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REVIEW

The global challenge of clean cooking systems

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Abstract
Cooking is an essential and energy-intensive activity. Populations in industrialized countries enjoy nearly universal access to electricity and gas for clean cooking, while about 2.5 billion people in low- and middle-income countries use solid fuels such as wood, charcoal, coal, crop residue and dung for their daily cooking. These traditional solid fuel cooking systems negatively affect the health and reduce the opportunities of cookstove users, who are disproportionately women and children. Solid fuel cooking also presents a number of detrimental environmental impacts, such as ambient air pollution and forest degradation in some regions. Access to cleaner cooking fuels such as gas and electricity is expanding, but is constrained by the higher costs and logistical challenges of such systems. This review investigates the technologies and systems that are currently used to cook food, with a focus on low-income populations. It identifies key challenges that hinder a global transition to clean and sustainable cooking. Finally, it reflects on the recent success of Liquified Petroleum Gas (LPG) along with other fossil fuel-based cooking systems, and discusses a potential transition to renewable energy-based cooking.

Keywords Clean cooking · Household air pollution · Energy access · Gender equity · Improved cookstoves · Renewable energy

1 Introduction

Cooking has been an essential component of human food security strategies for hundreds of thousands of years (Roebroeks and Villa 2011). Indeed, cooking food appears to now be obligatory for humans, after long-term digestive adaptations that favor tender cooked foods (Wrangham and Conklin-Brittain 2003). Cooking has traditionally been done over a wood fire during this long evolutionary time, and about a third of the world's population continue to burn traditional solid fuels such as wood, charcoal, coal, crop residue and dung to cook their meals (IEA 2017).

Modern cooking methods such as electricity and gas have numerous advantages over traditional methods. Burning traditional solid fuels inside homes creates household air pollution that contributes to respiratory diseases and other health problems, disproportionately affecting women and girls who often carry the responsibility of cooking and collecting fuel (IEA 2017). Traditional fuels are labor-intensive to procure, in some places requiring several hours of effort each day. Sourcing of solid fuels like wood and charcoal can lead to forest degradation, especially in East Africa and South Asia (Bailis et al. 2015).

Given the centrality of the cooking process to food security in human societies, it is unsurprising that substantial attention has been focused by researchers and practitioners on achieving universal access to modern cooking techniques. In 2011, the journal *Energy Policy* devoted a special issue on Clean Cooking Fuels and Technologies in Developing Economies (Foell et al. 2011). The contributors discussed a framework for assessment, described case studies of clean cooking experiences and offered perspectives on efforts by development agencies and practitioners. In 2018, the journal *Energy for Sustainable Development* published a special issue on Scaling Up Clean Fuel Cooking Programs (Quinn et al. 2018). It contained examples of successes and challenges of large-scale implementation of clean cooking in low- and middle-income regions. The International Energy Agency's 2017 Energy Access Outlook estimated the changes to global cooking systems over the coming decades using several different policy intervention strategies (IEA 2017). IEA highlighted that shifting to cleaner cooking systems in low-income rural regions will be especially difficult due to the current lack of viable energy infrastructure options available

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to these regions. Numerous other authors and organizations have contributed to a growing body of literature on cooking. For example, the Clean Cooking Alliance conducts research on cooking systems in its eight focus countries, and looks to create partnerships that lead to the implementation of clean cooking initiatives.

We contribute to this growing body of literature on the technologies, strategies and effects of cooking in different parts of the world. Our work strives to succinctly summarize the essential facts on how food is cooked around the world and present the associated effects of cooking on public health and the global environment, in order to inform practitioners and guide future research. Furthermore, we offer a long-term perspective on cooking, from our prehistoric adoption of the practice, to our current cooking patterns and options, to our future prospects for sustainable cooking.

This review is organized as follows. Section 2 is an overview of the global cooking systems landscape, including the importance of cooking, a comparison of different cooking methods, and differences across geographic locations. Section 3 describes the negative effects of solid fuel cooking systems in low- and middle-income countries (LMIC), including impacts on health, environment and gender equity. Section 4 discusses current improved biomass cookstoves and their variability of performance and health benefits. Section 5 follows with prospects for clean-burning next-generation advanced biomass cookstoves. Section 6 discusses cooking gases including liquified petroleum gas, natural gas, and biogas. Section 7 describes the advantages and potentials of using electricity for clean cooking. Section 8 summarizes the key challenges to universal clean cooking, including complex supply chains, cultural barriers, and inaccessible costs. Section 9 offers a discussion of the cooking-food security nexus and the inherent tradeoffs between different cooking systems. Section 10 concludes with thoughts on future prospects for sustainable cooking.

2 The cooking systems landscape

2.1 The importance of cooking

Cooking, or the thermal processing of food, is a defining characteristic of our species that is shared by all human societies and not practiced by any other species. Fossil evidence suggests that early hominins opportunistically used fire to cook food as early as 1.9 million years ago and had controlled use of fire about 400,000 years ago (Bowman et al. 2009). By at least 100,000 years ago, fire was routinely used by humans for domestic purposes (Roebroeks and Villa 2011). The controlled burning of wood enabled the cooking of foods, which gave early humans an advantage over other creatures because cooked foods required less endosomatic energy for digestion compared to raw foods, allowing more net food energy to be used for beneficial purposes (Carmody and Wrangham 2009; Carmody et al. 2011).

It is likely that cooking has become obligatory for modern humans, as digestive adaptations occurred over many thousands of years that no longer allow efficient processing of raw foods (Wrangham and Conklin-Brittain 2003). Thus, cooking has become an indispensable activity for human survival and reproduction, not an optional practice that improves our quality of life (Koebnick et al. 1999). All households, regardless of their social or economic status, eat cooked food every day, and typically multiple times per day. The daily cooking process is the most energy-intensive activity in typical households in low- and middle-income regions. Figure 1 shows the energy used by various components of an example 5-person household. Basic electrical appliances, such as lighting, fan, refrigerator and television, in total use roughly 8 megajoules of electrical energy per day. An electric cooker, by contrast, uses more energy than all these other appliances combined—roughly 11 megajoules per day. Even more energy is needed if a wood-fueled cookstove is used instead, due to the lower efficiency of converting the biomass energy to useful cooking. A traditional wood cookstove uses roughly 90 megajoules of thermal energy per day, while an improved biomass cookstove may use about 50 megajoules per day.

By comparison to these external energy uses, the endosomatic energy use of human metabolism by a five-person household corresponds to about 42 megajoules per day.[1]

2.2 Comparison of different cookstoves and cooking systems

A wide range of techniques can be used to cook food. Beginning with open wood fires that have been used for thousands of years, many types of stoves have been developed to provide more controlled cooking conditions. While wood and other solid biomass fuels like charcoal, crop residue and dung are still widely used for cooking, a number of other fuels such as coal, gas, kerosene and electricity are also increasingly used. Different fuel and stove combinations have varying characteristics in terms of health and environmental impacts, costs and complexities. Table 1 provides an overview of the

[1] Authors' calculations: For human metabolic energy, metabolism varies with age, weight, gender, activity, etc., and a reasonable household average is 2000 kcal (equivalent to 8.4 megajoules) per person per day (FAO 2001). For electrical appliances, typical power draw (in watts) is multiplied by daily hours of use, then converted to megajoules. For traditional woodstove, fuel consumption is average of 6 studies (Geller 1982; Njiti and Kemcha 2002; Miah et al. 2009; Johnson and Bryden 2012; Ochieng et al. 2013; Brooks et al. 2016) assuming wood moisture content of 40% and specific heat of 12.4 MJ per kg wet mass. For improved woodstove, efficiency improvement varies widely by stove, and 40% improvement is typical (MacCarty et al. 2010).

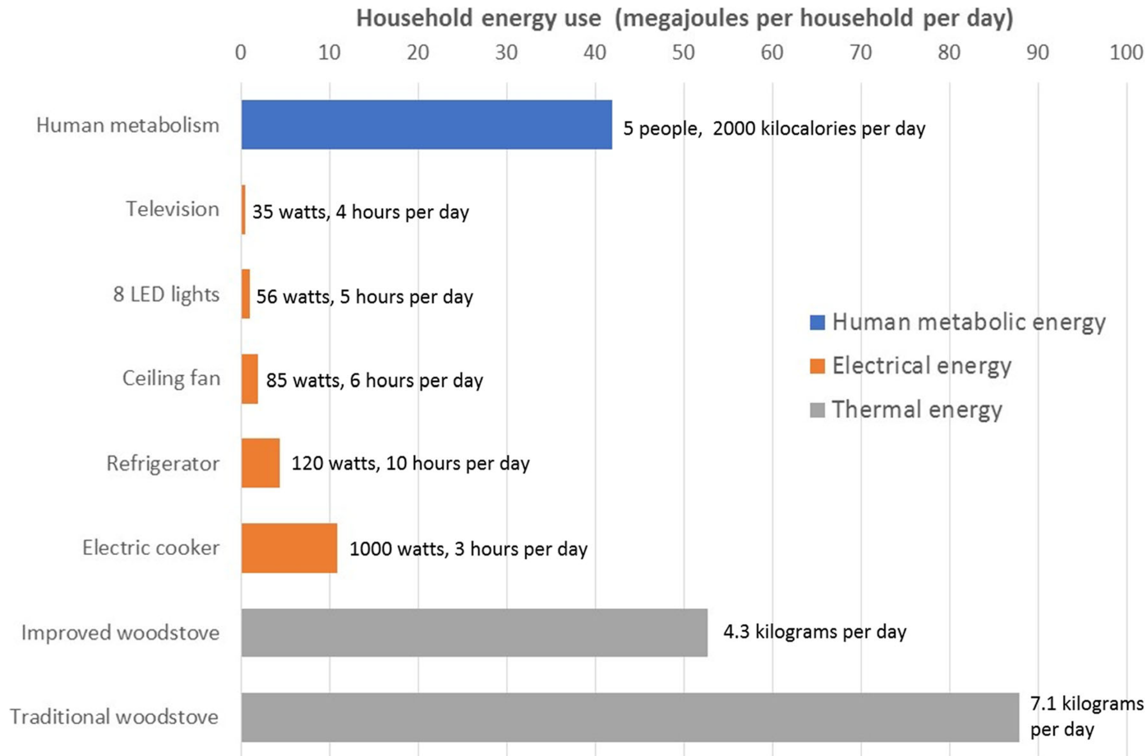


Fig. 1 Cooking is very energy intensive, relative to other household activities. (Source: authors' calculations, see Footnote 1)

range of household cooking options, and these options are described in more detail in the following sections.

Standard metrics for testing cooking methods are typically measured for the end use of a fuel and cookstove technology pair. These metrics include carbon monoxide emissions, particulate matter emissions and thermal efficiency (the percentage of energy stored in a fuel that is transferred to the pot or cooking dish), and are analyzed using a series of standardized tests such as boiling water in a controlled environment. These metrics are then synthesized into standardized tier-based performance levels published by the International Organization for Standardization (ISO 2018). Previously comprising five tiers (Tier 0 to Tier 4), the current standard released in 2018 is comprised of six tiers (Tier 0 to Tier 5) (ISO 2018). Higher tiers correspond to improved efficiency and reduced pollutant emissions. Figure 2 shows illustrative emissions levels of various combinations of stoves and fuels, based on laboratory data from Berkeley Air Monitoring Group (2012), and their correspondence to current ISO tiers.

These cookstove performance tiers are used to compare different cooking methods, but it is important to consider these tiers within the context of the proposed implementation areas. While the ideal cookstove would rank Tier 5 in all measurement categories, there are tradeoffs in performance characteristics, and a host of non-technical factors affect outcomes. Metrics outside of ISO standards are also important in determining the suitability of a particular cooking solution and should also be given significant weight. These include compatibility with local customs, reliability, ease of maintenance, employment potential and consideration of the effects of the entire supply chain using a life cycle analysis.

A cooking system is more than a stove. It comprises the stove technologies, fuels, supply chains, policies and economic strategies that together enable food to be cooked. Such a broad scope enables a robust way of thinking about cooking that incorporates the many processes and agents involved in the cooking process, from energy generation to end user (Putti et al. 2015). Improved cooking systems provide better performance than established cooking systems across metrics of health, environment, economy and others. While a general goal is the adoption of clean cooking systems, there is no definitive threshold that separates clean from non-clean cooking systems. Rather, each cooking system has measurable metrics that lie on independent spectrums and have different implications for users, communities and the environment.

There are various types of solid fuels, such as wood, dung, crop residue, charcoal and coal, that are used for cooking. These fuels are burned in different types of stoves with little to no treatment or improvement in combustion techniques to increase efficiency or reduce harmful emissions. These stove types have typically been used for hundreds or thousands of years and have strong roots in cultural history (Kshirsagar and Kalamkar 2014). The most basic example of a cookstove is

Table 1 Overview of cookstove types and their performance characteristics. Categories and rankings shown are based on analysis by the authors and provide an overview of topics discussed in depth later in the article

			Legend:	good	fair	poor	bad
Category	**Type**	**Health Impact**	**Environmental Impact**	**Initial Cost**	**Operating Cost**	**Fuel Availability**	**Installation & Maintenance Complexity**
Traditional Biomass Stoves	Wood	High PM, medium CO emissions	Ambient air pollution, GHG emissions	Very low	Fuel collection or purchase	Wood fuel usually easily available	Simple and traditional
	Charcoal	Medium PM, high CO emissions	Ambient air pollution, GHG emissions	Very low	Fuel collection or purchase	Requires charcoal supply chain	Simple and traditional
Coal Stove	Coal	Medium PM, high CO, carcinogenic emissions	Ambient air pollution, GHG emissions	Low	Fuel purchase	Mostly used in coal abundant areas	Simple and traditional
Improved Biomass Stoves	Basic	PM, CO emissions	Ambient air pollution, GHG emissions	Very low	Less fuel than traditional stoves	Wood fuel usually easily available	Simple and traditional
	Intermediate	Medium PM, CO emissions	Ambient air pollution, GHG emissions	Low	Less fuel than traditional stoves	Wood fuel usually easily available	May require chimney or maintenance
Advanced Biomass Stoves	Fan Gasifier	Inconsistently low emissions	Generally reduces emissions	Medium	Less fuel than traditional stoves	May require processed fuels	Typically requires maintenance
Modern Fossil Fuel Stove	Kerosene	Medium to low emissions, poisoning, burns	Ambient air pollution, GHG emissions	Medium	Fuel purchase	Requires kerosene supply chain	Simple
	LPG	Very low emissions	GHG emissions	Medium	Fuel purchase	Requires LPG supply chain	Requires installation
	Natural Gas	Very low emissions	GHG emissions	Medium	Fuel purchase	Lack of infrastructure	Requires installation
Electric Stove	Electricity	No emissions	Depends on electricity source	Medium	Typically high cost	Electricity supply often lacking or irregular	Requires installation
Renewable Fuel Stove	Biogas	Very low emissions	Recycles waste	Very high	Very low cost if digestible material is available	Requires supply of digestible biofuel	Requires skilled installation and operation
	Solar	No emissions	Clean, renewable	Low	Free sunlight	Depends on weather	Requires installation
	Ethanol	Very low emissions	GHG emissions	Medium	Fuel purchase	Requires ethanol supply chain	Simple

the three-stone fire, which is built by assembling three stones in a triangle, burning a solid fuel in the center, placing a pot on the stones and then cooking over the open flame. A slightly more technologically complex example is the traditional *chulha* used in India, which is a U-shaped platform made of local clay, within which a fire is made.

A major disadvantage of traditional solid fuel stoves is the high particulate matter emissions that cause indoor air pollution and consequent health effects (IEA 2017). Solid fuel stoves also typically have lower thermal efficiency than gas or electric stoves, which is the

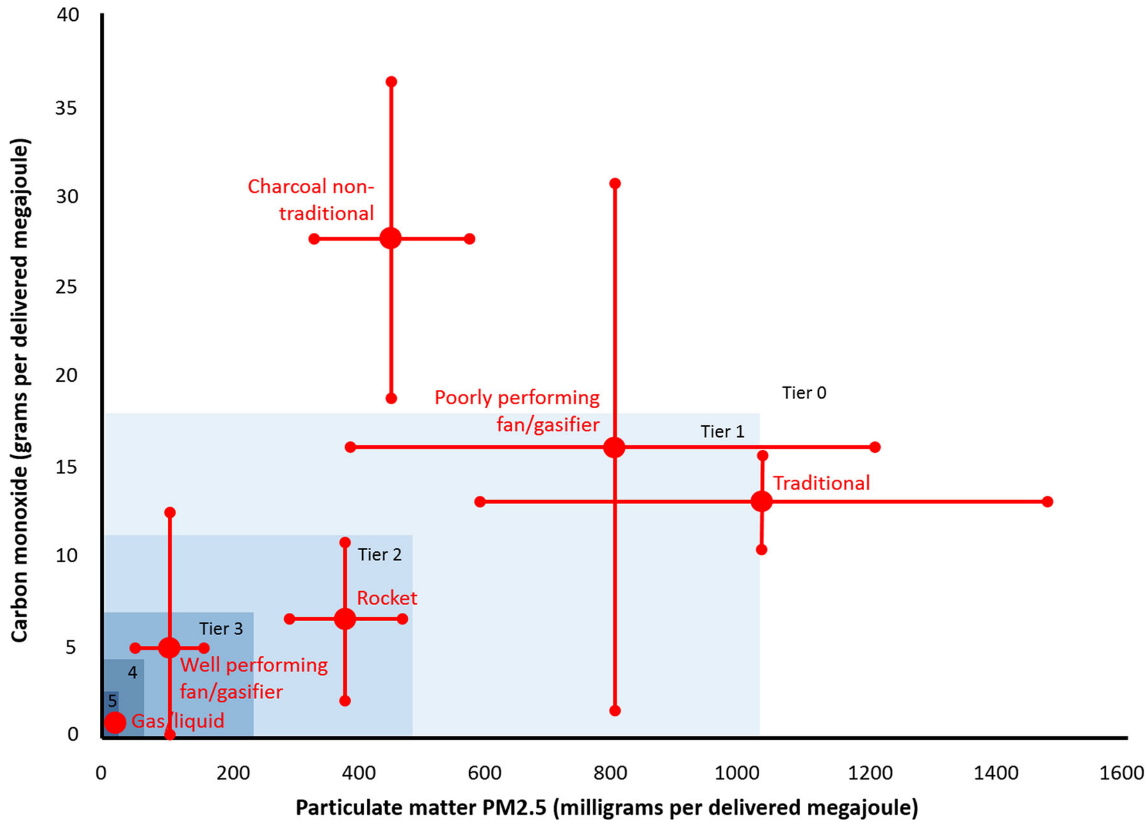


Fig. 2 Comparison of particulate matter (PM2.5) and carbon monoxide (CO) emissions of a variety of cookstoves and fuels tested under laboratory conditions. Blue shading indicates tier levels based on the ISO six-tier rating system. (Source: Emissions data from Berkeley Air Monitoring Group 2012; Tiers data from ISO 2018)

proportion of input energy that is actually used to cook food (Putti et al. 2015). However, such stoves are still widely used in low- and middle-income regions because they are easily accessible, require very low upfront costs, low maintenance, and are rooted in established cooking practices. Using solid wood and crop residue as fuel for traditional stoves is most common in rural areas due to their availability.

Charcoal is often the main cooking energy source for people living in urban areas within low- and middle-income countries (Mwampamba et al. 2013). Charcoal use is especially high in sub-Saharan Africa, as over of 80% of urban households reportedly used charcoal as their primary cooking fuel source (Zulu and Richardson 2013). Charcoal is created by the process of carbonization, where wood or other biomass is heated in the absence of air to break it down into liquids, gases, and charcoal. This process gives the charcoal properties, such as increased energy density, lower particulate emissions and higher burning temperatures, that make it preferable to wood fuel in many cases (Kshirsagar and Kalamkar 2014). Charcoal typically has a specific energy of 32–33 MJ/kg as opposed to 18–19 MJ/kg of dry mass in fuelwood (Santos et al. 2017). Charcoal is also more convenient for urban supply chains because it is easier to transport than wood fuel and can be stored for long periods of time without rotting. Although charcoal often creates less particulate matter emissions when burned than wood fuel, the carbon monoxide emissions from charcoal stoves are typically much higher than burning traditional wood fuel (MacCarty et al. 2010) (see Fig. 2).

While measuring the size of the formal and informal charcoal economy is difficult, the charcoal industry is a large source of employment and revenue in many low- and middle-income countries. The World Bank estimated that charcoal contributed $650 million to Tanzania's economy in 2009, almost six times more than the contribution from coffee and tea production (Zulu and Richardson 2013).

Burning fossil coal in traditional stoves is common among both rural and urban populations of East and Central Asia. Coal is burned unprocessed, and also in the form of processed briquettes. The World Health Organization (WHO) strongly discourages using coal as a cooking or heating fuel in households. Coal often contains toxic elements such as lead, mercury and cadmium that are released during combustion, and indoor emissions from combustion of coal have been deemed carcinogenic by the International Agency for Research on Cancer (WHO 2014).

2.3 Differences in cooking methods by geographic location

There are strong geographical differences in the types of cooking methods utilized (Fig. 3). In sub-Saharan Africa, more than three-quarters of households use solid cooking fuels, mainly wood (IEA 2017). Similarly, more than half of Indian households use solid fuels. Gas fuels are more commonly used in Latin America, North Africa and the Middle East. Chinese households use a wide range of fuels, including gas, wood, coal and electricity. In the United States, the most common cookstove is electric (61% of household stoves), followed by natural gas (33%) and LPG (5%) (EIA 2018). In addition to variation between countries, there is also a strong difference in cooking fuel type between urban and rural populations (Fig. 4). Rural populations tend to use more wood fuel, while urban populations use more gas (Putti et al. 2015).

Trends in many low- and middle-income regions during recent decades have shifted away from solid fuels and kerosene and instead moved towards fuels that emit less particulate matter and other harmful substances during combustion, such as natural gas, LPG and electricity. Between 2000 and 2015, the number of people using cooking systems other than those that rely on directly burning biomass fuels without improved combustion techniques increased by 60%, and the number of people using coal and kerosene for cooking decreased by more than 50% (IEA 2017). Several Asian countries, such as China, India and Indonesia, have made significant reductions in solid fuel and kerosene use during recent decades, with large shifts to LPG.

Despite trends toward cleaner cooking systems in many regions, about 2.5 billion people, or a third of the world's population, continue to use wood, charcoal, crop residue, dung, or other biomass fuels to cook their meals (IEA 2017) (Fig. 5). Another 170 million people, mainly in East and Central Asia, use coal for cooking. Although the percentage of total population that uses solid fuels continues to slowly decrease, more households currently use solid fuels for cooking today than at any time in human history, due to growing population size (Chafe et al. 2014). Between 2000 and 2015, the number of people cooking with biomass increased by 400 million people (IEA 2017). This is mainly due to the growing population of sub-Saharan Africa, which continues to rely largely on solid fuels for cooking. Cooking with solid fuels is limited to low- and middle-income regions, as the populations of industrialized countries now cook almost exclusively with clean fuels like gas and electricity. A relatively small number of people in industrialized countries choose to use solid wood fuel for cooking and heating.

3 Impacts of solid fuel cooking systems in low- and middle-income countries

3.1 Health

Household air pollution from solid fuel combustion affects global development because of chronic health impacts on affected populations. The smoke that causes household air pollution contains particulate matter (PM), carbon monoxide, benzene and other harmful agents. Particulate matter, which consists of a complex mixture of solid and liquid particles of organic and inorganic substances suspended in the air, contains sulfates, nitrates, ammonia, sodium chloride, black carbon, mineral dust and water. Generally, smaller particles are more dangerous than larger ones. Coarser particles tend to be captured in the nasal cavity, upper airways or thoracic cavity. Smaller particles, such as those with a diameter of 2.5 μm or

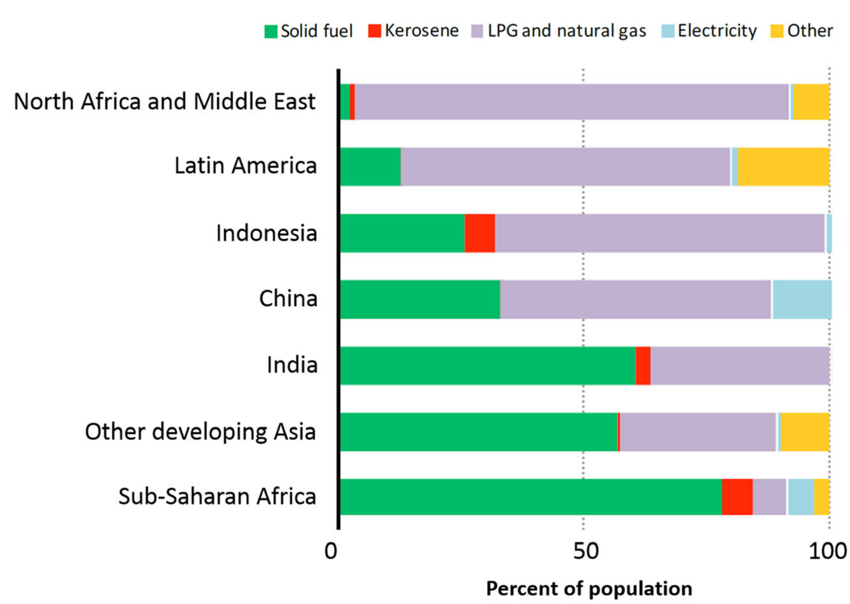


Fig. 3 The type of cooking fuel used by households varies widely by region. Most households in Sub-Saharan Africa and India use solid cooking fuels, mainly wood. Gas is the most common fuel used in many other regions. (Source: data from IEA 2017)

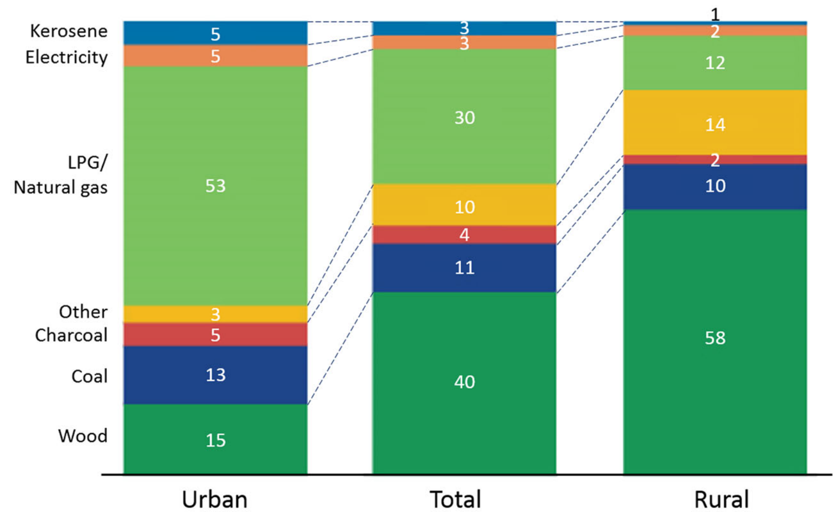


Fig. 4 There is a strong difference in cooking fuel type between urban and rural populations in low- and middle-income countries. In general, rural populations use more wood fuel, while urban populations use more gas. (Source: data from Putti et al. 2015)

less (PM2.5), can enter deep inside the body and deposit on the alveoli, the tiny sacs in the lungs where oxygen is exchanged with carbon dioxide in the blood.

Household air pollution from burning solid fuels indoors can cause severe health conditions, such as lower respiratory infection, lung cancer, ischemic heart disease, stroke and chronic obstructive pulmonary disease (Landrigan et al. 2018). WHO (2016b) estimated that household air pollution is responsible for large portions of disability-adjusted life years (DALY), a measure of overall disease burden expressed as the number of years lost due to ill-health, disability or early death. Specifically, household air pollution is responsible for 33% of global DALY from acute lower respiratory infections, 26% from stroke, 24% from chronic obstructive pulmonary disease, 24% from cataracts, 18% from ischemic heart disease and 17% from lung cancer (WHO 2016b). Additional health issues related to solid fuel use include birth defects, burns from wood fires and injuries related to fuel collection.

While there remains some uncertainty about the exact extent of health impacts of household air pollution, by all accounts they are substantial. Each year, household air pollution is estimated to cause more deaths than many other high-profile killers including malnutrition, alcohol use, road accidents, war and murder, tuberculosis, malaria and AIDS (Forouzanfar et al. 2016). Landrigan, et al. (2018) estimated that 2.9 million deaths in 2015 were the result of household air pollution. WHO (2016b) estimated that exposure to household air pollution resulting from the use of solid fuels caused 4.3 million deaths in 2012. The difference in estimated deaths can partly be explained by different approaches in quantifying exposure-outcome associations.

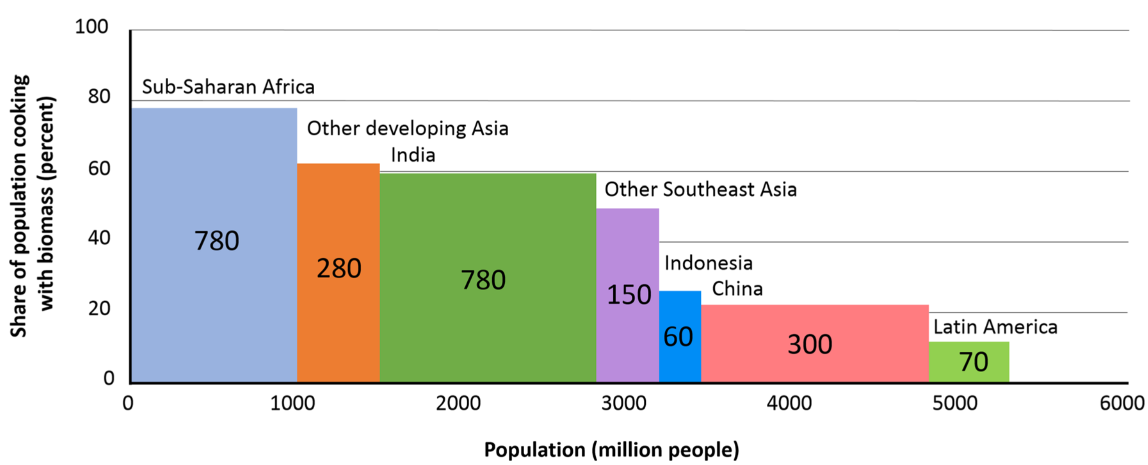


Fig. 5 About 2.5 billion people, or a third of the world's population, rely on the traditional use of solid biomass for cooking. (Source: data from IEA 2017)

In South Asia and sub-Saharan Africa, almost 6% of all deaths in 2017 were attributed to household air pollution from using solid fuels (IHME 2018) (Fig. 6). In India, an estimated 0.48 million deaths in 2017 were attributable to household air pollution, with the worst-affected states being Chhattisgarh, Rajasthan, Madhya Pradesh and Assam in north and northeast India (Balakrishnan et al. 2018). In China, households that regularly cook with solid fuels have a 20% higher mortality risk from cardiovascular disease than those that use clean cooking methods (Yu et al. 2018).

3.2 Environment

Cooking processes can be responsible for a range of environmental impacts including ambient air pollution, forest degradation and climate change.

3.2.1 Ambient air pollution

While smoke from indoor cooking fires directly causes household air pollution and associated morbidity and mortality (discussed above), the smoke then escapes from the houses and contributes to ambient (outdoor) air pollution. Although most ambient air pollution is caused by outdoor sources, such as power plants, vehicle exhaust and crop burning, an estimated 12% of global population-weighted fine ambient particulate pollution (PM2.5) is caused by cooking fuels, which escapes from houses and pollutes the outside air (Chafe et al. 2014). It is estimated that in East Asia, 22% of population weighted ambient PM2.5 is produced by household cooking with solid fuels (Chafe et al. 2014).

Within India, an estimated 39% of all PM2.5 pollution comes from residential sources, primarily solid cooking fuels (Sharma et al. 2016) (Fig. 7). The percentage varies from a low of 7% in urban Delhi to a high of 54% in predominantly rural Uttar Pradesh state.

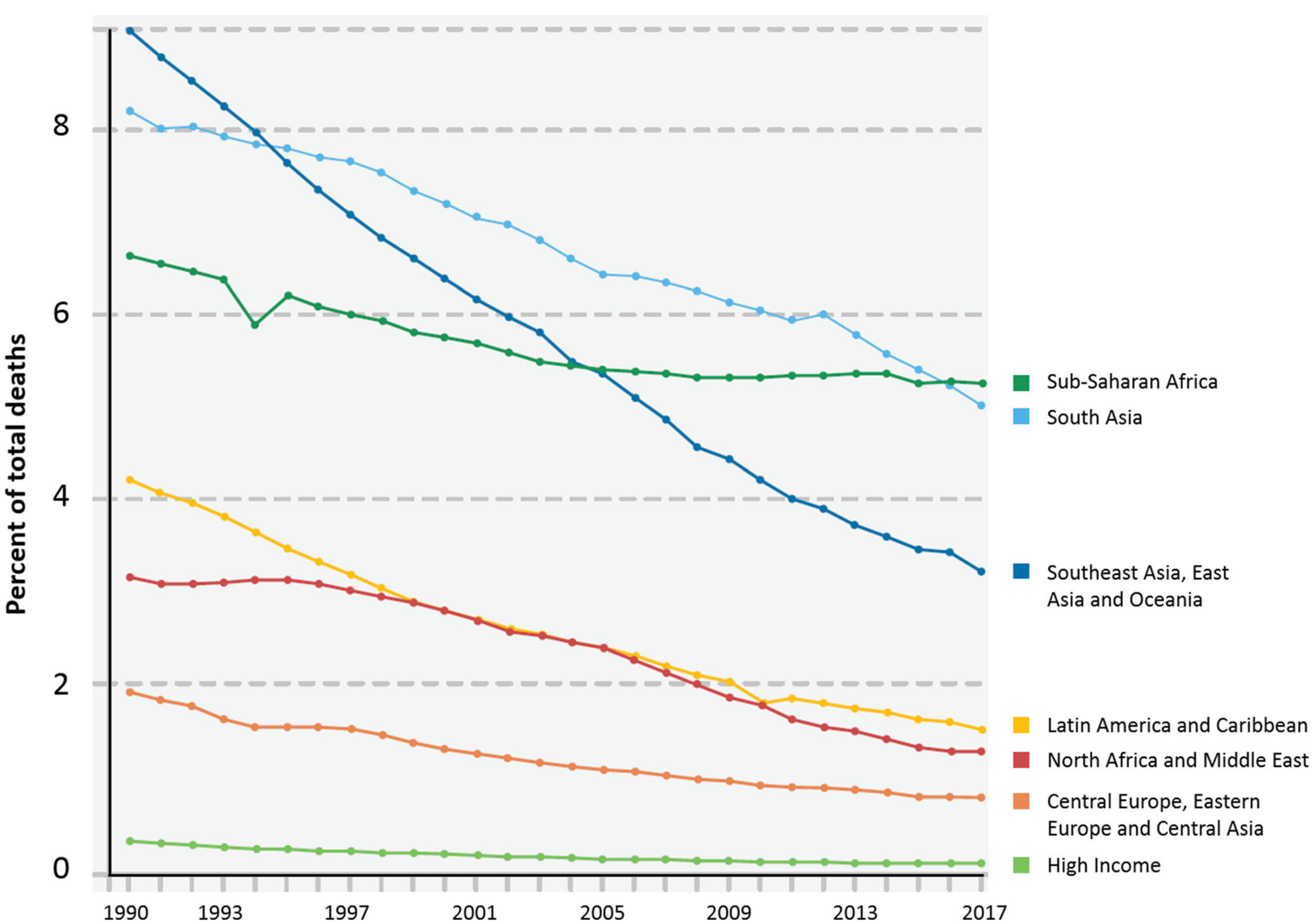


Fig. 6 The percent of deaths attributable to household air pollution is declining in all regions, but is still significant. Almost 6% of all deaths in South Asia and sub-Saharan Africa in 2017 were due to household air pollution from using solid fuels. (Source: data from IHME 2018)

3.2.2 Forest degradation and deforestation

Wood fuel can come from many different sources, such as the felling of live trees, trees that have died naturally and trees that were cleared for agricultural land. Because of this, it is often difficult to attribute forest degradation or deforestation directly to wood fuel collection. The sustainability of wood fuel use varies strongly from place to place, in "mosaics of varying levels of stress" (Munslow et al. 2013). Bailis et al. (2015) estimated that between 27% and 34% of all harvested traditional wood fuel is non-renewable, defined as annual harvest levels that exceed incremental growth.

There are large geographic variations in wood fuel sustainability (Fig. 8), and unsustainable wood use is concentrated in certain areas of South Asia and East Africa. About 275 million people—60% in Asia, 34% in Africa and 6% in Latin America—live in regions where more than half of harvested fuelwood is non-renewable (Bailis et al. 2015). In East Africa, unsustainable wood fuel use extends from Eritrea through western Ethiopia, Kenya, Uganda, Rwanda and Burundi. In Asia, such harvesting occurs in parts of Pakistan, Nepal, Bhutan, Indonesia and Bangladesh. People living in regions with unsustainable biomass harvesting are particularly amenable to adopting non-biomass cook stoves.

Charcoal production represents a substantial cause of forest degradation and possibly deforestation. Studies show that wood harvesting for charcoal manufacture is an important cause of forest degradation (Sedano et al. 2016; Mwampamba 2007). Charcoal demand continues to increase in Sub-Saharan Africa and other regions (Putti et al. 2015). Charcoal production in low- and middle-income countries is typically inefficient and can require four to six times as much wood to produce the same amount of end-use energy as burning unprocessed wood (Mwampamba 2007), though there is a wide range of charcoal production techniques with varying efficiencies.

Most interventions in the charcoal cooking sector have focused primarily on the demand side, such as improved charcoal stoves. There have been fewer supply side interventions, such as increasing kiln efficiency or improving sustainability of forest management for charcoal production (Mwampamba et al. 2013), and such efforts could bring long-term benefits of resource conservation. A combined approach of improving the efficiencies of both charcoal production and end-use offers the greatest opportunity to improve the sustainability of charcoal cooking systems (Hoffmann et al. 2018).

3.2.3 Climate change

The climate impacts of cooking fuels are complex, involving atmospheric emissions from both fossil and biological sources (Lee et al. 2014). All cooking methods tend to emit greenhouse gases (GHG), though their ultimate climate impacts are not always straightforward. Burning biomass directly emits carbon dioxide (CO_2) as a combustion byproduct, though if the biomass is harvested from sustainably managed forests on a landscape level there will be no net CO_2 emissions because forest regrowth removes CO_2 from the atmosphere at the same rate it is emitted by burning (Sathre et al. 2013). Biomass harvested from unsustainable forestry, on the other hand, causes net CO_2 emissions contributing to climate change.

Another important emission from cookstoves is black carbon, commonly known as soot, which is a component of PM2.5 particulate emission, and strongly absorbs light and emits heat. About 25% of total anthropogenic black carbon emissions come from household cookstoves burning solid fuels (Garland et al. 2017). Black carbon is considered a short-lived particle, but it has a very high global warming potential (GWP) and causes significant short-term, regional climate impacts. The impacts of black carbon vary locally, with stronger potential warming impacts in areas with high albedo surfaces, such as snow and ice. Accounting for the climate effects of black carbon can significantly improve the mitigation effectiveness of clean cooking initiatives (Freeman and Zerriffi 2014).

Shifting to clean cooking fuels does not necessarily reduce or eliminate climate impacts, because clean fuels also emit GHGs. Natural gas and liquified petroleum gas are both fossil fuels of geological origin, with CO_2 emissions of roughly half that of coal for the same amount of heat energy. In addition, leakage of methane from natural gas production and transport facilities can result in additional climate impacts that are about the same magnitude as those from CO_2 emission of gas combustion (Alvarez et al. 2018). Electric stoves have no direct climate impact at the point of use, but the source of electricity used by the stove may be very carbon intensive (Masanet et al. 2013). Globally in 2017, 38% of electricity was generated by burning coal and 23% from natural gas (IEA 2019). In India, coal was used to generate 74% of electricity in 2017 (IEA 2019), thus widespread adoption of electric cooking in India would cause significant climate impact, absent a corresponding reduction in carbon intensity of the electricity system.

3.3 Gender equity

Household air pollution disproportionately affects women and children due to their greater amount of time spent cooking and preparing food in households, compared to men (Fig. 9). Globally, it is estimated that women experience almost 5% more exposure to risk from solid fuel household air pollution than men, however the effects of this exposure discrepancy vary significantly between regions (Forouzanfar et al. 2016).

Women and children also bear a disproportionate opportunity cost for collecting wood fuel. The extent of this disproportion varies by region and can reach several

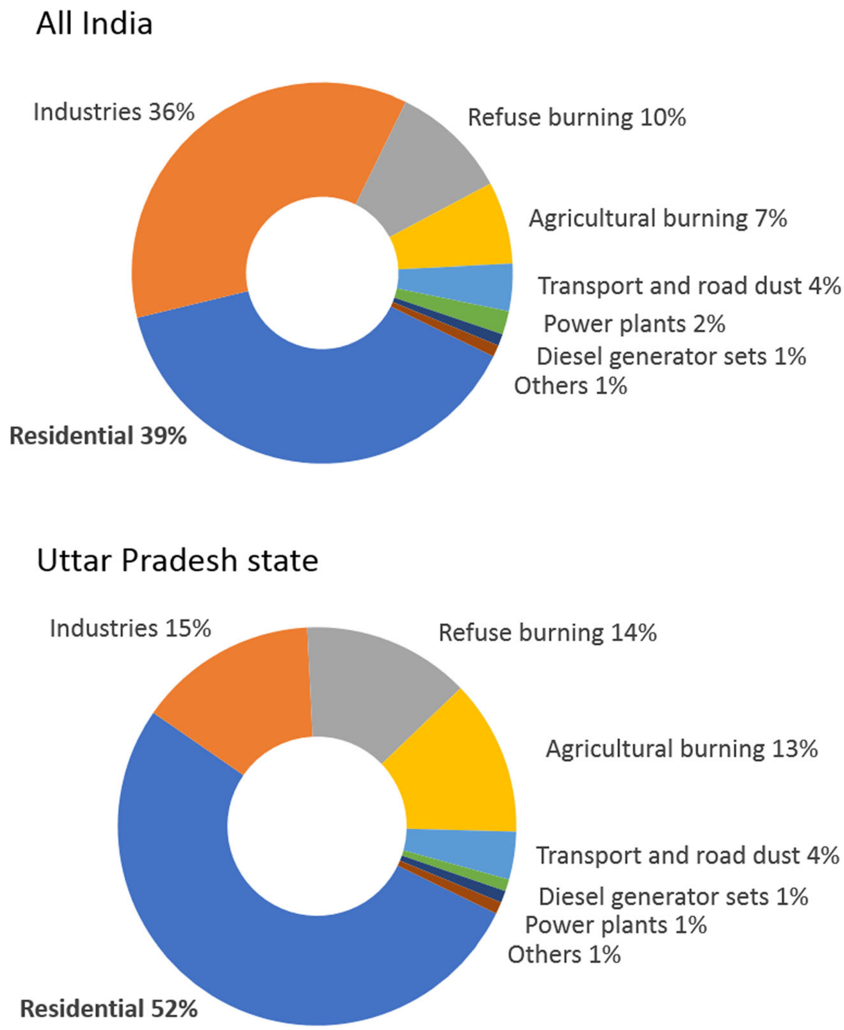


Fig. 7 Fine particulate matter (PM2.5) originates from various sources. Solid fuel use in households (here termed "Residential") contributes more than half of PM2.5 emissions in rural Uttar Pradesh state in India and more than one third in all of India. (Source: data from Sharma et al. 2016)

hours per day in areas facing wood fuel scarcity (WHO 2016a). Women are also more likely to miss opportunities to attend school and work and more likely to be injured or attacked while collecting fuel.

4 Improved biomass cookstoves

A wide range of biomass cookstove improvements have been proposed and trialed, and some have reached moderate levels of deployment (MacCarty et al. 2010). Improved cookstove initiatives have historically been promoted through government programs such as China's National Improved Stove Program, which has been effective in distributing and promoting improved stoves since the early 1980s. India's National Programme on Improved Chulha was founded during the same era as China's program, seeking to replace the traditional chulha stove with improved versions (Hanbar and Karve 2002). Efforts in India were not as successful as in China, as improved chulha stoves have not been widely adopted (Khandewal et al. 2017). More recently, international organizations such as the Clean Cooking Alliance (formerly called the Global Alliance for Clean Cookstoves) have advocated for the dissemination of improved cookstoves.

4.1 Varying levels of improvement in improved biomass cookstoves

Improved biomass cookstoves refer to a large spectrum of stoves that use traditional biomass (wood, charcoal, crop waste and dung) as fuel, but employ improved combustion and fuel loading methods to increase thermal efficiency and reduce indoor air pollutants that cause negative health, environmental, social and economic outcomes (Kshirsagar and Kalamkar 2014). Literature on improved biomass stoves often distinguishes between basic, intermediate and advanced stoves in order to differentiate and

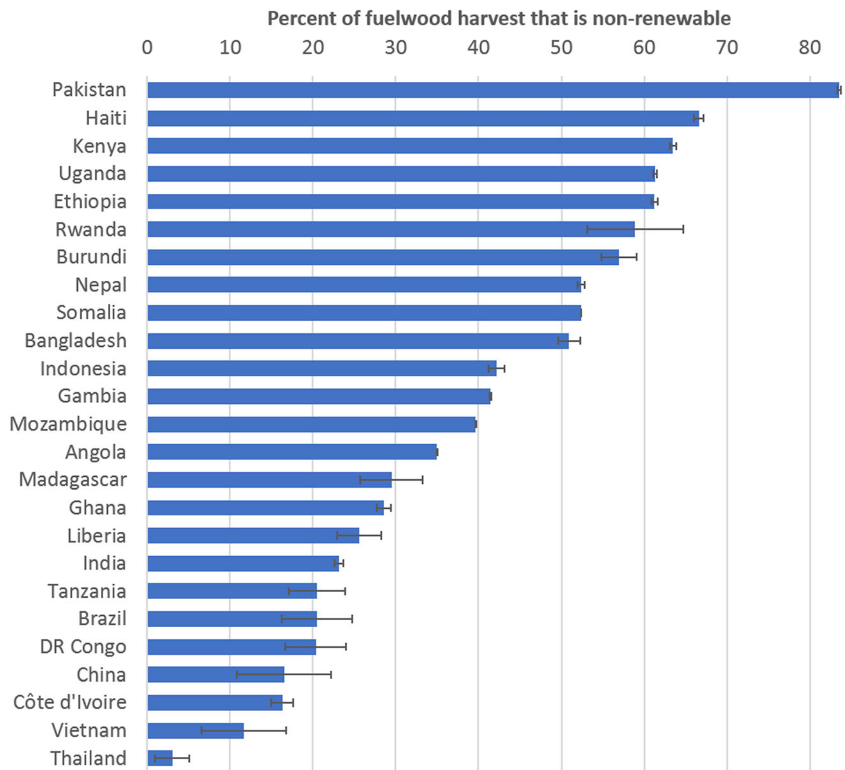


Fig. 8 There is wide variation between countries in sustainability of fuelwood harvest. In some countries, especially in East Africa and South Asia, more than half of harvested fuelwood is non-renewable, defined as annual harvest level that exceeds incremental growth. Error bars indicate uncertainty regarding growth rate of plantations and utilization of residues from forest clearance for agriculture. (Source: data from Bailis et al. 2015)

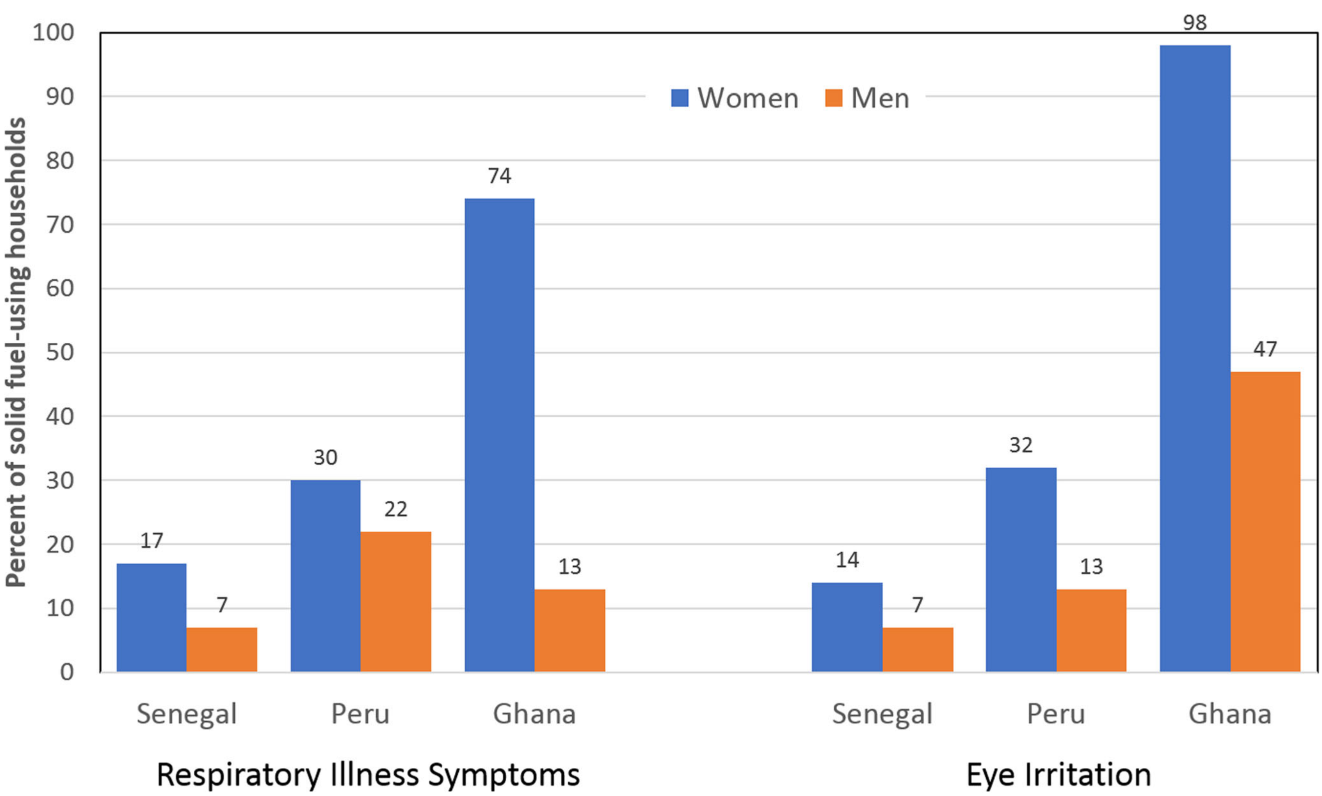


Fig. 9 Women in low- and middle-income countries are more likely than men to suffer from respiratory illness and eye irritation. (Source: data from Putti et al. 2015)

analyze the levels of technological complexity and benefits achieved by stove improvement. These umbrella categories are benchmarks for assessing the many stove technologies that currently exist and are being developed, but any individual improved biomass cookstove fits into a spectrum of stove technologies as opposed to one broad classification.

Basic improved cookstoves aim to increase thermal efficiency and redirect household air pollution without greatly changing the combustion mechanism of traditional cookstoves. The improved Kenya Ceramic Jiko is an example of a portable basic improved stove that uses metal cladding and a ceramic liner to increase the efficiency of charcoal combustion by up to 30% (NL Agency 2010). Basic improved cookstoves also include built-in-place traditional cookstoves with chimneys added to increase thermal efficiency and move smoke out of the house, such as the smokeless chulhas promoted in India. These basic improved cookstoves are often made artisanally and sold by local vendors, but also have been mass manufactured and distributed through governments, NGOs and other programs.

Intermediate improved cookstoves typically use simple means to improve the combustion process and achieve higher thermal efficiency. The rocket stove is an example of an intermediate cookstove, employing an L-shaped combustion chamber design with air ducts that direct preheated air into the top of the chamber. Although intermediate stoves have somewhat greater thermal efficiency, their particulate matter emission is only moderately less when compared to traditional stoves. Some rocket stoves are reported to have increased black carbon emissions compared to traditional stoves (Garland et al. 2017).

Improved biomass cookstoves are most often deployed in rural areas that have historically relied on traditional stoves and lack access to other clean cooking solutions. Such stoves vary widely in price, with higher prices usually translating to more advanced technology, higher efficiency and lower emissions. Manufacturing methods range from local and artisanal to large-scale industrial production (Putti et al. 2015).

4.2 Limited health benefits due to non-linear exposure-response functions

Improved cookstoves can bring a number of benefits to users, due to their moderate improvement in thermal efficiency that leads to reduced fuel use. This fuel efficiency means monetary savings for households that purchase fuel and time savings for those that gather fuelwood. Some studies have found that use of improved biomass cookstoves leads to decreasing respiratory illness symptoms and reduced school absences, compared to traditional cookstove use (van Gemert et al. 2019). Nevertheless, these cookstoves fail to reliably and significantly reduce exposure to household air pollution and the associated health risks.

A growing number of studies have reported exposure-response relationships for household air pollution exposure (Ezzati and Kammen 2001; Smith et al. 2011; Burnett et al. 2014; Liu et al. 2014). It is increasingly understood that the shapes of these relationships are non-linear, being steeper at lower exposure levels and tending to flatten off at higher exposures (Fig. 10). This non-linear relationship appears to be valid for acute lower respiratory infection in children and adults, ischemic heart disease and stroke. By contrast, the relationship for lung cancer is much closer to a linear function, while that for chronic obstructive pulmonary disease (COPD) is in between.

The implication of this non-linear function is that, while current improved biomass cookstoves can bring large reductions in emissions in both absolute and percentage terms, such reductions bring only a modest decrease in health risk (Bruce et al. 2015; Thakur et al. 2018). To effectively eliminate the serious health risk of household air pollution, stove emissions must be reduced much further than is possible with current biomass stove designs. Cooking options with sufficiently low emissions include the established solutions of gas and electric stoves, and potentially a new generation of advanced biomass cookstoves with greatly reduced emissions.

5 Advanced biomass cookstoves

Advanced biomass cookstoves employ more complex, multiple-stage combustion methods in order to burn fuel efficiently and minimize harmful emissions. Thus far these cookstoves have been challenged, inconsistently delivering clean cooking levels of efficiency and emissions in the field. If a biomass cooking system were created that could reliably lower particulate emissions to an acceptable rate, while simultaneously being easy to use, it would offer promise for rural communities without access to fossil fuels or electricity infrastructure. However, current versions of advanced biomass cookstoves offer less cooking flexibility and often require pre-processed fuels, which create barriers to adoption. Most advanced cookstoves have high upfront costs, are manufactured industrially to relatively high-quality standards and are not yet widely used (Putti et al. 2015).

There are several potential pathways towards clean biomass stoves, including air injection and gasification. Injecting air into the gas-phase combustion zone generates turbulence that leads to more complete combustion and reduced particulate emission (Rapp et al. 2016). Air injection promotes better gaseous mixing of fuel and air, and increases the residence time of soot in the flame thus promoting oxidation of soot. While this appears promising, current stove performance is quite sensitive to the flow rate and velocity of injected air, and the number of harmful ultrafine particles may be of concern (Caubel et al. 2018).

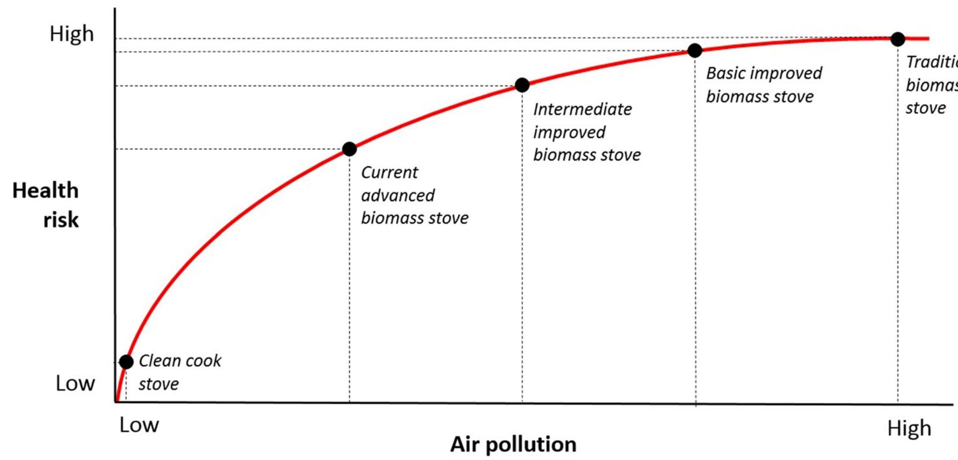


Fig. 10 The relationship between air pollution and health risk is non-linear, thus the large absolute reduction in pollution emission between traditional stoves and improved biomass stoves leads to a relatively small improvement in health risk. Stove emissions must be greatly reduced in order to achieve significant health benefits. This figure is illustrative, due to uncertainty in the shape of the curve and variability in the performance of stoves. (Source: based on data from Ezzati and Kammen 2001; Smith et al. 2011; Liu et al. 2014; Burnett et al. 2014)

Gasification is another process that is used in advanced biomass cookstoves. During gasification, fuel is first heated in a low-oxygen chamber to release gases, primarily hydrogen, carbon dioxide and carbon monoxide. These gases are then mixed with air towards the top of the cookstove and ignited (Kshirsagar and Kalamkar 2014). Gasifier cookstoves sometimes use internal fans to assist with airflow and proper combustion. These fans may be powered by batteries, solar panels or thermoelectric generators, which increase the cost and potential maintenance of the stoves. Under laboratory conditions, gasifier stoves have been able to reach ISO Tier 3 (based on previous ISO standards, Tier 0 – Tier 4) emission levels, which offers hope for gasifier stoves as a future clean cooking solution. Nevertheless, there is a large gap in efficiency and emissions between well- and poor-performing fan gasifier stoves (see Fig. 2). Furthermore, current gasifier stove designs tend to be costly, batch fed, slow to ignite and require specific fuel types.

Many advanced biomass stoves require users to process their fuel or use pre-processed fuel types. Fuel pellets and briquettes are made from compacted biomass, including dung and crop waste. Compacting the biomass into smaller units creates a more energy dense fuel that outperforms unprocessed biomass in efficiency and emissions when used to fuel gasifier stoves (Vesterberg 2014). Fuel processing can take place at various scales, from small-scale localized plants to large-scale centralized facilities, with trade-offs in terms of logistics, capital cost and unit production cost (Helbig and Roth 2017). Pellets and briquettes can be a renewable fuel if they are made from sustainably-sourced agricultural or forestry residues (Putti et al. 2015). However, the need for purchasing expensive processed fuel can hinder adoption of advanced biomass cookstoves.

6 Gas as a clean cooking option

Cooking gas burns very cleanly, as it can fluidly intermix with oxygen to enable complete combustion. Furthermore, it is composed of compounds containing hydrogen and carbon, which when completely combusted are converted to carbon dioxide and water vapor, with minimal health impact. Three main pathways are used to produce and distribute cooking gas: liquefied petroleum gas (LPG), natural gas and biogas.

6.1 Liquified petroleum gas (LPG)

Liquified petroleum gas (LPG) is a fossil fuel mixture of propane (C_3H_8) and butane (C_4H_{10}). It is obtained during the extraction or refinement of crude oil and can be stored in portable cylinders. LPG is considered a clean cooking solution because it burns efficiently and produces much less household air pollution than current solid fuel stoves (Fig. 2). LPG is also easy to store and cook with, which has led to it being used by a majority of urban households in low- and middle-income regions (Fig. 4). However, both the initial and operating costs of cooking with LPG is high when compared to solid fuel cooking systems. Transport of gas cylinders is challenging in regions with limited infrastructure, and LPG supply chains have yet to reach many rural areas of low- and middle-income countries (Fig. 4).

Despite these challenges, countries such as Brazil have had success establishing LPG supply chains through the use of government subsidies for low-income households, as more than 90% of rural households in Brazil have access to LPG (IEA 2006). In Indonesia, a state-led initiative to convert from kerosene to LPG cooking fuels has used economic subsidies to enable 50 million households to gain access to LPG for cooking in a five-year period (Thoday et al. 2018).

Organizations, such as the Global LPG Partnership, have had some success in expanding access to LPG supply chains and converting users to cleaner cooking solutions (GLPGP 2018). LPG holds promise for rural communities because it does not require the same investment in infrastructure as natural gas or electricity, but delivers similar health benefits. Use of LPG may scale up faster if high upfront costs are made more accessible, for example by introducing smaller LPG cylinders that better align with user cash flow, or by implementing flexible financing mechanisms.

6.2 Natural gas

Natural gas, primarily composed of methane (CH_4), is a fossil fuel extracted from underground deposits. Many countries around the world exploit natural gas deposits because it is a versatile fuel that has similar thermal efficiency and end use emissions as LPG. It is primarily transported in its gaseous form in industrialized countries, which requires high infrastructure costs and regulation, but can also be compressed and cooled into a liquid form and transported in a similar way as LPG (Culver 2017). In low- and middle-income regions, natural gas is used almost exclusively in urban areas (Fig. 4), mainly due to a lack of pipeline infrastructure in rural settings.

Although the expansion of the use of fossil fuels such as LPG and natural gas for cooking in low- and middle-income countries could be effective in reducing household air pollution, its wider use raises concern with regard to climate change and other environmental impacts. In addition, the global market price of fossil gases is quite volatile (Fig. 11), thus reliance on such fuels by low-income populations runs the risk of these households being unable to afford cooking fuel when prices increase (EIA 2020). Government programs looking to subsidize the cost of these fuels face large uncertainty in funding requirements due to market price volatility (Fig. 11). The nonrenewable nature of LPG and natural gas also means that they will become progressively more depleted and less available over the coming decades.

6.3 Biogas

Biogas is a clean burning fuel that is composed primarily of methane (CH_4) and carbon dioxide (CO_2). It is created by breaking down organic materials, such as animal or human manure and crop or food waste, typically through the process of anaerobic digestion. This process takes place in stationary biogas digesters, at rates that depend on the input material and ambient conditions such as temperature (IRENA 2017). Biogas can be produced on multiple scales, from small digester systems used to generate cooking gas at the village or individual household level, to large facilities using waste from agriculture, food processing or wastewater treatment. Household biogas cooking systems are ideal for rural farm owners that can turn their crop and livestock waste into a cooking and energy source at a much lower annual cost than other clean cooking options such as LPG and electricity. There are three main types of small-scale biogas digesters: the fixed dome, developed in China and now used in many low- and middle-income countries; the floating drum plant, mainly used in India; and the balloon/bag digester, mainly used in Latin America (IRENA 2017).

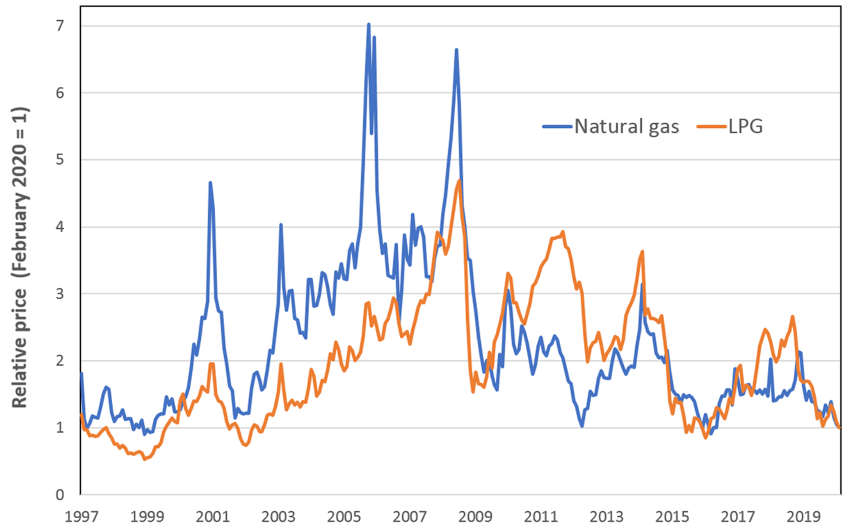
Biogas is currently used as the primary cooking fuel by less than 2% of global households (Putti et al. 2015). China is home to the great majority the world's biogas users (Table 2), as the Chinese government has successfully used economic subsidies to encourage its rural population to produce and use biogas at the household level (Zuzhang 2013). Biogas digesters require a large upfront cost, which makes them inaccessible to many rural households without subsidies or other financial incentives. In addition, many biogas digestion systems require skilled installation and maintenance which may be unavailable in some areas (Rajendran et al. 2012).

Despite these challenges, biogas still holds promise as a clean and renewable cooking fuel that offers the health benefits of clean burning fossil gas without the environmental impacts associated with fossil fuel use. With the use of government subsidies and microfinance, Cambodia has now installed more than 25,000 household biogas digesters (Hyman and Bailis 2018). While long term success of this program is yet to be seen, a focus on partnering with local government, maintenance training for local technicians, a goal to establish a prominent biogas sector, and emphasis on aftercare service for installed digester systems are all key features that have led to its accomplishments thus far (Hyman and Bailis 2018). Prefabricated digesters that are much less expensive than traditional biogas digesters and can be installed in a day without the use of skilled labor are being developed, but their long-term durability and reliability are important to consider (Cheng et al. 2014). More accessible and less expensive biogas digesters offer an opportunity to improve health and wellbeing in many rural regions of low- and middle-income countries. Maintenance concerns can be partly addressed by disseminating materials to educate users on proper maintenance and operation of biogas systems.

7 Electricity as a clean cooking system

Using electrical energy for cooking is a clean and convenient method with no end use emissions or smoke, thus posing very low direct health risk. Electricity is an ideal energy source for cooking, but in most low- and middle-income regions it is

Fig. 11 The prices of LPG and natural gas are quite volatile and are subject to sharp increases (Source: data from EIA 2020; monthly average spot prices of natural gas at Henry Hub and propane gas at Mont Belvieu)



currently too expensive and supply infrastructure is challenging. In industrialized countries, where electrification rates are very high, electricity is much more commonly used for cooking. For example, the most common cookstove in the United States is electric (61% of household stoves), followed by natural gas (33%) and propane (5%) (EIA 2018). Nevertheless, cooking consumes only a small fraction of total household electricity use in the United States, due to very high electricity consumption for non-cooking purposes, such as refrigerators, TVs, air conditioning, lighting and space and water heating.

Electricity is not widely used for cooking in low- and middle-income countries, as shown in Figs. 3 and 4. It is the primary cooking fuel for only 5% of urban households in low- and middle-income regions (Putti et al. 2015). In a few low- and middle-income countries the rate of electricity use for cooking is much higher. For example, 80% of the total South African population and 12% of the Chinese population cook with electricity (IEA 2017). In most low-income countries, electricity use for cooking is far lower than the electricity access rate. This is because cooking requires a large amount of energy (see Fig. 1), which strains most generation and transmission capacity, and it is relatively expensive.

Table 2 Most household-scale biogas digesters are installed in Asia, especially in China (Source: data from IRENA 2017).

Asia	
China	43,000,000
India	4,750,000
Nepal	330,000
Vietnam	182,800
Bangladesh	37,060
Cambodia	23,220
Africa	
Kenya	14,110
Tanzania	11,100
Ethiopia	10,680
Latin America	
Bolivia	500
Nicaragua	290

Household-scale biogas digesters in select countries, 2014.

Electric cooking is more prevalent in urban areas, largely due to access to grid infrastructure. Grid extension has been the primary mode of rural electrification, but where adequate service levels have not been achieved, it is because of gaps in generation, distribution or maintenance. Distributed mini-grids that provide reliable electricity to remote villages are projected to play a crucial role in electrifying the last 10 to 15% of the global population (ITT 2019). Electric cooking is generally not suitable for existing off-grid power systems, which have neither the power nor energy capacity that would be required. On a smaller scale, while there has been a recent proliferation of portable solar-powered appliances like lights and mobile phone chargers, such devices cannot provide cooking service, which is inherently a high-energy activity.

Electric cooking produces no indoor emissions that cause household air pollution, but it may contribute to other environmental problems such as ambient air pollution and climate change. The broader environmental effects of electric cooking depend largely on how the electricity is generated (Masanet et al. 2013). For example, in regions where coal is burned for electricity production, the overall electric cooking process would contribute more heavily to climate disruption than if the electricity were produced by wind turbines or solar farms. Globally, about 38% of electricity is made from coal (IEA 2019).

The most common electric cooking process is resistance, which works on the principle of Joule heating, where an electric current passing through a resistor is converted into heat energy. Inductance is a newer electric cooking method that is gaining acceptance among some users (Banerjee et al. 2016). With this method, an alternating electric current is passed through a coil of copper wire under the cooking pot, which induces an electrical current in the pot, directly heating the pot through resistance heating. For induction cooking to work, the cooking vessel must be made of a ferrous metal, such as cast iron or some kinds of stainless steel.

Although initial reports suggested that induction cooking was more energy efficient than resistance cooking, more rigorous analysis has shown that the efficiency of the two processes are roughly the same, around 70% to 72% (US DOE 2014; Sweeney et al. 2014). In certain cases, depending on pot size and cooking power, induction stoves may be slightly more efficient. Induction stoves do have several other advantages. They may be safer to use because only the cooking vessel generates heat, and the element itself reaches only the temperature of the vessel. Induction stoves are easier to clean because the cooking surface is flat and smooth, and they provide rapid heating with precise control.

8 Key challenges in implementing clean cooking systems

There are numerous challenges that have heretofore impeded universal access to clean cooking.

8.1 Clean cooking systems require more complex infrastructure and supply chains

Cooking systems used in industrialized countries, primarily based on natural gas and electricity, require a large investment in infrastructure for pipelines and distribution grids. In low- and middle-income regions, these systems are mostly limited to urban areas (Fig. 4). Rural areas are often outside LPG supply chains and require subsidized government programs to reach rural households (Thoday et al. 2018).

8.2 There are social and cultural barriers to changing cooking methods

Cooking practices are often deeply rooted in the traditions and culture of a given community or region, and clean cooking solutions that fail to accommodate existing cooking practices are often not adopted by users, even when these solutions are accessible (Puzzolo et al. 2016). This has become especially apparent in programs attempting to distribute improved biomass stoves that require changes in fuel loading methods, do not allow for the cooking of certain dishes or cooking styles or lack control over certain aspects of cooking such as heat intensity. A study in sub-Saharan Africa revealed that users often cook with multiple fires, which was observed to limit the reduction in fuelwood use by improved biomass cookstoves for an entire meal (Adkins et al. 2010). Users can also be opposed to the concept of cooking with animal or human waste, as is practiced with biogas cooking systems.

8.3 Clean cooking systems are more expensive than traditional methods

Traditional wood stoves have the advantage of both low upfront cost and low operating cost. Current clean cooking solutions have either high upfront costs or high operational fuel costs, and sometimes both, making them inaccessible to low-income households without financial assistance (Putti et al. 2015). Clean cooking systems using biomass fuels that can be produced, purchased or collected locally, such as biogas digesters and advanced biomass stoves, typically have high upfront costs but lower annual costs, making initial adoption a financial burden. Cooking systems that rely on natural gas, LPG or electricity typically have both high initial infrastructural cost and high operating cost, hindering access to low-income households. Current cooking systems with both low upfront cost and low operating cost, such as traditional wood stoves, are those with high pollutant emissions.

8.4 Fuel stacking often reduces the impact of clean cooking systems

Even after the introduction of a clean cooking system, many households continue to use traditional cooking methods in addition to the new system. This is true for all clean cooking systems, as households in low- and middle-income regions rarely rely solely on one fuel or cooking method (Morrison 2018). This is known as fuel stacking, and makes a complete transition to clean cooking difficult even when a clean cooking system is implemented successfully. The transition to clean cooking systems is complex, involving socio-economic, cultural and political factors (van der Kroon et al. 2013).

8.5 There are several technological obstacles to clean cooking solutions

8.5.1 Performance gap between lab and field tests

Laboratory tests are important for initial design and performance tracking, but field tests reveal that cooking systems perform differently and affect users in the world differently once they are implemented. Stove performance tends to be higher during carefully controlled experiments in a lab, and lower during actual field operation by users (Berkeley Air Monitoring Group 2012). Field testing among end users can be more difficult and time intensive than lab tests, but it is essential to understand cooking systems in their end-use settings.

8.5.2 Maintenance

Clean cooking methods, such as advanced wood stoves and biogas digesters, often use relatively complex fuel production and combustion technologies that may be difficult to maintain for users who are not familiar with the technology and lack access to skilled technicians. Adult illiteracy rates in many countries in sub-Saharan Africa are greater than 50% (UNICEF 2019), making written procedures and schedules challenging to follow. Obtaining replacement parts, such as thermoelectric generators for fan gasifier stoves, can be difficult in some rural and urban areas with weak supply chains. Biogas digester systems require regular maintenance, which can lead to non-adoption if users do not have access to training or skilled labor.

8.5.3 Sparse data

While information concerning clean cooking and household air pollution has been increasing in the last decade, there still exist important gaps in data and knowledge that are crucial to implementing effective clean cooking programs and initiatives. More in-depth data on fuel stacking practices, advanced biomass stove performance, and the life cycle impacts of cooking systems on the health of users and the environment would help to better inform policymakers, organizations and practitioners seeking to identify and implement clean cooking solutions.

9 Discussion

9.1 Are improved biomass cookstoves a viable solution?

Improved biomass cookstoves at first seem like an attractive option for rural communities due to the scalability of production and the fact that fundamental switches in energy supply chains are not required. However, improved cookstove programs have historically been attempted by NGOs, governments and commercial organizations with mixed results due to fuel stacking and technological discrepancy between lab and field performance (Khandelwal et al. 2017; Urmee et al. 2014). As discussed in Section 4, emissions reductions from improved cookstoves are often not sufficient to bring significant health benefits, or to be deemed clean cooking by ISO standards.

Improved biomass cookstove programs may be worthwhile in regions where clean cooking fuel infrastructure is absent and is not likely to be created in the near future. Yet, implementing successful clean cooking programs remains difficult. Urmee and colleagues report that even the national improved biomass cookstove programs in China and India, which have distributed over 100 million cookstoves each, had less than one third of the initially distributed cookstoves still in use (Urmee et al. 2014). They argue that top down cookstove programs where improved biomass cookstove dissemination is funded and distributed directly by a philanthropic organization or government program such as in China and India, have been less effective in the long term than programs that strive to create a more localized and sustainable cookstove industry in each area (Urmee et al. 2014). Integrating stove users of each region in the design, distribution and financial mechanisms of improved biomass cookstove programs–and generally any cooking system program—can help align the new cooking practices with existing practices, with greater chance of lasting results.

Those looking to implement improved biomass cookstove programs must carefully consider the technology and financial strategy within the social, economic and cultural context of given region. There should be significant consideration into whether investments should be made in improved biomass cookstoves, or in long-term energy system infrastructure that may ultimately bring greater reductions in household air pollution and provide other benefits.

9.2 Linking food security and cooking systems

A link between food security and cooking systems seems intuitive, given that cooking is such an integral part of the food preparation process. However, a definitive relationship between specific aspects of the two topics has not yet been consistently made in primary research.

Early literature in food security was dominated by large scale agricultural production research to meet growing global food demands while also dealing with the repercussions of environmental change. At the turn of the twenty-first century, an emphasis on conceptualizing food security through food systems emerged, which simultaneously examined food access, utilization and availability (Ingram 2011). Over the past decade, literature on the Water-Energy-Food-Climate nexus has emerged in an effort to create frameworks for policymaking that represent the four topics listed in ways that minimize tradeoffs and promote synergistic advantages (Leck et al. 2015; Conway et al. 2015). However, such nexus research does not focus heavily on the role of cooking systems specifically defined in this review, neither as an aspect of food security nor energy access. While our coverage of food security was less comprehensive than our investigation of cooking systems, we found that studies and reviews of cooking systems are primarily discussed as a subset of energy access and as a driver of air pollution related health effects, but not as a direct determinant of food security.

The limited literature that has focused on the link between cooking systems and food security has not yet yielded clear causal relationships. An analysis by Sola and colleagues of 19 articles on energy and food security concluded that existing primary research neither proves nor disproves three common hypotheses relating food security and energy access: 1. "Energy access influences dietary choices and cooking practices", 2. "Poor access to cooking fuel leads to reallocation of household resources from food production and preparation to fuel procurement", and 3. "Lack of access to energy leads to switches to inferior energy forms, thereby reducing agricultural productivity" (Sola et al. 2016). The first and third hypotheses are focused on the effects that multiple energy uses have on aspects of food security such as dietary choices and agricultural productivity. The second hypothesis considers how lack of access to cooking fuels can lead to reallocation of resources from obtaining food to acquiring cooking fuel, and clearly hypothesizes a direct link between food security and cooking systems. They go on to explain that several studies in regions experiencing resource scarcity showed that shortages of fuel wood led to an increased allocation of time to fuel wood procurement over activities that contribute to food security, however, this impact has yet to be quantified and explored further (Sola et al. 2016).

Extending the idea of the nexus, we suggest that future primary food security research aim to further investigate the hypotheses above, and formulate new ways of incorporating energy access and cooking systems into frameworks for approaching long-term food security. Additionally, cooking systems research should look beyond stove emissions and energy use, towards more holistic lifecycle-based criteria for clean cooking systems that consider food security, user health effects, environmental degradation, economic accessibility, social equity and resource management.

10 Conclusions: Towards sustainable cooking

Cooking food is a process that distinguishes humans from all other species. Indeed, evolutionary digestive adaptations appear to make cooking now obligatory for modern humans—we cannot live without it (Wrangham and Conklin-Brittain 2003). Since prehistory, our ancestors relied on abundant local biomass for their cooking energy. Still, about a third of the human population, or 2.5 billion people, rely on biomass for cooking, though now often less abundant and local (IEA 2017). Of the remaining 5 billion people, the vast majority use fossil energy for cooking, either directly as LPG, natural gas or coal, or indirectly as fossil fuel-fired electricity (authors' estimate based on IEA 2017; IEA 2019). Unearthing fossil fuels has given our societies an abundance of energy that has steadily increased for several centuries (Smil 2018). Nevertheless, non-renewable resources cannot continue to yield indefinitely due to physical constraints, as the energy-return-on-investment diminishes with declining resource quality (Hall et al. 2014). Future generations will progressively enjoy less of these depleting fossil stocks of coal, oil and gas (Mohr et al. 2015).

The transition away from traditional solid biofuel to LPG has enjoyed success on national levels in Brazil (IEA 2006), Indonesia (Thoday et al. 2018), India (Gould and Urpelainen, 2018) and elsewhere. LPG appears to be a practical solution in the short- to medium-term to bridge the clean energy access gaps in rural communities in low- and middle-income regions, due to its low end-use emissions compared to burning solid fuels and its lower infrastructure requirement compared to natural gas and electricity. However, increasing worldwide dependence on finite fossil gases will make an eventual transition to renewable energy sources more formidable in the future, introducing a conflict between immediate improvement of people's health conditions and the long-term sustainability of household cooking. A significant obstacle to implementation of universal clean cooking is the lack of scalable renewable energy infrastructure that reaches rural communities, is economically accessible, and that delivers adequate power for the cooking process.

Two major technology pathways exist to sustainable cooking based on renewable energy. The first is photosynthetic capture of solar energy and its organic conversion to biofuel, for example wood, biogas, ethanol and algae (Aro 2016). The second is electric cooking with renewable electricity generation, for example wind turbines and photovoltaic solar, while ensuring adequate capacity and dispatchability (Masanet et al. 2013). Other minor pathways such as direct solar and geothermal cooking also exist. As we endeavor to provide universal access to clean cooking around the globe, we are cognizant that current decades and centuries of rapid change are a brief moment in evolutionary (Wrangham and Conklin-Brittain 2003) and geological (Berner 2003) timescales. We should ensure that the cooking advances achieved in the present will not be taken away from later human generations.

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Compliance with ethical standards

Conflicts of interest/competing interests The authors declare that they have no conflict of interest.

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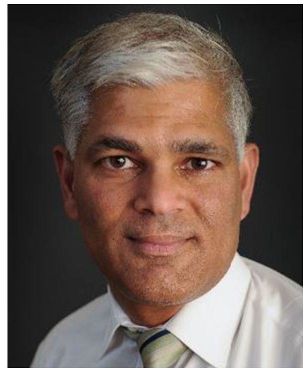

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