Comparison of Bottled Gas and Advanced Combustion Pellet Stoves

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Content

Acknowledgment .................................................................................................................................................. iii
Summary ........................................................................................................................................................ iv
Abbreviations, Acronyms, and Units ................................................................................................................ v
Context and Study Description ......................................................................................................................... 1
Factors Affecting Household Energy Choice ................................................................................................... 4
  Meeting specific needs ..................................................................................................................................... 5
  Lumpiness of fuel purchase ........................................................................................................................... 6
  Livelihood ................................................................................................................................................. 8
  Global warming potential .............................................................................................................................. 9
Challenges to Proper Regular Use of Advanced Combustion Stoves for Woodfuels ...................................... 10
  Pellet manufacture on the scale required ...................................................................................................... 10
  Stove repair ............................................................................................................................................ 12
  Proper operation ....................................................................................................................................... 13
  Disparity between laboratory and field emission measurements ............................................................. 14
Emissions from Cookstoves ........................................................................................................................... 15
Discussion ....................................................................................................................................................... 18
References ....................................................................................................................................................... 23

Figures

Figure 1: Comparison of free-on-board, cylinder refill, and pay-as-you-go prices in Kenya ....................... 7
Figure 2: Free-on-board prices of propane in the Persian Gulf and the U.S. Gulf .................................... 19
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ESMAP’s analytical and advisory services are fully integrated within the World Bank’s country financing and policy dialogue in the energy sector. Through the World Bank Group (WBG), ESMAP works to accelerate the energy transition required to achieve Sustainable Development Goal 7 (SDG7) to ensure access to affordable, reliable, sustainable, and modern energy for all. It helps to shape WBG strategies and programs to achieve the WBG Climate Change Action Plan targets.
Summary

For those who prefer to cook with gas but are not connected to a natural gas pipeline—and nearly all rural households fall under this category—liquefied petroleum gas (LPG) is the main option. For those for whom LPG is too costly and wish to cook with biomass because of its ready availability, lower cost, and familiarity, advanced combustion stoves burning pelletized biomass fuel may hold the best promise of clean energy.

LPG and advanced combustion stoves have many challenges in common but also unique challenges of their own. Arguably the greatest obstacle is the high cost of their use as primary energy sources. Essentially all challenges cited in the literature—stovetops being too small or unstable for large pots and pans and for vigorous stirring, the inability to cook large meals or several dishes in parallel, difficulties of reloading pellets in the middle of cooking, fears about explosions and burns, and the inconvenience of waiting for refill LPG delivery after finding the cylinder empty, to name a few—can be addressed, but at a significant cost. In high-income economies, millions of households have been using gas to meet all their cooking and heating needs (supplemented by electricity for certain appliances such as rice cookers and microwave ovens) but at a cost that would be unaffordable to many, if not most, households in developing countries. Commercially viable solutions to these problems for advanced combustion stoves, such as auto-ignition and automated pellet loading mechanisms, are not yet available.

The emission performance of advanced combustion biomass stoves has been compromised by use of polluting start-up materials and practices, heterogeneity of biomass used (size, moisture content, type), and excessive emissions during fuel reloading and the burn-out phase. Battery and other equipment failures increase emissions further or can even render the stove inoperative. Deterioration in emission levels with the stove age has also found to be worryingly high in one study, pointing to the need to improve the durability of stove performance in the field.

The neighborhood background air pollution and the widespread practice of fuel and stove stacking and other sources of high pollutant emissions inside the home contribute to elevated levels of air pollution even in homes where the primary cooking energy is clean. These observations point to the importance of tackling multiple sources of emissions and promoting community-wide use of clean energy.
Abbreviations, Acronyms, and Units

- **CO**: Carbon monoxide
- **CO₂**: Carbon dioxide
- **FOB**: Free on board
- **g**: Gram(s)
- **IEA**: International Energy Agency
- **ISO**: International Standard Organization
- **IWA**: International Workshop Agreement
- **kg**: Kilogram(s)
- **LPG**: Liquefied petroleum gas
- **PM₂.₅**: Particulate matter with an aerodynamic diameter of 2.5 microns
- **REACCTING**: Research on Emissions, Air quality, Climate, and Cooking Technology in Northern Ghana
- **SDG**: Sustainable Development Goal
- **VAT**: Value-added tax
- **WHO**: World Health Organization
- **µg/m³**: Micrograms per cubic meter
Context and Study Description

Universal access by 2030 to “affordable, reliable and modern energy services” is one of the targets of the United Nations’ Sustainable Development Goals (SDGs), captured in SDG 7.1.¹ Progress is measured by the share of the population with access to electricity (indicator 7.1.1) and that “with primary reliance on clean fuels and technology” (indicator 7.1.2) (United Nations 2017). Of the two indicators, the rate of progress for electricity has been much faster than that for clean fuels and technology. According to Tracking SDG 7: The Energy Progress Report 2021 (IEA, IRENA, UNSD, World Bank, and WHO 2021), the number of people without access to electricity fell from 1.2 billion in 2010 to 0.76 billion in 2019, but the number of those lacking access to clean cooking solutions was markedly higher, having fallen from 3 billion to 2.6 billion during the same period. Overall, the share of the global population with access to clean fuels and technologies for cooking increased from 56 percent in 2010 to 66 percent in 2019. In Sub-Saharan Africa, population growth outpaced the number of people gaining access to clean cooking solutions by nearly three to one from 2015 to 2019.

To define “clean” in indicator 7.1.2, the United Nations uses the emission rate targets and recommendations made by the World Health Organization (WHO) in the WHO Guidelines for Indoor Air Quality (WHO 2014). Most global estimations of adverse effects of air pollution are based on particulate matter with an aerodynamic diameter of 2.5 microns or smaller (PM2.5). This is because minute combustion particles can more readily travel systemically throughout the body than gaseous pollutants, which are less likely to reach and adversely affect the heart—a mechanism attributed to most air pollution deaths—or the ambient concentrations of which are too low to be plausible major contributors. In addition to their own effects, fine particles can adsorb gaseous air pollutants and vapors that would otherwise be scrubbed or reacted out in the upper airways, thereby enabling the pollutants that would otherwise have less effect to become more harmful (Thurston 2021). The WHO targets used for indicator 7.1.2 are for emissions in mass per minute of PM2.5 and carbon monoxide (CO), accompanied by target ambient concentrations for PM2.5. The WHO has set the final ambient concentration target for PM2.5 for 90 percent of all kitchens as a maximum PM2.5 annual average of 10 micrograms per cubic meter (μg/m³). Based on these target values, electricity, natural gas, LPG, and biogas, solar cookers and heaters, and alcohols such as ethanol are considered clean when the associated appliances are operated properly. There are also interim targets, which are less stringent. At the time of the publication of the guidelines, there was only limited evidence in the field of the impact on air pollution of advanced combustion stoves for solid biomass and no modeling had been attempted (WHO 2014). Since then, there have been more studies using advanced combustion stoves for solid fuels to measure emissions, ambient concentrations, and personal exposure.

International organizations have been making joint efforts to estimate and publish progress reports annually since 2016 on the proportion of the global population citing electricity, gas, solar energy, and ethanol as their primary sources of energy for cooking.² However, there are several limitations to the approach that should temper the interpretation of the findings. Binary classification of household energy use as clean or unclean does not capture fuel and stove stacking, with “clean” and “unclean” energy existing side by side in the same household. Their relative uses depend on a number of factors such as fuel availability (including seasonal variation in the availability of certain fuels such as dry wood or crop residues), fluctuations in cash inflows, global and local fuel price movements, government subsidy policies, the technical state of the stoves and their replacement and repair costs, dishes being cooked, and

² See the tab “PROGRESS AND INFO” at https://sdgs.un.org/goals/goal7 for the full set of progress reports.
the number of people for whom food is being prepared. Further, there are households, however few at the moment, who are beginning to use advanced combustion biomass stoves but up until now have not been captured under the “clean” category. As a result, this overly simplified binary classification risks distorting the state of cooking, and by discarding context- and situation-specific circumstances, overlooking otherwise effective, sustainable, and improved cooking solutions that meet specific local needs (ESMAP 2020, box 1.1).

Target emission rates set by the WHO may be reasonable in defining the maximum allowable emission rates for stoves, but meeting the target rates by no means ensures achieving an acceptable level of air quality to protect health. There are many sources of air pollution, of which cooking by households is only one. Energy for cooking may even comprise a very small fraction of total energy use—the European Statistical Office reports that, in 2018, cooking accounted for a mere 6 percent of total household energy consumption, while space heating, water heating, and electricity for appliances accounted for 64, 15, and 14 percent, respectively. Source apportionment to identify main contributors to air pollution, personal exposure levels, the duration of exposure, and the underlying health conditions of each family member are needed to estimate the impact of cookstove use on health.

It is also possible that basing the target ambient concentrations on studies in advanced economies with much less biomass combustion may be overly conservative. To date, in setting guidance for ambient concentrations, PM$_{2.5}$ has generally been treated as though it had the same toxicity on a mass basis irrespective of its source and composition, with each µg/m$^3$ of PM$_{2.5}$ from fossil fuel combustion weighed the same as that from biomass combustion. In practice, PM$_{2.5}$ varies in chemical composition as a function of its size, source, and formation pathway, and correspondingly its health effects vary by origin and nature. There is evidence that a given mass of PM$_{2.5}$ from biomass combustion may be less harmful than the same mass from combustion coal in stoves or diesel in vehicle engines. One example of supporting evidence comes from an examination of data from the United States, which found a statistically significant impact on ischemic heart disease mortality of elevated concentrations of PM$_{2.5}$ from coal combustion, but not PM$_{2.5}$ from wind-blown soil or biomass combustion on a common mass basis (Thurston et al. 2016). Reinforcing such findings, a recent study in Dhaka, Bangladesh concluded that biomass combustion was responsible for most PM$_{2.5}$ air pollution, but the effects on cardiovascular mortality and hospital admissions of PM$_{2.5}$ from fossil fuel combustion were about four times and double, respectively, those of PM$_{2.5}$ from biomass combustion on a µg/m$^3$ basis. As a result, above about 100 µg/m$^3$ of PM$_{2.5}$, the effects on emergency room visits, hospitalizations, and mortality were not statistically significant (Rahman et al. 2021).

In high-income countries, gas and electricity are the main sources of energy for cooking and heating and, aside from occasional use of charcoal for barbeques and firewood in wood-burning fireplaces, are in many cases the only sources of household energy. Gas is piped natural gas if available, and in its absence, liquefied petroleum gas (LPG), alternatively referred to as bottled gas, cooking gas, propane, or butane, the latter two depending on the market and the composition of LPG. The U.S. Department of Energy reported in 2018 that 63 percent of households in the United States had cooked with electricity, 33 percent with natural gas, and 5 percent with propane in 2015, and that these shares had remained broadly stable between 2001 and 2015. Turning to overall household energy use, in the European Union, household energy consumption in 2018 comprised 32 percent natural gas, 25 percent electricity, and 17.5 percent

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4 https://www.eia.gov/todayinenergy/detail.php?id=37552. The percentages do not add up exactly to 100 because of rounding-off errors.
renewable energy, with the balance made up by petroleum products (which would include LPG), derived heat, and a small amount of coal.3

In the developing world, cooking only with electricity, gas, or both is not as common. A recent review of primary energy sources for cooking in 52 developing economies (Kojima 2021a) found that households in only eight economies chose electricity and gas (natural gas or LPG) as their two top choices, and in these economies households did not choose electricity and gas in comparable proportions—in all economies but one, households overwhelmingly chose gas over electricity. When different primary energy sources for cooking were ranked in order of decreasing share of population using them in each economy, wood was cited in 21 economies and gas (natural gas or LPG) followed closely in 20 economies, while electricity was the top choice in only six economies. For the second most commonly cited primary energy sources for cooking, 19 economies cited gas, followed by 15 economies citing charcoal. The most observed pattern overall, found in 13 economies, was the largest share of the population citing wood as the primary cooking fuel followed by the second largest share citing charcoal. The second most observed pattern, found in 10 economies, was the largest share of the population citing gas as their primary cooking fuel followed by the second largest share citing wood.

Of the available options to achieve universal access to clean cooking solutions, the International Energy Agency (IEA) estimates that LPG will provide that access to approximately half of the population still lacking access, and that “improved and more energy-efficient biomass cookstoves [will play] … a more significant role in rural communities” (IEA 2019, 86). The latter group includes about 100 million people replacing traditional biomass with clean-burning stoves fed with biocharcoal or biomass briquettes (IEA 2020, 204). Electricity should play an increasingly important role going forward. The source of electricity is not only grid electricity but can also be a system comprising a solar photovoltaic panel backed up by a battery. Other options not used by households in high-income economies today but hold potential in the developing world include biogas,5 bioethanol, and solar cookstoves. However, to date, there have been several challenges to adoption of biogas and bioethanol, and the foregoing study of primary sources of energy for cooking by households in 52 economies found that reliance on biogas was extremely limited and that on bioethanol or solar cookstoves was essentially non-existent (Kojima 2021a).

As explained in the foregoing, attaining universal access to clean fuels and technologies as measured for the purpose of tracking progress toward the SDG 7 goal is a necessary but not a sufficient condition to achieve the desired health outcome because of a number of different sources of emissions in many, if not most, circumstances. Even when focusing on cooking alone, “primary reliance” is not the same as exclusive use, and fuel and stove stacking is widespread. There are plentiful examples of continuing use of traditional biomass alongside modern energy from around the world (Ruiz-Mercado and Omar Masera 2015):

- A study in China documented that after 30 years of electrification in a rural village, electricity replaced wood only for cooking noodles.
- In Guatemala, a study found that bathing accounted for 30 percent of wood used for cooking but 78 percent of the total exposure to CO among women who had a chimney stove in the kitchen. Exposure was higher following childbirth because women bathed more frequently.
- No significant reduction in wood use was observed in Indonesia after the national LPG program, in rural and peri-urban northern Thailand, in a region of rural China after 30 years of electrification, and in urban Botswana.

5 Although dedicated biogas is seldom used by households in high-income countries, biogas may be used in the future if it is increasingly blended with natural gas as a climate change mitigation measure.
In Mali, “improved” cookstoves were found to reduce wood consumption by 40 percent but cooking accounted for only half of the total household wood consumption, reducing the actual reduction in wood consumption to 20 percent at the most.

In rural Mexico, the dependence on open fires burning wood to heat water for bathing remained high for 25 years even after substantial penetration of LPG and electricity. Actual wood savings from wood users adopting LPG were found to range from 6 percent to 37 percent.

In light of the likely scenario reiterated in the recent issues of the IEA’s World Energy Outlook—that LPG and advanced combustion biomass stoves are likely to be the two of the most important choices for enabling the remaining 3 billions people to attain access to clean energy—this paper examines the challenges and opportunities associated with these two fuels and technologies. Confining the rest of the paper to these two options is by no means intended to imply that other options—such as appropriate use of chimneys for less advanced biomass stoves, solar cookers, and other fuels—are far less useful or far less likely to be adopted. In particular, as in many advanced economies, electricity will play an increasingly important role, and in the scenarios meeting the temperature goal of the Paris Agreement, net-zero-emission electricity may become the dominant, if not the only, household energy source in the coming decades.

Advanced combustion biomass stoves with very low emissions are relatively new and have not yet been adopted on a wide scale. For several years the most advanced biomass stove was the Philips fan stove HD4012 burning densified biomass pellets in a ceramic-lined stainless steel combustion chamber with an inbuilt fan and a rechargeable battery that forces air into the top and bottom of the combustion chamber. However, Philips has discontinued the production of this stove, prompting those wishing to continue to test advanced combustion stoves to switch from Philips HD4012 to Mimi Moto,6 a forced-air gasifier stove that claims to be world’s only mass-produced biomass stove to reach the highest efficiency and emissions rating, the tier 4 voluntary performance target set in the International Workshop Agreement (IWA) of the International Standard Organization (ISO). The discontinuity in stove production and use notwithstanding, the general conclusions drawn from the studies examining Philips HD4012 stoves should be broadly applicable to more recent models.

The paper first covers some of the potential challenges faced by adoption of LPG and advanced combustion stoves. The difficulties frequently observed with household use of LPG have been reported elsewhere (Kojima 2011, 2021b) and are not reproduced here. The paper next discusses the challenges specific to advanced combustion stoves, and lastly presents a review of the factors affecting emission levels that also touches upon measurements of ambient PM$_{2.5}$ concentrations. In the rest of the paper, “exclusive” use of LPG or advanced combustion stoves is not intended to imply that households are not using such commonly used electric cooking appliances as microwave ovens, electric rice cookers, and electric kettles, and instead refers to cooktops and ovens used for all other cooking activities.

**Factors Affecting Household Energy Choice**

Inadequate income relative to costs of using modern energy makes it difficult to cook exclusively or even primarily with LPG or advanced combustion biomass cookstoves. For many households, confining the use of these stoves to the level that is affordable would not make it possible to meet their cooking needs. Just as with any transition, shifting households from traditional charcoal and wood stoves to LPG or advanced combustion stoves entails winners and losers, with a very large number of the poor engaged in

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6 https://mimimoto.nl/.
low-earning activities collecting wood belonging to the latter. The growing attention on global warming has highlighted the mitigation as well as global warming potential of both LPG and biomass.

Meeting specific needs

Cooking for large families typically requires several large stoves while preparation of dishes requiring vigorous stirring for a long time requires a large, sturdy stove. Large and sturdy stoves with multiple burners using modern technology have been on the global market for decades but are seldom affordable for many households in developing countries. In this regard, three-stone fires are remarkably adaptable, flexible, durable, and affordable, and particularly suited for dishes such as tuo zaafi—a dish popular in northern Ghana that requires vigorous stirring—because they can accommodate large and heavy pots and pans and, being on the ground, are much more difficult to over-turn. For safety LPG stoves should not be placed on the ground (LPG has a higher density than air and sinks to the ground if it leaks), while combustion stoves are all elevated because the cooktop sits on top of the combustion chamber. Gitau et al. (2019) found in a study in Kenya that large families preferred three-stone fires because they cooked large meals in large pots. Ochieng et al. (2020) similarly found in Kenya that it could take as long as eight hours to cook githeri, a staple consumed by nearly all the 40 ethnic groups across the country and often cooked in bulk. The amount of fuel required and the size of the pot needed led most households to rule out LPG and other modern stoves for making githeri for reasons of costs and the inability of the stoves acquired by households to accommodate large, heavy pots.

In addition, traditional fires satisfy needs that extend beyond cooking meals to space heating, preparing animal feed, repelling insects, lighting, smoking crops and meats, disposing waste, heating water for bathing and washing, and drying clothes. Some of these activities and effects, such as smoke from biomass combustion repelling insects, are not possible with LPG or advanced combustion stoves, while space heating, preparing animal feed, and heating water using these stoves would be too costly for many households.

Studies looking at household use of various stove options confirm the foregoing observations. The researchers in a randomized intervention study in REACCTING (Research on Emissions, Air quality, Climate, and Cooking Technology in Northern Ghana) distributed, free of charge, Philips HD4012LS and Gyapa woodstoves to rural households in northern Ghana in December 2013 and January 2014. The average household size was about eight. At the time of the study the Philips model was one of the cleanest biomass cookstoves available on the global market. The Gyapa stove used in the study was a rocket stove designed specifically for REACCTING and manufactured in Accra. Each household in the intervention group received a total of two stoves in three different combinations: two Philips stoves, two Gyapa stoves, or one Philips and one Gyapa. The researchers were aware of the doubts raised by households about the suitability of modern stoves to make tuo zaafi and their concerns informed the design of the Gyapa stove, which was developed specifically for the study, as well as the design of a rebar stand to increase the stability of the Philips stove (Piedrahita et al. 2016). These design modifications notwithstanding, those receiving one Philips and one Gyapa used the Philips stove some for making soup but considered the Philips stove unsuitable for cooking tuo zaafi or rice, and after about a year did not use the Philips stove much for cooking. Those receiving two Philips stoves cooked largely with three-stone fires, although initially they used the Philips stoves to make soup, rice to a lesser extent, and tuo zaafi least of all. Panel regressions with household fixed effects showed that neither Philips nor Gyapa stoves had any statistically significant effect on the use of charcoal stoves. The data on the use of the Philips stove after the first year are marred by stove breakages, but even before the prevalence of stove breakages the effect on the frequency of three-stone fire use was not consistent: the use of the latter increased eight
months after receiving two Philips stoves compared to three months earlier before falling again after a year. After two years, there was no statistically significant difference in the use of traditional stoves (three-stone fires and charcoal stoves) between those who had not received any new stoves and those who had received two Philips stoves (Dickenson et al. 2019). Similarly, LPG stoves in many rural areas in developing countries do not have burners large enough nor are they sufficiently stable if vigorous stirring has to be maintained for a long time.

Similar findings were reported for a program in China, which distributed semi-gasifier stoves for cooking and heating water (Clark et al. 2017). Stove use was monitored for 48 hours at a time, during which only 4 percent was found to use the semi-gasifier stove exclusively while 77 percent continued to use traditional stoves. The program participants cited the ability to reach high temperatures, ease of operation (the stove included automated ignition), and less smoke as the desirable features of the intervention stove. Traditional stoves, however, could handle large pots and cook more food (85 percent of participants) and gave food good taste (71 percent). The semi-gasifier and traditional stoves were used to prepare different dishes. The decline in the use of traditional stove use from the pre-intervention levels was small. The semi-gasifier stove use declined considerably during the program, from 74 percent of days one month after the start of the intervention to 39 percent 13 months later. Households used more gas and electric stoves. Nearly two-fifths (38 percent) reported that they did not use the intervention stove to cook local dishes regularly.

Lumpiness of fuel purchase

Kerosene, charcoal, wood, and pellets can be purchased in small quantities at a time, while LPG is sold in increments of at the smallest about 2.5 kilograms (kg), which is rare, and typically 10 kg or more. There are economies of scale in all fuel supplies but especially for LPG because of cylinder management, and the larger the purchase, the greater the potential for reducing the unit cost. For LPG cylinder refills of 10 kg or more, LPG purchase is akin to paying for electricity or natural gas, for which households are billed once a month. Large, periodic cash payments (as opposed to paying small amounts frequently) are all the more challenging for those earning daily wages or seasonal income with limited disposable cash.

Recently a new contractual arrangement, akin to pre-paid meters for electricity, has been introduced for LPG. Known as pay as you go, this scheme uses a smart meter installed on each LPG cylinder and mobile money to enable LPG purchase in any quantity, however small, instead of paying for one full cylinder refill at a time. As such, should the pre-paid LPG credit run out in the middle of food preparation, the customer has the option of paying a small amount to finish cooking. The marketer monitors consumption in real time and delivers a refilled cylinder when the cylinder in use is close to empty. The cylinders are tagged and traced by the marketers, who have a greater incentive to maintain cylinders properly, thereby potentially improving safety. Pay-as-you-go LPG therefore holds the promise of enabling households who might otherwise find LPG unaffordable to start using LPG and easing concerns about LPG safety and supply reliability.

Nairobi is one of the first cities to market pay-as-you-go LPG. A recent study collected data from 426 pay-as-you-go LPG customers living in an informal settlement in Nairobi from January 2018 to June 2020 (Shupler et al. 2021). Seven interviewed participants reported feeling safer cooking with LPG because of the marketer’s tighter control of the cylinders—one commented that if a cylinder were to start leaking, the marketer would remotely detect the leak and shut off the gas. They also appreciated being able to finish cooking by making small payments and the convenience of the marketer’s delivering a refill cylinder before running out of LPG. During the Covid-19 pandemic lockdown, households with three or more family members, those who had already been buying LPG prior to setting up a pay-as-you-go
account, and those with female heads in employment tended to increase LPG consumption as more meals were cooked and eaten at home.

An important question is how much smart metering and home delivery add to the cost of supply. The cost of cylinder return and delivery is borne entirely by the LPG marketer, and the marketer also bears the cost of the inventory longer because, depending on how quickly customers consume LPG, the marketer will have a sizable amount of LPG delivered but not paid for by the customers. That is, each payment may be smaller but the unit cost can be markedly higher.

The above study on Nairobi found that unit prices were higher in the pay-as-you-go scheme by as much as US$0.20–0.25/kg between August 2020 and February 2021 against the average free-on-board (FOB) prices in the Arab Gulf—which sets benchmark LPG prices for Kenya—of US$0.44/kg. Although the incremental cost is high, this finding should be interpreted against the backdrop of historically high LPG prices in Kenya (Matthews and Zeissig 2011, 64). From September 2013 to June 2016, LPG was subject to a value-added tax (VAT) of 16 percent, but it is not obvious from the surveyed retail prices of LPG sold in 13-kg cylinders that the imposition or removal of the VAT increased or decreased the end-user prices by that magnitude after taking changes in the FOB prices into account (Figure 1). After five years of zero-rating the VAT on LPG, the government is re-imposing the 16-percent VAT in July 2021 (Daily Press 2021).

Figure 1: Comparison of free-on-board, cylinder refill, and pay-as-you-go prices in Kenya


Notes: PAYG = pay as you go. FOB prices are for an 80/20 mixture of butane and propane (Matthews and Zeissig 2011, 62) and with a one-month lag to account for the time it takes for shipping and delivery. The unit price of LPG cylinder refills is derived from the national average price for refilling 13 kg at a time. The unit prices of refilling 6-kg and 13-kg cylinders are virtually identical in Kenya. Each stacked column represents the incremental price. Taking February 2021 as an example, the FOB price was $0.53/kg (with a time lag of a month so that it is actually the FOB price from January), the refill LPG price averaged $1.42/kg nationally, and the pay-as-you-go LPG price in Nairobi was $1.64/kg.
During the above review of the Nairobi pay-as-you-go scheme (Shupler et al. 2021), 138 consumers deactivated their accounts, leaving two-thirds of the original account holders being studied, or 288 active accounts, in June 2020. One-third of account deactivations was due to households’ moving away from the area. A total of 17 deactivations was due to LPG being too expensive, while nine customers switched back to purchasing refilled LPG cylinders because of the lower unit price. Another two dozens said they had stopped using LPG altogether without citing specific reasons. The multi-tier framework for access defines affordability as spending no more than 5 percent of the household income on cooking, inclusive of stove and other acquisition costs (Bhatia and Angelou 2015). Regular use of LPG for cooking requires at least 10 kg per month and preferably 15 kg or more (Kojima 2011). At 10 kg per month, the minimal monthly household income required at US$1.90/kg (the pay-as-you-go price in June 2021 multiplied by 1.16 to account for the 16-percent VAT starting in July 2021) would be US$380, beyond the reach of many households, and the actual minimal monthly income for affordability would be higher once the initial adoption cost is amortized and added. Consistent with these observations, monthly consumption of LPG among the studied pay-as-you-go residential LPG customers in Nairobi was small, 3.2 kg per month. The average cooking time with LPG was less than 14 minutes, which supports the frequent observation that LPG is used by the lesser-off mainly for quick cooking but not for cooking githeri and other dishes that are energy-intensive to prepare.

Turning to advanced combustion stoves burning densified pellets, to make the sale of pellets for household use financially viable, a promising business model developed by Inyenyeri in Rwanda required signing an annual contract to make monthly purchases of pellets in 30, 45, or 60-kg lots, corresponding to one, two, or three stoves, respectively. The pellets were initially sold for RF 4,000 (US$5.83 in 2014 when this arrangement was first offered at scale and the customers numbered about 400), 6,000 (US$8.75), and 8,000 (US$11.67), for 30, 45, and 60 kg, respectively, but in late 2016 when the production capacity was increased to be able to supply 1,000 customers, the prices were raised to RF 6,000 (US$7.40 in late 2016), 9,000 (US$11.10), and 12,000 (US$14.80). Households could also purchase additional pellets by the kilogram should they run out before the next monthly supply. In exchange, the household could lease a Mimi Moto stove, rather than buy it, at an additional one-time payment of RF 5,000 (US$7.29 in 2014) (Jagger and Das 2018; Seguin, Flax, and Jagger 2018). Although prices were selected to make switching to Mimi Moto stoves competitive with charcoal use, the indivisibility of pellet purchase in contrast to charcoal presented a challenge to some households.

Livelihood

According to the Food and Agriculture Organization (FAO), more than 40 million people are engaged in commercial fuelwood and charcoal activities to supply urban centers. In extreme cases, the job opportunities provided could even avoid civil unrest, as found in a study that had collected primary data over 10 months in 2011 in Sierra Leone. Of the 64 charcoal-producing villages visited during the data collection, 63 had not been involved in charcoal production prior to the civil war. One charcoal trading village consisted entirely of ex-combatants who had turned to cooperative charcoal production as an exclusive source of income (Munro, van der Horst, and Healy 2017). Discouraging charcoal use and endeavoring to shift households to “clean and efficient” energy, all of which involve modern technologies, large economies of scale, or both, leaves unanswered the socioeconomic questions raised in such circumstances.

Woodfuel retailing is a major source of income for the poor, including headloaders who are often among the poorest. The ease of entry into this market results in strong competition and low profit margins, making it a livelihood of the last resort in many areas. While women may be involved in small-scale sale
of wood, as the scale of operation and the corresponding income-generation potential increase, the business tends to be taken over by men, depriving women of an important source of income. If not carefully designed, forestry projects designed to help increase the supplies of sustainable woodfuels (including wood to make pellets) can even harm the poor. One possible outcome of local collective management programs is that firewood sellers are forced to give up wood harvesting. In India, detailed studies of Joint Forest Management—involving partnerships between state forest departments and local communities—found that, although most user groups in local communities benefited from the changes arising from the management program, the poorest headloaders were left worse off (Arnold et al. 2003).

Fuelwood may also be an integral part of households’ livelihood. A paper on rural Andhra Pradesh found that the sticks used to grow tomatoes—a good cash crop—were later used for cooking. Women took sheep and goats to forests to feed them and collected firewood while there. Livestock sheds were also made of sticks and wood and were used for cooking once they became unusable. Not surprisingly, households relying on forests for multiple purposes use firewood for cooking. Firewood collection is time-consuming and hard menial work, and also takes children and adults away from school work, childcare, and other important activities, but not always—in some cases firewood collection could take on an almost recreational role in that women could go into forests and spend as much time together as they wished, and husbands would not question their time away (Malakar, Greig, and van de Fliert 2018). Neither LPG nor pellet stoves can provide or take advantage of these opportunities, except by chopping sticks and branches to the size suitable for pellet stoves.

Advanced combustion stoves are manufactured in a handful of developed countries (such as Mimi Moto in the Netherlands) and some large developing countries. Globally, about three-fifths of LPG is sourced from natural gas and the balance from crude oil refining, and the upstream supply chain tends to be dominated by large national oil companies—for example, Saudi Aramco of Saudi Arabia and Sonatrach of Algeria set benchmark prices for LPG in the Arab Gulf and North Africa, respectively—and large international oil companies. Promotion of LPG in particular might mean, in practice, that the supply chain would shift from local wood collectors, charcoal producers, stove manufacturers, and fuelwood and stove sellers to importers of cylinders and stoves, and major oil companies supplying LPG.

Global warming potential

From the point of view of impact on greenhouse gas emissions, LPG is a fossil fuel and its use always results in positive emissions of greenhouse gases and other substances that contribute to global warming. By contrast, the global warming potential of advanced combustion stoves burning biomass depends on the sustainability of the biomass harvested, the sources of electricity used during pellet manufacture and stove operation, and completeness of combustion. If biomass is not sustainably sourced, if electricity used is not decarbonized, or if the stove is operated improperly and the emissions of black carbon—the global warming potential of which is believed to be three orders of magnitude higher than that of carbon dioxide (CO₂)—are material, then LPG could out-perform even advanced combustion stoves from the point of view of the net contribution to global warming.

In in-home measurements of emissions from uncontrolled cooking (that is, cooking as practiced normally by households and not following any protocol) using various stoves for biomass in rural Malawi, Philips HD4012LS stoves were found to have the lowest global warming commitment of eight stove types tested. However, its global warming commitment was lower than that of three-stone fires by only 55 percent, higher by a factor of 2.8 than in laboratory measurements, and higher than that of LPG by a factor of 4 over a 100-year horizon. Over a 20-year horizon, elemental carbon contributed the most, accounting for 53–65 percent across all stoves. The unfavorable comparison with LPG is in part because, in addition to
much higher black carbon emissions in the field than in laboratory tests, the default value of 0.81 for the fraction of non-renewable biomass\(^7\) in Malawi was used in the calculations (Wathore, Mortimer, and Grieshop 2017).

Controlling cooking practices yielded much less global warming potential. Similar field measurements for Philips HD4012LS stoves in Rwanda restricted the households to using only pellets, except during the start-up when pellets were ignited with either kerosene or twigs with matches. The field performance under such conditions was much better than under unrestricted cooking practices in Malawi. If the default value for the fraction of non-renewable biomass in Rwanda of 0.98\(^7\) is used, even if electricity for pellet manufacture is assumed to be based entirely on hydropower, the global warming commitments of Philips HD4012LS and LPG stoves were similar: the median for Philips would be 1.2 tonnes of CO\(_2\) equivalent per year compared to 0.98 for LPG. If electricity is from diesel generators, the global warming commitment would rise by another 15 percent. If, on the other hand, the pellet feedstock were entirely renewable, the global warming commitment would be negligibly small (Champion and Grieshop 2019).

**Challenges to Proper Regular Use of Advanced Combustion Stoves for Woodfuels**

Advanced combustion stoves hold great promise for minimizing the emissions of harmful pollutants, especially in laboratory measurements. Given enough mixing and sufficient temperature, there are no technical barriers to complete combustion of wood (although such combustion would also produce oxides of nitrogen from nitrogen in air). For many households, especially in rural areas where delivery of LPG is difficult and electricity is unavailable or unreliable, advanced combustion stoves as the primary stoves may be the most realistic pathway forward for universal access to clean household energy. Several challenges need to be overcome, however, for advanced combustion stoves to make a material difference in SDG 7.

**Pellet manufacture on the scale required**

All modern stoves for woodfuels require some fuel processing, even if to chop wood into small pieces. Advanced combustion stoves burn small, compressed pellets made from ground, dried wood or other biomass wastes. Pellets can decouple fuel supply from global markets and their price volatility, but unlike traditional biomass, raw material supply, an industrial base, reliable power and associated electricity supply infrastructure, and infrastructure for fuel distribution must all be in place.

Carter et al. (2018) studied the difficulties of decentralized manufacture of densified biomass fuels in rural Jilin and rural Sichuan in China. The researchers identified several challenges: (1) heterogeneity of feedstocks that limits pellet and briquette energy density, (2) high operational costs for seasonally-varying collection, transport, and storage of raw materials, (3) high operational costs for storage and distribution of final products, (4) limited household demand for densified biomass fuels, and (5) inconsistent enforcement of national and provincial policies banning use of coal and open-field biomass burning. Most respondents in Jilin (where heating is necessary in winter) suggested that the energy density of densified biomass fuels for heating would need to approach that of coal, which in turn required reducing the moisture content of the raw material to less than 15 percent. There was not adequate financing available for machinery upgrades and inventory expansion to support collection of raw materials followed by drying, shredding, chipping, sieving, compressing, and packaging. In Sichuan, factories had to spend

\(^7\) [https://cdm.unfccc.int/DNA/fNRB/index.html](https://cdm.unfccc.int/DNA/fNRB/index.html).
RMB 90,000 (US$14,000) to set up electricity supply infrastructure. The breakeven price was RMB 4,000 (US$620) per tonne, more than four times the pellets produced commercially elsewhere in the province. In Jilin, concerns were raised about machine durability because of frequent and costly maintenance and repair needs. Some forms of biomass were too seasonal and hence unsuitable as raw materials. For example, maize stalk had to be collected from the fields within a month or even 15 days, and then stored for further processing.

On an even smaller scale, an innovative business model—albeit in the end unsuccessful (the firm was forced to suspend its operations in April 2020)—developed by Inyenyeri in Rwanda also encountered problems with pellet production. Challenges were related to acquisition, efficiency, and maintenance of the pelleting equipment; availability of reliable electricity; and supply of biomass feedstock with properties matching the amount of equipment available (such as feedstock with a limited moisture content so as not to exceed the available drying equipment capacity). As in rural Jilin and Sichuan, handling feedstock heterogeneity presented a significant challenge. Eucalyptus stems and branches—but not leaves, which customers complained changed the taste of the dishes cooked—were suitable. Sawdust and elephant grass were not, because sawdust from hardwoods gummed up the pelleting machine while elephant grass would rot easily, making it difficult to process. Production problems in 2015 and 2016 prevented Inyenyeri from signing up new households, and in late 2016 the company raised the price of pellets from RF 133 (US$0.16)/kg to RF 200 (US$0.25)/kg while limiting purchases of extra supplies to 5 kg at a time. These two developments led some customers to suspend or terminate their contracts (Jagger and Das 2018).

Factory owners in rural Jilin and Sichuan also told Carter et al. (2018) that machinery imported from overseas (Germany, the United States, and the Republic of Korea) to manufacture densified biomass was more durable but cost four to five times more, and their repairs were also costly with long turnaround times. Dickinson et al. (2019) made a more general observation (in the context of stove manufacture and after-sale service) that there was a tension between selecting appropriate, domestic technologies to meet the local needs and making the technology adoption affordable on the one hand, and ensuring high quality and long-lasting performance on the other.

The perceived environmental unsustainability of household use of woodfuel (fuelwood and charcoal) was one of the main reasons cited for LPG subsidy programs launched by various governments in the 1980s and 1990s. In practice, agriculture—and not household use of woodfuel—has been shown to be the main driver of deforestation in all regions and accounts for 70 percent or more of deforestation. However, woodfuel production is the major driver of forest degradation in Africa, although not elsewhere where timber logging is the main driver (FAO 2020). Use of charcoal in particular can be a driver of deforestation in hot spots, and particularly where charcoal is used in industries (FAO and UNEP 2020). Charcoal is especially problematic because it is very energy-intensive to make and up to six times the total energy contained in wood may be lost in the manufacturing process (GIZ 2014). Brazil is the world’s largest producer of charcoal, producing 6.4 million tonnes in 2019, followed by Nigeria at 4.7 million tonnes and Ethiopia at 4.6 million tonnes. In terms of regions, Africa is by far the greatest producer: Africa produced 35 million tonnes of charcoal in 2019, compared to 9 million tonnes each in the Americas and Asia.8

Against the above backdrop, wood pellets hold promise, but supplying pellets on a large scale from renewable biomass has been a challenge, as the study in Rwanda by Champion and Grieshop (2019) shows: because the bulk of biomass resources in Rwanda is not renewable, Mimi Moto stoves burning

wood pellets may even be marginally worse from the point of view of net greenhouse gas emissions than LPG. It may be possible to launch a pilot program based largely on renewable biomass because only a small amount of biomass would be needed, but scaling up to make a material difference and supplying pellets to a large segment of the population may not be possible without resorting to non-renewable biomass.

Stove repair

Gasifier pellet stoves are typically among the cleanest wood-burning heating appliances available today and deliver high overall efficiency. Unlike wood stoves and fireplaces, most gasifier pellet stoves need electricity to operate. The solar-battery combination, which is often part of these stoves, has run into durability problems. An important question is whether the installation rate exceeds repair capacity. Another question is the possibility that the manufacturer will change design and stop selling spare parts for older-vintage stoves.

As a concrete illustration, in the REACCTING study in northern Ghana (Dickinson et al. 2019), Philips stove batteries began to fail after a year. After two years, 62 percent of the batteries had stopped working. The manufacturer had redesigned the stove and switched to a different battery, making purchase of old batteries difficult and expensive. Other problems included breakdowns of the fan (14 percent of the stoves after two years) and the solar charger (8 percent).

Mortier et al. (2017) encountered similar problems in rural Malawi in their randomized controlled trial over two years with two groups of equal size comparing the effects of Philips HD4012LS stoves with continued use of open fire cooking on pneumonia in children under 5 years of age. Intervention households received two Philips stoves, a solar panel to charge the battery for the stove fan, and user training. Importantly, the research program provided free repair or replacement as needed, carrying out such repairs and replacements as quickly as possible. Each intervention household required such service four times on average over the course of the trial. Over the two-year trial period, repairs or replacements were carried out on 13,192 occasions (3.1 per household) for cookstoves and 5,259 occasions (1.2 per household) for solar panels. The researchers were surprised by the high rate of malfunction because the stove and its accessories had been specifically designed and developed for these end users and their environments. Failure of the rechargeable lead acid batteries was particularly common. During the follow-up visits after 3, 12, and 24 months, a progressively lower share of households reported meeting all their cooking needs using the Philips stoves: 73 percent, 59 percent, and 50 percent, respectively. Most households answering an optional follow-up question reported using the stoves for at least one meal a day on average over the two years of follow-up. The most common reason for not using the cookstoves for all cooking tasks was that the stoves had malfunctioned.

Another example of frequent stove breakdown despite extensive consultation with stove users and iteratively designing new stoves is provided by Clark et al. (2017), who studied semi-gasifier stoves in China. The intervention package, rolled out in two phases, provided a semi-gasifier stove for cooking and heating water and a two-year supply of pellets. The stove was designed iteratively through a five-year improvement process (Shan et al. 2017) to meet the ISO IWA’s tier 3 voluntary performance target for thermal efficiency and tier 4 for emissions and safety. Importantly, the stove had an automated ignition system and a small fan producing a synthetic gas-like flame. The stove had a pellet feeder mechanism to enable the cook to add pellets easily while cooking. Over the course of the program, 27 percent of stoves were repaired or replaced.

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from the first phase and 48 percent from the second phase reported repairs. The most commonly reported part requiring repair was the automated ignition mechanism.

Proper operation

Pellet stoves offer tremendous potential to reduce emissions but only when operated properly. There are several impediments to operating pellet stoves correctly at all times to ensure low PM$_{2.5}$ emissions.

The initial start-up of a pellet stove has been found to be a significant source of PM$_{2.5}$ emissions, a problem that gas and electric stoves eliminate entirely. A study in Rwanda measured the emissions of PM$_{2.5}$ and CO from Mimi Moto forced-air gasifier stove, three-stone fires burning wood, and charcoal stoves (Champion and Grieshop 2019). Mimi Moto stoves used pellets except during the initial fuel ignition. Ignition materials contributed disproportionately to PM$_{2.5}$ emissions of all stove types. For Mimi Moto stoves, starting up with anything other than kerosene increased emissions significantly, and even with kerosene, too much kerosene resulted in small plumes of black smoke, but too little kerosene would mean a longer ignition time. Highly emissive Mimi Moto stoves (one of which had a dead battery) and three-stone fires emitted half of total PM$_{2.5}$ in the first 20 percent of the testing time period. Refueling during testing increased PM$_{2.5}$ emissions markedly, the implication of which is that there needs to be sufficient fuel in the stove before starting cooking, ruling out dishes that take hours to prepare such as githerti in Kenya. Equally important was the end of cooking where refueling or burnout and pellet disposal could result in high, visible emissions. Charcoal PM$_{2.5}$ emissions were much higher than those in laboratory tests, largely driven by the high start-up emissions. The study highlights the importance of ignition, refueling (or alternatively the need to avoid refueling if at all possible), and burnout phases of cooking, as well as of proper disposal of pellet char rather than letting it smolder. If all the rules are followed to eliminate excessive emissions, pellet stoves could meet the ISO IWA’S tier 4 emission target for PM$_{2.5}$ and tier 5 (highest tier, lowest emissions) for CO. Otherwise, when operated incorrectly, pellet-fed gasifier stoves may have emissions as high as those of traditional wood and charcoal stoves. For example, reloading alone increased the emissions to tier 3, and the median PM$_{2.5}$ emissions exceeded the WHO’s emission target by 14-fold.

Given the evidence on the disproportionate contribution of ignition materials to emissions, Fedak et al. (2019) conducted a survey of experts in the field on the material types used to start cookstoves burning solid fuels. The survey identified 43 unique ignition materials. Whatever burns quickly and is available was the criterion in many cases. Accelerants (kerosene, paraffin/wax, burning charcoal from a previously lit stove) were cited the most, followed by plastic (plastic bags being the most commonly cited), paper, kindling (branches, twigs, leaves, sawdust), agricultural waste, high-resin wood, rubber (tire tubes, tire scraps, and flip flops), and others. Plastic use (of which plastic bags were the most prevalent) was high in Africa, East Asia, Southeast Asia, Mexico, Central America, and to a lesser extent South Asia, but not in South America. Rubber use was high in East and Southeast Asia. Plastics were cited as the second most commonly used starter for wood stoves, charcoal stoves, three-stone fires, and improved stoves (detached as well as built-in). Rubber was used more frequently in detached improved and traditional stoves. The pattern of start-up material use did not differ between “improved” stoves and three-stone fires. Availability was the most commonly cited reason for selection, followed by seasonality (seasonal availability of crop residues, dry versus wet season).

Households may burn fuels not intended for advanced combustion stoves because of costs or a lack of availability of clean alternatives. For example, in the REACCTING study in northern Ghana, although the Philips stove was not designed to burn charcoal, households burned charcoal because doing so required less upfront fuel preparation and subsequent tending. In rural Malawi, large wood pieces sticking out of
the top of Philips HD4012LS stoves were commonly found in the field by researchers. The size recommended is 1 centimeter by 5 centimeters, requiring additional work, a proper supply chain, and the willingness and the ability to purchase pellets. Hot charcoal left from previous cooking was commonly used to start the fire. The outsized contribution of the fuel ignition to PM$_{2.5}$ emissions from the Philips stove and another forced draft stove, ACE 1, has important implications for personal exposure, because the start-up period is when the cook is sure to be right near the stove (Wathore, Mortimer, and Grieshop 2017).

Disparity between laboratory and field emission measurements

Laboratory testing of emissions from stove use is conducted under near-ideal as well as simplified conditions and typically gives lower emissions than field measurements. The entire testing may be conducted using proper pelletized biomass (except during the initial ignition), usually without reloading, and the measurements may consist of those during water boiling tests only. Among the striking findings have been the large differences in the PM$_{2.5}$ emissions between laboratory and field measurements for advanced combustion stoves burning woodfuels. Field emission measurements have been reported as being typically three to five times higher than those in laboratory control tests. Mortimer et al. (2017) identified fuel and loading heterogeneity as two important contributors to higher emissions. By contrast, fuel and loading heterogeneity is seldom an issue for LPG and never for electric stoves. In-home measurements of PM$_{2.5}$ emissions from LPG cookstoves in Uganda found them to meet the ISO IWA’s tier 5 emission target, whereas forced draft gasifier stoves could not meet tier 2 (Johnson et al. 2019). Shen et al. (2018) found that even a worn-out LPG stove with a deteriorated burner obtained from a rural household in Cameroon met the tier 4 PM$_{2.5}$ emission target.

In the above field measurements of emissions from various biomass stoves in rural Malawi (Wathore, Mortimer, and Grieshop 2017), where households cooked as they would normally, Philips HD4012LS stoves were found to register the lowest emissions of four household stove types, the other three being (1) “traditional” stoves comprising either three-stone fires or simple mud stoves; (2) ACE 1, a forced draft stove with a price tag similar to Philips’ at about US$90; and (3) locally made natural-draft clay cookstoves costing only about US$1–2 each. The emission rates of PM$_{2.5}$ and CO were both lower by 70 percent for the Philips stove compared to the traditional ones. The instantaneous scattering emission factor—which represents the amount of light scattering related to particulate emissions—against normalized time for each cooking event showed a sharp peak at the beginning but Philips and ACE 1 stoves showed a much higher peak—by at least an order of magnitude and in many cases approaching two orders of magnitude—than other stove types during the first 20 percent of the cooking time. As a result, the mean PM$_{2.5}$ and CO emission factors—grams (g) of each pollutant per kg of wood combusted—in measurements following laboratory protocols were 80 percent and 65 percent lower, respectively, than in-home mean values for the Philips stove. Similarly, emission rates (g of each pollutant per minute) for wet wood were 76 percent and 61 percent lower for PM$_{2.5}$ and CO, respectively. The emissions from the best-performing forced-draft stoves were in the same range as the laboratory performance of a basic improved biomass cookstove. A number of factors reduced field performance in which heterogeneous fuels were burned under widely ranging conditions. The median emission factor for the Philips stove fell short of meeting even the ISO IWA’s tier 1 emission target for PM$_{2.5}$ while the tier 3 target was barely met for CO.

The REACCTING project in northern Ghana similarly allowed the cooks to prepare local dishes on the Philips HD4012LS stove using local fuels. Matches and crop stalks are said to have been typically used
during fuel ignition. The PM$_{2.5}$ emissions$^{10}$ in g per kg of dry wood by Philips stoves operated in the field were two to four times those observed in a laboratory and were not statistically different from three-stone fires, while the field CO emissions by Philips stoves were 46 percent lower. The average overall thermal efficiencies of three-stone fires in the field were about two-fold higher than the laboratory values and comparable to those for the Philips stoves. Philips stoves showed greater variation in emissions of elemental carbon or CO, which the researchers attributed to varying user behavior, such as varying fan speed, fuel over-loading, and inadequate fuel preparation (Coffey et al. 2020).

The field measurements in Rwanda that had also tested the Philips HD4012LS stove but in which cooks had been told to use only pellets (except when kerosene or twigs with matches were used for pellet ignition) showed much better performance than the Malawi or the Ghana study. Of more than 50 sets of measurements, one failed to meet the ISO IWA’s tier 1 emission target for PM$_{2.5}$, another failed to meet tier 2, five failed to meet tier 3, and the rest met tier 3 or tier 4 performance targets and several met tier 5 performance target. CO emissions met at a minimum tier 3 target and most met tier 4 or tier 5 targets. The variation in performance was related to (1) how ignition and char burnout were handled; (2) whether there was refueling, which increased emissions markedly, and (3) whether there was equipment failure, such as a dead battery. Stove performance declined measurably with age. Measurements were taken from November to December in 2017 and May to June in 2018 on stoves that had been acquired in 2017, 2016, or 2015. The median PM$_{2.5}$ emissions increased from 0.5 g of PM$_{2.5}$ per kg of wood in stoves acquired in 2017 to 0.9 for stoves acquired in 2016 and to 1.7 for stoves acquired in 2015. Similarly, CO emissions increased from 14.6 g per kg of wood to 17.3 and 28.2 for stoves acquired in 2017, 2016, and 2015, respectively (Champion and Grieshop 2019).

The impact on emissions of reloading of pelletized biomass was measured in a study in China where the stove had mechanisms for rotating the re-loading crank to manually load and reload pellets and an electric coil heater inside the combustion chamber for ignition (Deng et al 2018). PM$_{2.5}$ emissions in laboratory measurements were more than 70 percent lower than those in the field in the absence of reloading, and CO emissions were 60 percent lower. If a test involved reloading of pellets, emissions increased measurably in both laboratory and field testing, but the difference narrowed to less than 60 percent for PM$_{2.5}$ and 40 percent for CO. In laboratory water boiling tests, emissions increased with increasing amount of pellets loaded. In field measurements, reloading contributed to 30 percent of total PM$_{2.5}$ emissions.

**Emissions from Cookstoves**

“Clean” in “clean fuels and technology” in SDG 7 is intended to reduce and eventually eliminate exposure to harmful pollutants that cause morbidity and premature mortality. The health impact of air pollution depends on the toxicity of the pollutants, their concentrations, duration of exposure, and the number and the underlying health conditions of the individuals exposed.

If cooking were the only source of air pollution, examination of cooking practices alone would be sufficient to understand how to improve household air quality. In practice, cooking is just one of many activities contributing to the ambient concentrations of pollutants:

- Other household chores—such as space heating, heating water for bathing, kerosene lamps, and trash burning—can contribute substantially to poor air quality. The analysis of household energy

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$^{10}$ Total integrated particulate matter was collected with no size cut. However, size distribution analysis showed a unimodal biomass distribution with a peak in the range of 0.26–0.38 microns, and as such the particulate matter collected is expected to be largely PM$_{2.5}$.
use in 52 developing economies found that polluting energy was far more commonly used for space heating than for cooking (Kojima 2021a).

- Home-based income-earning activities and means of subsistence, such as preparing meals for animals, may and often do use polluting fuels and technologies to save costs.
- Field burning by farmers can substantially reduce air quality in the affected local areas including indoor air quality.
- The activities of the neighbors affect indoor air quality. This is one reason indoor PM$_{2.5}$ concentrations may not be low even in households using only clean fuels and technologies.

Reducing direct emissions by cookstoves is without question important but achieving acceptable household air quality requires addressing multiple sources of emissions. Johnson and Chiang (2015) concluded from running a model that that using a three-stone fire for a few minutes a day would elevate PM$_{2.5}$ concentrations above any of the targets set by the WHO. Traditional charcoal stoves could be used longer but still to less than 10 minutes a day. None of these restrictions are practical for households that rely on these stove types even as secondary stoves. That said, as described above, fine particulate pollution from combustion of biomass is likely to be less harmful on a µg/m$^3$ than the products of fossil fuel combustion, and hence meeting the interim WHO targets may be adequate until further evidence is gathered to demonstrate otherwise.

The above observations highlight, amongst others, the adverse environmental consequences of fuel and stove stacking. And yet, as explained in the foregoing sections, abandonment of polluting fuels, stoves, and practices is rare among many households. Quinn et al. (2018) studied 11 clean cooking programs in developing countries and observed that households overwhelmingly continued to retain traditional biomass stove use while adopting clean fuel stoves. In Ecuador, where decades of large LPG price subsidies enabled nine tenths of all households to adopt LPG largely as the primary cooking fuel, analysis of a sub-sample in a rural population showed that three-quarters of households continued to use woodfuels on a weekly basis. In Rwanda, exclusive use of pellet gasifier stoves was found to be extremely rare and about two-thirds of meals were still cooked using traditional stoves. In rural Kenya, Gitau et al. (2019) found that households used the gasifier stoves only when few household members were at home or when cooking food for a few people, the primary reason being the small size of the gasifier stove. Two-fifths of households reported fuel preparation as a challenge because of the need to chop firewood into small pieces, which they found time-consuming and tiring. Reloading the gasifier stove when making dishes that take a long time to cook was a challenge to 77 percent of households: the stove was hot and arranging pellets in it was tricky, raising the risk of a burn. Of the households that had been using the gasifier stove, 63 percent used it to make dishes that took a short time to cook, at a rate of five days and nine times a week on average.

Self-reported use of cleaner cookstoves tends to over-state their use, and yet even self-reported statistics show that considerable barriers remain. A cluster randomized controlled trial in Malawi in which the intervention households were provided with two Philips HD4012LS stoves with access to an intensive free repair and replacement service showed that their self-reported use was probably as high as could be realistically expected. The stove use declined with time. The share of the intervention households using the Philips stoves to cook two or more meals a day fell from 42 percent at three months after the start of the intervention to 26 percent at 24 months and those who used the Philips stoves to cook 1–2 meals a day fell from 23 percent to 15 percent, but those who used the Philips stoves to cook only once a day increased from 27 to 37 percent. Stove monitors generated less usable data due to technical problems but similarly indicated declining use over time (Mortimer et al. 2017).
As for the impact of other sources of emissions, personal exposure measurements of PM$_{2.5}$ in peri-urban Accra households showed that there were no statistically significant differences in the exposure levels of those living in households cooking with LPG and those cooking with charcoal, and the ambient air quality in such households appeared to have been dominated by the background air quality (Delapena et al. 2018). In a study of adoption of ethanol stoves in refugee camps in Ethiopia, measurements in households using ethanol showed a reduction in PM$_{2.5}$ concentrations from 1,250 to 200 $\mu$g/m$^3$. The researchers suggested that the high residual concentration could be due to use of kerosene wick lanterns and air pollution from neighbors (Benka-Coker et al. 2018).

A study measuring ambient concentrations of PM$_{2.5}$ in two villages in western Kenya found elevated concentrations even in homes that had been asked to use only Philips HD4012LS stoves during the measurement periods, although three-stone fires were not removed from these homes (Yip et al. 2017). Of the six improved stoves studied, the Philips stove delivered the lowest 48-hour concentration but the geometric mean (averaged over 36 measurements) was 326 $\mu$g/m$^3$, an order of magnitude higher than the WHO targets. Cooking with three-stone fires raised the geometric mean (over 45 measurements) to 586 $\mu$g/m$^3$. The researchers found that kerosene lamps raised PM$_{2.5}$ concentrations significantly. Burning tin kerosene lamps for 90 minutes resulted in concentrations in excess of 3,000 $\mu$g/m$^3$ a meter away and 1.5 meters above ground. Hurricane lamps reduced the concentrations to less than 200 $\mu$g/m$^3$. The moisture content of the wood burned also affected emissions. The researchers found a weak but statistically significant relationship between moisture and emissions, and estimated that PM$_{2.5}$ concentrations rose by 24 $\mu$g/m$^3$ for each percentage increase in moisture content.

Snider et al. (2018) measured indoor and outdoor air quality in summer and winter to estimate ambient PM$_{2.5}$ concentrations net of background pollution for different cooking technologies in rural Sichuan, China. The technologies examined were wood chimney, semi-gasifier, LPG or electric (grouped into a single category), and mixed stove use. Semi-gasifier stoves could potentially perform at the ISO IWA’s tier 4 emission target level, while LPG and electric stoves are classified as tier 4 or higher. Those with semi-gasifier stoves had received pelletized biomass fuel. Exclusive use of wood-chimney stoves was most common (59 percent of household days), followed by mixed stove use (24 percent), exclusive use of electric or gas stoves (11 percent), and exclusive use of semi-gasifier stoves (6 percent). When the outdoor concentrations were subtracted, the share of household-days meeting the WHO’s interim annual target of 35 $\mu$g/m$^3$ of PM$_{2.5}$ increased in all cases but one. That one exception was surprisingly semi-gasifier stove use, but that could have been due to the fact that there were measurements for only 2 household-days. In all cases, the share of household days meeting the WHO target was greater in summer than in winter. After subtracting the background concentrations, the highest share was for LPG and electric stoves at 89 percent in summer, followed by semi-gasifier at 77 percent. In winter, however, the highest share fell to 55 percent, again for LPG and electric stoves. Equally informative was the trend in PM$_{2.5}$ concentrations as a function of the stove use duration. With LPG and electric stoves, the longer the stove use, the lower the PM$_{2.5}$ concentrations, whereas with all other stoves, including semi-gasifier stoves, the longer the stove use, the higher the PM$_{2.5}$ concentrations. This would suggest residual ambient concentrations of PM$_{2.5}$ from earlier non-exclusive use of clean technologies, which gradually fall as air is cleared by use of LPG or electric stoves.

Consistent with the above observations, Delapena et al. (2018) could not find statistically significant differences in personal exposure to PM$_{2.5}$ between charcoal-only (11 households), LPG-only (7), and LPG-charcoal (18) user groups. Personal exposure was similar to the ambient concentration, viz., no distinction could be made between LPG and charcoal because the dominant factor was the background PM$_{2.5}$ concentrations. Trash burning and mosquito coils were the most common other sources of exposure.
(12 households). Only any-wood user group (which included three-stone fires) had higher exposure, although they had no trash burning during the study period. No charcoal production or exposure to emissions from smoking were reported. The average background PM$_{2.5}$ concentration was 26.5±14.9 µg/m$^3$, 15–42 percent of which was deemed to be due to biomass combustion from source apportionment analysis.

Wathore, Mortimer, and Grieshop (2017) estimated in their study in Malawi that health benefits were modest. Taking non-linearity of dose-response relationships into account, abandonment of traditional biomass stoves in favor of exclusive use of Philips HD4012LS stoves—the best-case scenario in the study—would reduce the all-age mortality relative risk from ischemic heart disease from 2.2 to only 1.9; the decrease in the relative risk for chronic obstructive pulmonary disease should be comparable because the dose-response relationships for the two diseases are similar. Despite reducing PM$_{2.5}$ emissions and intake by about 75 percent compared to three-stone fires and simple mud stoves, daily PM$_{2.5}$ intake associated with Philips stove use was still 2.8 times higher than laboratory measurements. Compared to estimated effects of LPG stoves, in-home use of a Philips stove resulted in 66 times higher daily exposure.

**Discussion**

LPG and advanced combustion stoves have been cited as two of the most promising pathways to achieving access to clean household energy. Household use of LPG in developing countries has been rising, especially when supported by targeted subsidies (Kojima 2011b), while technical improvements in advanced combustion stoves have enabled attainment of very low emissions of PM$_{2.5}$ and other harmful pollutants under controlled conditions. The number of publications examining advanced combustion stoves is a testament to growing interest shown by practitioners and policymakers.

These two stove types have several challenges in common as well as unique challenges of their own. The first and arguably the overriding one is the higher cost of their use as primary energy sources. LPG is subject to high volatility and high fuel price levels on the global market. Since 2016, the prices of propane (one of the two major components of LPG, the other being butane) in two important regions for trading LPG have fluctuated by nearly a factor of three in U.S. dollars (Figure 2);$^{11}$ countries with currency depreciation during the same period might have seen even higher volatility. The rapid price rise from early 2020 to early 2021 is particularly striking. It is entirely possible that a household that could afford LPG as the primary cooking fuel in April 2020 found it unaffordable a year later. Further, LPG is for households who do not live in urban centers with a network of natural gas pipelines. Virtually all rural households who want to cook with gas would have to use LPG, but rural households tend not to be as well-off as urban ones and are less likely to have regular cash income.

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$^{11}$ If price volatility were the only issue, the retail LPG price can always be frozen for years on end without incurring any price subsidies by adjusting taxes and setting it at, for example, the equivalent of US$2.50/kg, but that would make LPG out of reach for many more households.
Pay-as-you-go LPG schemes offer new possibilities because of the ability to sell LPG in small quantities and inform customers and marketers about when cylinders are running out. That so many households in informal settlement areas in Nairobi, which are presumably not inhabited by the better-off, increased rather than decreased LPG consumption during the Covid-19 pandemic lockdown—albeit from a low base—is remarkable. Metering consumption can in principle enable performance-based support to promote household use of LPG which, according to the subscribers of the scheme in Nairobi, is also perceived as being less prone to leaks and accidents under the schemes. Where home delivery is commercially feasible, not having to worry about running out of LPG is particularly attractive. Such an arrangement brings LPG close to natural gas in terms of supply availability and reliability, with the added advantage of breaking up payments into small increments instead of paying monthly gas bills.

The above benefits notwithstanding, home delivery to ensure continual supply of LPG would be commercially viable primarily where there is a critical mass of consumers living within relatively short distances of the supply points connected by tar roads. The fixed and variable costs of delivering LPG cylinders to meet household needs in a timely manner in areas with a low concentration of consumers who are not close to supply points and who do not consume much to begin with—as in many rural areas, which may also lack tar roads—would be high and most likely unaffordable. While the economies of scale for home delivery of LPG are not nearly as large as those for natural gas pipelines, trucking is markedly costlier than pipeline transportation per unit of energy delivered. The question of the extent to which pay-as-you-go schemes can make LPG affordable to those who are unable to buy even 6 kg of LPG at a time depends largely on how much the incremental costs can be driven down with scale and experience.

Advanced combustion stoves use locally available biomass, which should be far less vulnerable to the kind of price volatility seen in Figure 2. However, pellets still require cash outlays, and a market for environmentally sustainable and commercially viable pellet manufacture for use by households has yet to emerge. Carter et al. (2018), who studied the challenges of producing pellets, note that technologies employed by mid- and large-scale processing industries have limited application for smaller-scale biomass processing. The alternative to buying pellets is to spend time to prepare properly-sized wood pieces, a practice that two-fifths of households in rural Kenya found tiring and time-consuming (Gitau et al. 2019). Being tiring and time-consuming is one of the most cited shortcomings of wood collection for...
traditional stoves and one that access to modern energy is meant to overcome. Unsurprisingly, inadequate fuel preparation was one of the causes of high pollutant emissions found by Coffey et al. (2020).

The cost of stove purchase and repair is another barrier to regular use of these two stove types. It is entirely possible to do all cooking using an LPG cooktop: four-burner gas stoves capable of accommodating large pots and pans have been commercially available for decades in high-income markets, but they are costly and far beyond the means of many households in developing countries. Similarly, advanced combustion stoves are currently not suitable for cooking large dishes or dishes that take a long time to cook because the commercially available stoves are too small and not sturdy enough, and reloading wood in the middle of cooking is difficult and a safety hazard. Just as with gas stoves, it is possible to overcome these problems by having several stoves of varying size, each with an automated fuel loading mechanism, but the incremental cost would again make such stove use pattern unaffordable to many. The fact that forced-draft gasifier stoves are typically imported and have several components that can fail, including batteries, adds to the cost of operating these stoves.

The large differences observed in the emissions of harmful pollutants between laboratory and field measurements highlight how difficult it is to burn a highly variable solid fuel cleanly. Aside from sizing pellets properly, the moisture content has to be kept low, which adds to the transaction cost of fuel preparation. Many, if not most, households use inappropriate start-up materials because, although they increase emissions substantially, they are readily available and cheap or free. Compounding fuel heterogeneity is the impact on pollutant emissions of departure from strictly controlled stove handling during cooking. Igniting the stove correctly, avoiding reloading as much as possible if pellets are loaded in batches, and proper management of the burnout phase are all needed to avoid increasing emissions markedly. Worryingly, PM$_{2.5}$ emissions increased by nearly a factor of two with each year of stove use in a field study of the Philips HD4012LS stove in Rwanda (Champion and Grieshop 2019), pointing to the need to improve the durability of emissions performance.

Because the dose-response relationships between the levels of harmful pollutants and health outcomes plateau with increasing PM$_{2.5}$ concentrations for most illnesses, the ambient pollutant concentrations may have to be reduced by an order of magnitude or more and stove emissions similarly would likely have to be slashed correspondingly, requiring an advanced combustion stove in perfect working order fed with the right fuels and operated correctly at each phase of cooking. Further, although not mentioned in the literature cited, there are also seasonal and weather-related effects, such as thermal inversion trapping PM$_{2.5}$ in winter, thereby requiring a larger reduction in emissions under some conditions than in others. Meeting all these requirements for cooking by households with limited income would not be easy. The problems associated with start-up materials and reloading of pellets may be mitigated by installing an automatic ignition system and an automated pellet feeder, as measurements in China demonstrate (Clark et al. 2017; Deng et al. 2018), but doing so adds to the technical complexity and cost. The findings by Deng et al. (2018) that emissions increased with increasing amount of pellets fed to the stove during reloading would point to a need for an automated pellet feeding mechanism that supplies pellets continually in small quantities.

Although not an immediate concern in developing countries, the fact that LPG is a fossil fuel and concerns about the total amount of renewable biomass available could also affect support from governments and possibly from the international community in the long run. As an example of what could happen in the future, the California Energy Commission in revising building codes for new homes has required solar panels on all new homes starting in 2020 and plans to tighten rules on natural gas. The rules that will take effect in 2023 favor electricity, which can be decarbonized, at the expense of natural gas. More than 40 cities and counties in California have already tightened rules on natural gas use in new
homes, and cities such as San Francisco and Berkeley have banned natural gas in new homes altogether (Mulkern 2021). While these are concerns in high-income countries enjoying universal access to clean, modern energy, the global discourse on climate change is evolving rapidly and the push for electrification will only intensify. The current trend will favor solar energy and electricity generally in the coming years.

International experience points to the persistence of fuel and stove stacking, pellet stove operational procedures falling short of the ideal, and a tension between local stove production and repair capability on the one hand and performance of stoves on the other—several research groups encountered frequent technical failures with Philips stoves that could not be fixed by locally available materials and expertise. Where there are free fuel sources, including by-products from the local industry (such as sawdust) and agriculture, they will be used. Malakar et al. (2018) found that LPG-using households were less reliant on farms and forests and many also had women earning income, with which they had purchased LPG. The latter observation about income earned by women was echoed by Shupler et al. (2021) in their analysis of pay-as-you-go LPG in Nairobi, reinforcing participation of women in income generation as an important step toward universal access.

In many markets, LPG and pellet stoves must compete with traditional stoves, which can handle various sizes of wood, pots, and pans, and can be constructed at low cost with minimal technical skills. Policy development to promote clean cooking needs to recognize different drivers for the initial adoption of clean technologies, which are different from the drivers for abandonment of traditional stoves and fuels. The former will likely mean using clean stoves and fuels for making tea, preparing small meals quickly, and reheating food, but not for preparing large meals requiring hours of cooking. The latter will require doing all cooking with clean stoves and fuels around the clock, a rare exception in many markets today. The target and nature of a policy intended to promote adoption of clean household energy would therefore be different from those encouraging abandonment of all polluting forms of energy. In particular, the income levels and locations of households are likely to differ sharply. Promotion of initial adoption would likely focus on lower-income households in urban areas and rural households, while the probability of abandonment is likely the highest among upper-income households in urban areas. For the initial adoption of LPG and pellet stoves, awareness-raising and enabling payments in small amounts at a time may be particularly important. As for abandonment, devoting efforts targeting the urban middle- and upper-income families may not seem like a priority, but if not even the urban rich can be persuaded to adopt clean energy exclusively, it is certain that other households will not. As such, understanding the barriers among those who are best positioned to abandon traditional forms of energy would be informative. To the extent that demand for charcoal and traditional biomass has outstripped or is quickly outstripping sustainable sources of these fuels, anything that reduces demand for them—such as by persuading the rich to stop using them—would be environmentally and socioeconomically beneficial.

A shift to clean heating has progressed much more slowly than that for cooking, in part because the sheer amount of energy required is considerably more for heating than for cooking in cold-climate countries. If clean fuels and technologies are too costly for cooking, they are sure to be unaffordable for heating. Just as most households prioritize access to electricity before access to clean cooking (Kojima 2021b), they are likely to prioritize clean cooking before clean heating. Such a consideration would argue for the importance of facilitating initial adoption of clean cooking—even if fuel and stove stacking continues—because without the adoption of clean cooking, adoption of clean heating is even less likely.

There are several different sources of significant emissions that affect the ambient concentrations of harmful pollutants, raising background air pollution before households contribute their own. One study found no difference in personal exposure to PM$_{2.5}$ between those using LPG and those using charcoal because exposure was governed by background concentrations. To the extent that neighborhood
emissions contribute to background concentrations, the global drive for a clean home environment would be more effective if whole communities rather than individual households are targeted. Community-based approaches can also take advantage of peer learning and help realize economies of scale more quickly, thereby potentially driving down costs. Where exclusive use of clean household energy is rare—which is the case in the vast majority of developing countries—it would be unrealistic to expect government-funded programs and subsidies to achieve universal access. Even when stoves were designed iteratively with inputs from the local communities in rural Sichuan and the stoves and pellets were provided free of charge, households did not adopt them exclusively or even as their primary cookstoves. Policies and awareness-raising programs reflecting a good understanding of economic, social, and cultural drivers of household energy selection and use; setting realistic goals; and creating an investment climate conducive to market-driven solutions are all essential.
References


