Global scenarios of household access to modern energy services under climate mitigation policy

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Abstract

Emission reduction scenarios to meet various climate change mitigation policy goals often do not explore the differential impact of alternative pathways on access to energy for different economic strata of society across countries. Here we show that even under optimistic socioeconomic growth scenarios, inequalities in use of modern energy in homes could persist. We find that though access improves in high growth scenarios, over 10% of populations in sub-Saharan Africa and South Asia could lack access to energy services for thermal comfort, food preparation and conservation, and cleaning in 2050. Ambitious climate mitigation scenarios do not significantly alter household access to energy services in the Global South, and only affect gas consumption in high-income regions. Our work suggests that efforts to meet climate policy goals are not at odds with progress towards universal access to modern energy services in the Global South, however, directed policy will be needed to meet access goals.

Main

Access to modern, reliable, and affordable energy services is a prerequisite for development and providing a decent quality of life for all of humanity. The United Nations Sustainable Development Goal (SDG) 7, explicitly targets universal access to modern energy services, including a connection to electricity and modern cooking energy services by 2030. Several analyses of the existing status of access to modern energy services and scenarios of extending access universally, either implicitly or explicitly, to meet the SDG targets already exist[1–7]. However, existing studies focus largely on technologies and investments needed to achieve access goals and specific benefits that can ensue from gaining access. Less is understood of how preferences for energy services shift and demands change across diverse populations as modern forms of energy become more easily accessible and affordable over time. Here, we present a highly granular bottom-up residential appliance choice and energy demand model that we apply globally to assess how access to energy services in homes will change under scenarios of socio-economic growth and under policy scenarios that meet climate change mitigation goals.

As currently defined, achieving SDG7 does not imply regular use or access to all the services needed for decent living. There are vast differences today in how much energy people use at home[8,9]. While many enjoy the benefits of a multitude of appliances that provide comfort and convenience and meet a diverse set of service needs, others still lack access to even basic electric lighting and thermal comfort in their homes[10,11]. In many developing and emerging countries, much of the population even lacks access to reliable electricity and clean cooking services[12–14]. Understanding how household energy service demands for diverse end-uses will grow is fundamental to planning efforts to meet climate and other SDGs. Can fuel shifts and purchases of more efficient appliances dampen demand growth from expanding services and number of appliances owned? How much will climate mitigation policies affect access to and demands for home energy services and are rich and poor equally affected by associated price changes? These are questions we shed light on here.

Recent research has focused on normatively defining services that need to be provided universally to alleviate poverty and ensure decent living for all, and quantifying a minimum energy floor to fulfill these[15–17]. Other work has focused on developing low energy demand scenarios that focus on activity levels and service demands also consistent with a normatively defined ceiling on affluent and wasteful consumption, and subsequently quantifying associated energy requirements[18]. Beyond normatively defining or assuming demands, existing literature is largely silent on using empirical data to estimate bottom-up how access to energy services in homes will change as people are better able to afford these. Literature focused on residential energy demand estimation and projection at a global scale is rather aggregate[4,14,15]. The focus is often on population and income as drivers of aggregate demand, without differentiating between different end-uses or diverse consumers. The few studies that do focus on service demands or incorporate consumer heterogeneity are almost always specific to individual countries or regions or certain end-uses[21–24].

Here, we explore future shifts in access to key energy end-use services in homes by applying a highly granular residential end-use services of energy (MESSAGE-Access-E-USE) model (see Methods). We analyze appliance and energy demand using the model under three of the Shared Socio-economic Pathways (SSP) narratives SSP1, SSP2 and SSP3 that we refer to as no new (climate) policy – NNP scenarios) [25,26]. We expand the scenario descriptions to also include explicit assumptions regarding the diffusion of efficient appliances consistent with the harmonized quantitative elaborations of population[27], urbanization[28], income growth[29] and distribution[30] projections (see Methods). We run an additional two climate policy (CP) scenarios consistent with long-term mitigation targets limiting warming to below 2°C (CP2C) and 1.5 °C (CP1.5C) by the end of the century[31]. Our highly granular analysis of shifts in access to home energy services shows that, although access to modern energy sources and services improves in scenarios with higher income growth and lower inequality, a vast majority of the population in several regions of the world could still use little direct energy at home by mid-century. Even in 2050, under optimistic socioeconomic growth scenarios, residential energy demand could vary substantially by income group by as much as a factor of 10 and inequalities are likely to persist between and within regions. A significant share of households in sub-Saharan Africa and South Asia could continue to lack access to minimum energy services for thermal comfort, food preparation and conservation, and cleaning without additional policies. Nevertheless, scenarios where ambitious climate targets are achieved do not significantly alter the picture for the developing world, only affecting consumption levels in high-income regions, without diminishing the levels of access to different energy services for populations in these regions. Thus, we find that achieving climate mitigation goals is not at odds with achieving universal access to modern energy services.

Total and average modern residential energy use

How might total and per capita residential energy demand for electricity and gas change across regions in the future? We find a consistent rise in electricity use per capita till 2050 in all regions and scenarios, with this rise occurring faster under scenarios with higher income growth and urbanization (SSP1) and for regions in the Global South that start from a lower base level of use (see Fig 1a and 1b). Gas use, in most regions and under all scenarios, by contrast, initially rises but then declines after 2030 even though incomes continue to rise. This is in response to a sharper increase in gas prices relative to changes in electricity prices (see Supplementary Data). While per capita electricity use in most regions is not affected by price changes under stringent climate mitigation scenarios, we see the transition away from fossil gas in all regions, but particularly in North America (NAM) and Western Europe

(WEU), is more pronounced under climate policy scenarios (see Methods for details on regional aggregations). These differences can be explained by price dynamics of these two energy types under different scenarios as electricity prices in most regions do not increase significantly till mid-century even under stringent climate policy scenarios, while gas prices change more dynamically (see Supplementary Data).

Distribution of modern energy use across populations

These aggregate trends, however, hide significant differences in the distribution of modern energy use among populations across and within regions. Despite significant income growth and urbanization under future SSPs, stark inequalities in per capita residential final energy use persist till mid-century. Most populations in the Global South could continue to use little modern energy in their homes even by 2050 (see Fig 2). In sub-Saharan Africa (AFR), South Asia (SAS), Pacific Asia (PAS) and Latin America (LAM), over two-thirds of the population could continue to use <5GJ/capita in 2050 even under SSP1, with this share being as high as 85% in SSP3 (see Supplementary Figure S1 for density plots). Under climate policy scenarios, there is not much shift in the distribution of energy use, but an additional 2% of populations in these regions could use <5GJ/capita in 2050 even under SSP1.

In Western Europe (WEU) and North America (NAM), most of the population will use a factor 10 more, in excess of 50GJ/capita in 2050 even in SSP3. However, even in these richer regions, 12% of the population could continue to use less than 10GJ/capita in their homes even in SSP1 under no new climate policies. As we find that the rate of appliance ownership between those who use less than 10 GJ/capita and those who use more is not widely different, the low modern energy use may reflect a choice for more efficient use of energy at home. This is true except for appliances for water and space heating. In the case of these appliances, we find populations using less than 10 GJ own a higher share of oil-based appliances, which suggests the may experience some degree of energy poverty. This share could increase significantly under climate scenarios to around 19% in the CP2C scenario and to 22% in the CP1.5C. This significant increase in the share of populations using less than 10GJ/capita under climate scenarios, for these highly gas dependent regions, suggests increasing affordability challenges for these populations.

Access to key end-use services

The differences we observe in the amounts of energy used across populations, regions and scenarios is also reflected in the extent to which populations benefit from access to services associated with different end-uses in the home. We distinguish between end-uses related to thermal comfort (heating and cooling), food preparation and conservation, entertainment, and cleaning services (see Supplementary Table S2 for a description of appliances associated with each of these end-uses). Fig. 3 shows that while electricity used for entertainment services is more widely and democratically distributed across regions and populations, the use of energy for services related to food preparation and conservation, and cleaning could continue to be very unevenly distributed among populations in SAS and AFR in 2030, and even in 2050. Our finding of a strong preference for entertainment services is consistent with findings in other studies on observed preferences of households[32,33]. The ability of populations to afford these services and their access to these is strongly driven by income and urbanization, so a higher share of population gain access to these under SSP1 as compared to SSP3. Climate policy has little impact on access to different end use services because, based on our empirical analysis we find that the purchase of appliances is not very sensitive to changes in energy prices, although there is some impact of price changes on the actual usage of appliances (see Supplementary Figure S2 for a comparison of climate policy and NNP scenarios). Furthermore, electricity prices do not change much across most regions during the first half of the century even under aggressive climate mitigation policy scenarios (see Supplementary Data).

We next present how the level of access to key end-use services varies across income groups within each region under the NNP scenarios in Fig. 4. This figure shows results for only the regions in the Global South as much of the population in the Global North already has access to these services today. Even under the more optimistic SSP1 scenario, 10% of populations in AFR and SAS will earn less than \$10PPP/capita/day and could remain unable to afford access to thermal comfort, cleaning, and food related services in 2050. In SSP3, most of the population in SAS and AFR will earn less than \$10PPP/capita/day even in 2050 and most could lack access to essential end-use services in their homes. This is particularly true for rural areas (Fig. 4a) as compared to urban ones (Fig 4b). The proportion of population with access varies to some degree by end-use, too. Consistently, even in less developed regions more people have access to energy for entertainment services, like radio and television. By contrast, most populations in AFR and SAS could continue to lack access to energy services related to cleaning such as washing machines (see Supplementary Figure S4 for results on diffusion of specific appliances by scenario and region over time).

Effects of energy efficiency changes on end-use demands

Figure 5 shows the average energy use per year per appliance for different end uses (i.e. total energy consumption of a household for a particular end-use divided by the total number of associated appliances) by income group for different regions and scenarios in 2050 (see Supplementary Figure S3 for a similar figure depicting results under climate policy scenarios). We use this as a proxy indicator of efficiency of energy use for different home end-uses. Therefore, this should not be considered a measure of efficiency of the appliances themselves. (See *Methods* for how the indicator is derived and its interpretation). We find that efficiency improvements could attenuate demand growth, particularly in NAM and WEU, as average energy use per appliance is similar across income classes and does not vary significantly across SSPs in these regions. There are significant differences though for distinct end-use services across regions. In most OECD regions, energy use for thermal comfort is significantly higher than for other end-uses among all income classes. In the Global South, the energy use per appliance in all end uses is higher for high income groups, suggesting that poorer populations use their appliances more frugally. The opposite is observed in the Global North, where richer populations can afford more efficient appliances. In transition regions (CPA-EEU-FSU), we find that there is a distinct pattern of energy use for thermal comfort and food related services, wherein lower income populations use more energy per appliance than higher income populations. This pattern is more pronounced in SSP1 and is consistent with findings from other studies that suggest significant potential for efficiency gains in these regions that have a legacy of inefficient heating and cooking devices and systems, particularly among low-income households[22,34,35].

To better understand to what extent and in which end-uses we see the biggest efficiency gains over time, we undertake additional sensitivity runs for SSP1 and SSP2 excluding the assumptions on the more rapid uptake of efficient appliances (see Methods for a description of these assumptions). Fig 6 compares the average energy use per appliance owned for our no change in efficiency SSP sensitivity runs and those that assume a higher share of efficient appliances purchased in 2050. We see that, especially in rural areas, efficiency improvements could lead to lower household energy use for food, cleaning, and entertainment services, but higher energy use for thermal comfort, which is the most fundamental, but also the most energy intensive end-use. We observe two effects that explain this result of an overall high preference for thermal comfort. First, a rebound effect, wherein there is more-intensive use of higher efficiency thermal comfort appliances, and second a redistributive effect, wherein the increase in efficiency of other end-uses leaves additional budget that is spent to increase thermal comfort consumption. This may also reflect the high latent or unmet demand for thermal comfort across these populations and regions and relatively lower sensitivity of demand for thermal comfort. Evidence of high and growing unmet demand for cooling that may increase further due to potential future climate impacts is discussed in previous research, as well[11,20,21,36].

Discussion and Conclusions

Energy demand will likely rise till mid-century in most regions despite very different levels of access to basic services and appliances that provide comfort and convenience in homes across the globe today. Despite a more rapid rise in demand in regions with currently low levels of demand, vast inequalities in home energy use could persist till mid-century and beyond. Even in 2050, the richest 500 million people could consume about the same direct energy as the poorest 5 billion together. While access to key end-use services relating to thermal comfort, entertainment, food preparation and conservation, and cleaning will expand more rapidly under a more optimistic SSP1 future compared to SSP2 and SSP3, even under SSP1, in regions of the Global South including AFR, SAS, PAS and LAM, over two-thirds of the population could continue to use <5GJ/capita at home in 2050. This is lower than the lowest estimates of direct energy needed to provide decent living services or that meet ambitious low energy demand assessments[16,18,37]. Additionally, in AFR and SAS, 10% of populations could earn less than $10PPP/capita/day and lack the ability to afford access to thermal comfort, cleaning and food related services and appliances in 2050 in SSP1.

We find differences in socioeconomic conditions in the future will have a larger impact on access to services and demand than shifts brought about by policies designed to mitigate climate change till mid-century in most regions. This is because the price of electricity, the most preferred fuel of households as their income rises, does not change significantly in most regions till mid-century even under stringent climate policy. However, big shifts in gas prices that occur in climate policy scenarios drive a phase out of gas use in homes across the globe, most pronouncedly in developed regions of WEU and NAM, where gas use is currently high. We also find that in NAM and WEU particularly, efficiency improvements can attenuate demand growth, particularly in energy-intensive heating and thermal uses that continue to comprise the largest share of total home energy use in these regions. In most regions of the Global South, we find that in rural areas efficiency improvements can lead to lower household energy use for food, cleaning, and entertainment services. However, energy use for thermal comfort will likely continue to rise, as latent demand for this end-use is high.

Our bottom-up, household level approach to model demand for energy services is based on microdata and provides an opportunity for undertaking highly granular analysis but is naturally bounded by the availability of data. Microdata from individual countries used in this analysis vary in the set of appliances they include. We, therefore, harmonize at the level of key end-use services rather than individual appliances across regions. This is consistent with our services-based focus, wherein appliances are just instrumental to meeting certain end-use service demands. As the behavioral parameters estimated to represent each region in our model are based on data for a selected group of representative countries for each region, there are some regions that may not be completely represented because adequate country data is lacking in these regions. Better availability of national microdata in these regions in the future should allow for capturing the heterogeneity within them more accurately. As our model is not calibrated but rather estimated, the behavioral parameters in our simulated data mimick the empirical reality for a wide variety of variables and drivers jointly. This is because our estimation approach allows for matching the entire data distribution rather than individual points. As new appliances replace existing ones to meet specific and sometimes multiple services (e.g., smart phones and tablets replacing televisions for entertainment), these transitions have important implications for energy use in homes. Our model can capture these shifts only for appliances captured in the surveys, however, new technologies are not explicitly represented, and the implications of the spread of these for energy demands can only be captured through assumptions on future appliance efficiencies and costs.

There are several policy lessons that emerge from our analysis. An important insight is that climate policy scenarios may not significantly impact energy demand in homes, except in the richer regions of the world. Given that these regions have the economic means to adjust to lower their energy consumption without losing access to any of the most crucial end-use services, energy transformations required to meet ambitious climate targets do not seem at odds with efforts to improve social welfare and access to energy services in the Global South. For populations in NAM, WEU and EEU, efforts to shield the poor from rising gas prices over the next couple of decades may be required to avoid heating services becoming unaffordable. Efforts to improve efficiency also need to focus on technologies that provide thermal comfort, for heating in the Global North and cooling in the Global South. As income is a major determinant of appliances uptake and energy choices, low-income populations will remain excluded from the benefits of modern energy services without additional support. In other words, without subsidies, appliance rebates or easy access to credit, it is highly unlikely that households in developing regions will be able to afford access to key energy services related to thermal comfort, food preservation and preparation, and cleaning by mid-century. Besides the welfare increases that access to modern energy services bring, there are health benefits associated with improving access to modern energy alternatives for cooking and thermal comfort. Thermal needs, in particular, will be severely affected if climate targets are not achieved[38]. This suggests there are clear synergies between efforts to meet climate goals and expand access to modern energy services globally.

Methods

Overview

We use the MESSAGE-Access-E-USE (end-use services of energy) model, which consists of two modules, for the analysis in this work. [39] Here we provide an overview of the model and details relevant to the first global application. Supplementary Figure S5 shows a schematic overview of the model, differentiating between external inputs (in orange) and the internal modules and outputs (in blue). The *estimation* module, takes as input micro level data from nationally representative household surveys covering different regions of the world to estimate behavioral preference parameters that explain the choices of appliances and energy demands for different end-uses based on household socio-economic and demographic characteristics. The *simulation* module, subsequently uses the preference parameters estimated in the first module, plus additional external drivers that present potential future pathways of socioeconomic growth and energy prices, to simulate future appliances uptake and household energy demand under each scenario. We describe these two modules in further detail below.

We follow the regional aggregation of the world into eleven broad regions as defined in the MESSAGE model (see https://iiasa.ac.at/web/home/research/researchPrograms/Energy/MESSAGE-model-regions.en.html) to present results for ten out of eleven MESSAGE regions including: Sub-Saharan Africa (AFR), Centrally planned Asia and China (CPA), Central and Eastern Europe (EEU), Former Soviet Union (FSU), Latin America and the Caribbean (LAM), Middle East and North Africa (MEA), North America (NAM), Other Pacific Asia (PAS), South Asia (SAS), and Western Europe (WEU).

Data Sources

We use microdata from nationally representative household surveys of 25 countries that cover different socioeconomic realities, as well as different climatic zones within each region, in order to achieve global representation (Supplementary Table S1 provides a description of the countries and datasets used). Due to data limitations, the sets of household characteristics as well as the set of appliances that are available in each region differs (see Supplementary Table S2 for the variables and appliances considered in each region). However, appliances representing all end-uses that are analyzed in this study can be found in all regions. In addition, to account for the climatic factors that are especially relevant for the estimation of the demand for thermal comfort appliances, we used 0.5° spatial climate model data to define climate zones that are assigned to the different regions accounted for in the micro datasets. Climate zones were developed according to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) specification (see Supplementary Figure S6 for a World Map of the different climate zones). The standard defines approximately 20 zones based on the thermal climate (i.e. for heating and cooling degree days) and the moisture levels (dry, humid or marine). The climate zones dataset was developed using the EWEMBI dataset[40], which combines leading climate reanalysis datasets including ERA-Interim, WATCH, eartH2Observe and the NASA/GEWEX Surface Radiation Budget, to produce bias-corrected and downscaled data at 0.5° spatial resolution and daily timestep. In particular, we used daily data for the period 1980-2009 for the precipitation and surface air temperature variables[41]. Finally, given that, in many cases, the boundaries of some of the regions as presented in the micro datasets crossed more than one climatic zone, we ascribed the climatic zone that occupied the largest area of the region to all the households that can be traced to it.

Estimation Module

We develop a simulated structural econometrics model to estimate behavioral parameters that represent household decisions regarding energy consumption and appliance ownership. A fully detailed description of the methodology can be found in [42]. In brief, the model starts by creating a synthetic dataset of simulated households that mimics the empirical data in terms of joint distributions of urbanization, income, and a wide array of household characteristics relevant to the energy choice decision. The simulated households, based on their characteristics, optimally choose a set of appliances, and amounts of energy consumed for different energy services according to their preferences. In this way, we model two channels by which household characteristics, and in particular income, affect the demand for energy: indirectly through the choice of appliances, and directly, through the final energy used to run the appliances that the household had acquired.

Specifically, the demand for appliances is modeled using discrete choice methods considering the plausible alternatives for a single end-use given in the data (e.g., the choice of an electric, gas or biomass space heating appliance), as well as possible linkages between the appliances (e.g., the ownership of a washing machine when modeling the ownership of a dryer). Posteriorly, by solving an indirect utilization maximization problem, the consumption of electricity is calculated to be:

$$x_1 = \Phi_0 + \sum \delta_j \Phi_j + \left[\lambda_1 p_1 + \lambda_2 p_2 + \lambda_3 w + \lambda_4 \left(y - \rho \sum K_j \delta_j\right)\right]$$

where p_1 and p_2 are the prices of electricity and alternative fuels, respectively, w is a set of household characteristics, y is household income, ρ is the household's discount rate and K_j is the cost of buying the appliance j, which is obtained from a distribution that links the prices of the appliances in the region to the income level of the buyers, while the λs are the unobserved preference "weights" that households assign to the corresponding factors. Special attention should be given to the terms $\delta_j\Phi_j$, which represent average energy consumption (Φ_j) due to the ownership (δ_j) of the appliance j and Φ_0, which represents the average base electricity consumption of households, or better put, the average amount of electricity consumed that cannot be specifically assigned to any of the appliances included in the model.

Conversely, the consumption of alternative energy sources is:

$$x_2 = (\lambda_2/\lambda_4)\,(\alpha\text{-}1) + (\alpha/\lambda_4)\,(\Phi_0 + \lambda_1/\lambda_4 + \lambda_3 w)/p_2 + \alpha\,(\lambda_1/\lambda_4)\,(p_1/p_2)$$

$$+ (\alpha/p_2)\,\left[y - \rho \sum K_j\delta_j + \sum \delta_j\Phi_j/\lambda_4\right]$$

Finally, the specific energy use EU due to the ownership of the electric appliance k in a particular household i is backed up from the total electricity consumption of the household using the following equation:

$$EU_{k,i} = x_{1,i}\, \delta_{k,i}\, \Phi_k \Big/ \left(\Phi_0 + \sum \delta_{j,i}\, \Phi_j\right)$$

An analog equation is used to back out gas consumption of the household.

In this sense, the energy use that can be attributed to an appliance also reflects the effect of the remaining household characteristics that are used as controls. For example, the energy use for a thermal appliance may include the effect of household size, number of rooms, climate and other factors that can be obtained from the empirical data. However, more specific technical factors, such as, hours of use, set temperatures, capacity or efficiency of the appliances are not included in the model, as they are not available in the type of household datasets that were used for this study.

The behavioral preference parameters that determine the choices (namely the Φs, λs, α and ρ), although unobserved, are backed out from observed outcomes in empirical data using a simulation-based estimation technique[43] and a non-derivative optimization algorithm to minimize the distance between a set of relevant moments calculated both in the empirical and the simulated data. The estimation of these behavioral parameters is performed independently for each MESSAGEix[44] region to try to account for local idiosyncratic factors (hence the "structural" nature of the estimation model). Besides the main parameter estimates that are used in the study, a large set of additional 500 bootstrap estimates is obtained in order to calculate confidence intervals for the parameters, as well as to allow for the estimation of model uncertainty. Main point estimates and confidence intervals for the parameters obtained for each region and the estimated fit of the model in terms of moments matched for each of the model regions are available in the Supplementary Data File, whereas Supplementary Figure S7 display the fits in just two of the many dimensions in which the estimation is performed, namely, energy consumption and income, to give a visual sense of the fitting process.

Scenario Design and Simulation Module

We design several scenarios representing different combinations of socioeconomic and climate futures. The socioeconomic scenarios are based on the Shared Socioeconomic Pathways (SSP). We focus on three baseline SSP scenarios that describe varying degrees of challenge in meeting adaptation and mitigation goals[27–30]. The SSP1 scenario presents a world moving on a sustainable development path. This scenario has higher economic growth, lower inequality, higher urbanization rates and moderate demographic growth compared to the other scenarios. SSP2 describes a continuation of current trends without major shifts in either direction. At the other end of the spectrum, the SSP3 scenario, represents a future with low economic growth, high population growth, increasing inequality and lower urbanization rates than the other two scenarios.

Following the narrative of the SSPs, we enhance these by including assumptions on the uptake of efficient appliances. These assumptions are based on an econometric analysis of the uptake of efficient appliances in the largest countries in terms of population from the three income categories that have (statistically) significant proportions of energy efficient appliances data, namely, the United States (high income), China (upper middle income) and India (lower middle income). This analysis provides a statistical relationship between the probability of buying efficient appliances and a set of household characteristics related to socioeconomics and demographics correlates. We then make the following adjustments to these probabilities in line with the alternative futures that are represented by the SSP narratives. We make the following specific assumptions regarding the diffusion of efficient appliances. In SSP1, we assume a gradual increase (by 2050) in the likelihood of buying efficient appliances, up to three times that expected by simply following the current statistical relationships. In SSP2, we adjust the probabilities of buying efficient appliances in line with current statistical relationships following the projected increases in income and population. Finally in SSP3, we assume no changes in the probabilities of buying efficient appliances.

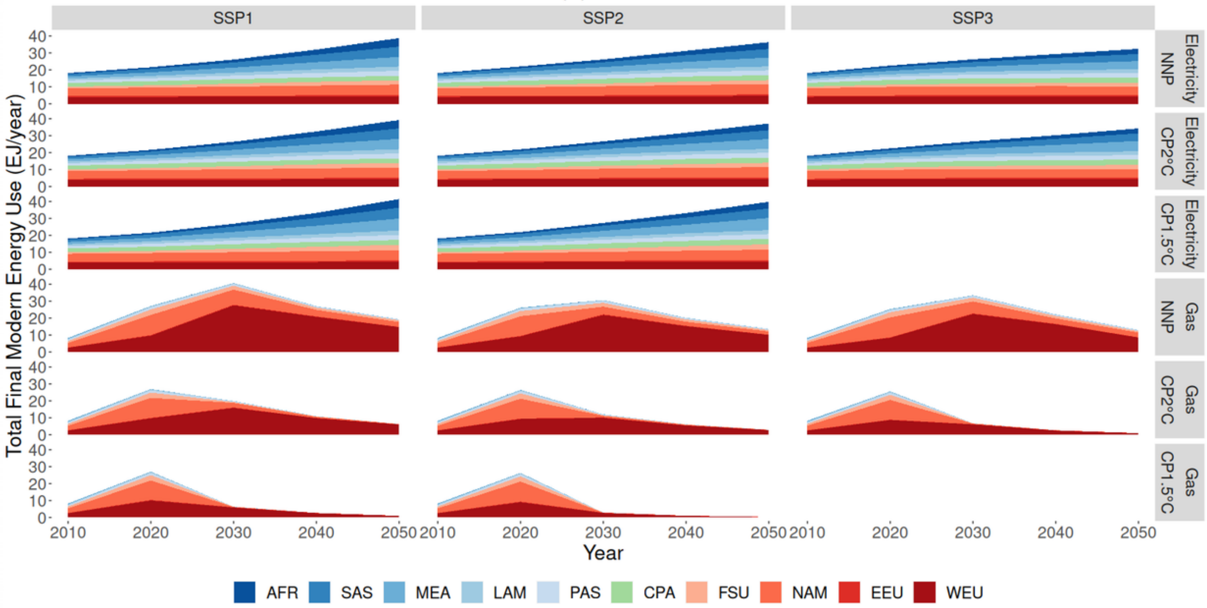
In a second step, we combine these scenarios with different climate mitigation futures[45]: We consider a stringent scenario where countries take measures to keep the increase of global temperatures below 1.5°C by the end of the century, and a more moderate scenario, targeting temperature rise to below 2°C by the end of the century. These scenarios have associated different fuel prices that affect the purchasing options of households. The combination of three SSP scenarios and climate scenarios are assessed to understand how appliance and electricity demand evolve over time. However, the most stringent climate scenario (<1.5°C degrees) is not achievable under SSP3, making this combination not available for analysis.

For each of these scenarios, we create simulated future datasets for each region that represent the expected evolution of the distribution of households' characteristics for that specific region over time. This process involves several steps, starting from stepwise, linking the income, population, and urbanization distributions, with the probabilities of having certain characteristics (e.g., the probability of being within a certain climate zone depends on income and urbanization, the probability of having a solid house depends on climate, income and urbanization, the probability of owning a certain thermal cooling appliance depends on having a solid house, climate, income and urbanization, etc.). The individual households in the simulated datasets then choose their set of appliances and energy consumption based on these characteristics and the structural preference parameters estimated in module 1, as described in the previous section.

Finally, confidence intervals for all the scenario analyses presented in the study are obtained using the set of bootstrap estimates of the parameters referenced. These estimates can be found in the Supplementary Data file.

Figures

(a) Total



(b) Average per Capita

Figure 1: Residential final energy consumption of modern energy by region and scenario between 2010 and 2050. (a) Total; (b) Average per capita. Three baseline scenarios are presented SSP1, SSP2 and SSP3. In addition to these baselinescenarios that include no specific climate policies (NNP); two scenarios with policies aimed at limiting global warming to below 2°C (CP2C) and 1.5 °C (CP1.5C) are presented. Regional disaggregation is in line with MESSAGE model regions (see Methods Section for additional information) and includes Sub-Saharn Africa (AFR), South Asia (SAS), Middle East and North Africa (MEA), Latin America and the Caribbean (LAM), Other Pacific Asia (PAS), Centrally Planned Asia

and China (CPA), Former Soviet Union (FSU), North America (NAM), Central and Eastern Europe (EEU) and Western Europe (WEU).

(a) Absolute Values

(b) Shares of Total Population

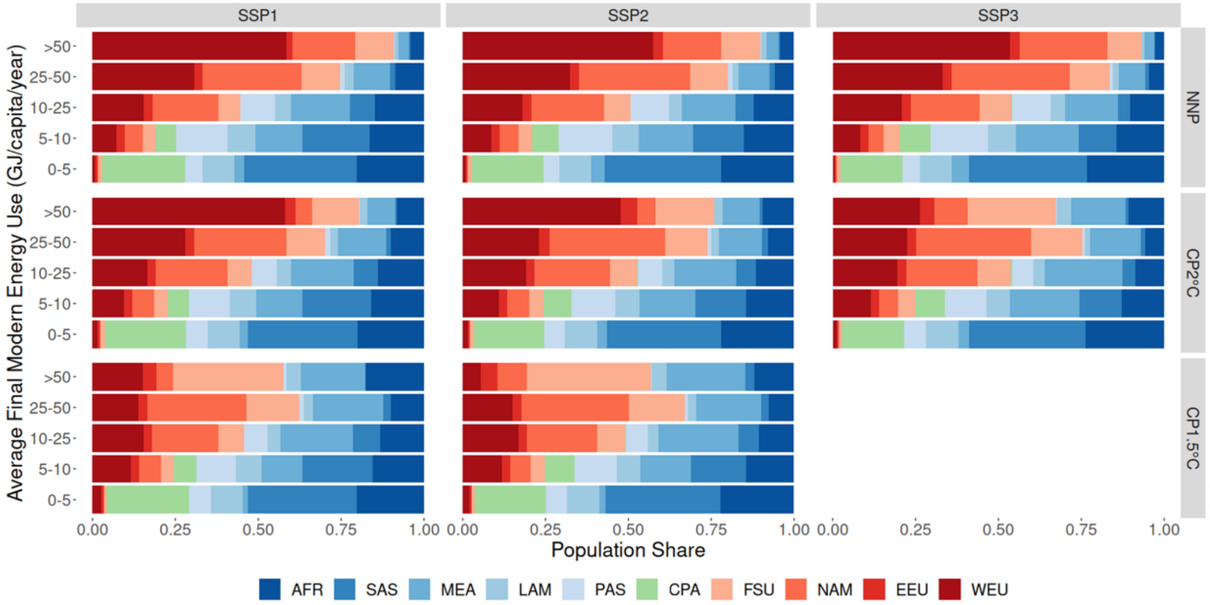


Figure 2: Distribution of modern final household energy use per capita across populations in each region by scenario in 2050 (a) Absolute values; (b) Shares of total population

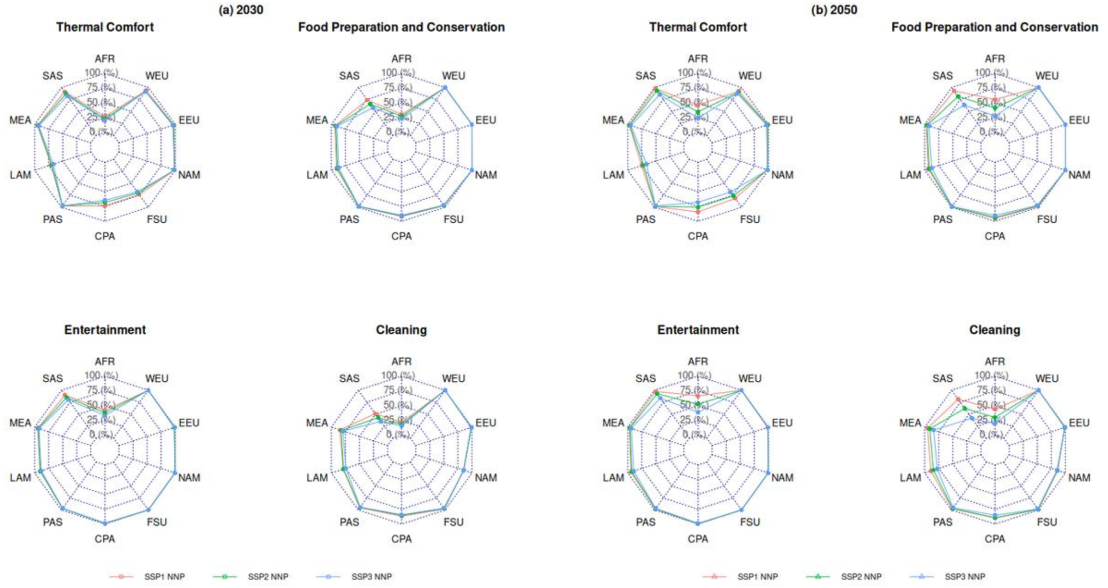
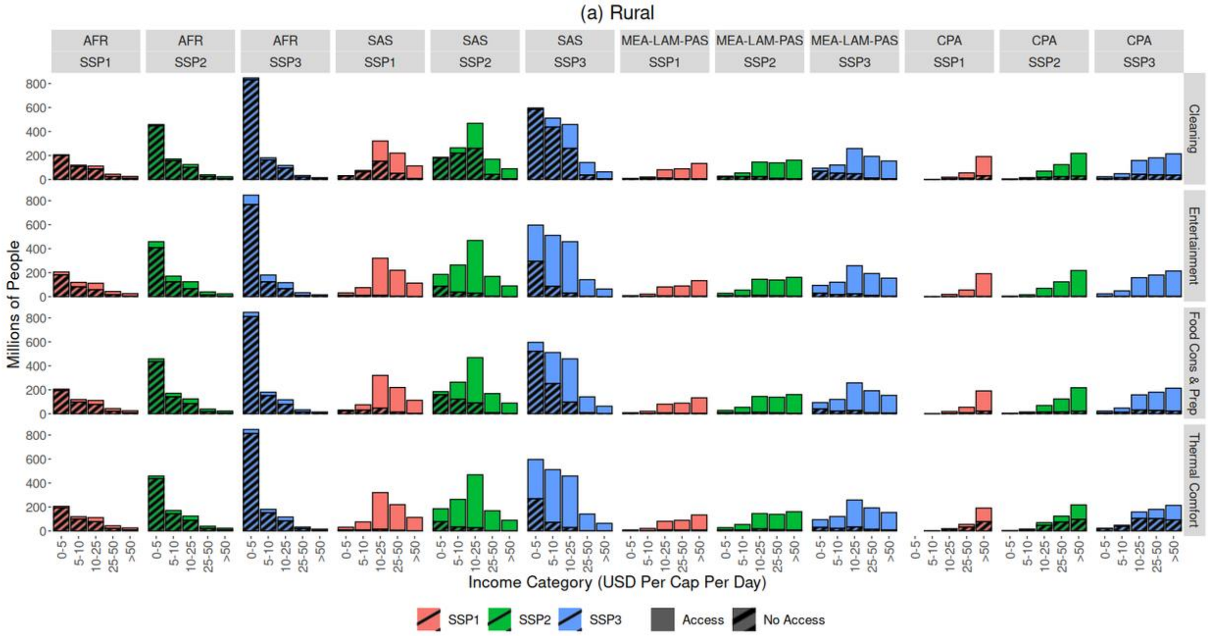


Figure 3: Share of population with access to key end-use services in the home by scenario and region in (a) 2030; (b) 2050. Access percentages for four categories of energy services including thermal comfort, food preparation and conservation, entertainment, and cleaning services is depicted for each region. In 2030, large percentages of populations in AFR, SAS, CPA and LAM still lack access to energy services related to thermal comfort food preparation and conservation, and cleaning services. By 2050, populations in AFR and SAS still lack access to services related to thermal comfort, food preparation and conservation, and cleaning services.



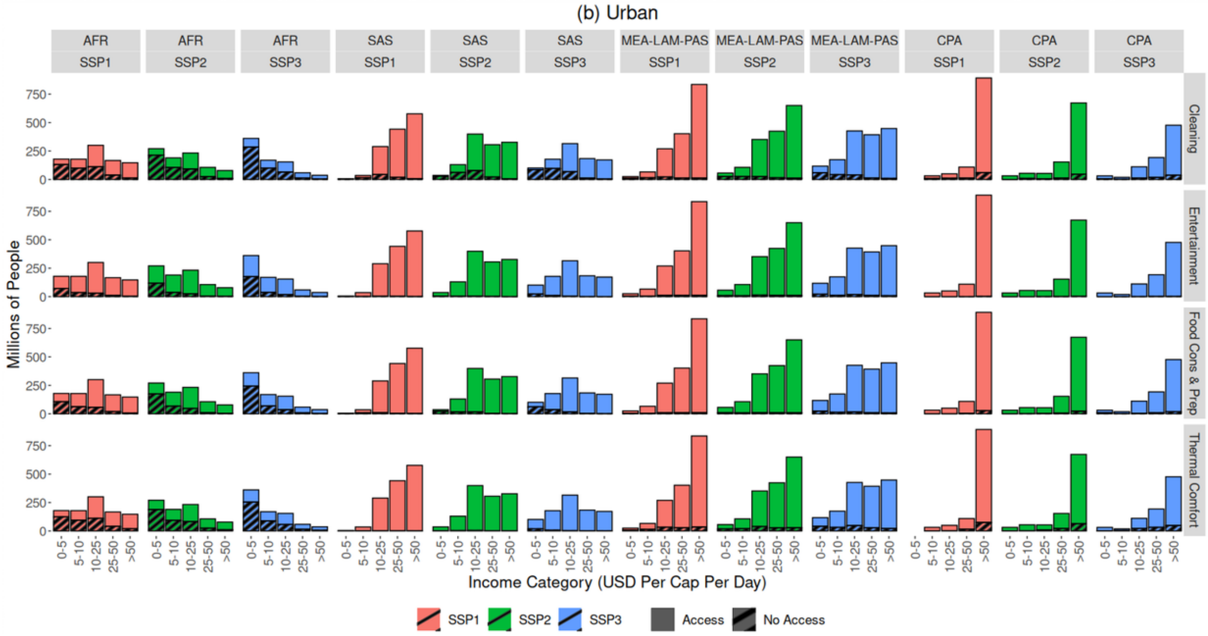

(b) Urban

Figure 4 Access to end-use services by income group for baseline SSP scenarios in Global South regions in 2050 (a) Rural; (b) Urban

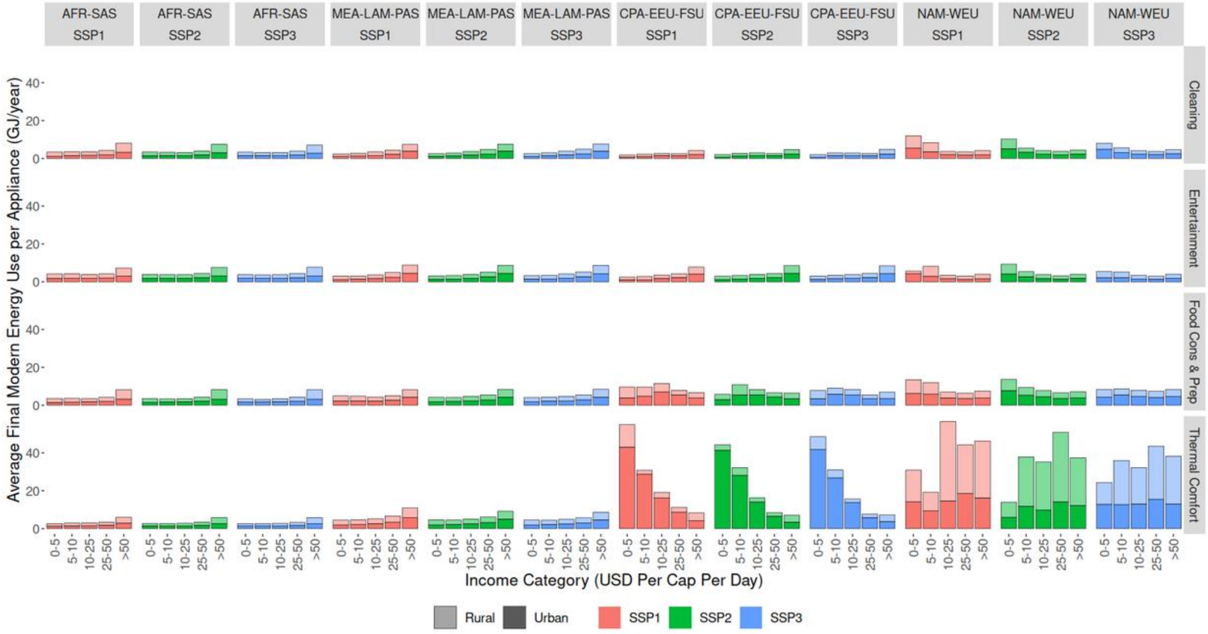


Figure 5: Average energy use per appliance owned for key end-uses by region in 2050 for SSP scenarios

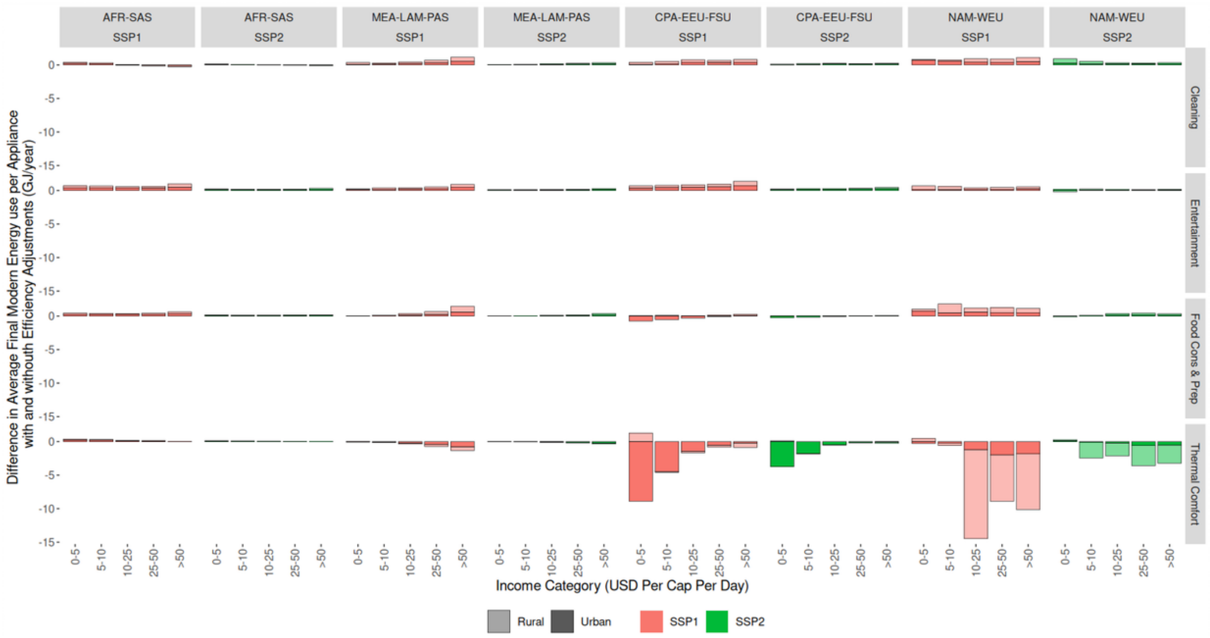


Figure 6: Deviations in average energy use per appliance by region for higher efficiency and no efficiency change sensitivities in 2050

Data Availability

Links to the micro datasets that were used in the analysis are included in the Supplementary Information File when available. Given that some of these datasets are not publicly available due to required pre-registrations or confidentiality aggreements (see Supplementary Table S1 in the Supplementary Information), the data used for the estimation module is only available from the corresponding author on reasonable request. The simulated datasets generated during the current study are also available from the corresponding author on reasonable request. Estimation and simulation results presented in the study are included in the Supplementary Data File.

Code Availability

The codes used during the current study are available from the corresponding author on reasonable request.

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Author Contributions

MPC and SP conceived the initial framework. MPC, SP and BvR designed the research. MPC, AM and EB prepared the data. MPC performed the modelling, wrote the codes and carried out the analysis. MPC and SP led the writing of the manuscript, with all other authors contributing.

Competing interests

The authors declare no competing interests.

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