What fuels the fire? Cooking fuel estimates at global, regional and country level for 1990-2030

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What fuels the fire? Cooking fuel estimates at global, regional and country level for 1990-2030

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Household air pollution generated from the use of polluting cooking fuels and technologies is a major source of disease and environmental degradation in low- and middle-income countries. Using a novel modelling approach, we provide global, regional and country estimates for 6 specific fuel categories (electricity, gaseous fuels, kerosene, biomass, charcoal, coal) and overall polluting/clean fuel use – from 1990-2020 and with urban/rural disaggregation. Model results show 53% of the global population relied on polluting cooking in 1990, dropping to 36% in 2020. In urban areas, gaseous fuels dominate, with a growing reliance on electricity; in rural populations, high levels of biomass use persist alongside increasing use of gaseous fuels. Future projections of observed trends suggest 31% will still lack access to clean cooking in 2030, and the Sub-Saharan African population relying on polluting fuels is on course to exceed 1 billion by 2025.

For 3 billion people[1] living in low- and middle-income countries (LMICs), the simple act of cooking is a major health and safety risk. The inefficient combustion of fuels in simple stoves and devices produces high levels of household air pollution (HAP). Chronic exposure to HAP increases the risk of noncommunicable disease including ischemic heart disease, stroke, chronic obstructive pulmonary disease, lung cancer, as well as pneumonia[2]; HAP exposure accounts for some 3.8 million premature deaths annually[3]. Open fires or poorly balanced pots also cause of burns and scalds, while kerosene and charcoal use in the home is a major source of poisonings from either ingestion or carbon monoxide exposure[2].

Households that rely on polluting energy systems frequently have to travel great distances to gather fuel – sometimes travelling hours each week – putting them at increased risk of musculoskeletal injury, and violence. Fuel collection is often tasked to women and children, perpetuating the negative socioeconomic and gender inequities of energy poverty by taking away time that could be spent on other activities likes schooling, income-generation and socializing.[4] Polluting cooking practices are also an important cause of environmental degradation and climate change: the black carbon from cooking, heating and lighting is responsible for 50% of anthropogenic global black carbon emissions[5] and around 30% of wood fuels harvested globally are unsustainable[6].

In recognition of these significant burdens, the global community has prioritized achieving universal access to clean cooking, enshrined in the 2030 Agenda for Sustainable Development[7] as one of three targets for Sustainable Development Goal (SDG) 7, to "ensure access to affordable, reliable, sustainable and modern energy". To inform and motivate policy towards this goal, the World Health Organization (WHO) publishes estimates of exposure to HAP[8] and related disease burdens[3], which have historically been calculated using the estimated population mainly using solid fuels[9] for cooking. In 2014, the WHO published the first-ever normative evidence-based guidance on the fuels and technologies that can be considered 'clean' for health[2], which highlight the importance of stove and fuel performance while also specifically discouraging the use of certain fuels – notably unprocessed coal and kerosene, a liquid fuel previously considered clean that emits high levels of harmful pollution. Since then, tracking of 'solid fuels' has been replaced with 'polluting fuels and technologies' – where polluting fuels consists of unprocessed biomass (wood, crop residues, dung), charcoal, coal, and kerosene (Figure 1). Meanwhile, estimates of the proportion of the population mainly using clean fuels and technologies – where clean fuels consists of gaseous fuels (liquified petroleum gas or LPG, natural gas, biogas), electricity, alcohol, and solar energy (Figure 1) – have informed monitoring of progress towards universal clean cooking[1]. Acknowledging very limited survey data on the technologies used for cooking, and the limited availability of truly clean-burning (for health) biomass stoves in LMICs, this analysis focuses only on the fuels used rather than stove technologies.

While the aggregate indicators polluting and clean fuel use are effective for summarising and communicating the global extent of polluting cooking and progress towards global goals, fuel-specific estimates are needed to optimally inform policies and decision-making on how to achieve the greatest reductions in HAP exposure as quickly as possible, in combination with local expert knowledge on challenges of affordability, availability, infrastructure and cultural preferences. Fuel-specific estimates are also desirable to refine estimates of HAP exposure and health burdens at regional, country level, and sub-national levels, fully taking into account the varying harm and types of pollution associated with different fuels (notably, carbon monoxide is currently absent from burden of disease calculations[10]).

Using a new model based on individual/specific fuel categories[11] (detailed in Section 4), we report estimates of cooking fuel use at country, regional (SDG and WHO regions) and global levels, for each year from 1990-2020, with urban/rural disaggregation. We provide estimates of aggregate clean and polluting fuel use (analysed in Section 1), and report for the first time estimates for 6 specific fuel categories: electricity, gaseous fuels, kerosene, unprocessed biomass, charcoal and coal (analysed in Section 2). For brevity, gaseous fuels and unprocessed biomass are from here onwards called "gas" and "biomass", respectively. We also report future projections of all estimates up to 2030, representing a possible scenario where trends seen in recent decades continue. All estimates are provided as supplementary material for download.

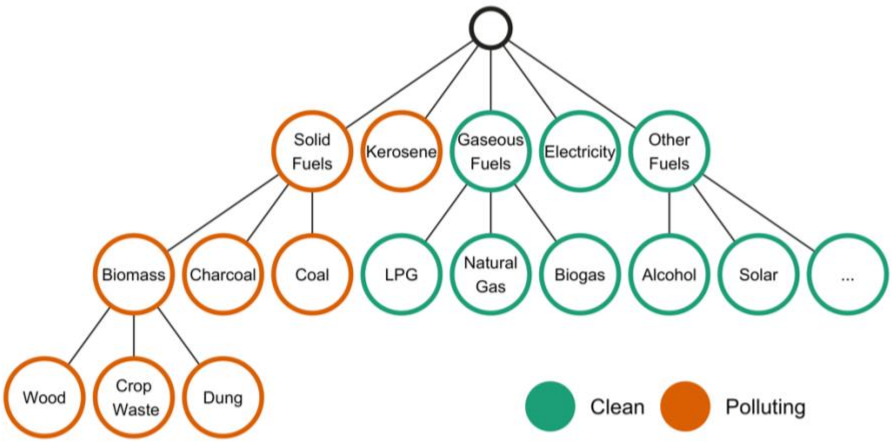

*Figure 1: **Classification of cooking fuels as clean or polluting**.*

1 Progress towards universal clean fuel use

The percentage of the global population mainly using polluting fuels for cooking has declined steadily over the last three decades, as illustrated in the right panel of Figure 2, from 53%

[45-60] in 1990 to 36% [30-43] in 2020. If observed trends continue, this percentage is expected to decline further to 31% in 2030. However, the percentage of the population mainly using polluting cooking fuels does not tell the whole story, as rising populations have contributed to an absolute number of people mainly using polluting fuels which has deviated little from 3 billion people since 1990 (2.8 billion [2.4-3.1] in 1990, 3.0 billion [2.8-3.3] in 2000, 3.0 billion [2.7-3.3] in 2010 and 2.8 billion [2.3-3.3] in 2020). This number is projected to drop only to 2.7 billion people by 2030.

Strictly at a global scale, the percentage of people in rural areas using polluting fuels for cooking (central panel of Figure 2) decreased only slightly between 1990 and 2010, from 75% [60-83] to 71% [66-76], but progress has since accelerated so that the estimated percentage cooking with polluting fuels in 2020 is 61% [52-69]. This is projected to decrease further to around 50% in 2030. These reductions have been matched by substantial decreases in the absolute rural population using polluting fuels, from a high of 2.5 billion [2.2-2.6] in 2003, to 2.1 billion [1.8-2.4] in 2020 and then a projected 1.7 billion in 2030.

Conversely, following a decrease from 1990 to 2020, the percentage of the global urban population using polluting fuels appears to have plateaued at 17% [13-25] in 2020 – projected to be 18% in 2030 – while the absolute urban population using polluting fuels may even increase from 0.7 billion [0.5-1.1] in 2020 to 0.9 billion in 2030.

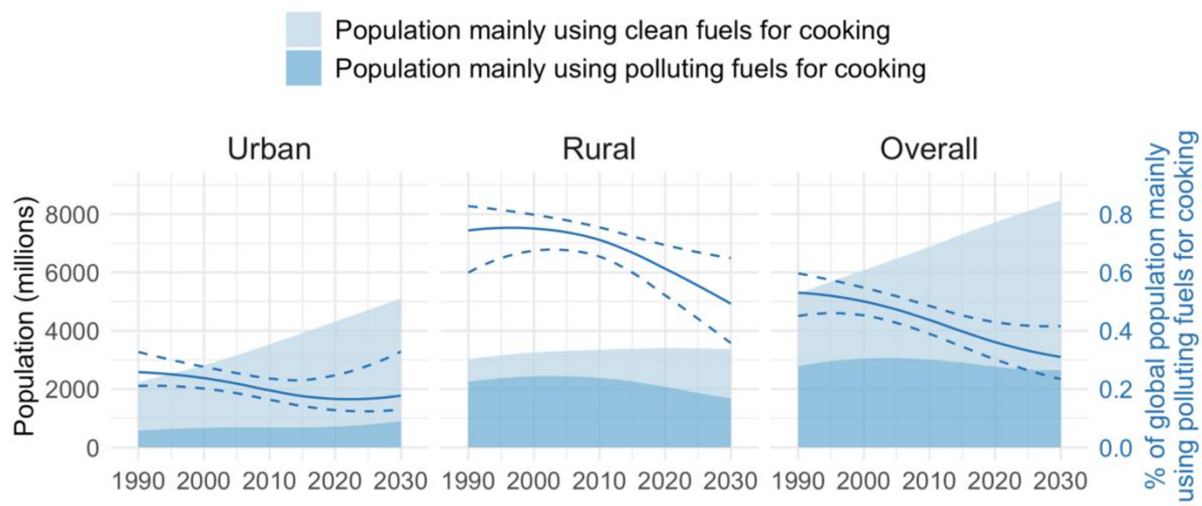

*Figure 2: **Global population mainly using clean and polluting fuels for cooking** (shaded area), shown alongside the percentage of the global population mainly cooking with polluting fuels (solid line), with 95% uncertainty intervals (dotted lines).*

The stagnation in the global population using polluting and clean fuels disguises important regional trends. In 1990, more than three quarters of people in the Central Asia and Southern Asia region and more than half of people in the Eastern Asia and South-eastern Asia region mainly used polluting fuels for cooking (Figure 3). Both of these regions have made significant progress over the last three decades in transitioning towards universal clean cooking. However, these successes are overshadowed by alarmingly little progress in the Sub-Saharan Africa region, where polluting fuel use has dropped from 90% [87-92] in 1990 to only 84% [82-86] in 2020. If observed trends continue, this is projected to drop to only 81% [76-85] in 2030, meaning four in five Sub-Saharan African people will continue to suffer the health and socioeconomic burdens of polluting cooking.

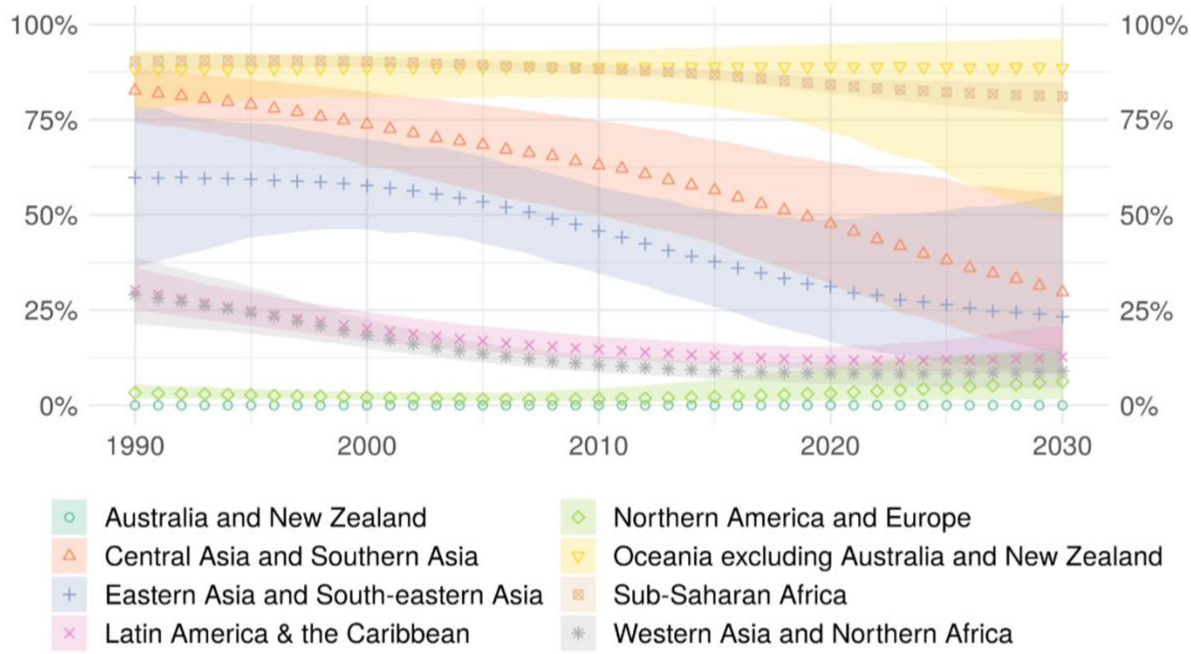

Figure 3: ***Percentage of the global population mainly cooking with polluting fuels in each SDG region****, with 95% uncertainty intervals (shaded).*

Once again, to truly understand the human cost of polluting cooking, it is more telling to consider the absolute number of people using polluting fuels (Figure 4). The number of people mainly cooking with polluting fuels is rising at an alarming rate in Sub-Saharan Africa and is projected to exceed 1 billion people by 2030 (perhaps by as early as 2025).

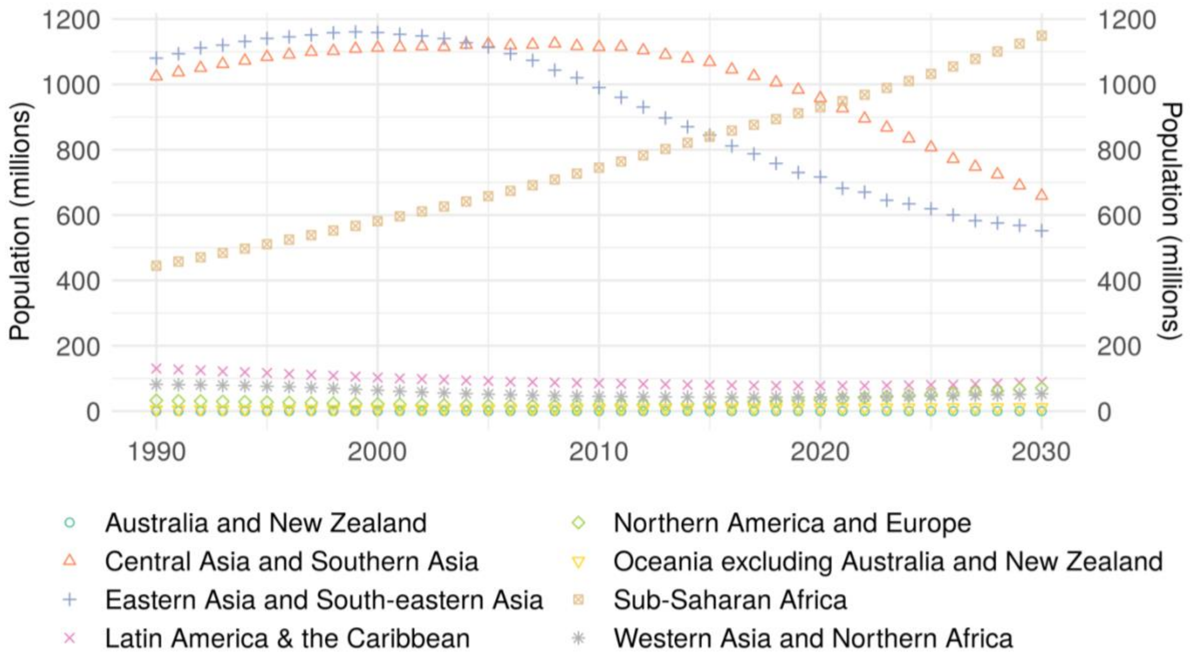

Figure 4: ***Population mainly cooking with polluting fuels in each SDG region****.*

In the year 2000, out of those mainly cooking with polluting fuels, 3 in 4 (75%) lived in either Central Asia and Southern Asia or Eastern Asia and South-eastern Asia, and only 1 in 5 (19%)

resided in Sub-Saharan Africa, as illustrated in Figure 5. In 2020, around 1 in 3 (34%) live in Sub-Saharan Africa and this is projected to approach to 1 in 2 (45%) by 2030.

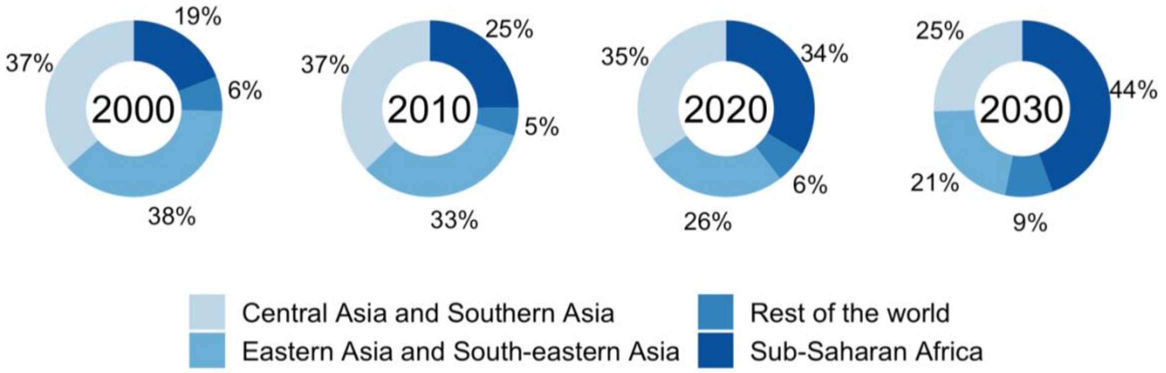

Figure 5: ***Regional breakdown of the global population mainly using polluting fuels for cooking.***

2 The changing fuel mix in low- and middle-income countries

Analysis of specific fuel use at regional, country and sub-national level can help to better estimate the impacts of current policies for household energy use well as inform the future development of policies and programs. Here we discuss some of the most notable trends across LMICs.

Among LMICs (Figure 6), use of gaseous fuels increased consistently from 31% [23-41] in 1990 to 49% [41-56] in 2020, overtaking unprocessed biomass fuels as the dominant cooking fuel type in the last decade. Use of electricity for cooking also rose, from 4% [3-7] in 1990 to 8% [4-14] in 2020, with a considerably larger increase in urban areas where infrastructure tends to be better established.

Between 1990 and 2010, increases in the use of clean fuels appear to be primarily explained by considerable decreases in the use of coal and kerosene. Coal use in rural areas has dropped from 12% [3-25] in 1990 to 5% [3-8] in 2010 then to 2% [1-6] in 2020. Kerosene use has also decreased: in urban areas it dropped from 10% [8-12] in 1990 to 4% [3-5] in 2010 then to 2% [1-3] in 2020, while in rural areas it dropped from 3% [2-5] in 1990 to 1% [0-2] in 2020. However, from around 2010 onwards the use of biomass fuels has also started to decrease consistently, mainly in rural areas where use of unprocessed biomass fuels has dropped from 68% [63-73] in 2010 to 60% [51-68] in 2020.

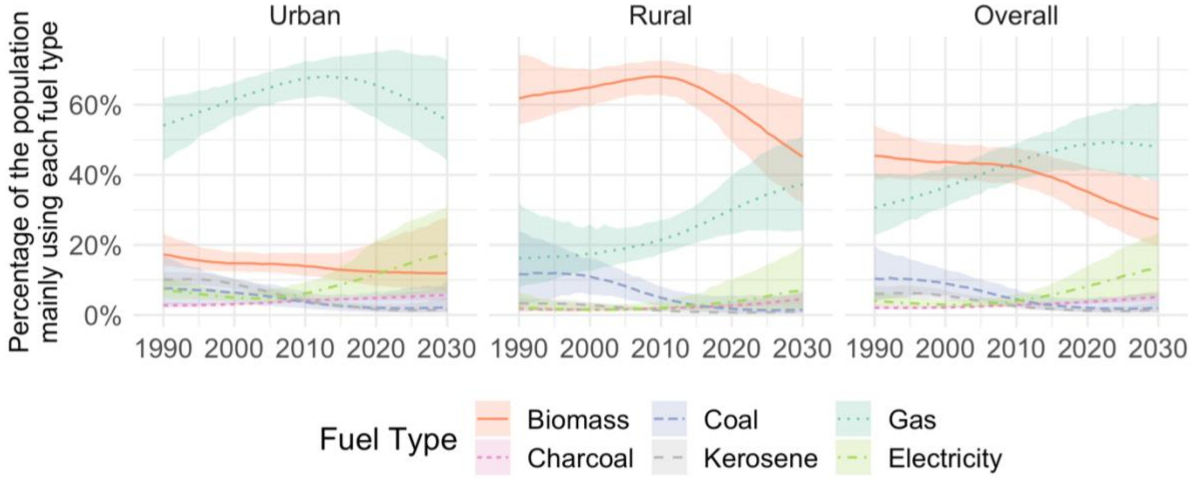

*Figure 6: **Cooking fuel use in LMICs.** Percentage of the population in LMICs mainly using each fuel type, with 95% uncertainty intervals.*

Although globally the use of kerosene has dwindled, it persists in urban areas of LMICs in both Oceania (15% [7-35] in 2018) and in Sub-Saharan Africa (6% [4-9] in 2020). Globally the proportion using charcoal is low (4% [3-4] in 2020), but in urban areas of Sub-Saharan Africa (Figure 7) it has overtaken biomass as the most popular fuel (30% [25-35] in 2020). If observed trends continue into the next decade, use of gaseous fuels in urban areas of LMICs is projected to start falling as more people switch to electricity, and eventually level-off overall.

2.1 Case studies: regional and country analyses of fuel use

Here we demonstrate how our estimates can be used for detailed analysis at the regional, national and sub-national level, using Sub-Saharan Africa and Ghana as case studies. In 2020, fuel use in urban areas of Sub-Saharan Africa (Figure 7) is highly pluralistic, consisting of charcoal (30% [25-35]), biomass (28% [24-34]), gaseous fuels (20% [17-23]) and electricity (13% [11-15]). In rural areas, however, use of biomass (86% [82-89]) and charcoal (8% [6-11]) constitutes a near duopoly, with only 6% using any of the other fuels.

If observed trends continue into the next decade, use of kerosene is projected to diminish to around 2% of the Sub-Saharan African population in 2030, with only a few countries maintaining high levels in 2030: 36% in Equatorial Guinea, 44% in Djibouti, and 76% in Sao Tome and Principe – where kerosene use is actually projected to increase. Meanwhile, modest decreases in the use of biomass fuels look likely to be largely offset by increases in the use of charcoal. Concerningly, very little progress is projected to be made in the use of gaseous fuels or electricity either in urban or rural parts of Sub-Saharan Africa.

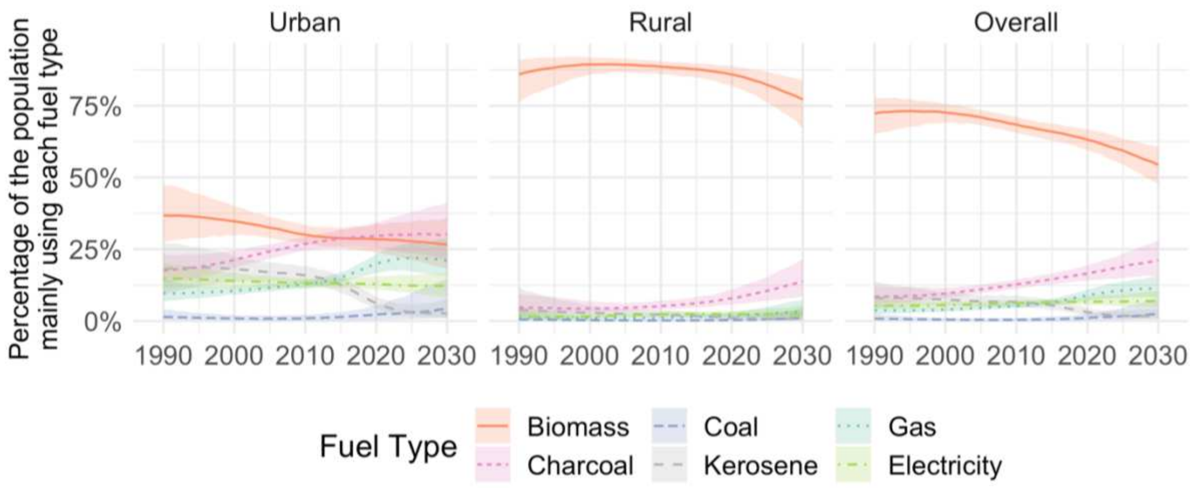

*Figure 7: **Cooking fuel use in Sub-Saharan Africa.** Percentage of the population in Sub-Saharan Africa mainly using each fuel type, with 95% uncertainty intervals. Plots for other regions are included as supplementary information.*

Zooming in to the national and sub-national level, Figure 8 shows modelled estimates for fuel use in Ghana alongside observed values from available household survey data – which are plotted to illustrate how the model captures non-linear fuel use trends, survey variability and uncertainty.

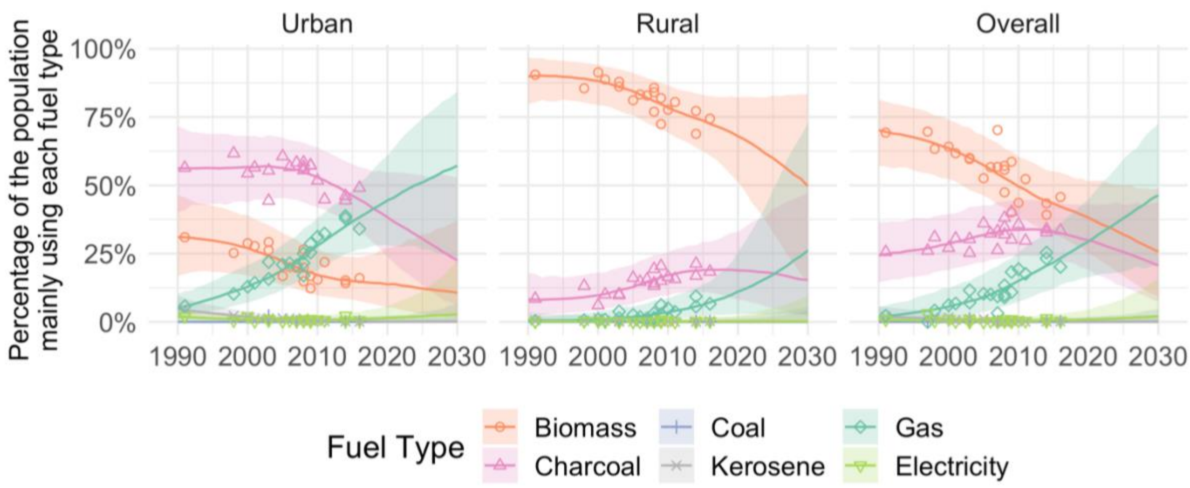

*Figure 8: **Cooking fuel use in Ghana.** Percentage of the urban population (left), the rural population (centre) and overall population (right) of Ghana mainly using each fuel type, with central estimates as lines. Points show available survey data. The 95% uncertainty intervals shown as shaded areas combine model uncertainty and survey variability: where data are plentiful, the uncertainty is small and the intervals capture the vast majority of survey points; where survey data are limited or unavailable, in particular when projecting into the future, the uncertainty grows, and our uncertainty intervals are wider. Plots for other LMICs are included as supplementary information.*

In Ghana the plurality of people uses biomass fuels in 2020 (38% [25-52]), with a further 30% [19-43] relying on charcoal (Figure 8). Use of biomass fuels remains high in rural areas, despite dropping from 90% [80-97] in 1990 to 68% [51-82] in 2020. Although use of charcoal was steadily rising in rural areas between 1990 (8% [2-18]) and 2010 (17% [10-26]), there is some evidence that this has stalled. In urban areas, meanwhile, use of gaseous fuels has risen consistently from 5% [2-10] in 1990 to 44% [28-61] in 2020. This is likely the result of concerted government efforts (starting around 1990) to promote the use of LPG as a substitute for the widely used charcoal and firewood[12]. Increased use of gas has come at the expense of biomass, which dropped about 14 percentage points between 1990 and 2010, and charcoal, which dropped about 15 percentage points between 2010 and 2020. Indeed, there is some evidence (65% probability) that in 2020 more people use gaseous fuels than any other fuel in urban areas of Ghana. If observed trends continue, use of gaseous fuels is projected to rise to 46% by 2030, meaning about 1 in 2 people in Ghana will still rely on polluting fuels for cooking.

3 Discussion

Previous estimates of cooking fuel use have been limited to clean versus polluting/solid fuel use, preventing detailed assessment of progress towards global goals and minimizing the utility of household energy use data for policymaking. Here we used a novel Bayesian hierarchical modelling approach to comprehensively and reliably estimate the use of 6 fuel types – as well as overall clean and polluting fuel use – under realistic constraints, from 1990 to 2020. We also presented future projections of existing trends up to 2030, representing a 'business-as-usual' scenario to motivate new policy and providing a baseline against which the effects of new interventions can be assessed.

Our analysis shows that although there has been progress towards clean household energy, the global community is far off track from reaching universal access to clean cooking by 2030. The global proportion mainly using polluting fuels dropped by an estimated 17% between 1990 and 2020, although the absolute number of people using polluting fuels has deviated little from 3 billion over the last 3 decades. Progress in urban areas is now static, although clean fuel use is increasing in rural areas (particularly gas and electricity). Indeed, our business-as-usual scenario projects 2.7 billion people, just under 1 in 3, will continue to mainly rely on polluting cooking fuels in 2030. A deeper regional analysis has highlighted the emergence of Sub-Saharan Africa as having the largest population mainly using polluting fuels for cooking after 2020, which is likely to exceed 1 billion people in the next 10 years; the need for greater focus and resources to implement policies and programmes promoting the adoption of clean in Sub-Saharan Africa cannot be overstated. Analysis at the level of specific fuels reveals further insights, such as the global elimination of kerosene and coal for cooking, and the emergence of charcoal as the most popular fuel in urban Sub-Saharan Africa.

While the availability of a complete set of estimates by specific fuel represents a significant step forward in the monitoring and understanding of polluting fuel use for cooking, these estimates do not take into account the technology used for cooking – due to a lack of data from nationally-representative surveys. Moving forward, access to technological solutions like low-emission advanced combustion biomass cookstoves should be monitored in national surveys to facilitate inclusion in global analyses, following the example of the Core Questions on Household Energy Use jointly developed by the WHO and the World Bank's Energy Sector Management Assistance Programme (ESMAP) to track SDG Target 7.1[13]. Finally, future modelling that accounts for all fuels used by a household for cooking (not just the main fuel), as well as polluting fuels used for heating and lighting, will improve understanding of exposure to total household air pollution, thus better informing policy and programmatic decision-making, as well as the global monitoring of health and environmental impacts.

Supplementary Information

Table 1, provided as supplementary information, details the sources and coverage of survey data contained within the WHO Household Energy Database, as of March 2020. Additionally, the following outputs are provided for download:

A. Country estimates (% and population) of clean, polluting, and specific fuel use, with urban and rural disaggregation, 1990-2030 (xlsx spreadsheet).
B. Global and SDG regional estimates (% and population) of clean, polluting, and specific fuel use, with urban and rural disaggregation, 1990-2030 (xlsx spreadsheet).

C. WHO regional estimates (% and population) of clean, polluting, and specific fuel use, with urban and rural disaggregation, 1990-2030 (xlsx spreadsheet).
D. Plots of country estimates (low- and middle-income only) of clean, polluting and specific fuel use (%), with urban and rural disaggregation, 1990-2030 (pdf document).
E. Plots of global and SDG regional estimates of clean, polluting, and specific fuel use (%), with urban and rural disaggregation, 1990-2030 (pdf document).
F. Plots of WHO regional estimates of clean, polluting, and specific fuel use (%), with urban and rural disaggregation, 1990-2030 (pdf document).

Reminder: regional and global estimates for specific fuels exclude high-income countries.

4 Methods

This section outlines the methodology we used to derive cooking fuel estimates for 1990-2030.

4.1 Household survey data and selection criteria

Data used in this analysis is drawn from the WHO's Household Energy Database[14], a regularly updated compilation of nationally-representative household survey data for WHO Member States from various sources, detailed in Table 1 (included as supplementary information). The version of the database used for this analysis comprises 1353 surveys collected from a total of 170 countries (including high income countries) between 1960 and 2018.

For this analysis we exclude surveys from before 1990, and only include data from surveys providing individual fuel breakdowns and with less than 15% of the population in total categorized as "missing", "not cooking in the household" or "mainly cooking with 'other' fuels". There was no differentiation in the model between surveys that reported only household- or population-weighted fuel use estimates. Where surveys reported both household- and population-weighted estimates, only population-weighted estimates were used, in order to best estimate the population reliant on different cooking fuels. Using this selection criteria 1136 surveys – collected from 153 countries – were used for modelling. Table 1 shows both the number of surveys in the database and the number used for modelling from each data source.

Surveys included in the database are inconsistent in the questions posed to households about cooking (typical questions by survey source are included in Table 1). Most survey questions are focused on the type of cooking fuel or energy rather than the cooking device, and thus the database version included in this study does not contain comprehensive data on solid fuel stove type (e.g. forced draft or brand information). Almost all surveys only assess the primary, or main, cooking fuel or energy source, which constrains the analysis to the primary fuel and technology used for cooking, although it is well documented that households often use multiple stoves and/or fuels, often referred to as 'stove-stacking'[15-17].

The WHO Household Energy Database contains data on the proportion of households mainly using a wide variety of cooking fuels, including alcohol fuels (e.g. ethanol); biogas; charcoal; coal; crop residues; dung; electricity; kerosene; liquid petroleum gas (LPG); natural gas; solar energy; and wood. However, surveys are not always consistent in the fuel options they present to respondents. In particular, some surveys combine fuels into a single option (notably natural gas and LPG are often combined into the category 'gas'). The result of this is that the time series of survey data for certain individual fuels can be unstable or unreliable in some countries.

Where appropriate in terms of similarity of health impacts, and relevance to policymakers, these issues can be remedied by combining affected fuels into a single category for modelling purposes. Here we combine wood, crop residues and dung into the category 'biomass', representing the combined use of unprocessed/raw biomass fuels, and we combine LPG, natural gas and biogas into the category 'gas' – refer to Figure 1 for a visual representation of these categories. Although solar and ethanol are considered clean fuels, they have been included under the category 'other fuels', due to the sparse number of data points available for these fuels (105 total data points for solar energy ranging between 0% and 0.8%; 7 total data points for ethanol ranging between 0% and 0.14%).

We therefore estimate the population mainly using six fuel types: 1. biomass, 2. charcoal, 3. coal, 4. kerosene, 5. gas, and 6. electricity. A final category, 'other fuels' represents the aggregate use of minor clean fuel types, e.g. solar and ethanol. Estimates for overall 'polluting' and overall 'clean' fuel use are then derived by aggregating estimates of relevant fuel types. 'Other fuels' were not modelled individually but are included in the aggregate 'clean' category.

4.2 The global household energy model

Previous statistical models for estimating fuel use have focussed on a single variable, i.e. solid fuel use or polluting fuel use[9,18]. Instead, we sought to model how a strongly related set of variables (the proportion of the population using each individual fuel type) changes over time, under the key constraint that as the use of one fuel increases the sum of the others must decrease, so that the total never exceeds 100%. No standard statistical procedure is available to achieve this, which merited the development of the bespoke Global Household Energy Model[11] (GHEM), a state-of-the-art Bayesian hierarchical approach[19] to jointly estimating the use of individual fuels for cooking.

Trends in the proportions using each fuel type are modelled together for both urban and rural areas of each country using smooth functions of time (thin-plate splines) as the only covariate. Estimates produced by the model are realistic in the sense that: a) as use of one fuel increases, the sum of the others automatically decreases, so that the total fuel use always equals 100%; and b) for each country, urban, rural and overall fuel use is linked by estimates of the survey sample urban proportion (including for years without surveys), also based on smooth functions of time.

The model outputs Bayesian 'posterior' probability distributions for fuel use in a given year and country, which can answer questions like "What is the probability that the use of coal exceeds 10% in urban areas of Mongolia?". For reporting purposes, summaries of these distributions can be taken to provide both point estimates (e.g. means or medians, the latter being what we present here and in the supplementary information) and measures of uncertainty (e.g. 95% prediction intervals (PIs) – which mean there is a 95% probability that fuel use lies within the given range).

GHEM is implemented using the R programming language and the NIMBLE[20] software package for Bayesian statistical modelling with Markov chain Monte Carlo (MCMC). The probability distributions assumed for input survey data do not allow for inputs where the sum of the percentage mainly using all mutually exclusive fuel categories exceeds 100% (110 surveys, with a median total excess of 0.01%), which can occur due to rounding at different stages of data collection. For these surveys, fuel use values were uniformly scaled (divided by the sum of mutually exclusive categories), to have a total of 100%. Countries classified as high-income according to the World Bank country classification[21] (60 countries) are assumed to have fully transitioned to clean household energy and are reported as >95% access to clean fuels and technologies[1]. In addition, no estimates are provided for LMICs where no surveys were available or suitable for modelling post-1990 (Bulgaria, Cuba, Lebanon, and Libya). Modelled estimates for the use of overall clean, overall polluting and specific fuels are therefore provided for a total of 130 countries – 128 LMICs plus 2 countries with no World Bank income classification (Cook Islands and Niue).

Population data from the United Nations Population Division (2019 version) were used to derive the population-weighted regional and global aggregates. We present aggregate estimates for the 8 SDG regions, as well as for the 6 WHO regions. LMICs without suitable survey data were excluded from all regional calculations and high-income countries were excluded from regional calculation for specific fuels – this means our regional estimates for specific fuels (e.g. gas) refer only to LMICs in those regions. Values of 100% clean fuel use were used for high income countries when calculating regional aggregates of clean and polluting fuel use.

4.3 Future projections

We also project observed trends in fuel use into the future using GHEM. These future projections were developed by extrapolating observed trends, representing a 'business-as-usual' scenario assuming no new policies or interventions.

The degree of uncertainty associated with such projections depends on a number of factors which vary by country, including the number of surveys conducted near present day and how changeable the trends are estimated to be over the available data period (1990-2018) – for example, projections for a country where trends are linear may display less uncertainty than a country with sudden changes in fuel use (e.g. Indonesia). The model has been validated[11] for making fuel use predictions up to 5 years beyond the end year of the data. Hence for years close to the end of the data period (e.g. 2019, 2020, 2021), point estimates and 95% prediction intervals can be interpreted as predictions of what may happen based on trends in the data. Further into the future, uncertainty tends to grow beyond practical levels but point estimates remain useful for policy purposes with a specific interpretation: what may happen if observed trends continue and no new policies or interventions are introduced.

Author Contributions

Oliver Stoner, Jessica Lewis, Itzel Lucio Martínez, and Heather Adair-Rohani developed the concept for the manuscript. Oliver Stoner developed the Global Household Energy Model, carried out the country and regional analysis and made major contributions to the manuscript. Jessica Lewis made significant contributions to the manuscript. Itzel Lucio Martínez was primarily responsible for updating the WHO Household Energy Database – including the addition of new surveys and validation of existing surveys – during the period over which this work was carried out and made significant contributions to the manuscript. Sophie Gumy contributed to the concept of the work, previously managed the WHO Household Energy Database and made minor contributions to the manuscript. Theo Economou previously supervised Oliver Stoner in developing the model and made minor contributions to the manuscript. Heather Adair-Rohani made significant contributions to the manuscript, manages the WHO Household Energy Database, and coordinated efforts for the development and application of the presented methodology for global household energy monitoring.

Competing Interests

The authors declare no competing interests.

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References

1. IEA, I., UNSD, World Bank, WHO. Tracking SDG7: The Energy Progress Report. (2020).
2. World Health Organization. Guidelines for indoor air quality: household fuel combustion. (2014).
3. World Health Organization. Burden of disease from household air pollution for 2016. (2018).
4. World Health Organization. *Burning opportunity: clean household energy for health, sustainable development, and wellbeing of women and children*. 113 p. (2016).
5. Bond, T. C. *et al.* Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres* **118**, 5380-5552, doi:10.1002/jgrd.50171 (2013).
6. Bailis, R., Drigo, R., Ghilardi, A. & Masera, O. The carbon footprint of traditional woodfuels. *Nature Climate Change* **5**, 266-272, doi:10.1038/nclimate2491 (2015).
7. United Nations. *Transforming our world: the 2030 Agenda for Sustainable Development*, <https://sdgs.un.org/2030agenda> (2021).
8. World Health Organization. Exposure to household air pollution for 2016. (2018).
9. Bonjour, S. *et al.* Solid Fuel Use for Household Cooking: Country and Regional Estimates for 1980-2010. *Environmental Health Perspectives* **121**, 784-790, doi:doi:10.1289/ehp.1205987 (2013).
10. World Health Organization. Burden of disease from household air pollution for 2016: Description of method. (2018).
11. Stoner, O. *et al.* Global household energy model: a multivariate hierarchical approach to estimating trends in the use of polluting and clean fuels for cooking. *Journal of the Royal Statistical Society: Series C (Applied Statistics)* **69**, 815-839, doi:10.1111/rssc.12428 (2020).
12. Asante, K. P. *et al.* Ghana's rural liquefied petroleum gas program scale up: A case study. *Energy for Sustainable Development* **46**, 94-102, doi:https://doi.org/10.1016/j.esd.2018.06.010 (2018).
13. World Health Organization. *Harmonized household energy survey questions - finalized*, <https://www.who.int/airpollution/household/survey-harmonization/en/> (2021).
14. World Health Organization. *Household Energy Database*, <https://www.who.int/airpollution/data/household-energy-database/en/#:~:text=The%20WHO%20Household%20energy%20database,cooking%2C%20heating%20and%20lighting%20fuels.> (2020).
15. Zhang, Y. O., Caroline. *Understanding cookstove and fuel stacking to achieve SDG7*, <https://blogs.worldbank.org/energy/understanding-cookstove-and-fuel-stacking-achieve-sdg7> (2020).
16. Jewitt, S., Atagher, P. & Clifford, M. “We cannot stop cooking”: Stove stacking, seasonality and the risky practices of household cookstove transitions in Nigeria. *Energy Research & Social Science* **61**, 101340, doi:https://doi.org/10.1016/j.erss.2019.101340 (2020).
17. Piedrahita, R. *et al.* Assessment of cookstove stacking in Northern Ghana using surveys and stove use monitors. *Energy for Sustainable Development* **34**, 67-76, doi:https://doi.org/10.1016/j.esd.2016.07.007 (2016).

18 Rehfuess, E., Mehta, S. & Prüss-Ustün, A. Assessing household solid fuel use: multiple implications for the Millennium Development Goals. *Environmental health perspectives* **114**, 373-378, doi:10.1289/ehp.8603 (2006).
19 Gelman, A. *et al. Bayesian Data Analysis, Third Edition*. (Taylor & Francis, 2013).
20 de Valpine, P. *et al.* Programming With Models: Writing Statistical Algorithms for General Model Structures With NIMBLE. *Journal of Computational and Graphical Statistics* **26**, 403-413, doi:10.1080/10618600.2016.1172487 (2017).
21 World Bank. *World Bank Country and Lending Groups*, <https://datahelpdesk.worldbank.org/knowledgebase/articles/906519-world-bank-country-and-lending-groups> (2020).

Figures

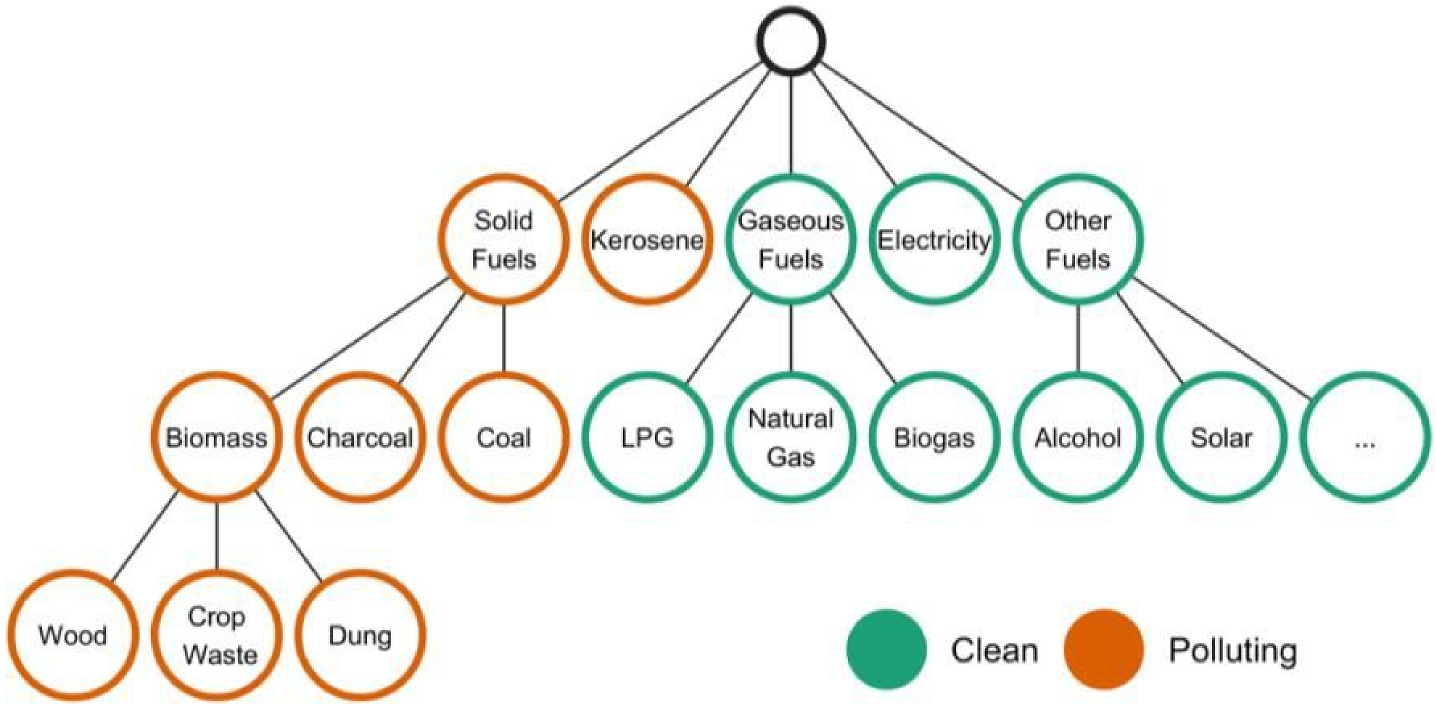

Figure 1

Classification of cooking fuels as clean or polluting.

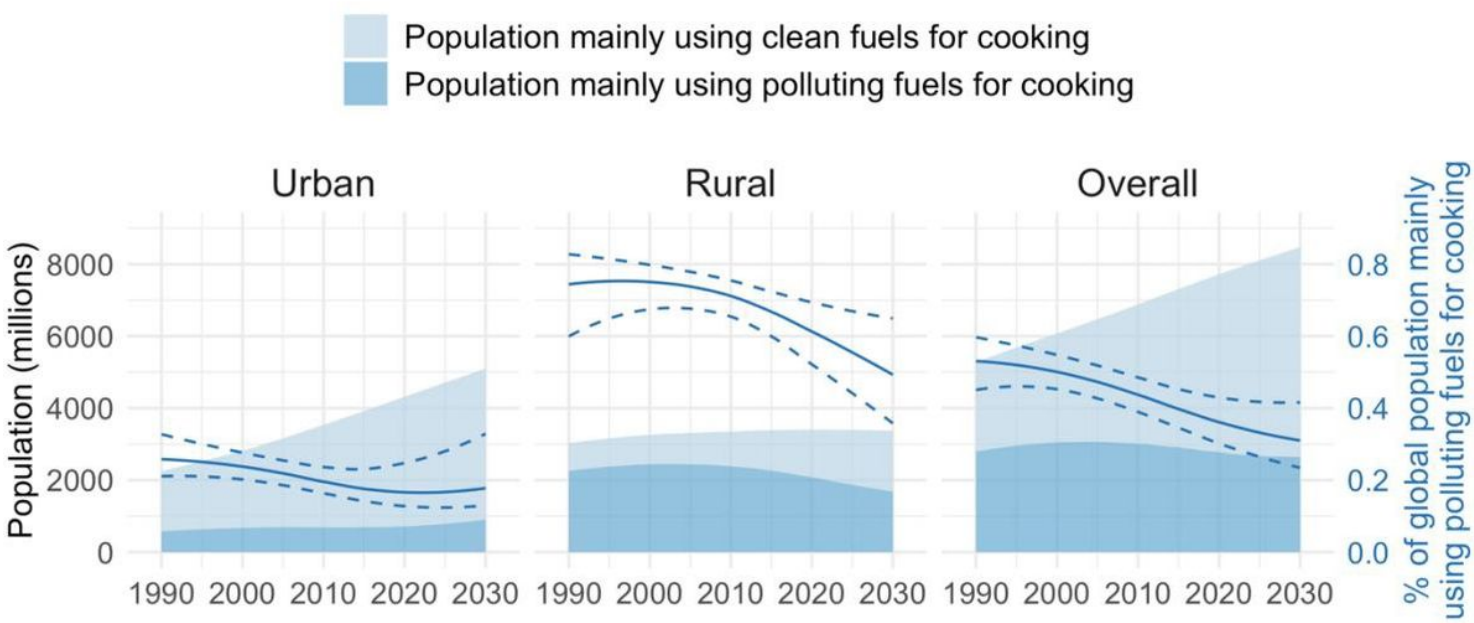

Figure 2

Global population mainly using clean and polluting fuels for cooking (shaded area), shown alongside the percentage of the global population mainly cooking with polluting fuels (solid line), with 95% uncertainty intervals (dotted lines).

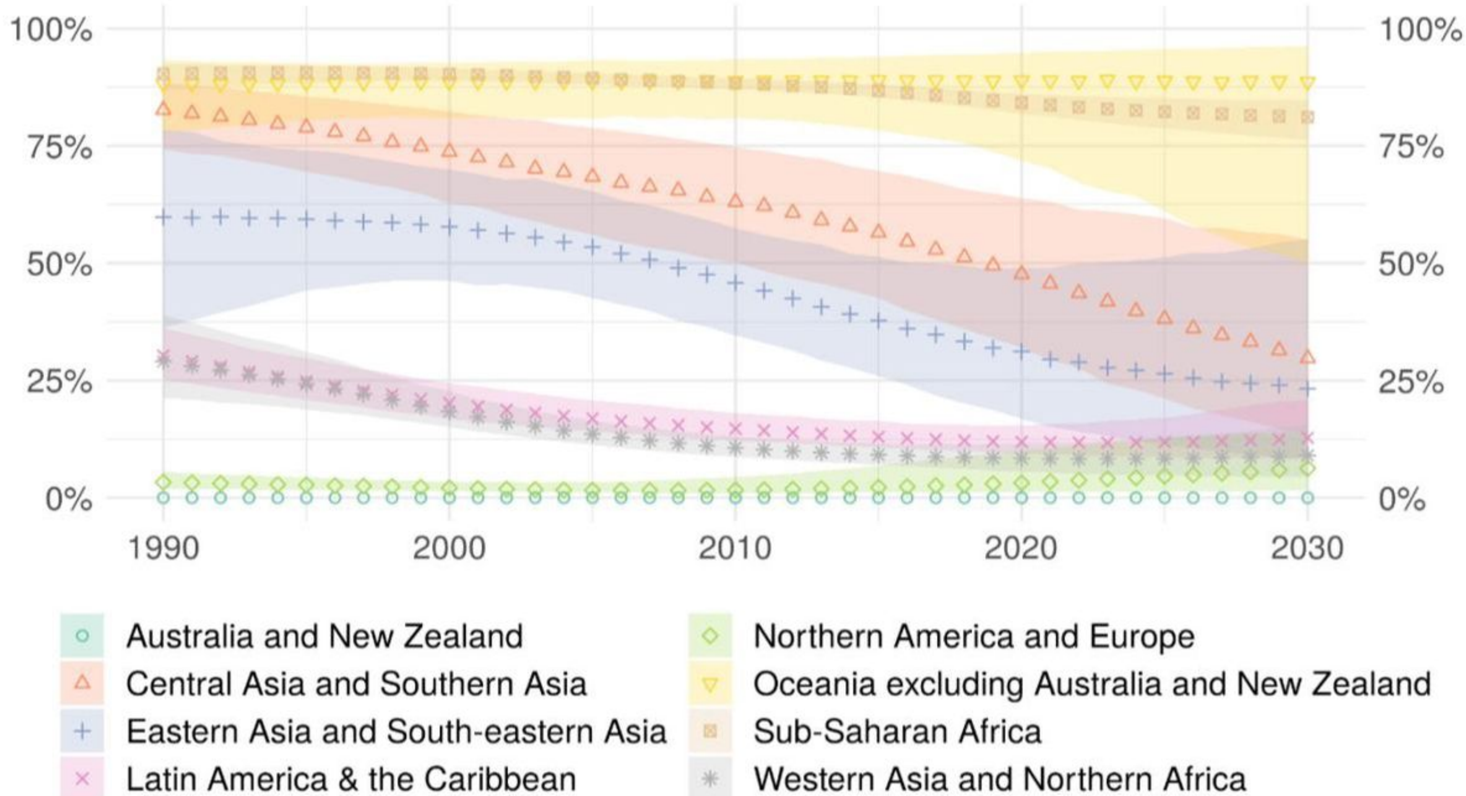

Figure 3

Percentage of the global population mainly cooking with polluting fuels in each SDG region, with 95% uncertainty intervals (shaded).

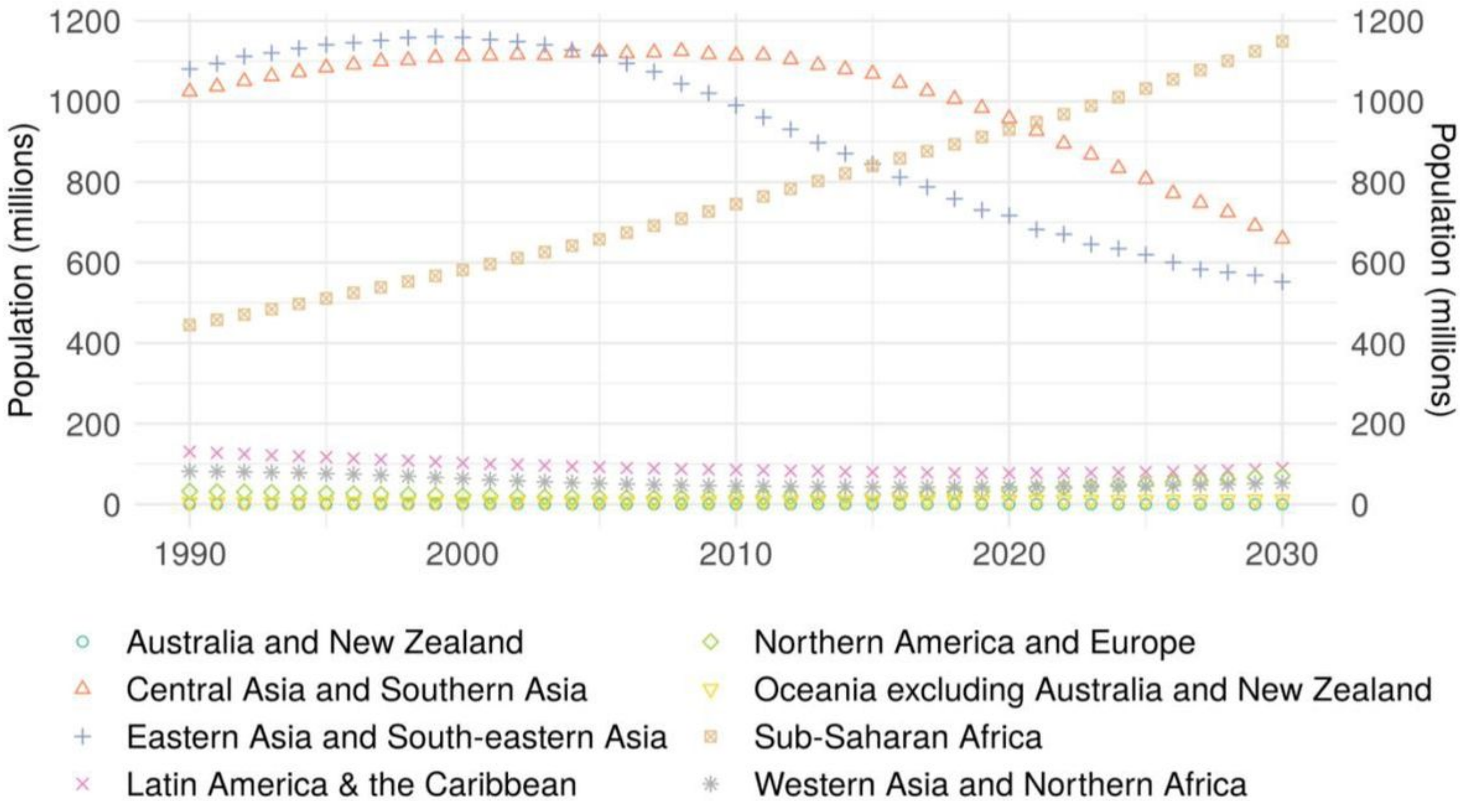

Figure 4

Population mainly cooking with polluting fuels in each SDG region.

Figure 5

Regional breakdown of the global population mainly using polluting fuels for cooking.

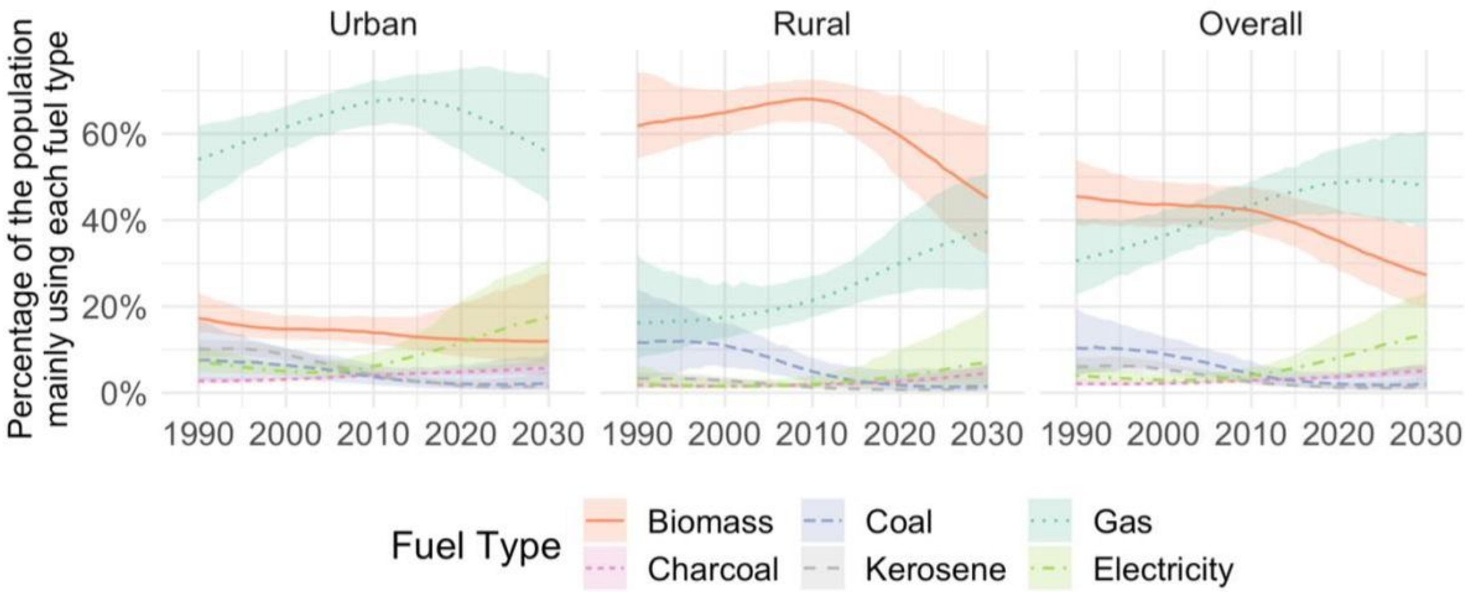

Figure 6

Cooking fuel use in LMICs. Percentage of the population in LMICs mainly using each fuel type, with 95% uncertainty intervals.

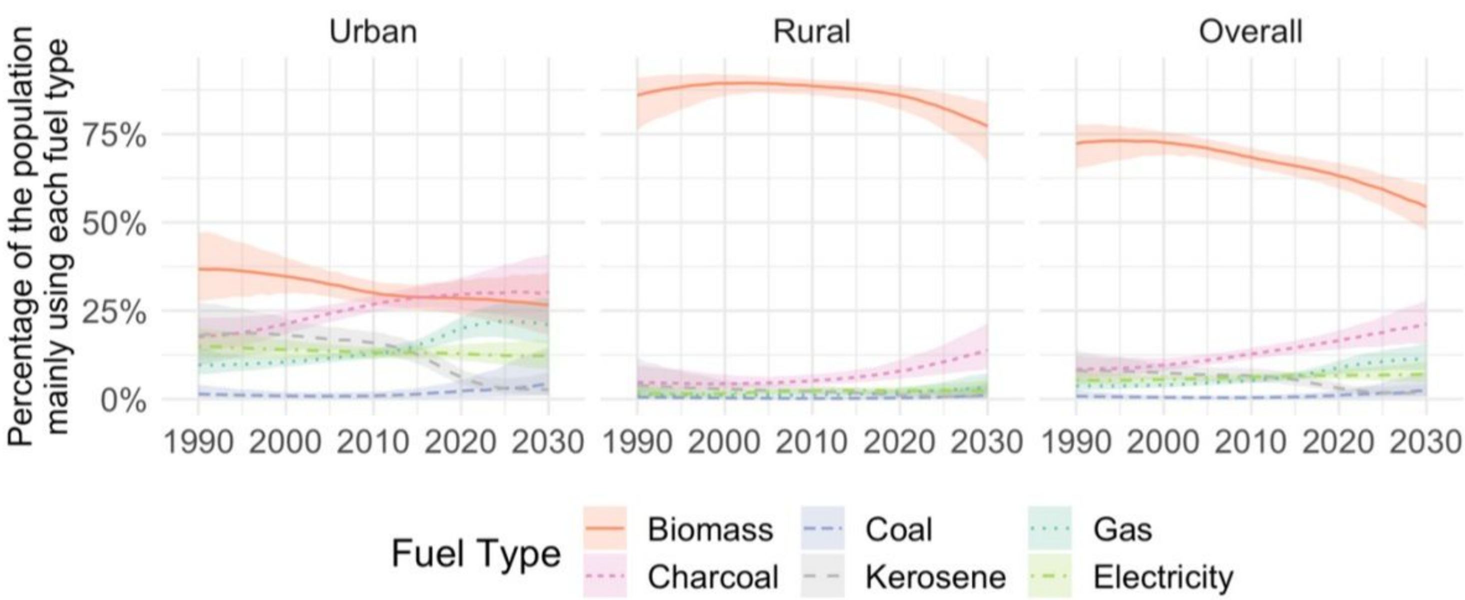

Figure 7

Cooking fuel use in Sub-Saharan Africa. Percentage of the population in Sub-Saharan Africa mainly using each fuel type, with 95% uncertainty intervals. Plots for other regions are included as supplementary information.

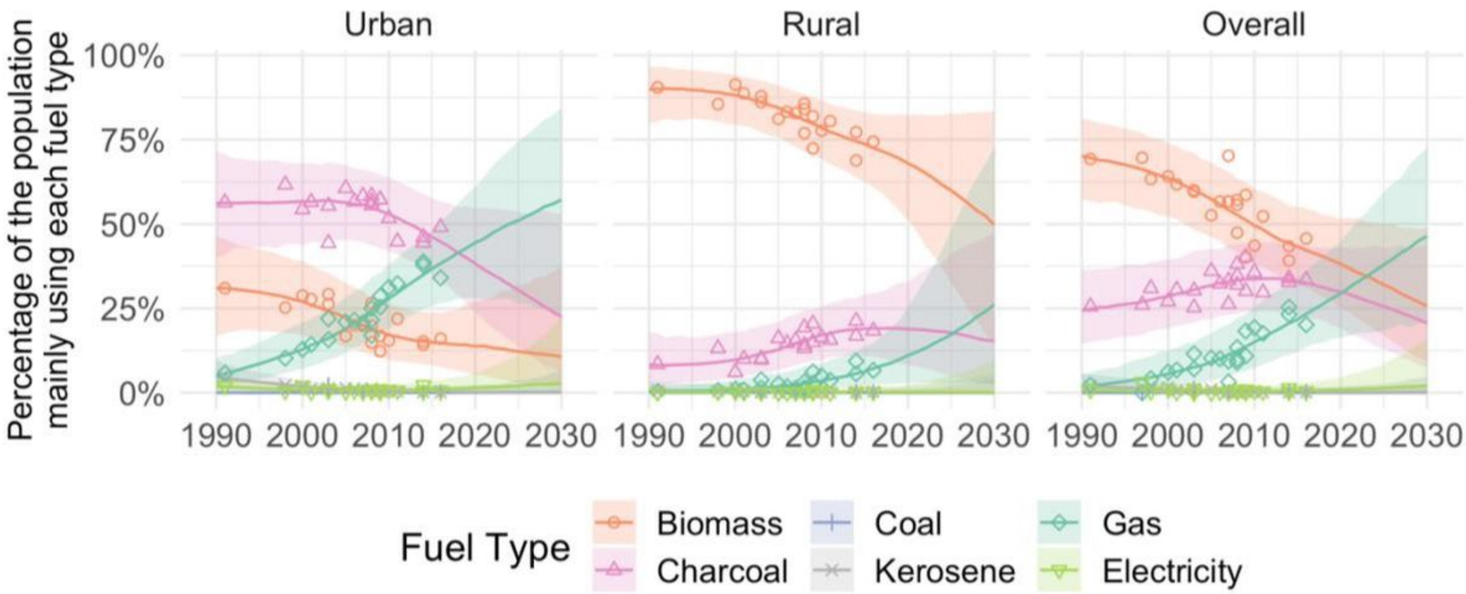

Figure 8

Cooking fuel use in Ghana. Percentage of the urban population (left), the rural population (centre) and overall population (right) of Ghana mainly using each fuel type, with central estimates as lines. Points show available survey data. The 95% uncertainty intervals shown as shaded areas combine model uncertainty and survey variability: where data are plentiful, the uncertainty is small and the intervals capture the vast majority of survey points; where survey data are limited or unavailable, in particular when projecting into the future, the uncertainty grows, and our uncertainty intervals are wider. Plots for other LMICs are included as supplementary information.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Table1.pdf
- ALMICEstimates2020Version.xlsx
- BSDGRegionGlobalEstimates2020Version.xlsx
- CWHORegionEstimates2020Version.xlsx
- DLMICPlots2020Version.pdf
- ESDGRegionGlobalPlots2020Version.pdf
- FWHORegionPlots2020Version.pdf