TECHNICAL ASSESSMENT FOR CLEAN AND IMPROVED COOKSTOVES

SECTOR: BUILDINGS
AGENCY LEVEL: HOUSEHOLD
KEYWORDS: CLEAN COOKSTOVES, IMPROVED COOKSTOVES, TRADITIONAL STOVES, SOLID FUEL, BIOMASS STOVES, RENEWABLE COOKING

BOOK EDITION 1

DRAWDOWN

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ACRONYMS AND SYMBOLS USED

- **BAU –** Business as Usual
- **BC** – Black Carbon
- **CH_4** - Methane
- **CO** – Carbon Monoxide
- **CO_2** – Carbon Dioxide
- **COPD** – Chronic Obstructive Pulmonary Disease
- **GACC** – Global Alliance for Clean Cookstoves
- **GT** – Gigaton (1 billion metric tons)
- **GWP** – Global Warming Potential
- **HAP** – Household Air Pollution
- **ICS** – Improved Cook Stoves
- **IEA** – International Energy Agency
- **ISO** – International Standard Organization
- **LPG** – Liquefied Petroleum Gas
- **MT** – Megaton (1 million metric tons)
- **N_2O** – Nitrous Oxide
- **OC** – Organic Carbon
- **PDS** – Project Drawdown Scenario
- **PM2**.5 – Particulate Matter of size no larger than 2.5 micrometers (micron)
- **REF** – Reference Scenario (of Project Drawdown)
- **TAM** – Total Addressable Market
- **TCS** – Traditional Cookstoves
- **TWh** – Tera Watt-hour
- **TWh (th)** – Tera Watt-hour of Thermal Energy
- **WHO** – World Health Organization

EXECUTIVE SUMMARY

Currently about a third of the world's population depends on solid fuels including fuelwood and crop residue, for cooking and this is projected to increase by 8% by the year 2030. The traditional cooking practices impact not only the global GHG emissions but also health of rural population of the developing world due to household air pollution (HAP).

Improved clean cookstove offers great opportunity for replacing traditional cookstoves around the world and can reduce GHG emissions and mortality and illness due to HAP. The type of cookstoves is determined by the ISO tiers based on thermal efficiency and emissions, where Tier 0 represents traditional stoves, Tiers 1-2 improved efficiency stoves, and Tiers 2-4 advanced improved cookstoves and clean fuels (solar, biogas) based stoves. This solution models all cookstoves that replace traditional stoves (Tier 0). It does not model biogas adoption. Biogas adoption is modeled as a separate Drawdown solution.

The Reduction and Replacement Solutions (RRS) model was used to evaluate the impacts of replacing traditional cookstoves with clean and improved cookstoves during the period from 2014 to 2060 with primary results being reported here for the period 2020-2050. The current adoption of clean cookstoves was found to be about 57% of the total addressable market in developing countries, but with Africa still having only 16% adoption. Drawdown's most aggressive scenarios are modeled to assume 100% adoption by 2030 representing achievement of the UN Sustainable Development Goal #7: Universal Access to Clean Energy by 2030.

Using these assumptions, climate and financial inputs it was found that the total CO_2-eq reductions that can be achieved during 2020-2050 are 83 Gt CO_2 eq. at an average rate of 2.7 Gt CO_2 per year. It is estimated that 32.3 Gt CO_2 eq was produced due to energy consumption around the world in 2012. The current estimates show that on average, this value can be reduced by clean cookstoves. But at the same time, it should be also noted that 17% of the world's black carbon, the second most impactful climate warmer, comes from biomass-based cooking and reducing this value to almost zero by replacing solid fuel burning stoves with ICS (including LPG), which can reduce black carbon by almost 99% is a huge step towards Drawdown. As Black Carbon is a short-term climate warmer, this reduction would have a more rapid impact on the climate that carbon dioxide reductions, and is therefore a great short-term climate strategy that also helps billions of the world's poorest people.

The financial results of the RRS model show the cumulative first cost of implementing 6.5 billion stoves by the year 2050 to be $494 billion. This translates to about $76 per stove disseminated.

1 LITERATURE REVIEW

Globally, the buildings sector is one of the largest end-use sectors, accounting for 30% of global final energy usage. Including building construction increases this to 36%. These two together account for 39% of energy-related CO_2 emissions (UN Environment & IEA, 2017). Thus, the global building sector needs innovative technologies and approaches to reduce energy consumption while ensuring building operations are not affected. Breaking down the building sector by energy end-use gives us an idea of where the potentials lie. Space heating consumed 32% of final building energy in 2014. The other top uses are cooking energy (22%), water heating (19%), appliances and equipment (16%), and lighting (6%) (IEA, 2017a). Clearly there are many opportunities across the building sector for energy efficiency. Space and water heating energy is affected by windows, walls and heat source, cooking energy is affected by source and cooking technology, appliance energy by appliance efficiency and use, and lighting is affected by light technology and use.

1.1 STATE OF CLEAN COOKSTOVES

Currently about a third of the world's population (2.7 billion people) rely on solid fuels including wood, charcoal, crop residue, and animal dung for cooking (Global Alliance for Clean Cookstoves, 2018; IWA 11:2012, 2012; Simon, Bailis, Baumgartner, Hyman, & Laurent, 2014). Of this population, about 1.9 billion are based in Asia, 657 million in Africa, and 85 million in Latin America (DIFFER, 2012). According to IEA projections (IEA, 2006), the number of people dependent on traditional biomass for cooking is set to increase by 8% by 2030 globally as compared to the baseline of 2004. Worldwide, the biomass use is set to increase in Southeast Asia (10%) and sub-Saharan Africa (25%) but also decrease by nearly 18% in China.

Traditional use of solid biomass for cooking accounts for the largest share of household energy consumption in Africa (International Energy Agency, 2014). About 81% of the sub-Saharan Africa's population depends on traditional use of biomass for their cooking needs (Casteleyn, 2017). The use of traditional cookstoves (TCS) used in rural areas such as Indian Chulha or three-stone fire stove (Figure 1.1) that provide extremely poor combustion of the firewood is a bigger issue than the use of solid fuels themselves.

Figure 1.1 Traditional 3-stone cookstove in Guatemala (Servinghandskc, 2011)

Traditional stoves can be improved in any of three ways: by (i) increasing thermal efficiency, (ii) reducing specific emissions and (iii) increasing ventilation (Grieshop, Marshall, & Kandlikar, 2011). One or more of these three pathways produce an improved cookstove (ICS) design. Increasing thermal efficiency can lead to reduction in fuel consumption and reduction in specific emissions per stove. Reduction in emission can also be caused by improved ventilation and cleaner combustion. The average fuel and cooking time saved increases as people gain more cooking experience with the cookstove (Toman & Bluffstone, 2016)

1.1.1   Implementation

Although the need for clean cookstoves and the benefits of their adoption are well identified, there is a basic lack of demand for them in low-income populations, living on $2 per day (Deloitte Consulting LLP, 2013), which has been the reason for the low adoption of this solution. Programs such as the cooking gas program (Pradhan Mantri Ujjwala Yojana) implemented in India, has increased the proportion of distribution of clean cookstoves of the higher tiers (Global Alliance for Clean Cookstoves, 2017).

1.1.2   Cooking fuels

Cooking fuels can be categorized as "traditional" (animal waste, agricultural residues and fuelwood), "intermediate" (wood pellets, charcoal, briquettes, coal and kerosene) or "modern" (solar, LPG, biogas, natural gas, electricity) (Malla & Timilsina, 2014). The cooking fuels can be further classified as primary or secondary based on the source or under renewable or non-renewable category. The current cooking fuel mix in three regions (China, India and sub-Saharan Africa) of the developing world used in this study is shown in Table 1.1. A weighted average was calculated based on the population of these three regions. It can be seen from Table 1.1 that solid fuel (firewood, crop residue, dung cake and coal/charcoal) dominate the cooking fuel mix in all three regions. The higher LPG mix in India mainly comes from the urban region where about 58.7% of the population uses LPG for cooking (Venkataraman, Sagar, Habib, Lam, & Smith, 2010).

Table 1.1 Current cooking fuel mix for developing regions (2005)

Fuel	China (Mainali, Pachauri, & Nagai, 2012)	India (Venkataraman et al., 2010)	Sub-Saharan Africa (International Energy Agency, 2014)
LPG	11%	24.7%	5.4%
Electricity	0.0%	0.4%	2.1%
Firewood (incl. crop residue)	38.2%	69%	67.1%
Biogas	0.4%	0.5%	0.0%
Coal	47.5%	1.9%	17.6%
Kerosene	0.0%	3.2%	7.7%
Charcoal		0.5%	

1.1.3 Classification of Cookstoves

Traditional and improved/clean cookstoves differentiated on the basis of better fuel efficiency and/or lower emissions as compared to the traditional stoves. Most of the literature on cookstoves uses the term "improved" to describe a wide range of replacements for traditional cooking methods. The overall cookstove technologies can be roughly categorized in 6 different types (Table 1.2) mainly based on guidelines for evaluating cookstove performance (IWA 11:2012, 2012). As the standards develop, improved and clean cookstoves are better defined. Conversion efficiency is also an important factor while considering the difference between traditional and improved cookstoves.

Table 1.2: Classification of Cookstove Technologies(Simon et al., 2014)

Type of stove		Description	Technology Examples	Preliminary ISO rating
Traditional cook stoves (TCS)		TCS are a very baseline technology. They mainly use solid fuels (fuel wood, coal and crop residue)	Three stone fires, basic traditional chulhas, Unvented coal stoves	ISO tier 0
Efficient Cookstoves	Basic Improved Cookstoves (ICS)	Mainly solid fuel based but with slightly higher fuel efficiency providing less than 25% lower fuel use than traditional stoves	Basic improved chimney chulhas, Basic biomass portable stoves, Basic vented coal stoves	ISO tier 0 - 1
	Intermediate ICS	Improved fuel efficiency and better fuel combustion leading to up to 50% fuel savings.	Rocket stoves, Highly improved charcoal stoves, Highly efficient coal stoves	ISO tier 1 -2

Type of stove		Description	Technology Examples	Preliminary ISO rating
Clean Cookstoves	Advanced ICS	Using gasification technology that reduces emissions through improved combustion	Natural draft gasifier, Fan gasifiers	ISO tier 2 -4
	Modern fuel solutions	Stoves using modern fuels such as LPG and natural gas	LPG stoves, Electric stoves Natural gas stoves	ISO tier 3 -4
	Renewable Energy solutions	Stoves that rely on renewable fuels such as solar energy or biogas.	Biogas stoves, Biofuels / ethanol stoves, Solar / retained heat cookers	ISO tier 3 -4

In rural areas where there is low or no availability of alternative fuels, replacing the TCS with improved cookstoves (ICS) is an achievable solution (International Energy Agency, 2014). ICS help to reduce the amount of smoke released due to combustion of biomass and also provide an improved combustion of the fuel used. Fuelwood or charcoal are the typical fuels used for combustion in the ICS (International Energy Agency, 2014). ICS are available in varied efficiencies and are classified as basic to advanced based on the fuel efficiency they can provide (Table 1.2).

Efficient Cookstoves (Biomass based)

More than 50 types of efficient biomass cookstoves exist (DIFFER, 2012), and they vary in design, structural materials, and assembly methods and locations. Cookstoves are made using many different materials, including concrete (Toman & Bluffstone, 2016), metal, plastic, ceramic, clay, bricks and dung (DIFFER, 2012). Improved biomass cookstoves can be classified as manufactured rocket stoves and improved cookstoves. The manufactured cookstoves have a standardized design and could be relatively expensive to bottom-of-the-pyramid customers (DIFFER, 2012). The most appropriate improved cookstoves are made or assembled locally using imported or local parts. Ideally, assembly is onsite reducing transportation needs, production costs, and retail costs (DIFFER, 2012). Typical designs range from portable ceramic bowls to large installations with chimneys. The expected lifetime of these improved cookstoves ranges from 1 year (for simplest versions)-10 years (permanent type). The price varies from $1-$90 depending on the design (DIFFER, 2012). Since locally manufactured improved cookstoves are cheaper, they are increasingly popular. Cookstove designs are evolving based on consumer needs, example, two pot cookstoves allow cooking several dishes at the same time.

1.1.4   Cookstoves and Climate Impact

Climate impact is an important reason for consideration of improved and clean cookstoves as a Drawdown solution. It is now widely recognized that household biomass combustion is a significant contributor to the greenhouse gas increase. While only 3% of building sector CO_2 emissions in the OECD come from cooking, this figure for the Non-OECD countries, where traditional cooking is more widespread, is 33% (IEA, 2017a). Inefficient combustion of solid fuels such as wood, charcoal, animal dung, crop residue, and coal, result in release of GHGs including CO_2 and short-lived climate pollutants such as black carbon. Given the short life time

of about 8-10 days (Putti, Tsan, Mehta, & Kammila, 2015) of black carbon, a reduction in the black carbon emissions delivers a comparatively rapid climate response when compared to reduction of CO_2 emissions (Global Alliance for Clean Cookstoves, 2018). It is estimated that combustion of wood fuel currently accounts for 1-1.2 Gt CO_2e/year which is equivalent to 1.9-2.3% (Bailis, Drigo, Ghilardi, & Masera, 2015) of global emissions, roughly equivalent of the entire aviation sector (Global Alliance for Clean Cookstoves, 2018).

In addition to CO_2, in recent years black carbon (BC) has emerged as an important factor in the climate change science. Black carbon (BC) is also commonly known as soot and on the global warming scale is thought to be the second or third largest individual warming agent following CO_2 and methane (Bond & Sun, 2005). In the context of India, it is estimated that improvements in 110 million wood fuel stoves would reduce the country's black carbon emissions by about $1/3^{rd}$ annually.

It should be noted that the science behind GWP impacts of open biomass combustion is still evolving (Palit & Bhattacharyya, 2014; Rajvanshi, Patil, & Mendonca, 2007). There is wide consensus on the impact of BC but the magnitude of the impact is under study (MacCarty, Ogle, Still, Bond, & Roden, 2008; Rajvanshi et al., 2007) mainly because of the impacts of other components emitted with BC during open combustion such as organic carbon (OC). OC consists of scattering particles and aerosols that are considered to have a global cooling effect. These aerosols alone or sometimes by acting as nuclei to form cloud droplets reflect sunlight to produce the said cooling. Some studies estimate the GWP of OC to be in the range of -50 to -75 CO_2 eq., which would offset the benefits produced by positive GWP of BC by about 20% (Putti et al., 2015).

Figure 1.2 illustrates the sources of BC in the world based on data from year 2000 (Bond & Sun, 2005). It can be seen that out of total 7620 Gg BC/yr (5.43 Gt CO2e/yr) emissions globally, in all categories, biofuel cooking (17%) produces the second highest amount of BC right after open burning of grasses and woodlands (20%). On a 100-year timescale, black carbon has a global warming potential as high as 900 times that of CO_2 (Myhre et al, 2013). From a geographic perspective, the highest emitters of black carbon are in Africa (22%) followed closely by East Asia (20%). The high value of East Asia can be explained by the amount of industrial coal still in use in China. For only biofuel cooking, the three regions with highest BC emissions are South Asia which includes the Indian subcontinent, Africa and East Asia which together account for almost 75% of global BC emissions from biomass-based cooking.

There is conflicting science about the global warming potential of BC emissions from traditional cookstoves due to the organic carbon (OC) emissions that occur at the same time as black carbon emissions.
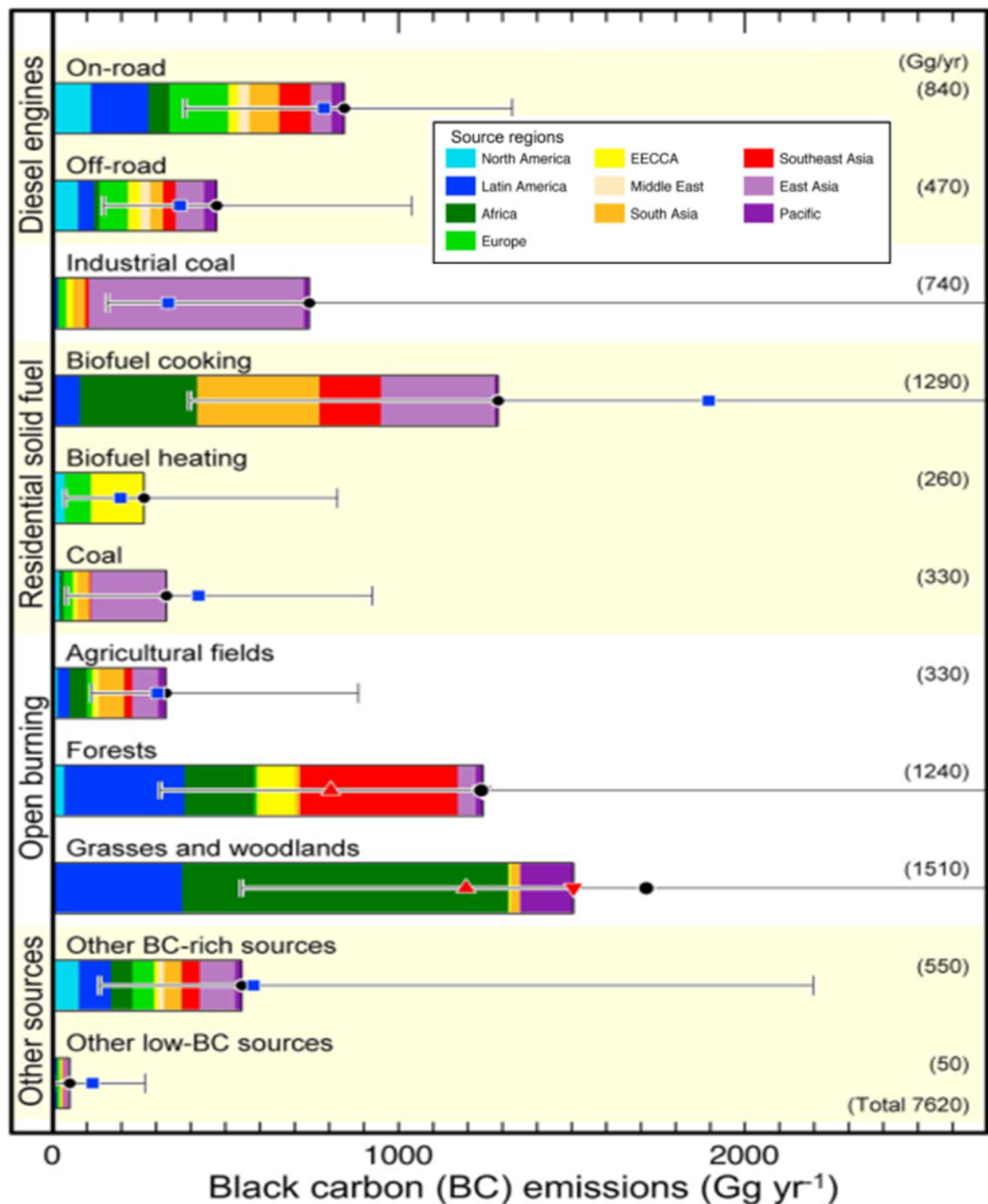
Figure 1.2: Emission rate of BC in the year 2000 by source category(MacCarty et al., 2008)

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1.1.5   Cookstoves and Health Impacts

Incomplete combustion of solid cooking fuels such as fire wood, crop residue and dung cakes in developing countries produces household air pollution (HAP). According to WHO (2014), HAP is the single most important environmental health risk factor worldwide (WHO, 2014). About 12% of the ambient air pollution globally comes from household air pollution (Clean Cooking Alliance, 2019). According to the WHO, HAP from cooking is responsible for 4.3 million premature deaths each year (7.7% of global mortality). The map in Figure 1.3 shows the distribution of mortality rates worldwide attributed to polluting cooking.
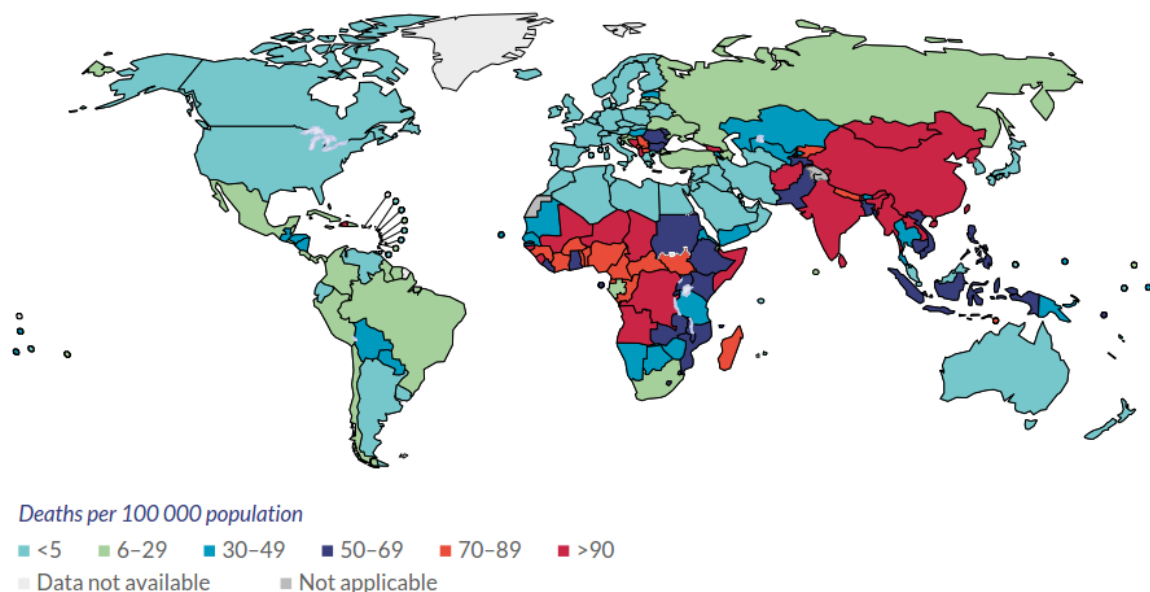
Figure 1.3: Map of deaths per 1,000,000 populations, per year, attributed to HAP from polluting cooking energy use in 2012(WHO, 2016) (WHO, 2016)

Three meta-analyses (Kurmi, Semple, Simkhada, Smith, & Ayres, 2010; Po, FitzGerald, & Carlsten, 2011; Sharma & Jain, 2019) show extensive risks of Chronic Obstructive Pulmonary Disease (COPD), along with other impacts from exposure to HAP such as child cognitive function, low birth weight, cervical cancer, adverse pregnancy outcomes, asthma, and tuberculosis. Burning of solid biofuels releases pollutants including particulate matter, carbon monoxide and certain hydrocarbons including polycyclic aromatic hydrocarbons and volatile organic compounds which adversely affect human health (Sharma & Jain, 2019). Health impacts include respiratory infections, ischemic heart disease, stroke, lung cancer, and cataract formation (Wolf, Mäusezahl, Verastegui, & Hartinger, 2017).

1.2   ADOPTION PATH

1.2.1   Current Adoption

IEA reports that in 2030, based on their analysis, 2.3 billion people will still lack access to clean cooking facilities(International Energy Agency, 2017a). A lot of literature has been published in recent years about global adoption paths of improved clean cookstoves. Most of the work has

been focused in South Asia and sub-Saharan Africa since a vast majority of population relying on solid biomass for cooking resides in these regions (Palit & Bhattacharyya, 2014; Shen et al., 2015). The current penetration of clean and improved cooking stoves in some of these areas is particularly low. In 2017, although over 54% of the households in the developing world had access to clean cooking, only 16% in Africa had access. Asia (56%) and Latin America (88%) were fairing much better (IEA, 2017b). Based on data from the IEA (2017b), the GACC and other sources like the IEA (2011), REN21 (2015), and World Bank (2010), the 2017 adoption is found to be 57.9% of current TAM (or 2,558 TWh th).

The share of people relying on solid biofuels has decreased in China from 55% in 2000 to 33% in 2015. In 2015, 250,000 homes in China gained access to clean cooking. In India, the share of population relying on biomass for cooking reduced to 59% in 2015 compared to 66% in 2011, mostly owing to the government's LPG program in India. IEA estimates that in rural areas, 370 million people will gain access to clean cooking by 2030. In India, by 2030, more than 300 million people are estimated to gain access by 2030 (International Energy Agency, 2017a). According to GACC's 2017 progress report, 20 million houses in India, were connected to clean cooking gas. This was a result of the Pradham Matri Ujjwala Yojana (PMUJ) program, launched in 2016 to increase access to clean cooking fuels and protect the health and safety of women and children, the households targeted are below the poverty line (Global Alliance for Clean Cookstoves, 2017).

The adoption of clean cookstoves is increasing each year. Based on the 2016 report by GACC, in 2015, 13 million clean and/or efficient cookstoves were distributed. Cumulatively, 53 million clean and/or efficient cookstoves have been distributed since 2010. An analysis of adoption from 2013 -2015 by GACC, showed that the overall market is shifting towards higher tiered stoves and fuels as a result of increase in distribution of clean fuels.

Both clean and efficient stoves were distributed, mostly adopted in rural areas to people below the poverty line, according to GACC. The fuel types used vary from country to country (Table 1.3). Based on ISO categories of clean cookstoves, biogas, solar, natural gas and electricity stoves from Table 1.3 would fall under clean cookstoves, the rest would be improved cookstoves. At least in the GACC focus countries, this adoption is very low.

Lack of data on clean cookstoves is mentioned in the household air pollution database maintained by WHO and Clean cooking access database by IEA (International Energy Agency, 2017a; World Health Organization, 2018a). Both sources include adoption of cleaner fuels and cooking technologies and were used to estimate the current adoption due to lack of better data on adoption of only clean and improved cookstoves. The adoption from the IEA and WHO databases were estimated to be 418 TWh and 256 TWh respectively (for 2015 based on household estimates), after removing biogas adoption estimated on the biogas adoption model.

Table 1.3 Adoption of clean and/ or efficient cookstoves in GACC focus countries in 2013

Focus country	Stoves distributed	Stove fuel types

(in 1000's)	Dung	Multiple Fuel	Biomass (non-specific)	Briquettes/ pellets	Coal	Biogas	Solar	Other	Methane /Natural gas	Electricity	Wood	Charcoal	Crop residue
Bangladesh 695	95%	3%	2%										
China 6,300		2%	20%	50%	15%	3.75%	3%	3%	2%	2%	1 %		
Ghana 414		40%										60%	
Guatemala 8.2													
India 159								5%			4%		5%
Kenya 1,000		20%									77%	3%	

Source - (GACC, 2014)

The clean cookstoves industry is becoming increasingly commercial, and may replace the traditionally used method of distributing clean cookstoves for free or with heavy subsidization (DIFFER, 2012). To ensure adoption of cookstoves, reduced fuel consumption to save fuel collection time, reduced cooking time compared to traditional cookstove, and practical design aspects such as size- stoves too large or too small to cook traditional meals, resemblance to traditional cookstove, usability, functionality, are key factors. Emissions and particulate matter reductions although appreciated are not the key attributes contributing to adoption.

1.2.2   Trends to Accelerate Adoption

Global and Regional Programs

There is a long history of efforts to replace the traditional cooking stoves and fuels with modern technologies both globally and regionally. The most notable global effort is the Global Alliance of Clean Cookstoves(GACC, 2014; now called the Clean Cooking Alliance) which has been initiated under public and private partnership with the goal to promote adoption of 100 million clean cookstoves by 2020. In addition to this global effort, many regional clean cooking initiatives launched by the World Bank such as Africa Clean Cooking Energy Solutions (ACCES) and the Pacific region's Clean Stove Initiative (CSI) were implemented (Malla & Timilsina, 2014). The National Biomass Cookstoves Initiative (NCI) was launched by the Government of India in late 2009 with the aim of expanding clean energy to all of India's households via next generation cookstoves. The goal was to achieve an energy service quality comparable to that from other clean energy sources such as LPG (Venkataraman et al., 2010). As a follow up to NCI, the Indian Ministry of New and Renewable Energy (MNRE) launched their Unnat Chulha program in 2014 (Ministry of New and Renewable Energy, 2019) with the goal of disseminating 2.75 million improved cookstoves by the year 2017.

Fiscal Incentives and Disincentives

Encouraging the use of regionally available natural resources using subsidies has been used to make the adoption of fuels affordable compared to scenarios where fuel is imported and thus subjected to taxes making it comparatively expensive to adopt (Ostojic et al., 2011). On the other hand, until early 1990's China, limiting import of LPG to use locally available coal, hindered adoption of a cleaner fuel making LPG more expensive, although available. Nature of import

policies is an important factor in avoiding solid biomass as cooking fuel (Ostojic et al., 2011). To increase adoption of LPG, uniform pricing was used for different areas of Bangkok. Overtime however, the share of LPG used for cooking decreased due to use of LPG in other sectors such as petrochemicals and automobiles (Ostojic et al., 2011).

Fixing Implementation Issues

While better efficiency were provided by the improved coal stoves in China, issues such as pollution still existed in the 1990's. ICS helped reduce indoor air pollution but their relatively low efficiencies resulted in community level air pollution via use of chimneys to remove smoke from homes (Ostojic et al., 2011). China developed a program later for more efficient and cleaner burning biogas stoves as well, however, dissemination of the technology has been much slower compared to improved coal stoves due to restricted government programs and existing reliance on older cooking technologies still being disseminated by the private sector (Ostojic et al., 2011).

Supply Chain Improvement

Setting up a viable supply chain for the manufacturing and delivery of stoves, while ensuring product quality and service has been beneficial in promoting improved cookstoves on a wide scale in Cambodia, via an NGO (Ostojic et al., 2011). Technology and business innovation, such as the smart meter based pay-as-you-go solutions, are making fuels such as biogas, ethanol and LPG more affordable but only in urban and peri-urban markets (Global Alliance for Clean Cookstoves, 2017).

Community Involvement

Involvement of local communities, especially women in rural areas may be necessary for achieving higher adoption via better reflecting local needs and expectations. Just provision of funds is not sufficient in adoption of this solution. Attention to social and cultural factors and involvement of women is equally important for programs to succeed (International Energy Agency, 2017a) .

1.2.3   Barriers to Adoption

Even though attractive due to health and environmental perspectives, clean and improved need to overcome many barriers to achieve faster adoption rates, especially in rural areas.

Economic Barriers

There is enough evidence suggesting that one of the major barriers to rapid uptake is the stove price (Kshirsagar & Kalamkar, 2014). Clean and improved stoves, which can typically cost $2.5-$109 compared to traditional stoves costing $0-$35[1]. So even though over its lifetime an improved stove can save money, the first cost may prevent the rural poor in developing countries from purchasing ICS.

A variety of financial approaches are recommended for improving the uptake of clean and improved cookstoves by providing financial assistance either through subsidies, financial

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[1] Based on data gathered by the author which is presented in the model along with all the references used

incentives or microfinance loans. Microfinance may help to overcome costs for stove purchase. Furthermore existing microfinance institutions have marketing channels that may be used for cookstove distribution (Rao, Miller, Wang, & Byrne, 2009). Subsidies are not always guaranteed to produce a successful cookstove program; e.g., the success of the National Improved Stove Program in China was mostly due to the higher rural income and purchasing capacity and not the federal funding which was only 15% (Smith, Shuhua, Kun, & Daxiong, 1993). In Sub-Saharan Africa however, despite an increase in incomes, the number of people using traditional cookstoves increased (International Energy Agency, 2014). The Indian Ministry of New and Renewable Energy (MNRE) proposes a gradually decreasing subsidy program that will make the stoves more affordable while still providing enough opportunity for commercialization in long term. This was successful implemented in Ethiopia in 1995 (GACC, 2014).

Under-Emphasis on User Research

Many rural areas are used to the practice of stove stacking, i.e., clean or improved cookstoves may not be the only stove type owned by the households and thus use of traditional practices continue, despite increased adoption (Wolf et al., 2017). In the Hubei Province of China, 99% of households used two types of fuels and only 10% abandoned traditional biomass cookstoves when they could afford to do so. In Philippines, despite growth in GDP, the reliance on biomass cookstoves increased, owing to perceptions about security and reliability of alternative fuels, and cultural and social factors of maintaining traditions (International Energy Agency, 2017a).

Most of the current clean and improved cookstove programs are technology centric but not focused on user research. Many times, stoves are not adopted locally because they do not fit the regional cooking needs. For example, in Bhutan, smokeless ICS that were introduced in 1985, did not provide enough heating and lighting effect that is essential for the cold climate and was provided by the traditional stoves. Similarly, the uptake of ICS was not successful in Kenya because the traditional food (Ugali) required continuous stirring which was not provided by the unstable metal stoves (Hu et al., 2010). Thus, additional testing in actual user conditions is essential before disseminating ICS on large scales and would increase successful adoption.

In many regions, adoption of clean and improved cookstoves requires a major lifestyle change e.g. instead of spending the major part of day gathering fuel wood for cooking, women can participate in income-generating activities. But it can difficult to adjust to these changes. Many families feel that the food might also taste different, e.g. studies show that people in Mexico continue to use fuelwood for cooking since LPG cooking of local food (tortillas) takes more time and negatively changes the taste (Malla & Timilsina, 2014). Community interactions also impact the decision to purchase a clean or efficient stove, a modern stove purchased by relative or a neighbor can influence many families to also adopt them as found by studies done in Kenya (Person et al., 2012).

Institutional Barriers

Currently there are not enough institutions that support and fund production and distribution of cookstoves. Global Alliance for Clean Cookstoves is the leading organization that is a public-private partnership hosted by the UN Foundation. But it is also important to have participation and buy in of local governments for a successful ICS program.

In some regions (especially those with proximity to forests), traditional wood fuel is abundantly available for the households free of cost and collection time is also not substantial. In these cases, the benefits of an improved or clean cookstove are less visible, and end-users may be unwilling to adopt or use them. Other fuels like LPG and biogas are considerably more expensive. Both have a high start-up cost. For LPG, the ongoing fuel cost and availability is also substantial. Biogas plants require a substantial amount of infrastructure setup and need constant attention to maintain necessary conditions for production. Also, proximity to manure to feed the digester is critical which limits the access of biogas fuel in urban areas (Puzzolo, Stanistreet, Pope, Bruce, & Rehfuess, 2013). More renewable fuels such as alcohol are relatively less expensive than LPG and can be produced from a wide range of agricultural biomass and residue. Quite a rigid excise regime is applied to the production of ethanol mostly to prevent drinking (Rajvanshi et al., 2007).

Other Barriers

Biomass burnt in traditional open fires is used not only for cooking, but lighting and heat (space and water), smoking of crops and meat, waste management and keeping away insects and animals (Ilse & Omar, 2015). Hence reduction support heating and lighting solutions are also important for avoiding use of traditional biomass for cooking.

1.2.4   Adoption Potential

One of the factors influencing adoption of cleaner fuels is urbanization. Two scenarios were developed by Ostojic et al: a Business as Usual (BAU) and a Universal Access scenario to predict the use of fossil fuels (Ostojic et al., 2011). The BAU does not assume any growth in adoption of clean fuels. However, due to increase in urbanization, the absolute number of people using modern fuels increases (meaning rural TAM decreases as urbanization increases). The Universal Access scenario assumes a full adoption of clean cooking fuels by 2030 but only in urban areas, rural areas are assumed to have reached a partial adoption only due to lower income and lack of availability or access to modern fuels.

In Africa, in 2012, about 80% of the population did not have access to clean cooking facilities(IEA, 2014). With the adoption of alternative fuels and improved biomass cookstoves, an estimated 10% decline in people using TCS can be achieved(International Energy Agency, 2014). This means that 650 million people still would not have access to clean cooking in 2040. Of the 1.1 billion people that will gain access to clean cooking, two-thirds would be living in urban areas.

About 2.7 billion people lack access to clean cooking facilities (International Energy Agency, 2017c), suggesting a large potential for adoption of clean cookstoves (Deloitte Consulting LLP, 2013). In the absence of major policy or technology changes the number of people depending on TCS is projected to be large till 2030 (Toman & Bluffstone, 2016).

1.3   Advantages and disadvantages of Clean Cookstoves

Clean and improved cookstoves have strong health advantages including improved reparatory health and reduced eye problems especially in women and children. Reported disadvantages of improved cookstoves include, small cooking capacities, increased cooking time and not enough heat generation (FINCA International Research Team, 2018).

1.3.1   Similar Solutions

Improved and clean cookstoves are a very broad set of technologies. Biogas has been defined as a solution by itself, although it's classified as a clean cookstove technology, and has been referred to in this report as well. Besides improved and clean cookstoves, there are few ways of reducing cooking energy and emissions in the developing world. The various types of stoves included in this report are compared in Table 1.4 and Table 1.5.

1.3.2   Arguments for Adoption

Improved health

Adoption of clean fuels improves the health of pregnant women and their babies, resulting in healthy babies at birth. Replacement of biomass and kerosene cookstoves, with clean-burning ethanol cookstoves have been shown to reduce cardio-vascular risk and hypertension in pregnant women, supporting the removal of kerosene as a home energy source (Global Alliance for Clean Cookstoves, 2017). Female cooks, compared to male cooks, face higher impacts of particulate emissions, up to 4 times more in Kenya and double in South Asia (Putti et al., 2015). In both cases, the impact significantly exceeds minimum levels.

Lower Environmental Impacts

Traditional biomass has very low conversion efficiency (10%-20%) (International Energy Agency, 2017b), and burning it causes indoor air pollution. Deployment of clean cookstoves can reduce the indoor air pollution of a kitchen area by 21-62% for PM10, 20-80% in case of PM2.5, 24-87% in case of PM1 and CO by 19-93% (Sharma & Jain, 2019). TCS use leads to release of significant short-lived climate pollutants that have a comparatively higher local impact compared to GHG's(Clean Cooking Alliance, Gold Standard, Global Alliance for Clean Cookstoves, & Clilmate and Clean Air Coalition (CCAC), 2017). Environmental benefits of using clean cookstoves include reduction in black carbon emissions which is emitted from incomplete combustion of biomass-based fuels.

Time Savings

While health benefits from basic ICS are limited(Putti et al., 2015), there are many other advantages of clean and improved cookstoves including time and fuel savings. Time savings are a bit varied in literature. As per IEA, households relying on biomass spend about 1.4 hours a day collecting firewood (International Energy Agency, 2017a). According to WHO, many countries in sub-Saharan Africa spend up to 4 hours a day collecting fuel wood for cooking (World Bank, 2010), and about 4 hours per day cooking using traditional cookstoves(International Energy Agency, 2017a). According to Putti et al., the collection time is 5 hours a day. Families typically

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have to spend time in collecting, buying or trading their food for fuel, given the scarcity of readily available biomass(Clean Cooking Alliance et al., 2017; DIFFER, 2012).Women are the main wood collectors in Sub-Saharan Africa and large parts of Asia such as China (Putti et al., 2015). Rural women transport an average of roughly 20 kgs and travel between 1-10 kms during wood collection trips, leading to injuries from firewood collection (Putti et al., 2015). Women being collectors are also at risk of gender-based violence. In some other countries, men are the primary collectors or collection is a joint family effort. The Energy Sector Management Assistance Program estimates that 140 million potentially productive person-years annually wasted on biomass fuel collection and avoidable cooking (Putti et al., 2015).

Clean and efficient cookstoves can free up time not only for women but also for children who may be kept away from school to collect cooking fuel or earn money to buy fuel (Clean Cooking Alliance et al., 2017).

Economic Valuation of Benefits

A typical South Asian household can get monetary benefits of about $30 per year from switching to clean or improved cookstoves(World Bank, 2010). The mid-range economic value of the negative externalities of using solid fuels for cooking is estimated to be over $120 billion annually. As the estimate quantifies only a subset of known health, economic and environmental impacts, it is a conservative estimate.

1.3.3   Additional Benefits and Burdens

Benefits

In addition to health, time and environmental benefits, local production and distribution of clean cookstoves offers many job opportunities (Clean Cooking Alliance et al., 2017).

Burdens

Operating costs are one of the largest burdens of clean and improved cookstoves adoption considering traditional biomass costs labor time and not money (Ostojic et al., 2011). Fuels such as LPG are expensive and need a substantial infrastructure in place for distribution especially in rural areas. Clean and improved stoves that offer more efficient use of biomass reduce the operating cost by requiring less fuel to be gathered or purchased. There is a lack of financial aid availability to rural areas for adoption of petroleum fuels. Policymakers therefore prefer ways to more efficiently use the available biomass (Ostojic et al., 2011). While nations rely on programs to increase the adoption of cookstoves, by providing an initial connection and first gas cylinder, in case of LPG based cookstoves, for example, it is important to persuade people to invest in refills of fuel to achieve the intended benefits(Global Alliance for Clean Cookstoves, 2017).

Chopping of wood into smaller pieces to be able to use in the improved stoves, continuous monitoring to add more wood to the stove, need for very dry wood for the stove, are cited as burdens of clean cookstoves(FINCA International Research Team, 2018). In addition, low durability of certain stove types is also undesirable.

Dependence on solid fuels has positively impacted tens of millions of small-scale wood collectors, charcoal producers, transporters and last-mile retailers. About 7 million Africans are employed with the Sub-Saharan Africa's charcoal sector, expected to reach 12 million by 2030

(Putti et al., 2015). Country level estimates for firewood are expected to be in the comparable scale (15 million - ~9% of Sub-Saharan Africa households, exceeding employment levels in large economic sectors such as tourism, industrial manufacturing, coffee and tea). Formal and informal employment in charcoal and wood fuel markets also play and important role in Asian (Bangladesh, Bhutan, Nepal, Myanmar, Cambodia, Lao PDR, and Vietnam), Latin American (Brazil and Peru) and Central American countries (Honduras, Nicaragua and Guatemala). Although earnings from the wood fuel and charcoal sector are low, they are an important source of cash income and a significant contributor to alleviating poverty.

Table 1.4 Technology Comparison

	Stove type	Conversion Efficiency	Cooking time	First Cost	Fuel costs	Operational CO_2 emissions	CO reduction	PM reduction	Durability	Fuel savings
TCS	Traditional Biomass	Low	Med	Low	Low	High				
	Kerosene			Med	Med				Med	
Basic ICS	Legacy chimney improved stove	Low	Med					Low	Low	Low
Intermediate efficiency	Site built ICS			Low-High	Low-High	Med	Med		Low-Med	Med-High
	Rocket stoves (manufactured stoves)			low	Low		Med	Med	Low	Med
ACS (Biomass)				Low-High		High	High			
Clean cookstove	LPG	Med		High	Med	Med-High			High	High
	Solar cookers		High							
	Biogas			High						
	Electricity	High							Med	

*ACS- Advanced Cookstoves

Table 1.5 Technology comparison key

	Cookstove type	Conversion Efficiency	Cooking time	First Cost	Operational CO_2 emissions	CO reduction	PM reduction	Durability	Fuel reduction
T C S	Wood	14%-16%						3	

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	Cookstove type	Conversion Efficiency	Cooking time	First Cost	Operational CO_2 emissions	CO reduction	PM reduction	Durability	Fuel reduction
								yrs	
	Kerosene	40%-60%		$30-$40				7 yrs	
Basic ICS								Few months to 2-3 yrs	25-35%
Intermediate efficiency cookstoves	Site built ICS			$1-$100	54-60%	60%		1-10 yrs	45-70%
									45-65%
	Rocket stoves (manufactured stoves)		38 min	$30		46%	56%	2-5 yrs	38%
ACS (Biomass)	Natural draft stoves			$25-$50					
	Fan gasifiers			$32-$120					>50%
Clean cookstove	LPG	60.4%		$45-$60				20 yrs	
	Biogas		70 min						
	Electricity – Hot plate	71.3%						7 yrs	

*Sources – Cooking time (DIFFER, 2012), first costs (DIFFER, 2012), operational CO_2 emissions (DIFFER, 2012), PM reduction (DIFFER, 2012), Cooking efficiency (Energy Technology Systems Analysis Programme, 2012), Fuel collection time -(Putti et al., 2015).
** Cooking time is compared for boiling water only

2 METHODOLOGY

2.1 INTRODUCTION

Project Drawdown's models are developed in Microsoft Excel using standard templates that allow easier integration since integration is critical to the bottom-up approach used. The template used for this solution was the Reduction and Replacement Solutions (RRS) which accounts for reductions in energy consumption and emissions generation for a solution relative to a conventional technology. These technologies are assumed to compete in markets to supply the final functional demand which is exogenous to the model but may be shared across several solution models. The adoption and markets are therefore defined in terms of functional units, and for investment costing, adoptions are also converted to implementation units. The adoptions of both conventional and solution were projected for each of several scenarios from 2015 to 2060 (from a base year of 2014) and the comparison of these scenarios (for the 2020-2050 segment[2]) is what constituted the results.

The functional unit for this is TWh (th) of final cooking energy and the implementation unit is cookstove unit. This implementation unit was chosen since the costs, both first and operational are reported in most literature on a per stove basis. The agency level is household.

The Total Addressable Market (TAM) covers all demand for the function provided by the solution e.g. if the solution focuses on solar hot water heating, the TAM would be global demand for total hot water including conventional and emerging solutions. But for the Clean and Improved Cookstoves solution, the decision was made that TAM would be cooking energy only in regions that have a high usage of traditional cookstoves. Traditional cookstoves use only traditional fuels or solid fuels such as biomass. This assumption eliminates the developed regions of the world such as the USA and EU and only focuses on developing regions including Asia, Middle East and Africa and Latin America (see Table 1.1). It should be noted that some countries in Eastern Europe and Western Asia also have high use of solid biofuels.

2.2 DATA SOURCES

The data sources used for the model have been divided in two main sections: Total Addressable Market (TAM), and Adoption Projections and Variable Inputs.

2.2.1 Total addressable Market

The Total Addressable Market (TAM) covers all demand for the function provided by the solution. For clean and improved cookstoves solution, the decision was made that TAM would be cooking energy only in regions that have a high usage of traditional cookstoves. Traditional cookstoves use only traditional fuels or solid fuels such as biomass. This assumption eliminates

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[2] For most results, only the differences between scenarios, summed over 2020-2050 were presented, but for the net first cost, the position was taken that to achieve the adoptions in 2020, growth must first happen from 2015 to 2020, and that growth comes at a cost which should be accounted for, hence net first cost results represent the period 2015-2050.

the developed regions of the world such as the USA and EU and only focuses on developing regions including Asia, Middle East and Africa and Latin America (see Table 1.1). Global TAM was projected mainly using regional energy use data from peer reviewed literature (Daioglou, van Ruijven, & van Vuuren, 2012; Putti et al., 2015).

2.2.2   Climate

Data for black carbon emissions for traditional cookstoves was collected from 5 sources including Venkataraman et al (2010), Jetter (2012), Habib et al (2004), Preble (2010)(Jetter et al., 2012; Venkataraman et al., 2010) and weighted. Direct emissions data for black carbon from traditional cookstoves was available in literature. The data for clean cookstoves was calculated using a ratio for PM2.5(Smart Freight Centre, 2017). Data for CO from traditional stoves was also obtained from Venkataraman (2010) and Jeuland and Tan Soo (2016). CO data from improved stoves was obtained from Jeuland and Tan Soo (2016) and Differ et al (2012) (DIFFER, 2012).

Fuel consumption based data was obtained from 4 sources including reports from World Bank, WHO, IEA and 1 peer reviewed source Miah et al (2009) (IEA, 2014; Miah, Al Rashid, & Shin, 2009; The World Bank, 2011a; World Health Organization, 2010). Average fuel consumption data is listed in Table 2.1.

Fuel efficiency factor data was obtained from 9 sources including GACC, IIAS, IEA and 6 peer reviewed sources (Cashman, et al, 2016; DIFFER, 2012; Dresen et al, 2014; GACC, n.d.; IEA-ESTAP, 2012; M. Jeuland & Tan Soo, 2016; Johansson et al, 2012; Malla & Timilsina, 2014; The World Bank, 2011a; World Health Organization, 2010).

The GWP of black carbon data is very variable and was obtained from only a few peer-reviewed sources(Garland et al., 2017; Venkataraman et al., 2010)

The fuel consumed was obtained mainly from agency reports for traditional fuels and peer reviewed literature (IEA, 2014; Miah et al., 2009; The World Bank, 2011a).

Fuel efficiency factor based on different thermal efficiencies of improved and clean stoves for various fuels was obtained from various peer reviewed sources and agency reports (Cashman et al., 2016; DIFFER, 2012; Dresen et al., 2014; GEA, 2012; IEA-ESTAP, 2012; M. Jeuland & Tan Soo, 2016; Malla & Timilsina, 2014; World Health Organization, 2010)

2.2.3   Financial

Most of the financial variables (cost of traditional and improved stoves) have been obtained from various sources (Clean Cooking Alliance, n.d.; COMPETE, 2009; Energica, 2009; Energy Technology Systems Analysis Programme, 2012; Gallagher, Beard, Clifford, & Watson, 2016; IEA, 2014; IEA-ESTAP, 2012; M. Jeuland & Tan Soo, 2016; Ostojic et al., 2011; Putti et al., 2015; The World Bank, 2011a; Toman & Bluffstone, 2016; US EPA, 2015; USEPA, n.d.). Operating costs data for other types of traditional stoves using traditional coal, firewood, or kerosene based traditional stoves and improved stoves were obtained from 5 sources (Global Alliance For Clean Cook Stoves, 2015; Grieshop et al., 2011; M.A. Jeuland et al., 2014; Marc A. Jeuland & Pattanayak, 2012; SustainTech, 2012; World Bank, 2010).

2.3 TOTAL ADDRESSABLE MARKET (TAM)

Global data

Daioglou et al (2012) and Putti et al (2015)

Regional energy use in TWh from Asia, Latin America, Middle East and Africa, were calculated and summed to develop a global TAM projection using cooking energy use data from Daioglou et al., (Daioglou et al., 2012) and population dependency on solid biofuels data from Putti et al., (Putti et al., 2015). This projection takes into account useful energy for cooking per capita (0.83 kWh or 3 MJ per cap/ day) and weighted energy efficiency factor (22.7%) of fuel mix for 2005. The useful (delivered) energy for cooking divided by a weighted average energy efficiency factor (22.7%) for stove/fuel type mix to obtain a total average energy use (13.19 MJ/cap) for each region. To calculate the weighted average, the fuel efficiencies for the 2007 fuel mix were used from Daioglou et al., (Daioglou et al., 2012). The weights used were an average of the fuel mix for China (Mainali et al., 2012), India (Venkataraman et al., 2010) and Sub-Saharan Africa (IEA, 2014) for the year 2005.

To obtain the total cooking energy demand from solid fuels, for this projection the total average energy used for cooking (13.19 MJ/cap) was multiplied by the population dependent on solid fuels in each of the 3 regions. Population data from the Ampere model was used to make the projection for the annual average energy use from 2012-2060 for the three regions. Data for population dependent on solid fuels (urban +rural) for the year 2010 was obtained from ESMAP Technology paper (Putti et al., 2015) for the regions of Sub-Saharan Africa (82%), South Asia (71%), East Asia (49%), Southeast Asia (53%), Latin America and Caribbean (19%), Europe and Central Asia (17%). The population of India was used as a proxy to represent the population of South Asia and the population of China was used as proxy for East Asia. Based on these assumptions, the total population for South East Asia was calculated (i.e., the population of Asia (sans Japan) subtracted from the solid fuel dependent populations of South Asia and East Asia). The dependency % from Putti et al. was used to obtain the population dependent on solid fuels for South East Asia. The sum of the dependent population for the 3 regions was divided by the population of Asia (sans Japan) to obtain the dependency (77.1%) for all of Asia (sans Japan). It was assumed that Sub-Saharan Africa's dependency on fossil fuels will represent the drawdown region of Middle East and Africa. It should be noted that that most of the Middle East has access to clean cooking fuels (International Energy Agency, 2017a; REN21, 2015a). The 19% dependency for Latin America and Caribbean was used to represent the drawdown region of Latin America. This regional energy use data obtained was summed to represent the global TAM.

Daioglou et al (2012) and REN21 (2015)

Regional energy use in TWh data from Asia, Latin America, Middle East and Africa, were calculated and summed and used as a global TAM projection for the developing world using cooking energy use data from Daioglou et al., (2012) and population dependency on solid biofuels data REN21(REN21, 2015a). This projection takes into account useful energy for cooking per capita (3 MJ/cap/per day) from Daioglou et al., (2012) and weighted energy

efficiency factor (22.7%) of fuel mix for 2005, similar to the previous projection using data from Daioglou et al (2012)., and Putti et al (2015).

Data for population dependent on solid fuels was obtained from REN21 (REN21, 2015a) for the regions of Africa (67%)(Sub-Saharan Africa (80%), North Africa (1%)), Developing Asia (51%), Latin America (15%), Middle East (4%). The sum of the population relying on traditional biomass from Africa and Middle East regions was divided by the total population of Middle East and Africa from the Ampere database (AMPERE, n.d.) for 2012 to obtain the dependency (56.7%) for Middle East and Africa. The percentage for developing Asia from REN 21 was used to represent the Drawdown region of Asia (sans Japan) for this projection.

Daioglou et al (2012) and IEA (2013)

Regional energy use in TWh data from Asia, Latin America, Middle East and Africa, were calculated and summed to develop a global TAM projection using energy use cooking energy use data from Daioglou et al., (Daioglou et al., 2012) and population using traditional biomass for cooking from IEA 2013 (International Energy Agency, 2013) for the years of 2011 and 2030. The data from IEA 2013, are from the new policies scenario, that the number of people relying on traditional use of biomass is projected to drop by about 30% of the global population in 2030. The scenario also takes into consideration factors such as economic growth, urbanisation and efforts of clean cooking programs due to which the number of people without access to clean cooking reduces by around 290 million. However, large populations in India (730 million) and in Sub-Saharan Africa (800 million – 63% of the population) will still not have access to clean cooking by 2030.

Regional sum for global projection

Regional TAM data from Asia, Middle East and Africa and Latin America were summed to obtain a global TAM. A low-growth trend (low-growth in demand for traditional fuels) of 4 projections for Asia was chosen to represent the TAM from Asia (sans Japan). A low growth is consistent with other projections in literature for countries like India in this region, suggesting adoption increase but also a large population still using traditional fuels. A medium-growth trend was used of 4 projections for Middle East and Africa. Among all regions most of Sub-Saharan Africa is expected to lack access to clean cooking in 2030. A medium-growth trend is also used of 4 projections for Latin America considering Latin America already has a very low use of traditional fuels for cooking.

IEA (2006)

Global data for TAM was obtained from two sources IEA (IEA, 2006) and (IEA, 2013) and constructed from others. IEA (2006) states that the residential demand for biomass in developing countries (which is the TAM focus for this solution) will rise from 8,967 TWh in 2004 to 9,513 TWh in 2030. The authors of this IEA report have taken into account the fuel substitution and market penetration of improved cookstoves for these projections.

Asia (sans Japan)

Three projections for each of the regions of Asia (sans Japan), Middle East and Africa and Latin America were derived from 1) Putti et al., (Putti et al., 2015) and Daioglou et al.,(Daioglou et al., 2012) (Two projections were derived for Asia (San Japan) region from these two sources), 2) Daioglou et al., and REN21 (REN21, 2015b). 3) IEA 2013. The methodology for calculation of TAM projections from all these sources is presented in the global TAM projections methods explanation.

Middle East and Africa

An additional projection for Middle East and Africa was made using data for Nigeria. The per capita cooking energy use for Nigeria was obtained from Ibitoye (2013) (Ibitoye, 2013) for the years 2005, 2015 and 2020. These values were then scaled to obtain total cooking energy use in the Middle East and Africa based on population projections from World Bank.

Specific countries

India

Projections from India were made using data from 5 sources 1) Daioglou et al. and Putti et al (2015) 2) Daioglou et al (2012) and REN21 (2015), 3) IEA 2013 (IEA, 2013) 4) Nakagami et al., (Nakagami, Murakoshi, & Iwafune, 2008), 5) Venkataraman et al., (Venkataraman et al., 2010). To make projections from the first 3 sources, the procedure used for global TAM projections was followed with data for India provided by the sources. An Average (urban+rural) energy use per household (HH) per year of 15.5 GJ/per HH/year was obtained for heating (cooking and water) from Nakagami et al., (2008) and 11 MJ/day from Venkataraman et al (2010). Number of households in India from 2000-2060 were used to obtain the energy use numbers for the entire population. The population data was obtained from Ampere Message Model WP3 Population (AMPERE, n.d.) and the number of households were calculated based on the Indian census data (Office of the Registrar General & Census Commissioner, 2019) for the average number of people in a household.

China

For China, four independent sources have been found for TAM values. Mainali et al. provide a detailed analysis of total cooking energy demand in rural and urban China for 2005, 2010, 2020 and 2030 (Mainali et al., 2012). These energy values have been also presented by fuel types which helps to differentiate between traditional fuels and modern fuels. The cooking energy provided by modern fuels has also been used in the adoption scenarios. (Yuan & Zhao, 2013) have provided the per capita consumed cooking energy for three rural northern regions of China. These values have been converted to national numbers on the basis of population projections using population data from the Ampere database and average household size for China using UN data (United Nations data, 2019). Other two sources, (Zhu & Pan, 2007) have provided total direct energy required for cooking and annual energy per household.

2.4 ADOPTION SCENARIOS

Two different types of adoption scenarios were developed: A Reference (REF) Case which was considered the baseline, where not much changes in the world, and a set of 3 Project Drawdown Scenarios (PDS) with varying levels of ambitious adoption of the solution. Published results show the comparison of one PDS to the REF, and therefore focus on the change to the world relative to a baseline.

2.4.1 Reference Case / Current Adoption

This model defines the REF adoption scenario as a fixed percentage of TAM over the modeling period, using the percentage of adoption in the base-year as the fixed percentage of TAM projecting forward.

2.4.2 Project Drawdown Scenarios

Three Project Drawdown scenarios (PDS) were developed for each solution, to compare the impact of an increased adoption of the solution to a reference case scenario. Three sources were used to make the PDS projections, Global Alliance for Clean Cookstoves (GACC), The World Bank and the IEA (Global Alliance for Clean Cookstoves, 2012; Putti et al., 2015, IEA, 2017b). Global data was available from all the first two sources in the form of number of cookstoves distributed or adopted. These values were converted into the functional unit (TWh (th)) with the help of the model variable *Average Annual Use* for the solution in the model. The third source matched the UN's Sustainable Development Goals in its Sustainable Development Scenario where 100% of clean cooking access is achieved by 2030. This scenario was used for both the PDS2 and PDS3 considering the importance of the goal of universal access to clean cooking energy for health, development and environmental reasons for the world.

Plausible Scenario (PDS1)

This scenario assumes an adoption limit of 95% of TAM. This scenario assumes that clean and improved cookstoves can achieve that limit TAM by 2040. 65% of the adoption target is projected to be reached by 2030.

Drawdown Scenario (PDS2)

This scenario assumes that advanced clean cookstoves can achieve an adoption of 100% of TAM by 2030 matching the UN SDG Goal 7: Universal Clean and Affordable Energy.

Optimum Scenario (PDS3)

Similar to PDS2, this scenario assumes that advanced clean cookstoves can achieve an adoption of 100% of TAM by 2030 matching the UN SDG Goal 7: Universal Clean and Affordable Energy.

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2.5 INPUTS

Many variables have been defined and calculated for this analysis. Almost all of the variables have been weighted based on the fuel mix used for cooking. Table 1.1 lists the fuel mix that was obtained for year 2005. A similar fuel mix was obtained for the same three regions for the year 2030. First an average cooking fuel mix for 2005 and 2030 was calculated separately based on the populations for the respective regions. Then an arithmetic average of these two values was calculated and used to weight different variables in the variable meta-analysis.

Another important variable for this model was average annual use for the solution which was found to be 1003 kWh/stove/year. This value was obtained from reported cooking energy use per household per year from various regions such as Nepal and India (International Institute for Sustainable Development and Integrated Research and Action for Development, 2016; Pokharel, 2004)

2.5.1 Climate Inputs

Fuel consumed

Fuel consumption data obtained from literature was mostly available in the form of amount of fuel used per cooking energy generated. This data was converted into TJ/TWh (th) of final energy, using net calorific values of the fuel used. The data was weighted using average of 2005 and 2030 market shares. This weighting to applied to all variables where applicable.

Direct Emissions (Black Carbon)

Combustion of solid fuels in traditional and certain improved cookstoves result in black carbon emissions. This data was collected from literature and converted to tCO2-eq/TWh(th) Final energy based on GWP.

CH_4, N_2O, $PM_{2.5}$ and CO

Data for methane emissions was available in the form of g/MJ from 2 sources (M. Jeuland & Tan Soo, 2016; Venkataraman et al., 2010) for both traditional and improved cookstoves. The difference was calculated and converted to t CO_2eq per TWh thermal to present reduction in methane emissions. Similarly, tons of N_2O reduced was calculated using available data from the same sources. $PM_{2.5}$ and CO data were collected for both traditional and improved stoves from multiple sources.

Global Warming Potentials

A new variable was created in the model to calculate the global warming potential (GWP) of black carbon. The range of GWP of black carbon as compared to CO_2 on a 100-year basis was found to be from 534.16-890.28 and average of 9 values from 6 sources was found to be 712 CO_2 eq. (Bachmann, 2009; Bond & Sun, 2005; de la Sota et al., 2019; Rypdal et al., 2009; Schulz et al., 2013).

Table 2.1 Climate Inputs

Variable	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Fuel consumed per functional unit – Conventional	Fuel unit (TJ) per TWh (th) Final Energy	435-26,424	16,998	8	4
Fuel Efficiency Factor – Solution	Fuel % saved	23.98% - 63.63%	41.60%	18	9
Direct Emissions (Black carbon) – Conventional	t CO2-eq per TWh (th) Final Energy	93,337- 652,647	372,992	9	5
Direct Emissions (Black carbon- Solution)	t CO2-eq per TWh (th) Final Energy	8- 63	35	3	2
GWP for Black Carbon	CO_2 eq.	534.16- 890.28	712	9	6
CH_4 reduced	t CH4-CO2eq per TWh (th) Final Energy	10- 958	632	7	2
N_2O reduced	t CH4-CO2eq per TWh (th) Final Energy	545- 1,933	1,239	7	2
$PM_{2.5}$ Conventional	ton/Twh(th) Final Energy	2,845 - 15,157	9,001	6	3
$PM_{2.5}$ Solution	ton/Twh(th) Final Energy	5.42- 2,485.5	1,115.23	6	2
CO – Conventional	Tons CO/TWh Final Energy	49,895 - 380,784	215,339	6	2
CO – Solution	Tons CO/TWh Final Energy	16,254 – 109,612	62,933	5	3

Note: Project Drawdown data set range is defined by the low and high boundaries which are respectively 1 standard deviation below and above the mean of the collected data points[3].

2.5.2   Financial Inputs

First Costs

The costs have been converted to US$2014 based on inflation. Weighting based on cooking fuel mix was applied to all the costs. The average first cost of conventional stove was found to be $1.28 whereas the average first cost of improved cookstove was found to be $37.80. The higher costs for the solution are mostly from renewable stoves such as solar ($60/stove) or LPG stoves ($24-$100/stove).

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[3] In some cases, the low boundary is negative for a variable that can only be positive, and in these cases the lowest collected data point is used as the "low" boundary.

First cost of the stoves, both conventional and solution were easier to find than the operating costs. Most of the cooking fuelwood is collected by rural women in the developing world for free so the cost of fuel is zero as no *time* costs are included and no maintenance cost is usually associated with these types of primitive stoves. In case of biomass based improved cookstove, the operating cost obtained for traditional cookstove was multiplied by the fuel efficiency factor obtained for the solution . Average fuel and other operating costs were obtained from several sources and weighted by the demand data explained earlier.

Discount Rate

A discount rate of 4% was used.

Disposal Costs

The disposal cost was not considered in this study as no mention of disposal related costs for either conventional stove or improved stove was found in the literature.

Table 2.2 Financial inputs- Conventional

Variable	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs	US$2014 to acquire and install per cookstove	$0-$2.49	$1.28	9	6
Variable Operation Costs	US$2014 per kWh (th)	$0.000-$0.015	$0.009	7	3

Table 2.3 Financial inputs -Solution

Variable	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs	US$2014 to acquire and install per cookstove	$21.14 - $69.31	$45.23	19	10
Variable Operation Costs	US$2014 per kWh (th)	$0.002 – $0.14	$0.07	7	5

2.5.3   Technical Inputs

Besides strictly climate and financial inputs, several general variables were used in the analysis which had important impacts on both the climate and financial results.

Lifetime Capacity

A life time capacity for conventional and improved cookstoves was available from a few sources (Clean Cooking Alliance, n.d.; DIFFER, 2012; M. Jeuland & Tan Soo, 2016; Marc A. Jeuland & Pattanayak, 2012; Mainali et al., 2012; Pattanayak et al., 2014; State of Green, Denmark, 2016; Stockholm Environment Institute, 2019; The Glacier Trust, 2012; The World Bank, 2011b; Toman & Bluffstone, 2016; UpEnergy, n.d.; Wang, Franco, Masera, Troncoso, & Rivera, n.d.)in the form of number of years. This data was converted to heat in TWh per number of cookstoves using an annual average data for conventional and solution technologies.

Average Annual use

Average annual use data for conventional and solution technologies was available from literature in the form of energy use per stove or household and was converted to TWh(th)/stove/year. This data was mostly available from peer reviewed sources (Demierre, Bazilian, Carbajal, Sherpa, & Modi, 2015; Grieshop et al., 2011; IISD, 2016; Miah et al., 2009; Pachauri, Rao, & Cameron, 2018; Pokharel, 2004; Rijal, Bansal, & Grover, 1990; Tucho & Nonhebel, 2015; Venkataraman et al., 2010; Zhu & Pan, 2007).

Fuel consumption-based emissions

Fuel consumed per functional unit is obtained from literature and is converted to tons/TWh/year using the average annual use of conventional stove. Weighting factor for fuels were used.

Fuel efficiency factor

Fuel efficiency data was calculated based on difference in thermal efficiencies of improved or advanced stove and traditional stoves for different fuel types. Average of 2005 and 2030 fuel mix types was used for weighting.

Table 2.4 Technical Inputs Conventional Technologies

Variable	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity (Conventional)	kWh (th) per cookstove	1,347.63 – 12,889.48	7,118.56	6	6
Average Annual Use (Conventional)	kWh (th) per cookstove	47.52 – 14,322.92	5,933.12	11	7
Fuel consumed per functional unit – Conventional	Fuel unit (TJ) per TWh thermal	435-26,424	16,998	8	4

Table 2.5 Technical Inputs Solution

Variable	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity (Solution)	kWh (th) per cookstove	3,038.76 – 16,415.52	9,727.14	14	10
Average Annual Use (Solution)	kWh (th) per cookstove	298.87 – 1,707.39	1,003.13	9	3
Fuel Efficiency Factor – Solution	Fuel % saved	25.99%-56.81%	41.03%	18	9

2.6 ASSUMPTIONS

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology will be available at www.drawdown.org. Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

Assumption 1: The global and regional TAM's can be projected sufficiently based on population growth only.

Assumption 2: The more developed regions of the world e.g. USA and EU can be excluded from the model due to their low use of traditional cooking.

Assumption 3: A global projection using only data from the three selected lesser developed regions is appropriate (a lack of adoption data makes this necessary).

Assumption 4: Most of the variables used in the model have been weighted according the cooking fuel mix. The past and projected mixes were available for Africa, India and China for 2005 and 2030. The model uses the average of the two years. This decision was made in order to better account for additional improved cookstoves in the solution stage which wouldn't have been possible if only the 2005 fuel mix with only 3.88 % of modern and 12.71% of intermediate fuels was used.

Assumption 5: An implementation unit of cookstove can accurately capture the intricacies and wide varieties of the actual implementation of this solution. This decision was made for the ease of calculation of financial variables since most literature reports first costs and operational costs per stoves.

Assumption 6: Additional variable was created for Black carbon global warming potential. This variable was used to calculate the annual direct emissions for conventional and improved stoves. This was done to avoid double counting the emissions from the fuel efficiency factors.

Assumption 7: Due to very few data sources available for adoption of cookstoves, current adoption is estimated using adoption of clean and improved fuels and cookstove technologies.

2.7 INTEGRATION

The complete Project Drawdown integration documentation (will be available at www.drawdown.org) details how all solution models in each sector are integrated, and how sectors are integrated to form a complete system. Those general notes are excluded from this document but should be referenced for a complete understanding of the integration process. Only key elements of the integration process that are needed to understand how this solution fits into the entire system are described here.

Clean Cookstoves is chiefly a household technology that supports families with cooking energy. Integration of cooking solutions is discussed. Cooking solutions include Clean Cookstoves and Small Biogas, or solutions for families in developing countries to generate cooking energy that is healthier for them (fewer inhaled pollutants) and the environment and climate all at the same time. The chief points of integration are:

1. Sharing of TAM and avoiding double counting

2. Sharing of Conventional Technology variables (first cost, operating cost, emissions etc.)

These integration points are manually dealt with in each solution model and report. The TAM data for instance are duplicated in each model and adoptions in any one year are collectively limited to the total TAM in that year. Similarly, conventional technology variables are duplicated in each model.

Clean Cookstoves also have an impact on Drawdown's Biomass model since they help reduce demand for firewood for domestic cooking in developing countries. The Biomass model begins with projected global biomass demand through 2060, based on FAO historical data and other sources, in categories including sawnwood, other woody biomass, and herbaceous biomass (which includes crop residues). It determines the impact of demand reduction solutions including clean cookstoves and recycled paper, resulting in an adjusted demand projection through 2060. Biomass supply reductions are modeled as well, which result from protection of forests, reducing biomass availability. Biomass supply increases are modeled through the increased adoption of solutions including afforestation, bamboo, perennial biomass and agroforestry solutions like tree intercropping, silvopasture, and multistrata agroforestry. Biomass availability from crop residues, seaweed farming, and dedicated biomass crops planted on cropland freed up by sustainable intensification is also modeled.

Surplus biomass is allocated to climate solutions that require biomass as feedstock. These include biochar, biomass electricity, bioplastic, 2nd generation biofuels, building with wood, insulation, small-scale biogas, and district heating. This biomass feedstock allocation was a constraint to the adoption of this solution.

2.8 LIMITATIONS/FURTHER DEVELOPMENT

The main limitation of the cookstove model is the lack of adoption data and some global TAM data. Data is often available for combined adoption of better fuels and cookstoves. Large databases with data on lack of access to clean fuels and technologies for cooking are also available (International Energy Agency, 2017a; World Health Organization, 2018b). The adoption from these sources is as high as 213 TWh for the year 2005 (World Health Organization, 2018b) translating to 271 million households with access for developing countries (lacking access to clean cooking technologies) using an average household size of 5.5 calculated based on UN data(United Nations, Department of Economic and Social Affairs, 2018). Adoption data from GACC on the other hand is reported at times in terms of cookstoves, and was about 300,000 cookstoves for 2005(Clean Cooking Alliance, 2012). Data from GACC for combined adoption of clean cookstove and fuels estimate is also low from GACC (53 million)(Global Alliance for Clean Cookstoves, 2016) compared to WHO data (385 million).

The model would benefit greatly from regional adoption data since current results are based on only 3 sources for global projections. More sources for black carbon emissions for both conventional and improved cookstoves would make the emission model more robust. Another important variable in this model is annual fuel consumed per functional unit. Currently the data available has a lot of variability and there needs to be further investigation done into the variability and robustness of this data.

3 RESULTS

3.1 ADOPTION

Below are shown the world adoptions of the solution in some key years of analysis in functional units and percent for the three Project Drawdown scenarios.

Table 3.1 World Adoption of the Solution

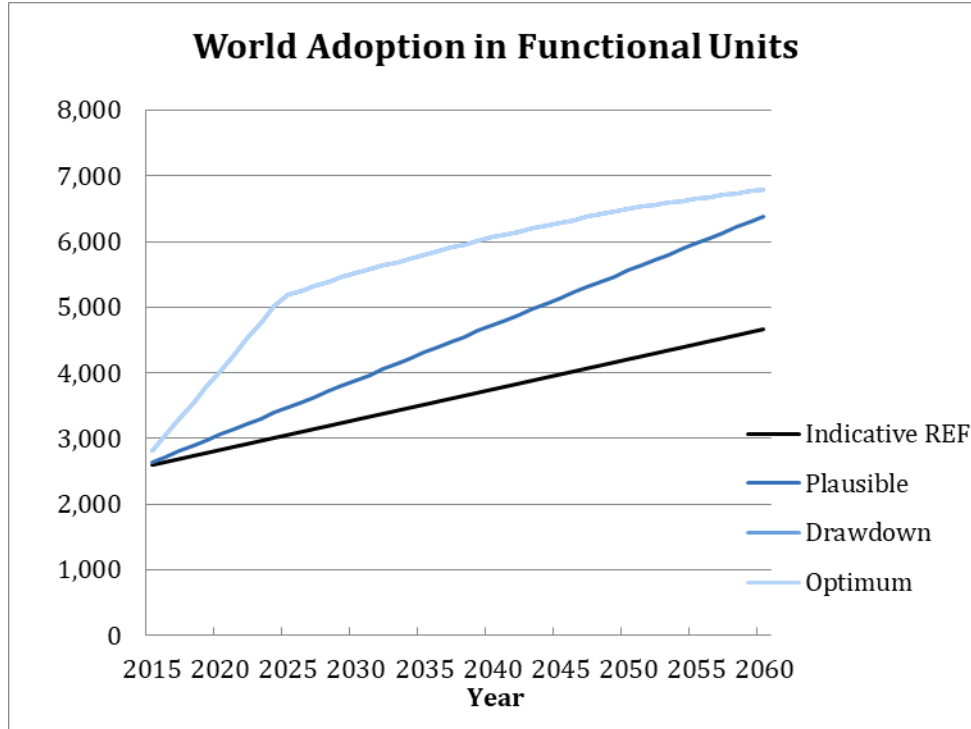| Solution	Units	Base Year (2014)	World Adoption by 2050		
			Plausible	Drawdown	Optimum
Clean and Improved Cookstoves	TWh Thermal	2,558	5,553	6,494	6,494
	(% market)	57.9%	85.5%	100%	100%

Figure 3.1 World Annual Adoption 2020-2050 (Drawdown and Optimum are same)

3.2 CLIMATE IMPACTS

Below are the emissions results of the analysis for each scenario which include total emissions reduction, atmospheric concentration changes, and sequestration where relevant. For a detailed explanation of each result, please see the Glossary (Section 6).

Table 3.2 Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Emissions Reduction in 2030	Emissions Reduction in 2050
	(Gt CO_2-eq/yr.)	Gt CO_2-eq/yr. (2020-2050)	(Gt CO_2-eq/year)	(Gt CO_2-eq/year)
Plausible	1.69	30.51	0.75	1.69
Drawdown	2.90	83.73	2.79	2.86
Optimum	2.90	83.73	2.79	2.86

The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the models. This is due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined).

Table 3.3 Impacts on Atmospheric Concentrations of CO_2-eq

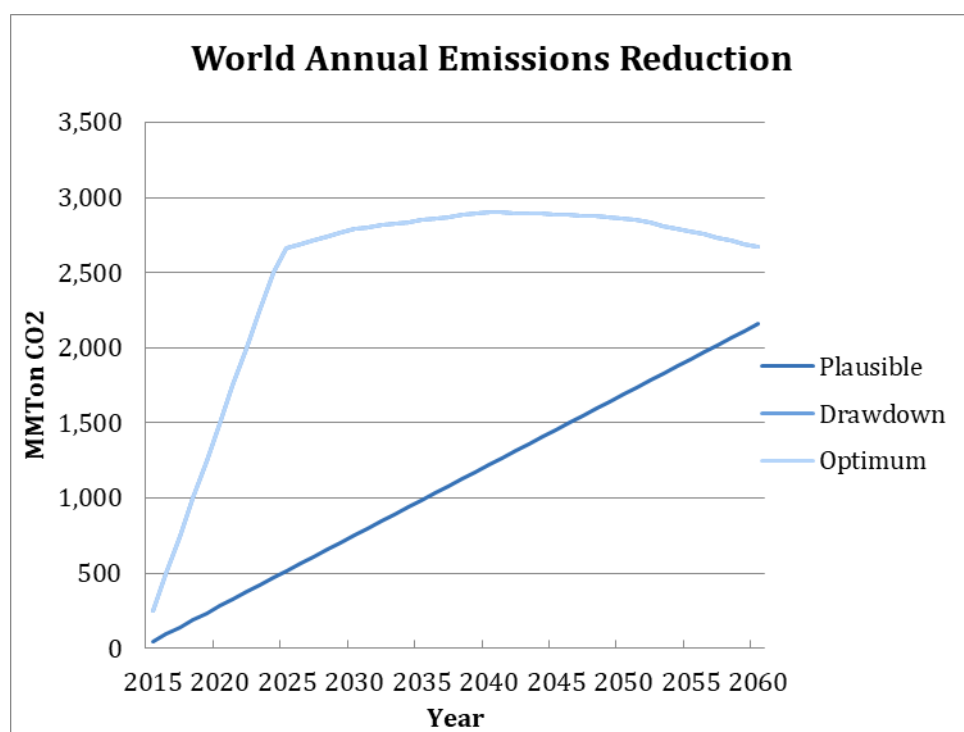| Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	PPM CO_2-eq (2050)	PPM CO_2-eq change from 2049-2050
Plausible	2.53	0.13
Drawdown	6.60	0.18
Optimum	6.60	0.18

Figure 3.2 World Annual Greenhouse Gas Emissions Reduction (Drawdown and Optimum are same)

3.3 FINANCIAL IMPACTS

Below are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary.

Table 3.4 Financial Impacts

| Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Savings	Lifetime Operating Savings	Lifetime Cashflow Savings NPV (of All Implementation Units)
	2015-2050 Billion USD	2015-2050 Billion USD	2020-2050 Billion USD	2020-2050 Billion USD	Billion USD
Plausible	292.58	129.09	-1,550.18	-1,963.17	-789.36
Drawdown	494.11	325.69	-4,216.76	-5,011.20	-2,384.24
Optimum	494.11	325.69	-4,216.76	-5,011.20	-2,384.24
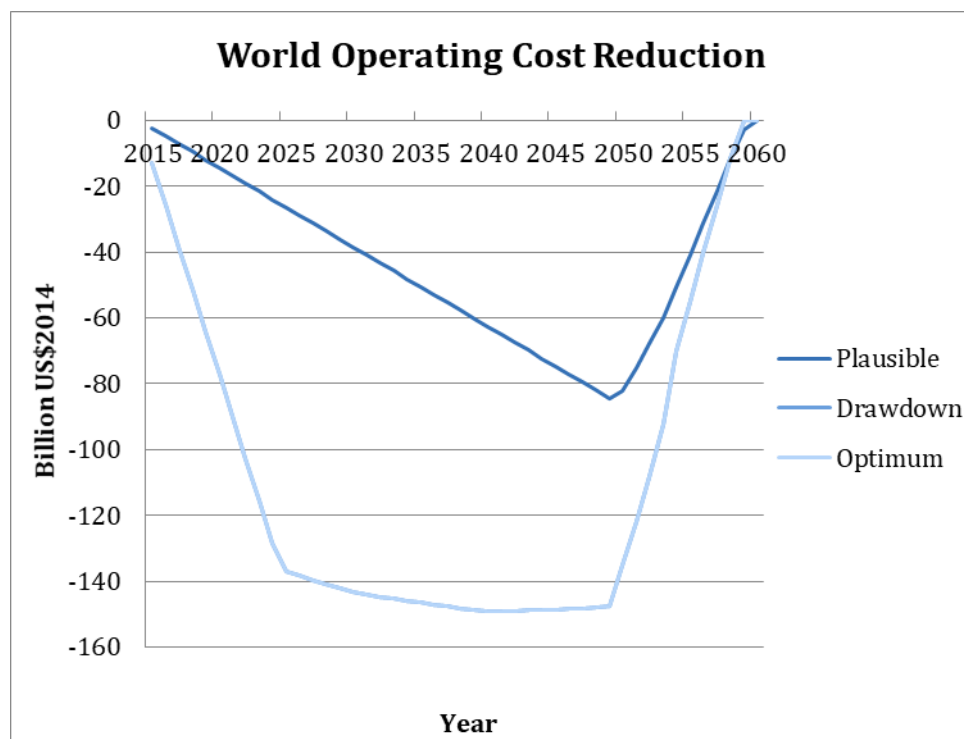
Figure 3.3 Net Profit Margin /Operating Costs Over Time (Drawdown and Optimum are same)

3.4 OTHER IMPACTS

Implementation of clean and improved cookstoves have health benefits due to reduction of other pollutants, such as carbon monoxide, nitrous oxide, methane, black carbon and fine particulate

matter. Data on these pollutants was collected and emission reductions were calculated from 2014-2060, for the 3 PDS scenarios.

Table 3.5 Other climate pollutant reductions (2020-2050)

Scenario	Carbon Monoxide (CO) Million Tons	Black Carbon (BC) Million Tons CO_2-eq	Fine particulate matter (PM) Million Tons	Nitrous Oxide (N_2O) Million Tons CO_2-eq	Methane (CH_4) Million Tons CO_2-eq
	Short lived climate pollutants			Long lived climate pollutants	
Plausible	3,514	8,600	182	29	15
Drawdown	9,860	24,129	510	80	41
Optimum	9,860	24,129	510	80	41

4 DISCUSSION

Improved clean cookstoves is definitely an important solution to consider for Drawdown. Currently it is estimated that 32.3 Gt CO_2 eq was produced due to energy consumption around the world in 2012(EIA, n.d.). The current estimates show that replacing traditional solid fuel based cookstoves with clean improved stoves can reduce CO_2 eq per year by 984 Mt (on average for 2020-2050 in the Plausible Scenario-PDS1). But at the same time it should be also noted that 17% of world's black carbon comes from biomass based cooking (MacCarty et al., 2008) and reducing this value to almost zero by replacing solid fuel burning stoves with renewable fuel stoves, which can reduce black carbon by almost 99% (Venkataraman et al., 2010) is a huge step towards the Drawdown goal, particularly in the short term.

In addition to climate impacts the health impacts of this solution are very significant. In India it was estimated that dissemination of 150 million clean cookstoves over 10 years could help avoid 2.2 million premature deaths due to HAP over this period in the country and that the reduction in health burden in 2020 (measured in lost healthy life years) would be equivalent to about half the total national cancer burden projected that year(Venkataraman, 2005). The potential rebound effects of improved health outcome on fertility rates, consumption rates and emissions are hard to predict and not studied in the literature.

The financial results presented in Table 3.4 show the cumulative first cost of implementing 5.5 billion stoves by the year 2050 to be $293 billion. This translates to less than $53/stove disseminated which is much lower than some of the other high technology solutions such as Solar PV.

This study is quite comprehensive in considering all the currently available relevant data but also has quite a few data limitations in the global and regional adoption data.

One of the major benefits of adoption of cookstoves is rapid reduction of short-lived climate pollutants and reduction of long-lived pollutants such as methane given that methane is more

potent than Carbon dioxide. Burning of traditional fuels are one of the largest sources of Carbon monoxide besides transportation fuels use. Replacing traditional cookstoves with their cleaner alternatives has the potential to cool global surface temperatures by about 0.08C by 2050, due to reduction in black carbon and other short lived climate pollutants(Pidcock, 2017).

Effect of emissions from all regions is not equal. On a per cookstove basis, emissions in Azerbaijan, Ukraine, and Kazakhstan, have a comparatively larger effect on climate as black carbon is transported to the artic, where it darkens the snow, causing it to reflect less heat These regions (Eastern Europe and Central Asia) in addition, are not targeted for clean cookstoves implementation programs(Pidcock, 2017).

4.1 LIMITATIONS

Clean cookstoves have a wide range of benefits in the area of health and environment. Higher tier cookstoves however, may not be the larger share of the market in the near future. Not using a modern fuel with an improved stove will result in smaller advantages. Discarding the traditional stove is a challenge. Supply of the right fuels is critical to the continuous use of the clean and improved cookstoves.

4.2 BENCHMARKS

A paper by Bailis (GACC, 2014) recently published in Nature Climate change estimates that only 161 million tons of CO_2 per year can be saved with dissemination of 100 million improved clean cookstoves globally.

The IEA Energy Technology Perspectives modeled the projections of cooking energy (International Energy Agency, 2017b). The projections consider reduction in fossil fuel use with a shift to high performance, renewable energy technologies (clean fuels+ clean cookstoves) leading to cumulative savings in various sectors including cooking in the IEA's *Beyond 2D Scenario* (B2DS).

Mehetre et al., cited reports and publications estimating the global reduction in CO_2 emissions to be 1 Gt of CO_2 per year from adoption of improved cookstoves (Mehetre, Panwar, Sharma, & Kumar, 2017). Fuel cost savings exceeding net savings was also reported by Mehetre et al.Table 4.1

Table 4.1 Benchmarks

Source and Scenario	Emissions reduced (Gt of CO2) 2020-2050	Maximum Annual emissions reduction (Gt of CO_2e)	Lifetime Cashflow Savings (Billion USD)
Difference between IEA 2017 RTS and B2DS*	9.5		
Difference between IEA 2016 6DS and 2DS*	17.9		

Source and Scenario	Emissions reduced (Gt of CO2) 2020-2050	Maximum Annual emissions reduction (Gt of CO_2e)	Lifetime Cashflow Savings (Billion USD)
Project Drawdown – Plausible Scenario (PDS1)	30.5	1.69	-789.36
Project Drawdown – Drawdown/Optimum Scenario (PDS2/3)	83.7	2.90	-2,384.24
Mehetre (2017)	-	1	-34

* - the IEA emissions scenarios were interpolated for missing years using polynomials curves and the difference between the two for the years of our analysis 2020-2050 were summed for figures above.

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6 GLOSSARY

Adoption Scenario – the predicted annual adoption over the period 2015 to 2060, which is usually measured in **Functional Units**. A range of scenarios is programmed in the model, but the user may enter her own. Note that the assumption behind most scenarios is one of growth. If for instance a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate high growth of the solution.

Approximate PPM Equivalent – the reduction in atmospheric concentration of CO_2 (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

Average Abatement Cost – the ratio of the present value of the solution (**Net Operating Savings** minus **Marginal First Costs**) and the **Total Emissions Reduction**. This is a single value for each solution for each **PDS Scenario**, and is used to build the characteristic "*Marginal Abatement Cost*" curves when Average Abatement Cost values for each solution are ordered and graphed.

Average Annual Use – the average number of functional units that a single implementation unit typically provides in one year. This is usually a weighted average for all users according to the data available. For instance, total number of passenger-km driven by a hybrid vehicle in a year depends on country and typical number of occupants. We take global weighted averages for this input. This is used to estimate the **Replacement Time**.

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Cumulative First Cost – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Direct Emissions – emissions caused by the operation of the solution, which are typically caused over the lifetime of the solution. They should be entered into the model normalized per functional unit.

Discount Rate- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis takes into account not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate.   Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

Emissions Factor– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO_2e/kWh.

First Cost- the investment cost per **Implementation Unit** which is essentially the full cost of establishing or implementing the solution. This value, measured in 2014$US, is only accurate to the extent that the cost-based analysis is accurate. The financial model assumes that the first cost is made entirely in the first year of establishment and none thereafter (that is, no amortization is included). Thus, both the first cost and operating cost are factored in the financial model for the first year of implementation, all years thereafter simply reflect the operating cost until replacement of the solution at its end of life.

Functional Unit – a measurement unit that represents the value, provided to the world, of the function that the solution performs. This depends on the solution. Therefore, LED Lighting provides petalumen-hours of light, Biomass provides tera-watt-hours of electricity and high speed rail provides billions of passenger-km of mobility.

Grid Emissions – emissions caused by use of the electricity grid in supplying power to any operation associated with a solution. They should be in the units described below each variable entry cell. Drawdown models assume that the global electric grid, even in a Reference Scenario, is slowly getting cleaner, and that emissions factors fall over time resulting in lower grid emissions for the same electricity demand.

Implementation Unit – a measurement unit that represents how the solution practice or technology will be installed/setup and priced. The implementation unit depends on the solution. For instance, implementing electric vehicles (EV) is measured according to the number of actual EV's in use, and adoption of Onshore Wind power is measured according to the total terawatts (TW) of capacity installed worldwide.

Indirect Emissions – emissions caused by the production or delivery or setup or establishment of the solution in a specified area. These are NOT caused by day to day operations or growth over time, but they should be entered into the model normalized on a per functional unit or per implementation unit basis.

Learning Rate/Learning Curve - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experienced is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for

calculating how costs change due to learning. A 2% learning rate means that the cost of producing a *good* drops by 2% every time total production doubles.

Lifetime Capacity – this is the total average functional units that one implementation unit of the solution or conventional technology or practice can provide before replacement is needed. All technologies have an average lifetime usage potential, even considering regular maintenance. This is used to estimate the **Replacement Time**. and has a direct impact on the cost to install/acquire technologies/practices over time. E.g. solar panels generate, on average, a limited amount of electricity (in TWh) per installed capacity (in TW) before a new solar panel must be purchased. Electric vehicles can travel a limited number of passenger kilometers over its lifetime before needing to be replaced.

Lifetime Operating Savings–the operating cost in the PDS versus the REF scenarios over the lifetime of the implementation units purchased during the model period regardless of when their useful life ends.

Lifetime Cashflow NPV-the present value (PV) of the net cash flows (PDS versus REF) in each year of the model period (2015-2060). The net cash flows include net operating costs and first costs. There are two results in the model: Lifetime Cashflow NPV for a Single **Implementation Unit**, which refers to the installation of one **Implementation Unit**, and Lifetime Cashflow NPV of All Units, which refers to all **Implementation Units** installed in a particular scenario. These calculations are also available using profit inputs instead of operating costs.

Marginal First Cost – the difference between the **First Cost** of all units (solution and conventional) installed in the **PDS Scenario** and the **First Cost** of all units installed in the **REF Scenario** during the analysis period. No discounting is performed. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Net Annual Functional Units (NAFU) – the adoption in the PDS minus the adoption in the REF in each year of analysis. In the model, this represents the additional annual functional demand captured either by the solution in the **PDS Scenario** or the conventional in the **REF Scenario**.

Net Annual Implementation Units (NAIU) – the number of **Implementation Units** of the solution that are needed in the PDS to supply the **Net Annual Functional Units (NAFU).** This equals the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use.

Net Operating Savings – The undiscounted difference between the operating cost of all units (solution and conventional) in the **PDS Scenario** minus that of all units in the **REF Scenario**.

Operating Costs – the average cost to ensure operation of an activity (conventional or solution) which is measured in 2014$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

Payback Period – the number of years required to pay all the **First Costs** of the solution using **Net Operating Savings**. There are four specific metrics each with one of **Marginal First Costs** or **First Costs** of the solution only combined with either discounted or non-discounted values. All four are in the model. Additionally, the four outputs are calculated using the increased profit estimation instead of **Net Operating Savings**.

PDS/ Project Drawdown Scenario – this is the high growth scenario for adoption of the solution

PPB/ Parts per Billion – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

PPM/ Parts per Million – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

REF/ Reference Scenario – this is the low growth scenario for adoption of the solution against which all **PDS scenarios** are compared.

Regrets solution has a positive impact on overall carbon emissions being therefore considered in some scenarios; however, the social and environmental costs could be harmful and high.

Replacement Time- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

TAM/ Total Addressable Market – represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth. For this solutions sector, it represents world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

Total Emissions Reduction – the sum of grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as "emissions avoided" as they may have occurred in the REF Scenario, but not in the PDS Scenario.

Transition solutions are considered till better technologies and less impactful are more cost effective and mature.

TWh/ Terawatt-hour – A unit of energy equal to 1 billion kilowatt-hours