Chapter 10

Mitigation Approaches for Residential Heating and Cooking

10.1 Summary of Key Messages

- In the developed world, residential combustion is a small but potentially important source of BC emissions. There are clear health benefits of reducing residential wood smoke both indoors and outdoors. The climate impacts depend on the relative proportion of OC emissions, location of emissions (over ice/snow) and the type of wood-burning appliances used. Upgrading old wood stoves in areas with snow and ice to cleaner-burning appliances (particularly gas-burning) appears to be the most effective strategy to reduce BC and OC from residential wood combustion (RWC).
  - U.S. RWC is approximately 3% of the domestic BC emissions inventory. Residential wood smoke contains $PM_{2.5}$, air toxic pollutants (e.g., benzene), CH_4, CO_2, OC, BC, and BrC.
  - EPA is currently working to establish new or revised new source performance standards (NSPS) for all types of residential wood heaters, including hydronic heaters, furnaces, and wood stoves.
  - Mitigation strategies for RWC sources have generally focused on either replacing inefficient units (wood stoves, hydronic heaters) with newer, cleaner units through voluntary or subsidized changeout programs, or retrofitting existing units to enable use of alternative fuels such as natural gas (fireplaces). New EPA-certified wood stoves have a cost-effectiveness of about $3,600/ton $PM_{2.5}$ reduced, while gas fireplace inserts average $1,800/ton $PM_{2.5}$ reduced (2010$).
  - The Arctic Council Task Force on Short-Lived Climate Forcers has identified wood stoves and boilers as a key mitigation opportunity for Arctic nations. The Task Force has recommended countries consider measures such as emissions standards, change-out programs, and retrofits to reduce BC from wood stoves, boilers, and fireplaces.
- In the developing world, about 3 billion people depend on rudimentary stoves or open fires fueled by solid fuels (e.g., wood, dung, coal, charcoal, crop residues) for residential cooking and heating. This number is expected to increase in the coming decades. Cleaner cooking solutions have the potential to provide huge public health benefits, and may be particularly important for reducing regional climate impacts in sensitive regions such as the Hindu Kush-Himalayan-Tibetan region.
  - According to the WHO, exposure to cookstove emissions leads to an estimated 2 million deaths each year; indoor smoke from solid fuels ranks as the six largest mortality risk factor and the fifth largest disease risk factor in poor developing countries. Reductions in exposure to these emissions likely represent the largest public health opportunity among all the sectors considered in this report.
  - The BC climate impacts from cookstoves are likely to be strong in a regional scope, and additional source testing and modeling is needed to clarify the composition of emissions from these sources and their net climate impact.
  - Cookstove mitigation activity today is difficult to quantify definitively: while the EPA-led Partnership for Clean Indoor Air (PCIA) reported that PCIA Partners sold about 2.5 million stoves in 2010, it is likely that 5-10 million "improved" stoves are sold each year by commercial entities. In addition, there are no reliable data on the quality or performance of many of these stoves and thus considerable uncertainty regarding the benefits of their use. The full market of stoves is on the order of 500-800 million homes (3 billion people); thus, significant expansion of current clean cookstove programs would be necessary to achieve large-scale climate and health benefits.

- Many improved cooking solutions exist, but all face important supply, cost, performance, usability, marketability and/or other barriers to large-scale progress. The potential climate and health benefits vary substantially by technology and fuel.
    - The performance hierarchy for improved cooking solutions appears to be as follows, in generally decreasing order for both costs and emissions performance: 1) electricity; 2) clean fuels such as LPG or ethanol; 3) advanced biomass stoves (e.g., forced air fan or gasifier stoves); 4) rocket stoves; and 5) other improved stoves. For all solid fuel stoves (3 and 4), processing the fuel into pellets or briquettes allows for greatly improved combustion with significant reductions to harmful emissions.
    - Well-designed biogas may be the cleanest, most climate-neutral (renewable) cooking solution suitable for large-scale use; solar stoves are ultimately the cleanest solution, but have not yet demonstrated an ability to reach large scales of sales or adoption.
- A number of recent developments—including the growth of a variety of promising businesses and business models; innovations in stove design, testing, and monitoring; carbon financing; research quantifying the health benefits of improved stoves; and new country-based and global efforts to address health risks—have created a real opportunity to achieve clean cooking solutions at a global scale.
    - Over the past nine years, the EPA-led PCIA has built a network of more than 540 Partners working in 117 countries to increase the use of affordable, reliable, clean, efficient, and safe home cooking and heating technologies. PCIA Partners sold approximately 2.5 million stoves in 2010, which may result in reduced indoor air pollution exposures for more than 12 million people—primarily women and children.
    - Launched in September 2010, the rapidly growing Global Alliance for Clean Cookstoves (the Alliance) is led by the United Nations Foundation and currently has over 275 partners, including 28 countries and significant U.S. government participation. The Alliance represents an enormous opportunity to rapidly increase the use of clean cooking solutions by building on the past experiences and successes of PCIA and other leaders in this field (e.g., Shell Foundation, GIZ, SNV, United Nations agencies, World Bank).
    - The Alliance's interim goal is for 100 million homes to adopt clean cooking solutions by 2020, with sales accelerating through this period. Achieving this scale of progress will not be easy—it will require significant investments, demand a coordinated global approach, and need to be based primarily on sustainable commercial businesses that produce high-quality stoves and fuels that meet local users' needs.
    - Developing globally recognized performance standards for stoves that are widely accepted by the cookstove community and adopted by country governments could spur wider development of clean cookstoves.

10.2 Introduction

Household energy use represents an extremely important source of BC emissions worldwide, accounting for 25% of the total global BC inventory. In developed countries, most of these emissions are associated with residential wood combustion (RWC), generally for heating. Total emissions from RWC in developed countries are estimated at about 4% of the total global inventory (311 Gg) and 16% of total residential emissions worldwide. In developing countries, emissions from residential combustion are more often linked to widespread use of small stoves for cooking and/or heating. These cookstoves utilize a wider range of fuels, including coal, natural gas, and dung as well as wood, charcoal, and other biomass-related fuels. The emissions from residential cookstoves represent a much larger fraction of the global inventory, accounting for 21% of total global BC emissions (1635 Gg) and 84% of emissions from residential sources worldwide. The variety of sources and fuels within the residential category, and the significant differences between developed and developing countries make this sector among the most challenging from a mitigation perspective. However, given the vast number of people dependent upon residential sources for everyday needs, such as heating and cooking, this sector likely represents the biggest opportunity for public health improvements through reductions of BC and overall $PM_{2.5}$.

This chapter is divided into two parts. First, it presents information regarding available mitigation approaches for residential wood combustion in the United States and other developed countries. There are a number of cost-effective, advanced mitigation technologies that are well known and easily deployed; the biggest challenge remains one of implementation and outreach. The chapter then examines the technologies and approaches available for reducing emissions from the residential sector in developing countries, where the scale of the problem is much broader, the range of sources and fuels more complicated, and the challenges to effective implementation much larger. It describes the advanced cookstove technologies that are currently available and their costs, and considers the emissions reduction potential if these technologies were adopted on a large scale.

10.3 Residential Wood Combustion in Developed Countries

There are an estimated 29 million wood-burning fireplaces, over 12 million wood stoves and hundreds of thousands of hydronic heaters (also known as outdoor wood boilers) throughout the United States. Emissions from these appliances contain $PM_{2.5}$, toxic air pollutants, and other pollutants that can adversely impact health and climate. The majority of these emissions come from old, inefficient wood stoves built before 1990. Wintertime wood smoke emissions contribute to $PM_{2.5}$ nonattainment and localized problems in many areas in the United States. For this reason alone, replacing inefficient wood stoves and educating wood burners on proper burn practices and stove operation are important strategies for reaching domestic air quality goals. In fact, there is far greater certainty about the public health benefits of reducing residential wood smoke emissions, both indoors and outdoors, than about the net climate impacts, especially in light of the high level of OC emissions from these sources.

10.3.1 Emissions from Residential Wood Combustion

Incomplete combustion of wood results in emissions of fine and ultrafine particles, including BC, BrC and other non-light absorbing OC particles. Inorganic materials, such as potassium, are also present in lesser quantities as part of the mix of emitted particles. In the United States, RWC contributes over 350,000 tons of $PM_{2.5}$ nationwide—mostly during the winter months. Of this, approximately 21,000 tons is BC, which is about 3% of total U.S. BC emissions. The key emitting source categories that comprise RWC are wood stoves, manufactured and masonry fireplaces, hydronic heaters, and indoor furnaces. The 2005 $PM_{2.5}$ inventory shows that cord wood stoves contribute about 52%, fireplaces 16%, hydronic heaters 16%, indoor furnaces 11% and pellet stoves and chimineas (free-standing outdoor fireplaces) the remaining 5%. Since 2005, the popularity and use of outdoor hydronic heaters has grown. As a result the emissions from these units are growing and are of particular concern to many areas, like the Northeast and Midwest.

In addition to $PM_{2.5}$ and BC, wood smoke contains toxic air pollutants such as benzene and formaldehyde, as well as CH_4, CO, and CO_2. Nationally, RWC accounts for 44% of polycyclic organic matter (POM) emissions and 62% of the 7-polycyclic aromatic hydrocarbons (PAHs), which are classified as probable human carcinogens.[1] All of these pollutants are products of incomplete combustion (PIC). These emissions are the direct consequence of poor appliance design and improper owner operation (e.g., using unseasoned wood) leading to incomplete combustion of the fuel.

OC emissions from RWC generally far exceed the BC emissions, making the OC/BC ratio relatively large. However, different wood burning appliances combust wood in varying ways, resulting in different OC/BC ratios. In general, wood stoves have lower OC/BC ratios than fireplaces (see Figure 10-1), and also represent a significantly larger percentage of the $PM_{2.5}$ emissions inventory. The type of wood burned also affects the amount of BC and OC emissions.

Despite the relatively high OC/BC ratio from RWC in general, it is important to consider the location of these emissions. While OC emissions are generally considered to have a cooling effect, OC emissions over areas with snow/ice may be less reflective than OC over dark surfaces, and may even have a slight warming effect (see Flanner et al., 2007). Significantly, the vast majority of residential wood smoke emissions occur during the winter months; the highest percentage of wood stove use is in the upper Midwest (e.g., Michigan), the Northeast (e.g., Maine), and the mountainous areas of the Pacific Northwest (e.g., Washington), where snow is present a good portion of the winter months.

10.3.2 Approaches for Controlling Emissions from RWC

Mitigation of RWC $PM_{2.5}$ emissions generally involves increasing the combustion efficiency of the source.

[1] See EPA's 2005 National-Scale Air Toxics Assessment at *http://www.epa.gov/nata2005*.

Wood burning appliances with lower combustion efficiencies tend to have higher emissions of most pollutants than do those with higher efficiencies. Due to design, conventional wood stoves, most fireplaces, and outdoor hydronic heaters do not burn wood efficiently or cleanly. Mitigation strategies for RWC sources have generally focused on either replacing inefficient units (such as wood stoves and hydronic heaters) with newer, cleaner units through voluntary or subsidized changeout programs, or retrofitting existing units (such as fireplaces) to enable use of alternative fuels like natural gas. The United States has been working to establish emissions standards for certain RWC sources, but it takes time for such programs to become effective, as they depend on the turnover in existing units. This is discussed more fully below.

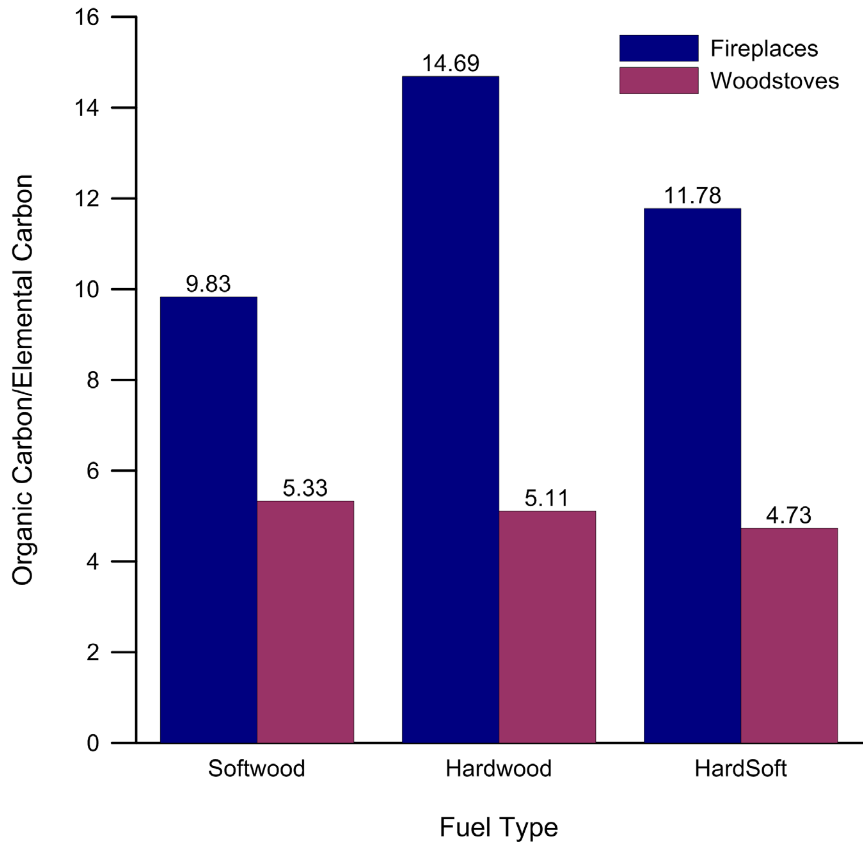

Figure 10-1. OC/BC Emission Ratios by Source Category and Fuel Type. (Source: U.S. EPA)

To achieve the cleanest and most efficient combustion, the appliance needs to reach and maintain a sufficiently high temperature for all the necessary reactions to occur; adequate time for those reactions; and enough turbulence to ensure oxygen is available when and where it is needed. EPA-certified wood stoves, wood pellet stoves and Phase-2 qualified outdoor wood-fired hydronic heaters[2] are typically designed to increase temperature in the firebox and to allow for adequate outside air to mix long enough for more complete combustion. The importance of the combustion conditions within these home-heating appliances, and the wood species used as fuel, in determining the composition of the resulting wood smoke is reflected by the observed variability in measured OC/BC ratios discussed above.

In general, greater combustion efficiency leads to reductions in the mass of direct PM emissions, including BC, as well as reductions in emissions of the gas-phase pollutants such as CO, CH_4, and the volatile PAHs. For example, in an EPA study comparing a New Source Performance Standard (NSPS)-certified wood stove to a traditional zero clearance fireplace, the total PAH emission factor was found to be up to twice as high for the fireplace as for the more efficient stove burning the same oak fuel (Hays et al., 2003). The same can be observed for other pollutants depending on appliance type, wood species, moisture content, and so forth. A more efficient appliance also burns less wood for the same heat output, leading to additional emissions reductions. However, a recent wood stove changeout study conducted by the University of Montana showed significant reductions in emissions of OC and levoglucosan (a wood-burning tracer) but little or no change in BC emissions from the changeout (Ward et al., 2011).

10.3.3 Emissions Standards for New Wood-burning Units

EPA has authority to establish NSPS emissions standards for new RWC sources, such as fireplaces, wood stoves, and hydronic heaters. These standards establish manufacturing requirements to limit emissions from new units. Such standards can be updated over time as new technologies become available. Since 1988, EPA has regulated $PM_{2.5}$

[2] For a list of such appliances, see *http://www.epa.gov/burnwise/owhhlist.html*.

emissions from new residential wood heaters sold in the United States. The Residential Wood Heaters NSPS (also referred to as the wood stove NSPS) defines a wood heater as an enclosed, wood burning appliance capable of and intended for space heating or domestic water heating that meets specific criteria, including an air-to-fuel ratio in the combustion chamber averaging less than 35-to-1; a usable firebox volume of less than 0.57 cubic meters (20 cubic feet); a minimum burn rate of less than 5 kg/hr (11 lb/hr) tested by at an accredited laboratory; and a maximum weight of 800 kg (1,760 lb). Many types of sources are exempt from the existing NSPS, including:

- Wood heaters used solely for research and development purposes
- Wood heaters manufactured for export (partially exempt)
- Coal-only heaters
- Open masonry fireplaces constructed on site
- Boilers
- Furnaces
- Cookstoves

The Residential Wood Heaters NSPS is unusual in that it applies to mass-produced consumer items and compliance for model lines can be certified "pre-sale" by the manufacturers. A traditional NSPS approach that imposes emissions standards and then requires a unit-specific compliance demonstration would have been very costly and inefficient. Therefore, the NSPS was designed to allow manufacturers of wood heaters to avoid having each unit tested by allowing, as an alternative, a certification program that is used to test representative wood heaters on a model line basis. Once a model unit is certified, all of the individual units within the model line are subject to similar labeling and operational requirements.

EPA is currently in the process of revising the Residential Wood Heaters NSPS. Specifically, the Agency is considering tightening the air pollution emission limits, adding limits for all pellet stoves, reducing the exemptions, and adding regulations for more source categories, including hydronic heaters and furnaces. EPA expects to propose appropriate revisions in 2012, and finalize revisions in 2013. The tightening of the wood heater NSPS has the potential to help reduce future residential wood burning emissions throughout the United States.

10.3.4 Mitigation Opportunities for In-Use RWC Sources

A fundamental limitation of the standards for new sources discussed above is that they cannot influence emissions from units that were purchased prior to establishment of the NSPS. It can take a long time for NSPS to actually reduce emissions, depending on the rate of replacement of existing units—and in many cases, these units can remain in service for decades. Thus, alternative mitigation strategies are needed to reduce emissions from existing sources.

In 2004, a panel convened by the National Academies of Science made several recommendations to the EPA for improving air quality management in the United States. One of their recommendations was to develop and support programs to address residential wood smoke. Since 2005, EPA has developed a residential wood smoke reduction initiative that has various components to support state, local, and tribal communities in addressing their wood smoke challenges. This initiative focuses on ensuring that wood burning is as clean and efficient as possible to help reduce emissions of harmful pollutants, the amount of fuel used, and the risk of chimney fires from creosote that builds up due to incomplete combustion. In general, these programs were developed to reduce $PM_{2.5}$ and toxic air pollutants, but can be employed to help reduce BC and other GHG (e.g., CH_4 and CO_2) from RWC. The initiative has the following key components.

10.3.4.1 Great American Wood Stove Changeout Program

The hearth industry estimates that of the 12 million wood stoves in U.S. homes today, 75% are wood stoves built before 1990. EPA is working with the hearth products industry and others to help state, local, and tribal agencies create campaigns to promote replacement of old wood stoves and wood-burning fireplaces with new, cleaner-burning and more energy efficient appliances. Programs vary from one community to another, with some areas focusing on changing out old wood stoves and others on retrofitting open fireplaces with cleaner burning options (e.g., gas stoves). The campaigns are typically led by local government or non-profit organizations at the county or regional level.

Residents of participating communities generally receive incentives such as cash rebates, low/no interest loans and discounts to replace their old, conventional wood stoves and fireplace inserts with cleaner-burning, more efficient EPA-certified

New Wood Stoves and Pollution Reduction

EPA estimates that every 1,000 old wood stoves changed out to cleaner burning hearth appliances will result in annual pollution reductions of

- 815 tons of CO_2
- 53 tons of CH_4
- 27 tons of $PM_{2.5}$
- 4 tons of toxic pollutants
- 14 tons of OC
- 1.6 tons of BC

(Numbers generated using EPA's Wood Stove and Fireplace emissions calculator: *http://www.epa.gov/burnwise/resources.html* and EPA's speciation profile data base.)

gas, pellet, electric, wood stoves and fireplaces or even geothermal heat pumps. A new EPA-certified wood stove, new flue, and professional installation cost, on average, $3,500 (2010$). Some areas have provided cash incentives to low-income participants only, while others have provided incentives to everyone in the community. The local agency leading the replacement program will sometimes include weatherization programs which insulate homes to help reduce heat loss and reduce fuel consumption. Households that participate in these programs are required to surrender their old wood stoves to be recycled.

Some of the benefits of replacing inefficient wood stoves include:

- Reduction in $PM_{2.5}$ and toxic air pollutants (e.g., benzeno(a)pyrene) by 70%
- Reduction in indoor $PM_{2.5}$ emissions by 70% according to University of Montana[3]
- Improvement in energy efficiency by 50%, using one-third less wood
- Reduction in CH_4, BC, and CO_2 from improved combustion efficiency and use of less fuel wood.

A variety of examples of state and local efforts to reduce emissions from older appliances are available at EPA's Burn Wise website: *http://www.epa.gov/burnwise/casestudies.html*.

EPA's wood stove changeout effort has focused primarily on counties at or near nonattainment for $PM_{2.5}$ where wood smoke is an important local source. EPA estimates that through 2011, the Great American Woodstove Changeout Program has helped changeout or retrofit nearly 24,000 wood stoves and fireplaces in 50 areas. From 2010 on, this program is anticipated to reduce approximately 370 tons of $PM_{2.5}$ and 63 tons of hazardous air pollutants (HAPs) each year after 2010, providing approximately $120 million to $330 million (2010$) in estimated health benefits in the U.S.[4]

The best available cost-effectiveness information on residential wood smoke mitigation comes from a

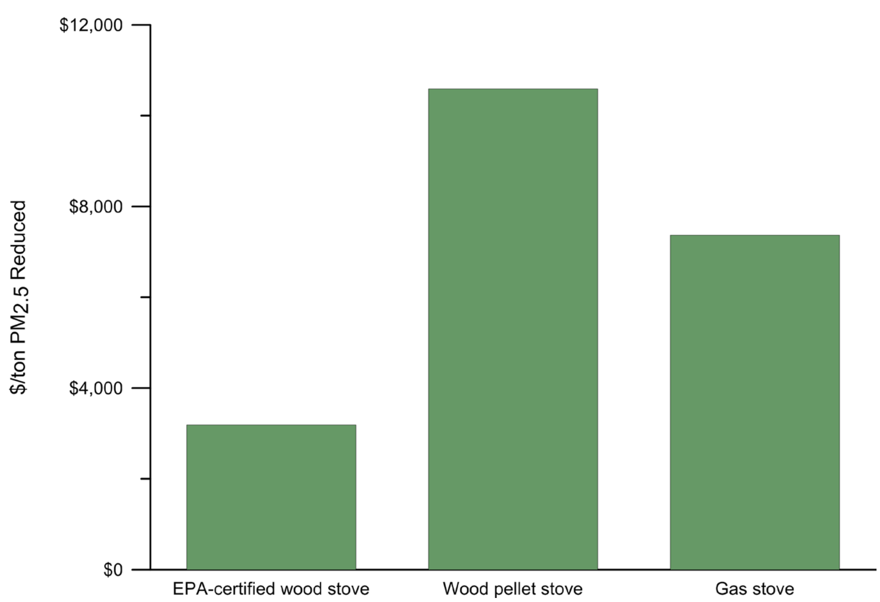

Figure 10-2. Cost Per Ton $PM_{2.5}$ Reduced for Replacing Non-EPA-Certified Wood Stove with EPA-Certified Woodstove (in 2010$). (Source: U.S. EPA, based on data from *http://www.marama.org/visibility/ResWoodCombustion/RWC_FinalReport_121906.pdf*)

[3] For more information, see: *http://www.ncbi.nlm.nih.gov/pubmed/18665872*.

[4] These estimates reflect national average benefit-per-ton estimates for directly emitted carbonaceous particles from area sources from *http://www.epa.gov/air/benmap/bpt.html* (data accessed February 2011) and Fann, Fulcher, Hubbell 2009 methodology. These estimates have been inflated from 2006$ to 2010$.

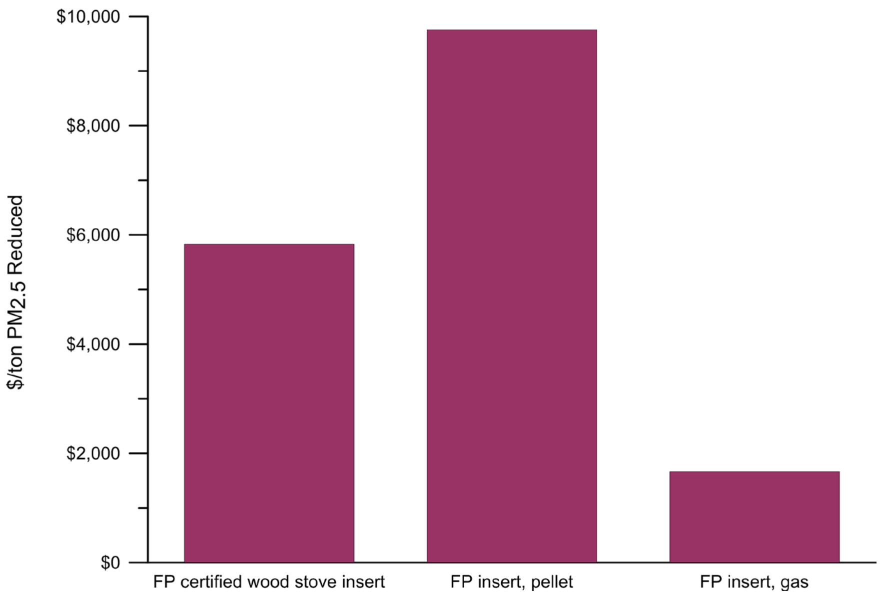

Figure 10-3. Cost Per Ton $PM_{2.5}$ Reduced ($/Ton) for the Addition of an Insert into a Fireplace (2010$). (Source: U.S. EPA, data courtesy of MARAMA)

Mid-Atlantic Regional Air Management Association (MARAMA) document called *Control Analysis and Documentation for Residential Wood Combustion in the MANE-VU Region (2006)*. This document focused on the costs of total $PM_{2.5}$ mitigation. The results suggest that the cost per ton of $PM_{2.5}$ emissions reduced from wood stove changeouts and fireplace retrofits is similar to the cost of other $PM_{2.5}$ controls discussed in previous chapters of this report. Figures 10-2 and 10-3 summarize the MARAMA estimates of the cost per ton $PM_{2.5}$ reduced from these measures; these costs vary depending on the type of wood burning appliance being replaced (old wood stove vs. open fireplace) and on the replacement technology (e.g., EPA-certified wood stove vs. wood pellet stove).

10.3.4.2 Outdoor Wood-Fired Hydronic Heater Program

In 2007, EPA initiated a partnership to reduce emissions from new outdoor wood-fired hydronic heaters. This program is aimed largely at areas with $PM_{2.5}$ air quality problems. EPA has worked with industry to reach agreement on voluntary performance levels for new heaters to bring them to market faster than feasible under regulation. Similar to the wood stove changeout program, there are potential climate change, air quality, and energy efficiency benefits with this program. The program is structured in two phases: under Phase 1, qualified new units were 70 % cleaner than existing units and, under Phase 2, which began in October 2008, new units are required to be 90% cleaner than existing units.[5] EPA has now expanded the program to include indoor models and hydronic heaters that are fueled by other kinds of solid biomass (e.g., wood pellets).

As of 2011, nearly 10,000 EPA-qualified units had been sold; 24 manufacturing partners had agreed to produce units 70%-90% cleaner; and 22 models had been placed on the market, reducing approximately 6,100 tons of $PM_{2.5}$ emissions each year after 2011 and providing approximately $2.2 billion to $5.4 billion (2010$) in estimated health benefits in the U.S.[6]

10.3.4.3 New Construction Wood-Burning Fireplace Program

The EPA voluntary Wood-burning Fireplace Program is modeled after the Hydronic Heater Program and helps reduce wood smoke emissions growth in areas with $PM_{2.5}$ air-quality problems. The two-phase program covers new installation of low mass (i.e., pre-manufactured) and masonry fireplaces, and is expected to drive technology improvements much sooner than possible through regulation. The program qualifies models achieving a Phase 1 (34% reduction) or a Phase 2 (54% reduction) $PM_{2.5}$ emission level. EPA has worked closely with the hearth products industry to develop this program; however, growth in the program has been hampered by the slowdown in new home construction in the United States.

10.3.5 Additional Regulatory Approaches to Limiting Wood Smoke Emissions

A variety of regulatory programs, including wood burning curtailment programs and requirements to remove old stoves upon resale of a home, have proven effective in helping to address wood smoke.

[5] Use of Phase 1 labels was prohibited after March 31, 2010. See *http://www.epa.gov/burnwise/owhhlist.html*.

[6] These estimates reflect national average benefit-per-ton estimates for directly emitted carbonaceous particles from area sources from *http://www.epa.gov/air/benmap/bpt.html* (data accessed February 2011) and Fann, Fulcher, Hubbell 2009 methodology. These estimates have been inflated from 2006$ to 2010$.

Education and Outreach: EPA's Burn Wise Campaign

Perhaps one of the biggest opportunities to reduce wood smoke emissions, including BC, lies in the hands of those who burn wood, regardless of the type of appliance they own. How wood stoves are operated and what is burned are as important as the type of stove used. EPA has heard from state, local, and tribal governments and from the public that even people who own an EPA-certified wood stove are often times burning "green" unseasoned wood, trash, and/or improperly operating their appliance, resulting in high wood smoke emissions.

In October 2009, EPA launched an education campaign called Burn Wise to promote responsible wood-burning and to educate users on the connection between what they burn, how they burn, and the impacts on their health and the environment. The campaign provides a website (*www.epa.gov/burnwise*), fact sheets, posters, and public service announcements. EPA has coordinated with the hearth products industry, chimney sweeps (Chimney Safety Institute of America), and other partners on the development and implementation of the campaign.

Getting people to change their habits and behaviors, including their wood burning practices, is typically not a trivial or inexpensive task. Equally challenging is measuring the effectiveness of social marketing or education campaigns like Burn Wise. However, EPA does believe the benefits, particularly the public health benefits, are worth it, and that some methods are more effective than others. For example, Environment Canada implemented a "Burn It Smart" campaign that included conducting community based workshops. The workshops were targeted in areas where government officials believed heating with wood was very common. Even though they did not calculate emissions reductions, a follow-up survey of 174 people indicated that

- 3% percent of the respondents said the workshops brought about positive change on how they burned wood
- 34% have updated their wood burning appliances; 90% of those chose EPA approved appliances
- 41% of those surveyed have changed out or intend to change out their old wood burning appliances for cleaner technology.

Wood Burning Curtailment Programs: One of the most effective ways a community can reduce wood smoke is by developing a mandatory curtailment program or instituting "burn bans." Some communities implement both a voluntary and mandatory curtailment program depending on the severity of their problem. Curtailment programs often have two stages, with Stage 1 allowing EPA-certified wood stoves to operate and Stage 2 banning all wood burning appliances, unless it is the homeowner's only source of heat. Although curtailment programs are not always popular with the public, this measure can be highly effective at reducing wood smoke. As an example, the Sacramento Air Quality Management District's Stage 2 program, implemented in 2008-2009, reduced $PM_{2.5}$ levels by 12 $\mu g/m^3$. The cost effectiveness was estimated to be approximately \$6,300 - \$11,100 per ton of $PM_{2.5}$ reduced (2010\$) (SMAQMD, 2009). To increase the likelihood of success, curtailment programs should include a forecasting and public notification system. In addition, an enforcement component is important to ensure the public takes the program seriously.

Removal of Old Wood Stove Upon Re-Sale of a Home: Old wood stoves are usually made of metal, weigh 250 to 500 pounds, last for decades, and can continue to pollute for just as long. As a result, homeowners are less likely to replace old stoves with a new, cleaner burning technology or remove the old stove, especially if they are not using it. To help get these old stoves "off-line," the state of Oregon and some local communities in other states have required the removal and destruction of old wood stoves upon the resale of a home. Specifically, this requirement has proven very effective in locations like Mammoth Lakes, CA and Washoe County, NV.[7]

10.3.6 Wood Smoke Reduction Resource Guide

In October 2009, EPA released a resource guide called *Strategies for Reducing Residential Wood Smoke*[8] that was written for state, local, and tribal air pollution control officials so they would have a comprehensive list of strategies to help reduce wood smoke from residential heating. The guide provides education and outreach tools, information on regulatory approaches (e.g., burn bans) to reduce wood smoke, as well as voluntary programs to change out old, inefficient wood stoves and

[7] For more information, see: *http://www.gbuapcd.org/rulesandregulations/PDF/Reg4.pdf*.

[8] *http://www.epa.gov/ttncaaa1/t1/memoranda/strategies-doc-8-11-09.pdf.*

fireplaces. It also notes the upcoming wood heater NSPS has the potential to help reduce future residential wood burning emission throughout the United States. Several state and local communities have effectively implemented residential wood smoke control strategies and have significantly reduced harmful wood smoke pollution. For example, Lincoln County, MT and Sacramento Metropolitan Air Quality Management District have encouraged comprehensive wood smoke reduction strategies to help these areas clean the air and protect public health.

10.4 Residential Cookstoves in Developing Countries

More than 3 billion people worldwide cook their food or heat their homes by burning biomass (e.g., wood, dung, crop residues, and charcoal) or coal in polluting and inefficient traditional stoves (International Energy Agency, 2010). As discussed in Chapter 4, BC emissions from these sources are estimated to account for 21% of the total global inventory. This use of solid fuels also represents a significant part of energy use in developing regions—including nearly 50% of total primary energy supply in Africa, and about 27% in India (International Energy Agency, 2009). Use of biomass and waste in developing nations—nearly all of which is for household cooking and heating—accounts for about 60% of global renewable energy use (International Energy Agency, 2009, Annex A). About 82% of those who rely on traditional biomass fuels for cooking live in rural areas; however, in Sub-Saharan Africa, nearly 60% of people living in urban areas also rely on biomass (International Energy Agency, 2010).

As discussed in Chapter 3, several decades of research document the significant risks to public health associated with traditional cookstoves. Exposure to cookstove emissions leads to an estimated 2 million deaths each year and ranks as the sixth highest mortality risk factor and fifth highest disease risk factor overall (in terms of disability adjusted life years—DALYs) in poor developing countries (World Health Organization, 2009). Emissions from cookstove use have been linked to adverse respiratory, cardiovascular, and neonatal outcomes and to cancer (Smith et al., 2004). Of the total global mortality associated with exposure to cookstove smoke, Sub-Saharan Africa, China and India each account for approximately 25-30%, with the remainder of deaths attributable to cookstoves occurring elsewhere in Asia and Latin America.

The contribution of this source category to emissions of BC and other aerosols has been the focus of growing interest, especially in terms of impacts on sensitive regions such as the Himalayas. A recent study on BC emissions from cookstoves in northern India indicated that cooking with solid fuels is a major source of ambient BC in the region, with peak ambient BC concentrations of about 100 $\mu g/m^3$ (Rehman et al., 2011). Furthermore, the study indicated that OC concentrations (which exceeded BC concentrations by a factor of five) contained significant absorbing BrC, and suggested that previous estimates of atmospheric solar heating in the region due to particles from cookstove emissions should be increased by a factor of two or more. However, there remains significant uncertainty about the extent of BC and associated emissions from cookstoves, and the effect of those emissions on climate. Given the complex emissions mixture resulting from cookstove use, further study is needed to pinpoint the most beneficial strategies for reducing BC emissions from this source. Unquestionably, however, this sector represents the area of largest potential public health benefit of any of the sectors considered in this report. Mitigation of emissions from cookstoves offers a tremendous opportunity to protect health, improve livelihoods, and promote economic development—particularly for women and children. For this reason alone, irrespective of the additional climate benefits that may potentially be achieved, mitigation of cookstove emissions is a pressing priority.

Mitigating BC emissions from cookstoves depends first on identifying technologies that are proven effective in reducing BC emissions, and second on encouraging adoption of these technologies on a large scale. As discussed below, very few improved stoves have been designed specifically to reduce BC emissions, and while some improved technologies are emerging, no advanced stoves that burn solid fuel have yet been adopted on a broad scale (though LPG has been widely disseminated as a clean cooking fuel, and China (see below) implemented a very large earlier stoves program using intermediate stoves). The problem is complicated by the fact that both the impacts of cookstoves and the solutions are regionally dependent. Specifically, the extent of achievable BC reductions, and the impact of those reductions, will depend on the type of stove, the type of fuel used, and the location of emissions. Improved cookstoves and fuels must satisfy the needs of local users, enabling them to cook local foods at the time and in the manner they prefer, using the fuels that are available and affordable. Given the array of different technologies and fuels currently in use, and the sheer number of sources involved, mitigation of BC emissions from cookstoves represents an enormous challenge. However, given their significant contribution to the global inventory of emissions, and the increasing availability of cost-effective and locally appropriate solutions and several other factors noted in section 10.4.3, this sector represents one of the most promising opportunities for mitigation of BC internationally.

10.4.1 Emissions from Cookstoves

Currently, residential cookstoves contribute approximately 21% of the global BC emissions inventory, with emissions concentrated in Sub-Saharan Africa, China, India, and other developing regions of Asia. Dependence on traditional biomass fuels is highly correlated with poverty; countries with higher household income also tend to have a higher share of modern fuels for residential consumption. While the percentage of people relying on traditional biomass fuels for basic household energy needs is expected to decrease in most areas over the coming decades, the aggregate number of people relying on biomass for cooking and heating is expected to increase by 100 million people by 2030 due to population growth (International Energy Agency, 2010). IEA projects that the fastest shift toward modern fuels will occur in India, and the slowest shift will occur in Sub-Saharan Africa (International Energy Agency, 2010). The impact of these changes on emissions is still unclear: as discussed in Chapter 7, under most scenarios, residential emissions are projected to decline significantly by 2030 and further still by 2050 (Streets et al., 2004). However, a decline in emissions, and the rate of decline will depend on rates of adoption of cleaner fuels and cooking technologies described below, and some regions may experience near-term increases in emissions.

10.4.2 Technologies and Approaches for Controlling Emissions from Cookstoves

Because cooking is such a variable, individual-specific activity, there are many complexities related to achieving reductions in BC emissions from improved cookstoves. The type of fuel and its moisture content, the type of stove, the purpose for which it is used (heating vs. cooking), and the manner in which the stove is tended all affect composition of emissions (MacCarty et al., 2008). Cooking practices vary both daily and seasonally due to variation in available foods and fuels, and variation in fuel quality. Additionally, there may be significant variation in the efficiency and durability of stoves, even those that are mass produced.

There is currently no formal definition of what constitutes an "improved" stove. In the past, "improved" stoves typically meant low-cost, locally made stoves aimed at improving efficiency and reducing fuel use. A primary motivation for the use of improved stoves was to reduce demand for fuel wood, thereby reducing pressures on forests as well as the time spent by women and children gathering fuel (Graham et al., 2005; Partnership for Clean Indoor Air, 2005). However, not all such stoves functioned as intended. For example, stoves that have a large amount of heated mass, such as the Lorena stove, may remove smoke with a chimney, prevent burns, and help warm a house, but may not save fuel compared with an open fire (USAID, 2007).

Over the last ten years, a new suite of more effective stoves has been introduced to the marketplace. As a group, these new improved stoves are designed to be much more efficient and clean (as well as safe), and utilize a variety of different technologies and fuels. Most are produced locally for the nearby market, while there are a few that are mass produced internationally and can be shipped anywhere in the world. The stoves span a wide range of cost, durability, and performance, and are designed for different types of staple foods. Importantly, however, these stoves are generally designed to reduce fuel use and emissions of $PM_{2.5}$ and CO (as proxies for the broader suite of emissions from these stoves). Few of the stoves currently on the market were designed to reduce BC specifically (the new Turbococina stove is an exception). In laboratory settings, most of these stoves achieve $PM_{2.5}$ reductions of 40% to 70%. Results from MacCarty et al. (2008) indicate that some non-advanced stoves may not substantially reduce BC emissions, but some gasifier and forced draft (or "fan") stoves significantly reduce BC emissions compared to the open fire. Field testing has begun to determine whether stoves perform as well in actual (real-world) conditions as in the laboratory. Results from field tests indicate that stove performance under actual conditions varies (Roden et al., 2009; USAID, 2011). Much more such testing is needed, as well as additional research and development in stove design to determine if the stoves are reducing BC in addition to total $PM_{2.5}$.

Among the new technologies now emerging on the cookstove market, there are a few advanced solutions that have been shown to reduce $PM_{2.5}$ by 90% or more in laboratory settings; the limited lab testing performed on these stoves to date indicates that some stoves reduce BC by a similar percentage (MacCarty et al., 2008). These new technologies include advanced forced-draft stoves and "gasifier" stoves (Roth, 2011) that use various solid biomass fuels (including wood, pellets, crop residues, etc.); biogas stoves; and liquid-fuel stoves

Figure 10-4. The Turbococina Stove, which burns wood, is made of a stainless steel cylinder fitted with 10 air injectors, an internal fan that runs on electricity, and a steel plate that regulates the air flow to improve combustion efficiency. This stove is currently available primarily for institutional settings. (Photo courtesy of René Nuñez Suárez, Turbococina)

that burn ethanol, plant oil, or other biomass fuels. It is important to note, however, that few of these stoves are widely commercially available and their performance in the field has not been fully evaluated. Some stoves require electricity to drive a fan (see Figure 10-4), while others have been designed to convert waste heat to electricity to power a fan, which enables excellent emissions performance (including BC emissions reductions) without the need for access to electricity (see Figure 10-5).[9] Some of these stoves are being further tested for emissions in both the lab and the field. These new stove technologies have the potential to reduce emissions from cookstoves nearly to the levels of clean fuels such as LPG (Wilkinson et al., 2009), but many (though not all) require specific and/or highly processed fuels, which increases the total cost of use (Venkataraman et al., 2010). In some cases, clean fuels (ethanol, biogas) are not widely commercially available for cooking. Forced-draft stoves that do not generate their own electricity require access to another electricity source, which can be costly. Even battery-powered fan stoves require intermittent access to electricity. Some gasifier stove designs use natural draft (natural convection) and do not require a fan.

While the basic outlines of lab and field tests have been in place for decades, it is only in the past five years that organizations funding household energy interventions have begun requiring emissions pre-testing, or that performance benchmarks (even informal ones) have been established. Recent testing in both lab and field settings (see below) demonstrate that this new generation of stoves is achieving real and measurable results. Developing globally recognized standards that are widely accepted by the cookstove community and adopted by country governments could spur wider development of clean cookstoves.

Based on available performance and cost data, currently available technologies exhibit a wide range of performance. These options include:

- electric stoves
- gas and liquid fuels
- processed solid fuels
- advanced biomass stoves
- rocket stoves

Figure 10-5. Woman Prepares Banku on a BioLite HomeStove in Kintampo, Ghana. BioLite stoves convert their waste heat into electricity, which is used to power the fan and can be used to charge a battery for a mobile phone (as shown in photo), LED light, or other low-power purpose. (Photo courtesy of Jonathan Cedar, Biolite)

[9] These stoves may also soon be able to reliably generate enough electricity to be used for other purposes (e.g., lights or cell phones), which could increase consumer demand. The change in emissions with the new stove would depend in part on the extent to which overall stove usage increased due to demand for these extra services (Venkataraman et al., 2010).

- simple stoves
- solar cookers
- behavioral and structural solutions

10.4.2.1 Electric Stoves

Cooking with electricity produces zero emissions within a household, and therefore is highly effective at reducing personal exposures of stove users. However, from a broader public health or climate perspective, emissions associated with the increase in power production must also be considered. The ongoing electricity costs for these stoves can vary substantially by region.

10.4.2.2 Gas and Liquid Fuels

Switching from solid fuels to gaseous or liquid fuels is often the easiest means of dramatically lowering emissions from cooking. In laboratory testing, the Aprovecho Research Center (Aprovecho) found that using liquid petroleum gas (LPG) decreased the amount of energy used by 69%, the mass of fuel used by 89%, particle emissions by over 99%, CO emissions by 98%, and time to boil by 40%, as compared to cooking over an open fire (MacCarty et al., 2010). Field research in Guatemala showed that LPG stoves could reduce indoor 24-hr $PM_{2.5}$ concentrations by over 90% (Naeher et al., 2000). Liquid fuels such as ethanol, kerosene, and plant oils are also options (see Figure 10-6). Aprovecho's lab tests found that cooking with well-made ethanol or kerosene stoves decreased the mass of fuel used by 75% and 82% respectively and particle emissions by over 99% for each; CO emissions by 92% and 87% (MacCarty et al., 2010).

Figure 10-6. CleanCook Ethanol Stove. Currently these stoves are being deployed in refugee camps in Ethiopia and Kenya, with over 3,800 stoves already in use. Deployment of additional stoves is dependent partly on the availability of ethanol. (Photo courtesy of Harry Stokes, Project Gaia)

Biogas derived from waste biomass is potentially as clean as LPG, and in addition it is renewably derived (reducing CO_2 impacts) and requires no distribution infrastructure. Emissions testing of biogas stoves to date suggests that these stoves perform significantly better than solid fuel/stove combinations with regard to emissions of methane, CO, VOC, and CO_2 (Smith et al., 2000b). Plant oils are another liquid fuel being used today for cooking, but independent testing results for stoves using these fuels have not yet been published. Stoves using gas and liquid fuels involve an upfront cost of \$5 to \$50 per stove, as well as an ongoing cost for the fuel that varies substantially by region, fuel, and changing economic conditions. LPG stoves can also require significant deposits on the cylinders, another serious barrier for the very poor. It is also important to note that poorly made kerosene stoves in particular pose safety concerns, including the potential for severe burns and injury associated with accidental fires (Peck et al., 2008).

10.4.2.3 Processed Solid Fuels

For much of the developing world, the advanced solutions described above may be unavailable or simply too costly to use in the near-term. Stoves utilizing processed solid fuels in the form of charcoal, pellets, prepared wood, and briquettes, may be more accessible, and these can also represent very clean solutions. However, like the clean fuels noted above, using processed fuels also involves an ongoing operating cost, which may serve as a barrier for these solutions, especially in regions where fuel wood can be collected free of charge. However, in markets where fuel is purchased, stoves that increase combustion efficiency by 50% are often the easiest stoves to market, since the consumer can expect a quick payback period on the initial investment.

Charcoal is the most common processed solid fuel used today. A number of charcoal stove models are available (see Figure 10-7). Lab tests of charcoal

Figure 10-7. Charcoal Stoves. (a) Charcoal Stove by Burn Design. (Photo courtesy of Peter Scott, Burn Design) (b) Charcoal Zoom Versa Stove produced by EcoZoom. (Photo courtesy of Ben West, EcoZoom) (c) Prakti Charcoal Stove. (Photo courtesy of Mouhsine Serrar, Prakti Design) (d) Envirofit CH-4400 Charcoal Stove. (Photo courtesy of Envirofit) (e) Toyola Charcoal Stove in use in a village in Ghana. (Photo courtesy of Suraj Wahab, Toyola Energy)

stoves for climate forcing emissions found that these stoves—relative to an open fire—reduced the BC/OC ratio somewhat, and reduced total particles by about two thirds (MacCarty et al., 2008). It is important to note that the laboratory emissions tests do not account for emissions in the charcoal production process, which is highly inefficient and polluting, with significant net climate impacts (Bailis et al., 2005). Aprovecho has tested many charcoal stoves for $PM_{2.5}$, CO, and fuel use, finding that $PM_{2.5}$ emissions were 90% lower than for a 3-stone fire and fuel use savings ranged from 45% to 65%. Most charcoal stoves cut time to boil, though only modestly. However, CO emissions increased for all stoves except one (MacCarty et al., 2010). In 2007, EPA tested two charcoal stoves and found that relative to a 3-stone fire, $PM_{2.5}$ emissions from the charcoal stoves fell by over 90% from a hot start but increased when operated from a raw, cold start, and both stoves increased CO emissions (Jetter and Kariher, 2008).

Creating pellets from biomass or briquettes from either coal or biomass can lead to substantial improvements in efficiency and emissions when pellets are burned in well-designed stoves. The Oorja stove (developed by BP and now owned by First Energy of India) is an example of a very clean-burning pellet stove—in this case the pellets are made from crop residues by a partner company. More than 400,000 Oorja stoves have been sold and between 250,000 and 350,000 are in use every day. However, given the cost of pellets, this stove competes with LPG. Other examples include project-based work that have developed briquettes from waste biomass (Haiti, Ghana, and Uganda), stoves designed to burn pellets made from locally available waste biomass (West Africa and elsewhere), and a stove that burns rice hulls (Philippines), though EPA is not aware of any examples where this work has been carried to a large scale. With regard to coal cooking, laboratory measurements indicate that the combination of using improved stoves with processed coal briquettes could have a dramatic impact on aerosol emissions. Zhi et al. measured reductions in particles of 63%—with OC decreasing 61% and BC decreasing 98%. This reduced the BC/OC ratio by about 97%, from 0.49 to 0.016 (Zhi et al., 2009).

10.4.2.4 Advanced Biomass Stoves

There are two types of advanced biomass stoves that can achieve high levels of performance: forced

Figure 10-8. Philips Woodstove (forced draft) Manufactured in Lesotho. (Photo courtesy of Stephen Walker, African Clean Energy Ltd.)

draft and gasifier stoves. Gasifier stoves can be forced-draft or natural draft. These stoves can burn processed or raw biomass, though it is likely the case (field testing data forthcoming) that those using processed fuels will perform better in the field, since processed fuels eliminate a major variable in real-world use of the stoves. It is also likely that lab and field emissions test results will be more consistent for stoves that burn processed fuels. Lab testing of advanced biomass stoves to date generally confirms that these advanced biomass stoves can achieve remarkable emissions reductions—up to 93% lower than traditional stoves (Venkataraman et al., 2010). One study found that these stoves achieved substantial reductions in both overall particles and BC specifically, with the fan stove significantly reducing particle emissions and the gasifier stoves reducing total particles by about two-thirds (as well as reducing the BC:OC ratio). The study also showed that the fan stove was able to reduce time to boil, at least under the lab conditions (MacCarty et al., 2008).

Under Aprovecho's broader lab testing, forced draft fan stoves all reduced (relative to a 3-stone fire) fuel use (by 37% to 63%), CO emissions (in all cases by over 85%), $PM_{2.5}$ emissions (from 82-98+%), and time to boil (11% to 65%). Similarly, the gasifier stoves tested by Aprovecho saved on fuel use, reduced CO emissions, achieved dramatic reductions in particle emissions (with one exception), and cut the time to boil, though generally all to a lesser extent than the fan stoves (MacCarty et al., 2010). In EPA's 2007 testing, the one advanced fan stove tested (Philips) had the best overall performance and the lowest pollutant emissions, reducing emissions of key pollutants such as $PM_{2.5}$ and CO by about 90%. Notably, of the wood burning stoves tested, this stove was also the one that required the least attention to operate (Jetter and Kariher, 2008), although it required fuel with short (<10 cm) lengths (see Figure 10-8). A forthcoming study from investigators in India of recently completed field testing of two forced draft cookstoves and indicated that both stoves substantially reduced BC emissions in both the breathing zone (85% and 49% BC reduction respectively, compared to the traditional mud cookstove) and in the plume zone (86% and 64% respectively) (Kar et al., 2012). Indoor cooking-time BC concentrations were reduced to 5-100 µg/m^3 by the top-performing forced draft stove (as compared to 50-1000 µg/m^3 for the mud stove).

It is important to note that, while very promising in terms of performance, most of these models are still in the research and development stage, though a few have been introduced in the market today. These stoves are typically more costly than other biomass stoves, currently costing in the range of $25-100 per unit (plus any processed fuel costs, which can be substantial[10]), though prototypes for newer versions have been developed that manufacturers estimate will cost in the $40-60 range at full production.

10.4.2.5 Rocket Stoves

Where advanced stoves are not widely available in the marketplace, or are not affordable, rocket type stoves are typically the most efficient and clean biomass-burning alternative (see Figure 10-9). Rocket stoves have a combustion chamber designed to allow for better mixing of combustion gases and higher combustion temperatures which slightly improves combustion efficiency (compared to the open fire) and reduces emissions. Additionally, rocket stoves have substantially better heat transfer efficiency, so as they save fuel, they reduce emissions (for a given cooking task). Thus, rocket stoves substantially reduce emissions without relying on electricity or other sophisticated components. However, rocket stoves have not been designed to date to reduce BC emissions. MacCarty et al. (2008) found that the rocket stove reduced total particle emissions by about 40%, but that nearly all of the emissions reductions were of organic matter; BC emissions for this stove did not decrease (and thus the BC:OC fraction increased dramatically). The study also showed that the rocket stove was able to

[10] For example, the pellets for the Oorja stove in India cost roughly 7 Rupees (~15¢) per kilogram of pellets.

Figure 10-9. Rocket Stoves. (a) Envirofit G3300 Biomass Cookstove in Use in Tanzania. (Photo courtesy of Nancy Ryden, Envirofit) (b) Zoom Dura Biomass Cookstove produced by EcoZoom. (Photo courtesy of EcoZoom)

reduce time to boil, though to a lesser extent than an advanced fan stove.

Aprovecho tested a wide variety of rocket stoves and found important variability in performance indicating that design is critical. Most saved significantly (but not equally) on fuel use (26% to 51% savings relative to a 3-stone fire), though two failed to cut fuel use. All rocket stoves cut CO emissions by 70% or more, while performance on $PM_{2.5}$ emissions varied much more widely (one actually increased emissions), with 60% of those tested achieving reductions of over 50%. Some of the rocket stoves actually increased the time to boil, though most cut it modestly (MacCarty et al., 2010). In EPA's 2007 testing, several non-advanced wood stoves were tested and results varied depending on the design and the stage of operation. Generally, emissions were lower than the 3-stone fire, with faster times to boil. For example, the UCODEA wood stove—now called Ugastove—reduced $PM_{2.5}$ and CO emissions by 48% to 65% when operated at high power, and 35% to 50% at low power (Jetter and Kariher, 2008).

The U.S. Agency for International Development (USAID) recently conducted extensive field testing of five non-advanced biomass stoves in the Dadaab refugee settlements in Kenya. They tested for fuel use, time to boil, and several user preferences—but did not test for BC or any other emissions—and concluded that "all five tested stoves outperformed the open fire, requiring significantly less fuel to cook the test meal....with savings ranging from 32% to 65" (USAID, 2010b). Additional testing of two manufactured rocket stoves by Columbia University researchers demonstrated "substantial and statistically significant fuel savings relative to the three-stone fire" (38% and 46% on average, for the two stoves), but further stressed that fuel savings is just one factor that affects suitability of any given stove in a particular community. Other relevant factors include stove size, ease of use, and cooking time (Adkins et al., 2010).

USAID (2011) also completed a recent round of cookstove testing in the field in Uganda that did examine BC and other emissions and factors, comparing a traditional stove to a leading rocket stove. The study found that with the greater fuel efficiency of the rocket stove (42% savings were measured) came lesser emissions of $PM_{4.0}$ and carbon monoxide. However, the rocket stove (which was not designed to reduce BC emissions) had more than twice the fractional BC content in its PM emissions (15.5%) compared to the traditional stove (7.2%).

Recent field testing in India (Kar et al., 2012) noted above found preliminary results showing that the natural draft stoves had much wider variation in performance than the forced draft stoves, and did not achieve nearly as great reductions in BC. For example, these natural draft stoves reduced BC emissions in the breathing zone by a factor of 1.5 on average (22% to 55%), as compared to a factor of 4 for forced draft stoves. However, BC reductions varied significantly among natural draft stoves: only micro-gasification stoves were shown by Kar et al. (2012) to be effective in reducing BC, while other models occasionally emitted more BC than a traditional cookstove. BC emissions were shown to vary significantly among cooking cycles with same stove, and the use of mixed fuel (reflective of local practices) was shown to increase plume zone BC concentration (compared to hard wood) by a factor of 2 to 3 across the stoves tested.

Figure 10-10. Prakti Double-Pot Woodstove with Chimney. (Photo courtesy of Mouhsine Serrar, Prakti Design)

Several studies have measured changes in indoor concentrations of $PM_{2.5}$ (but not BC) in kitchens in Latin America due to the transition from a traditional open fire to the use of a griddle stove (known in Latin America as a *plancha* stove)—a raised wood-burning stove with a chimney, typically designed with a flat griddle to make tortillas. Naeher et al. (2000) reported reductions in 24-hour $PM_{2.5}$ concentrations of over 80%, and reported earlier measurements that achieved reductions ranging from 57% to 82%. (See Figure 10-10 for a picture of an improved wood-burning stove with a chimney.) Masera et al. found that CO and $PM_{2.5}$ concentrations in the kitchens using a so-called *Patsari* stove were reduced by 66% and 67%, respectively, compared to traditional cooking methods (Masera et al., 2007). Johnson et al. (2007) further reported that while *Patsari* stoves reduce overall particulate emissions in homes (including net BC emissions), the BC/OC ratio went up, making the net warming implication more ambiguous. McCracken et al. measured personal exposures (always less than reductions in indoor air concentrations since individuals do not spend all of their time in kitchens) and reported reductions in daily average exposure to $PM_{2.5}$ of over 60% (McCracken et al., 2007).

These stoves typically cost anywhere from \$8-\$100 per unit, depending on the design, quality of materials, performance, use of a chimney, use of a metallic *plancha* (for making tortillas), and durability. Certain models of these stoves have combustion chambers that might also be used to build quality-controlled mud stoves—the combustion chambers themselves may cost as little as \$4 to produce.

10.4.2.6 Simple Stoves

Aprovecho test results for a wide variety of simple stoves without a rocket or other improved combustion chamber indicated that the performance of these stoves varies enormously, with only two of seven tested achieving meaningful emissions and fuels use reductions. Most achieved some fuel savings, but increased particle emissions (MacCarty et al., 2010). These stoves typically cost only \$2 to \$10 per unit, but may last only a few months due to use of less durable materials and lower quality construction.

10.4.2.7 Solar Cookers

Solar cookstoves are emissions free, and thus the cleanest solution. However, the constraints of current solar cookers are significant: they have limited use in the early morning, late afternoon, or on cloudy or rainy days; they can greatly increase cooking time; and they are not suitable for cooking many foods. For this reason, the potential for current solar cookers is best thought of as part of an integrated solution. EPA is not aware of any example of solar cookers (which range in cost from \$20 to \$75 per stove, including the pot) being adopted at a large scale in a given region. However, with additional advances, such as improvements in energy storage capacity, it is conceivable that solar stoves could be an effective tool for this field in the future.

10.4.2.8 Behavioral and Structural Solutions

Many behavioral and structural steps can be taken to reduce human exposures to cookstove smoke. These include cooking outdoors, keeping children away from cooking stoves, adding ventilation to the kitchen, preparing fuel (drying and cutting to a smaller size), tending stoves more carefully, lighting stoves with improved techniques, or requiring stoves to have chimneys. Each of these solutions will diminish immediate human exposures to cookstove smoke, and are thus to be encouraged as much as possible, though the net benefit to human health may be tempered non-trivially by worsened ambient air quality when use of a chimney alone is the intervention. For purposes of this report, it is also critical to note that some of these behavioral and structural solutions will have little impact on BC emissions or related climate impacts (and may increase forcing by increasing direct emissions to the atmosphere), while others (such as preparing the fuel, tending stoves more carefully, and using improved lighting techniques), may reduce climate forcing emissions.

10.4.3 Programmatic Considerations for Cookstove Mitigation

As this extended discussion of currently available technologies indicates, there are a number of promising opportunities in the cookstove field. Advanced stoves can provide dramatic improvements in public health, and may also offer opportunities to reduce BC emissions. However, with the important exception of widespread adoption of LPG as a cooking fuel, the current scale of total stove replacements is limited, and the number of advanced stoves deployed as part of these programs is very small.

There have been many efforts to bring improved cookstoves to different parts of the world, ranging from large-scale government efforts in both China and India to countless small non-governmental organization-led efforts in communities across the globe. These efforts have had varying degrees of success. By far the most successful effort historically in terms of level of penetration of improved stoves was China's National Improved Stove Program (NISP), introduced by China's Ministry of Agriculture in the 1980s. The NISP targeted 860 of China's 2,126 counties, and the government statistics indicate that from 1982 to 1992, 129 million improved stoves had been installed in rural households (Graham et al., 2005). Gradually, the Chinese government shifted to focus on supporting stove manufacturers (Sinton et al., 2004), and follow-on programs increased total penetration to close to 200 million households (Graham et al., 2005). This program was primarily designed to reduce fuel use (to prevent deforestation). Thus, while the use of chimneys allowed China to lower indoor pollution somewhat, they were not able to reduce overall air pollution and GHG emissions (Wilkinson et al., 2009). It is not clear what impact, if any, this effort may have had on BC emissions.

In 1983, the government of India launched its National Program of Improved Chuhlas (NPIC). Over the next 17 years, the program introduced about 32 million improved biomass stoves to rural households around the country (Barnes and Kumar, 2002). While results varied substantially from region to region, "A 1995-96 survey conducted by the National Council of Applied Economic Research (NCAER) in 18 states indicated that 71% of the cookstoves were in working order and 60% were in use" (Sinha, 2002). Like the Chinese program, India's NPIC was designed to lower demand for fuel wood. The removal of indoor smoke was a secondary priority (Partnership for Clean Indoor Air, 2005). The NPIC has several shortcomings that limited its long-term success, including poorly designed subsidies, poorly designed stoves developed without user input, poor maintenance programs, and—in most regions—no commercial basis for sustained results (much greater success resulted where a commercial model was followed) (Partnership for Clean Indoor Air, 2005). In spite of its shortcomings, India's earlier program remains—after China's NISP—the largest cookstove program ever implemented (Barnes and Kumar, 2002).

Ethiopia, Indonesia, Mexico, Nepal, Nigeria, and Peru are examples of countries that have launched national stove programs; many other countries are actively working in this field. In December 2009, the government of India announced that it would launch a new National Biomass Cookstove Initiative to build on India's earlier national program, but be based almost entirely on a commercial business model in close cooperation with leading manufacturers of clean stoves and fuels in India. India will also seek to catalyze further stove and fuel innovations, for example via a global stove design prize.

The United States has been an active participant in the effort to address the many health risks associated with traditional cookstoves. At the 2002 World Summit on Sustainable Development, U.S. EPA brought together leaders from the government, private, academic, and nongovernmental sectors to launch the PCIA. Through 2010, key PCIA Partners have reported helping 6.6 million households adopt clean cooking and heating practices, reducing harmful exposures for more than 30 million people. PCIA has found that succeeding with sustainable household energy and health programs in developing countries requires focusing on four essential elements: meeting social and behavioral needs of users; developing market-based solutions; improving technology design and performance; and monitoring impacts of interventions.

Over time, the scale and pace of cookstove replacements have been increasing worldwide. Based on reporting from its network of more than

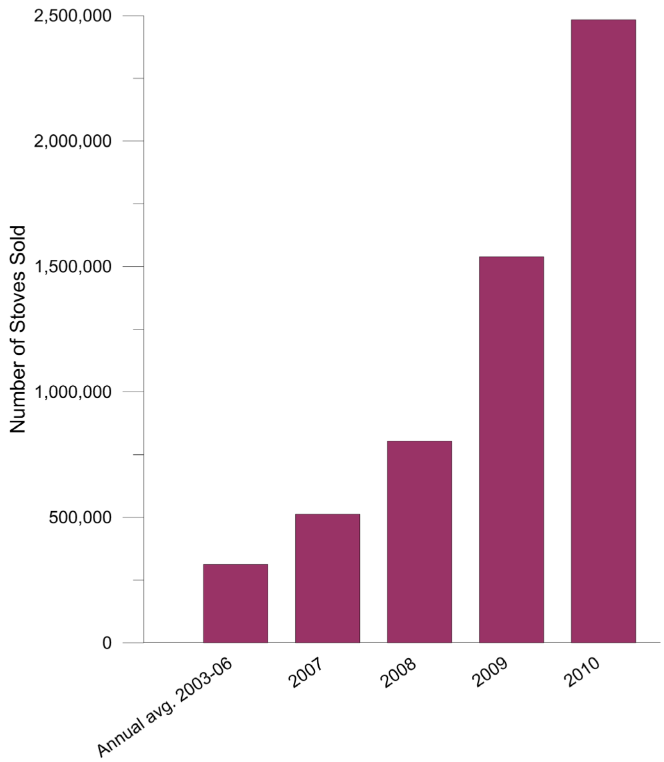

Figure 10-11. Number of Improved Stoves Sold by PCIA Partners, 2003-2010. (Source: U.S. EPA)

500 partners, PCIA indicates that partners sold 2.5 million stoves in 2010 (see Figure 10-11). Based on the latest survey results, PCIA Partners are more than doubling their stove sales every other year. This does not include the internal Chinese stove market and independent manufacturers that make and sell different versions of the so-called "Jiko" charcoal stove across Africa. Including these sales, the total number could be as high as 5 million to 10 million stoves per year, though there is not reliable international data on the quality or performance of many of these stoves, limiting the assessment of climate and health benefits. Despite this progress, the total impact of the cookstove replacements to date has been small, given that the total stove market is on the order of 500 million to 800 million homes.

In addition to the design and fuel innovations noted above, a number of recent developments point to a much greater potential for making large-scale progress in the cookstove sector. These include:

- *Growth of Existing Businesses and Business Models:* An increasing number of businesses are manufacturing and/or selling improved stoves and fuels, utilizing a wide range of business models. These models include non-governmental organizations (NGOs) working to catalyze local businesses around a common and tested stove design (e.g., GERES Cambodia's local partners just sold their 1.5-millionth stove); working to develop local businesses to make and sell artisanal stoves (e.g. GIZ's global efforts to provide over 4 million homes with improved stoves over the past 5 years); a local factory selling directly (e.g., HELPS/Guatemala has grown rapidly and sold over 100,000 stoves); international manufactures with local distributors (e.g., a partnership between the Aprovecho Research Center in Oregon on design, Shengzhou Stove Manufactures in China, and Colorado-based EnviroFit International on sales); and major corporations building their business in emerging markets (e.g., Philips, Bosch-Siemens).

- *New Scalable Technologies:* Many of the stoves noted above represent a new suite of stove technologies that are well designed and durable, and for which extensive emissions testing has been conducted. Such stoves could be mass produced, which would improve the scalability of these solutions (Venkataraman et al., 2010).

- *Carbon Financing:* Cookstove businesses are increasingly leveraging carbon financing in both the formal and voluntary markets to provide capital and increase public awareness. The financing arrangements vary substantially, but typically yield about 0.5 to 2 tons of CO_2-equivalents per stove per year for improved wood and charcoal stoves, and up to 3 to 5 tons of CO_2-equivalents per stove per year for improved coal stoves. Importantly, however, these credits are based on GHG (mostly CO_2) emissions reductions, as measured by reductions in fuel use during in-field tests. Additional work would be required to establish credits for BC reductions. Carbon financing is already transforming financing of cookstove efforts into more rigorous financial transactions with rigor and accountability for stoves sold, stove performance in the field, and stove utilization over time. The high transactions costs involved in obtaining project approval also incentivize large-scale projects and encourage the continued use of approved stoves for many years to generate ongoing credits. Impact investing is a separate, but important opportunity to bring social capital investments to this field, and examples of this tool applied to the cookstove field are beginning to emerge.

- *New Testing and Monitoring Tools:* The demand for rigorous monitoring for carbon and other financing, research, and other needs has also led to the development of less expensive and more effective monitoring technologies that greatly improve our ability to measure and interpret field results. These include relatively inexpensive $PM_{2.5}$ monitors, BC monitors, personal exposure monitors for CO and $PM_{2.5}$, portable stove emissions testing hoods, stove use monitors, and cell-phone based wireless monitoring tools.

In spite of this progress, achieving large-scale adoption of clean cooking solutions will not be easy, and many remaining barriers must be addressed. A recent World Bank study has summarized some of the key challenges, emphasizing the need for a range of stoves that meet users' needs, with demonstrated ability to reduce fuel use and indoor smoke, while maintaining durability and safety. The report also notes that successful programs require functioning commercial markets in order to reach and maintain a large scale of success globally. Innovative financing techniques and well-constructed monitoring and evaluation programs were other tools highlighted as critical to success in reaching the poor (World Bank, 2010). Other major considerations include:

- *Institutional Barriers:* Such barriers include the lack of accepted international standards for different stove-fuel combinations, the lack of independent stove testing facilities in market places around the world, and the lack of health guidelines regarding what interim targets on what is considered a "clean" stove.

- *Cost:* The cost of improved stoves and fuels alone pose a major challenge for many households. Additional financial barriers include tariffs and duties to import stoves, the large investment needed to take a prototype stove to mass production, the cost and difficulty of developing distribution chains in target markets, the high transactional costs of carbon financing, and the costs of managing an inventory for a widely fluctuating market during business start-up. Separate financing tools are needed make advanced stoves affordable for the poorest populations.

- *Social Barriers:* Cooking solutions must be designed to meet local cooking needs – cooking the local food, in the timeframes needed, with locally available fuels. Solutions for one part of the world may not be applicable in other parts of the world. Past "improved" stoves have not always been designed with the needs and social practices of end users in mind. By extensively testing prototype stoves with users, commercial businesses have been able to lessen these risks. Experience indicates that a full portfolio of solutions will be needed to meet the many cooking needs of the developing world – including preferences for a variety of cooking options (just as most kitchens in the developed world use not use a gas or electric stove, but an oven, a microwave oven, an outdoor grill, a toaster, and many more specialized cooking devices).

- *Global Leadership:* Coordination and cross-disciplinary leadership is needed to pursue integrated solutions that address each of the climate, health, gender, forestry, energy, agricultural, and other dimensions of the cookstove issue. In the past decade, several new efforts have emerged that have brought new focus to the health and climate risks of cookstoves, and new rigor to solutions to these risks. These include the U.S. EPA-led PCIA, the Shell Foundation's Breathing Space program, GIZ's HERA program, and SNV's global biogas efforts, as well as more isolated investments by the World Bank, USAID, and several agencies focused on refugee camps (e.g., United Nations High Commissioner for Refugees and World Food Programme).

In September 2010, the United Nations Foundation and nineteen founding partners launched the Global Alliance for Clean Cookstoves. The Alliance is a new public-private initiative whose mission is "to save lives, improve livelihoods, empower women, and combat climate change by creating a thriving global market for clean and efficient household cooking solutions." The Alliance will work closely with private, non-governmental, UN and other partners to expand efforts to address the global and local barriers that have limited the scope of cookstove replacements. The Alliance has set an interim goal of having 100 million new homes adopt clean and safe cooking solutions by 2020. Achieving this goal will likely entail the sale through commercial distribution channels of well over 100 million stoves in total, with both the quantity of sales and the quality of performance growing substantially over time (see Figure 10-12).

The development of standards for what constitutes a low-emitting stove is essential for ensuring improvements in performance over time. PCIA and the Alliance have joined together with the cookstove community to pursue the development of voluntary global standards through an inclusive, transparent process with the International Standards Organization (ISO). The development of these standards will proceed in parallel with growth in the global stove market. In the early years, distribution chains and businesses will be built around the sale

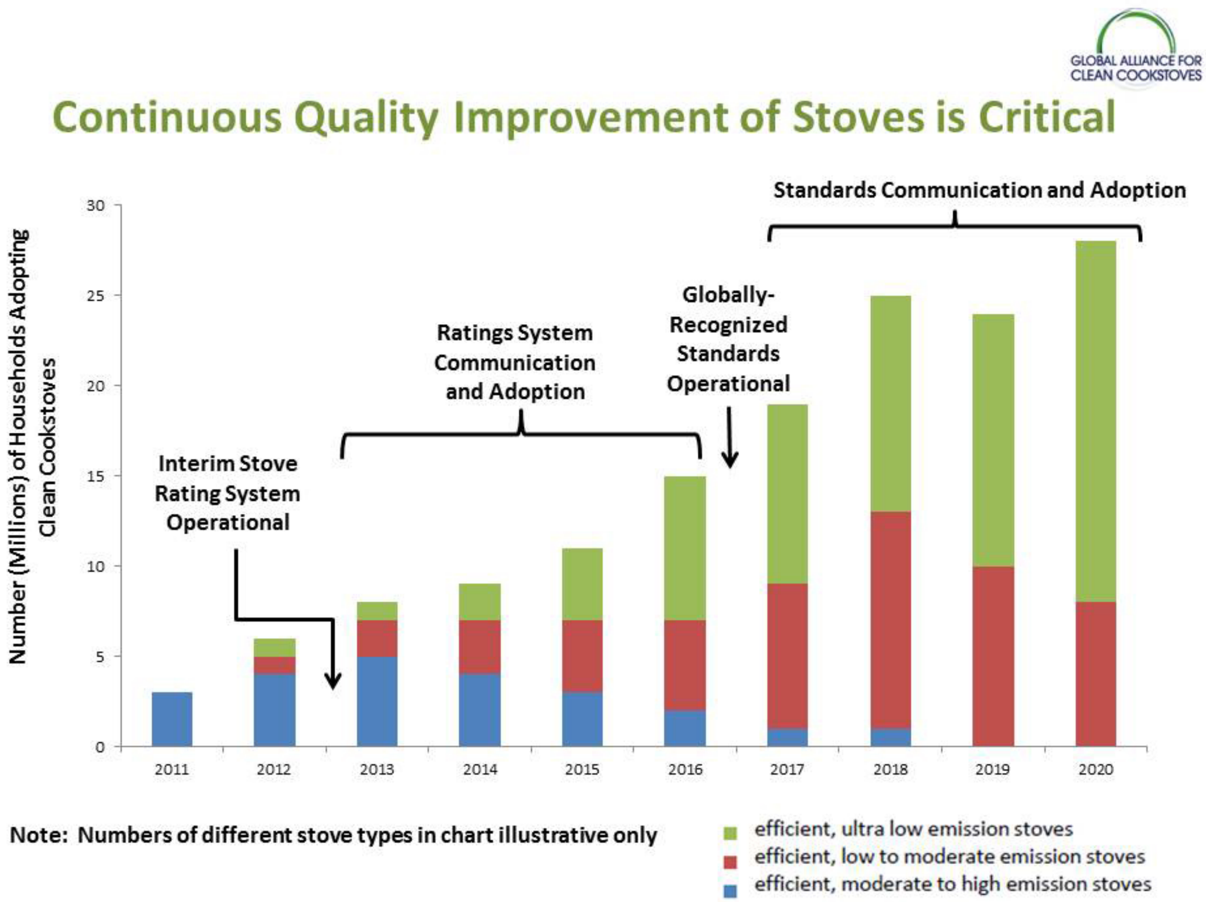

Figure 10-12. Potential Growth in the Number of Households Adopting Clean Cookstoves Globally through 2020. The Global Alliance anticipates that the market for clean cookstoves will continue to evolve, in parallel with development of cookstove standards. The Alliance has set a goal of 100 million clean stoves by 2020. Numbers of different stove types in the chart are illustrative only. (Reproduced from U.N. Foundation, 2011.)

of available, mostly mid-range stoves. As these distribution channels are built, however, newer advanced solutions will supplant them as the early purchases wear out and are replaced. By the end of the decade, it is the Alliance's goal that most stoves sold will be of the advanced (efficient and very low emission) variety. It is these more advanced solutions that are likely to achieve the more significant BC reductions, as well as the more dramatic health benefits.

While open fires or crude stoves are not a significant source of BC emissions in the United States, the U.S. government has been at the forefront of the effort to establish the Alliance and is a leading partner to the Alliance. The U.S. Department of State is leading Alliance diplomacy to raise the visibility of the issue and engage new country and other partners, and several agencies (EPA, U.S. Department of Health and Human Services [HHS, including the National Institutes of Health and the Centers for Disease Control and Prevention], DOE, USAID, Overseas Private Investment Corporation, Peace Corps, U.S. Department of Agriculture, and the National Oceanic and Atmospheric Administration) are contributing substantially to the Alliance through applied research (on technology, health, stove testing, distribution, adoption, climate, biofuels, forestry), financing, and distribution.

Since its launch , the Alliance has identified up to $120 million in partner commitments, including about $20 million for operations, over $50 million for research, and up to $50 million in financing; brought on more than 275 partners, including 28 country partners; catalyzed the process to develop international consensus standards for clean cookstoves; funded a Kenya study to assess various cookstoves to determine the benefits for children's health; supported regional Alliances in Asia, Latin

America, and Africa to spur local businesses and solutions; built up technical capacity of regional stove testing centers in China, Ethiopia, and other countries; executed comprehensive market analyses of the clean cookstove sector in five countries; supported the development of indoor air guidelines by the World Health Organization; ensured inclusion of household air pollution as a risk factor for non-communicable diseases in the Political Declaration for the UN General Assembly; sponsored the Fifth Biennial PCIA Forum and two international technical research workshops; begun integration of the Alliance with the Partnership for Clean Indoor Air; and worked with UN agencies to improve collaboration among UN cookstoves and fuel programs. The Alliance recently released a first-ever sector-wide strategy report (called *Igniting Change*; U.N. Foundation, 2011) that lays out a strategy for universal adoption of clean cookstoves and fuels, and its 10-year business plan is forthcoming in 2012.

Solutions on this scale are needed to resolve the tremendous human health and environmental burden—including the climate impacts—of traditional cookstove use. As the above discussions indicate, large scale success in this field may be within reach. Substantial reductions in BC on the order of 90% to 95% per household likely depend on switching to cleaner fuels or advanced biomass stoves. Such highly efficient, clean stoves help meet multiple goals, including fuel efficiency, health protection, low climate impacts, and reduction of outdoor pollution (Venkataraman et al., 2010).

Currently, simple unimproved stoves dominate the marketplace. Most current improved stove sales are of the intermediate variety – rocket stoves or other solutions that achieve important health[11] and fuel use benefits, but will not achieve the large health and BC benefits sought. As the Alliance advances towards its interim goal of reaching 100 million homes, solutions will need to evolve towards cleaner fuels and more advanced stoves to ensure that substantial public health and BC benefits are achieved. Additional research and innovations are needed to bring these very clean solutions to massive populations and to move as rapidly as possible to achieve the health and climate benefits that advanced stoves can bring to families and the environment.

[11] As head of the Department of Environmental Health Engineering at Sri Ramachandra University in Chennai, India, Kalpana Balakrishnan has said, "[These] existing improved stoves have to go some way before they can meet a health-based standard, but they are much, much better than the traditional stoves we have now" (Adler, 2010).