

Towards Sustainable Development Goal 7 “Universal Access to Clean Modern Energy”: National Strategy in Rwanda to scale clean cooking with bottled gas

SUPPLEMENTARY MATERIALS

1. Methodology for modeling LPG adoption projections

1.1. Modelling assumptions based on Cooking Fuel Energy and Technologies in Households, Commercial and Public Institutions in Rwanda (CEFT) 2020 survey data

The *Cooking Fuel Energy and Technologies in Households, Commercial and Public Institutions in Rwanda* (CFET) dataset provides details on household fuel use and fuel accessibility in Rwanda in 2020 [1] and was used as a baseline for the household demand analysis and projections of future LPG use. Included in the models were the following questions:

- **Fuel use to identify mixed and exclusive use of LPG:** Respondents were asked to identify which fuel types they had used for cooking in the past month among firewood, charcoal, pellets, briquettes, biogas, kerosene, LPG, electricity, cow dried dung, crop residue, papyrus and sawdust. Exclusive use of LPG was designated as only using LPG in the past month. Mixed use of LPG was designated as a combination of LPG with one or more other fuels.
- **Quantity and price of fuel:** Respondents were asked to report how much of each fuel their household had used in the past month (in Kg), and how much they had spent on purchasing the fuel in the same time period. Note that for LPG there were not specific questions on cylinder size or cost of refills, leading to likely recollection bias and uncertainties in the respondents’ answers about amount spent for fuel use.
- **Accessibility of fuel:** Respondents were asked to report the distance to the place their household purchases the consumed fuel in one of the five categories (<500m; <500m-1km; 1km-2km; 2km-4km; 4km+). Means of accessing each fuel were not included, but a question asked “who is in charge of obtaining fuel”, with one of the answers being “they bring it to us”, which was coded as home delivery (distance of 0m).

1.2 LPG adoption model

Full output of the prediction model for LPG adoption annually from 2020 to 2030 for each combination of predictor variables is presented in Table S1.

Table S1. Outcomes of the LPG adoption model under different combinations of predictor levels

Predictors					Outcome		
Year	Regional Context	Ubudehe	Price	Distance	No LPG	Mixed LPG	Exclusive LPG
2020	Urban (not Kigali)	First	1000	1000	99.59%	0.40%	0.01%
2020	Urban (not Kigali)	First	1000	2000	99.65%	0.30%	0.05%
2020	Urban (not Kigali)	First	2000	1000	99.67%	0.32%	0.01%
2020	Urban (not Kigali)	First	2000	2000	99.76%	0.22%	0.03%
2020	Urban (not Kigali)	Second	1000	1000	97.54%	2.33%	0.12%
2020	Urban (not Kigali)	Second	1000	2000	98.99%	0.83%	0.18%
2020	Urban (not Kigali)	Second	2000	1000	97.72%	2.20%	0.09%
2020	Urban (not Kigali)	Second	2000	2000	99.22%	0.66%	0.12%
2020	Urban (not Kigali)	Third	1000	1000	91.46%	7.79%	0.75%
2020	Urban (not Kigali)	Third	1000	2000	97.69%	1.81%	0.50%
2020	Urban (not Kigali)	Third	2000	1000	91.36%	8.00%	0.64%
2020	Urban (not Kigali)	Third	2000	2000	98.07%	1.57%	0.36%
2020	Urban (not Kigali)	Fourth	1000	1000	77.97%	18.68%	3.34%
2020	Urban (not Kigali)	Fourth	1000	2000	95.20%	3.57%	1.23%
2020	Urban (not Kigali)	Fourth	2000	1000	76.66%	20.16%	3.18%
2020	Urban (not Kigali)	Fourth	2000	2000	95.71%	3.32%	0.97%
2020	Rural	First	1000	1000	100.00%	0.00%	0.00%
2020	Rural	First	1000	2000	100.00%	0.00%	0.00%
2020	Rural	First	2000	1000	100.00%	0.00%	0.00%
2020	Rural	First	2000	2000	100.00%	0.00%	0.00%
2020	Rural	Second	1000	1000	99.69%	0.31%	0.00%
2020	Rural	Second	1000	2000	100.00%	0.00%	0.00%
2020	Rural	Second	2000	1000	99.67%	0.33%	0.00%
2020	Rural	Second	2000	2000	100.00%	0.00%	0.00%
2020	Rural	Third	1000	1000	93.35%	6.64%	0.01%
2020	Rural	Third	1000	2000	99.97%	0.03%	0.00%
2020	Rural	Third	2000	1000	92.02%	7.97%	0.01%
2020	Rural	Third	2000	2000	99.98%	0.02%	0.00%
2020	Rural	Fourth	1000	1000	60.44%	38.87%	0.69%
2020	Rural	Fourth	1000	2000	99.67%	0.33%	0.00%
2020	Rural	Fourth	2000	1000	53.65%	45.58%	0.77%
2020	Rural	Fourth	2000	2000	99.73%	0.27%	0.00%
2020	Kigali (urban)	First	1000	1000	95.35%	3.91%	0.75%
2020	Kigali (urban)	First	1000	2000	96.46%	2.23%	1.32%
2020	Kigali (urban)	First	2000	1000	95.72%	3.70%	0.58%
2020	Kigali (urban)	First	2000	2000	97.01%	1.98%	1.01%
2020	Kigali (urban)	Second	1000	1000	88.41%	9.03%	2.55%
2020	Kigali (urban)	Second	1000	2000	93.83%	3.65%	2.53%
2020	Kigali (urban)	Second	2000	1000	88.60%	9.17%	2.23%
2020	Kigali (urban)	Second	2000	2000	94.53%	3.41%	2.06%
2020	Kigali (urban)	Third	1000	1000	77.95%	15.69%	6.35%

2020	Kigali (urban)	Third	1000	2000	90.43%	5.31%	4.26%
2020	Kigali (urban)	Third	2000	1000	77.44%	16.57%	5.99%
2020	Kigali (urban)	Third	2000	2000	91.18%	5.17%	3.65%
2020	Kigali (urban)	Fourth	1000	1000	63.49%	22.94%	13.57%
2020	Kigali (urban)	Fourth	1000	2000	85.82%	7.33%	6.84%
2020	Kigali (urban)	Fourth	2000	1000	61.84%	24.67%	13.49%
2020	Kigali (urban)	Fourth	2000	2000	86.51%	7.37%	6.12%

2. Methodology for environmental and health impacts estimations

2.1. Averted deforestation

Averted deforestation was calculated as the difference between the number of trees used per year before and after households begin using LPG as their primary or secondary fuel (i.e. the difference between the baseline and the Intervention/ NST-1 scenarios). This was calculated as the sum of the number of trees necessary for firewood use and the number of trees necessary for charcoal use.

The equivalent number of trees for firewood use and charcoal use was calculated using the equations below where the fNRB is the fraction of Non-Renewable Biomass. The fNRB indicates what proportion of wood for fuel was unsustainably harvested and was estimated to be 59% (52%-66%) based on Bailis et al. [2] - for charcoal, the conversion to equivalent wood consumption was estimated using a ratio of 7 based on data from Tanzania [3].

$$\begin{aligned}
 \text{Trees(Firewood)} &= (fNRB) \left(\frac{\text{Firewood consumption}}{\text{Mass per tree}} \right) & (1) \\
 &= (59\%) \left(\frac{\text{Firewood consumption}}{100 \text{ kg/tree}} \right)
 \end{aligned}$$

$$\begin{aligned}
 \text{Trees(Charcoal)} & & (2) \\
 &= (fNRB)(\text{Ratio charcoal: wood}) \left(\frac{\text{Charcoal consumption}}{\text{Mass per tree}} \right) \\
 &= (59\%)(7) \left(\frac{\text{Charcoal consumption}}{100 \text{ kg/tree}} \right)
 \end{aligned}$$

2.2 Carbon emissions

The following equation was used to calculate the metric tons of carbon emissions per household.

$$\begin{aligned}
 CO_2(eq) &= 10^{-6} \left[\frac{\text{Fuel consumption}}{\text{Number of households}} \right] [(\text{CO}_2 \text{ emissions factor})(fNRB) & (3) \\
 &+ (\text{N}_2\text{O emissions factor})(GWP_{\text{N}_2\text{O}}) \\
 &+ (\text{CH}_4 \text{ emissions factor})(GWP_{\text{CH}_4})]
 \end{aligned}$$

The emissions factors used vary depending on both fuel and stove, and the fNRB was dependent on the fuel used.

The energy method considers the emissions rate of particles as grams per mega-Joule (MJ). In this method, the following equation was used to calculate the metric tons of carbon emissions per household.

The Global Warming Potential (100 year horizon) (GWP₁₀₀) values for the included gases and particles are summarized in Table S2.

Table S2. Global Warming Potential (GWP) values used for modelling

Pollutant	GWP ₁₀₀	Source
BC	660	IPCC 2014 (Myhre et al. [4], based on Bond et al. [5])
CO ₂	1	IPCC 2013 [4]
CH ₄	32	IPCC 2013 (Myhre et al. [4], but increased by 14% based on Etminan et al.[6])
N ₂ O	298	IPCC 2013 [4]

The net calorific value of the fuel (NCV) and thermal efficiency of the stove used in the impact calculations are summarized in Table S3.

Table S3. Fuel calorific values and average stove thermal efficiencies

Fuel/stove combination	Net fuel calorific value (MJ/kg)	Average stove thermal efficiency used and efficiency range*
Average value used for LPG	46.1	51% (46%; 57%) [7]
Average value used for charcoal	29.5	20% (17.5%; 30%)[8, 9]
Average value used for firewood	15.6	15% (9-18% for traditional stoves; 20-29% for improved)[8, 9]

*For charcoal and firewood, this is an average between traditional stoves and improved stoves efficiencies based on the literature and type of stoves commonly available in the local Rwandan market (ISO Tiers 1-2).

The emissions factors for CO₂, CO, CH₄, BC and total non-methane organic carbon (TNMOC) are based on Water Boiling Tests results compiled in Edwards et al. (2014) [10]. The N₂O emissions rates were set as in previous similar modeling [11, 12].

Similarly to the CO₂eq calculations, the tonnage differential of black carbon (BC) emissions is calculated as the difference between the CO₂ equivalent tonnage emitted in the baseline analysis and both the interventional and policy target scenarios.

$$\begin{aligned} \text{Black carbon} = & (\text{Fuel consumption})[\text{BC emissions factor} \\ & - (\text{OC emissions factor}) + (\text{CO emissions factor}) \\ & + (\text{TNMOC emissions factor})] \end{aligned} \quad (4)$$

2.3. Health impacts data

To estimate the health impacts of transitioning from charcoal and firewood to LPG using the HAPIT III tool (<https://www.cleancookingalliance.org/resources/450.html>), we used the following set of assumptions for data on personal exposure to fine particulate matter (PM_{2.5}):

2.3.1 Firewood and charcoal PM_{2.5} personal exposure data

The data for personal exposure in homes using firewood in traditional or improved stoves for our model was based on Rwanda data collected in the study by Kirby et al. 2019 [13] that recorded PM_{2.5} personal exposure before and after an improved stove intervention (Table S4). The study included 231 primary cooks and 159 children providing valid measures of exposure across the various follow up phases - a large sample size for this type of impact assessment. The study was conducted in the Western Province of Rwanda between 2014 and 2016.

Data on personal exposure to PM_{2.5} from charcoal use in traditional and improved charcoal stoves were conservatively estimated as one third of the personal exposure to PM_{2.5} from firewood from the same Rwandan study due to the lack of objective exposure data on charcoal derived PM_{2.5} in the literature. This correction factor is made given combustion of charcoal generally emits low emissions of PM_{2.5}, although higher carbon monoxide (CO) levels (CO is not currently included in projections of health estimated by the HAPIT tool).

The following assumptions were held constant at baseline and in 2030 for each scenario, using typical fuel/stoves combinations for Rwanda:

Table S4: Personal exposure values for woodfuels using households

FIREWOOD	TRADITIONAL STOVE mean (SD), µg/m ³	IMPROVED STOVE mean (SD), µg/m ³
48-hour mean personal exposure to PM _{2.5} – ADULTS (Cooks)	218 (204)	223 (200)
48-hour mean personal exposure to PM _{2.5} – CHILDREN	224 (198)	231 (238)

CHARCOAL	TRADITIONAL STOVE mean (SD), $\mu\text{g}/\text{m}^3$	IMPROVED STOVE mean (SD), $\mu\text{g}/\text{m}^3$
48-hour mean personal exposure to $\text{PM}_{2.5}$ – ADULTS (Cooks)	72.7 (204)	74.3 (200)
48-hour mean personal exposure to $\text{PM}_{2.5}$ – CHILDREN	74.7 (198)	77.0 (238)

2.3.2 Personal exposure to $\text{PM}_{2.5}$ from LPG

Whilst there is a paucity of data on personal exposure to $\text{PM}_{2.5}$ for homes using LPG fuel in Sub-Saharan Africa, data indicates that it is possible to achieve the WHO Interim Target 1 level for health ($35 \mu\text{g}/\text{m}^3$) when using the fuel in homes [14]. We used personal exposure data from the HAPIN trial in Rwanda through personal communication (baseline assessment of personal exposure was found to be $45 (\mu\text{g}/\text{m}^3) \pm 35 \mu\text{g}/\text{m}^3$ and a publication on this analysis is currently under review (HAPIN/Berkeley Air Monitoring Group, 2021).

Table S5. Personal exposure values for LPG using households

LPG	WHO ITT-1 mean (SD), $\mu\text{g}/\text{m}^3$	FIELD-BASED (double burner stove) mean (SD), $\mu\text{g}/\text{m}^3$
48-hour mean personal exposure to $\text{PM}_{2.5}$ – ADULTS (Cooks)	35 (10)	45 (35)

2.3.3 Scenarios assumptions

According to the CEFT survey data, 30% of biomass using households in Rwanda used improved cookstoves (ICS), with about a third using an improved charcoal stove [1]. The following assumptions were used with respect to growth of improved access and adoption of improved firewood and charcoal stoves up to 2030 (with linear growth):

- Firewood
 - 2020 – 20% of households using improved stoves
 - 2030 – 80% of households using improved stoves (of the projected % of households under each scenario)

- Charcoal
 - 2020 – 10% of households using improved stoves (of the projected % of households under each scenario)
 - 2030 – 100% of households use improved stoves (of the projected % of households under each scenario)

In addition, as it was not possible to accurately predict how many biomass users will switch to LPG from traditional or improved firewood/charcoal stoves, an equal split was assumed:

- Firewood
 - 2020 – 50% of households that switch to LPG use improved stoves (of the projected % of households under each scenario)
- Charcoal
 - 2020 – 50% of households that switch to LPG use improved stoves (of the projected % of households under each scenario)

The ICS penetration rate did not emerge from the modelling as a major contributor to impacts. If starting at 50% (as shown above), and the penetration is either cut in half (to 25%), or increased by half (to 75%), the change in deaths averted and DALYs saved changes by only about 0.2% in either direction.

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