**Technical assessment for**

**Methane Digesters**

Sector: Buildings

Agency Level: Household

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# Acronyms and Symbols Used

* **AD** – Anaerobic digestion
* **CH4**– Methane
* **CHP** – Combined Heat and power
* **CO2** – Carbon dioxide
* **dm** – decimeters (tenth of a meter)
* **ETP** – Energy Technology Perspectives (Report of the IEA)
* **EU** – European Union
* **GHG** – Greenhouse gases
* **IEA** – International Energy Agency
* **LCA** – Life Cycle Assessment
* **MJ** – Megajoule (million Joules of energy)
* **MSW** – Municipal Solid Waste
* **Mtoe** – Million Tons of Oil Equivalent
* **MWh** – Megawatt-hour (million watt-hours of energy)
* **N2O** – Nitrous Oxides
* **O&M** – Operation and Maintenance
* **PDS** – Project Drawdown Scenario
* **PM** – Particulate matter
* **ppm** – parts per million
* **REF** – Reference Scenario
* **SO2** – Sulfur dioxide
* **TAM** – Total Addressable Market
* **TWh (th)** – Tera-Watt-hour (thermal) – 1,000 billion Watt-hours of heat energy
* **USA** – United States of America
* **WWTP** – Wastewater Treatment Plant

# Executive Summary

Anaerobic digestion is a biological process that produces a gas (biogas) principally composed of methane and carbon dioxide. Anaerobic or methane digesters come in a variety of different tank designs to capture methane, combust it, to create heat. One premier application of anaerobic digesters is at dairy and hog farms and in sludge from wastewater plants, where they provide a variety of environmental and public health benefits including greenhouse gas abatement, reduced deforestation, improved indoor air quality, organic waste reduction, odor reduction, and pathogen destruction.

Digesters have been installed throughout the world and at relatively high rates in China, the EU and Southeast Asia in the past 20 years. The digesters can be divided into two main categories, first is the small bio-digesters used at the household level to replace fuelwood, charcoal or even fossil fuel based cookstoves. The second category includes large bio-digesters installed at dairy, hog farms, waste water facilities and landfills to, among others, produce electricity and heat for use on site or for providing electricity or gas into the grid. The small bio-digesters are mostly used in developing countries while large bio-digesters are found in developed countries, especially in the USA and EU. This report analyses the potential of small bio-digesters in reducing emissions.

Through advanced global adoption of small anaerobic digesters from 2020-2050, around 86 million inefficient biomass/firewood or charcoal cookstoves can be replaced in a scenario designed to achieve Drawdown. This could have a climate impact avoidance of 10.4 Gt CO2 eq. Small biogas digesters have an impact of approximate PPM equivalent in 2050 of 0.86.

The total installation cost of about $63 billion for small bio-digesters is required. The manure fed into small bio-digesters is from the cattle owned by the household and burning crop residue so there is no fuel cost but some expenditure as part of maintenance cost contributes to the O&M cost.

The benefit of small bio-digester includes saving of fuelwood or charcoal cost and avoidance of CH4 emissions that would have occurred due to anaerobic degradation of manure. This avoidance of CH4 is partially discounted in the model due to the prevalence of fugitive emissions from poorly maintained household biogas systems.

# 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 CO2 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, 2017). 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.

## State of Small Bio-digesters

Traditional cooking energy and pollution can be reduced in many ways by using different cooking methods. One of these is Anaerobic Digestion (AD). AD is a biological process of natural bacterial decomposition of organic matter in the absence of oxygen. The AD process generates three by-products including biogas, bio-liquid (or liquid digestate), and fiber digestate (Caruso et al., n.d). The digestate or slurry is rich in ammonia and nutrients, used as organic fertilizer (Rajendran, Aslanzadeh, & Taherzadeh, 2012).

Digestion produces a gas (biogas) principally composed of methane (CH4), carbon dioxide (CO2) and trace amounts of other gases (e.g. hydrogen sulfide and ammonia) (Duerr, 2005). These gases are typically produced from organic wastes such as livestock farm effluent from animal manure, sludge settled in wastewater treatment plant (WWTP), or food processing waste (e.g. in landfills). However, biogas can also be made from a wide variety of organic feedstock including both wastes and biomass energy crops. Carbohydrates, proteins and lipids are all readily converted to biogas (PEW, 2011; Wilkie, 2015). Crop residues have higher potential of producing biogas compared to dung and could also potentially replace dung as a substrate. Using just crop residue, it is estimated that Kenya could produce about 1,313 million m3 of biogas annually (73% of Kenya’s annual energy demand) (Hamid & Blanchard, 2018).

Anaerobic processes can occur naturally, where gases are simply released to the air, but can also occur in a controlled environment, such as an anaerobic or methane digester that captures the so called “biogas” or in covered lagoons in landfills. To harvest this gas in landfills, wells are drilled into the landfill, and from these can be collected between 60% and 90% of the biogas which is processed for flaring, refining or generating heat or electricity (PEW, 2011; Wilkie, 2015). In addition, liquid and fiber digestate can be used as a fertilizer or compost to improve soils (Friends of the Earth, 2002). According to Mills et al. (2012) AD achieves the required “sterilization” or pathogen kill to allow the sludge from wastewater to be recycled to land.

Anaerobic digesters, as a carbon neutral technology, provide several environmental and public health benefits. They help in greenhouse gas abatement, pathogen destruction, organic waste reduction, and odor reduction. Since methane is the principal component of biogas as well as natural gas, biogas can be used to replace natural gas in many applications and be used for heating, vehicular fuel mechanical energy, or for supplementing the natural gas supply (PEW, 2011; Wilkie, 2015). Cooking is the main application of biogas in rural areas. About 0.16 m3 of Biogas is needed to cook a one-person meal (Gosens, Lu, He, Bluemling, & Beckers, 2013). For a 2-4 persons household this could be equivalent to biogas about 88-186 kg CH4/year, with biogas supplying about 55-80% of the household cooking energy. Typically, the average volume of the digester is approximately 5–7 m3 and provides about 0.5 m3 biogas per m3 digester volume. (Khan et al., 2016). Although digesters between 1-150 m3 size are also categorised under household digesters. To generate 3 m3 of biogas per day, manure from 5 cows is required. For a smaller digester of 1.2 m3 manure from at least 4 cows is required (Rajendran et al., 2012).

There is a range of possible digester technology designs, all of which are essentially different types of tanks that allow for biogas capture. Smaller-scale anaerobic digester technology includes fixed domes, stacked domes, and tubular and bag digesters (GMI, 2012); smaller-scale designs may also be referred to as flexible balloon or floating drum digesters. Floating drum designs have been prevalent in areas likes India; in other areas like Vietnam, uptake has been highest with flexible balloon digesters due to lower cost, subsidies, and proactive policy. Fixed dome digesters are low maintenance, and they require less space than balloon digesters, and have a longer lifespan than balloon, but are more expensive.

Depending on the waste feedstock and the system design, biogas is typically 55 to 75 percent pure methane (California Energy Commission, nd). Both livestock and wastewater treatment plants typically produce a mix of 60 to 70% CH4 and the 30 to 40% CO2, along with trace gases (e.g. <1% hydrogen sulfide). The biogas can then be flared to just destroy the methane or heat the digester, lowering the overall energy requirements of the system. In Asia and Africa, the biogas is often used for cooking heat.

The primary contribution of anaerobic digestion to GHG reduction is in its capture of methane gas, which has a global warming potential at least 21 times that of carbon dioxide by weight (possibly as high as 36 times). Destroying methane via flare converts it to carbon dioxide.

### Small bio-digesters design

There are different designs for small bio-digesters some of the most common designs include the following.

#### Fixed-dome Plants



Figure 1.1 Fixed dome digester (Rajendran, Aslanzadeh, & Taherzadeh, 2012)

The fixed dome type digesters (Figure 1.1) consist of a fixed, non-movable gas holder, which is placed on top of the underground digester. Fixed-dome biogas plants have low costs since there are no moving parts, and no rusting steel parts. Therefore a long life of the plant (20 years or more) can be expected. There are several variants of the fixed dome biogas plant including the Chinese model, Deenbandhu model and CAMARTEC model, the variations are mostly to simplify the structure, reduce cost and increase suitability (SGPindia, nd). The size of the fixed dome digesters differs in different countries. In Nepal, it is 4-20 m3, 6-10 m3 in China, 1-150 m3 in India, 6 m3 for a family of 9 in Nigeria.

#### Floating Drum Plants

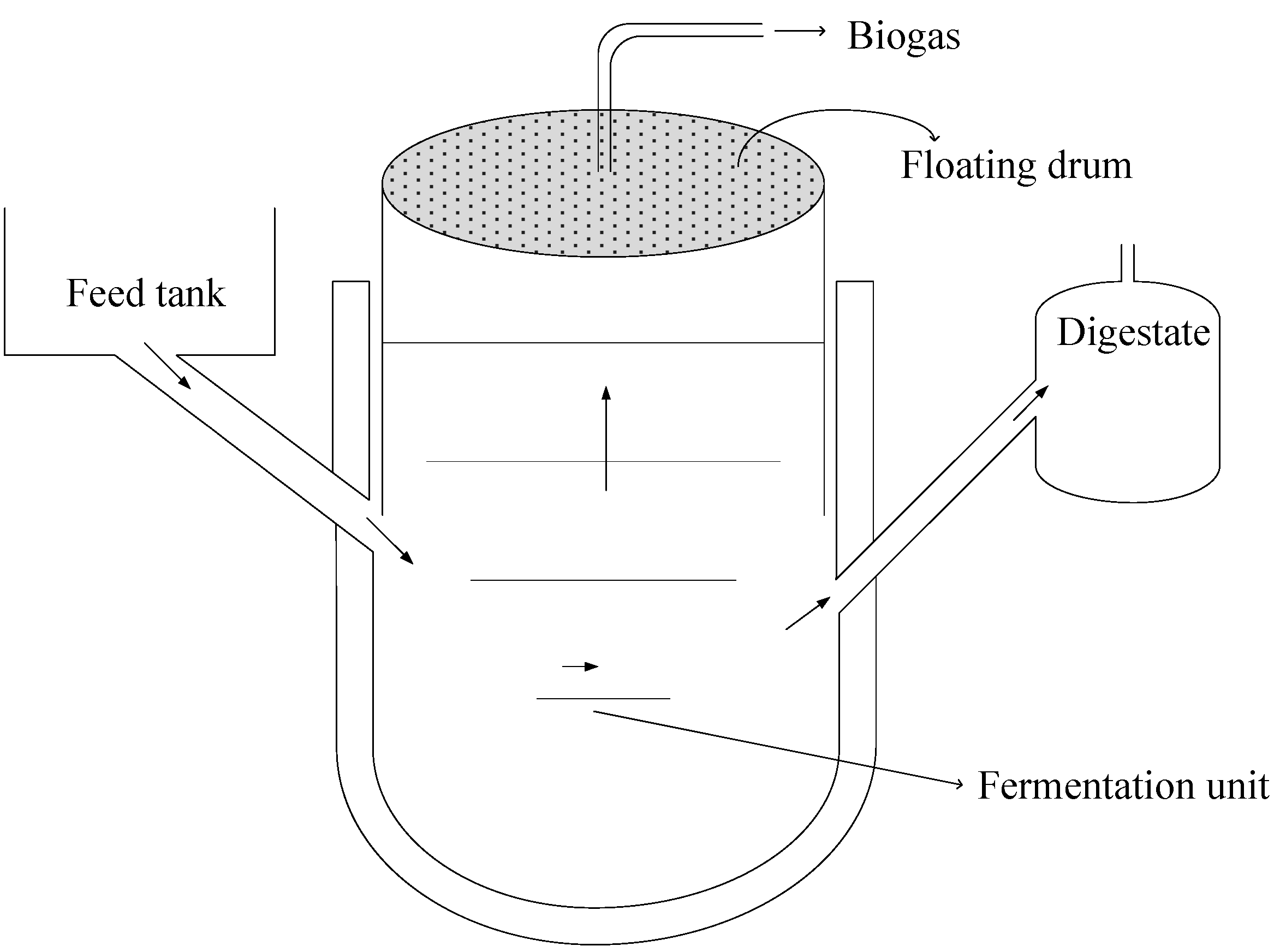


Figure 1.2 Floating drum plant (Rajendran et al., 2012)

The floating drum plants consist of the underground digester with a floating metal drum (mostly steel) on top which rises with production of biogas. The gas-holder floats either directly on the fermentation slurry or in a water jacket of its own. The limited lifetime of the metal drum and relatively high costs are disadvantages of the model. However, advantages include simpler construction, indication of gas production and constant gas pressure due to weight of the floating drum. Floating-drums may be also made of other materials such as glass-fiber reinforced plastic and high-density polyethylene. These tend to increase construction costs though (SGPindia, ND). The average size of these digesters is about 1.2 m3 (Rajendran et al., 2012)

#### Polyethylene Tube Digesters

Low-Cost Polyethylene Tube is used to form digesters. The tubular polyethylene film mostly contains two coats of 300 microns and is bended at each end around a rubber strap of recycled tire-tubes. With this system, a hermetic isolated tank is obtained. Disadvantages of polyethylene tube digesters include low gas pressure (making additional gas pumps necessary); difficult scum removal; relatively short useful life-span of the plastic balloon (partly due to mechanical damage) (SGPindia, ND). The size of these digesters varies from 2.4-7.5m3 (Rajendran et al., 2012). These are low cost digesters and portable. It is a challenge to dig a hole in high altitude to place the digesters.

## Adoption Path

### Current Adoption

The estimated current adoption for small biogas is 25 % of the technical potential (129 TWh(th)) or 3% of cooking energy demand in the regions included (Asia (sans Japan), Middle East and Africa and Latin America). Globally by the end of 2016, a cumulative of 50 million biogas cookstoves were distributed. Of this, about 112 million people in China and 10 million people (~13 million m3 of biogas produced) in India (~2 million m3 of biogas produced) used biogas for cooking (Renewable Energy Policy Network for the 21st Century, 2018).

The number of units reported are varied from different sources (Table 1.1). This could be due to exclusion of certain types of methane digesters in data collection (International Renewable Energy Agency, 2017). The higher reported number is considered in this report. However, in certain cases, higher installations don’t necessary mean that the distributed digesters are being utilized, for example, although 5 million units were installed in India, not all are functioning due lack of technical skills and cultural habits.

Small-scale methane digesters have been widely installed in Asia, using fixed dome designs in Bangladesh, Nepal, and other countries (SNV, 2016). China ranked first in the number of biogas installations (Table 1.1) with 43 million installations followed by India with 4.7 million, Vietnam 500,000, Nepal with 330,000, and Bangladesh with 700,000 (Rajendran et al., 2012). China is expected to have about 80 million households using digesters by 2020 (300 million people) (Rajendran et al., 2012).

Biogas installation in Africa has been less widespread than in Asia, but adoption of domestic systems is increasing. This is due to national domestic biogas programs with targets of at least 10,000 systems in 5 years (e.g. in Rwanda, Tanzania, Kenya, Uganda, Ethiopia, Cameroon, Benin and Burkina Faso) (Smith et al., 2013).

In developing countries, small-scale anaerobic digesters are used to directly provide heating, lighting and cooking in rural communities. This is more likely than being coupled with a generator to create electricity. These digesters can be operated using feedstock from as little as a few head of livestock (two cattle or five hogs), compared with U.S. digesters designed to typically serve either greater than 500 cattle or greater than 2,000 hogs.

Table 1.1 Bio digester installations from different sources

|  |  | **REN 21 2017 [2014 data]** | **Khan and Martin, 2016 [2012 Status]** | **Rajendran et al., 2012** | **National Environmental Protection Agency of the Islamic Republic of Afghanistan, n.d.** | **Msibi & Kornelius, 2017** |
| --- | --- | --- | --- | --- | --- | --- |
|  | **Region /Country** | **Number of units** | | | | |
| Asia | China | 43,000,000 | 42,000,000 | >30,000,000 |  |  |
| India | 4,750,000 | 5,000,000 | 3,800,000 |  |  |
| Nepal | 330,000 | 270,000 | 200,000 |  |  |
| Vietnam | 182,800 | 500,000 |  |  |  |
| Bangladesh | 37,060 | 70,000 | 60,000 |  |  |
| Cambodia | 23,220 |  |  |  |  |
| Indonesia | 15,892 |  |  |  |  |
| Pakistan | 5,360 |  |  |  |  |
| Laos | 2,890 |  |  |  |  |
| Afghanistan |  |  |  | 300 |  |
| Bhutan | 1,420 |  |  |  |  |
| Africa | Kenya | 14,100 |  |  |  |  |
| United Republic of Tanzania | 11,100 |  |  |  |  |
| Ethiopia | 10,680 |  |  |  |  |
| Uganda | 5,700 |  |  |  |  |
| Senegal |  |  |  |  | 334 |
| Burkina Faso | 5,460 |  |  |  |  |
| Rwanda | 1,700 |  |  |  |  |
| Cameroon | 300 |  |  |  |  |
| Benin | 110 |  |  |  |  |
| Central America | Nicaragua | 280 |  |  |  |  |

### Trends to Accelerate Adoption

The identification of trends to accelerate adoption of biogas is limited by lack of evaluations of existing biogas interventions. Household biogas technology currently suffers a slow and declined growth in its adoption. An increase in well-educated population is expected to improve the adoption chances of Biogas (Abadi, Gebrehiwot, Techane, & Nerea, 2017).

Income growth, in rural farming and livestock sector (Diouf & Miezan, 2019) may increase adoption of biogas for cooking (Pachauri, Rao, & Cameron, 2018), given the current annual income in certain areas is lower than the average expenditure for biogas post subsidization (Abadi et al., 2017). In rural China, increase in income in rural areas is also linked to favored use of coal or electricity instead of biogas (Wang, Lu, Yang, Feng, & Ren, 2016). Increase in subsidies for household biogas have shown to increase digester installations (Mengistu, Simane, Eshete, & Workneh, 2015; Wang et al., 2016). However, large dependency on the subsidies has not been a positive factor to adoption given subsidies are eventually reduced, resulting in a decline in motivation to adopt the digesters (Mengistu et al., 2015). Reduction in operational and maintenance costs can also be a key driver to the rapid adoption of household digesters (Wang et al., 2016). External financing obtained by Cambodia and Sri Lanka has been beneficial to expand their biogas activities (Renewable Energy Policy Network for the 21st Century, 2018).

Importance of government-created awareness and support such as policies, laws, regulations etc., are highlighted as more effective compared to friends and family based in rapid adoption of biogas (Wang et al., 2016) and has been cited as a cause for successful adoption (Mengistu et al., 2015). The adoption improvement in Africa is however attributed to the efforts of NGO’s in initiating Biogas programs (Roopnarain & Adeleke, 2017). Support during initiation of the project is essential in beneficial adoption of methane digesters (Roopnarain & Adeleke, 2017). Government involvement in Africa, similar to China, may be helpful in beneficial adoption of the technology (Roopnarain & Adeleke, 2017). The generation of support/social networks is also identified as a potential factor in successful dissemination of clean cook stove technologies (Kumar & Igdalsky, 2019). In addition, policies to address the unaffordability of biogas technology in rural areas are required to improve adoption (Pachauri et al., 2018). Reducing the low initial cost bias could be beneficial in the adoption of small methane digesters, eliminating a major obstacle for wide spread dissemination of the technology (Mengistu et al., 2015).

Better availability of cement for construction of Biogas plants (Abadi et al., 2017) or use of other diverse materials, local and cheaper materials, or a different design (Clemens, Bailis, Nyambane, & Ndung’u, 2018) for construction have the potential of increased adoption of Biogas (Roopnarain & Adeleke, 2017; Wang et al., 2016). Improved construction and design of biogas digesters would result in successful installation and maintenance delivering higher adoption rates. This would require skilled craftsmen to construct and maintain digesters to ensure sustainability of the technology (Quinn et al., 2018). Also, encouraging use of prefabricated digesters can improve the adoption of this technology as the digesters would then be subject to multiple quality assurance tests and ensure minimal failures on site (Roopnarain & Adeleke, 2017) and in turn increase positive feedback, promoting increased adoption rates. Improved follow-up service and management are also expected to improve the adoption of household biogas, given the rise in demand for household biogas digesters (Pachauri et al., 2018; Wang et al., 2016). Standardization is also recommended to improve adoption as it suggests that the particular biogas technology is no longer in experimental stages (Roopnarain & Adeleke, 2017).

Use of alternative input to the biogas digesters could be a factor in its rapid adoption. Table 1.2 provides a comparison of crop, wastewater and dung as feedstocks. Livestock are not owned by all rural families and in some cases, not enough livestock are owned (Pachauri et al., 2018). On an average, adopters of biogas digesters are shown to own a minimum of 4 livestock (Pachauri et al., 2018), which might be a sign of wealth in rural areas (Roopnarain & Adeleke, 2017). Suitable feedstock includes crop residues and human waste in addition to animal waste (Rupf, Bahri, Boer, & McHenry, 2016). Also, encouraging co-digestion (i.e., combination of different feedstock), has the potential to increase the yield in such situations, and thus can contribute to accelerated adoption in areas with scarcity in livestock manure as input, in compatible digesters. Co-digestion can provide a higher yield of methane (Rajendran et al., 2012).

Table 1.2 Methane and Biogas production potential of different feedstocks

| **Source of Biogas** | **Biogas production potential (Billion m3/year)** | **Methane production potential (Billion m3/year)** | **Energy production equivalency (TWh/yr)** | **Biogas yield (m3/kg oDM)\*** | **Methane content (%)** | **Country/Region** |
| --- | --- | --- | --- | --- | --- | --- |
| Crop residue (Maize, wheat, rice from paddies) | 15.6 | 9.35 | 96.9 |  |  | Sub-Saharan Africa |
| Livestock manure (dairy and non-dairy cattle, chicken, ducks, turkeys, goats, pigs, sheep, asses, camels, horses and mules) |  | 0.681 | 7.056 |  |  | Sub-Saharan Africa |
| Maize (Maize, Straw) |  |  |  | 0.7 | 60% (assumed by source) | Sub-Saharan Africa |
| Rice, paddy |  |  |  | 0.59 | 60% (assumed by source) | Sub-Saharan Africa |
| Wheat |  |  |  | 0.41 | 52% (assumed by source) | Sub-Saharan Africa |
| Domestic wastewater (flush/ pour flush systems to a piped sewer, septic tank, or pit latrine, as well as ventilated improved pit (VIP) latrine, pit latrine with slab, and composting toilet) |  | 2.4 | 25.2 |  |  |  |

Source: Biogas yield -Rupf et al., 2016

\*oDM – Organic dry matter.

The water requirements are about 50 dm3/day (50 l/day) for each cow and 10 dm3/day (10 l/day) for each pig providing manure to the digester or 25 dm3/day (25 l/day) for each person in household using a digester volume of 1.3 m3 per capita (Bansal et al., 2017). In areas with low supply of water, domestic recycling, rainwater harvesting, and aquaculture are potential sources of water needed by the digester (Bansal et al., 2017). Sub-Saharan Africa where there is high potential and need for growth of bio-gas as a cooking fuel, is classified as having economic water scarcity, meaning available water resources are, for various reasons, not being used to their full potential (Bansal et al., 2017). Africa was also reported to have the lowest share of cultivated land being irrigated (5.9% in 2003) (Heegde & Sonder, 2007). Lack of infrastructure makes minimum water collection, a tedious job, linked to numerous, health and social problems. Water use for bio-digester thus an extra water requirement, needing more water collection trips by women, reducing time for activities such as education (Bansal et al., 2017).

Biogas implementation has multiple benefits, including energy for cooking, waste management, production of fertilizer, better sanitation, and environmental benefits (International Energy Agency, 2018). Waste managed from areas with improper sanitation management if captured and digested has the potential to produce 20-50 billion cubic meters, sufficient to provide clean cooking energy to 60-180 million households. Promoting its multiple benefits may help drive the adoption of this technology considering the by-product digestate may be more valuable to households than biogas energy itself (Roopnarain & Adeleke, 2017). Bio slurry as fertilizer increases agricultural production (Mwirigi et al., 2014). The potential of small/household biogas plants in creating jobs can also be a key driver in promoting the adoption of this technology (Roopnarain & Adeleke, 2017).

### Barriers to Adoption

The most commonly encountered barrier to adoption of methane digesters is its upfront cost (Diouf & Miezan, 2019; Global Alliance For Clean Cook Stoves, 2015). Larger size digesters have better financial stability (Rajendran et al., 2012), provided there is sufficient feedstock to run the digester. The net present value of the digester could be high or low (~$50-$200) depending on a few factors. The technology is unaffordable by extremely low-income bearing households that mainly rely on agriculture and livestock for their income, having access to feedstock that they are not able to generate biogas with. Rural population that cannot afford cattle, and sufficient water (Bansal, Tumwesige, & Smith, 2017), are not able to benefit from methane digesters.

Government policies established for dissemination of the technology have failed to reach their adopted targets, due to inadequate subsidies. Social barriers to adoption may also exist in demonstrated rigidity to involve cattle in commerce in some cultures, where cattle are counted as wealth and are a symbol of social status. Improper construction, leading to high maintenance, or repair costs, and inadequate training of operators are also factors slowing hindering the adoption of household digesters (Global Alliance For Clean Cook Stoves, 2015).

The other major barrier to adoption of methane digesters is failures in their operation, including leaks and also malfunctioning of the digesters (Roubík, Mazancova, Banout, & Verner, 2016). Such issues lead to dis-adoption of methane digesters (Rajendran et al., 2012). Various other barriers to adoption of this technology exist such as availability and proximity to free biomass (International Energy Agency, 2014), availability of livestock, lack of good roads to transport clean cooking stoves, low access to repair centers. Space for installation is also a barrier especially in countries like Nigeria where the houses are clustered. A community scale biogas is more beneficial for adoption in such scenarios (Rajendran et al., 2012).

### Adoption Potential

The adoption of household digesters is estimated to rise in Asian countries (Hyman & Bailis, 2018). In China, about a 100 million people in rural areas have access to biogas for clean cooking (Zuzhang, 2013). In India about 95% of the urban population has access to LPG as a cooking fuel at subsidized rates. In rural India (159 million people), based on 2007-2008 data, 77.6% of the population used firewood/chips (Bansal, Saini, & Khatod, 2013). In rural households, in India, middle- and high-income households were found to be the larger share of biogas users (Bansal et al., 2013). Fuelwood is still projected to hold the maximum share in 2031-32. This increase is expected based on a projected increase in rural population in India and continued lack of access to commercial fuels for cooking (Bansal et al., 2013). Biogas share for the year 2003-04 was estimated at 0.44% in India (0.71 MTOE) (Bansal et al., 2013). India has a large cattle population and the quantity of dung produced is expected to grow from 2 million tonnes/day to 3 million tonnes/day in 2022. Similarly, with increasing consumption of poultry, poultry waste can also be used as feedstock and is estimated to supply 438,227 m3/day of biogas. India being an Agrarian country, it can benefit from bio-methanation crop residue that is typically burnt for waste management (Vijay, Kapoor, Trivedi, & Vijay, 2015).

A high technical potential of 18.5 million households is also possible across 24 African countries. However, the adoption is slow (Heegde & Sonder, 2007). In rural east Africa, about 95% of the households report using solid fuels (Clemens, Bailis, Nyambane, & Ndung’u, 2018). Biogas based cooking is technically feasible for 18.5 million households in 24 African countries based on an analysis of livestock ownership, water availability, fuel scarcity, population density, and climate (Clemens et al., 2018). Investment costs in Africa are estimated to be double compared to Asia, due to high labor, raw material and appliance costs (Clemens et al., 2018).

For biogas to be an attractive option, a generation of at least 0.8-1 m3 of methane per day is essential to provide at least 2-3 hours of cookstove time to prepare at least 1 family meal. This requires about 20-30 kg of dung on a daily basis. Typically, 2 cattle would be sufficient to produce this amount of dung. However, given the small and undernourished animals, for example in Africa, this minimum number of cattle required, increases from 2 to 4, for sufficient input to bio digesters.

## Advantages and Disadvantages of Methane Digesters

Use of methane digesters for household cooking has several advantages including reduced use of traditional fuels, saved time used to generate income, cost savings from switching to a natural fertilizer, return in a higher NPV. In cases where saved time does not generate income, or animal manure was already a fertilizer, the income generated could be very low.

Disadvantages include long periods of digestion (~30 days) (Rajendran et al., 2012). Leakage from biogas digesters releases methane and carbon dioxide emissions into the environment. These leaks can also cause fire explosions in households.

### Similar Solutions

Similar solutions to biogas for cooking include improved, clean and renewable cooking solutions including, solar based cookers and ovens. Table 1.3 provides a comparison of traditional and clean cooking solutions for some key indicators. Worldwide an estimated 3.1 million solar cookers were distributed by the end of 2017 (Global Alliance For Clean Cook Stoves, 2015; REN21, 2015). Other solutions include use of ethanol, high efficiency biomass stoves, and renewable sourced electricity (Vianello, 2016).

Cooking with ethanol results in lower emissions compared to conventional cooking technologies. It heats up quickly but has a low heating value. It needs a special stove, which may also be the case for biogas. Solar based systems have expensive stoves. It is costly to produce and distribute unlike biogas which as high installation costs but low production costs. Renewable electricity is either unreliable or absent in rural communities but if affordable, are adopted in urban areas of developing countries. Special stoves are needed in this case as well. Biogas use can satisfy demands mainly in rural areas.

Urban areas in developing countries like India and Nepal, do not use Biogas and neither have the high potential feedstock to run the systems. They are associated with high social and cultural barriers, such as the need to cook outside in the middle of the day. Biogas production is not free of social and cultural barriers either, the idea of using dung or sewage is not culturally accepted in some areas. Similar to Biogas, solar cooking systems cannot be used for all kinds of cooking example, frying or roasting. While biogas is a very old technology solar based systems need much more awareness and training for better adoption.

### Arguments for Adoption

Biogas is a renewable and clean source of energy. Household scale biogas systems, typically in rural areas of developing countries, burn biogas for heat and cooking use, displacing propane, kerosene, cookstove wood and\or other fuels (U.S. EPA, 2016). Well-functioning biogas plants can replace the entire consumption of firewood or charcoal of individual households by biogas. Adoption of biogas can save time (up to 4 hours per day) for both women and children that are typically responsible for household duties of collection of wood as fuel (myclimate, n.d.; The World Bank, 2011). Women also benefit the most from cleaner indoor air due to use of biogas for cooking.

The World Health Organization estimates 1.3 million people die each year from indoor burning of solid biomass. Reduction in use of conventional cooking fuel such as wood, crop waste, dung, and charcoal can reduce premature deaths (approximately 3 million a year) caused by household air pollution due to burning of these fuels (Quinn et al., 2018). Other perceived health benefits of adoption of bio-digesters include reduced eye and respiratory problems (Clemens et al., 2018).

Methane losses from manure management are 12–41% of total agricultural CH4 emissions for most countries (Chadwick et al., 2011). Biogas generation and use reduce fugitive CH4 emissions in manure storage. In addition, N2O emissions in application of digested manure on cropland, are reduced (Massé et al., 2011). Manures from livestock production systems are estimated to contribute 30 to 50% to the global N2O emissions from agriculture. There is a reduced number of pathogens, reduction in odor, and viability of weed seeds in manure that is to be used on cropland (Chadwick et al., 2011). There is also reduced NH3 volatilization in application of digested manure on cropland (Massé et al., 2011).

### Additional Benefits and Burdens

#### Benefits

Biogas systems provide numerous benefits for families, businesses, farms, and communities (including economic, energy, and environmental benefits). They enable the capture and use of wastes and nutrient recovery. The amount of firewood or charcoal saved can be directly translated into hectares of forest saved. The economic benefit of biogas can then be reflected in re-afforestation costs saved (Energypedia, 2016). Excess biogas produced can be stored or sold for additional income. Use of bio-digesters can be a source of revenue if bio-slurry/digestate (a co-product of the bio-digesters), is used to increase agricultural production (Clemens et al., 2018).

#### Burdens

Methane digesters require certain operational conditions, maintenance and feedstock supply, which may not always be available. Optimum temperature needs to be maintained for biogas production. In higher altitude in winters, biogas production decreases. Solar energy has been used in the past to help maintain this temperature (Rajendran et al., 2012). Digester buried underground also benefit from geothermal heat that helps maintain the temperature required for digestion. Insulation in the digesters could also help avoid heat loss.

Incomplete digestion may be a problem, possibly caused by poor feedstock or poor management. If this happens, the resulting digestate may not meet government standards, and could lead to contamination of the land where it is further used. The combustion of biogas produces nitrogen oxides, which are associated with respiratory problem.

Table 1.3 Sector Technology Comparison

| **Cooking Fuel type** | **HAP\*** | **Deforestation** | **Monetary benefits** | **CH4 emissions Reduction** | **N2O emissions Reduction** | **Time savings** | **Fuel Efficiency** |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Firewood | High | Med |  | Low | Low | Low | Low |
| Coal |  | Low |  | Low |  |  | Low |
| Dung |  | Low |  |  |  | Low | Low |
| Charcoal |  |  |  | Low |  |  | Low |
| Kerosene | High | Low |  | Low |  |  | Low |
| Biogas | Low | Low | Med | High | High | High | Med |
| Solar | Low | Low | High | Low |  | High | High |
| LPG | Low | Low | High | Low |  | High | High |
| Electric | Low | Low | High | Low |  | High | High |

\*HAP- Household Air Pollution

Table 1.4 Key for sector solution comparisons

|  |  |
| --- | --- |
| **Cooking fuel type** | **Average efficiency** |
| Biogas | 53% |
| Wood | 20% |
| Dung cake | 15% |
| Crop residue | 15% |

\*Source -(Grösch, Delivand, Barz, & Bittrich, 2018)

# Methodology

## 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 2020 to 2060 (from a base year of 2014) and the comparison of these scenarios (for the 2020-2050 segment[[1]](#footnote-1)) is what constituted the results.

The biogas produced in the bio digesters can, as aforementioned in Section 1, be used for different purposes. This report focuses on the evaluation of the climate and financial impacts of the use of small bio-digesters for traditional cook stove replacement in developing countries. A Drawdown RRS model was constructed for this analysis.

The RRS model constructs both Project Drawdown Scenarios (PDS) and a Reference (REF) global adoption pathway for small bio-digesters for biogas production. A forecast of global and regional demand is used to represent the total addressable market (TAM). The REF scenario is then created by assuming that the future adoption of the bio-digesters remains fixed at the current base-year percentage of TAM (*i.e.* 2014).

The PDS scenario is constructed by drawing on existing adoption scenarios for biogas small bio-digesters to model adoption pathways. The model contains both financial and climate analyses designed to model the global and regional impacts of adoption in the PDS scenario compared to the REF scenario. The model thus prognosticates the total financial costs and benefits of optimistically plausible adoption cases for small bio-digesters, as well as the contribution these adoptions can make to annual emissions reduction.

## Data Sources

Data inputs for the models come from a variety of sources, primarily from peer-reviewed publications and from institutional reports. For all the variable inputs, this report conducts a meta-analysis of existing literature to create low, high, and mean estimates, based on data from widely respected sources. This allows the calculation of robust and reliable inputs for the financial and climate analyses that represent both optimistic and conservative estimates for the future costs and benefits of adopting this solution. The functional unit for this solution is TWh thermal and the implementation unit is a Cookstove Unit (whether a biogas system or a traditional stove). The implementation unit for this *small biodigesters* model was chosen as number of improved cook stoves. This decision was made for the ease of calculation of financial variables since most literature reports first costs and operational costs per stove.



## Total Addressable Market (TAM)

As small bio-digesters are used by households to replace inefficient fuelwood and charcoal cook stoves in most cases, the total addressable market (TAM) for small bio-digesters includes the demand for traditional fuelwood or charcoal cook stoves. This assumption eliminates the developed regions of the world such as U.S.A. and E.U. region and only focuses on developing regions including Asia, Middle East, Africa, and Latin America. The TAM units used are TWh (th) of final cooking energy in the given regions.

#### Global data

##### Daioglou et al (2012)., and V.R.Putti et al (2015)

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 cooking energy use data from Daioglou et al., (Daioglou, van Ruijven, & van Vuuren, 2012) and population dependency on solid biofuels data from Putti et al., (Putti, Tsan, Mehta, & Kammila, 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, Pachauri, & Nagai, 2012), India (Venkataraman, Sagar, Habib, Lam, & Smith, 2010) and Sub-Saharan Africa (IEA, 2014) for the year 2005.

To obtain the total population dependent on 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 (Asia (Sans Japan) minus population from South and East Asia that are dependent on solid biofuels) and the dependency % from putti et al., was applied to obtain the population dependent on solid fuels from South East Asia. The sum of the 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 Sus-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, 2017; 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 to develop a global TAM projection using energy use cooking energy use data from Daioglou et al., (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., (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 V.R.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 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 8967 TWh in 2004 to 9513 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.

#### Regional Data

##### 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. 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 and V.R.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 and Zao (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 and Pan (Zhu & Pan, 2007) have provided total direct energy required for cooking and annual energy per household.

## Adoption Scenarios

How many small bio-digesters can be installed in developing countries? While few countries have set up targets for installation of small bio-digesters, no estimates of total biogas potential are available. Therefore, as part of this analysis, an estimate of the total number of biogas plants that can be installed has been calculated. Two feedstocks were considered for the adoption scenarios, animal manure (including cattle, pigs, and buffalo) and burning crop residue (maize, rice, sugar cane, and wheat).

The cattle, buffalo, and pig population along with the quantity of manure produced by each animal has been used to calculate the total quantity of manure available in the developing countries. Quantity of dung per animal type in kg/ day was obtained from IRENA 2016 (International Renewable Energy Agency, 2016). Since bio-digesters were available in various sizes and the input to digester varies based on the size of the digester, an average of size data, ~5 m3 was calculated, using data from various sources for size of a household digester. Input to a digester of that size was determined to be 40 kg of feedstock /day. It was assumed that both crop and dung using bio digesters would require the same input. This input per digester data and total feedstock availability data were used to determine how many biogas plants could be installed in each country.

It is not possible to collect manure from all the animals due to use of pasture land and also it is not always possible to produce biogas due to climatic conditions for instance in extremely low temperatures that do not allow anaerobic digestion or may require heating arrangements not possible at small scale. A minimum temperature of 15 degrees C is essential for anaerobic digestion (Heegde & Sonder, 2007). The feasibility factor of 0.5 and availability of 50% have been assumed. The feasibility factor has been applied to crop feedstock as well.

The total number of small biogas plants that can be installed in the developing world is estimated at around 191 million as per this approach. The total number of inefficient cook stoves in use is around 700 million however due to the highly inefficient combustion process the energy required for cook stoves is much higher.

To determine the TWh produced by small bio-digesters Equation 2 was used, it was assumed that 0.034 m3/Kg with 50% CH4 which is a conservative estimate compared to the range of biogas generation potential from cattle and pigs’ manure. The calorific value of CH4 of 37 MJ/m3 is used to calculate the total energy in biogas generated through bio-digesters the energy is then converted to MWh by using conversion factor of 1/3600 MWh per MJ. The total MWh generation potential is converted to TWh by dividing with the total number of small biogas plants feasible in the country to get the TWh generation per small bio digester per year.

|  |  |
| --- | --- |
|  | Equation 1 |

Where:

* is the biogas yield in m3/yr
* is the mass of feedstock in kg/yr
* is the Dry matter content in percent
* is the Organic dry matter content in percent
* is the Biogas potential in m3/kg

|  |  |
| --- | --- |
|  | Equation 2 |

Where:

* is the energy generated in TWh
* is the number of feasible biogas digesters
* is the feedstock input required per plant per day in kg
* is the percent by mass of feedstock that has Methane
* is the caloric value of Methane in MJ/m3

For the burning crop residue, the data was obtained from FAO (Food and Agriculture Organization of the United Nations, 2016), similar to livestock population data (Food and Agriculture Organization of the United Nations, 2014). Biogas potential was calculated from using this data and Equation 1, where m (kg/yr) is the available feedstock from Rupf et al (Rupf et al., 2016).

From different sources, the number of bio-digesters currently installed presently in a country are determined. This number was then multiplied by the average energy generated in TWh, calculated per plant based on plant and animal feedstock. The countries of Asia (sans Japan), Eastern Europe, Middle East and Africa, and Latin America have been included in the small bio digester analysis leading to the calculation of regional potential which is added to achieve global potential as provided in table below.

Table 2.1 Current energy generation and technical regional potential from small-biogas plants

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Variable** | **World** | **Asia (sans Japan)** | **Middle East and Africa** | **Latin America** | **Eastern Europe** |
| Current Generation (TWh) | 129.3 | 129.1 | 0.2 | 0.01 | 0.0 |
| Total Regional Potential (TWh) | 606 | 397.4 | 98.4 | 99.13 | 11.05 |

For inefficient cook stoves the average annual use was found to be 1.15E-06 TWh/stove/year (or 1.15 MWh/stove/year). This value was obtained from reported cooking energy use per household per year from various regions such as Africa (Demierre *et al*., 2015, Tucho and Nonhebel, 2015) and Asia (Rijal *et al.*, 1990).

There are no reliable sources for adoption scenario for small scale bio-digesters so low, medium, and, high growth adoption scenarios were developed. In the high growth scenario, it is expected that the total potential of installation of small bio-digesters can be achieved by 2050 and in case of the low growth scenario around 36-46% of the potential installation is expected to be achieved by 2050.

Several assumptions were considered for these scenarios:

1. The global and regional TAM projections are based on population growth since only few data points were available from 2015-2050. Cooking energy per capita is also assumed to be constant.
2. The more developed regions of the world e.g. USA, EU, and Eastern Europe were not considered during TAM calculations. This is mainly because the cooking fuel mix in both the regions is already cleaner than the developing regions and it would not be appropriate to consider these as addressable markets for dissemination of clean cook stoves.
3. Most of the variables used in the model have been weighted according to the cooking fuel mix. The mix was available for Africa, India and China for 2005 and projected for these regions for 2030. The model uses the average of the two years. This decision was made in order to accurately account for additional improved cook stoves in the solution stage which would not have been possible if the report had only used the 2005 fuel mix with only 0.7% improved cook stoves.

### Reference Case / Current Adoption

The Reference scenario fixes the adoption of household biogas digesters at the current % adoption of the TAM. The market for traditional cookstoves is prognosticated to grow along with growth in population and then start to decline as electrical stoves and other alternatives begin to lessen the reliance on traditional stoves and traditional fuel mixes. This scenario is likely counterfactual as China is indicating continued growth in adoption and the current investment in form-factor and efficiency modifications to biogas digester design.

### Project Drawdown Scenarios

The PDS scenarios are hampered due to the general lack of prognostications. However reasonable cases are developed and described below.

#### Plausible Scenario (PDS1)

This scenario scales the regional adoption (in Middle East & Africa and Latin America) to the current adoption in Asia (sans Japan) at 32% of the technical potential (determined by the availability of common feedstocks – manure and crop). Asia (sans Japan) itself grows by an additional 32% of technically feasible utilization of feedstock). Linear extrapolation is used to scale adoption from the current adoption to these future benchmark ceilings.

#### Drawdown Scenario (PDS2)

In this scenario, each Region (except Asia) achieves China's Current Capacity of 49.9% of technical potential in 2050. Adoption % assumptions for Asia are set for PDS2 at 100 % of Technical Potential.

#### Optimum Scenario (PDS3)

This scenario assumes full technical capacity adoption by 2050 (with linear growth).

## Inputs

Below are the details on model inputs used to calculate the results shown in this report. The format of the inputs is based on the Drawdown model template used to ensure standardization which allows integration. This section focuses on the customized inputs needed for this solution. For details on the template model design, inputs and calculations, please see documentation at www.drawdown.org.

### Climate Input

Due to avoidance of CH4 emissions through use of small bio-digesters and replacement of inefficient fuelwood cookstoves each bio-digester reduces around 1.25 tCO2e (Zhang *et al.*, 2013) to 2.95 tCO2e (Izumi *et al.*, 2016) per year per household. While the replacement of inefficient cookstoves and avoidance of CH4 emissions contribute to emission reductions. However, leakages from biogas can contribute to small amount of CH4 emissions. An average of 166,705 tCO2e/TWh therms was obtained using data from Zhang et al., (Zhang, Liu, Lutes, & Brambley, 2013), Mengistu et al., (Mengistu et al., 2015), and Grösch et al., (Grösch, Delivand, Barz, & Bittrich, 2018).

|  |  |
| --- | --- |
|  | Equation 3 |

Where:

* is the CO2-eq emissions reduction associated with the additional energy generation provided by bio-digesters in the PDS scenario.
* is the total energy generation of bio-digesters in the PDS scenario; likewise, for in the REF scenario.
* is the emissions factor (in t CO2-eq per TWh) of the conventional sources in the REF scenario for each region and year.
* is the average indirect emissions (in t CO2-eq per TWh) generated by the manufacturing, transportation, and operation and maintenance of bio-digesters systems over their lifetime.

In addition to CO2 emissions, black carbon is also an important factor to consider for the small bio-gas solution. 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 CO2 on a 100-year basis was found to be from 534-890 and an average of 9 values was found to be 712 CO2 eq. This value was used to calculate direct CO2 emissions for conventional and improved cook stoves.

Table 2.2 Climate Inputs

| **Variable** | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| Direct Emissions (Conventional) | *tCO2eq/ TWh(th)* | 93,337-652,647 | 372,992 | 9 | 7 |
| Direct Emissions (Solution) | *tCO2eq/ TWh(th)* | 3,413 | 3,413 | 1 | 1 |
| Black Carbon GWP | *CO2eq* | 534 - 890 | 712 | 9 | 6 |
| Fuel Consumed per Functional Unit (Conventional) | *Fuel unit (TJ) per TWh (th)* | 435-26,424 | 16,998 | 8 | 4 |
| Fuel Efficiency Factor (Solution) | *Fuel % saved* | 53%- 64% | 59% | 3 | 3 |
| CO (Conventional) | *Tons CO/TWh (th)* | 49,895- 380,784 | 215,339 | 6 | 3 |
| CO (Solution) | *Tons CO/TWh (th)* | 5.8 | 5.8 | 1 | 1 |

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[[2]](#footnote-2).

### Financial Input

Most of the financial variables (cost of traditional and improved stoves) have been obtained from sources such as World Bank (The World Bank, 2011), IEA (International Energy Agency, 2014), IRENA (International Renewable Energy Agency, 2017) peer reviewed articles and U.S. EPA (2015). The costs have been converted to US$ 2014 based on inflation. Weighting based on cooking fuel mix was applied to all the costs.

The first cost of stoves was obtained from various global and regional sources and weighted according to fuel mix. The average first cost of conventional stove was found to be $1.28 whereas the average first cost of biogas system was found to be $591.9

First cost of the stoves, both conventional and solution, were easier to find than the operating costs. Most of the fuel wood required for traditional wood burning stoves is collected by women in rural parts of developing world instead of being purchased, so technically the cost of fuel is zero, in these cases and no maintenance cost is usually associated with these types of traditional stoves. U.S. EPA (2015) has done a very detailed analysis of costs, fuel use and efficiency of various stoves from around the world in a lab setting.

The cost of small bio-digesters depends on the country of installation, size, design and material used and ranges from US$185 in Thailand for a 1.2 m3, cement fixed dome model digester (Rajendran et al., 2012) due to US$1,500 in Kenya which are mostly metal, or masonry based (SGPindia, ND). The operational cost of small bio-digesters is mainly from feeding it with manure and from minor maintenance to ensure that there is no leakage. Costs are very low as the manure is almost free of cost, and maintenance cost range from US$0.001 (Berhe, 2017) to 0.13 US$/KWh (Pydipati, 2010).

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.

The models constructs three PDS adoption scenarios for small bio-digesters globally and regionally for each year until 2050. This report models both the capital costs and the fixed and variable OM costs associated with each PDS scenario compared to those of the REF scenario.

Table 2.3 Financial Inputs for Conventional Technologies

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| First costs (Conventional) | *US$2014/Cookstove Unit* | 0-2.49 | 1.28 | 9 | 6 |
| Variable Operation and Maintenance Costs (Conventional) | *US$2014/kWh (th)* | 0.000-0.014 | 0.007 | 7 | 3 |

Table 2.4 Financial Inputs for Solution

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| Solution First Cost | *US$2014/Cookstove Unit* | $353.1- $830.6 | 591.9 | 34 | 14 |
| Solution Variable Operating Cost | *US$2014/kWh (th)* | 0.0014- 0.0830 | 0.0357 | 5 | 4 |
| Revenue (Solution) | *US$2014/kWh (th)* | 0.0002-0.0013 | 0.001 | 4 | 2 |

### Technical Inputs

Besides climate-only and financial-only inputs, there are some inputs that affect both sets of results. These are termed “Technical’ inputs and are described hereunder.

#### Life time capacity

Life time capacity of conventional and solution technology was calculated using average annual use data. Data for life time in years was obtained from literature and multiplied with the average annual use in TWh/stove/year. The data was weighted using the 2005 and 2030 average fuel mix to keep the relative market shares constant. Data for conventional technology’s life time was collected from 1 peer reviewed source and 5 agency reports, and ranged between 0.5-3 years for firewood and charcoal based traditional stoves (Energica, 2009; M. A. Jeuland & Pattanayak, 2012; Stockholm Environment Institute, 2019; The Glacier Trust, 2012; The World Bank, 2011). For biogas plants, data was available from 7 peer reviewed sources and 2 agency reports and the life time ranged between 5-25 years (Berhe, 2017; Centre for Environment Education, 2019; Mainali et al., 2012; Rupf, Bahri, Boer, & McHenry, 2016; The World Bank, 2011).

#### Average Annual Use

Average annual use data was available in energy use per stove per or per household from various peer-reviewed and public agency reports for Bangladesh, India, Nepal, Nigeria, Ethiopia and China. This data was converted into TWh (thermal)/Stove/year(Demierre, Bazilian, Carbajal, Sherpa, & Modi, 2015; Grieshop, Marshall, & Kandlikar, 2011; IEA, 2014; Miah, Al Rashid, & Shin, 2009; Parikh, Sharma, Singh, & Neelakantan, 2014; Pokharel, 2004; Rijal, Bansal, & Grover, 1990; Tucho & Nonhebel, 2015; Venkataraman et al., 2010; Zhu & Pan, 2007). Average of 2005 and 2030 data for average fuel mix was used to keep the relative market shares. Data for the average annual use of biogas was retrieved from peer-reviewed literature (Bruun, Jensen, Khanh Vu, & Sommer, 2014; Hou et al., 2017; Hyman & Bailis, 2018). Average annual use for solution was also calculated using Drawdown data collected for various regions.

#### Fuel consumed per functional unit

For the conventional technology, the amount of fuel consumed per functional unit, was obtained mostly from public agency reports, in amount of fuel consumed in Kg or tons per energy generated in MJ or GJ, per household or per stove. This data was converted to tons/TWh/year (IEA, 2014; Miah et al., 2009; The World Bank, 2011).

#### Fuel efficiency factor

Fuel efficiency factor for small methane digesters was obtained from only 3 sources, ranging from 53%-65% (Grösch et al., 2018; IEA, 2014; The World Bank, 2011).

#### Size of the Bio-digester

Data for size of the household bio digester was collected for various regions from two sources (Ferrer-Martí, Ferrer, Sánchez, & Garfí, 2018; Rajendran et al., 2012). Size of the digester ranged from 0.25 m3 to 12m3. The average size obtained from using this variable was 5.21 m3. Input to the digester varies with the size of the digester. Feedstock input to the digester is calculated based on this input.

#### Crop feedstock availability

Burning crop feedstock availability was obtained using FAO data (Food and Agriculture Organization of the United Nations, 2016). In integration with land sector, the global availability of burning crop residue decreases to what excess can be supplied.

#### Animal Manure Availability

The number of cattle, buffalo and pigs that are available to provide input manure for the biogas reactors is an important limitation. Data for each of the countries in the regions of focus has resulted in an estimate that’s used to identify the amount of manure that may be available (with some feasibility factors applied) for biogas reactors.

Table 2.5 Technical Inputs Conventional Technologies

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| Lifetime Capacity (Conventional) | *TWh (th)/ Cookstove unit* | 1.35E-06 - 1.29E-05 | 7.12E-06 | 6 | 5 |
| Average Annual Use (Conventional) | *TWh (th)/ Cookstove unit /year* | 4.75E-08 - 1.43E-05 | 5.93E-06 | 11 | 11 |
| Fuel consumed (Conventional) | *TJ/TWh (th)* | 435-26,424 | 16,998 | 8 | 5 |

Table 2.6 Technical Inputs Solution

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| Lifetime Capacity (Solution) | *TWh (th)/ Cookstove unit* | 2.8E-05– 6.7E-05 | 4.7E-05 | 9 | 6 |
| Average Annual Use (Solution) | *TWh (th)/ Cookstove unit/year* | 2E-06 - 14E-06 | 5.7E-06 | 10 | 4 |
| Fuel Efficiency factor (Solution) | *%* | 53%-65% | 59.33% | 3 | 3 |
| Size of the Bio-digester | *m3* | 0.23-12 | 5.21 | 8 | 2 |
| Crop Feedstock Availability (in included countries) | *Tonnes/year* | 279,117,268 | Depends on Scenario | (Based on several inputs) | Several |
| Manure Feedstock Availability (in included countries) | *Tonnes/year* | 6,502,276,639 | 6,502,276,639 | (Based on several inputs) | Several |

## 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](http://www.drawdown.org). Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

1. For this model, a 10% discount rate is used consistent to what other similar solutions and conventional technologies have used.
2. Fixed and variable operating costs, as well as average fuel costs (from 2005-2014) are assumed constant through the modeling period. Biogas digesters is an old technology, so learning rate for the small bio-digesters was not considered since the development of biogas technologies has passed the experimental stage.
3. A single average bio digester size accurately represents all the bio digester sizes in use worldwide. The average size used was 5 m3.
4. For the financial calculations, the owner of a biogas digester is assumed to already have livestock and crops ready to provide feedstock, and this feedstock was originally unused.

## Integration

The complete Project Drawdown integration documentation (will be available at [www.drawdown.org](http://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.

Small Biogas is chiefly a household technology that supports families with cooking energy. As the focus here is on Small Biogas, the 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 for the Clean Cookstoves and Small Biogas models are:

* + - 1. Sharing of TAM and avoiding double counting
      2. Sharing of Conventional Technology variables (first cost, operating cost, emissions factors etc.)

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

Small Biogas also has an impact on Drawdown’s Biomass model since it helps reduce demand for firewood for domestic cooking in developing countries, and it uses crop waste to generate biogas. 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.

## Limitations/Further Development

1. Users are exposed to other conventional cooking technology and fuel impacts such as volatile organic compounds (VOC) and particulate matter (Dooho, Guernsey, Gibson, & VanLeeuwen, 2015) that are not modeled in this solution.
2. Based on available data on most commonly used size of the bio-digester, size of the bio-digester as an input will change, changing the input required in each bio-digester and the number of plants feasible, ultimately changing the adoption. A regional analysis would be beneficial here given that sizes within a region are less variant.
3. A better learning rate could be beneficial. Costs of bio-digester are very high considering their use is mainly in rural areas. With the limited data currently available costs seem to increase over time.
4. Modeling co-digestion could be considered using different feedstocks, including cooking waste, human waste, animal manure and burning crop residue.
5. Due to data limitations methane reductions have not been captured. Methane reduction is a benefit of this solution and should be tracked.

# Results

## 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** |
| Methane Digesters (Small) | *TWh (th)* | 129.3 | 331.48 | 501.45 | 605.95 |
| *% Market Share* | 3% | 5.1% | 7.7% | 9.3% |

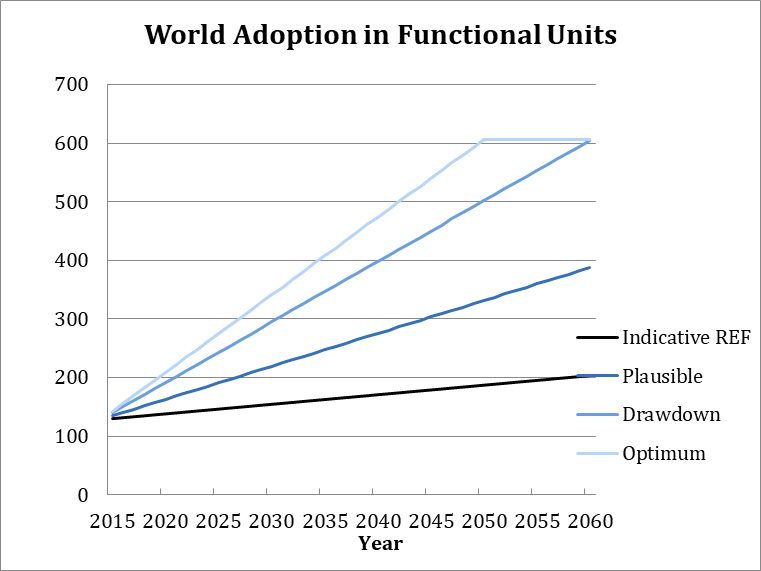


Figure 3.1 World Annual Adoption 2020-2050

## Climate Impacts

Below are the emissions results of the analysis for each scenario which include total emissions reduction. 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 CO2-eq/yr.)* | *Gt CO2-eq(2020-2050)* | (Gt CO2-eq/year) | *(Gt CO2-eq/year)* |
| ***Plausible*** | 0.26 | 4.77 | 0.12 | 0.26 |
| ***Drawdown*** | 0.57 | 10.37 | 0.25 | 0.57 |
| ***Optimum*** | 0.76 | 13.81 | 0.34 | 0.76 |

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 CO2-eq

| **Scenario** | **GHG Concentration Change in 2050** | **GHG Concentration Rate of Change in 2050** |
| --- | --- | --- |
| *PPM CO2-eq (2050)* | *PPM CO2-eq change from 2049-2050* |
| **Plausible** | 0.40 | 0.02 |
| **Drawdown** | 0.86 | 0.04 |
| **Optimum** | 1.15 | 0.06 |

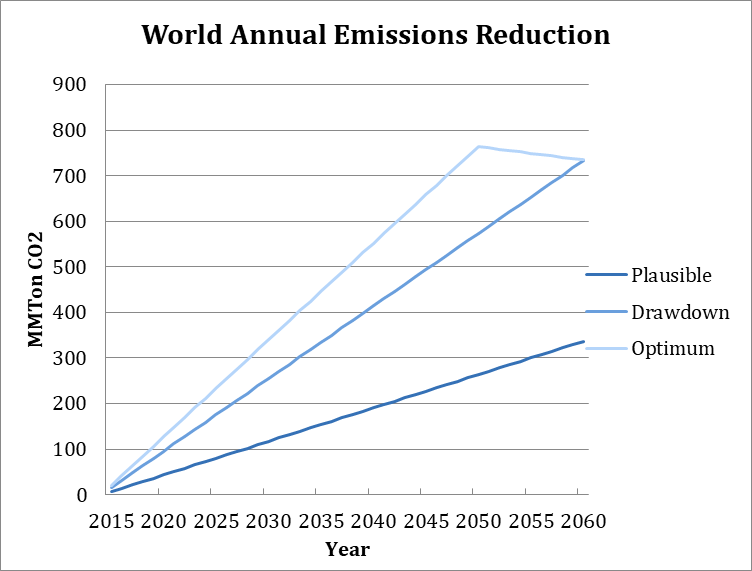


Figure 3.2 World AnnualGreenhouse Gas Emissions Reduction

## 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 Cost 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** | 34.50 | 24.40 | -75.48 | -110.59 | -49.37 |
| **Drawdown** | 63.50 | 53.06 | -163.13 | -240.47 | -107.39 |
| **Optimum** | 122.00 | 106.44 | -217.99 | -267.17 | -147.66 |

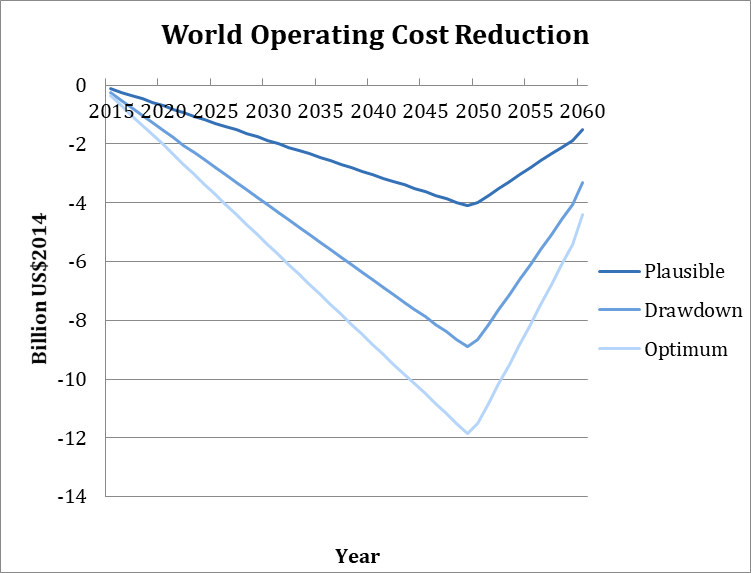


Figure 3.3 Operating Costs Over Time

# Discussion

The conversion of waste material in bio digesters into fertilizer and biogas have several financial and environmental benefits for families. Appropriate feedstock for small digesters is available in adequate quantity across the world from sewage sludge and agriculture systems, as well as in the form of crops and crop residues. Small household sized biogas digesters have potential to provide reliable, carbon emissions mitigation for household heating, cookery and other uses. However, the adoption in the best-case scenario does not exceed about 9% of cooking energy market share, by 2050. The major risk associated with adoption is disrepair and fugitive emissions. Creative feedstock switching and community scale aggregating are in development to increase the overall technical feasibility which is currently the limiting factor for the technology. Life time savings from adoption of this technology are an attractive adoption criterion.

The model holds a number of factors constant in order to keep global-scale modeling from becoming too complex and with increased uncertainty on assumptions, however, many of these factors, including prices of fuel operating costs might change significantly in the modeled timeframe.

The model could also improve regional and country level adoptions but currently this bottom up approach is difficult, and instead being presented are coarse estimates. An increased level of detail by country will be necessary to help local project developers identify the specific benefits of methane digesters when compared to other cooking and waste management practices. Importantly, producing high quality fertilizer is possible in other, cheaper ways (including traditional approaches). What makes biogas an attractive option is the fact that this technology can provide solutions to a variety of problems simultaneously and its use has the strong advantage of net emissions reduction avoidance related to methane and nitrous oxides.

Use of traditional fuels is associated with forest degradation. Although in some cases research has shown that these impacts are not detrimental. In Uganda, between 2007-2012, a 22% reduction was observed in fuelwood sourced from proximate forests and an 18% increase in fuelwood sourced from fallows and other areas with lower biomass availability and quality due to rapid land use change (Jagger & Shively, 2014).

This solution prevents methane emissions that are generated when storing manure. Crop residue is an attractive option to avoid methane emissions that may leak from bio-digesters. Improper biomass management strategies can release about 5g of methane /kg. When spread in the fields without pre-treatment, this kind of biomass is characterised with high methane emissions rates (Paolini et al., 2018).

## Limitations

The affordability of a bio digester and its operation is dictated mainly by household income and bio-digester feedstock availability. While bio-digester feedstock availability is factored in the adoption calculations, household income data if available could also be a useful variable for better adoption estimates. In addition, water availability is also key to anaerobic digestion. Availability of water per household could also be a useful indicator of adoption. Number of cattle owned and amount of other materials available as useful feedstock per household can also provide better estimates of adoption. The world adoption estimation may also benefit improving the TAM by critically reviewing the market share of cooking fuels more relevant to rural areas in developing countries where bio-gas is mainly used due to ready access to feedstock availability.

## Benchmarks

There is a lack of global scale modeling of environmental impacts of small methane digesters. IEA’s Energy Technology Perspectives 2016 and 2017 reports model the reductions in cooking emissions. A reduction of 9.5 GT CO2 and 17.9 GT CO2 is reported for 2 scenarios. Reductions from adoption of Biogas modeled in project drawdown scenarios can be compared to IEA scenarios. The Plausible scenario is comparable to IEA’s 6DS -2DS scenario and the Drawdown scenario is comparable to the RTS-B2DS scenario. The emission reductions from Drawdown scenarios are expected to be lower compared to IEA’s estimates because this solution is modeling only the reductions in emissions from adoption of small methane digesters.

Table 4.1 Benchmarks

| **Source and Scenario** | **Emissions reduced (2020-2050) GT CO2** |
| --- | --- |
| IEA-ETP 2017 RTS and B2DS | 9.5 |
| IEA-ETP 2016 6DS and 2DS | 17.9 |
| Project Drawdown – Plausible Scenario (PDS1) | 4.77 |
| Project Drawdown – Drawdown Scenario (PDS2) | 10.37 |
| Project Drawdown – Optimum Scenario (PDS3) | 13.81 |

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# 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 CO2 (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**.

**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 CO2e/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

1. 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. [↑](#footnote-ref-1)
2. 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. [↑](#footnote-ref-2)