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Liquefied Petroleum Gas as a Clean Cooking Fuel for Developing Countries: Implications for Climate, Forests, and Affordability

Authors: Nigel G. Bruce, Kristin Aunan, Eva A. Rehfuess

Content

Abbreviations

ALRI	Acute Lower Respiratory Infections
BC	Black Carbon
CDM	Clean Development Mechanism
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COPD	Chronic Obstructive Pulmonary Disease
ECOWAS	Economic Community Of West African States
ECREE	ECOWAS Centre for Renewable Energy and Energy Efficiency
EU-AITF	European Union African Infrastructure Fund
HAP	Household Air Pollution
IAQG	Indoor Air Quality Guidelines
IER	Integrated Exposure-Response Function
IHD	Ischemic Heart Disease
ISO	International Organization for Standardization
GHGs	Greenhouse Gases
GS	Gold Standard
GWC	Global Warming Commitment
GWP	Global Warming Potential
LCA	Life Cycle Analyses
LCEE	Life Cycle Energy Efficiency
LMICs	Low and middle income countries
LPG	Liquefied Petroleum Gas
N_2O	Nitrous Oxide
NG	Natural Gas
NMHC	Nonmethane Hydrocarbons
NO_x	Nitrogen Oxides
OC	Organic Carbon
PAHs	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter of a diameter of up to 2.5 micrometres
RR	Relative Risk
SDG	Sustainable Development Goal
SEforALL	Sustainable Energy For All
SLCPs	Short-Lived Climate Pollutants
SO_2	Sulphur Dioxide
SSA	Sub-Saharan Africa
UN	United Nations
USEPA	US Environmental Protection Agency
WHO	World Health Organization

Preface

With the adoption of the 2030 Agenda for Sustainable Development by the United Nations in 2015, the global community recognised the central role of access to modern energy for development. Against this background, a growing number of governments of countries in Sub-Saharan Africa, and in other regions, have now set out ambitious plans for scaling up liquefied petroleum gas (LPG) as a cooking fuel. Countries have taken this initiative for a number of inter-related reasons, including meeting the Sustainable Energy For All (SEforALL) goal and Sustainable Development Goal (SDG) 7 of universal access to modern energy, economic development, forest protection and for reducing the health burden from household air pollution due to biomass and kerosene fuel use.

Ministries in a number of these countries have sought advice on the development of policies and investments required for securing the expansion of effective, safe, and sustainable markets for LPG cooking fuel. For three in Sub-Saharan Africa, namely Cameroon, Ghana and Kenya, this support is being delivered through the 'Clean Cooking for Africa Programme' of KfW, funded through the European Union-Africa Infrastructure Fund[1] and implemented by the Global LPG Partnership. Within this Programme, country-specific assessments of the LPG markets as well as the impacts of LPG on the climate and forests, and on affordability and equity of access and the viability of investments into LPG infrastructure for clean cooking will be provided. Furthermore, the Clean Cooking for Africa Programme may support investments into LPG infrastructure for clean cooking in two of the three countries.

The starting point for this report includes recognition of the following points. First, countries seeking to achieve major transitions in household energy must respond to the needs, resources and circumstances of their populations, which will vary markedly across urban and rural settings, by socio-economic status, and over time. A variety of fuels and technologies may therefore be required, with roles for both modern fuels such as LPG and electricity, as well as improved biomass. Second, LPG is already a widely used, efficient and safe (given appropriate regulation and correct use) cooking fuel across the developed world and in many low and middle income countries[2]. Third, in recent years, LPG has been selected by a growing number of low and middle income country governments to be the primary cooking fuel for expanded access to clean and modern energy for their populations.

Against this background, important questions around the impacts on climate and forests, and on scalability and fuel affordability, are examined in this report. As the focus is on work in Sub-Saharan Africa, the main fuels considered for comparison are wood and charcoal (including prospects for improving the technology used to burn them) and, to a lesser extent, kerosene.

A wide range of findings are presented and discussed in this report. In doing so, one limitation to making comparisons between LPG and biomass fuel has emerged. LPG is a well-established cooking fuel, and data are available on many aspects of its performance. By contrast, the long-term performance and sustaina-

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[1] http://www.eu-africa-infrastructure-tf.net/index.htm
[2] Including Brazil, El Salvador, Gabon, Malaysia, Morocco and Thailand, to name some.

bility of improved biomass stoves in everyday use, in particular the more recent fan-assisted and gasifier technologies ('advanced biomass') have not yet been extensively evaluated. Accordingly, the relative paucity of such data has implications for the interpretation of some of the comparative analyses reported, in particular for life cycle energy efficiency (LCEE). Despite this limitation, data compiled for this report do allow for balanced assessment of some of the other key questions, including for climate emissions and life cycle analysis (LCA) of environmental impacts.

Authors of this report

Nigel Bruce is Emeritus Professor of Public Health at the University of Liverpool, UK, and he is the chair of the Scientific Advisory Board (SAB) for the KfW Clean Cooking for Africa Programme. Previously, he worked as a consultant at the World Health Organization supporting the programme on household energy, air pollution, health and climate change. Professor Kristin Aunan is Senior Research Fellow at the Center for International Climate and Environmental Research (CICERO) in Norway. She is SAB member of the KfW Clean Cooking for Africa Programme. Dr Eva Rehfuess is Senior Scientist at the Institute of Medical Informatics, Biometry and Epidemiology at Ludwig-Maximilians-University, Munich, and Adjunct Professor at the Department of Environmental Sciences and Engineering at the UNC Gillings School of Global Public Health. She also coordinates the Collaboration for Evidence-Based Healthcare and Public Health in Africa and is SAB member of the KfW Clean Cooking for Africa Programme.

Executive Summary

Problem statement

Well into the second decade of the 21st century, more than 3 billion people are still exposed to high concentrations of air pollution from the burning of solid fuels and kerosene in open fires and simple cookstoves for home cooking[3]. This household air pollution (HAP) far exceeds 'safe' levels defined in World Health Organization (WHO) air quality guidelines.

Reliance on inefficient and polluting household fuels has substantial impacts in terms of health, biomass resources, the persistence of poverty and gender inequalities, and contributions to global climate change. The main cause of such far-reaching impacts is that these fuels are typically burned in traditional and other simple stoves characterised by incomplete combustion. The resulting emissions contain many pollutants that pose major risks to health, as well as black carbon and methane, with important short-term warming effects on the climate. In addition, much biomass fuel harvesting is non-renewable, thereby adding to atmospheric CO_2.

According to the WHO, HAP from solid cooking fuels is responsible for around 4 million premature deaths annually, due to childhood pneumonia, chronic lung disease, cardiovascular disease and cancer. Furthermore, recent evidence on the relationships between levels of exposure to pollution and health risk indicates that levels of household particulate matter would have to be reduced nearly to WHO guideline levels for a large proportion of this health burden to be averted.

In Sub-Saharan Africa, four out of five people use wood fuel or charcoal as their main source of energy for cooking. Considering the rapid population growth in Africa (projected to reach 2.5 billion by 2050)[4], the total number of solid fuel users – along with the associated adverse health, environmental and developmental risks – will increase unless urgent, effective, and far-reaching action is taken.

LPG as an option for clean cooking

Community-wide use of clean fuels is required if air quality is to consistently achieve WHO guideline levels of particulate matter. In the transition towards universal use of clean fuels, countries will be looking to strategies that address the energy needs of their varied populations over time, involving a portfolio of energy carriers and technologies to meet cooking and other household requirements.

In the context of Sub-Saharan Africa over the next 10-20 years, this energy and technology mix is expected to include improved (e.g. rocket-type) and advanced (e.g., fan-assisted, pellet fueled, etc.) biomass stoves for those unable to transition

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[3] WHO (2016). Burning Opportunity: Clean Household Energy for Health, Sustainable Development, and Wellbeing of Women and Children Report. Geneva: World Health Organization.

[4] United Nations, Department of Economic and Social Affairs, Population Division (2015). World Population Prospects: The 2015 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP.241.

quickly to existing clean liquid or gaseous fuels, or electricity. For these populations, it will be important to ensure that the cleanest possible technologies are promoted and that their correct use and maintenance is encouraged, as recommended by the WHO.

Among the existing liquid and gaseous fuel options, LPG can make an important contribution, with the potential to deliver substantial benefits for health, climate, the environment, and development. As with biomass fuels and stoves, building the market and other conditions required for ensuring adequate supply, and correct and safe use of LPG, is also a key policy requirement.

A number of country governments, including India, Ghana, Kenya, and Cameroon, have made it a priority to serve a majority of their populations with LPG for a mix of reasons including tackling energy-related air pollution, forest preservation and economic development. At a global level, however, the fact that LPG is a fossil fuel raises questions about its environmental credentials. Issues around the overall affordability and accessibility for poorer and more rural populations also need to be addressed.

This report brings together the most recent findings suggesting that the use of LPG instead of traditional biomass fuels and kerosene among the 3.1 billion people currently using these[3] would contribute little or no net climate warming effect and would protect forest resources. Life cycle assessments, which include analysis of climate-active emissions for a range of fuel options (including examples of advanced biomass technologies) across production, processing, distribution and use, provide valuable comparative evidence. These have found that LPG as a cooking fuel performs similarly to advanced biomass stoves for net CO_2 emissions in settings where fuel harvesting for the latter is partially renewable and better than these technologies for black carbon and other short-lived pollutants.

These advantages are the result of (i) LPG having a lower Carbon-to-Hydrogen ratio (C:H of about 1 to 3) than any other hydrocarbon fuel except for natural gas (e.g. coal has a C:H ratio of about 2 to 1), (ii) very efficient combustion compared with other fuels, thereby keeping emissions lower; (iii) the completeness of combustion, which means that black carbon and other climate-active pollutant emissions are much lower than from biomass-burning stoves and open fires; (iv) the emissions performance of LPG stoves generally remaining good over time and being relatively independent of user-operating factors, and (v) LPG fuel supply placing no burden on forest resources.

Where all or most cooking fuel is purchased, which occurs mainly in urban and peri-urban settings, LPG has been shown to cost no more than kerosene, wood fuel, biomass pellets or charcoal. These latter fuels are typically bought in small quantities, and while overall costs of LPG may be similar, the outlay for refilling a cylinder may be problematic for low-income households. A number of options are available to address this issue with LPG refill costs, including smaller (e.g. 3 kg) cylinders which are well-established, along with newer initiatives involving pay-as-you-go LPG use and partial cylinder refills (although this last example has raised safety concerns). Some households may also need assistance with the initial acquisition of the stove, cylinder and associated equipment, as traditional stoves are in general less costly than the equipment required for cooking with LPG.

For poorer and more rural populations currently gathering all or most of their fuel, initial and ongoing costs for LPG refills present significant barriers. This is why smart subsidies or other forms of financial support, which preferentially assist poorer households, have a role in facilitating acquisition and use of LPG outside urban centres. This type of targeted financial assistance is already a key component of policy on LPG access in several countries, including India, Brazil and Peru.

LPG is a well-established fuel for cooking which offers a mature option within a country's energy portfolio, albeit there can be significant challenges including enforcement of regulation, ensuring adequate supply, and with distribution where poor roads and long distances exist. There is also the need to develop and implement sustainable fiscal policy, which can support more equitable access.

For the user, the speed and controllability of LPG cooking, combined with the convenience of storage, result in substantial convenience and time savings. This has particular implications for women, children, and others currently engaged in collecting biomass fuel, and for cooking. The added convenience and time savings offer the potential for making more of employment and education opportunities.

Conclusions

LPG is a mature technology already used by almost 3 billion people globally with the potential to change the landscape of household energy in the developing world, by providing substantial and linked benefits for health, climate, forest protection and development. It can play an important role in permitting those households currently exposed to high concentrations of household air pollution to benefit from reliable and efficient clean household energy – benefits that about 60% of the world's population are already enjoying on a daily basis. While well-planned financial and fiscal instruments may be needed to assist transition among poorer and more rural populations, building a sound infrastructure for those who can currently benefit can also help accelerate adoption within nations.

Key messages

In summary, a substantial proportion of current biomass/kerosene users switching to LPG would result in:

1. **Significant direct health benefits** from substantially reducing exposure to household air pollution from burning of solid fuels and kerosene;
2. **A negligible increase in global energy-related CO_2 emissions** when compared to currently available biomass burning stoves and other fuels, even though LPG is a fossil fuel;
3. **A reduction in emissions of other climate active pollutants** such as methane, black carbon and organic carbon released by inefficient solid fuel stoves, with the first two species contributing to global warming in the near-term;
4. **Less pressure on forests**, where wood fuel including charcoal use is harvested non-renewably and contributing to loss of forests;
5. **A reduction in women and children's labour time** in fuel collection and cooking where there is dependence on solid fuels, and opening up opportunities for greater engagement with education and the labour market;
6. **The opportunity to increase societal benefit from global LPG use**, given that LPG is abundant, with a current excess of production over consumption; much is used by industry (e.g. for plastics) or wasted through flaring/venting.

In order to realise these benefits among all of those who stand to gain from a transition to LPG use, national policy and planning need to address the key challenges of supply, regulation, distribution and affordability for the poor. A number of low and middle income countries have shown, and are showing, that this is possible at scale, and this experience can serve as an example for other countries seeking to extend access to and use of LPG.

1. Why is clean cooking a high priority for global public health?

1.1 Health risks and intervention impacts

Globally, approximately 4.3 million premature deaths each year are estimated by WHO to be attributable to HAP from inefficient burning of solid fuels (1), making HAP the single most important environmental health risk factor worldwide. These deaths result from pneumonia among children and cardiovascular disease, chronic lung disease and lung cancer among adults.

Recent evidence on the relationships between levels of exposure to smoke and risks of these diseases (2) has been compiled in the *WHO Indoor Air Quality Guidelines (IAQG) for Household Fuel Combustion*. This evidence includes so-called integrated exposure-response functions (IERs).

IER curves are statistical models ('functions') that combine research findings on the health risks associated with different levels of exposure to small particulate matter ($PM_{2.5}$) for four sources of combustion-related pollution, namely outdoor air, secondhand tobacco smoke, household air pollution and active tobacco smoking. These IERs are now available for four adult health outcomes, namely ischemic heart disease (IHD), stroke, chronic obstructive pulmonary disease (COPD) and lung cancer. For children, the only IER available to date is for acute lower respiratory infections (ALRI) and only the first three combustion sources are used as young children do not smoke. The IER function for child ALRI is presented in Figure 1.1.

Figure 1.1 shows that the relationship between exposure and relative risk (RR)[5] for ALRI is not linear, but curved; it is steep at low levels of exposure and then tends to flatten off. This is also the case for the adult outcome IERs, with the exception of that for lung cancer which is more or less linear (a straight line). For child ALRI, the risk is more than three times greater at exposure levels of around 600 $\mu g/m^3$ $PM_{2.5}$ when compared with the risk at very low levels of exposure. This non-linear shape, however, means that risk remains substantial as exposure is reduced from high levels; for example, the RR is still approximately double at 100 $\mu g/m^3$, despite this being only 17% of the exposure (600 $\mu g/m^3$), for which the risk was three times.

This evidence led WHO to conclude that reduction of exposure to levels at or close to the guideline value for the key pollutant $PM_{2.5}$ to 10 $\mu g/m^3$ for the annual average was needed in order to prevent the majority of cases of disease and associated premature deaths attributable to $PM_{2.5}$ (3).

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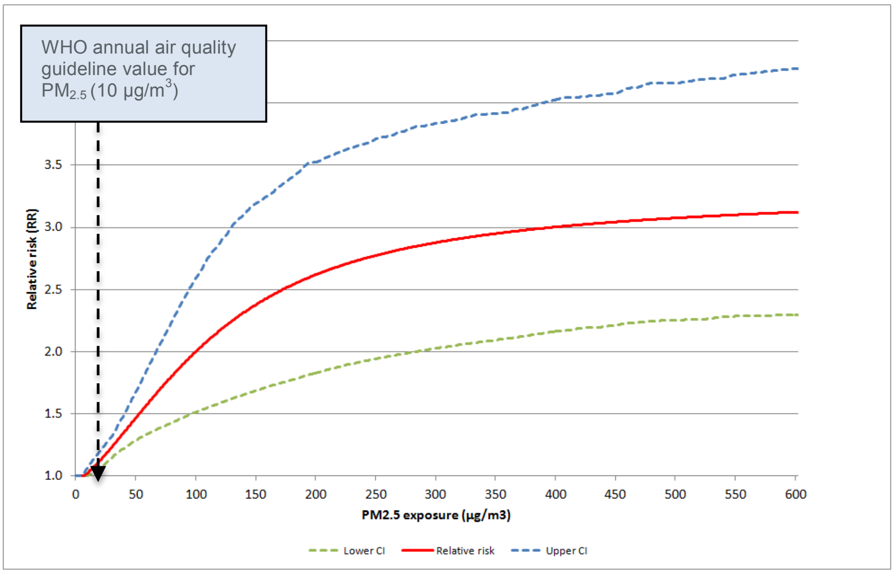
[5] The relative risk (RR) is the risk of a disease that, on average, an individual exposed to one level of a risk factor will experience, compared to that experienced by an individual exposed to a lower level of the same risk factor.

Figure 1.1: The relationship between levels of $PM_{2.5}$ exposure ($\mu g/m^3$) and relative risk of child acute lower respiratory infections (ALRI) based on the integrated exposure response (IER) function, for exposure over the range 0–600 $\mu g/m^3$ (see text for further explanation).



Source: WHO, 2014 (3).

This emerging knowledge on exposure and health risks is highly relevant to policy as – based on evidence for the performance of currently available stove technologies - use of clean fuels will be required to achieve $PM_{2.5}$ levels at or close to the WHO guidelines. While solid biomass stoves are being continually improved, and some can produce relatively low emissions when used optimally in laboratory testing (4), results from evaluations of use in the home have to date been generally less impressive (5). The combined evidence from more than 30 studies of improved biomass cookstoves (rocket-type, chimney and advanced) in everyday use across Asia, Africa and Latin America has shown that, while on average levels of $PM_{2.5}$ were reduced by 40-50%, the resulting indoor concentrations were still substantially above WHO guidelines levels (6-10). The IER functions, when applied to the changes in measured exposure, imply that reductions of health risks from these interventions would be relatively limited. In rural Guatemala, the RESPIRE randomised trial showed that a chimney wood stove reducing exposure by around 50% in comparison with continued use of the open fire resulted in a non-significant 22% reduction in the incidence of child pneumonia (11). In Malawi, results from the recently completed CAPS trial show even less effect, with no impact on child pneumonia reduction through the use of a fan-assisted advanced biomass cookstove vs. open fire, in spite of good laboratory performance (12). Results for the exposure reductions achieved during this trial are awaited, however.

Over and above the inherent combustion properties of biomass stoves, the main reasons for these continuing high $PM_{2.5}$ levels are (i) how the stoves are used in practice (e.g. overloading of wood and other biomass residues into the stove), (ii) the type and moisture levels of wood or other biomass, (iii) the continued use of traditional stoves (stacking) and (iv) pollution from other sources (e.g. lighting, heating, trash burning) in and around the home, including from neighbours. In addition, some studies have found improved/advanced solid fuel cookstoves to have limited durability in everyday use (from a few months to one to three years) and require regular maintenance and repair to ensure optimal performance over time (7, 12-14), while others have reported less maintenance requirements (15, 16).

Although some of these factors apply also to the use of clean fuels in the home, and further development of technology and improvements in the use of the best solid fuel stoves will likely yield some performance improvements, modern liquid and gaseous fuels, including LPG, do generally perform well in everyday use. LPG has a clean emissions profile (blue flame)[6], high stove thermal efficiency and the technology deliver low emissions, essentially independently of condition and age of the equipment (unless badly corroded or otherwise damaged) and, importantly, how users operate it (17-19).

1.2 Options for the transition to clean household energy

In its IAQGs for Household Fuel Combustion, WHO recognised that transition from the current situation to universal use of clean household energy would take time, especially for poorer and more rural populations. Accordingly, Recommendation 2 of these Guidelines stated:

Governments and their implementing partners should develop strategies to accelerate efforts to meet air quality guidelines (Ref: Recommendation 1); where intermediate steps are judged to be necessary, transition fuels and technologies that offer substantial health benefits should be prioritised (3).

Among the further guidance on this issue, WHO went on to recommend that *"implementing agencies should work to increase access to, and sustained use of, clean fuels as widely and rapidly as is feasible"*, and that *"technologies and fuels being considered for promotion should have emission rates tested, and where possible, actual air pollution levels in everyday use in homes measured.*"

A strategy for transition in household energy over the next 30 or so years therefore envisages a combination of (i) accelerated access to clean fuels and (ii) development and promotion of improved (and as much as possible advanced technology) solid fuel stoves. Implementation of clean fuels and improved solid fuel options should both be accompanied by laboratory and field testing of emissions, efficiency, and safety; in the field testing, air quality, exposure and user-related factors should also be assessed. Figure 1.2 illustrates – in a simplified way – how different mixes of fuels and technologies and speeds of transition may be appropriate for different segments of populations that vary by socio-economic circumstances and geography. Investments in policy and infrastructure made for clean fuels now can help lay the basis for later adoption among those currently unable to afford or access reliable supplies of LPG, electricity, etc.

We also know that adoption of new technologies and fuels often leads to these being added to existing practices, leading to so-called 'stacking' within households whereby one set of tasks (e.g. cooking) may be carried out with more than one type of fuel and technology, and different needs (cooking, heating, lighting, processing food, etc.) will almost certainly be carried out using different energy sources and technologies (20, 21). This applies as much to the introduction of clean fuels as it does to improved solid fuel options (12, 22), and clearly has important implications for the resulting total emissions, indoor and outdoor air quality and personal exposure to health-damaging pollutants. The goal should therefore be to help households move steadily towards more exclusive use of the cleanest options available to them.

Within the context of a mixed and dynamic strategy for this household energy transition, LPG offers one of the most practical clean alternatives to solid fuels and kerosene for delivering household energy on a global scale over the short to me-

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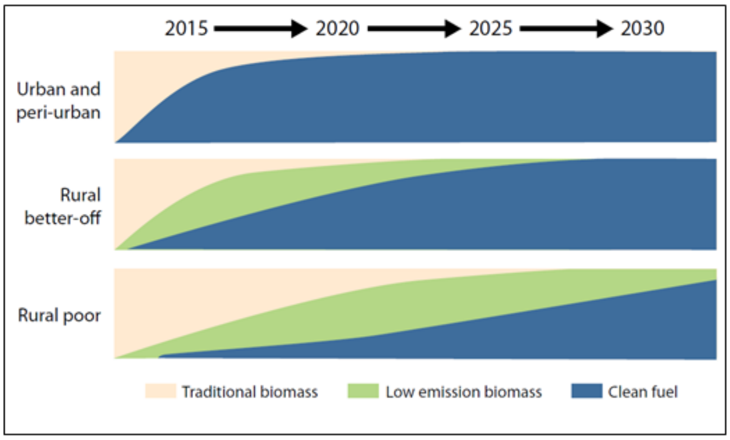
[6] As compared to biomass and coal burning characterised by a yellow flame.

dium-term. LPG is widely available and there is now a wealth of experience in developing effective national markets. Even in countries with limited endogenous production, LPG can become the primary and secondary household fuel if the right policy decisions and conditions are in place, as shown by countries such as Gabon (79% LPG usage) (23) and Brazil (95% LPG usage) (24).

Figure 1.2 - Hypothetical, simplified scenarios for rates of transition from predominantly traditional solid fuel use for cooking in the home to low-emission improved solid fuel stoves, clean fuels and/or electricity across three differing socially and geographically defined groups.



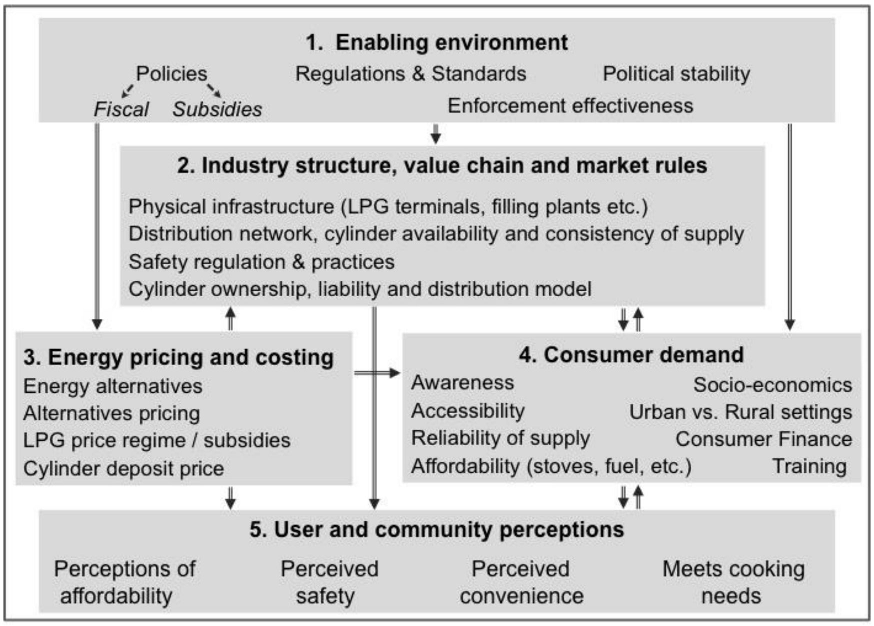
Source: WHO 2014 (3)

A wide range of factors govern the success of efforts to promote adoption and sustained use of cleaner and more efficient household energy, including of LPG (22, 25). These factors fall into a number of domains ranging from household circumstances, income and cultural preferences, through to government policy, regulation and investment conditions. In the case of LPG, the research literature on these factors, while extensive in many respects, does not represent well those political, policy and commercial conditions that are critical for LPG market systems to function effectively in poor countries. The Implementation Science Network on Clean Cooking, recently established by the US National Institute of Health (NIH) to bring an evidence-based approach to securing more effective adoption and use of clean household cooking, has brought together the published scientific evidence and practical experience to develop the more comprehensive model shown in Figure 1.3 (26).

LPG has the potential to make a major contribution to creating a step-change in how the poor use energy, and accelerate the move towards parity in energy access between developed and developing regions, as called for by the United Nations' Sustainable Development Goal (SDG) 7. Indeed, SDG 7 has put a global spotlight on air quality, through access to clean energy for all. The International Energy Agency, in its 2016 report on the energy policies required to achieve WHO air quality guidelines, recognises the contribution of household fuel combustion to indoor and outdoor air pollution, and notes the important role that LPG can play in addressing this (27).

Against this background of the potential of LPG as a clean and efficient cooking fuel for the world's poorer countries, this report now considers in further detail the characteristics of LPG, and its impacts with respect to climate change, forest protection, affordability and supply, and in promoting opportunities for social and economic development. Consideration is also given to the scalability of LPG and investment needs in the regions and countries concerned.

Figure 1.3 – Model describing the key dimensions and factors for LPG scaling-up and sustained adoption



Source: Rosenthal et al. 2017 (26).

2. Use, affordability and safety of liquefied petroleum gas

2.1. Features, production and availability of LPG

2.1.1 Sources and composition

LPG is a by-product of oil and natural gas production and petroleum refining, and is produced in a highly-purified state. It consists of a varying blend of light hydrocarbon compounds, the two main ingredients being propane (C_3H_8) and butane (C_4H_{10}). LPG can generally be differentiated from other energy sources on the basis that combines portability with convenience, high energy and low sulphur content, and its clean burning nature. LPG is non-toxic, colorless and odorless; the characteristic smell is from an odorant added to aid detection of leaks (28). Although today some 40% of LPG still comes from oil refineries (29), it is expected that this fraction will decline in both relative and absolute terms as LPG supplies rise due to increased natural gas production worldwide (30).

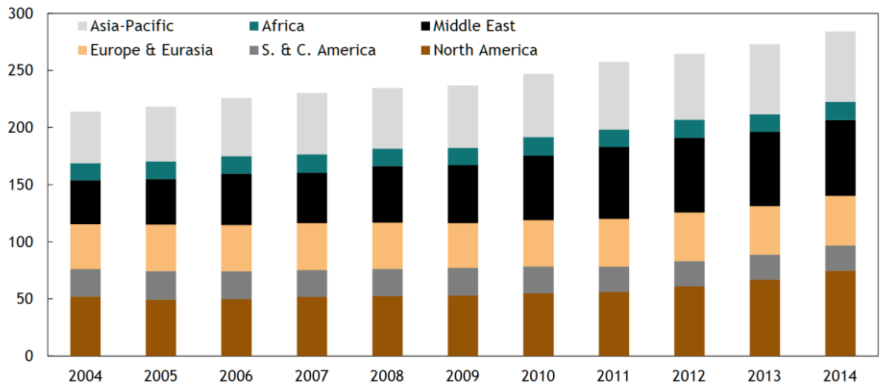
Unlike natural gas, LPG can be easily liquefied under moderate pressure (28). The resulting ease of transport and storage of LPG gives this fuel considerable advantages in terms of efficiency and distribution in LMICs compared with other major clean cooking alternatives. Electricity for example, while clean (at the point of use) and practical, requires costly and extensive distribution infrastructure as well as sufficient generation capacity with often negative climate impacts due to continuing widespread reliance on coal. Natural gas is not available in many LMICs and has to be piped into homes. However, in cities where electricity and natural gas grids can successfully displace LPG as countries develop, LPG assets can be increasingly redeployed to peri-urban and rural settings. This has occurred in China since the mid-2000s (31) and the same trend is now being seen in India (32). Two other clean fuels, bio-ethanol and biogas, have considerable potential but are unlikely to be suitable for meeting cooking needs at national scale. Biogas requires specific conditions that are not usually available for all homes, nor across national territories. Bio-ethanol, while contributing substantially to vehicle fuel, has not yet been widely adopted for cooking but has the potential to be used more extensively. Solar cooking devices can contribute effectively to household cooking systems, but need to be used when sunshine is available and have not been shown to be practical for meeting the majority of cooking needs (25).

2.1.2 Current and projected availability

LPG is primarily used by commerce and households for cooking and heating purposes. The residential sector accounted for almost 50% of LPG global consumption in 2014 (33). LPG is currently abundant and its production has recently been growing at 3% to 4% a year, such that LPG availability has consistently exceeded consumption (Figure 2.1). From 2009, this trend has been mainly the result of US shale gas development, which provides LPG as a by-product (29). In 2014, LPG production reached just over 284 million tonnes/year, while consumption reached just over 275 million tonnes/year (with an LPG excess of almost 10 million tonnes, equal to 3.5% of total production) (33). Some of this excess portion is vented or flared at oil and gas production sites on a daily basis, thereby wasting this valuable fuel resource and still putting the fuel carbon back into the atmosphere.

Furthermore, a large portion of current LPG global production (28%) is used in the petrochemical sector as a feedstock in plastics production in industrialised nations or as a blending component for gasoline (petrol) (29, 33). Commercially viable alternatives, such as ethane, which is found along with butane and propane, could be used by the petrochemical industry - as was the case before the discovery of shale gas and associated increased production of LPG - instead of being left in the natural gas stream as is currently practiced (29).

Figure 2.1: LPG production by region 2004-2014, million tonnes



Source: Adapted from Argus/WLPGA, Statistical review of Global LPG 2015 (33)

All world regions currently produce LPG, with North America, the Middle East and the Asia-Pacific region being the top three producers. Industry forecasts predict continued growth in LPG production, driven mostly by natural gas extraction (30). These trends are leading many governments, including in Africa and Asia, to confidently plan LPG into their future energy portfolios. In 2014, 16 million tonnes of LPG were produced in Africa, primarily by Algeria (55%), followed by Angola (13%), Egypt (10%) and Nigeria (9%), while total consumption in the region was 13 million tonnes. The Asia-Pacific region produced 61 million tonnes, primarily by China (41%), followed by India (12%), Japan (9%), South Korea (5%) and Thailand (3%), and consumed 99 million tonnes (33).

In the most recent (2016) G20 summit in Hangzhou, global leaders reaffirmed their commitment “*to building well-functioning, open, competitive, efficient, stable and transparent energy markets”.* They went on to say “*Given that natural gas is a less emission-intensive fossil fuel, we will enhance collaboration on solutions that promote natural gas extraction, transportation, and processing in a manner that minimizes environmental impacts. We stress the importance of diversification of energy sources and routes”.* The G20 commitment to promote natural gas usage as part of this strategy would also be expected to result in increased production and availability of LPG.

Based on estimated LPG consumption in India of approximately 24.7 kg per capita per year when used for cooking in stoves with 55% efficiency[7], around 24.7 million tonnes annually would be needed to meet the needs of an additional one billion LPG users (corresponding to almost 8.7% of global LPG production in 2014). Even with potential future reductions in global fossil fuel production to meet international commitments to address climate change, LPG production can be expected to

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[7] The average daily heat energy requirement per household for cooking activities in India has been estimated at 2150 kcal (equivalent to 9 MJ) based on Singh & Gundimeda, 2014 (37). This corresponds to 620 MJ per capita per year (based on an average household size of 5.3 according to 2011 Census data). Considering that LPG cookstoves can reach an efficiency rate of 60%, and assuming that LPG contains 45.5 MJ/kg of energy (see Table 2.1), the total minimum annual requirement for cooking is approximately 22.7 kg per capita. With a more conservative value for efficiency of 50%, the annual requirement would be 27.2 kg per capita.

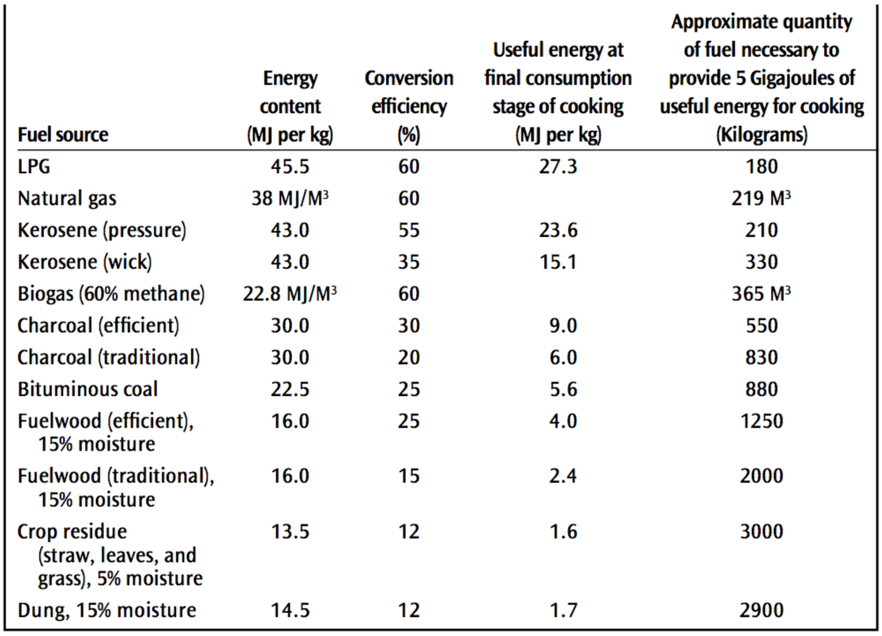
remain more than adequate for projected global use as a cooking fuel (30). In addition, LPG wastage due to flaring could be reduced by efforts such as the World Bank's initiative on Zero Routine Flaring by 2030 (34).

2.2. LPG as a cooking and heating fuel

2.2.1 Combustion efficiency

As a gas, LPG can easily be burned efficiently and also has a relatively high energy value for its carbon content (35), making it a relatively low carbon alternative to conventional fossil alternatives such as coal, heating oil or kerosene. It can be used in simple cooking stoves cleanly and efficiently; reported thermal combustion efficiency is in the range of 45-60% depending on the stove used (Table 2.1) with low pollutant formation (36-40). This efficiency is comparable to that for natural gas.

Table 2.1: Typical Efficiencies at the Final Consumption Stage of Cooking

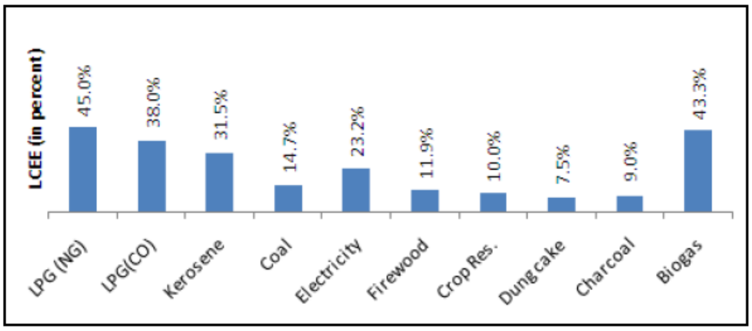


Fuel source	Energy content (MJ per kg)	Conversion efficiency (%)	Useful energy at final consumption stage of cooking (MJ per kg)	Approximate quantity of fuel necessary to provide 5 Gigajoules of useful energy for cooking (Kilograms)
LPG	45.5	60	27.3	180
Natural gas	38 MJ/M^3	60		219 M^3
Kerosene (pressure)	43.0	55	23.6	210
Kerosene (wick)	43.0	35	15.1	330
Biogas (60% methane)	22.8 MJ/M^3	60		365 M^3
Charcoal (efficient)	30.0	30	9.0	550
Charcoal (traditional)	30.0	20	6.0	830
Bituminous coal	22.5	25	5.6	880
Fuelwood (efficient), 15% moisture	16.0	25	4.0	1250
Fuelwood (traditional), 15% moisture	16.0	15	2.4	2000
Crop residue (straw, leaves, and grass), 5% moisture	13.5	12	1.6	3000
Dung, 15% moisture	14.5	12	1.7	2900

Source: O'Sullivan and Barnes, 2007 (35), adapted from "Energy Statistics: A Manual for Developing Countries" Series F, No. 56. United Nations: New York.

This characteristic of high efficiency is also seen when a life cycle energy efficiency (LCEE) analysis is carried out for LPG and other fuels. The LCEE is defined as the useful energy delivered, divided by the consumption of energy for the entire life cycle. One such analysis for a range of cooking fuels in the Indian setting is shown in Figure 2.2. This includes cleaner fuels such as LPG, electricity, biogas, as well as solid fuels burnt in traditional and improved stoves. One limitation of this Indian study for the current purposes, however, is that no advanced biomass cookstoves were included.

Figure 2.2 – Life Cycle Energy Efficiency (LCEE) of cookfuels used in India



Source: Singh and Gundimeda, 2014 (41).

Results for LPG derived from crude oil (LPG-CO) differ from LPG derived from natural gas (LPG-NG); these two are treated separately because they follow different production pathways (see also Section 3.2). Among all of the fuels analysed in this study, LPG derived from natural gas has the highest LCEE of 45%, which is comparable to biogas (43.3%) (41). Biogas is a very energy efficient option, with the added advantage of renewability, but has practical limitations in respect of where and how widely it can be used (25). Electricity production in India relies mainly on coal and lignite and therefore the performance of electric cooking is only moderate, despite very high stove efficiency (above 60%), due to poorer conversions efficiencies of coal power plants in addition to transmission losses (41).

LPG cookstoves perform at or above Tier 4 (the best tier level) for both $PM_{2.5}$ and carbon monoxide (CO) emissions as specified under the International Organization for Standardization (ISO) International Workshop Agreement 11 (42), and in most cases also meet the WHO final emission rate target for $PM_{2.5}$ (3, 43).

2.2.2 Time savings and convenience

LPG cookstoves heat quickly, and provide considerable control over the desired level of cooking power, so users can benefit from time savings through faster cooking. In Sri Lanka, for example, this time saving was estimated at 2 to 3 hours per day (44).

For those households currently collecting solid biomass fuel, the convenient storage of LPG in cylinders within the home offers further and potentially very substantial time savings. For example, a study from India reported that after introduction of LPG in the lower regions of Himalaya, men stopped fuelwood collection and women reduced the time spent for collection from 2.2 to 0.2 hours per day (45). In other Indian regions, time savings were estimated between 1.5 and 2 hours per day (46, 47). In addition, some further time savings (estimated between 15 to 30 minutes) arise from utensils not getting blackened by smoke and requiring less time to be washed and cleaned (47, 48). In less secure settings removal of the need to collect biomass fuel can also reduce threats to personal security (49). Time savings have also been reported to provide the opportunity to develop skills and generate income through the establishment of small individual and group enterprises in some settings (48), and to facilitate entry into the labour market in others (44).

A basic LPG system for household cooking consists of a LPG cylinder, valve connector, a pressure regulator, a rubber pipe and a cookstove (single or multi-burners). The majority of LPG cookstoves are durable, lasting 5 to 10 years depending on the type of stove, quality of materials and design (50, 51). It is also possible to fit the cookstove directly onto the top of the cylinder, making sure that the base of the cylinder is large enough to ensure stability in use. This is usually done with small size cylinders (e.g. 3 to 6 kg) to reduce the cost of the LPG system, while fixing the safety issue of cookstoves connected by a pipe being placed on the ground/floor by some users (52).

LPG is highly portable, so that it can be used for indoor or outdoor cooking according to household needs and preferences. Surveys have consistently shown that notwithstanding safety concerns (see Section 2.4), energy-poor consumers consider LPG to be an aspirational fuel, because it is clean, cooks quickly, is easy to use, and is practical to handle (50, 53, 54). Having LPG is also perceived to be a status symbol, and adoption is often associated with other improvements in the home. The notion of "modernisation" frequently accompanies the adoption of LPG cookstoves (54).

2.2.3 Use of household fuels for space heating

Households living in many temperate and mountainous areas of the world need some form of space heating. One feature of the open fire or traditional solid fuel stove is that it can provide warmth as well as being used for cooking. Switching to cooking with LPG may result in continued use of the solid fuel stove for warmth, since it is neither practical nor affordable to use the LPG cookstove itself for household space heating. LPG, however, is already widely used with space heaters designed for this purpose. Some countries, like Turkey, have extensively promoted LPG as a portable heating fuel in households and rural schools, where previously wood fired stoves had been used to heat the classrooms (55). Recurrent refill costs might be a barrier for lower income households, but addressing space-heating needs with low-emission fuels and technologies is almost as important as offering clean cooking solutions in some parts of the world. Further consideration of the affordability of LPG is provided in Section 2.3 below.

2.3. Affordability and supply of LPG

A substantial proportion of biomass users (50% in Sub-Saharan Africa as estimated by the World Bank), mainly living in urban and peri-urban areas, already purchase all or most of their fuel and could afford to use LPG for daily cooking (56). Indeed, multiple studies show that in these cash-market conditions solid fuels are as expensive as liquid and gaseous fuels and cleaner fuels are usually considered aspirational (56-58). However, lack of cost comparisons between LPG and fuelwood/charcoal cooking that are easily available to the consumer may discourage adoption of LPG as many assume that it would cost more to use than traditional fuels.

One reason for this perception of higher relative cost is that solid fuels and kerosene can be purchased daily in small amounts, whereas LPG users have (mostly) been obliged to purchase a cylinder refill (often of 11-15 kg) every few weeks in a single larger outlay. Evidence from Guatemala shows that households that make a careful comparison of the costs of LPG and fuelwood become aware of the cost savings of cooking with LPG (59). A number of other countries, including Indonesia, have adopted smaller sized cylinders to facilitate refill purchasing among poorer households (60). Other initiatives for addressing this constraint include use of small cylinders and filling equipment that allows partial refills of LPG cylinders such as PIMA in Kenya[8] (although this has led to some safety concerns because of use of 1kg cylinders and mobile LPG pumps), and smart metering pay-as-you-go systems, for example PAYGO in Kenya[9] and Kopagas in Tanzania[10].

For poorer and more rural households, which still gather all or most of their biomass fuel, adoption of LPG is more challenging because of the costs involved, problems with accessibility and potential unreliability of supply (25). The initial purchase of LPG equipment including the cylinder will also be a barrier for some, and the ongoing costs of refilling cylinders will be difficult for those on low and/or irregular incomes. Accordingly, some countries address LPG affordability for the poorest with subsidies for initial costs, for cylinder refills, or for both.

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[8] See case study in ftp://ftp.ecn.nl/pub/www/library/report/2013/o13063.pdf.

[9] http://www.paygoenergy.org/

[10] http://www.kopagas.com/

Most governments have tended to promote subsidies (especially in the initial phases to promote access to modern energy services), which can help in the switching phase but may not be sustainable over the long term. More recently, a number of countries have introduced various forms of targeted subsidy, which offer a more efficient and sustainable approach to support lower income households. The two country case studies in Box 1, as well as in India (further discussed in Chapter 5), show different aspects of the way these can be implemented, and how the have performed over time.

Box 1 – Examples of country experience with LPG subsidies

Senegal

An LPG subsidy (initially in the form of a gas stove attached to a 2.7 kg LPG cylinder, with all equipment exempted from custom duty) was introduced in Senegal in 1974 with the primary aim of reducing pressure on forest cover (61). This 'butanisation programme' continued in 1976 in the form of 6 kg gas cylinders and gas stoves, plus subsidy on the fuel itself. The policy led to a rapid increase in LPG consumption, which grew from less than 3,000 tonnes before 1976 to nearly 100,000 tons in 2004 (61). The programme was initially very successful at converting households across widely different income quintiles, with a 2004 survey data showing that 85% of households used gas in combination with other traditional fuels across urban, peri-urban and rural areas. The subsidised 2.7 and 6 kg cylinders that were intended to assist the poor, however, ended up benefitting wealthier citizens more over the longer term (62) and smuggling of subsidised LPG cylinders into neighbouring countries was also reported (63).

After removal of the fuel subsidy in 2009, the direct effect was that many less wealthy households, especially in the rural areas, reverted to charcoal and wood and no further policies were introduced for these poorer segments of the population. Annual LPG per capita consumption dropped from 11.7 kg per person in 2005 to 8.6 kg per person in 2009 (52). Nevertheless, as of 2013, only 29% of the urban population continued to primarily rely on solid fuels for cooking, implying that many had adapted to the higher LPG prices as well as to other modern fuels. In the same year in rural areas, however, 85% of households still relied on biomass as their primary cooking fuel, indicating that Senegal needs to address the continuing barriers to clean fuel use among the rural poor (64).

Brazil

During the 1980s and 1990's Brazil strongly promoted LPG as a cooking fuel across the country, with the aid of a general subsidy on the fuel. Following LPG market liberalisation in 2001 and removal of the subsidy, which resulted in the LPG price increasing rapidly by around 20%, the government introduced a cash transfer scheme[11] to assist poorer homes.

This took the form of a special 'gas assistance' programme (*Auxilio-Gas*) targeted at low-income families as a compensatory measure for the phasing out of LPG subsidies. Qualifying families were those with incomes less than half the minimum wage.

This programme, together with other cash-transfer schemes within the country, were consolidated in 2003 in what is now called the *Bolsa Familia* scheme, one of the largest conditional cash transfer schemes in the world (65). However, the success of Brazil in achieving such a high level of LPG penetration (more than 90%) is primarily due to its consolidated cylinder recirculation model[12] – where users exchange their empty cylinder for a full one – and well-established LPG delivery infrastructure throughout the country, including in the poorer Northern and North-eastern rural areas of the country (24).

A priority for LPG should be building sustainable markets that address all of the factors illustrated in Figure 1.3. These efforts should initially be focused on those currently buying all or most of their solid fuel or using kerosene, mainly in urban

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[11] Cash transfer schemes have been used in many countries as a means of targeting financial assistance to poorer families, usually on condition of compliance with health, educational or other requirements.

[12] See further explanation on the cylinder 'recirculation' or 'exchange' model in Section 2.4.

and peri-urban areas, for whom this transition will be cost neutral and may even save money. Such action will also lay the foundations for progressively expanding the availability of LPG into more rural areas and ultimately all of those who may be able to benefit from it. As part of an energy strategy, governments should consider the potential role of targeted subsidies and/or loans for overcoming the initial costs of stove, cylinder deposit cylinder, hose and regulator as well as helping with the ongoing costs of fuel for poorer families, as has already been done in a number of countries.

2.4. Safety of LPG in everyday use

LPG is a non-toxic but highly flammable fuel that needs to be handled according to good safety practices. All LPG appliances throughout the supply and distribution system (e.g. storage tanks, trucks, cylinders etc.) are designed specifically for accepting only this fuel, providing an additional level of safety and control (66). Where good industry safety practice and national regulations are in place and complied with, LPG does have a good safety record. Unfortunately, the converse is also true with evidence showing that poor regulation and enforcement do lead to fires and explosions (67). LPG for household use is generally stored in cylinders made of steel or, increasingly in some wealthier countries, of mixed materials[13]. Cylinders need to be inspected, maintained and 'requalified'[14], or scrapped if in poor condition. Cylinders have a life span of twenty or more years if correctly maintained. Requalification standards and practices (including requalification time) vary from country to country. Effective scrapping policies are therefore important (68).

In countries where proper safety regulation is enforced, LPG cylinders are sold only by legitimate marketers and filled to the correct level (28). Overfilling of cylinders, as happens for example in situations where 'black markets' are active and the cylinder filling is not carried out at an authorised filling station, can increase the risk of explosions. Countries such as Ivory Coast, Cameroon, India, Bangladesh and Morocco enforce the so-called 'cylinder recirculation model', widely regarded as a requirement if high levels of safety are to be achieved. With this model, the cylinders are owned by the fuel supplier who is then responsible for inspection, filling, and maintenance. However, in many other countries the customer is expected to own the cylinder; consequently, cylinders do not regularly come back to an expert facility for inspection and repair, thereby increasing safety hazards.

Since LPG is invisible as a vapor, consumers using it for the first time need to be trained adequately. As noted, explosions and fires do occur where safety regulation and practices are poor; these are generally caused by undetected leaks (at the level of the cylinder or valve, and piping system) that occur close to an ignition source (e.g., cigarette, lighter, matchsticks). The gas, however, is characterised by a distinctive "rotten egg" odor due to the presence of added odorants that can help in the recognition of leaks. A study from India found that most of the LPG-related burns occurred because of cylinder leakages, particularly with smaller size (5 kg) cylinders with the stove attached directly on top of the cylinder (69).

Consumer safety can be protected by adequate regulation and enforcement of safety practices, as well as by provision of adequate user training in the correct use of the LPG equipment and early detection of leaks in case these occur. Proper cylinder and stove positioning, adequate ventilation and regular inspections of the cylinder and piping system can effectively prevent accidents. Of particular note, it is important that the LPG cookstoves are placed on an elevated platform, counter or table above the top of the cylinder to avoid risk of LPG accumulation near the ground in case of a leak.

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[13] Composite cylinders are a more recent development in the cylinder manufacturing industry. They are made of a combination of plastic material and steel, providing a significant reduction in tare weight and corrosion protection. They are mostly popular in richer countries as their cost is considerably higher than standard steel cylinders.

[14] A term used by the LPG industry to indicate that the cylinders need to be re-tested and certified for future safe use.

3. Impact on climate change of transition to LPG

3.1. Climate change impacts from cookstove emissions

3.1.1 Types of emissions and biomass renewability

Climate impacts of solid fuel use depend on the net greenhouse-gas (GHGs) emitted, such as CO_2 (the most important GHG) and methane (CH_4), but also on other co-emitted gases and particles that can affect climate (denoted as short-lived climate pollutants – SLCPs). The total amount of GHGs and SLCPs emitted per meal depends mainly on the type of fuel used and the amount of fuel required. The latter in turn depends on the overall cookstove efficiency, which in turn depends on the combustion performance, the fuel carbon content, and the heat transfer efficiency to the pot.

The net CO_2 emission from wood fuels depends, however, on whether biomass is regrown, i.e. if there is renewable harvesting of woodfuel (since agricultural residues are assumed to always be renewably harvested). An important factor in the climate impact equation for biomass stoves is the failure, in practice, to re-plant woody biomass stock in many LMICs, which shifts the GHG advantage towards the use of more efficient gaseous fuels, such as LPG (27). Even in the case of 100% re-planting, the CO_2 from biomass burning will lead to some global warming, especially when the rotation period of the biomass is long (70). This is because CO_2 stays in the atmosphere for a certain period of time before uptake by regrowth, and for forest trees the rotation period can be several years.

Although biomass fuel cycles based on fully renewable harvesting of wood or agricultural residues are much closer to being CO_2 neutral than fossil fuel burning, traditional and even most improved and some advanced biomass stoves have a lower thermal efficiency (in the range of 12-25% efficiency, see Table 2.1), than liquid or gaseous fuel technologies. The resulting incomplete combustion of fuel carbon, which produces SLCPs, means that solid fuel stoves make an important contribution to global warming even when the fuel is renewable (71, 72).

LPG cookstoves have efficiencies of 45-60% (see Table 2.1), which are generally consistent across a wide range of conditions (61-63). Although some fan-assisted advanced biomass cookstoves can reach efficiencies of 30-55% when tested in the laboratory (4), approaching that of LPG and other clean fuels, their performance in everyday use is notably lower (5, 73). For example, one study from India found in-home efficiency of between 17-25% for two types of advanced biomass fan stove (6). This striking difference between performance found with ideal laboratory protocols compared to real-world conditions is, unfortunately, a persistent feature with biomass stoves. This needs to be addressed by further technical development and training in correct use to narrow this gap.

3.1.2 The role of short-lived climate pollutants

The short-lived climate pollutants emitted from biomass cookstoves include carbonaceous aerosols [black carbon (BC) and organic carbon (OC)] and trace amounts of the aerosol precursors sulphur dioxide (SO_2) and nitrogen oxides (NOx) (4, 74). Whereas BC exerts a positive radiative forcing on a global scale, i.e. contributes to global warming, OC and aerosols created from SO_2 and NOx have the opposite effect by reflecting solar radiation, thus contributing to cooling on a global scale. In addition, cookstoves emit carbon monoxide (CO) and non-methane hydrocarbons (NMHC) that affect the life-time and abundance of GHGs such as methane and ozone, and thereby affect climate indirectly (4, 38, 75, 76). SLCPs can also force local or regional perturbations to the climate, for example by reducing surface temperatures and changing the timing and amount of rainfall, even when their globally averaged effect on temperature is small (77).

Black carbon is an important climate forcing agent as it has a high global-warming potential per gram and a global climate impact only exceeded by CO_2 and methane (78). The atmospheric lifetime of BC is short, lasting only a week or two, during which time some of the emitted material can travel great distances (79). BC also contributes to increasing snow and ice melt as it absorbs heat where it settles (80). A large fraction of atmospheric BC is due to anthropogenic activities, and overall it is estimated that household use of solid fuels emits around 25% of the global total. However, in Africa and Asia, residential biomass and coal burning can contribute 60-80% of total BC emissions for those regions (81). Kerosene use (particularly in wick lamps and stoves) is also an important and previously underestimated source of BC (82).

3.1.3 Comparison between LPG, solid fuel cookstoves and kerosene

Figure 3.1 shows the climate active emissions (most of which are warming, while some are cooling) for a range of solid biomass fuel stove types including wood and charcoal, and also for coal, kerosene and LPG, compiled in Grieshop et al. (83) from five studies on cooking stoves carried out in India, China and Mexico (17, 18, 74, 84, 85).

Comparing the Global Warming Commitment (GWC) of different fuel/stove combinations requires multiplying the emissions of individual GHGs by their global warming potentials (GWP) and combining these into an overall GWC. By definition, the GWP of CO_2 is 1.0. Different time horizons can be used (e.g. 20 years) but the Kyoto Protocol specifies 100-year periods. The Kyoto Protocol gases that are emitted by biomass burning in cookstoves include CO_2, CH_4 and N_2O[15].

The following points apply to the information provided in Figure 3.1:

- For biomass (wood and charcoal) fuel, both renewable and non-renewable portions of the CO_2 emissions are shown. In the illustration, it is assumed that 50% of total CO_2 emitted is renewable – the upper cross-hatched sections of the bars – and that this renewable part does not contribute to climate change.
- Biomass is the only fuel in this analysis for which the renewable proportion varies according to setting and circumstances. Although the proportion of biomass that is renewable can in theory be close to 100% as explained earlier in the text, in practice this has been shown to vary greatly and is often considerably less. Bailis et al. estimated that 27-34% of fuelwood harvested globally in 2009 was non-renewable, with large geographic variation (86). Areas in which a large share of fuelwood is unsustainably harvested (i.e. where the non-renewable fraction exceeds 50%) encompass parts of East, Western and Southern Africa, as well as countries in Asia, such as Pakistan, Nepal and Indonesia (86, 87). The 50% value shown in Figure 3.1, which was chosen (by the authors) to explore the sensitivity of the results to this parameter, thus provides a reasonably realistic average across many LMICs where biomass is

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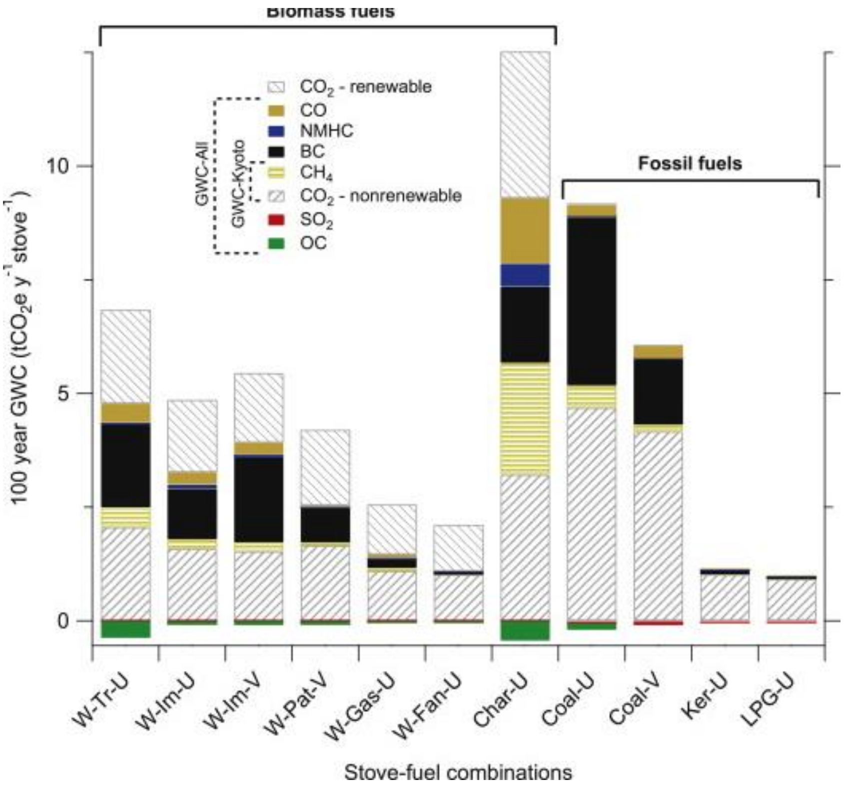
[15] The Kyoto Climate Treaty assigned these gases official global warming potentials (GWPs) to be used in such analyses. N_2O emissions from cookstoves are usually small and therefore omitted from most calculations and are not reported in Figure 3.1.

used extensively for household fuel.

- For fossil fuels (coal, kerosene and LPG), since no part is renewable, all of the CO_2 emitted contributes to climate change; this is shown in the lower cross-hatched sections of the bars.
- In the key, the GWC-Kyoto legend identifies the gases, CO_2 and CH_4 which are emitted from cookstoves and contribute to warming, and are included in the Kyoto Protocol. The GWC-All legend identifies all climate forcing pollutants considered in this analysis. The renewable portion of CO_2 from biomass is separate, as this does not contribute to climate change.
- The negative (green and red) components at the lower end of some of the bars represent the cooling effects of OC and SO_2, respectively.

Figure 3.1: Climate impact of stove/fuel combinations estimated using Global Warming Commitment (GWC) over a 100-year horizon



Acronyms: W=wood, Tr=traditional stove, U=unvented (i.e. stove no chimney); Im=improved stove; Pat=Patsari improved stove; V=vented (i.e. stove with chimney); W-Gas=wood gasifier (advanced) stove; W-Fan=wood fan-assisted (advanced) stove; Char-U=charcoal stove; Kero-U=kerosene wick stove, LPG-U=LPG metal stove. BC=black carbon, CO=carbon monoxide, CO_2=carbon dioxide, CH_4=methane; NMHC=nonmethane hydrocarbons, OC=organic carbon, SO_2=sulphur dioxide).

Source: Grieshop et al., 2011 (83)

The Grieshop et al. study (Figure 3.1) shows wide variation in the overall GWC of the different fuel and stove types. The emissions from the climate active pollutants are presented on the basis of estimated annual fuel usage per stove, i.e. adjusted for the efficiencies of the various fuel/stove combinations. The highest contributions come from charcoal (even when fully renewable) and from coal. The other fossil fuels, LPG and kerosene, have lower contributions to warming than most of the wood-burning stoves when 50% renewability is assumed. For LPG, the GWC is lower even than the advanced fan-assisted stove under the same renewability assumption, but not when the full renewability is assumed. The study included an improved chimney stove (Patsari), an advanced fan-assisted stove (Philips), and a gasifier stove (Karve), thereby allowing comparison between these technologies, LPG and other clean fuels.

While newer advanced biomass stoves may have still better performance, the question of actual performance over time when in everyday use remains important for such comparisons. Also, the finding that some of the improved and advanced biomass cookstoves emit relatively large amounts of BC and considerably more than from LPG, has also been demonstrated by individual field studies (5, 88, 89).

3.1.4 Summary of climate impacts

The evidence summarised here shows that, even when the assumed 50% renewable portion of CO_2 emissions from solid biomass stoves are taken into account, LPG has a similar or even lower global warming impact than the most advanced biomass stoves currently in the market when the latter are operating in optimal conditions. If a greater proportion of the biomass CO_2 emissions were non-renewable, then LPG would have lower warming impacts than biomass, although the reverse would be true if a higher percentage of renewability was achieved. The reasons for these findings, which may seem counter-intuitive for a fossil fuel, are the high efficiency and completeness of combustion which can be consistently achieved with LPG. As previously noted, completeness of combustion is critical for achieving very low levels of emission of climate forcers other than CO_2.

Estimates of the impact on global warming of alternative scenarios for fuel switching in the residential sector relies on a range of assumptions, e.g., fuel and stove technologies and associated emissions as well as the elements in the climate system that are included. Assuming residential LPG as an important element in ‘energy access’ scenarios, modeling studies find that increasing energy access for poor populations across the world will have a net cooling impact on climate by 2100, although the impact may be small (90-92).

3.2. Life cycle assessments of LPG vs. other cooking fuels

Although the emissions at the point of fuel/stove use are valuable for assessing climate warming contributions, it is also useful to consider the overall emissions of each step of the fuel cycle from sourcing to end use normalised to provide equivalent amounts of usable energy for cooking for each fuel. Such ‘Life Cycle Assessments’ (LCA) are used to compare the environmental footprint of products (including cooking fuels) for a given setting and cover the full process from extraction from raw materials, through processing, distribution, use in the home and finally end-of-life disposal.

The US Environmental Protection Agency (EPA) has recently completed a LCA study to compare various cooking fuels used in India and China using the approach of the voluntary international standards for LCAs defined by the International Organization for Standardization (ISO) 14040 (93). This study, to the best of our knowledge one of the few comprehensive analyses published at the time of writing, compares the main cooking fuel options for each country (see Annex) and includes two types of advanced biomass cooking technologies that burn biomass pellet fuel. Data are based on fuel modeling data published in a range of publicly available sources (18, 41) (no new data were produced for this analysis), all of which are available in the appendices of the original report.

The level of emission estimate accuracy available for each cooking fuel type is dependent on the fuel/stove combinations originally tested and the level of detail reported in the original literature sources. Some limitations should be acknowledged. For biomass pellets, for example, the cookstove use emissions and efficiency profiles are based on 2012 laboratory tests conducted under controlled conditions, including pellets with very low moisture content. These laboratory conditions are unlikely to reflect the real-life conditions where these stoves are used – particularly in wet and tropical settings (4). Studies demonstrate that emission factor measurements conducted during normal daily cooking in real settings are higher and the amount of products of incomplete combustion per kg of fuel used is approximately double compared to laboratory tests (5). For LPG, several types of stove with differing thermal efficiencies were included, with the choice based on local availability in the Chinese and Indian markets in 2000 (18, 94, 95).

For pellets, the biomass is typically collected manually from local areas in India and China and pelletised using motorised machinery in small-scale manufacturing units. The emissions resulting from non-renewable biomass production (for pellets and wood fuel) have been accounted for within the cookstove use stage (see Annex). In this study, between 35% (pellets) and 43% (wood fuel) was assumed to be non-renewable, and it is important to note that the calculated Global Climate Change Potential (GCCP) is highly dependent on these values. Agricultural residues are assumed to be by-products of agricultural production; therefore, no climate emissions were directly allocated to the crop residues.

LPG production in India derives from both natural gas and crude oil (21% and 79%, respectively), while in China it derives from crude oil only, extracted in two modern refineries built in 2000. Because LPG is a byproduct, the production and processing emissions attributed to LPG are also those associated with natural gas and crude oil extraction, which would be released independently of LPG production. Extraction stage emissions used in the report were based on default emission factors from standard literature on drilling, testing and servicing operations (94). The LPG produced in natural gas separation plants and refineries is then sent to bottling plants where the cylinders are filled, and some non-methane volatile organic compounds can be released during this stage. LPG is then transported to the distributor/retail network by road to supply households.

In summary, the US EPA LCA studies from India and China show that stove efficiency and the emissions resulting from their use are the most important contributors to the overall climate impact, for both CO_2 and BC equivalents. For CO_2 equivalent emissions, the impact of LPG was found to lie between fully and partially renewable biomass in both countries. For BC equivalent emissions (i.e. all SLCPs), the LPG impact was very much less than for biomass, and similar to other clean fuels such as natural gas, biogas and ethanol.

The US EPA analysis also concluded that biomass pellets had relatively low impacts for both CO_2 and BC equivalents, but these findings were based on laboratory emissions testing and should therefore be treated with caution until comparable LCA analyses using field-based data are available.

Of the two production routes for LPG, natural gas and crude oil, the former has the lower GCCP. For the natural gas route, total emissions derived from production, processing and distribution account only for 6% of all CO_2 equivalent emissions (as compared to 9-22% emissions for LPG derived from oil refineries). LPG derived from natural gas therefore has a considerably lower environmental impact than LPG derived from crude oil.

Two other LCA studies were reviewed, one of which is from India (94) and is fully incorporated into the US EPA study, and hence represented here. The other study was conducted in Ghana and compared only LPG, charcoal and biogas (96). This study found that LPG performed similarly to biogas and had the lowest GWP in terms of overall global warming emissions among the three fuels. For the Ghanaian market, the great majority of LPG is produced from crude oil imported from Nigeria, and none derives from natural gas extraction. Most charcoal in the country is produced from unsustainably harvested wood with only 2% of this fuel being renewably produced at the time this study was published in 2014. For biogas, mostly produced from cattle dung, methane losses were assumed at 1%. Although not factored into the analysis, the authors also noted that biogas digesters in Ghana were frequently of poor design and construction, with many plants no longer functioning (97).

The strength of the LCA analyses reported here lies in the comparison of climate and other impacts of multiple fuels and technologies using standard, accepted methods. There are also limitations, including the assumptions used for many of the model inputs, the availability of relevant data, the system boundaries chosen by authors and the fact that there are to date relatively few LCA studies. In addition, conditions may change, such as the percentage renewability of biomass, or the percentage of LPG produced from natural gas as opposed to from oil refining.

The part that LCA should play in planning energy (including household energy) strategy for a country, alongside assessments of the potential for health and other benefits, therefore needs further consideration.

3.3. Limitations of carbon-credit accounting mechanisms in comparing biomass and LPG

Since programmes to promote cleaner and more efficient household cooking technologies may bring benefits in terms of avoided emissions of GHGs and SLCPs, this can open up opportunities to secure carbon finance (98). There are, however, major obstacles to using carbon offset mechanisms as they are currently designed. The two main mechanisms available for accounting for climate impacts of cookstoves in the carbon market are the Clean Development Mechanism (CDM) and the Gold Standard (GS). The CDM is restricted to CO_2 and N_2O, while the GS also includes CH_4 and since 2015, it has introduced a new methodology for BC reductions[16].

The CDM does not allow carbon credits for fossil fuels (since these are defined as non-renewable), and therefore LPG is not eligible for carbon credits under CDM despite the fact that overall the impact on climate forcing is similar to or less than even the best biomass stoves when all emissions are considered (see Section 3.1.3). Recent evaluation studies of CDM-approved, more efficient biomass stoves also demonstrate that there is a substantial risk that these interventions fail to realise the expected fuelwood and associated-carbon reductions under real-life conditions because of technology performance, fuel stacking (the ICS is used together with the traditional stove instead of replacing it) and/or because of extra cooking tasks performed due to previously ‘suppressed demand’ (5, 88). In addition, some improved stoves (including rocket and natural draft stoves) have been shown to emit more BC and $PM_{2.5}$ emissions than traditional biomass stoves and open fires (5, 99, 100). On the other hand, the GS offers a more complete account as it includes the Kyoto Protocol gases and BC, although it still does not include CO, SO_2, OC and NMHC.

A number of LPG projects have now been funded through the GS carbon credit mechanism including the Darfur Low Smoke Stoves Project implemented by Practical Action and CarbonClear Ltd, which began stove dissemination in 2010. This project received a Lighthouse Project award from the United Nations Framework Convention on Climate Change (UNFCCC) in 2013 because of its contribution to climate change mitigation and adaptation and benefits to vulnerable communities[17]. About 9000 LPG cookstoves have been distributed and repaid on credit up to 2015[18]. Each stove avoids about 4.6 tons of CO_2 equivalent a year compared to traditional and improved mud wood stoves (15-20% efficiencies) and to traditional

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[16] http://www.goldstandard.org/articles/black-carbon-and-other-short-lived-climate-pollutants

[17] https://carbon-clear.com/what-we-do/carbon-offsetting/carbon-offsets-our-projects/darfur-low-smoke-cookstoves/

[18] http://practicalaction.org/page/32463

and improved metal charcoal stoves (20-25% efficiencies)(101). In total, across the households involved, more than 300,000 tonnes of CO_2 are expected to be reduced over 10 years (101).

More recently, the French Non-Governmental Organisation, Entrepreneur du Monde, has also been implementing carbon credit GS-approved projects to expand access to LPG in Burkina Faso[19] and in Haiti[20] through microfinance.

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[19] http://www.entrepreneursdumonde.org/downloads/EdM-StakeholderConsultationReport0612112.pdf

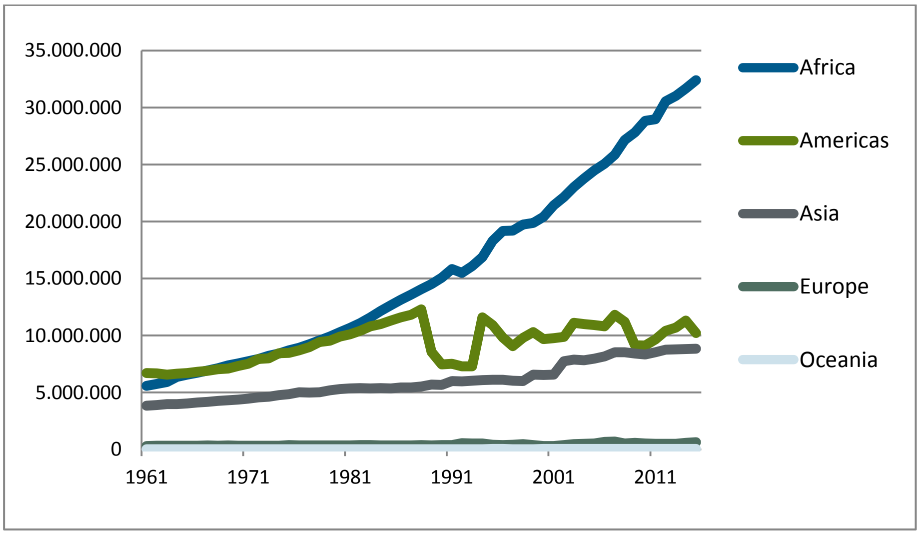
[20] http://www.climatesolutions.net/images/Documents/Expanding_LPG_access_through_microfinance_services_Design_Document.pdf

4. The contribution of LPG use to forest preservation

Many governments and international agencies are concerned about depletion of forest resources. The role of biomass for cooking, in various forms including cut fuelwood and charcoal, can be an important contributing factor in some settings. Where this is the case, switching from biomass fuel to LPG for cooking (along with more efficient biomass stoves) can help to protect the local environment in a variety of ways, since trees contribute to capturing CO_2 and forest cover is vital for soil stabilisation, flood control and protection against extreme heat in urban and peri-urban settings.

Charcoal, which is widely used as a cooking fuel, especially in urban areas of Sub-Saharan Africa (102), is produced by slow-burning of wood under low oxygen conditions and consumes far more forest resources per meal than using fuelwood directly. Because of rapidly increasing LMIC populations and accompanying urbanisation, charcoal-driven forest degradation is a serious problem in many Sub-Saharan African countries (103, 104). Figures 4.1 and 4.2 illustrate the alarming increase in charcoal production in the African continent (40).

Figure 4.1: Global charcoal production trends by region up to 2015 (in tonnes)



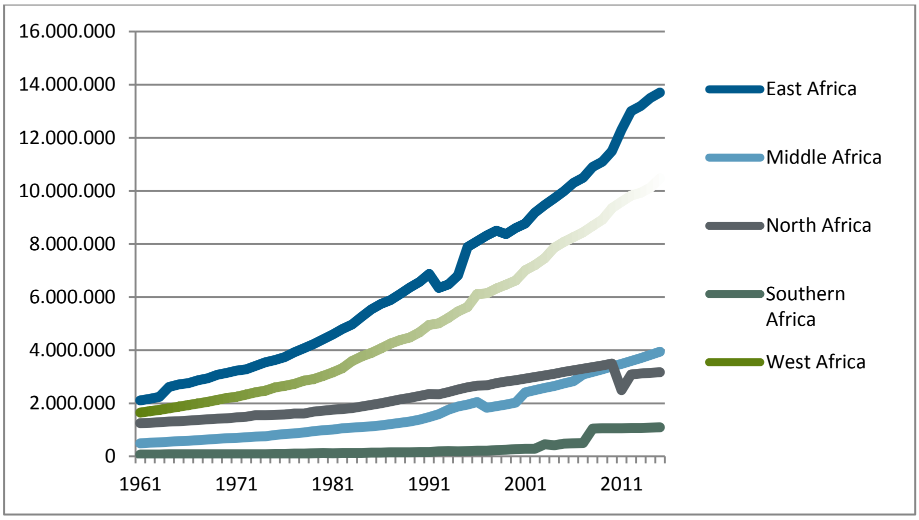
Source: FAO, Faostat 2016 (faostat.fao.org)

Although – as with harvesting of fuelwood – charcoal production is just one of many causes of forest degradation and deforestation in the region, its contributing role is exacerbated by lack of post-harvest management policies, unsustainable fuelwood harvesting and inefficient conversion technologies (105, 106). While a higher percentage of renewable biomass harvesting would help to mitigate the trends in deforestation, this is currently running at between 30% and 50% non-renewability in several LMICs countries (86, 87) (see Section 3.1.3).

In 2012, fuelwood collection and charcoal production in Africa accounted for nearly

50% of forest degradation in the region (107). In 2009, the highest proportion of deforestation in Africa attributable to charcoal production was reported for Tanzania at 33% (103). In Dar es Salaam, for example, the proportion of households using charcoal climbed from 47% to 71% between 2001 and 2007, while the annual population growth rate was 4% (108), implying an additional increase in absolute numbers using this fuel. Deforestation waves were dominant at 20-50 km from the city for providing cooking fuels, and beyond 50 km for extracting timber for consumption and export (104).

Figure 4.2: Charcoal production trends in Africa sub-regions up to 2015 (in tonnes), with constituent countries listed below



East Africa: Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Ethiopia PDR, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Réunion, Rwanda, Seychelles, Somalia, South Sudan, Uganda, United Republic of Tanzania, Zambia, Zimbabwe

Middle Africa: Angola, Cameroon, Central Africa, Chad, Congo, Democratic Republic of the Congo, Equatorial Guinea, Gabon, Sao Tome and Principe

North Africa: Algeria, Egypt, Libya, Morocco, Sudan, Tunisia

Southern Africa: Botswana, Lesotho, Namibia, South Africa, Swaziland

West Africa: Benin, Burkina Faso, Cape Verde, Gambia, Ivory Coast, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Togo

Source: FAO, Faostat 2016 (faostat.fao.org)

Dependence on fuelwood as the primary source of energy is growing in other countries, including Nigeria (109); with a rapidly increasing population, the amount of charcoal and fuelwood consumed is expected to rise further if alternative clean and affordable cooking fuels are not made more easily available.

In studies of villages in the Himalayan region of India carried out among communities where LPG use had been encouraged by government action, fuelwood use decreased from 475 kg per capita per year in 1980-85 to 46 kg per capita per year in 2000-05, suggesting that LPG can play a very significant role in forest preservation in a low-income environment (110). The energy savings from total fuelwood requirements for cooking in these villages were estimated to be as high as 70% in lower level Himalayan altitudes (3,742 MJ per capita per year), but considerably less in the higher altitude regions with considerably less LPG usage and greater heating needs (111). In Senegal, the growth in LPG use in the 1970s resulted in the avoided consumption of about 70,000 tonnes of fuelwood and 90,000 tonnes of charcoal annually (equivalent to 700,000 m^3 of wood per year). The Ministry of Energy estimated a 15% decrease in deforestation rates due to LPG adoption (63).

5. Prospects for scaling-up LPG to meet national requirements

A steadily increasing number of middle and low–income countries have now achieved 50-90% LPG use by their populations, demonstrating that LPG cooking can be rapidly scaled up when the proper enabling environment (see Figure 3) is in place. Examples include Brazil, Ecuador, Indonesia, Malaysia, Morocco, Thailand and Vietnam (24, 52, 60, 112-115).

The convenient and portable nature of LPG storage and transport allows for a relatively fast scale up of the infrastructure and distribution assets required. While LPG does require investment in importation/exportation terminals, storage facilities, cylinder assets and distribution, this is less intensive and more adaptable across national territories than the investment required for electric grid and natural gas distribution.

The meticulously planned ‘Kerosene to LPG Conversion Programme’ in Indonesia (2007-12) provides an important example of a successful large-scale national initiative from which important lessons can be learned. This programme was designed to facilitate a switch from kerosene to LPG for cooking and to reduce the financial burden for the state associated with the subsidies to kerosene. A total of 44 million households were converted to LPG use (with initial free LPG start-up kits including a 3kg LPG cylinder, double burner stove and equipment) in less than four years. The users were then responsible for covering the subsequent costs of refills which were sold at a subsidised price. The total investment up to 2009 was US$ 1.7 billion (approximately US $40 per household across the entire supply chain, fuel subsidies excluded) (60). It has been reported that, between 2007 and 2010, the Government saved US$ 1.75 billion shifting kerosene users to LPG and created 28,176 new jobs (60). Market data and populations surveys confirm that this increase in LPG use has been sustained over time (64, 116).

Considering that Indonesia is the world’s largest archipelago and the fourth most populated country in the world, the success of the conversion programme (although not targeted at the Eastern and more rural areas of the country where biomass users reside) demonstrates the great flexibility and scalability potential of this clean and portable form of energy. The three main factors identified as contributing to the success of this conversion were: (i) strong governmental policies and enforcement capability; (ii) an effective business model and promotion of an extensive LPG delivery and distribution infrastructure; (iii) a sole national oil company (which controlled both kerosene and LPG markets) with extensive operational and financial capabilities (60).

A number of other countries including India have recently embarked on very ambitious programmes directed at promoting use of LPG by targeting subsidies to the poor using a range of technologies including digital ID cards, electronic bank accounts, integrated national LPG user databases, and mobile phones (117). Through a series of national initiatives implemented rapidly since 2015, India has embarked on plans to provide LPG access to 90% of its population by 2019. These initiatives included the Direct Debit Transfer for LPG Scheme (PAHAL) (through which the LPG subsidy is transferred to users' bank accounts instead of providing the subsidy at point of sale), the 'Give it Up!' Campaign (to encourage wealthier households to voluntarily give up their LPG subsidies for transfer to poor households) and the 'PMUY' Initiative (to further expand LPG access to the rural poor by use of government funds to pay for upfront costs for poor households). By removing the barrier of upfront cost, it is expected that 50 million below poverty line families (~300 million people) will subscribe to LPG by March 2019[21]. Importantly, LPG subsidies are no longer applied at the point of sale, but rather deposited into the bank accounts of households qualifying for the subsidy. If households stop purchasing LPG, the subsidy is not deposited. As all LPG is now sold in the market at international prices, this greatly reduces the "leakage" that often accompanies subsidy at sale in which much fuel is diverted into non-household uses, such as restaurants. The driving force behind this national commitment to promoting clean cooking LPG at scale is to reduce the health burden associated with solid cookfuel use, India being the country with the single largest burden of disease from HAP (900 000 premature deaths a year).

Even in some highly developed countries, for example Japan, LPG is still one of the main cooking and heating energy sources, showing that it remains an affordable, efficient and desirable household fuel in the face of other clean energy sources such as electricity and natural gas (118).

Electricity and natural gas variously present challenges of supply, particularly in less urban areas, notwithstanding the potential of decentralised electricity generation. In the case of electricity, even if available in more rural areas, the power consumption required for cooking may limit the potential for widespread use (119). In South Africa for example, where most on-grid connected households use electricity for cooking (although with traditional somewhat inefficient electric stoves, not modern highly efficient induction stoves) peak power demand significantly exceeds supply. As a result, electrical blackouts have become commonplace since 2005. In order to reduce the demand on electrical power, the Government has begun promoting LPG as an alternative clean cooking fuel (50). On the other hand, Ecuador is doing the reverse, i.e. substituting modern electric induction stoves for LPG to use local hydropower to avoid the costs of LPG imports after more than 30 years of LPG promotion (120).

All countries require a strategy that provides a mix of energy carriers to households across urban and rural settings. Among these carriers, electricity must be a priority for all, given its many social benefits, but may not be affordable or available with sufficient capacity for cooking. Natural gas – where available – can contribute to cooking energy requirements, but will be suitable mainly for urban residents. To meet the cooking needs of the majority of the population, however, experience from many low and middle-income countries is showing that LPG can be scaled-up relatively quickly across settings, due to the lower infrastructure investments required and the ease of transport and storage.

Studies of the investments required to extend access to LPG in different countries and settings (i.e. urban and rural), along with those for other cleaner household energy options, would provide valuable information for countries and other agencies currently supporting, or planning to support, this transition. Such data can also contribute to comparative economic evaluation, for example cost-benefit analyses, for LPG, cleaner biomass, and other options.

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[21] http://energyinfrapost.com/category/ujjwalapahal/

6. Conclusions: the potential of LPG to contribute to health, climate and development objectives

The evidence reviewed in this document has shown that LPG has the potential to deliver major health benefits as well as to reduce the adverse climate impacts of cooking practices current among the 3.1 billion relying on solid fuels and kerosene used in simple stoves. Under their Clean Air Scenario, developed to evaluate the policies required to move countries towards air quality that meets WHO guidelines, the International Energy Agency proposes strategies to reconcile the world's energy requirements with its need for cleaner air and to keep the average global temperature increase below 2°C. Promoting access to cleaner cooking fuels and devices, including specifically LPG, would contribute substantially to reducing global air pollution emissions while also promoting climate co-benefits, achieving both environmental and development goals (27).

Bearing these facts in mind, and given the projected availability of LPG and the feasibility of its use at scale (see Sections 2.1.2, 2.3 and Chapter 5), there is a strong case for LPG being put to best societal use as a household fuel in the world's poorer countries where substantial health benefits can be secured. A substantial proportion of current LPG production is used as petrochemical industry feedstock or is being wasted by flaring and venting as described in Section 2.1.2. Within the context of global energy policies designed to secure vitally important limits on climate warming, which are likely to control and ultimately reduce the production and use of fossil fuels, there is a strong moral case for ensuring that LPG is deployed in a way that maximises the social benefits to the global community. Any increasing cost of LPG resulting from more stringent climate policies will require access policies that shield poor households from the burden of carbon taxation (121).

In energy terms, LPG is actually an energy-carrier, like electricity, and like electricity, can be derived from many primary sources. Indeed, production of renewable (i.e. non-fossil fuel derived) LPG is already underway and holds promise for further expansion. Bio-LPG, as a product, is identical to fossil fuel-derived propane and is produced from renewable feedstocks such as vegetable oil, animal fat (e.g. tallow), waste oils or other cellulosic waste material (122). Because bio-LPG is identical to conventional LPG, it can be substituted in all existing applications of LPG, from transport to cooking and heating. Although current production is primarily aimed at vehicle fuel (autogas) for the European market (123), in due course appropriate policy and investment could make Bio-LPG production available for contributing to the market for cooking fuel.

Replacement of traditional cooking with fuels that are truly clean at point of use such as LPG can contribute to achieving universal energy access under SDG 7. A growing number of national governments in Asia and in Sub-Saharan Africa have set up ambitious targets for LPG, including India, Cameroon, Kenya and Ghana among others, with the latter countries under the guidance of the African Development Bank and the ECOWAS[22] Centre for Renewable Energy and Energy Effi-

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[22] Economic Community of West African States

ciency (ECREE) and with support from the Clean Cooking Programme for Africa.

Many governments are in the process of drafting and publishing their SEforALL Action Agendas, and have included LPG as part of their strategy for shifting to modern cooking services to meet the needs of growing peri-urban and urban populations[23,24,25,26]. For example, Cape Verde has set the ambitious goal of 90% LPG penetration and eradication of three stone fires and stoves which are currently used by 65% of the rural population by 2030[27]. A supportive regulatory framework and adequate LPG infrastructure development are therefore crucial to make modern energy access for all a reality.

LPG use in the home can also contribute to achieving development objectives as it can support broader social goals by freeing the time and labour of women and children currently taken up with gathering biomass fuels (47, 111). This direct time saving, together with the greater efficiency and convenience of LPG as a cooking fuel, has been shown to help women engage with the labour market opportunities and children to make the most of educational opportunities in some settings (44, 48, 54). Finally, by replacing biomass fuel, LPG can make an important contribution to forest protection in those countries where depletion for wood fuel and charcoal are important factors (63, 111).

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[23] Sustainable Energy for All (SEforAll). Action Agenda for Sierra Leone. See: http://www.ecreee.org/sites/default/files/events/presentation_se4all_action_agenda_sierra_leone.pdf

[24] Sustainable Energy for All (SEforAll). Kenya Action Agenda. See: http://www.se4all.org/sites/default/files/Kenya_AA_EN_Released.pdf

[25] Cooking gas: Federal Government [of Nigeria] targets 4 million households by 2018. See https://theeagleonline.com.ng/cooking-gas-fg-targets-4m-households-by-2018/

[26] State to subsidise gas cylinders for 1.2 million households in Kenya. See: https://www.standardmedia.co.ke/business/article/2000225574/state-to-subsidise-gas-cylinders-for-1-2m-households

[27] Action agenda for the Sustainable Energy for All, Cape Verde. See http://www.se4all.org/sites/default/files/Cape_Verde__AA_EN_Released.pdf

Annex: US EPA life cycle assessment study of cookstove fuels in India and China

This Annex provides additional results extracted from the 2016 US EPA *Life cycle assessment of cookstove fuels in India and China* study. These illustrate, in greater detail, results from the life cycle analysis across the four stages (production, processing, distribution, and use) and overall for the individual cooking fuels used in India and China (93). The main results on climate effects are expressed in two ways:

1. The Global Climate Change Potential (CO_2 equivalent)[28] in Annex Table 1, and;
2. The Black Carbon (BC) equivalent in Annex Table 2 (this includes the main SLCPs).

Annex Table 1 - Detailed Results for Global Climate Change Potential (expressed as Kg CO_2 equivalent) by Cooking Fuel Type in India and China

Per GJ Delivered Heat for Cooking		Life Cycle Stage								Total	
		Feedstock Production		Fuel Processing		Distribution		Cookstove Use			
		India	China	India	China	India	China	India	China	India	China
Global Climate Change Potential (Kg CO_2 eq[29])	Hard coal	16.2	N/A	0	N/A	1.62	N/A	945	N/A	963	N/A
	Coal Mix*	N/A	212	N/A	8.8	N/A	95.3	N/A	699	N/A	1014
	LPG from NG	**3.13**	N/A	**2.77**	N/A	**12**	N/A	**274**	N/A	**292**	N/A
	LPG from Oil	**5.29**	**22.6**	**11.2**	**1.35**	**12**	**19.1**	**274**	**145**	**303**	**188**
	Kerosene	6.54	33.4	13.9	12.6	12.7	1.3	148	160	181	207
	Electricity	0	0	0	0	0	0	415	496	415	496
	Natural gas	N/A	9.33	N/A	30.1	N/A	27.1	N/A	147	N/A	213
	Sugarcane Ethanol	79.8	N/A	5.29	N/A	9.71	N/A	0.96	N/A	95.7	N/A
	Biogas from Cattle Dung	0	N/A	9.19	N/A	0	N/A	1.33	N/A	10.5	N/A
	Charcoal from wood	0	N/A	274	N/A	29	N/A	270	N/A	572	N/A
	Biomass Pellets	0	0	27.8	40.9	1.1	0	105	77.3	134	118
	Firewood	0	0	0	0	0	0	539	281	539	281
	Crop/Agricultural residues	0	0	0	0	0	0	132	54.7	132	54.7
	Dung cake	0	N/A	0	N/A	0	N/A	191	N/A	191	N/A

Source: Modified from Cashman et al 2016 (93), with original tables (Table B-1 and B-11) combined. *Notes*: N/A=estimates not included as not a major cookstove fuel in the country. *Coal mix in China includes: coal powder, coal briquettes and honeycomb coal briquettes.

In addition, the assumptions used in these analyses are summarised in Annex

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[28] The global climate change potential impact category represents the heat trapping capacity of GHGs over a 100 year time horizon. All GHGs are characterised as kg CO_2 equivalents according to the IPCC 2013 5th Assessment Report global warming potentials.

[29] CO_2 equivalent is a measure used to compare the emissions from various greenhouse gases based upon their global warming potential.

Table 3 for all fuels. Some of the key issues for the biomass stove and fuel types are discussed further below.

For biomass pellets, the mix of fuelwood and crop residue varies and in India is assumed at 85% and 15%, respectively. The feedstock (biomass) was assumed to be collected manually from local areas and pelletised using motorised machinery in small-scale manufacturing units. The processing energy and distribution transport are based on estimates from Central Europe, which might be different from LMICs settings. According to the model, 41% and 43% of wood in India and China respectively, is non-renewable; for pellets, renewability of 35% was assumed. The resulting non-renewable biomass emissions have been accounted for within the cookstove use stage, rather than in the feedstock production, resulting in zero emissions for the analysis of that stage (Cashman S., personal communication).

BC and co-emitted SLCPs (Annex Table 2) are summarised as BC equivalents, based on methodology developed by the Gold Standard Foundation (124).

Annex Table 2 - Detailed Results for Black Carbon (expressed in Grams BC equivalent) by Cooking Fuel Type in India and China.

Per GJ Delivered Heat for Cooking		**Life Cycle Stage**								**Total**	
		Feedstock Production		**Fuel Processing**		**Distribution**		**Cookstove Use**			
		India	**China**	**India**	**China**	**India**	**China**	**India**	**China**	**India**	China
Black Carbon and other Short Lived Climate Pollutants (g BC eq)	Hard coal	340	0	0	0	0.013	0	3580	0	3910	0
	Coal Mix*	N/A	-4.5	N/A	38	N/A	17	N/A	-6.7	N/A	43
	LPG from NG	**0.36**	N/A	**-6.1**	N/A	**0.81**	N/A	**5.5**	N/A	**0.55**	**N/A**
	LPG from Oil	**0.62**	**2.8**	**7.2**	**-19**	**0.81**	**-6.2**	**5.5**	**4.6**	**14**	**-18**
	Kerosene	0.76	-29	8.9	-4.7	1	-0.23	34	2.3	45	-32
	Electricity	0	0	0	0	0	0	-19	-120	-19	-120
	Natural gas	N/A	-3.7	N/A	0.051	N/A	-0.072	N/A	1.5	N/A	-2.2
	Sugarcane Ethanol	-1.7	N/A	-7.3	N/A	0.81	N/A	2.8	N/A	-5.4	N/A
	Biogas from Cattle Dung	0	0	0	-10	0	0.14	6.8	21	6.8	11
	Charcoal	0	N/A	4.02	N/A	0	N/A	0.26	N/A	4.27	N/A
	Biomass Pellets	0	0	-1	0	0.089	0	21	0	20	0
	Firewood	0	0	0	0	0	0	1040	300	1040	300
	Crop / agricultural res	0	0	0	0	0	0	2420	690	2420	690
	Dung cake	0	N/A	0	N/A	0	N/A	5.01	N/A	5.01	N/A

Source: Adapted from Cashman et al 2016 (93), with original tables (Table B-10 and B-20) combined. Note that figures have been converted to grams (Kg in the original report) for clarity of presentation. N/A=estimates not included as not a major cookstove fuel in the country. *Coal mix in China includes: coal powder, coal briquettes and honeycomb coal briquettes.

Annex Table 3 – Assumptions used for estimating the Global Climate Change Potential and BC equivalent by Cooking Fuel Type in India and China

Assumptions for each fuel considered	Renewability assumptions		Cookstove being used and thermal efficiency	
	India	**China**	**India**	**China**
Coal	Non-renewable	Non-renewable	Metal stoves, 15% efficiency (94)	Traditional and improved metal and brick stoves, with 14-37% efficiencies (18)
LPG	Non-renewable	Non-renewable	LPG stoves, 57% efficiency (94)	LPG traditional and with infrared head (45% and 42.1% efficiency, respectively) (18)
Kerosene	Non-renewable	Non-renewable	Type not specified; 47% efficiency (94)	Wick and pressure stoves; 44-45% efficiency (94)
Electricity	Non-renewable	Non-renewable	Electric stoves, 67% efficiency (125)	
Natural gas	Non-renewable	Non-renewable	N/A	Stoves with 54-60% efficiencies (18)
Sugarcane Ethanol	Assumed to be fully renewable	Assumed to be fully renewable	Unspecified ethanol stove, 53% efficiency (126)	N/A
Biogas from cattle dung	Assumed to be fully renewable	Assumed to be fully renewable	Unspecified biogas stove, 55% efficiency (94)	N/A
Charcoal from wood	41% wood estimated as non-renewable	N/A - not considered as a main cookfuel in China	Type not specified, 17.5% efficiency (94)	N/A
Biomass Pellets	35% feedstock estimated as non-renewable	24% feedstock estimated as non-renewable	Advanced biomass stoves (Oorja and TILUD), 53% efficiency (4)	
Firewood	41% firewood estimated as non-renewable	43% firewood estimated as non-renewable	Traditional mud stoves, 13.5% efficiency (94)	Traditional and improved metal and brick stoves (16-19% efficiency) (18)
Crop residue	Assumed to be fully renewable	N/A - not considered as a main cookfuel in China	Traditional mud stoves, 11% efficiency (94)	Traditional and improved metal and brick stoves (10-17% efficiency) (18)
Dung cake	Assumed to be fully renewable	N/A	Traditional mud stoves, 8,5% efficiency (94)	N/A

Source: Extracted and complied from Cashman et al 2016 (93) using the main text and Tables 1-6 and 1-9. *Note:* Stove thermal efficiencies modeled are based on the average mix of stove technologies and are generally not representative of specific stoves.

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KfW Group
KfW Development Bank
Palmengartenstrasse 5-9
60325 Frankfurt am Main, Germany
Telephone +49 69 74310
Fax +49 69 7431 2944
info@kfw-entwicklungsbank.de
www.kfw.de

Scientific Advisory Board members for the Clean Cooking for Africa Programme: Nigel G. Bruce, Kristin Aunan, Eva A. Rehfuess and Kirk R. Smith

Peer-reviewers: Tami C. Bond and Hisham Zerriffi
Review editor: Kirk R. Smith

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