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Towards Sustainable Development Goal 7 "Universal Access to Clean Modern Energy": National Strategy in Rwanda to Scale Clean Cooking with Bottled Gas

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Abstract: More than 90% of Rwandans rely on polluting solid fuels to meet their cooking needs. The negative impacts on health, climate, and the environment have led the Rwandan government to set a target of halving that number to 42% by 2024. A National Master Plan to promote scale up of liquefied petroleum gas (LPG) has been developed to define (i) the necessary market conditions, (ii) public and private sector interventions, and (iii) the expected societal impacts. Findings are reported from modelling scenarios of scaling LPG use towards the 2024 policy target and the 2030 target for "universal access to clean modern energy" (SDG7). Household LPG use is projected to increase from 5.6% in 2020 to 13.2% by 2024 and 38.5% by 2030. This level of adoption could result in a reduction of 7656 premature deaths and 403,664 disability-adjusted-life-years (DALYs), as well as 243 million trees saved. Reductions in carbon dioxide and black carbon emissions equivalents (CO_2e and BCe, respectively) are estimated to reach 25.6 million MT and 14.9 MT, respectively, by 2030. While aggressive policy intervention is required, the health, environmental, and developmental benefits are clear. Implementation of the Rwanda National LPG Master Plan will provide a model for other sub-Saharan African countries to address the priorities for cessation of reliance on solid fuels as an energy source.

Keywords: modern cooking; LPG; Rwanda; master plan; adoption; SDG7

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1. Introduction

Rwanda, a small landlocked country situated in East Africa, is the most densely populated country in sub-Saharan Africa with a population density of 1 per 525 square meters and a total population of 12.952 million (2020) [1]. In 2019, almost one-fifth (17%) of the population lived in cities and urban environments [2], projected to increase to one-third (35%) by 2024 [3]. Rwanda's gross domestic product (GDP) per capita was US$ 801.7 in 2019 [2], representing an overall growth of 9.4% annual change [4], aligned with the government's intention to transform Rwanda's current agricultural-based economy to one that is industry- and service-based.

Similar to most countries in sub-Saharan Africa (SSA), the household energy market in Rwanda is dominated by cooking energy, and cooking energy is dominated by reliance on solid fuels. The primary fuels used for cooking are firewood (used by as many as 83% of rural households of whom more than a quarter can gather firewood for free) and charcoal (which is the most common fuel in urban settings, with more than 40% of urban households relying on it) [5]. While use of liquefied petroleum gas (LPG) or bottled gas for cooking has doubled in Rwanda since 2016 [6], still only 5.6% of households report using it as a primary cooking fuel in 2020 [5]. Other clean fuels are even less prevalent in household cooking, with 0.23% of households reporting using biogas and 0.19% using electricity for cooking [5].

Burning solid fuels and/or kerosene results in high levels of household air pollution (HAP), including production of respirable particulate matter with a diameter of 2.5 micrometers or less ($PM_{2.5}$), which is known to be causally related with a number of respiratory; cardiovascular; and other diseases including ischemic heart disease, stroke, chronic obstructive pulmonary disease (COPD), lung cancer and diabetes in adults, acute lower respiratory infection (ALRI) in children, and adverse pregnancy outcomes (e.g., low birth weight) [7–10]. Based on global burden of disease calculations for these health outcomes, in 2020, a total of 3255 deaths and 172,643 DALYs were estimated to result from $PM_{2.5}$ related to use of polluting fuels in Rwanda [11].

Population transition from these polluting fuels, often burned in inefficient poor quality stoves, to clean, modern LPG can have significant public health, environmental, and gender benefits owing to reduced personal exposure to HAP, preservation of forests, and time savings for women and girls who typically are responsible for the gathering of fuels and for cooking [12,13]. These benefits are achieved through LPG having very high combustion efficiency and, consequently, having low emissions of products of incomplete combustion (detrimental to health and climate) [14,15]. This efficiency is independent of the operation, age, or condition of the stove used [16,17].

Comparatively, combustion of wood for cooking is very inefficient, resulting in high levels of HAP including $PM_{2.5}$ and black carbon (BC) [18]. BC is particularly relevant in relation to its impact on the climate given its short-term climate forcing properties (second in importance in terms of global warming potential (GWP) to carbon dioxide (CO_2)) [19]. More than a quarter of global emissions of BC are estimated to originate from combustion of solid fuels for cooking and, in Africa and Asia, where reliance on solid fuels is highly prevalent, such use has been estimated to contribute 60–80% of total BC emissions [20]. Using electricity and gas (including LPG) for cooking is thus recommended by the Intergovernmental Panel on Climate Change (IPCC) as a preventive measure to reduce BC emissions from cooking [21].

Between 2001 and 2019, Rwanda lost 34.5 kilohectares (kha) of forest cover through unsustainable harvesting of wood for domestic energy, representing 6.9% of Rwanda's total tree coverage. Combustion of wood for energy was estimated to generate 8.89 MT of total CO_2 emissions, including domestic and agricultural use [22].

To address the detrimental effects of reliance on solid fuels for energy on public health, the environment, and the climate, the government of Rwanda (GoR) set as a national priority to transition a significant proportion of the country to clean modern energy within a very aggressive timeframe. Rwanda's National Strategy for Transformation (NST-1) 2017–2024 set a target of halving reliance on biomass fuels for cooking from 82% in 2017 to 42% by 2024, with an associated aspiration of achieving a sustainable balance between supply and demand for wood by 2030 [23].

As part of the strategy to achieve this target, the government identified LPG as the most rapidly scalable solution to clean cooking in the country and selected urban conurbations (Kigali and six secondary cities), and public institutions (e.g., schools, prisons) as priority targets for accelerated rollout of LPG for clean cooking. The policy target for LPG adoption was set at 40% of the population (across residential, institutional, and industrial sectors) by 2024. In addition to LPG, other promoted alternatives to meet the overall 42% biomass fuel target included biogas, electricity, and improved high-efficiency biomass cookstoves (including pellet- and briquette-burning stoves).

The prioritization of LPG over alternatives was motivated by its proven status as a technology that is a clean energy at point of use and for which the infrastructure can rapidly be scaled up [24,25]. LPG is highly portable and is stored, transported, and used in small cylinders—convenient for domestic use. LPG safety and regulatory best practices, market and financing models have been successfully and extensively implemented across dozens of countries globally [25–29]. In addition, households see LPG as an aspirational fuel, given its cleanliness, the ability to control the flame precisely, and faster cooking times [24,30,31]. As a critical step to achieve its policy goal of scaling up LPG for clean cooking, the government (under the coordination of the Ministry of Infrastructure (MININFRA)) undertook to create a national LPG Master Plan (Master Plan) to set the policies and actions required for all relevant stakeholders (public and private sector) to achieve the national LPG use target. The Master Plan development was carried out by The Global LPG Partnership (GLPGP) and representatives of the government, with funding from the European Union's Infrastructure Trust Fund through its Clean Cooking for Africa Programme (CCAP), administered by the German Development Bank KfW. The scope of the Master Plan was similar to previous work undertaken by the GLPGP under the CCAP in other sub-Saharan African countries [32–34].

The Master Plan process was informed by an intensive multi-stakeholder consultation with all relevant local Rwandan stakeholders (including government agencies, private sector players, and financing and investing institutions). Among the public sector stakeholders, a key role was played by the Rwandan Regulatory Agency (RURA), Rwanda Standards Board (RBS), and Rwanda Energy Group (REG), among others.

The Master Plan covered holistically and comprehensively all aspects of how and how much the LPG demand and supply chains need to be expanded, optimized, and made adequately robust to achieve the national target for displacement of biomass fuel. It carefully reviewed and offered recommendations on essential enhancements to the national enabling environment of policies and regulations needed to foster sustained private sector-led investment in expanding LPG infrastructure (e.g., cylinder inventory, filling and storage facilities, cylinder distribution, and retailing operations) in order to serve new portions of the population with LPG. It also identified the specific and coordinated investments and interventions necessary to unlock and expand LPG demand, and to ensure the corresponding optimal supply, storage, and distribution infrastructure, systems, and network to serve the market on an economically sustainable basis. Finally, it included an implementation roadmap for both the near term (2024) and longer term (SDG7 time horizon of 2030).

This paper reports findings from demand and impact modelling commissioned by GoR/MININFRA and undertaken by the University of Liverpool to address two main aims: (i) to understand the market conditions needed to scale transition to clean cooking with LPG to the government target by 2024 and SDG 7 target by 2030, and (ii) to estimate the associated societal impacts (environment, climate, and health) from achieving these target levels of LPG adoption by 2024 and 2030.

2. Materials and Methods

In line with the main study aims, there were two main foci to the analyses: firstly, to model the potential proportion of the population using LPG under varying conditions affecting market growth. This included (i) a scenario of no policy or market intervention with current demographic, market and LPG industry trends projected into the future and (ii) a scenario with implementation of specific policies and interventions, in addition to increased private sector investment supportive of LPG market expansion. Secondly, it included an analysis of the potential impacts of increasing LPG adoption to policy target levels (by 2024 and 2030) on (i) the environment (reduced deforestation and emissions detrimental to climate) and (ii) health (averted premature mortality and morbidity (DALYs) from reductions in exposure to household air pollution ($PM_{2.5}$)).

2.1. *Enhancing Adoption of LPG through Market Enhancement: Modelling Impacts towards Government Adoption Targets*

Rwanda has seen a small, but significant increase in adoption of LPG over the last 5 years owing to increased availability of and accessibility to LPG, specifically in urban environments. The aim of the National LPG Master Plan was to consider how to significantly build on this growth through the setting of conditions that positively affect and stimulate further LPG adoption and corresponding availability and accessibility, above current growth trends.

Specific consideration was given to the potential effects of policies and interventional measures that (i) improve access to LPG (with an emphasis on home delivery), (ii) implement and fully enforce the branded cylinder recirculation model (BCRM) of LPG distribution in accordance with world standards and international best practices [35], (iii) mandate public institutions to transition to clean cooking/LPG use from traditional use of wood fuel, and (iv) promote LPG transition (especially among urban and middle-income households) through consumer campaigns. Alongside these market enhancements and increased supply, it is anticipated that LPG adoption would also increase with the population size and rate of urbanisation over time.

To model the potential of stimulated LPG adoption to achieve target levels by 2024 and 2030, analyses contrasted three scenarios including (i) a baseline (***business-as-usual scenario***) where no intervention is employed; (ii) an ***interventional scenario*** where market enhancements (informed by the Master Plan) in the form of increased retail density, home delivery, and institutional LPG use are promoted; and (iii) a ***policy target scenario*** incorporating the interventional scenario enhancements with additional regulatory/legislative measures governing fuel use. The three scenarios are described below:

- ***Business-as-usual (BAU) scenario***. In this scenario, existing demographic, market, and LPG industry trends were projected to continue according to current trends to 2024 and to 2030, assuming no additional government/private sector-led intervention. Under this scenario, the majority of the LPG adoption growth relates to external factors such as increased population size and rate of urbanisation with an assumption that the private sector will continue to invest and expand LPG availability (in bulk and through additional cylinders) according to business as usual.
- ***Interventional scenario***. This scenario models a combination of interventions and market measures designed to simulate population adoption of LPG and to build consumption of LPG in the country. The modelled market developments include increased consumer access to LPG primarily by enhancing retail point density (including home delivery), implementing best practices in LPG distribution (fully enforcing the BCRM), and mandating LPG use in public institutions that currently rely on polluting fuels.
- ***Policy target scenario (NST-1).*** This scenario represents the government's aspirational target of 40% of the population, including public institutions, adopting LPG for cooking by 2024. In addition to conditions set out under the interventional scenario, pro-LPG mandates are added that create significant additional urban and institutional LPG demand and anti-biomass fuel mandates (e.g., a charcoal ban) that make competing biomass fuels less available or unavailable, wherever practical.

2.1.1. Data Sources for LPG Adoption Projections in the Residential Sector

The LPG adoption modelling scenarios were informed by nationally representative data sources used to project trends of population uptake of LPG into the future. These included the latest available nationally representative population-based surveys with information on self-reported use of household fuels, including (i) the 2016 World Bank's multi-tier framework (MTF) survey on household access to electricity and cooking practices (sample n = 3300 households) [6] and (ii) the National Survey on Cooking Fuel Energy and Technologies in Households, Commercial, and Public Institutions in Rwanda (CFET) [5], commissioned by MININFRA (sample of n = 5020 households and 469 institutions). Fuel and population data of public institutions were obtained through direct correspondence with the relevant authorities in the country, desk review, and information contained in the CEFT dataset [5]. Population data for the modelling were based on the Rwandan National Institute of Statistics (NISR)'s official projections for population size and urbanization rates [36]. LPG fuel price data over time were modelled using RURA published data [37]. To set the modelling scenarios for LPG adoption, a number of informed assumptions were made based on available data, and are summarised in Table 1.

Table 1. Data informed assumptions and assumed interventions used to model the three liquefied petroleum gas (LPG) adoption scenarios in the residential sector based on available routine data.

Characteristic	**Business-as-Usual (BAU) Scenario**
Urbanisation	25% in 2024, 35% in 2030
Population	15.7 million in 2030
Household size	3.2 people/HH in 2030
Socio-economic status	Follows a linear trend in logit scale projected from 2016 and 2020 survey data
Household average LPG consumption	28.8 kg/capita per year
LPG consumer price	**Kigali City:** 1060 RwF/Kg in 2020; 1834 RwF/Kg in 2030 **Other urban areas:** 1166 RWF/Kg in 2020; 2017 RwF/Kg in 2030 **Rural areas:** 1484 RwF/Kg in 2020, 2567 RwF/Kg in 2030
Distance from LPG sale point	**Kigali:** 632 m in 2020, 569 m in 2030 **Other urban areas:** 940 m in 2020, 846 m in 2030 **Rural areas:** Remain the same in 2030 as in 2020 (3.1 km)
	Interventional scenario (same as BAU scenario except):
Distance from LPG sale point	**Kigali:** 632 m in 2020, 163 m in 2030 **Other urban areas:** 940 m in 2020, 221 m in 2030 **Rural areas:** 3.1 km in 2020, 988 m in 2030
Market enhancement (home delivery using bikes, motorbikes, and other means)	**Kigali:** 27% in 2020 up to 75% in 2030 **Other urban areas:** 20% in 2020 up to 75% in 2030 **Rural areas:** 50% in 2030
Awareness raising and regulatory conditions	The modelled market enhancements underpin consumer-education campaigns and full enforcement of the best practice LPG distribution model (i.e., the branded cylinder recirculation model).
	NST-1 policy scenario (same as Interventional scenario except):
Policy intervention	This model assumed that the policy target level of 40% LPG adoption by 2024 is achieved through (i) accelerated investment by the private sector and GoR to ramp up LPG supply and access even faster than the interventional case and (ii) anti-biomass fuel mandates (e.g., charcoal ban enforced in Kigali and other main cities) and pro-LPG fuel mandates/regulation.

Note. Urbanisation, population, and average household size estimates are taken from the Rwandan National Institute of Statistics (NISR) projections [36]. LPG use per capita is a median value for mixed users from the CFET, 2020 survey [5]. Consumer price is based on RURA 2019 LPG price data [37] and IMF-based projections of future RWF–USD exchange rates [4].

In addition, for all scenarios, a sub-analysis of LPG household uptake by socio-economic status (SES) was performed to consider differential trends in adoption patterns over time by SES according to the official Rwanda *Ubudehe* categorisation, which, as of 2020, classified Rwandan households according to four categories [38,39] (reorganised under five categories since February 2021). It is worth noting that *Ubudehe* categories are not based on income ranges alone, but include a combination of income, assets, education, and household expenditure, formed by the government to inform social welfare programs [38,39].

2.1.2. Statistical Analysis

To project the increased proportion of LPG adoption according to the different modelling scenarios, a probit cumulative link model with scale effects and flexible thresholds was fitted to the MTF [6] and CFET datasets [5]. The dependent variable (LPG adoption) was a three-level categorical variable based on self-reported cooking fuel in the last month (prior to completion of the household survey) and was coded as 'no LPG', 'LPG + other fuels' (mixed use), and 'LPG exclusive use'. The choice of independent variable was theory-driven and pragmatic from the limited set of common variables between the two datasets. We used (i) survey year, (ii) socioeconomic status of the household (*Ubudehe*), (iii) geographical context (Kigali urban city, other urban areas, or rural), (iv) distance from LPG source/retail point, and (v) LPG price per Kg as independent variables. The model allows for the independent variables to have additive and multiplicative effects with the latter interpreted as effects on the scale (or dispersion) of a latent distribution. To identify which of the independent variables had multiplicative effects, we fitted models with different sets of them as multiplicative variables and we used the Bayesian information criterion for model selection. The final model used year, socioeconomic status of the household, regional context, distance from LPG source/retail point, and LPG price per Kg as additive variables and year, regional context, retail distance, and LPG price as multiplicative variables. We used the model to predict the dependent variable in the years 2024 and 2030 under assumptions concerning improvements in socioeconomic circumstance (projecting existing favourable trends), rates of urbanisation (based on NISR projections), distance from LPG source, and LPG price. Specifically, assumptions for the modelling scenarios are presented in Table 1. All analyses were conducted using R version 4.0.1. [40].

2.2. Evaluating Impacts on Environment, Climate, and Health of Scaled LPG Adoption for Cooking

Estimation of the health, climate, and environmental impacts from the increased adoption of LPG for cooking in the residential and public institutions sectors, under the three scenarios, was assessed according to the following outcomes:

- *Environment and Climate Impacts*. The impacts on environment and climate of displacement of solid fuels for cooking through increased adoption of LPG were assessed through (i) averted deforestation (number of trees saved that would otherwise be used as source of firewood or for charcoal production), (ii) averted CO_2 emissions (measured as CO_2 equivalents or CO_2e (including CO_2, methane (CH_4), and nitrous oxide (N_2O)), (iii) averted BC emissions equivalents (including BC, organic carbon (OC), carbon monoxide (CO), and total non-methane organic compounds (TNMOC)), and (vi) the economic value of averted CO_2e emissions in terms of carbon financing.
- *Health*. Health impacts from reductions in household air pollution ($PM_{2.5}$) from combustion of solid fuels through increased adoption of LPG was assessed through (i) averted number of premature HAP related-deaths, (ii) averted HAP-related morbidity (disability-adjusted life years (DALYs)), and (iii) the potential economic value of the projected reductions in mortality and morbidity according to the main global burden of disease (GBD) outcomes.

Data Sources and Methodology Used for the Environmental, Climate, and Health Impact Assessments

To estimate the impacts on health, climate, and environment of scaled LPG adoption (household and institutional), estimates from the projected proportions of the population using LPG for each time horizon (2024 and 2030) for each of the three modelling scenarios were used. Environmental impacts (averted deforestation/trees saved) were calculated based on existing household and institutional use of firewood and charcoal that was converted to equivalent wood consumption, using a ratio of 7 based on data from Tanzania [41]. Deforestation was defined according to the fraction of non-renewable biomass (fNRB) (this is the percentage of wood removed unsustainably from forests, applicable to both charcoal and firewood). The fNRB was estimated to be 59% (52–66%) for Rwanda based on Bailis et al. [42] with tree mass set at 100 kg [43] (see Section S2.1 in the Supplementary Materials for detailed procedures and equations used to estimate the deforestation impacts).

To calculate reductions in CO_2e emissions resulting from projected household and institutional transition from solid fuels to LPG (under each scenario), the Gold Standard Technologies and Practices to Displace Decentralized Thermal Energy Consumption (TPDDTEC) Methodology was adopted. This methodology estimates total CO_2e emissions by calculating the CO_2 equivalent (CO_2e) emissions of three greenhouse gases—CO_2, CH_4, and N_2O. The emission rates were multiplied by the global warming potential (GWP_{100}) conversion factors for each gas (32 for CH_4 and 298 for N_2O) (see Table S2). As a second step, the CO_2e emissions for different fuel use were calculated by multiplying household level fuel consumption by the net calorific value of the fuel and average stove efficiencies using global averages obtained from the literature [14,15] (see Table S3). This results in the energy use per fuel (megajoules delivered or MJd), which was multiplied by the CO_2e emissions factor (in g/MJd) to obtain the total CO_2e emissions (in grams, which was then converted to metric tonnes). The CO_2e tonnage differential was calculated by subtracting the CO_2e emissions under the interventional scenario from CO_2e emissions in the BAU scenario.

Similarly, to calculate the BCe emissions, reductions per annum from scaled adoption of LPG, the same four-step approach was used following the gold standard methodology: (i) the BCe emissions per unit of fuel use were calculated using the TPDDTEC Guidelines on Black Carbon Quantification Methodology [44]; (ii) the BCe emission per fuel was multiplied by the GWP_{100} conversion factor for BC (equal to 660) based on the IPCC 2013 report [20], but increased by 14% based on Etminan et al. [45]; and (iii) the global warming potential of BCe emissions per fuel type was then multiplied by the total consumption per fuel in kg. This calculation estimated the BCe emissions from fuel use, and they were calculated for LPG, charcoal, and firewood, reflecting the fuel projections trends under the various adoptions scenarios up 2030.

The economic value of reduced CO_2 equivalent emissions was estimated by multiplying the total emissions averted by 2030 by the prevailing price of carbon for the latest available year (2019). The price of carbon was derived from existing carbon values and was set at a mean of US$ 3.8 of CO_2 equivalent (ranging from US$ 1.4 to 4.3) and the transacted volume in 2019 corresponded to 6.4 MT CO_2 equivalent [46]. The economic value of reduced carbon was estimated using the observed prevailing carbon price in Africa and multiplying it by the carbon emissions averted.

To estimate averted HAP-related deaths and disability (ADALYs) achieved through scaled adoption of LPG under each of the three modelling scenarios, 'pre'- and 'post'-intervention (i.e., LPG adoption) $PM_{2.5}$ exposure values were used as inputs into the Household Air Pollution Intervention Tool (HAPIT version 3.1.1) [47]. This is an analytical tool based on established global burden of disease methods incorporating five disease outcomes that are causally associated with $PM_{2.5}$ exposure from household fuel combustion—COPD, lung cancer, ischemic heart disease, and stroke in adults as well as pneumonia in children. HAPIT is widely used for modeling health impacts of interventions to reduce HAP exposure. Full details of the values used for health impact modelling are provided in the Supplementary Materials (Section S2.3).

The economic value of averted HAP-related deaths was estimated by multiplying the annual GDP per capita for 2019 in Rwanda (US$ 801.7) [2] by the total number of averted deaths for Rwandan working age adults (aged 15–64 years). Similarly, the economic value of HAP-related averted DALYs (ADALY) was calculated by multiplying the annual GDP per capita for 2019 by the number of ADALYs for working age adults (aged 15–64 years).

The full list of assumptions, equations, and values used to calculate climate and health impacts is provided in the Supplementary Materials (Sections S2.2 and S2.3).

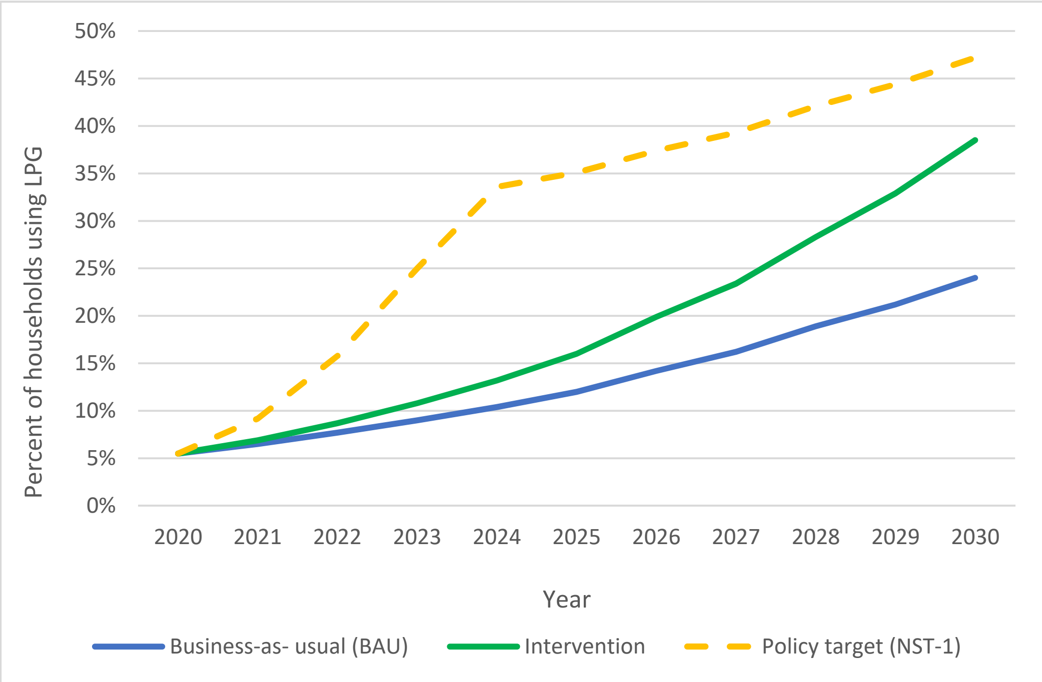
3. Results

3.1. Enhancing Adoption of LPG through Market Enhancement: Modelling Impacts towards Government Adoption Targets

The results from the three modelling scenarios were considered according to both domestic (e.g., household) and institutional use of LPG following the two time horizons of 2024 (Rwanda government policy target) and 2030 (SDG 7).

3.1.1. Projections of Household LPG Adoption

Household LPG adoption was projected to increase from 5.6% in 2020 to 10.4% in 2024 and 24% in 2030 under the business-as-usual scenario (i.e., without market enhancement) (Figure 1). Under this scenario, the greatest growth was projected for urban settings, with 65.9% of the households in Kigali city projected to use LPG in 2024 (from 45.1% in 2020), increasing to 86.4% in 2030. Similarly, 25.2% households in 'other urban' areas were projected to be using LPG in 2024, increasing to 56.7% in 2030. By contrast, for rural contexts, only very limited growth was projected (0.6% of the households estimated to adopt LPG by 2024 rising to 3.4% in 2030).



	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
BAU	5.6%	6.5%	7.7%	9.0%	**10.4%**	12.0%	14.2%	16.2%	18.9%	21.2%	**24.0%**
Interventional	5.6%	6.9%	8.7%	10.8%	**13.2%**	16.0%	19.9%	23.4%	28.3%	32.9%	**38.5%**
NST-1 target	5.6%	9.2%	15.8%	25.0%	**33.6%**	35.1%	37.4%	39.3%	42.1%	44.4%	**47.2%**

Figure 1. Adoption scenarios based on proportion of households using liquefied petroleum gas (LPG) for cooking.

With the intervention scenario (implementation of market enhancement strategies as described above), household LPG adoption was projected to increase to 13.2% in 2024 and to 38.5% by 2030 (Figure 1). While increases in LPG adoption under this scenario are primarily driven by urban contexts (expected to reach 89.2% by 2030 in urban areas other than Kigali and 94.4% in urban Kigali), LPG adoption in rural areas was also estimated to increase modestly (projected to reach 12.4% in 2030).

In contrast to the business-as-usual and interventional scenarios, the policy target scenario for household adoption of LPG was 33.6% in 2024 and 47.2% by 2030 (Figure 1).

To understand the projected LPG use under the interventional scenario according to household income, projections over time were stratified by SES (according to the four *Ubudehe* categories) (Figure 2). While the proportion of homes using LPG with the largest income (highest SES category) had the greatest predicted growth in LPG adoption under the intervention scenario (33.2% in 2020; 51.6% in 2024; 75% in 2030), adoption of LPG is also projected to significantly increase in households with lower incomes. Even in the poorest quartile of income (lowest category of SES), 19% of households are projected to be using LPG by 2030 (Figure 2).

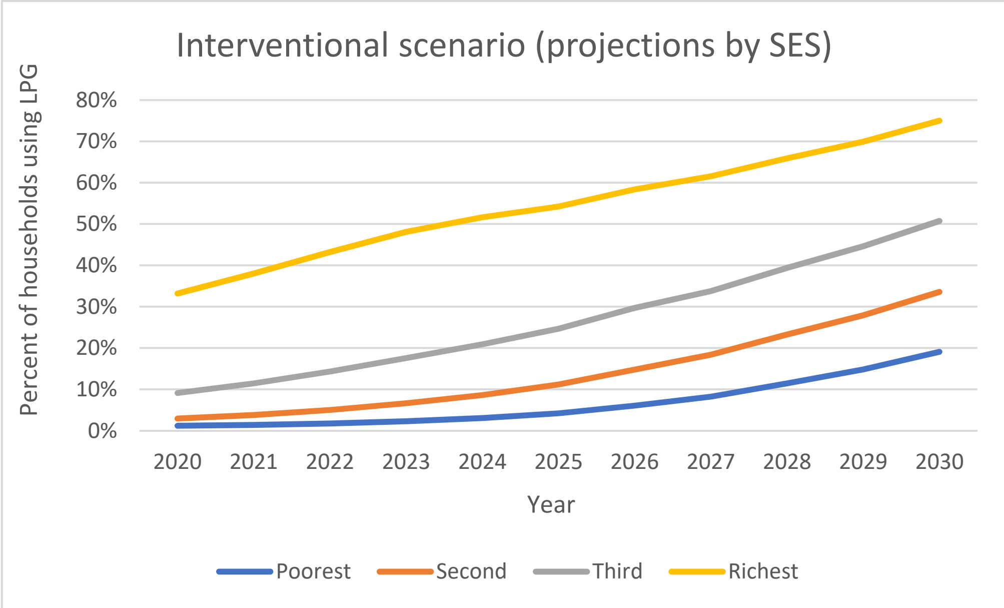


Figure 2. Projected LPG household adoption by socio-economics status *(Ubudehe)* categories.

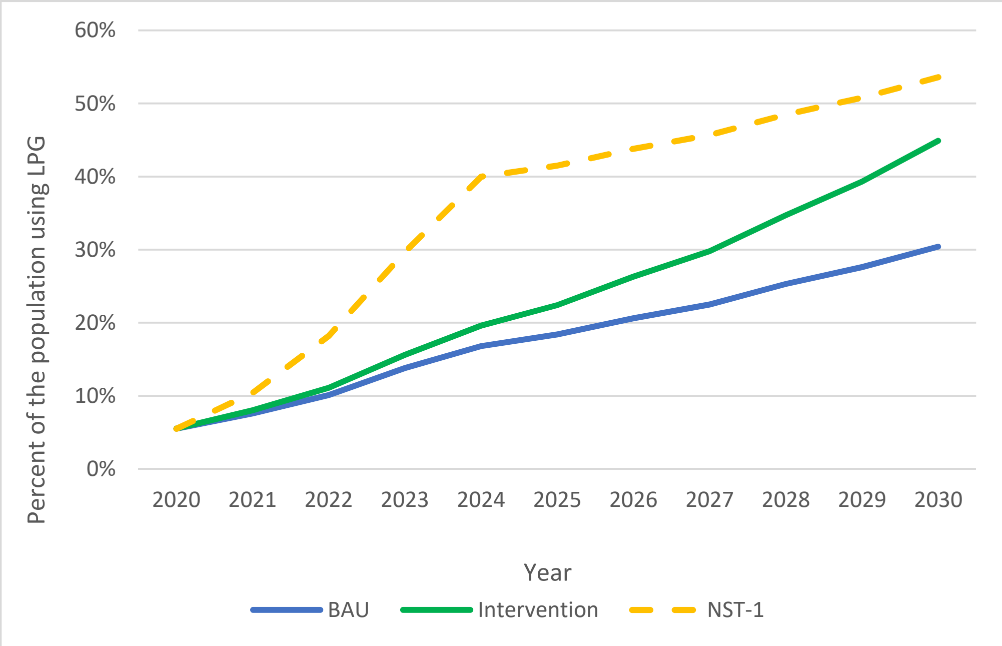
A detailed breakdown of values of projected adoption of LPG by different combinations of the predictor variables is shown in the Supplementary Material (Table S1).

3.1.2. Overall LPG Adoption Projections (Residential, Institutional, and Commercial Sectors)

One of the priorities for the government was to include public institutions in projections, given the potential to mandate fuel use in this sector. The use of LPG by the following institutions was modelled: schools, prisons, police stations (with temporary detention centres), healthcare facilities, military barracks, and refugee camps. Other non-public institutions were also included in the analyses including private catering institutions such as hotels and restaurants and other industrial users of LPG.

In 2020, approximately 4500 MT of LPG was estimated to be consumed by both public and commercial institutions (based on [5] and commercial data). With effective national mandate of public institutions to use LPG for clean cooking, it is expected that almost full conversion can be achieved by 2024, leading to predicted growth of 29,670 MT of consumed LPG in 2024 and 34,760 MT in 2030 (based on NISR population projections calculated for each category of institution between 2024 and 2030). While it is assumed that all institutions will adopt LPG within this time frame, it should be noted that is unlikely that all institutions will use LPG exclusively within this time horizon. In addition, LPG target projections in boarding schools and prisons took into account the existing level of adoption of biogas, which has been promoted in institutions since 2000 [48] as well as for rural household uptake since 2007 [49,50]. It is estimated that only about 40% of the total institutional cooking needs are met through biogas [5], and the remaining 60% was projected to be LPG from 2024 onwards.

Modelling of the three scenarios according to projected adoption of LPG uptake from all sectors (residential, institutional, and commercial) is summarised in Figure 3.



Scenario	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
BAU	5.6%	7.6%	10.1%	13.8%	**16.8%**	18.4%	20.6%	22.5%	25.3%	27.6%	**30.4%**
Interventional	5.6%	8.0%	11.1%	15.6%	**19.6%**	22.4%	26.3%	29.8%	34.7%	39.3%	**44.9%**
NST-1 target	5.6%	10.4%	18.2%	29.7%	**40.0%**	41.5%	43.8%	45.7%	48.5%	50.8%	**53.6%**

Figure 3. Proportion of population using LPG for cooking (household, institutional, and commercial use) under the three adoption scenarios.

Across all sectors, LPG adoption was projected to increase from 5.6% in 2020 to 16.8% in 2024 and 30.4% in 2030 under the business-as-usual scenario (e.g., without market enhancement). By contrast, the interventional scenario (enhanced market conditions) projected 19.6% of the population to be using LPG in 2024, reaching 44.9% in 2030. According to this scenario, the NST-1 policy goal of 40% LPG adoption across all sectors will be reached by 2030.

3.2. *Evaluating Impacts on Environment, Climate, and Health of Scaled LPG Adoption*

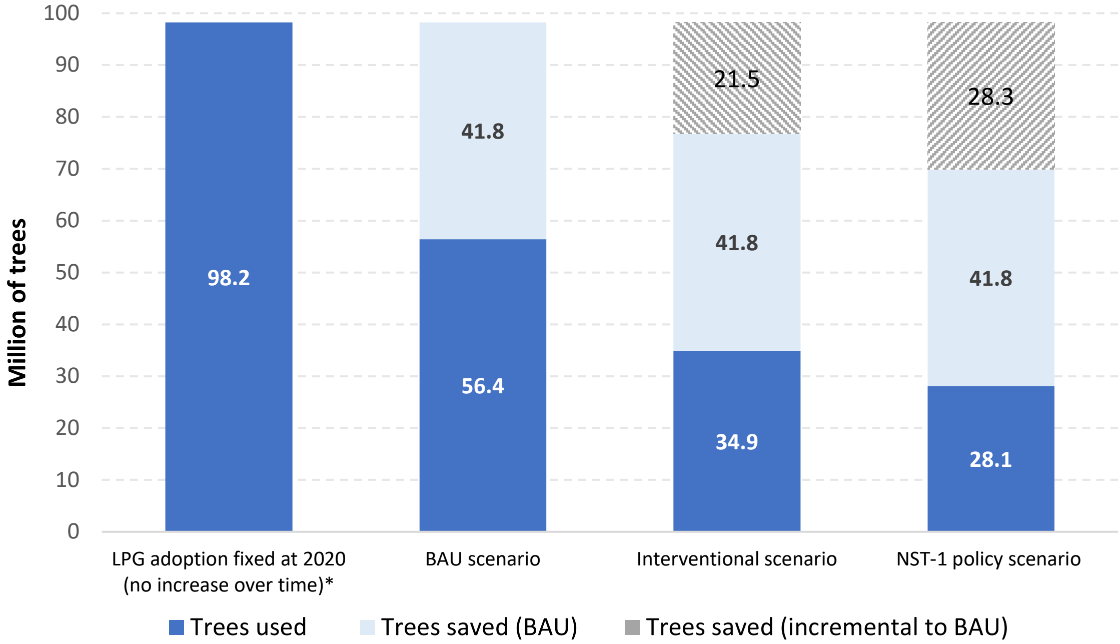
3.2.1. Impacts on the Environment and Climate

Population transition to LPG for cooking is estimated to have a dramatic impact on prevention of forest degradation and corresponding loss of biodiversity in Rwanda. If the intervention scenario is effectively implemented to the predicted 44.9% adoption by 2030 (for all sectors), 83 million trees could be saved compared with lower levels of increased adoption following the business-as-usual scenario (Table 2).

Table 2. Cumulative impacts on the environment and climate of projected LPG adoption for each of the modelled scenarios (2021–2030).

Impacts (2021–2030)	BAU	Intervention	NST-1 Policy Target
Averted deforestation (trees saved)	185 million	268 million	354 million
Reduction in CO_2e emissions	18.6 million MT	28.5 million MT	40.1 MT
Reduction in BCe emissions	11.1 million MT	17.1 million MT	25.8 MT
Economic value of averted CO_2e emissions	US$ 70.6 million	US$ 108.2 million	US$ 152.4 million

Achieving levels of LPG adoption in line with the NST-1 policy target (projected to reach 53.6% in 2030) could save an additional 86 millions trees over the intervention scenario, for a total of 354 million trees in 2030 (Table 2). Figure 4 summarises the projected reduction in harvested trees by 2030 (SDG 7 target) (see Figure 4 compared with the 2020 adoption levels).



Note: *This is an approximation including effects on household and institutional cooking.

Figure 4. Number of trees saved due to reduction in solid fuel use from LPG adoption in 2030 per each of the scenarios.

In terms of climate impacts, the transition from charcoal and firewood to LPG for cooking will decrease total and per capita carbon emissions through two mechanisms: (i) decreased emissions from combustion of solid fuels and (ii) decreased fuel production (in the case of charcoal). The total cumulative CO_2e emissions reductions between 2021 and 2030 were estimated to be between 28.5 million (under the intervention scenario) and 40.1 million emissions averted (under the NST-1 policy scenario) (Table 2). Similarly, the overall cumulative (2021–2030) reductions in BCe emissions resulting from scaled transition to LPG for cooking in Rwanda are projected to be 17.1 million emissions averted if the interventional scenario is fully implemented or 25.8 million emissions averted if the NST-1 policy target is achieved, assuming no further increase in adoption of LPG from levels in 2020.

Finally, the cumulative economic value of averted CO_2e emissions following national transition to LPG for clean cooking over 2021–2030 was estimated to be US$ 108.2 million (intervention scenario) and US$ 152.4 million (NST-1 policy scenario), assuming no further increase in adoption of LPG from levels in 2020.

3.2.2. Health Impacts

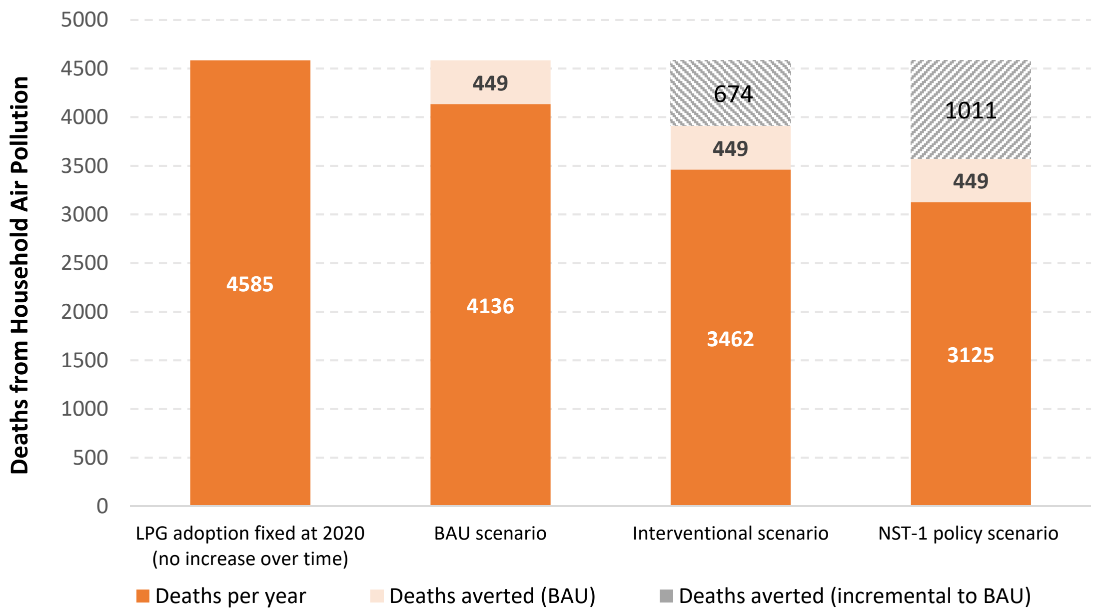
The cumulative number of deaths saved (adults and children) from the adoption of LPG among residential cooks between 2021 and 2030 was estimated to be 3832 (under the interventional scenario) and 7656 (under the NST-1 policy scenario) (Table 3). Similarly, the cumulative number of ADALYs was estimated to range from 201,333 to 403,664 from 2021 to 2030. The averted deaths and DALYs generated by transitioning to LPG by public institutions (impacting cooks, catering staff, and to a less extent residents of public institutions such as school pupils and so on) could not be modelled owing to the paucity of data in this sector. Figure 5A,B present the results for year 2030 alone in comparison to no further increase in adoption of LPG from levels in 2020.

Table 3. Cumulative health impacts of projected LPG adoption for each of the scenarios (2021–2030).

Impacts (2021–2030)	BAU	Intervention	NST-1 Policy Target
Averted premature deaths	1133	3832	7656
Averted disability adjusted life years (ADALYs)	58,973	201,333	403,664
Economic value of averted deaths and DALYs	N/A	US$ 9.8 million	US$ 19.5 million

Note. The impacts on health are modelled only for the household sector. They are based on the five health conditions (COPD, lung cancer, ischemic heart disease, and stroke in adults as well as pneumonia in children) known to be causally associated with HAP for Global Burden of Disease calculations in 2013. Since this time other health outcomes (e.g., diabetes, asthma and adverse pregnancy outcomes (2019)) are also used in GBD calculations and therefore our estimates are likely to be conservative.

(**A**) Number of deaths saved thanks to increased LPG adoption by households in 2030



(**B**) Number of averted DALYs thanks to increased LPG adoption by households in 2030

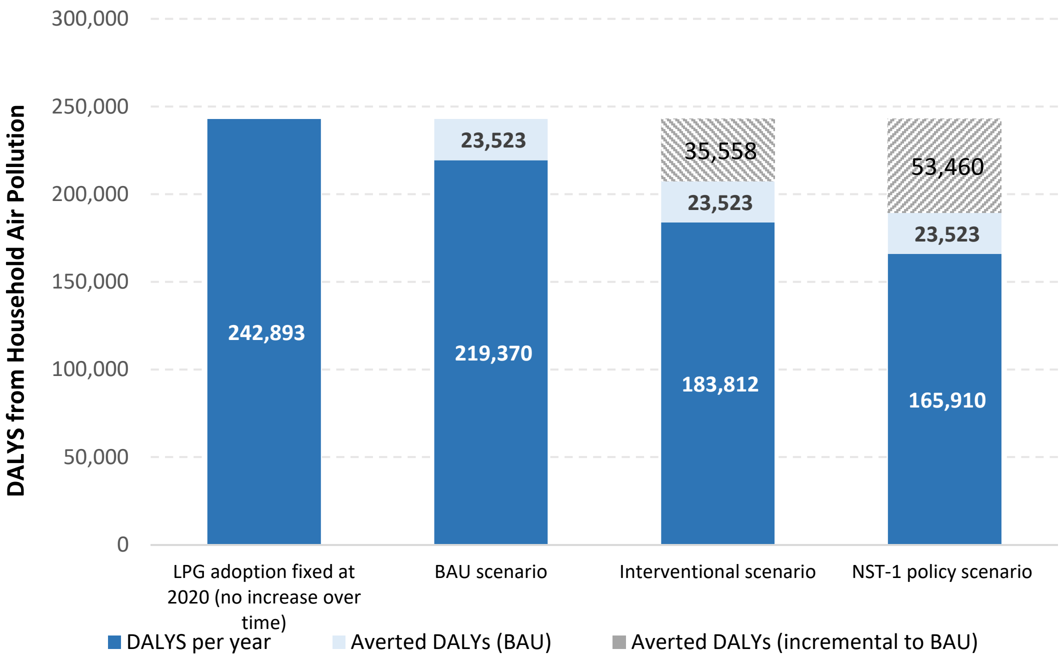


Figure 5. Results on projected health impacts in 2030 according to each LPG adoption scenario. Note: This is an approximation and the figures reflect only projected benefits for use of LPG at the household level, not institutional cooking.

These values are estimated to lead to a total economic value (based on the prevailing average wage rate times the labour time and productivity gained from the averted deaths and DALYs) of US$ 9.8 million (under the intervention scenario) and US$ 19.5 million (under the NST-1 policy scenario) cumulatively for the years 2021 to 2030.

4. Discussion

Similar to a growing number of countries in sub-Saharan Africa, transition to clean modern energy for cooking, including LPG, is being targeted as a public health and environmental priority in Rwanda [51,52]. Accelerated expansion of LPG in residential and institutional sectors requires effective policies and investment necessary to stimulate this change and the Rwandan government is implementing this through its Master Plan. The current analysis provides some context in moving towards the government biomass fuel reduction target investigating the impact of factors that will stimulate LPG adoption over time (both those that can and cannot be controlled). An 'intervention scenario', including strategies to increase market expansion and accessibility of LPG and mandating institutional use of LPG, estimates that, with effective implementation, adoption of LPG can be expected to increase from 5.6% in 2020 to one-fifth of the population (19.6%) by 2024. While this falls short of the government target, extrapolating to the SDG 7 "universal access to clean modern energy" time horizon of 2030, it is estimated that the target can be achieved over this extended time horizon, with almost half of the population (44.9%) using LPG in 2030.

Achieving this level of adoption is estimated to have significant positive impacts on both the environment and climate. Expansion to 45% population adoption of LPG by 2030 (as conservatively modelled in the intervention scenario) will (i) save an estimated 268 million trees cumulatively (compared with 185 million saved under BAU conditions), (ii) reduce CO_2e emissions to 28.5 million MT (compared with a reduction of 18.6 MT under BAU conditions), (iii) reduce BCe emissions by 17.1 MT (compared with a reduction of 11.1 MT under BAU conditions), and (iv) yield estimated economic savings of US$ 108.2 million from these reduced environmental and climate detriments (compared with a reduction of US$ 70.6 million under the BAU scenario). Achieving this expansion of LPG will also significantly improve public health with an estimated 2,590 premature deaths from exposure to HAP being averted and an additional 135,716 DALYs being averted from associated reduction in HAP-related morbidity (with values estimated as a difference between the totals achieved under the intervention scenario compared to BAU conditions, see Table 2). These positive gains in health are estimated to result in economic savings of US$ 9.8 million between 2021 and 2030.

The tangible benefits from scaling adoption of clean cooking with LPG, including environment and health, make a compelling case for supporting the conditions necessary for expansion of the LPG market through the National LPG Master Plan. It will also be necessary to accompany policy and regulation with investment and interventions to positively stimulate adoption, especially by households.

4.1. Scaling Adoption of LPG to Government and SDG7 Time Horizons

It is clear that LPG uptake is positively correlated with increasing urbanization at societal level and increasing socio-economic status and level of education (particularly for the head of the household) at an individual/household level. Unsurprisingly, our results find that increasing trends of LPG adoption are substantially greater in higher income/SES strata than lower strata, particularly in urban contexts, consistent with findings reported in other studies [53–56]. However, of note is the projected increase in adoption by 2030 in the lowest SES stratum with 19.1% of the poorest households adopting LPG by 2030 if the intervention scenario conditions are achieved (see Figure 2).

The potential for national policies, private sector investment, and the donor community to address inequality in income/SES to facilitate access to LPG for clean cooking by resource poor households warrants consideration. International research in sub-Saharan

Africa and other lower-and-middle-income countries (LMIC) highlights that mechanisms to reduce the up-front cost of switching to LPG can accelerate its adoption, especially when combined with education and sensitization efforts. These include consumer innovations such as microfinance for initial purchase of LPG equipment [57–59] and the potential for paying for LPG in small amounts through pay-as-you-go smart meter technology (PAYG LPG) [35,60]. This latter commercial innovation is receiving increasing attention for its potential in opening up clean cooking with LPG to low-income households given (i) no (or greatly reduced) upfront LPG equipment costs and (ii) the ability to pay for LPG in small increments (although at higher costs per kg) [35,60,61]. Another attraction of this model for consumers is that consumption can be tracked through the LPG smart meters in real time, facilitating timely home delivery to ensure a household never runs out of LPG for cooking [60]. While no PAYG LPG company currently operates commercially in Rwanda, BBOXX Ltd. (an electricity off-grid company offering supply through PAYG technology) conducted pilot studies of a PAYG LPG system in 2019–2020 in urban Kigali. While their preliminary results were encouraging, an expansion of the pilot work has not been initiated [61]. A successfully implementation of PAYG LPG expansion may facilitate consumer adoption of LPG in line with the government's national LPG road map with the benefit of opening up access to clean cooking for the poorest segments of society that may benefit from paying in small fuel amounts.

Proximity to outlets selling LPG, as a proxy for access, was identified to be an important predictor of its uptake, reinforcing the requirement for private sector-led investment stimulated by government intervention to scale adoption according to aspirational targets. The modelling found that a minimum distance of 2 km is required to ensure household uptake of LPG. This finding is consistent with previous research in sub-Saharan Africa (Cameroon, Ghana, and Kenya) that quantifies distance from an LPG retail point as a key driver for more use of the fuel [32–34,60]. Home delivery will address the issue of proximity providing convenient access to LPG without the need for travel to secure the fuel—national data suggested that, currently, one-quarter (27%) of urban households have access to home delivery of the LPG cylinder refills [5], which is a high rate for sub-Saharan Africa. However, outside of urban areas, home delivery might become more problematic without a greater density of retail outlets and poor road quality may add home delivery costs.

Interestingly, the cost of LPG refills was found to be less important than access, although it is considered to be an important driver of uptake and, specifically, of exclusive use. As of 2020, the LPG retail price in Kigali city was estimated to be an average of 1060 Rwf/kg (1.09 US$/kg) [37]. The cost of an LPG cylinder deposit (for first time users) plus the initial gas ranged from 38,000 RwF (US$ 38.9) for a 6 kg filled cylinder to 80,000 RwF (US$ 82) for a 12 kg filled cylinder. Modelling of the costs of LPG found only a very minimal correlation between LPG price and usage. While it might be expected that increases in LPG price might correspond to a decrease in usage, such an analysis was not possible given the paucity of available data from households using LPG from national data sources [5]. We hypothesise that, in the early stages of LPG market development where the majority of the population is rural with limited or no access to LPG fuel, expanding access to cylinders and LPG equipment will be the main driver of LPG uptake. Fluctuations in price will impact levels of adoption of LPG only once an accessible and reliable supply is established.

4.2. Impacts of Scaling LPG Adoption to Government and SDG7 Time Horizons on Environment, Climate, and Public Health

An increasing number of countries in sub-Saharan Africa are setting aspirational targets for transition to LPG to address the significant detrimental effects on environment, climate, and public health of reliance on solid fuels and kerosene for energy [51,52]. Despite this, there is a paucity of evidence on the potential positive impacts that can be achieved by scaling LPG for clean cooking. Indeed, concern has been expressed over the potential additional negative contributions to the climate that might result from the promotion of a fossil fuel such as petroleum-based LPG (although entirely a by-product of petroleum sector refining and production of other fuels). Our findings are fully consistent with recent modelled evidence of the combined climate and health impacts from increased population adoption of LPG in Cameroon [13], across 40 diverse LMIC settings [62] and other countries [63–65]. Rosenthal et al. [62] conducted modelling based on a theoretical intervention scenario (25,000 homes) whereby solid fuel use was replaced with cleaner cooking options including (i) improved solid fuel stoves, (ii) an advanced combustion (e.g., with fan assistance) solid fuel stove, and (iii) use of LPG for cooking. The modelling was conducted over a 3-year period with an assumption of 60% adoption. Compared with the improved stove intervention, use of LPG was found to lead to an estimated fourfold reduction in morbidity (averted DALYs) with a corresponding reduction of more than 100,000 tons of CO_2e emissions. The authors concluded that programs focusing on scaling adoption of LPG were more effective in terms of both health and climate gains than those involving improved and advanced biomass burning cookstoves [62]. Similar to the current analysis, Kypridemos et al. [13] modelled the climate and health impacts of scaling LPG adoption in Cameroon to an aspirational target by the SDG7 time frame of 2030. The Cameroon government's target of 58% of the population using LPG by 2030 (from 20% in 2014) through successful implementation of its national LPG Master Plan was found to result in an estimated 28,000 saved lives and a reduction of 770,000 DALYs [13]. In addition to reductions in health-damaging household air pollution ($PM_{2.5}$) that led to this health gain, emissions of BC and other climate forcing pollutants were found to be reduced by one-third. These reductions, together with reductions in non-renewable harvesting of wood for fuel, were found to lead to a global cooling effect of -0.1 milli °C by 2030. When forecast for a longer theoretical time frame of 2100 (more relevant for climate impacts), the global cooling effect was found to be -0.7 milli °C using a conservative fraction of non-renewable harvested wood. Consistent with these results is our finding that the health gain that can be achieved from scaling adoption of LPG in Rwanda in line with the NST-1 policy target (a theoretical 7,656 saved lives and 403,664 ADALYs) is not at the expense of climate through scaled adoption of a fossil fuel (with an estimated reduction in 28.5 million MT of CO_2e emissions and the preservation of 354 million trees). It is also important to note that the estimated health gain from our modelling is likely to underestimate the true impacts of sustained and exclusive adoption of LPG for all domestic cooking. Firstly, modelled reductions in exposure to $PM_{2.5}$ from LPG adoption were based on values taken from the HAPIN trial for Rwanda [66] that found households using LPG for cooking (intervention) in the field had an average exposure of 45 $\mu g/m^3$ (Johnson et al. personal communication). This level of personal exposure is higher than the WHO Indoor Air Quality Guideline Interim Target 1 level for Health of 35 $\mu g/m^3$, and is likely indicative of community contamination from ambient air pollution (mixed use of LPG and solid fuels was unlikely in the HAPIN trial given that LPG fuel was given for free). Second, $PM_{2.5}$ from solid fuel use is now known to be causally associated with a variety of other health issues (including adverse pregnancy outcomes and diabetes) considered in later iterations of global burden of disease estimation than that used for the HAPIT tool. In addition, other conditions including cataracts in adult women, tuberculosis, and laryngeal cancer [67], which are not considered in burden of disease estimation $PM_{2.5}$, have not been included in estimates of health impact for the Rwandan modelling. Fourthly, the modelling was restricted to household personal exposures (main cook and children) and did not include potential detrimental health impacts on catering staff operating in public institutions. Finally, as noted in the study by Kypridemos et al. [13], global warming is likely to increase the global burden of disease [68], thus any reductions in global warming potential from population transition away from polluting solid fuels can potentially reduce this associated disease burden. This has not been considered in the current health impact modelling.

4.3. Supply Considerations to Facilitate Population Adoption of LPG for Clean Cooking and Role of the Donor Community

As highlighted in the analysis, supply of LPG (including density of retail outlets) will be a critical issue in facilitating population transition (domestic and institutional) away from reliance on polluting solid fuels to clean cooking with LPG. This supply needs to be sufficient to fulfil scaled adoption across Rwanda, requiring necessary investment in provision of LPG cylinders, stoves, infrastructure, and distribution networks. Rwanda currently relies entirely on importing its supply of LPG for both residential and commercial markets. While value added tax on the fuel is zero-rated, there are currently LPG import taxes including a 1.5% infrastructure development tax and a 1.2% African Union tax.

One exciting new initiative that might benefit countries that currently solely rely on imported LPG, like Rwanda, is the potential development of domestic bioLPG production that can lead to greater diversification of LPG supply, reduce the average LPG wholesale price in the country, and hedge against importation price increases. BioLPG (chemically identical to fossil-derived LPG and derived from fully renewable sources) can be produced from feedstocks such as municipal solid waste (MSW) from appropriately engineered landfills sites [69,70]. Advantages of bioLPG include (i) its renewable credentials that can secure international investment, (ii) its resistance to currency devaluation against the U.S. dollar (currently an issue for imported LPG), and (iii) the fact that it can be blended with imported LPG. Of course, it also retains all the benefits of the current credentials of petroleum-based LPG as a scalable fuel (e.g., highly efficient, not detrimental to climate, and well-liked by consumers). In Kigali, and perhaps other major urban conurbations in Rwanda, there is potential to produce bioLPG from processing of MSW that would secure and enhance the Rwandan LPG market—a potentially important future step in its clean energy road map.

The donor community/Official Development Assistance (ODA) funding also has a key role to play in an effort to support scaling up of clean cooking. Rwanda has been the first country to benefit from the World Bank (WB) Clean Cooking Fund initiative [71]. Under the WB-promoted Rwanda Energy Access and Quality Improvement project, Rwanda will be receiving over US$ 150 million of funding to support access to modern energy for households and public institutions [2,72].

5. Conclusions

Effective implementation of the National LPG Master Plan for transition away from inefficient polluting solid fuels in Rwanda, replaced by LPG for clean cooking in homes and institutions, will have significant positive gains in terms of health, environment, and climate. The findings from the modelling of an 'intervention scenario' of scaling LPG use towards the 2024 policy target suggest that household LPG use is projected to increase from 5.6% in 2020 to 13.2% by 2024 and 38.5% by 2030. If achieved, this level of adoption would result in the reduction of 7,656 premature deaths and 403,664 disability-adjusted-life-years, as well as 243 million trees saved. Reductions in CO_2 and BC emissions equivalents are estimated to reach 25.6 million MT and 14.9 MT, respectively, by 2030.

To achieve aspirational targets of transition to clean cooking within the SDG 7 time horizon of 2030, significant public and private sector mobilisation is required to effect the required market changes to scale population adoption of LPG. This will include creating favourable conditions for new consumers to adopt LPG as a main source of cooking fuel (e.g., through positive regulation and supporting private sector investment and innovation that can facilitate both adoption and sustained use of LPG, including the likes of pay-as-you-cook smart meter technology and microfinance). The Rwandan National LPG Master Plan, commissioned and supported by the Ministry of Infrastructure, is an important initial step in mapping out the conditions necessary to achieve this scale and the positive health, environmental, and climate gain that can be achieved in this relatively short time frame.

Supplementary Materials: A Supplementary Materials document describing the methodology for modeling LPG adoption projections and for the environmental and health impacts estimations is available online at https://www.mdpi.com/article/10.3390/en14154582/s1.

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writing—original draft preparation, I.Č., E.P. and D.P.; writing—review and editing, I.Č., E.P., A.W.E., C.K. and D.P.; visualization, I.Č. and E.P.; funding acquisition, E.P. and A.W.E. All authors have read and agreed to the published version of the manuscript.

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References

1. United Nations. *World Statistics Pocketbook*, 2020 ed.; Series V; No. 44; Available online: https://unstats.un.org/unsd/publications/pocketbook/ (accessed on 10 July 2021).
2. World Bank. *World Bank Data Indicators*. 2020. Available online: https://data.worldbank.org/country/rwanda?view=chart (accessed on 10 July 2021).
3. Gubic, I.; Baloi, O. Implementing the New Urban Agenda in Rwanda: Nation-Wide Public Space Initiatives. *Urban Plan.* **2019**, *4*, 223–236. [CrossRef]
4. IMF. *International Monetary Fund Country Report No. 20/115. Rwanda*; International Montery Fund: Washington, DC, USA, 2020.
5. CFET. *National Survey on Cooking Fuel Energy and Technologies in Households, Commercial and Public Institutions in Rwanda*; Ministry of Infrastructure and Ministry of Finance: Kigali, Rwanda, 2020.
6. World Bank Group. *Rwanda—Multi-Tier Framework (MTF) Survey*; The World Bank: Washington, DC, USA, 2018.
7. Okello, S.; Akello, S.J.; Dwomoh, E.; Byaruhanga, E.; Opio, C.K.; Zhang, R.; Corey, K.E.; Muyindike, W.R.; Ocama, P.; Christiani, D.D. Biomass Fuel as a Risk Factor for Esophageal Squamous Cell Carcinoma: A Systematic Review and Meta-Analysis. *Environ. Health Glob. Access Sci. Source* **2019**, *18*, 60. [CrossRef]
8. Amegah, A.K.; Quansah, R.; Jaakkola, J.J.K. Household Air Pollution from Solid Fuel Use and Risk of Adverse Pregnancy Outcomes: A Systematic Review and Meta-Analysis of the Empirical Evidence. *PLoS ONE* **2014**, *9*, e113920. [CrossRef]
9. Dherani, M.; Pope, D.; Mascarenhas, M.; Smith, K.R.; Weber, M.; Bruce, N. Indoor Air Pollution from Unprocessed Solid Fuel Use and Pneumonia Risk in Children Aged under Five Years: A Systematic Review and Meta-Analysis. *Bull. World Health Organ.* **2008**, *86*, 390C–398C. [CrossRef]
10. Kurmi, O.P.; Arya, P.H.; Lam, K.-B.H.; Sorahan, T.; Ayres, J.G. Lung Cancer Risk and Solid Fuel Smoke Exposure: A Systematic Review and Meta-Analysis. *Eur. Respir. J.* **2012**, *40*, 1228–1237. [CrossRef] [PubMed]
11. IHME. *Rwanda Profile*; Institute for Health Metrics and Evaluation, University of Washington: Seattle, WA, USA, 2020.
12. Puzzolo, E.; Cloke, J.; Parikh, J.; Evans, A.; Pope, D. *National Scaling up of LPG to Achieve SDG 7: Implications for Policy, Implementation, Public Health and Environment*; Working Paper; MECS: Loughborough, UK, 2020; Available online: https://www.mecs.org.uk/wp-content/uploads/2020/02/MECS-LPG-Briefing-Paper_Jan-2020.pdf (accessed on 10 July 2021).
13. .Kypridemos, C.; Puzzolo, E.; Aamaas, B.; Hyseni, L.; Shupler, M.; Aunan, K.; Pope, D. Health and Climate Impacts of Scaling Adoption of Liquefied Petroleum Gas (LPG) for Clean Household Cooking in Cameroon: A Modeling Study. *Environ. Health Perspect.* **2020**, *128*, 047001. [CrossRef]
14. Shen, G.; Hays, M.D.; Smith, K.R.; Williams, C.; Faircloth, J.W.; Jetter, J.J. Evaluating the Performance of Household Liquefied Petroleum Gas Cookstoves. *Environ. Sci. Technol.* **2018**, *52*, 904–915. [CrossRef]
15. Morelli, B.S.C.; Rodgers, M. *Life Cycle Assessment of Cooking Fuel Systems in India, China, Kenya, and Ghana*; U.S. Environmental Protection Agency: Washingon, DC, USA, 2017.
16. MacCarty, N.; Still, D.; Ogle, D. Fuel Use and Emissions Performance of Fifty Cooking Stoves in the Laboratory and Related Benchmarks of Performance. *Energy Sustain. Dev.* **2010**, *14*, 161–171. [CrossRef]
17. Grieshop, A.P.; Marshall, J.D.; Kandlikar, M. Health and Climate Benefits of Cookstove Replacement Options. *Energy Policy* **2011**, *39*, 7530–7542. [CrossRef]
18. WHO. *Indoor Air Quality Guidelines: Household Fuel Combustion*; World Health Organization: Geneva, Switzerland, 2014.
19. Ramanathan, V.; Carmichael, G. Global and Regional Climate Changes Due to Black Carbon. *Nat. Geosci.* **2008**, *1*, 221–227. [CrossRef]
20. Bond, T.C.; Doherty, S.J.; Fahey, D.W.; Forster, P.M.; Berntsen, T.; DeAngelo, B.J.; Flanner, M.G.; Ghan, S.; Kärcher, B.; Koch, D.; et al. Bounding the Role of Black Carbon in the Climate System: A Scientific Assessment. *J. Geophys. Res. Atmos.* **2013**, *118*, 5380–5552. [CrossRef]
21. IPCC. *IPCC Special Report on Global Warming of 1.5 Degrees: Chapter 4: Strengthening and Implementing the Global Response*; Intergovernmental Panel on Climate Change: Geneva, Switzerland, 2018; Available online: https://www.ipcc.ch/sr15/ (accessed on 10 July 2021).

22. World Resources Institute. *Global Forest Watch—Rwanda*; World Resources Institute: Washington, DC, USA, 2020; Available online: https://www.wri.org/initiatives/global-forest-watch (accessed on 10 December 2020).
23. MININFRA. *Biomass Energy Strategy. A Sustainable Path to Clean Cooking: 2019–2030*; Ministry of Infrastructure: Kigali, Rwanda, 2019.
24. Bruce, N.G.; Aunan, K.; Rehfuess, E.A. Liquefied Petroleum Gas as a Clean Cooking Fuel for Developing Countries: Implications for Climate, Forests, and Affordability. In *Materials on Development Financing, No. 7*; KfW Development Bank: Frankfurt, Germany, 2017.
25. Thoday, K.; Benjamin, P.; Gan, M.; Puzzolo, E. The Mega Conversion Program from Kerosene to LPG in Indonesia: Lessons Learned and Recommendations for Future Clean Cooking Energy Expansion. *Energy Sustain. Dev. J. Int. Energy Initiat.* **2018**, *46*, 71–81. [CrossRef]
26. Mani, S.; Jain, A.; Tripathi, S.; Gould, C.F. The Drivers of Sustained Use of Liquified Petroleum Gas in India. *Nat. Energy* **2020**, *5*, 450–457. [CrossRef]
27. Coelho, S.T.; Goldemberg, J. Energy Access: Lessons Learned in Brazil and Perspectives for Replication in Other Developing Countries. *Energy Policy* **2013**, *61*, 1088–1096. [CrossRef]
28. Troncoso, K.; Soares da Silva, A. LPG Fuel Subsidies in Latin America and the Use of Solid Fuels to Cook. *Energy Policy* **2017**, *107*, 188–196. [CrossRef]
29. Troncoso, K.; Segurado, P.; Aguilar, M.; Soares da Silva, A. Adoption of LPG for Cooking in Two Rural Communities of Chiapas, Mexico. *Energy Policy* **2019**, *133*, 110925. [CrossRef]
30. Billah, S.M.; Islam, S.; Tasnim, F.; Alam, A.; Arifeen, S.E.; Raynes-Greenow, C. Self-Adopted 'natural Users' of Liquid Petroleum Gas for Household Cooking by Pregnant Women in Rural Bangladesh: Characteristics of High Use and Opportunities for Intervention. *Environ. Res. Lett.* **2020**, *15*, 095008. [CrossRef]
31. Williams, K.N.; Kephart, J.L.; Fandiño-Del-Rio, M.; Simkovich, S.M.; Koehler, K.; Harvey, S.A.; Checkley, W.; CHAP trial Investigators. Exploring the Impact of a Liquefied Petroleum Gas Intervention on Time Use in Rural Peru: A Mixed Methods Study on Perceptions, Use, and Implications of Time Savings. *Environ. Int.* **2020**, *145*, 105932. [CrossRef]
32. *GLPGP National Feasibility Study: LPG for Clean Cooking in Ghana*; The Global LPG Partnership: New York, NY, USA, 2018; Available online: http://glpgp.org/country-feasibilityand-investment-reports (accessed on 19 June 2021).
33. *GLPGP National Feasibility Study: LPG for Clean Cooking in Cameroon*; The Global LPG Partnership: New York, NY, USA, 2019; Available online: http://glpgp.org/country-feasibilityand-investment-reports (accessed on 19 June 2021).
34. *GLPGP National Feasibility Study: LPG for Clean Cooking in Kenya*; The Global LPG Partnership: New York, NY, USA, 2019; Available online: http://glpgp.org/country-feasibilityand-investment-reports (accessed on 19 June 2021).
35. CCA. *Scaling LPG for Cooking in Developing Markets: Insights from Tanzania*; Clean Cooking Alliance: Washington, DC, USA, 2019.
36. NISR. *RPHC4: Population Projections*; National Institute of Statistics of Rwanda: Kigali, Rwanda, 2019. Available online: http://www.statistics.gov.rw/publication/rphc4-population-projections. (accessed on 10 July 2021).
37. RURA. *Countrywide Supply Survey on Liquefied Petroleum Gas*; Utilities Regulatory Authority: Kigali, Rwanda, 2020.
38. Ezeanya, C. *Home-Grown and Grassroots-Based Strategies for Determining Inequality towards Policy Action: Rwanda's Ubudehe Approach in Perspective*, 8th ed.; WIDER Working Paper; UNU-WIDER: Helsinky, Finalnd, 2015; Volume 2015, ISBN 978-92-9230-893-3.
39. Niringiye, A.; Ayebale, C. Impact Evaluation of the Ubudehe Programme in Rwanda: An Examination of the Sustainability of the Ubudehe Programme. *J. Sustain. Dev. Afr.* **2012**, *14*, 141–154.
40. R Core Team. 2019. Available online: https://www.r-project.org/ (accessed on 20 April 2021).
41. Morgan-Brown, T.; Samweli, B. *A Comparison of Traditional and Improved Basic Earth Charcoal Kilns in Kilosa District, Tanzania*; Tanzania Forest Conservation Group (MJUMITA): Dar es Salaam, Tanzania, 2016.
42. Bailis, R.; Wang, Y.; Drigo, R.; Ghilardi, A.; Masera, O. Getting the Numbers Right: Revisiting Woodfuel Sustainability in the Developing World. *Environ. Res. Lett.* **2017**, *12*, 115002. [CrossRef]
43. Ray, C.D. *Calculating the Green Weight of Wood Species*; Penn State University: State College, PA, USA, 2014.
44. TPDDTEC. *Gold Standard Guidelines on Black Carbon Quantification Methodology*; Technologies and Practices to Displace Decentralized Thermal Energy Consumption: Geneva, Switzerland, 2017; Available online: https://www.goldstandard.org/our-work/innovations-consultations/black-carbon-quantification-methodology (accessed on 20 July 2021).
45. Etminan, M.; Myhre, G.; Highwood, E.J.; Shine, K.P. Radiative Forcing of Carbon Dioxide, Methane, and Nitrous Oxide: A Significant Revision of the Methane Radiative Forcing. *Geophys. Res. Lett.* **2016**, *43*, 12614–12623. [CrossRef]
46. State of Voluntary Carbon Markets 2020. *Voluntary Carbon and the Post-Pandemic Recovery*. 2020. Available online: https://share.hsforms.com/1ICNqRm4gSRGccSuyRZF-dg1yp8f (accessed on 15 July 2021).
47. Pillarisetti, A.; Mehta, S.; Smith, K.R. HAPIT, the Household Air Pollution Intervention Tool, to Evaluate the Health Benefits and Cost-Effectiveness of Clean Cooking Interventions. In *Broken Pumps and Promises*; Thomas, E.A., Ed.; Springer International Publishing: Cham, Switzerland, 2016; pp. 147–169. ISBN 978-3-319-28641-9.
48. Munyehirwe, A.; Kabanda, E.P. *Performance Assessment of Institutional Biogas Systems in Rwanda Report 47*; Inclusive Business and Consultancy Ltd. (IBC Ltd.): Kigali, Rwanda, 2008.
49. Kabera, T.; Nishimwe, H.; Imanantirenganya, I.; Mbonyi, M.K. Impact and Effectiveness of Rwanda's National Domestic Biogas Programme. *Int. J. Environ. Stud.* **2016**, *73*, 402–421. [CrossRef]

50. Landi, M.; Sovacool, B.K.; Eidsness, J. Cooking with Gas: Policy Lessons from Rwanda's National Domestic Biogas Program (NDBP). *Energy Sustain. Dev.* **2013**, *17*, 347–356. [CrossRef]
51. Van Leeuwen, R.; Evans, A.; Hyseni, B. *Increasing the Use of Liquefied Petroleum Gas in Cooking in Developing Countries*; LiveWire; World Bank: Washingon, DC, USA, 2017.
52. Bruce, N.; de Cuevas, R.A.; Cooper, J.; Enonchong, B.; Ronzi, S.; Puzzolo, E.; MBatchou, B.; Pope, D. The Government-Led Initiative for LPG Scale-up in Cameroon: Programme Development and Initial Evaluation. *Energy Sustain. Dev.* **2018**, *46*, 103–110. [CrossRef] [PubMed]
53. Shupler, M.; Hystad, P.; Gustafson, P.; Rangarajan, S.; Mushtaha, M.; Jayachtria, K.G.; Mony, P.K.; Mohan, D.; Kumar, P.; Pvm, L.; et al. Household, Community, Sub-National and Country-Level Predictors of Primary Cooking Fuel Switching in Nine Countries from the PURE Study. *Environ. Res. Lett.* **2019**, *14*, 085006. [CrossRef]
54. Hanna, R.; Oliva, P. Moving Up the Energy Ladder: The Effect of an Increase in Economic Well-Being on the Fuel Consumption Choices of the Poor in India. *Am. Econ. Rev.* **2015**, *105*, 242–246. [CrossRef]
55. Alem, Y.; Beyene, A.D.; Köhlin, G.; Mekonnen, A. Modeling Household Cooking Fuel Choice: A Panel Multinomial Logit Approach. *Energy Econ.* **2016**, *59*, 129–137. [CrossRef]
56. Lewis, J.J.; Pattanayak, S.K. Who Adopts Improved Fuels and Cookstoves? A Systematic Review. *Environ. Health Perspect.* **2012**, *120*, 637–645. [CrossRef] [PubMed]
57. Pope, D.; Bruce, N.; Higgerson, J. The Bottled Gas for Better Life Pilot: An Evaluation of the First Microfinance Initiative in Cameroon to Support Households Switch from Solid Fuel to LPG for Cooking. In Proceedings of the Addressing Complex Local and Global Issues in Environmental Exposure and Health, Ottawa, SO, Canada, 26–30 August 2018; Available online: https://ehp.niehs.nih.gov/doi/abs/10.1289/isesisee.2018.S01.04.23 (accessed on 20 July 2021).
58. Hsu, E.; Forougi, N.; Gan, M.; Muchiri, E.; Pope, D.; Puzzolo, E. Microfinance for Clean Cooking: What Lessons Can Be Learned for Scaling up LPG Adoption in Kenya through Managed Loans? *Energy Policy* **2020**, *154*, 112263. [CrossRef]
59. Entrepreneurs du Monde. *Expanding Access to LPG in Haiti through Microfinance Services*. Gold Standard Monitoring Report. 2017. Available online: https://registry.goldstandard.org/credit-blocks/details/2879 (accessed on 28 July 2021).
60. Shupler, M.; O'Keefe, M.; Puzzolo, E.; Nix, E.; Anderson de Cuevas, R.; Mwitari, J.; Gohole, A.; Sang, E.; Čukić, I.; Menya, D.; et al. Pay-as-You-Go Liquefied Petroleum Gas Supports Sustainable Clean Cooking in Kenyan Informal Urban Settlement during COVID-19 Lockdown. *Appl. Energy* **2021**, *292*, 116769. [CrossRef]
61. Perros, T.; Buettner, P.; Parikh, P. *Understanding Pay-As-You-Go Customer Behaviour*. 2021. Available online: https://mecs.org.uk/publications/understanding-pay-as-you-go-lpg-customer-behaviour/ (accessed on 15 July 2021).
62. Rosenthal, J.; Quinn, A.; Grieshop, A.P.; Pillarisetti, A.; Glass, R.I. Clean Cooking and the SDGs: Integrated Analytical Approaches to Guide Energy Interventions for Health and Environment Goals. *Energy Sustain. Dev.* **2018**, *42*, 152–159. [CrossRef]
63. Singh, D.; Pachauri, S.; Zerriffi, H. Environmental Payoffs of LPG Cooking in India. *Environ. Res. Lett.* **2017**, *12*, 115003. [CrossRef]
64. Permadi, D.A.; Sofyan, A.; Oanh, N.T.K. Assessment of Emissions of Greenhouse Gases and Air Pollutants in Indonesia and Impacts of National Policy for Elimination of Kerosene Use in Cooking. *Atmos. Environ.* **2017**, *2017*, 82–94. [CrossRef]
65. Goldemberg, J.; Martinez-Gomez, J.; Sagar, A.; Smith, K.R. Household Air Pollution, Health, and Climate Change—Clearing the Air. *Environ. Res. Lett.* **2018**, *51*, 030201. Available online: https://iopscience.iop.org/article/10.1088/1748-9326/aaa49d/pdf (accessed on 28 July 2021). [CrossRef]
66. Clasen, T.; Checkley, W.; Peel, J.L.; Balakrishnan, K.; McCracken, J.; Rosa, G.; Thompson, L.M.; Barr, D.B.; Clark, M.L.; Johnson, M.A.; et al. Design and Rationale of the HAPIN Study: A Multicountry Randomized Controlled Trial to Assess the Effect of Liquefied Petroleum Gas Stove and Continuous Fuel Distribution. *Environ. Health Perspect.* **2020**, *128*, 47008. [CrossRef]
67. Smith, K.R.; Bruce, N.; Balakrishnan, K.; Adair-Rohani, H.; Balmes, J.; Chafe, Z.; Dherani, M.; Hosgood, H.D.; Mehta, S.; Pope, D.; et al. Millions Dead: How Do We Know and What Does It Mean? Methods Used in the Comparative Risk Assessment of Household Air Pollution. *Annu. Rev. Public Health* **2014**, *35*, 185–206. [CrossRef]
68. Gasparrini, A.; Guo, Y.; Sera, F.; Vicedo-Cabrera, A.M.; Huber, V.; Tong, S.; de Coelho, M.S.Z.S.; Saldiva, P.H.N.; Lavigne, E.; Correa, P.M.; et al. Projections of Temperature-Related Excess Mortality under Climate Change Scenarios. *Lancet Planet. Health* **2017**, *1*, e360–e367. [CrossRef]
69. GLPGP. *Assessing Potential for BioLPG Production and Use within the Cooking Energy Sector in Africa*; The Global LPG Partnership: New York, NY, USA, 2020; Available online: https://mecs.org.uk/wp-content/uploads/2020/09/GLPGP-Potential-for-BioLPG-Production-and-Use-as-Clean-Cooking-Energy-in-Africa-2020.pdf (accessed on 14 July 2021).
70. Chen, K.C.; Leach, M.; Black, M.J.; Tesfamichael, M.; Kemausuor, F.; Littlewood, P. BioLPG for Clean Cooking in Sub-Saharan Africa: Present and Future Feasibility of Technologies, Feedstocks, Enabling Conditions and Financing. *Energies* **2021**, *14*, 3916. [CrossRef]
71. The World Bank. World Bank Project to Boost Household Access to Affordable Energy. Available online: https://www.worldbank.org/en/news/press-release/2020/09/17/world-bank-project-to-boost-household-access-to-affordable-energy (accessed on 14 July 2021).
72. World Bank Development Projects: Rwanda Energy Access and Quality Improvement Project—P172594. Available online: https://projects.worldbank.org/en/projects-operations/project-detail/P172594 (accessed on 14 July 2021).