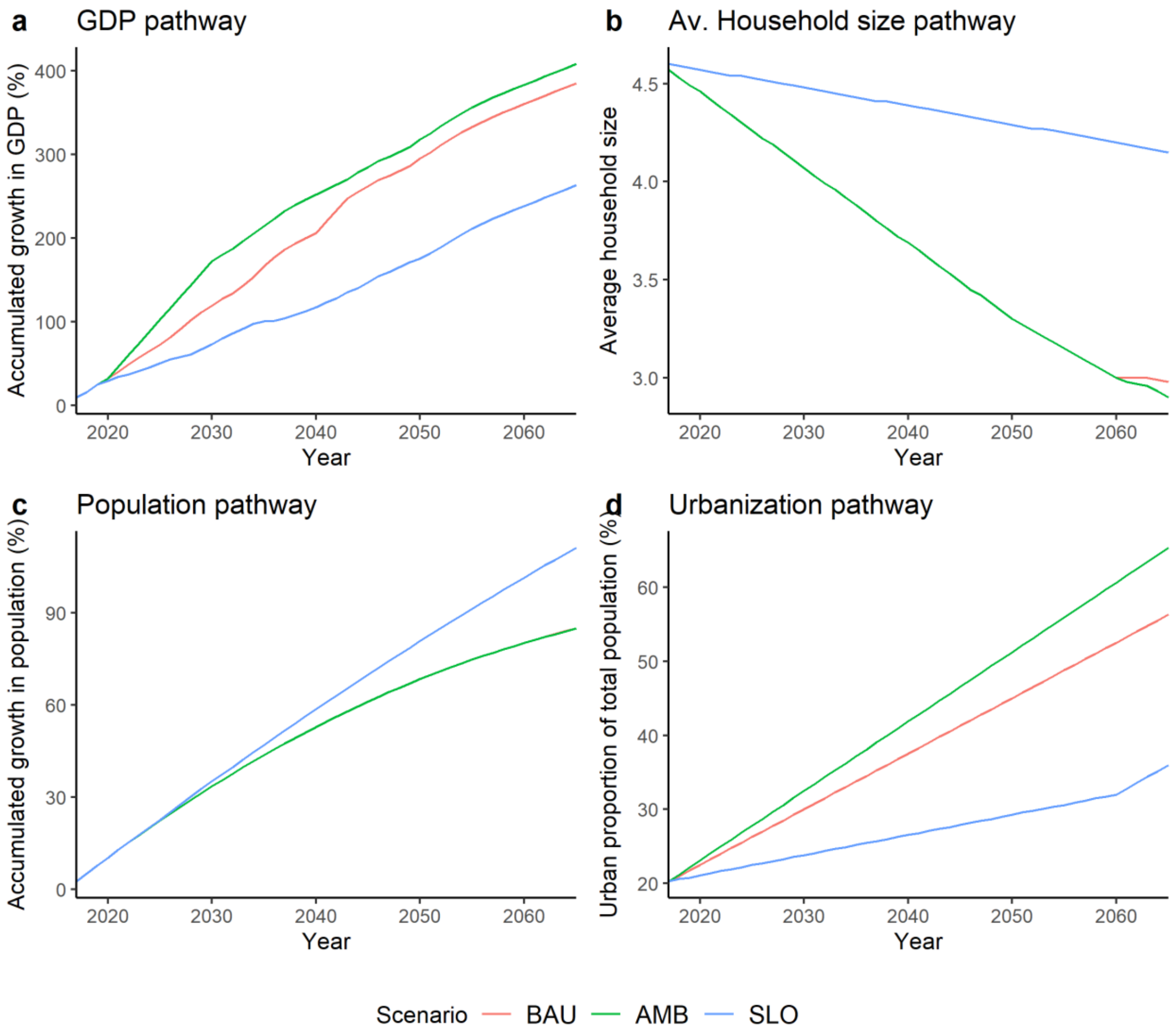


Figure 5. Driver pathways across scenarios

[1] In "**c**" AMB and BAU pathways are close to identical. In "**b**" AMB and BAU pathways are identical prior to 2060.

4.2. Model Outputs

4.2.1. Residential electricity demand pathways

Figure 6 presents the annual electricity demand in the BAU and alternative scenarios from the base year 2017 through to 2065, under a full implementation of Minimum Energy Performance Standards (MEPS) (i.e., diffusion of efficient technologies) by 2030 – by which time all inefficient technologies will no longer be available for sale in the market. Since the change in the market stock of appliances over time is the same in each scenario, as is the UEC for all appliances (see method details in Appendix A), there is minor variation in the share of energy services that dominate consumption across the scenarios. The main differences can be found in magnitude of overall demand for each service, arising from different diffusion levels of technologies primarily between the Ambition and Slow Down scenario, where growth in average income varies considerably.

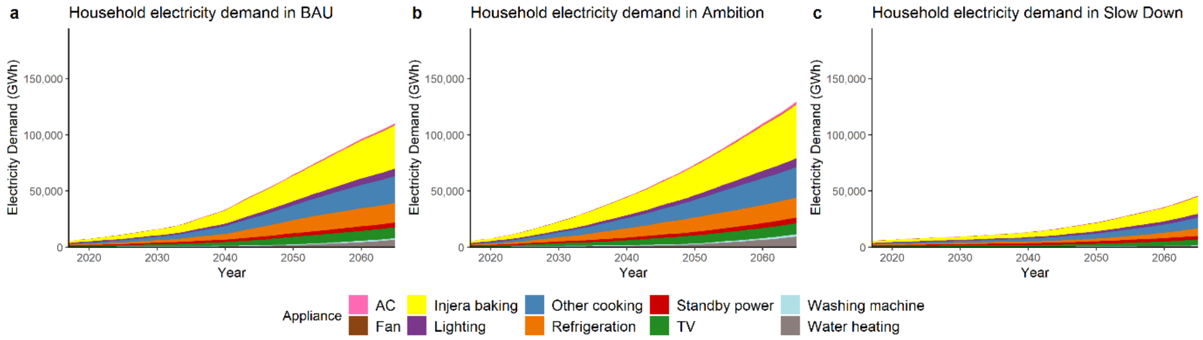


Figure 6. Residential electricity demand pathway across scenarios in 2030 MEPS

In the BAU, overalls residential demand totals 110,645 GWh in 2065. In the Ambition and Slow Down 2065 demand is 130,132 GWh and 46,151 GWh respectively. These differences illustrate the different social and economic development narratives across the scenarios, which impact the uptake (diffusion) of services. Thus, in BAU, the average amount of electricity demanded from an Ethiopian in a full year (per capita *residential* demand) is 460 kWh in 2065. In 2065 AMB it is 542 kWh, and in 2065 SLO it is 149 kWh. To put this into context, per capita residential electricity demand in Ethiopia in 2017 was 49 kWh, in 2018 Brazil it was ~657 kWh, and in 2016 Vietnam it was ~155 kWh. These comparisons give an indication of the level of growth the country experiences across the scenarios by 2065.

Figure 7 presents a comparison between the accumulated residential demand over the model timeline, under the 2030 MEPS and under no change to the stock shares of appliances sold in the market, to determine the level of savings resulting from the 2030 MEPS. The increased sale of efficient technologies under the 2030 MEPS has the potential for ~30% in cumulative savings in residential electricity demand between 2017 and 2065.[2] In the Ambition scenario – where growth in household demand is highest – cumulative savings amount to over 1.08 million GWh, or an average of over 22,000 GWh saved per year.

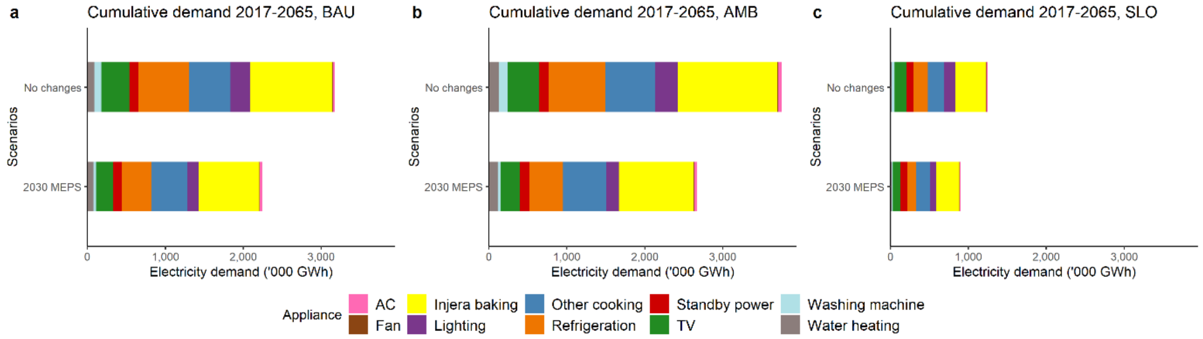


Figure 7. Accumulated residential electricity demand across scenarios (2017-2065), with and without 2030 MEPS

4.2.2. EEA targets

Beginning in 2019/2020, the EEA tentatively began implementing MEPS for electrical appliances serving household lighting, with further plans for injera baking, cooking, refrigeration, clothes washing, air conditioning, and water heating. Detailed plans are in place for the full implementation of standards for cookstoves by 2020, for lighting by 2025, and for injera baking by 2026, with estimated savings on these appliances by 2030 [22]. The exact status of plan implementation is uncertain. We explored these plans for the above three appliances in our model to provide further analysis on possible savings (Figure 8).

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[1] The proportion of savings in efficiency comparisons across scenarios are similar since market stocks pathways for appliances are the same across scenarios, as previously indicated. Only magnitude of savings will largely differ across scenarios.

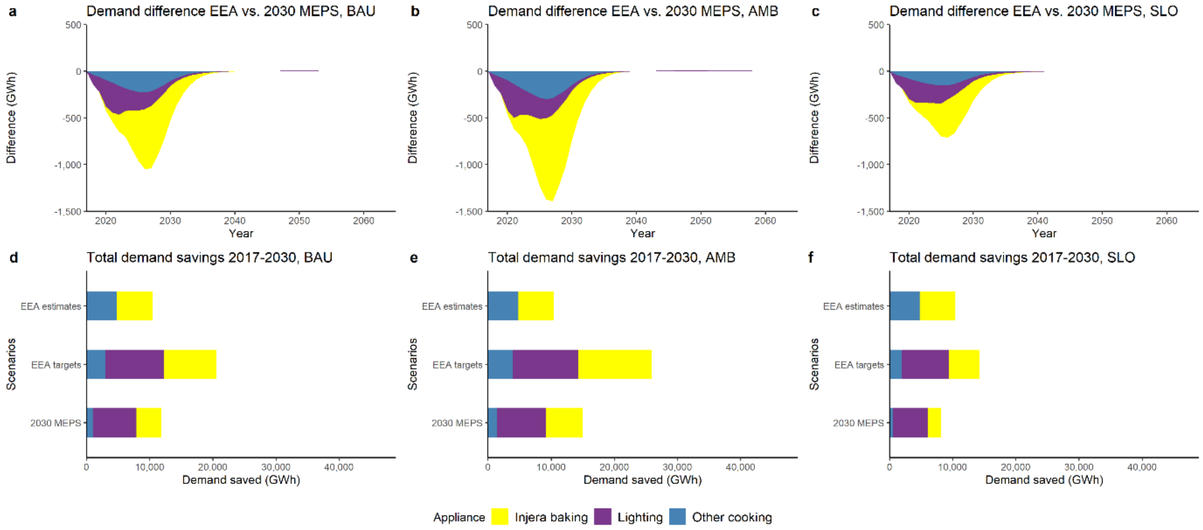

Figure 8. Extra electricity demand saved under EEA timetable compared to 2030 MEPS across scenarios (**a-c**); EEA timetable comparison of total possible demand savings by 2030 across scenarios (**d-f**)

Figure 8a-8c present the extra electricity demand saved as a result of the EEA's faster timetable for the implementation of MEPS for the selected appliances, compared to the 2030 MEPS. As expected, most of the extra savings are observed in the years to 2035, a period in which there would have been less penetration of efficient technologies under the 2030 MEPS. From 2035, much of the inefficient technologies in homes under the 2030 MEPS scenarios would have either been retired or close to the end of their lifetimes, and the available replacements would be efficient, as with the EEA timetable scenarios, thus closely matching savings possible from that period. The modest long term extra savings observed for lighting is due to the aim of EEA targets for LED light bulbs to dominate the market from 2025, whereas in the 2030 MEPS, compact fluorescent light bulbs (CFLs) are assumed to maintain a strong market presence in the long term.

Figure 8d-8f present a comparison of accumulated savings in demand for the selected appliances, over the period 2017-2030, across the 2030 MEPS cases, the model outputs for the EEA timetable cases, and the EEA's own estimated savings for the period (see EEA (2019a)). Under the EEA's quicker timetable for full implementation of lighting, baking and cooking appliance efficiency standards, it is possible to save almost double that which is possible by 2030 under the cases where MEPS were only fully implemented by 2030 (2030 MEPS). Our analysis, which covers a range of scenarios, also shows that the EEA's own estimates for savings possible under its plan were probably at their maximum level for cooking, and possibly under half of what can be possible from injera baking demand if the future takes the path of the Ambition scenario.

4.2.3. MEPS timeline sensitivity

The model outputs are sensitive to input assumptions in a number of areas, some of which can usefully be examined, others which would require further data, serving as avenues for future work (see Section 5). These areas of future work include assumptions about appliance stock changes in the market over time under MEPS implementation, appliance lifetimes, and appliance UECs across scenarios. The sensitivity of appliance lifetimes is not so significant under this study as market stock shares primarily determine the household ownership patterns. Where a cost analysis is being undertaken, lifetimes become more significant due to the impact on appliance replacements and is therefore useful for future work using new data (see Section 3.3.). Average UECs would vary by growth scenario in reality, where different behaviour patterns would be observed. Further data is required to perform a useful analysis on this.

We therefore perform a sensitivity analysis on the assumptions about market stock shares only. Specifically, to determine the significance of a later timetable for MEPS, i.e., 2040 MEPS. Figure 9 shows a comparison of accumulated residential electricity demand over the model timeline between the 2030 MEPS case, a 2040 MEPS case, and a no change case in market stock shares. In AMB, cumulative added demand due to delayed full implementation in the 2040 MEPS compared to the 2030 MEPS is 165,199 GWh, or 6% in extra electricity demand, an average of 3,371 GWh per year. The savings from earlier implementation, though desirable, are not so significant compared to the 30% savings achieved overall by embarking on the MEPS at all (see Section 4.2.1.).

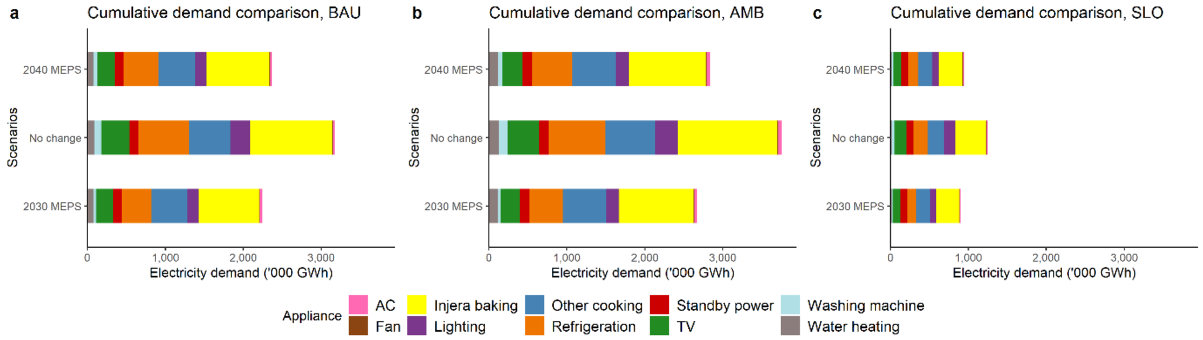

Figure 9. Accumulated residential electricity demand across scenarios (2017-2065), with 2030 MEPS, 2040 MEPS, and no MEPS

From the above insight it would seem it is more important to prioritise effective MEPS implementation over a fast timetable. This is important in a context where regulatory implementation have not always been effective. For example, the importation and sale of incandescent lamps have been banned in Ethiopia since 2011, yet they are still in use, as recent as 2020 [16], [31]. Thus, it could be more expedient to ensure effective governance of MEPS standards, even if a longer timetable is required to do so.[3]

5. Conclusion

We explored potential pathways for residential electricity demand growth in Ethiopia, and the potential impacts of Minimum Energy Performance Standards (MEPS) on appliances using a mixed method that combined expert elicitation with bottom-up energy demand modelling. We observed a potential 30% in cumulative savings on residential electricity demand between 2017 and 2065 from mandating the sale of energy efficient household technologies by 2030. The Ethiopian government, under its energy efficiency program, aims to administer MEPS for technologies serving key household services earlier than this. Our supplementary analysis across a range of plausible scenarios of potential energy savings under the government's plan suggests the potential cumulative savings by 2030 from an energy intensive household activity – electrical injera baking – can be twice what has been estimated by the EEA. Our analysis also suggests that the government's approach to the implementation of appliance standards should prioritize rigor for effective implementation, monitoring and enforcement, over speed. This study, and the model developed for Ethiopia's residential sector presents a starting point for useful future work, some of which are outline below.

- Model extension to include appliance costs data to explore costs under different scenarios.
- The addition of non-electrical household energy demands, including the significant consumption of biomass fuels for baking and cooking in lieu of ongoing efforts for efficient biomass technology development in the country, which together can usefully be used to explore strategies for efficiency and clean fuel adoption. [54]
- As noted in Section 4.2.3., there is opportunity to update appliance lifetimes with local data, which will be particularly pertinent for any cost analysis. Also, a behavioural component can be added to analysis with varying UECs across scenarios or over time.
- Finally, exploration of scenarios around changing market stock share under different MEPS timetables can be explored in further detail to support standards strategy.

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[2] It should be noted that both the 2030 and 2040 MEPS are assumed to experience a steady increase in efficient appliance market share between the base and target years. If, for example, the 2040 MEPS only achieved substantial changes to market stock in the 5-7 years before the deadline, this may increase the cumulative demand over the model timeline. Further analysis around this will be useful for future work.

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Appendix A

The adaptation of the BUENAS methodological framework in this study as presented in Figure 2 under Section 3.1. is described in this appendix. The modelling framework has three main analytical steps following the first step of expert elicitation which was introduced for this study. Step 2 determines the annual Activity (no. of households making use of a service e.g., lighting, cooking) over the model timeline. Step 3 uses LEAP's endogenous stock accounting framework to determine the breadth of appliances used to meet Activity in each year (e.g., CFL, LCD TV). Step 4 prescribes the annual Unit Energy Consumption (UEC) for each appliance in model. The final residential electricity demand is the summed product of Activity and UEC in the urban and rural regions of the country. Steps 2 to 3 are described below.

Step 2: Activity projections

In step 2, pooled cross-sectional data, panel data (for some services), and time-series data for a range of countries (minimum 20 data points) are used to estimate regression models for service diffusion (or other related activity measure for some services). The driver variable is primarily income-related i.e., GDP per capita, monthly income per capita, depending on the literature and the significance of the relationship as estimated by the regression model. For some services, driver variables such as household size or urbanisation were also used as explanatory variables. The pooled cross-sectional data and panel data are selected to cover a wide range of income levels and diffusion levels. Time-series data for China's urban and rural subsector service diffusions were used to obtain regression models for the location disaggregation (urban vs. rural). The national level regressions and urban/rural regressions served to correct and clarify relationships to be relied on for projections. The projections are based on driver variable pathways that came out of the elicitation process, as depicted in Figure 5.

We used the S-shaped logistic growth function to estimate diffusion of each service:

$$Diff = \frac{\alpha}{1 + \gamma \exp(\beta_{GDP} I + \cdots + \beta_n N)} + \varepsilon \tag{1}$$

where, $Diff$ is the diffusion of the service in question for a given country, α is the saturation level, I is the GDP (or equivalent income variable) for that country, N for any other relevant describing variables for that model, and ε is the error term. Rearranging and taking the logarithm of both sides of the equation converts the logistic function to a linear function, to allow for linear regression analysis:

$$ln\left(\frac{\alpha}{Diff} - 1\right) = ln\,\gamma + \beta_{GDP} I + \cdots + \beta_N N + \varepsilon \tag{2}$$

The diffusion calculations for the air conditioning service adopted an alternative estimation method found in McNeil, Letschert and de la Rue du Can [27].

Step 3: Stock turnover analysis

Under the BUENAS framework, LEAP is used to perform annual stock turnover of appliances based on input data for appliance vintages, average appliance lifetimes, appliance lifecycles where the probability of appliance survival over its lifetime is specified with an S-curve, typically over 1.5 times its average lifespan (see McNeil, Letschert and de la Rue du Can [27], and specified pathways in the annual proportion of appliances in the market stock. With the above data, LEAP endogenously retires failing appliances, and replaces retired appliances in addition to allocating appliances as diffusion grows, both according to the spread of appliance types in the market to meet a given service in that year. BUENAS' formulaic description of this process can be found in McNeil et al. [26]. However, the computation of this stock analysis in LEAP was adapted in this study to follow the stock allocation (appliance sales) rule described below, so as to ensure the model did not calculate erroneous sales figures.

- D < 0, we compare abs(D) with the retirements
    - r(y) < abs(D) → do not sell
    - r(y) = abs(D) → do not sell
    - r(y) > abs(D) → sell r(y) - abs(D)
- D = 0
    - r(y) < 0 → impossible (retirements are positive)
    - r(y) = 0 → do not sell
    - r(y) > 0 → sell r(y) (i.e., replace retirements only)
- D > 0
    - r(y) < D → sell r(y) + D
    - r(y) = D → sell r(y) + D
    - r(y) > D → sell r(y) + D

where D is the demand for a service(a) in year(y) minus the demand for service(a) in year(y-1), and r is the total retirements of all appliances used to meet service(a) in year(y). The above appliance sale rules were computed using LEAP's "IF" function.

Step 4: Annual Unit Energy Consumption (UEC)

The determination of annual UEC for each appliance varied depending on availability of data, but generally involved the product of wattage and average annual hours of use. In some cases, estimated daily or annual UEC values were available in the data resource. The UEC values were fixed over the model timeline for all appliances in the model. Useful attention was given to the potential future developments in appliance energy performance using CLASP and IEA data and reports (see **Error! Reference source not found.** in Appendix B).

Appendix B

For the diffusion projections in step 2 of the modelling framework (see Figure 2), the study made use of Historical data collated by the developers of BUENAS (see McNeil, Letschert and de la Rue du Can [27]), supplemented with data from the World Bank's Multi-tier Framework Survey for Ethiopia [16], the World Bank's DataBank [40] and China's Energy Databook [41].

Error! Reference source not found. provides details of the data used to develop the model in LEAP. For all household electric services – except injera baking and to a large extent cooking – Ethiopia relies on appliances imported from China, the US, Europe and a few other countries to a lesser extent. Therefore, it was reasonable in some cases, to rely on appliance data from these countries.

Table A2: Data Sources for model built in LEAP

Stage	Data	Source
Stocks and appliance data	Lighting	[16], [22], [27]
	Cooking	[22], [32]
	Injera baking	[22], [42]
	Refrigeration	[16], [27], [32], [43]
	Television	[16], [44]
	Fan	[16], [27]
	Air conditioning	[32], [45]
	Standby power	[16]
	Washing machine	[32]
	Water Heating	[16], [27]
UEC Data	Lighting	[16], [22], [27], [46], [47]
	Cooking	[22], [48]
	Injera baking	[22], [42], [48], [49]
	Refrigeration	[7], [32], [43], [50]
	Television	[50]
	Fan	[27], [46]
	Air conditioning	[27], [45]
	Standby power	[27]
	Washing machine	[27], [32], [51]
	Water Heating	[27], [52]

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