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Scaling up gas and electric cooking in low- and middle-income countries: climate threat or mitigation strategy with co-benefits?

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Abstract

Nearly three billion people in low- and middle-income countries (LMICs) rely on polluting fuels, resulting in millions of avoidable deaths annually. Polluting fuels also emit short-lived climate forcers (SLCFs) and greenhouse gases (GHGs). Liquefied petroleum gas (LPG) and grid-based electricity are scalable alternatives to polluting fuels but have raised climate and health concerns. Here, we compare emissions and climate impacts of a business-as-usual household cooking fuel trajectory to four large-scale transitions to gas and/or grid electricity in 77 LMICs. We account for upstream and end-use emissions from gas and electric cooking, assuming electrical grids evolve according to the 2022 World Energy Outlook's 'Stated Policies' Scenario. We input the emissions into a reduced-complexity climate model to estimate radiative forcing and temperature changes associated with each scenario. We find full transitions to LPG and/or electricity decrease emissions from both well-mixed GHG and SLCFs, resulting in a roughly 5 millikelvin global temperature reduction by 2040. Transitions to LPG and/or electricity also reduce annual emissions of $PM_{2.5}$ by over 6 Mt (99%) by 2040, which would substantially lower health risks from household air pollution. Full transitions to LPG or grid electricity in LMICs improve climate impacts over BAU trajectories.

1. Introduction

Nearly 3 billion people, 40% of the world's population, lack access to clean cooking fuels and technologies [1]. Instead, they rely on polluting fuels like wood, charcoal, other solid biomass, kerosene, and coal [2]. Commonly-used household stoves cannot burn these fuels efficiently and cleanly, resulting in exposure to products of incomplete combustion or 'household air pollution' (HAP) that contributes to nearly 4 million premature deaths each year [3]. Polluting fuels also contribute to ambient air pollution [4] and emit well-mixed greenhouse gases (GHGs) and short-lived climate forcers (SLCFs) that cause climate change [5, 6]. Unsustainable harvesting of biomass fuels contributes to local environmental degradation [7]. Impacts of polluting fuel use fall disproportionately on women, adding to preexisting gender inequalities [8]. These challenges have persisted for decades despite thousands of programs and policies designed to facilitate a transition to cleaner cooking.

The global prioritization of clean cooking is reflected in the seventh sustainable development goal, which aims to achieve universal 'access to affordable, reliable, sustainable and modern energy' by

2030 [9]. 600 million people gained *primary access* to clean cooking fuels or technologies between 2010 and 2020 [1]. Following WHO and others, we use the term *primary access* to refer to populations that use a clean fuel for most or all their cooking needs [10]. There is some ambiguity in this indicator because the household surveys that provide this data only collect information about the most frequently used cooking fuel in each household [11].

Despite these increases in access to clean cooking options, progress is uneven and some regions lag (SI section 1). Over 75% of the population that gained primary access to clean cooking between 2010 and 2020 did so by adopting liquefied petroleum gas (LPG) [10]. LPG is well-suited to near-term scale-up [12], and many low- and middle-income country (LMIC) governments have set ambitious targets promoting adoption [13]. Unlike electricity and piped natural gas, LPG does not require major investment in infrastructure to scale. It is clean-burning and simple to use [14, 15]. Electricity accounts for most of the remaining increase in primary access to clean cooking. While access to electricity is increasing rapidly in LMICs, cooking with electricity is less common [10]. Other clean cooking options like biogas, ethanol, solar thermal cookers, and biomass pellets burned in advanced stoves have gained traction in some markets, but globally they are much less prevalent than LPG and electric cooking.

Transitions from polluting to clean fuels and technologies results in large reductions in HAP exposure [16–18]. However, the past growth and planned scale-up of LPG raises questions about trade-offs between mitigating the health impacts of polluting fuels and the potential climate impacts of large-scale increases in fossil fuel consumption. Conventional LPG is a by-product of the petroleum and natural gas industries, with emissions arising from extraction, processing, and transport [19]. Grid-based electricity, completely clean at point of use, is derived primarily from fossil fuels in LMICs, and has similar issues [12, 20].

Fuelwood, charcoal, and other biomass fuels are *potentially* renewable. However, a substantial fraction of current woodfuel consumption is unsustainable and causes declines in standing stocks of biomass [7]. In addition, biomass fuels emit more SLCFs than LPG or grid-based power (SI section 7) and are detrimental for health due to the formation of products of incomplete combustion. Thus, a transition from polluting fuels to LPG or grid-based power could mitigate climate change through two mechanisms: lower consumption of unsustainable biomass and reduced SLCF emissions.

Previous work has quantified the global carbon footprint of biomass dependence at one point in time [7], examined climate impacts of individual cooking choices [6], and modeled the climate impacts of 'shutting off' biomass demand [21, 22]. One analysis estimated that a transition to LPG in Cameroon resulted in net global cooling of 0.3–1.3 millikelvin by 2100, depending on the levels of LPG adoption and biomass sustainability [23]. We build on these previous studies with the first global analysis of health and climate implications of transitions to both LPG and electricity.

2. Methods

2.1. Fuel transition scenarios

The analysis included LMIC countries with a population of at least 1 million households using polluting solid fuels and/or kerosene in 2018 (the baseline year) based on the WHO global database of primary fuels/energy used for cooking [10]. The analysis includes over 2.6 billion polluting fuel users from 77 countries. The scenarios are described below and summarized in table 1.

The business as usual (BAU) scenario assumes that past rates of change in primary household fuel choice are extended into the future. Past household cooking fuel choices were calculated for rural and urban areas of each country using WHO's household cooking fuel choice database, which includes six fuel categories: Biomass (consists mainly of unprocessed firewood, but also includes crop residues and dung), Charcoal, Coal, Kerosene, Gas (includes LPG, natural gas, and biogas), and Electricity [10]. Average rates of change for each fuel and other key assumptions are described in SI section 3.

The Full Transition-LPG (FT-LPG) scenario makes two key assumptions: (a) households using polluting fuels (Kerosene, Coal, Charcoal and Biomass) transition steadily to LPG such that use of polluting fuels falls to zero by 2040 and b) any electricity use at baseline evolves as in the BAU scenario. Therefore, by 2040, all cooking is done with either LPG or a mix of LPG and electricity.

The Full Transition to LPG and Electricity (FT-LE) scenario follows the same pattern as the FT-LPG scenario, but uses electricity as the main transition, while allowing BAU rates of LPG to continue. The Full Transition to Electricity examines a hypothetical transition to 100% cooking with electricity (including LPG-using households transitioning to exclusive use of electricity by 2040). The Intermediate (IT) scenario assumes BAU rates for each clean option increase by 50%.

2.2. Emissions

Household fuels emit a wide variety of pollutants including well-mixed GHGs like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) as well as SLCFs like black and organic carbon (BC and OC), non-methane volatile organic carbon

Table 1. Descriptions of the scenarios developed for this analysis.

Scenario name (abbreviation)	Description
Business as usual (BAU)	Future primary cooking fuels adoption rates follow recent country-specific trends as defined by WHO disaggregated by rural and urban populations [10].
Intermediate transition (IT)	Adoption rates of LPG and electricity increase by 50% by 2040, displacing more polluting fuels than in BAU
Full transition to LPG (FT-LPG)	All polluting cooking fuels are displaced with LPG by 2040 but rate of electricity adoption proceeds as in BAU, resulting in an LPG dominant future.
Full transition to LPG and Electricity (FT-LE)	All polluting cooking fuels are displaced with grid-based electricity by 2040, but the rate of LPG adoption proceeds as in BAU, resulting in a balanced mix of LPG and electricity in the future.
Full transition to Electricity (FT-Elec)	All polluting cooking fuels and LPG are displaced with grid-based electricity by 2040, resulting in electricity dominant future.

(NMVOC), sulfur and nitrogen oxides (SO_x and NO_x) and carbon monoxide (CO) [24]. BC and OC are constituents of fine particulate matter ($PM_{2.5}$), exposure to which is associated with numerous health risks [25]. Exposure to SO_x, NO_x, and CO can also damage health.

Emissions from 'upstream' processes like extraction, refining, and transportation of fossil-based cooking fuels (kerosene, LPG, and coal) were derived from Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET), a life cycle model developed by Argonne National Labs primarily for analyzing transportation fuels [26]. GREET was also used to estimate transportation emissions associated with charcoal. GREET's default parameters reflect current US conditions, but the model allows users to adjust inputs to reflect other regions. For the global analysis, we determined the dominant consumers of each fuel from our sample of 77 countries, as well as the major exporters supplying these countries and adjusted GREET accordingly. We describe specific approaches for each fuel in SI section 4.

For upstream emissions from charcoal production, the average emission factors for CO, NO_x, $PM_{2.5}$, SO_x, BC, OC, CH_4, N_2O, CO_2, and NMVOC were compiled from previous collections of field emission factors [19, 27, 28] and converted to a delivered energy basis using an assumed stove efficiency [19] (table S9). For biomass, we assumed that wood is locally collected and has no upstream emissions. The end use emission factors for biomass, charcoal, kerosene, coal and LPG were taken from previous compilations of lab and field data [6, 19, 27, 28].

Shares of electricity production and total production for different years were taken from the World Bank Development indicators [29] with missing data supplemented by International Energy Agency (IEA) statistics [30]. Future grid mixes were simulated using projections from the IEA's World Energy Outlook 'Stated Policies' scenario through 2040 [31]. Lifecycle grid emissions per kWh of electricity produced from each type of power generation were estimated using GREET [26]. Plant-specific emissions are included in GREET's database with some tunable parameters. GREET's default values assume a US-based grid and power plant feedstock. We changed some parameters for coal, as mentioned above. Parameters for other feedstocks were left at their default values. We describe grid projections, emission factors, and additional assumptions in SI section 5.

When woody biomass is harvested and burned as fuelwood or charcoal, much of the carbon in the wood is converted to CO_2, contributing to climate change. However, depending on the rate of harvest and land management practices, some, or all the woody biomass regenerates, reducing the impact of the CO_2 emitted during combustion. When there are imbalances between woody biomass harvest and regrowth, CO_2 emitted during combustion is not fully sequestered by regenerating trees. This is called 'non-renewable biomass' (NRB). The ratio of NRB to woody biomass consumption is the 'fraction of non-renewable biomass' (fNRB). We use country-specific pan-tropical estimates of fNRB from a previous study [7] to account for net CO_2 emissions from wood and charcoal (see SI section 6 for more detail).

For the global health impact assessment, we did not estimate contributions of emissions to specific health outcomes. Instead, we estimated changes in emissions of (and assumed exposure to) the following health-damaging pollutants: $PM_{2.5}$, CO, NO_x, and SO_x [32]. This research group carried out a parallel study of national-level assessments in five priority countries using the ABODE model to estimate health impacts associated with changes in exposure [33]. The results of these health models are discussed in a separate paper.

2.3. Climate impacts

We estimate climate impacts of the different scenarios using the FaIR v1.6.2 climate model, which is a simple emissions-based model that accounts for non-linearities in the carbon cycle and includes simplified processes representing greenhouse gas, aerosol, ozone, and other forcings from precursor emissions [34–36]. We use the multi-species configuration, with the RCP4.5 scenario as a baseline for the BAU scenario [36, 37]. RCP4.5 is a pathway for stabilization of radiative forcing by 2100, projecting somewhere in the region of 2.5 °C–3 °C global mean temperature increase above pre-industrial by the end of this century, and is the closest RCP scenario to current global climate policy [38]. Uncertainty was calculated based on runs using parameters derived from a 2237 member ensemble developed for analysis in IPCC's Sixth Assessment Report [37]. This ensemble is observationally constrained in order to span the assessed range in climate system uncertainty, including global temperature change (1850–2019), atmospheric CO_2 concentrations (1750–2014), change in ocean heat content (1971–2018), and assessments of equilibrium climate sensitivity, transient climate response and airborne fraction of CO_2 emissions [37, 39]. Differences in emissions between the BAU and other scenarios were calculated for CO_2, CH_4, N_2O, SO_x, CO, NMVOC, NO_x, BC, and OC, and added to the RCP4.5 baseline emissions trajectory. The resulting emissions trajectories were run in the FaIR climate model to obtain annual changes in GHG concentrations, climate forcing, and temperature projected to 2040. To estimate uncertainties, we report the median and 5th, 25th, 75th and 95th percentile values of the ensemble simulations, with emissions held constant. Therefore, uncertainty estimates do not represent uncertainties in scenarios, only in climate system response [40].

3. Results

3.1. Future household energy transitions

Figure 1 compares energy consumption, number of fuel users and energy consumed under BAU and a full transition to LPG (FT-LPG). Under BAU, demand for biomass, coal, and kerosene decrease by 25%, 96%, and 25%, respectively, between 2018 and 2040. However, these patterns are not consistent across all regions. For example, BAU biomass demand decreases steeply in Asia/Pacific regions but increases in Africa. In addition, BAU charcoal consumption increases globally over this period by over 125%, driven mainly by growth in urban consumption in Africa. Clean fuel use also increases under BAU: LPG consumption increases by 50% and electricity demand for cooking doubles.

3.2. Changes in emissions of health-damaging pollutants

To gauge health impacts, we report changes in emissions of health-damaging pollutants including fine $PM_{2.5}$, CO, NO_x and SO_x. Here, and below, we refer to emissions from cooking fuels in the 77 countries included in our analysis. In 2018, approximately 7.6 Mt of $PM_{2.5}$ were emitted from cooking fuels (figure 2(A)). Under the BAU scenario, this is projected to decline by 24%, driven by transitions from polluting fuels to LPG and electricity described above. Under the IT scenario, a modest increase in clean fuel adoption results in a 12% reduction of $PM_{2.5}$ emissions relative to BAU. Under full transitions to either LPG or electricity, $PM_{2.5}$ emissions from residential cooking are nearly eliminated.

CO emissions follow a similar pattern as $PM_{2.5}$ (figure 2(B)). In 2018, we estimate that 71 Mt of CO was emitted from cooking fuels. Under the BAU scenario, CO emissions decrease 5% to 67 Mt by 2040 (CO declines less than $PM_{2.5}$ due to growth in charcoal consumption). In the IT scenario, 2040 CO emissions are ∼10% lower than BAU, and in the full transitions to either LPG or electricity, CO emissions decrease by over 95%.

NO_x emissions result primarily from atmospheric nitrogen and increase with higher combustion temperatures. LPG, coal, and thermal power generation occur at higher temperatures than biomass combustion in household stoves; therefore life-cycle NO_x emissions are higher from LPG, gas and electric cooking [41]. SO_x emissions primarily occur because of fuel-bound sulfur [42], which occurs in trace amounts in biomass but can be several percent by weight in coal [43]. Under the BAU scenario, NO_x emissions increase by ∼20% between 2018 and 2040 and SO_x emissions decrease by a similar magnitude (figures 2(C) and (D)). Under IT and FT-LPG scenarios NO_x emissions increase further because of increased LPG consumption. In contrast, SO_x emissions are lower in all scenarios relative to BAU except for FT-Elec. In that scenario, SO_x emissions are nearly 30% higher than BAU due to increased coal-based electricity consumption (see SI section 10 for a discussion of regional variation in health-relevant emissions).

3.3. Emissions of well-mixed GHGs and SLCFs

Figure 3 shows fuel-specific emissions of well-mixed GHGs and BC in 2018 and in 2040 for each scenario. CO_2-equivalent units (CO_2e) represent the climate impacts of well-mixed GHGs (CO_2, CH_4, and N_2O) weighted by their 100 year Global Warming Potentials. In 2018, total emissions of well-mixed GHGs from residential cooking was 1.02 Gt-CO2e. Under BAU, we project these to increase by 12%, to 1.15 Gt-CO_2e by 2040. Under the IT scenario, emissions decrease 2% relative to BAU (to 1.12 Gt-CO_2e) by 2040. More substantial reductions relative to BAU occur under the full-transition scenarios: 15%, 32%, and 26% for the FT-LPG, FT-LE, and FT-Elec scenarios, respectively.

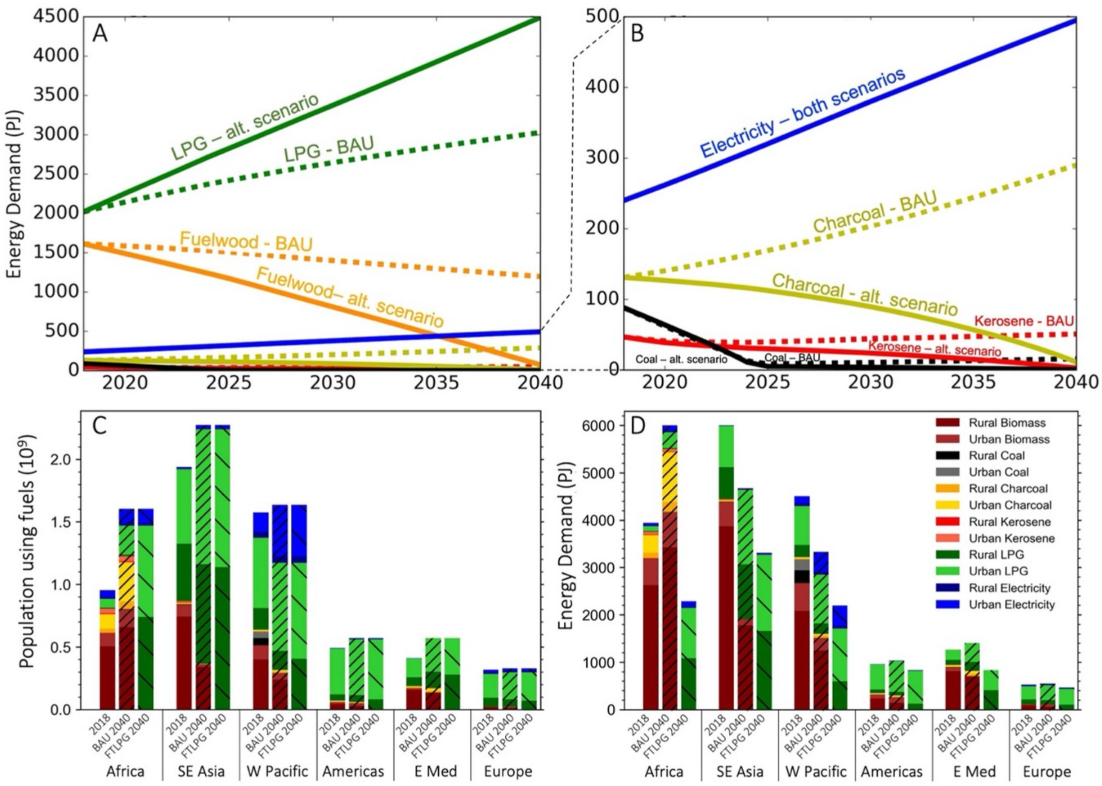

Figure 1. Energy demand in BAU (dashed) and FT-LPG (solid) scenarios (A) and the same graph zoomed in to show the less common fuels in more detail (B). The number of fuel users in 2018 and 2040 (C) and rural/urban energy demand by fuel (D) in 2018 and 2040 for all scenarios. (C) and (D) are disaggregated by WHO regions.

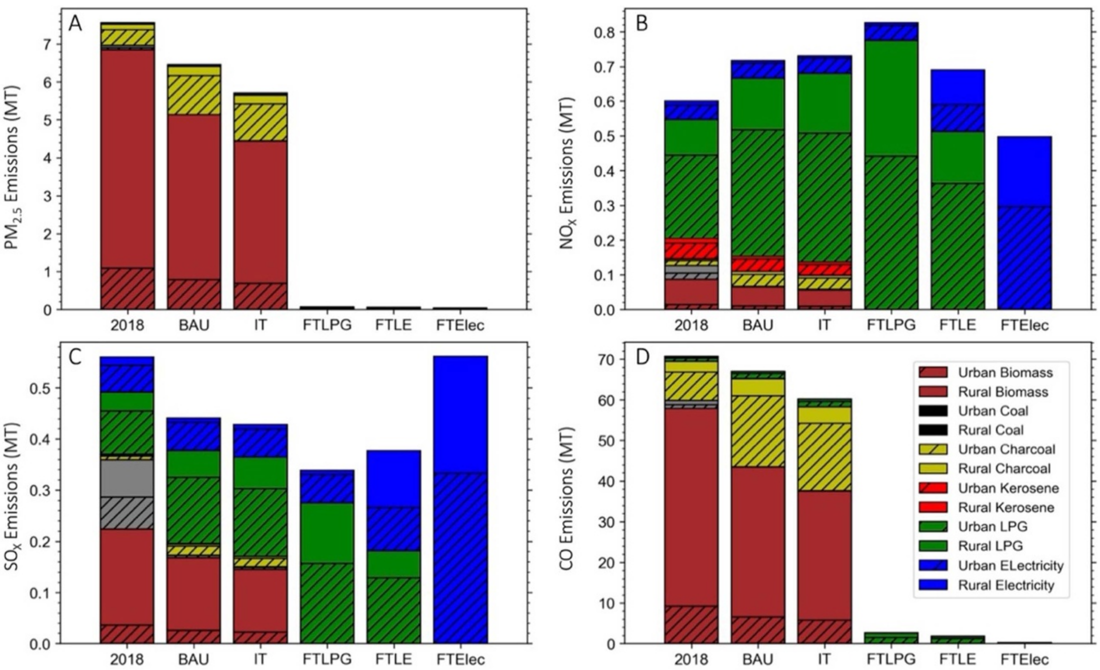

Figure 2. Fuel-specific emissions of health-damaging pollutants in 2018 and 2040 for each scenario: $PM_{2.5}$ (A), NO_x (B), SO_x (C), and CO (D).

In 2018, household cooking emitted ∼1.2 Mt of BC. Emissions decrease to 1.0 Mt by 2040 in the BAU scenario, decline by ∼12% under the IT scenario and are nearly eliminated under full transitions to LPG and/or electricity. OC and NMVOC emissions follow similar patterns (see SI section 10).

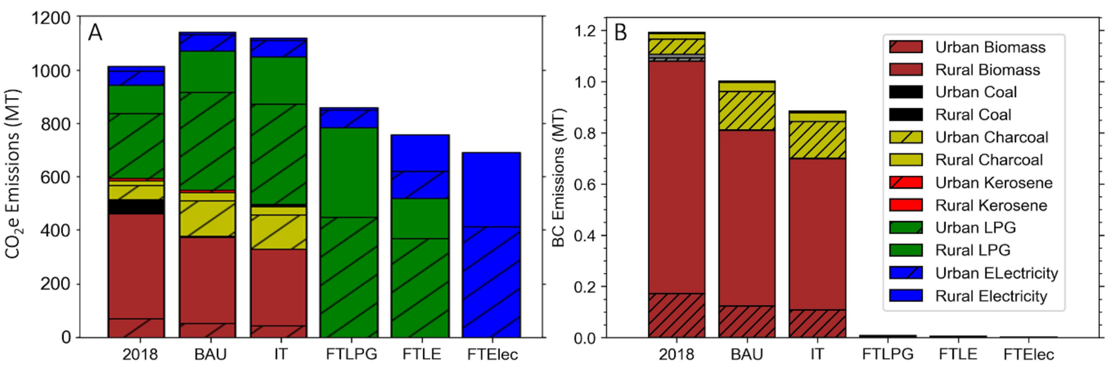

Figure 3. Fuel-specific emissions of well-mixed GHGs (A) and BC (B) in 2018 and in 2040 for all scenarios.

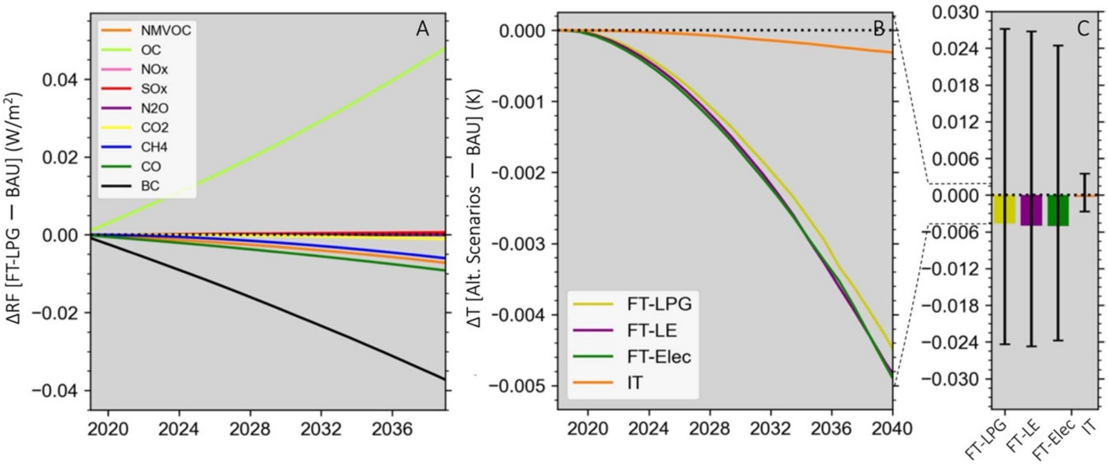

Figure 4. Pollutant-specific changes in radiative forcing between BAU and FT-LPG (A) and change in temperature between BAU and all scenarios (B), with 95% confidence intervals for temperature in 2040 shown by expanding the y-axis from B (C). Error bars show the 95% confidence intervals from runs using a 2237-member ensemble of model parameters (see methods).

3.4. Impacts on radiative forcing and temperature

Under BAU, compared to a scenario of zero emissions from cooking, household cooking emissions contribute to an increase in effective radiative forcing of roughly 39 mW m^{-2} (−97 to 42 mW m^{-2}; 95% CI) and 15 millikelvin (−41 to 26 millikelvin; 95% CI) of warming by 2040. Our alternate intervention scenarios result in both reduced forcing and lower temperature (figure 4). By 2040, median temperature is 0.3 millikelvin lower in the IT scenario and 4.7–5.1 millikelvin lower in the full transition scenarios (figure 4(A)). However, the confidence intervals for each scenario significantly overlap with zero (FT-E: −0.0238 to 0.0245, FT-LE: −0.0247 to 0.0267, FT-LPG: −0.0244 to 0.0271, IT: −0.0027 to 0.0035) so that we cannot state with certainty that the transitions would result in net cooling. Nevertheless, full transitions to LPG and/or electricity cause sustained reductions in annual emissions, resulting in median temperature pathways that will continue to diverge from BAU well into the future. Moreover, relative uncertainty in the temperature response should decrease in the future, due to the longer lifetimes of well-mixed GHGs and higher certainty associated with their effects.

Short-term climate forcing is dominated by aerosols, with reductions in OC and BC resulting in net warming and cooling, respectively (figure 5). Reductions in well-mixed climate GHGs like CO_2 have minimal impact on temperature during the timeframe of our analysis. We note that cumulative CO_2e emissions do not necessarily correspond well with their associated climate response for mixtures of long- and short-lived GHGs as in our transition scenarios [44, 45]. However, changes in CO_2e (figure 3) provide some indication of the long-term impacts of each scenario. For example, under the BAU scenario, cumulative CO_2e emissions are 24.6 Gt between 2018 and 2040. The three full transition scenarios reduce cumulative emissions of well-mixed GHGs by 2.6–3.5 Gt CO_2e over the simulation period (see SI section 11 for more detailed discussion of GHG and SLCF emissions).

SLCFs dominate the projected climate impacts and associated uncertainty through 2040. Figure 5(A) shows the net temperature change and uncertainty (shown as the 5%–95% confidence interval of an

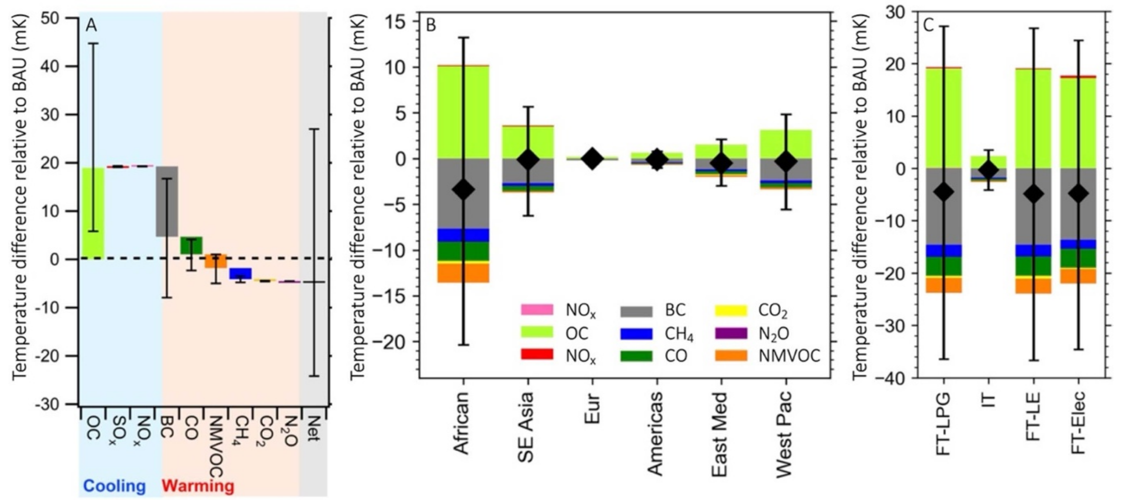

Figure 5. Pollutant-specific contributions to temperature difference between BAU and FT-LPG scenarios (A) and disaggregated by contributions from each WHO region (B). Pollution-specific temperature changes for all scenarios are shown in (C). Error bars show the 95% confidence intervals as defined in figure 4.

observationally constrained, perturbed parameter ensemble) between FT-LPG and BAU scenarios attributed to each pollutant. Figure 5(C) summarizes this for each scenario. BC and OC have the largest impacts as well as the widest confidence intervals due to uncertainties in climate response to aerosol emissions; CH_4, NMVOC, and CO also have substantial impacts, largely due to their roles in tropospheric ozone formation. The net effect could be positive or negative based on overall uncertainty; however, the median response of the ensemble for all scenarios shows that cooling due to decreases in emissions warming agents (BC, CO, CH_4, and NMVOCs) overcomes warming arising from OC reductions. Figure 5(B) shows how regional emission reductions contribute to overall temperature changes by 2040. The African region has the largest impact, driven by reductions in BC, $CH_{4,}$ NMVOC, and CO from decreased demand for fuelwood and charcoal. Under BAU, the African region has substantial increases in charcoal and fuelwood consumption (figure 1). Under the FT-LPG and other full transition scenarios, which phase out demand for charcoal and fuelwood, SLCF emissions are nearly eliminated.

Changes in $PM_{2.5}$, BC, and temperature are well-correlated because BC is a constituent of $PM_{2.5}$ and a key driver of short-term temperature change. Figure 6 shows that the modeled short-term temperature changes, though mostly driven by SLCF reductions, also scale with changes in CO_2e. These are reductions for all counties except Thailand and Myanmar (not shown). CO_2e is a more robust indicator of long-term temperature impacts. The generally linear relationship between ΔCO_2e and ΔT is moderated by several factors. For example, variation in the fNRB, a geographically-specific parameter characterizing the sustainability of woodfuel demand (see SI section 6), has a strong influence on ΔCO_2e. Further, the varying relative contributions of CH_4 and CO_2 to total CO_2e reductions (table S10) affects this relationship, as warming from CH_4 is more strongly associated with annual emission changes than warming from CO_2, which is well-understood to be a function of cumulative emissions.

4. Discussion

We have analyzed emissions and climate impacts of global transitions from BAU to clean residential cooking fuels in 77 countries. Over half of the population in our sample used either LPG (48%) or electricity (6%) as a primary cooking fuel in 2018. Our BAU scenario projects increases in the primary use of LPG (58%) and electricity (10%) by 2040, with polluting fuels decreasing in the same proportion. However, the rate of charcoal use doubles from 3% to 6% of the population, driven by expansion in Africa, where the number of people using charcoal as a primary fuel increases by nearly 220 million. Similarly, while global dependence on biomass decreases, in Africa the population using it increases by nearly 190 million.

Under BAU, overall emissions of most health-damaging pollutants decrease, though the reductions are modest. Health and environmental impacts decline by 2040, particularly in Asia, but we estimate over 700 million people across the region would still use polluting fuels. In addition, negative health and climate impacts will increase substantially in Africa as the use of polluting fuels expands. Increasing the pace of LPG/electricity cooking transitions will lead to large global benefits. However, in the absence of

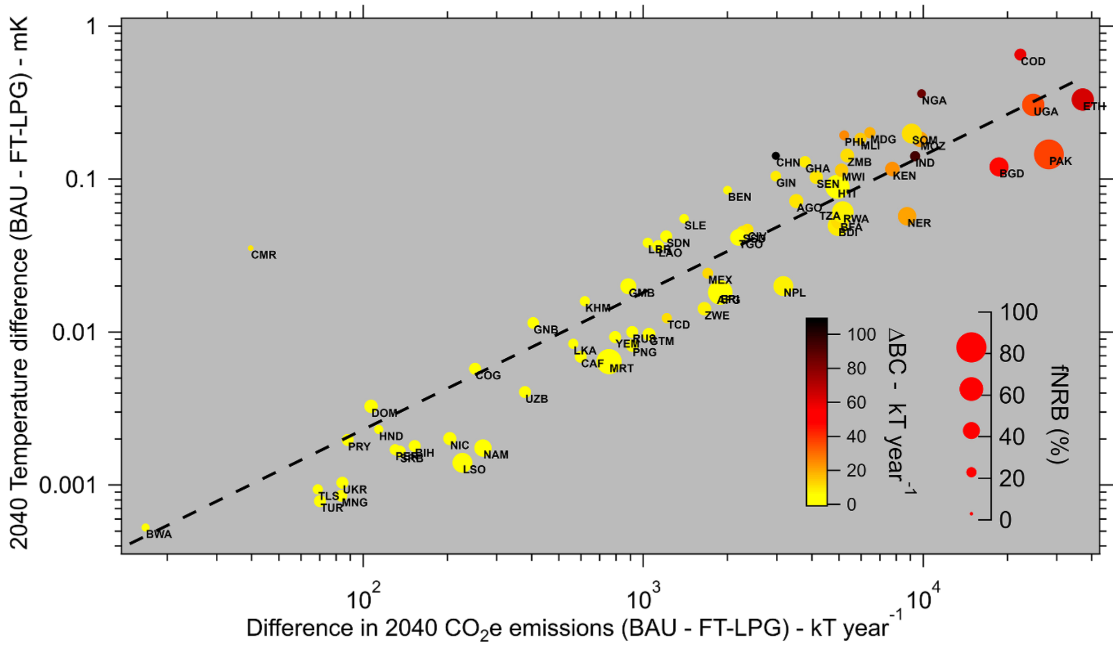

Figure 6. A scatter plot of the country-attributed differences between BAU and FT-LPG scenarios; *x*-axis indicates differences in modeled temperature in 2040, *y*-axis shows differences in CO_2e emissions in that year. The color indicates changes in BC emissions and size indicates national level fNRB. Three letter country codes are defined in table S1. The dashed black line is a log-transformed linear fit and is included to guide the eye. Note that temperature differences shown (BAU—FT-LPG) are the additive inverse of figures 4(C) and 5, to enable the use of log axes.

major investments and shifts in policy, full transitions to such clean fuels by 2040 is only likely to occur in a handful of countries included in this analysis [10]. Achieving universal adoption of LPG and/or electricity for cooking would entail meeting multiple challenges [46, 47] and require substantial investment [48]. To date, investment has been slow, in part because of donor fears that financing expanded access to fossil-derived LPG sends the 'wrong message' or will harm the climate. This analysis demonstrates that continuing along a BAU trajectory results in larger emissions of both SLCFs and well-mixed GHGs than a shift to LPG and/or grid-based (also largely fossil-derived) electricity. Moreover, despite large uncertainties in near-term temperature change (figure 5), if we extend median trends into the future, the transitions from BAU pathways to LPG (and/or electricity) will likely result in net cooling while also essentially eliminating the sector's HAP emissions and associated health risks.

Incremental changes, illustrated by our IT scenario, result in modest reductions in climate forcers and negligible short-term temperature impact relative to BAU. In contrast, full transitions to LPG and/or electricity result in near elimination of the strongest SLCFs resulting in 4.7–5.2 millikelvins near-term cooling compared to BAU as well as substantial reductions of well-mixed GHGs that would contribute to long-term cooling. The same transitions result in near elimination of $PM_{2.5}$. Under some scenarios, emissions of NO_x or SO_x increase, but the health benefits of zeroing out $PM_{2.5}$ emissions from household sources would far outweigh the impacts of additional NO_x and SO_x. This is a rare example in which a fossil fuel-based energy transition can mitigate short- and long-term climate change while bringing large co-benefits: reduced health risks, time savings, and other social benefits associated with access to clean cooking options.

As with any complex modeling effort, our study has several limitations. Upstream emissions for most fuel pathways were taken from GREET, which is a life cycle model parameterized for fuels used in the US [26]. We made changes to reflect global conditions (SI section 5), but the resulting emission factors may be inaccurate. The same applies to end-use emissions. In addition, we use total life cycle emissions as a proxy for health risk, but this does not consider that upstream emissions result in different exposures than end use emissions.

The fNRB data used in this analysis is the only available global estimate of woody biomass renewability. There are numerous sources of uncertainty in the models used to derive fNRB, which may over- or underestimate net CO_2 emissions from woodfuels [7]. In addition, fNRB is held constant in these scenarios; however, it is a function of woodfuel demand among other factors. In the full transition scenarios, as woodfuel demand decreases, fNRB should also decrease, leading to higher rates of regeneration and larger climate benefits from those transitions.

The FaIR model is a reduced-complexity climate model calibrated to an ensemble of observationally-constrained climate model simulations to estimate the range of plausible climate response [34]. However, impacts of SLCFs vary depending on source location [21] and the radiative forcing response to emissions of aerosol species is highly uncertain.

There is increasing interest in cooking with electricity from decentralized sources [49], which was not explored in this analysis. Off-grid options have become more feasible as the costs of renewable energy generation and storage have decreased and more efficient and inexpensive appliances like induction stoves and electric pressure cookers have become accessible [50].

5. Conclusion

To our knowledge, this is the first study to examine emissions reductions and climate impacts of global clean cooking transitions in LMICs from polluting fuels to LPG and electricity. Under BAU conditions, HAP emissions decline modestly between 2018 and 2040, driven by a transition already underway in parts of Asia. However, in Africa, the population relying on polluting fuels will grow in the absence of substantial interventions. A full transition to LPG will lead to drastic reductions in emissions of nearly all climate-forcing and health-damaging pollutants, and possibly contribute to a small reduction in global temperature relative to the BAU scenario. A transition to grid electricity would require larger investment but have a similar result. Thus, a rapid transition to LPG and/or electricity will reduce health risks for over 2 billion people, by reducing household exposures and addressing a major contributor to ambient air pollution. Transitions are also likely to result in both near- and long-term cooling. Larger climate benefits would result from transitioning to clean fuels with lower life-cycle carbon emissions than conventional LPG and grid-based electricity such as bio-LPG, bioethanol, or 100% renewable electricity. However, it is unclear if these options can be scaled-up at the same rate as fossil-based LPG or grid expansion.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.5061/dryad.jq2bvq8d9.

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Author contributions

AG and RB developed the concept, designed the research, and secured funding. EP and DP advised on research design. NL and CJS developed the FaIR model and heavily supported its use in this application. E F, A G, and R B developed BAU and alternate scenarios with input from EP, DP. EF and KL developed tools to manage and analyze scenario data. RB, EF, and AG compiled life-cycle emissions data for each cooking option. EF developed code to integrate emission factors and transition scenarios into FaIR with support from KL, EF, AG, EP, DP, RB, AGW and KL coauthored an internal report that forms the basis for this manuscript. EF, AG, RB, EP, DP, and AGW wrote the manuscript. NL and CJS provided additional text about FaIR output and related discussions.

Ethical compliance

This study involved no human subjects.

Conflict of interest

The authors declare no conflicts of interest.

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