**Technical assessment for**

**Large Methane Digesters**

Sector: Electricity generation

Agency Level: Utilities

Keywords: Methane, Agriculture, livestock, biogas, bioenrgy, Electricity Generation, Grid, Renewable Energy Source

Version 4 (June 2020)

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# Acronyms and Symbols

* AMPERE – Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates
* BAU – Business as Usual
* CH4 – Methane
* CO2 – Carbon Dioxide
* CO2 eq. - Carbon Dioxide equivalent
* DOC – Degradable organic carbon
* DS – Degree Scenario
* EPA – Environmental Protection Agency
* ETP – Energy Technology Perspectives
* EU – European Union
* FOM – Fixed Operation and Maintenance Costs
* GEM-E3 – General Equilibrium model for Economy, Energy and Environment
* GHG – Greenhouse Gases
* GMI – Global Methane Initiative
* Gt – Gigatons
* GW - Gigawatts
* GWP – Global Warming Potential
* IEA – International Energy Agency
* IMAGE/TIMER – Integrated Model to Assess the Global Environment/The Targets IMage Energy Regional model
* IPCC – Intergovernmental Panel for Climate Change
* IRENA – International Renewable Energy Agency
* LCA – Life Cycle Assessment
* LED – Light Emitting Diode
* LMOP – Landfill Methane Outreach Program
* MESSAGE-MACRO – Model for Energy Supply Strategy Alternatives and their General Environmental impact with macroeconomic feedback
* MSW – Municipal Solid Waste
* MW – Megawatt
* N2O – Nitrous Oxides
* O&M - Operation and Maintenance
* OECD – Organization for Economic Co-operation and Development
* PD – Project Drawdown
* PDS - Project Drawdown Scenario
* PPM – Parts Per Million
* PV – Photovoltaic
* RE – Renewable Energy
* REF – Reference Case
* RES – Renewable Energy Sources
* RRS – Reduction and Replacement Solutions
* TAM - Total Addressable Market
* TES – Thermal Energy Storage
* TWh - Terawatt-Hours
* US – United States
* USAID – United States Agency for International Development
* USD – United States Dollars
* VOCS – Volatile Organic compounds

# 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 and reduce GHG emissions. 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.

Current adoption (in 2018) is 63 TWh, equivalent to 0.28% of total electricity generation. Through advanced global adoption of large bio-digesters with biogas plants, around 389.2 TWh can be produced globally by 2050 in the Plausible Scenario, representing 0.85 percent global total electricity generation. This will have a climate impact of a cumulative avoidance of 5.46 Gt CO2 eq. from large bio-digesters. In the Drawdown Scenario and the Optimum Scenario, both will have a 0.57 percent share of total electricity generation and will result in a cumulative avoidance of 6.3 gigatons carbon dioxide equivalents.

The total installation cost of $141.14 billion for large bio-digesters is required for the Plausible Scenario. The net operating cost savings are U$28.87 billions net O&M cost savings from increased adoption of large bio-digester in the Plausible Scenario. As for both the Drawdown and Optimum Scenarios, a marginal first cost of US$183.1 billion and a net operating cost saving of US$32.83 billion will result. The benefit of large bio-digesters in addition to generation of clean electricity and heat there is benefit of avoidance of GHG emissions that would have occurred due to anaerobic degradation of CH4 and N2O.

# Literature Review

## State of Small and large Bio-Digesters

Anaerobic digestion (AD) is a biological process the 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 fibre digestate (Caruso et al., ND).

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) (Figure 1). However, biogas can also be made from almost any feedstock containing organic compounds, both wastes and biomass (energy crops). Carbohydrates, proteins and lipids are all readily converted to biogas (PEW, 2011; Wilkie, 2015).

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, operators drill a series of wells into the landfill, collecting between 60% and 90% of the biogas. The gas is then pumped to a central processing facility where it can be flared, refined or used for heat or electricity generation (PEW, 2011; Wilkie, 2015). In addition, liquid and fibre 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 “sterilisation” or pathogen kill to allow the sludge from wastewater to be recycled to land.

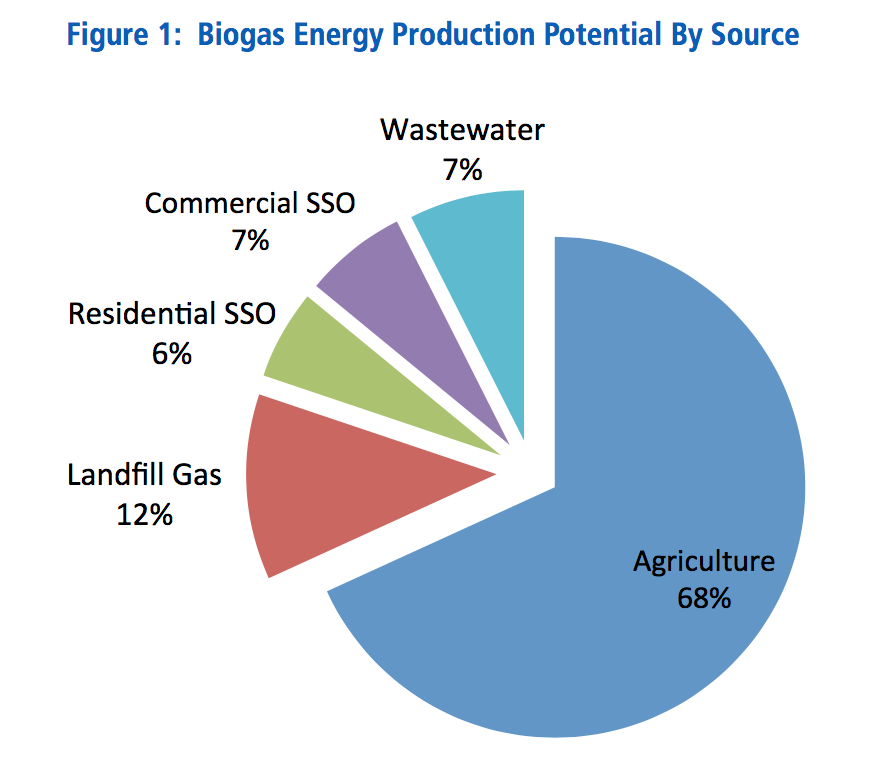


Figure 1 – Biogas energy production by source in Canada (Source: Biogas Association, 2013)

Anaerobic digesters provide a variety of environmental and public health benefits including: greenhouse gas abatement, organic waste reduction, odor reduction, and pathogen destruction. Anaerobic digestion is a carbon-neutral technology to produce biogas. Since methane is the principal gas in biogas and methane is also a main component in natural gas; biogas can also 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 (Figure 2) (PEW, 2011; Wilkie, 2015).

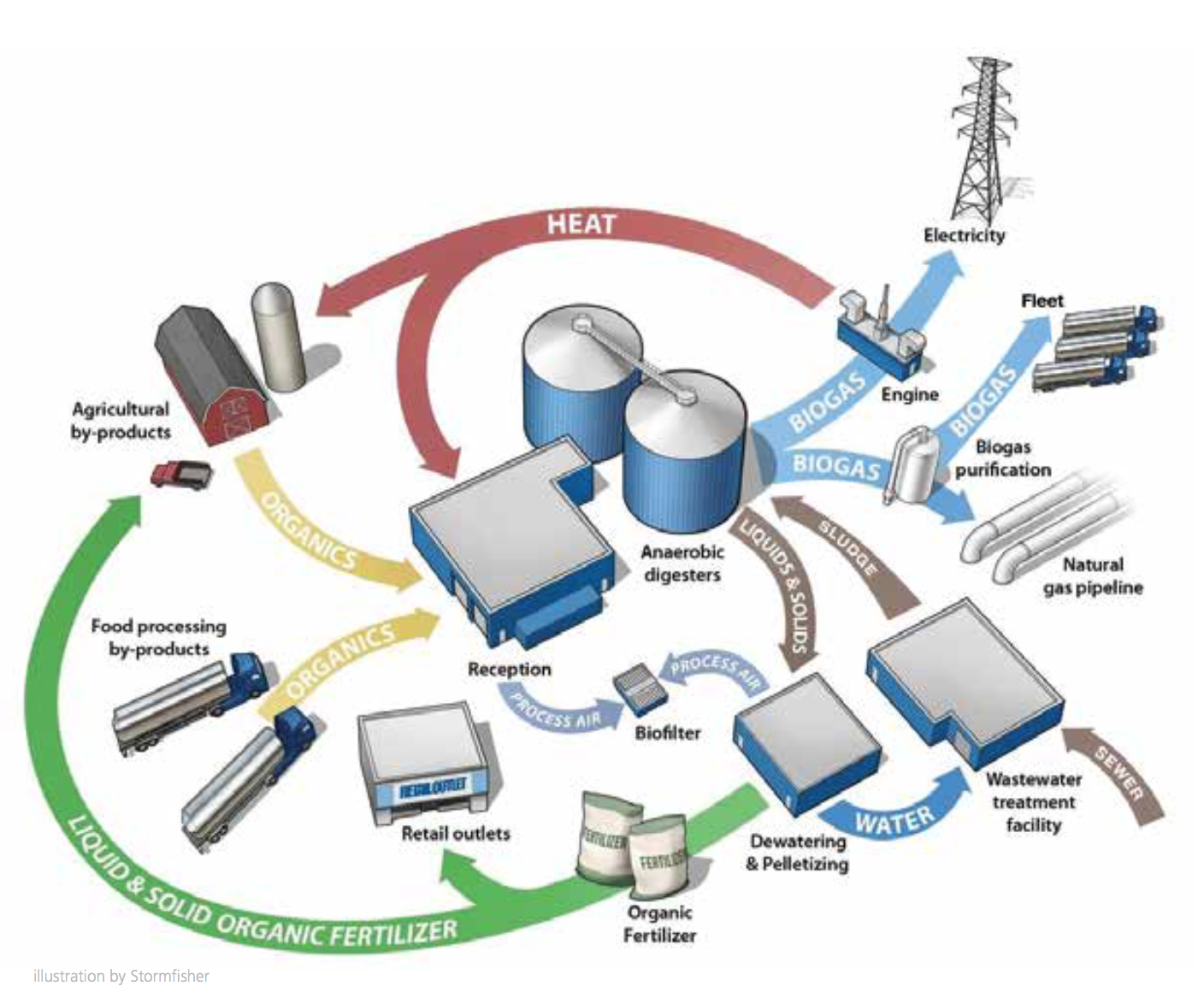


Figure 2 – Biogas: integrated renewable energy network (Source: Biogas Association, 2013)

There is a range of possible digester technology designs, all of which are essentially different types of tanks that allow for biogas capture. At livestock farms, the three most common technology types in the U.S. are covered lagoons, plug flow digester, and complete mix digester U.S. EPA (2016a), suitable for larger systems in regions where engineering resources are available. 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, 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. A third option, particularly in larger scale systems, is to combust the gas and produce electricity with a turbine in biogas powerplants (U.S. EPA, 2013).

The primary contribution of anaerobic digestion to GHG reduction is in its capture of methane gas, which has a potent global warming potential 21 times that of carbon dioxide by weight. Destroying methane via flare converts it to carbon dioxide.

### Large bio-digesters with biogas plants

There are different designs of large biogas plants (Giraldo et al., 2013):

**Plug-flow digester:** It is a long and narrow rectangular concrete tank with a flexible or rigid cover to capture the biogas. The tank is heated, insulated, and built partially or fully below the ground in order to limit heating requirements. The tank operates at the mesophilic range and is best suited for dairy manure from a scraped system with 11-14 percent total solids. The manure does not mix as it makes its way longitudinally through the digester. As new manure is added, it displaces an equal volume out, hence the name plug-flow, because the manure moves as a plug through the digester without mixing.

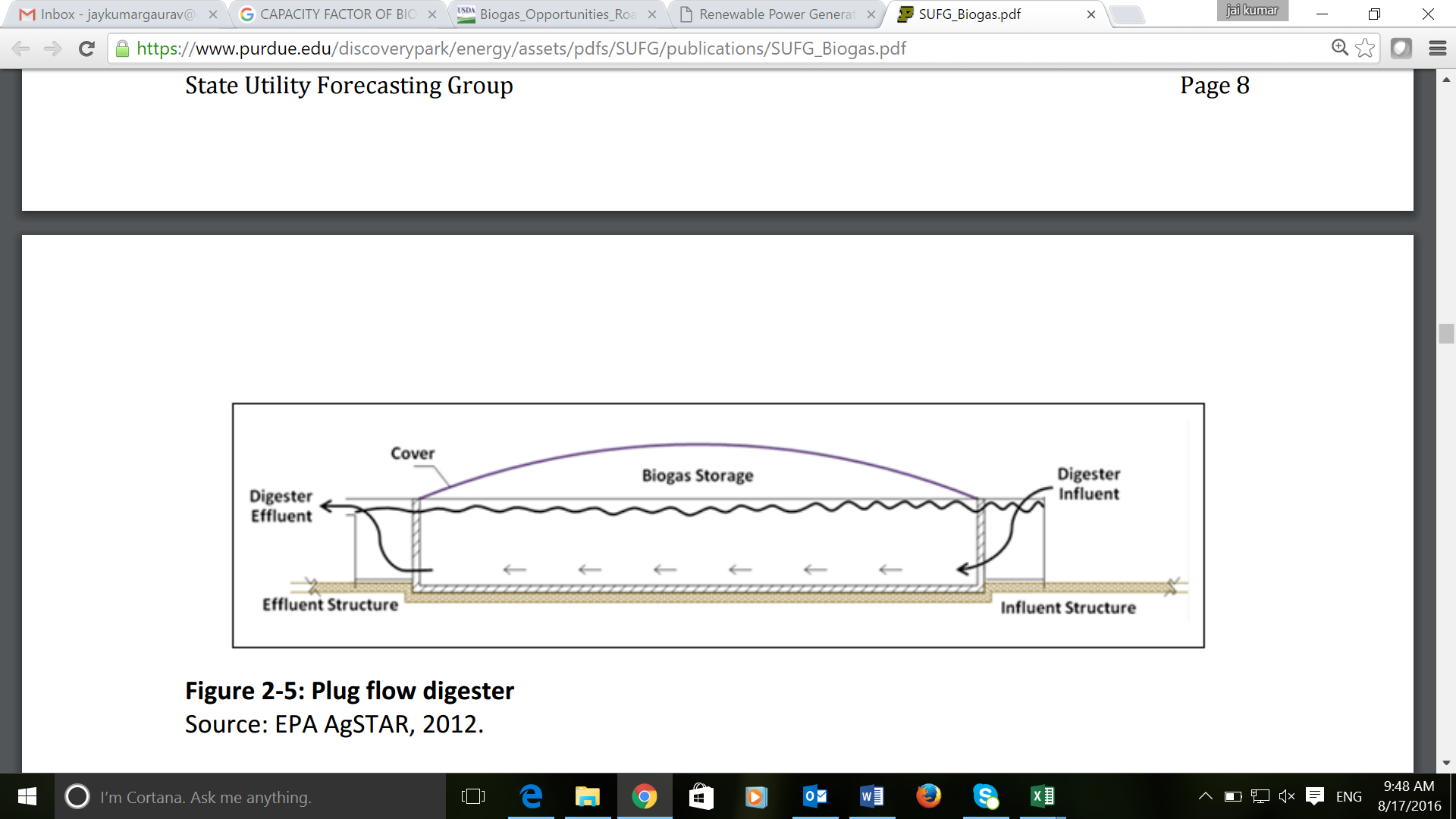


Figure 3 – Pluf Flow digester (Source: Giraldo et al., 2013)

**Complete Mix Digester:** It is an enclosed insulated tank, made of reinforced concrete, steel or fiberglass. Heating coils inside the tank circulate hot water in order to keep the operational temperature warm enough to maintain active AD. The contents are mixed with a mechanical, hydraulic, or gas mixing system. As the influent enters the digester, it displaces volume, causing an equal amount to flow out. The system uses a gas-tight cover (that can be flexible or rigid) to trap the biogas. The complete mix digester is best suited to process liquid manure that has 3-12 percent total solids.

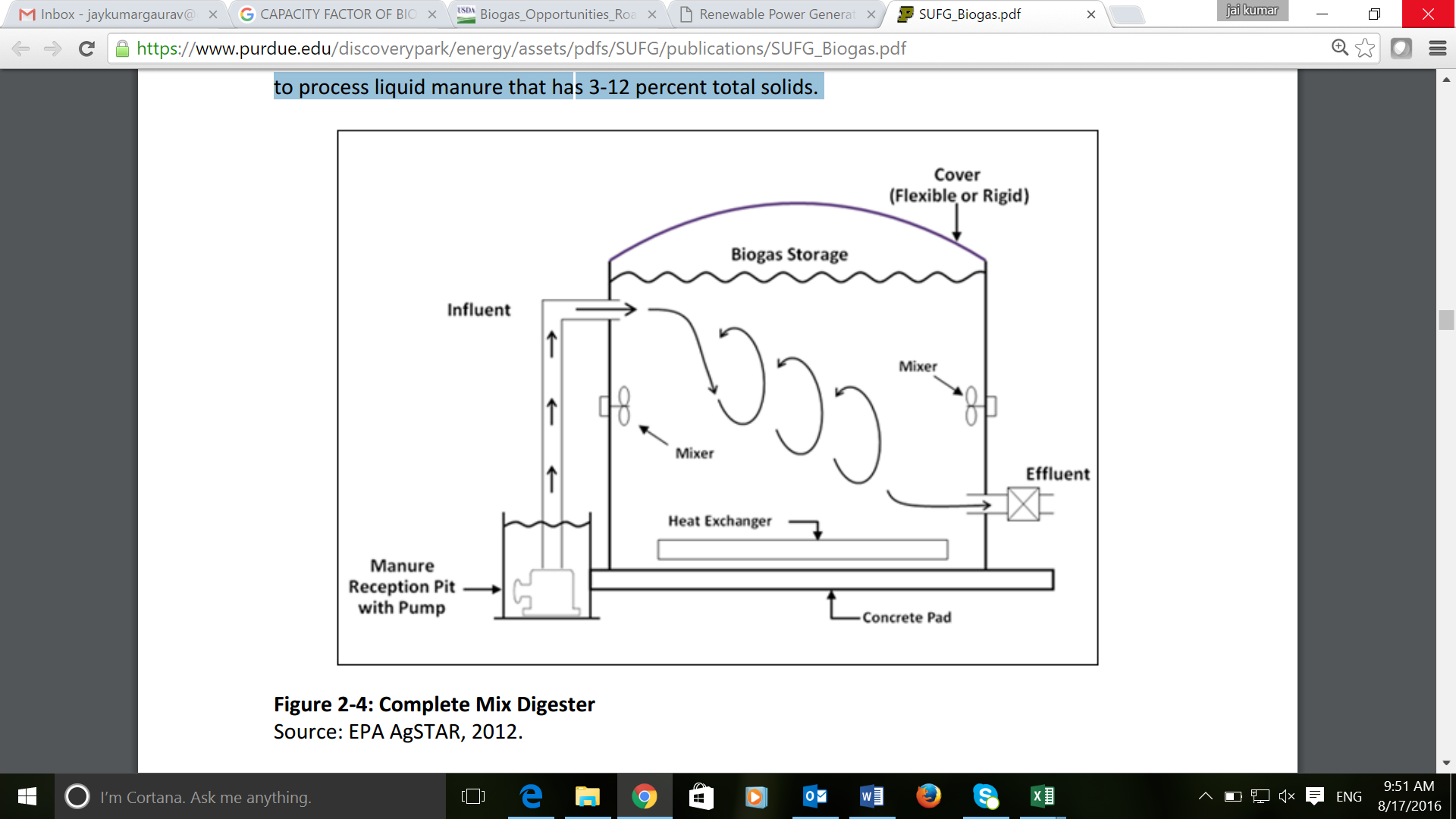


Figure 4 –Complete Mix Digester (Source: Giraldo et al., 2013)

**Covered Anaerobic Lagoon:** It consists of a pond-like earthen basin that is sealed with a flexible cover that captures the biogas. Anaerobic lagoons are used to treat manure with less than 3 percent solids, therefore they are best suited for systems that handle manure in a liquid form. Because they are unheated and operate at ambient temperature, for energy production they are only viable below the 40th parallel. This is because warmer ambient temperatures are required to produce enough biogas to support an electricity generator.

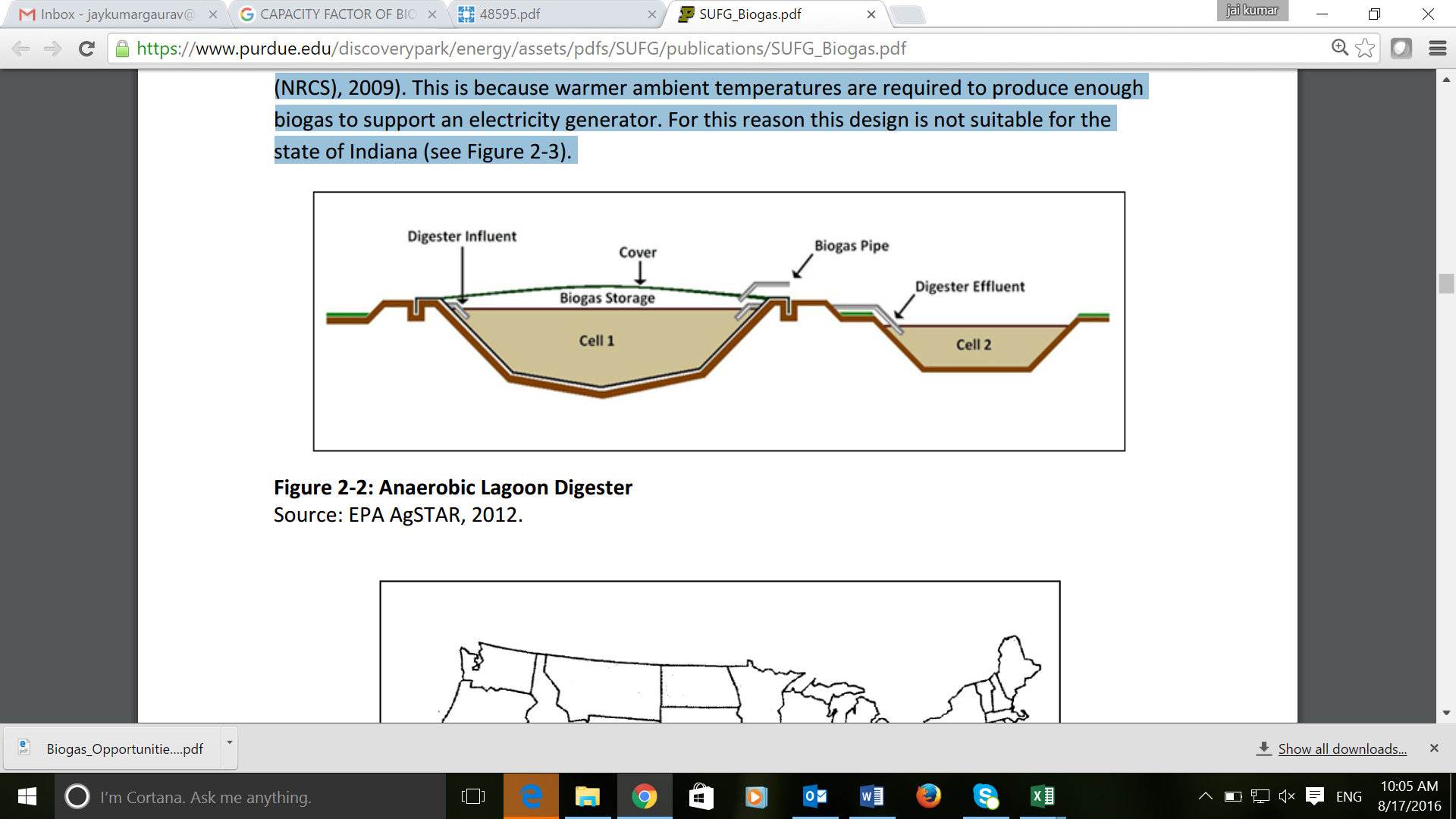


Figure 5 – Anaerobic Lagoon Digester (Source: Giraldo et al., 2013)

### Small bio-digesters

There are different designs for small bio-digesters as well some of the most common designs including the following:

**Fixed-dome Plants:** These consists of a fixed, non-movable gas holder, which is placed on top of the underground digester. The costs of a fixed-dome biogas plant are relatively low. It is simple as no moving parts exist. There are also no rusting steel parts and hence 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).

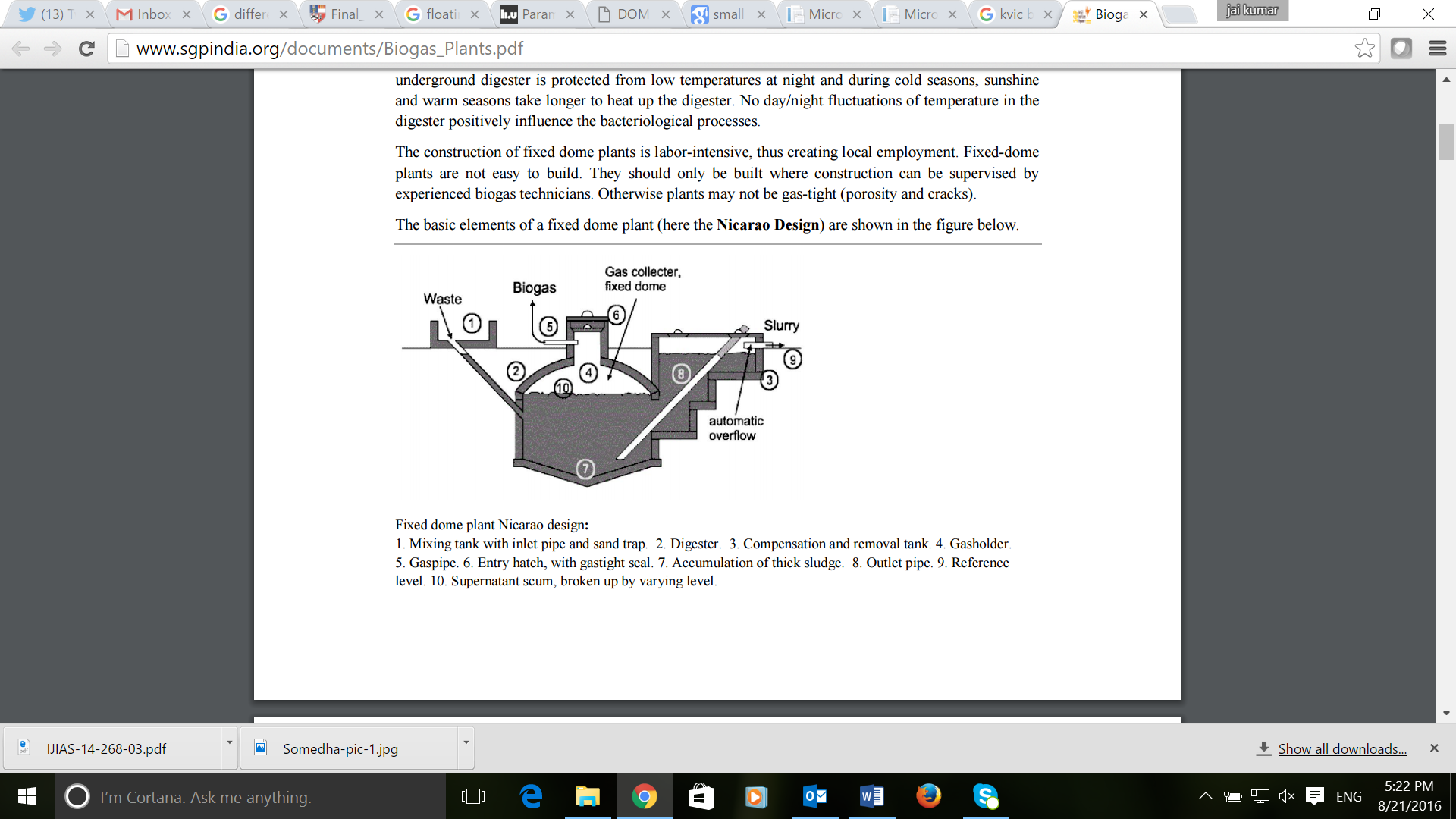


Figure 6 –Fixed dome plant Nicarao design (Source: Giraldo et al., 2013)

**Floating drum Plants:** These 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 made of glass-fiber reinforced plastic and high-density polyethylene have been used successfully, but the construction costs are higher compared to using steel (SGPindia, ND).

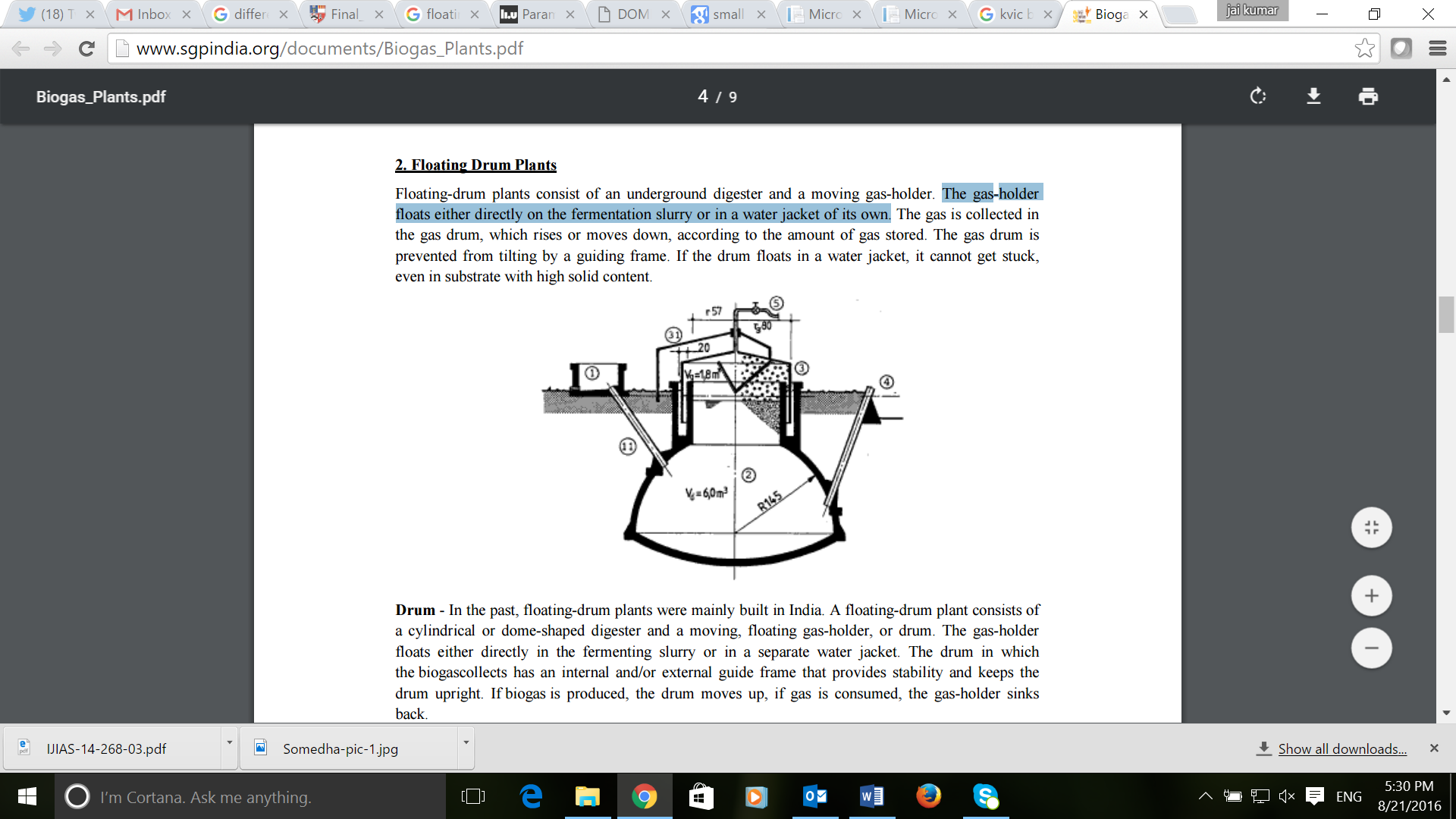


Figure 7 – Floating drums plant (Source: Giraldo et al., 2013)

**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 polyrthylene tube digesters include low gas pressure that may require gas pumps; scum cannot be removed during operation; the plastic balloon has a relatively short useful life-span and is susceptible to mechanical damage (SGPindia, ND).

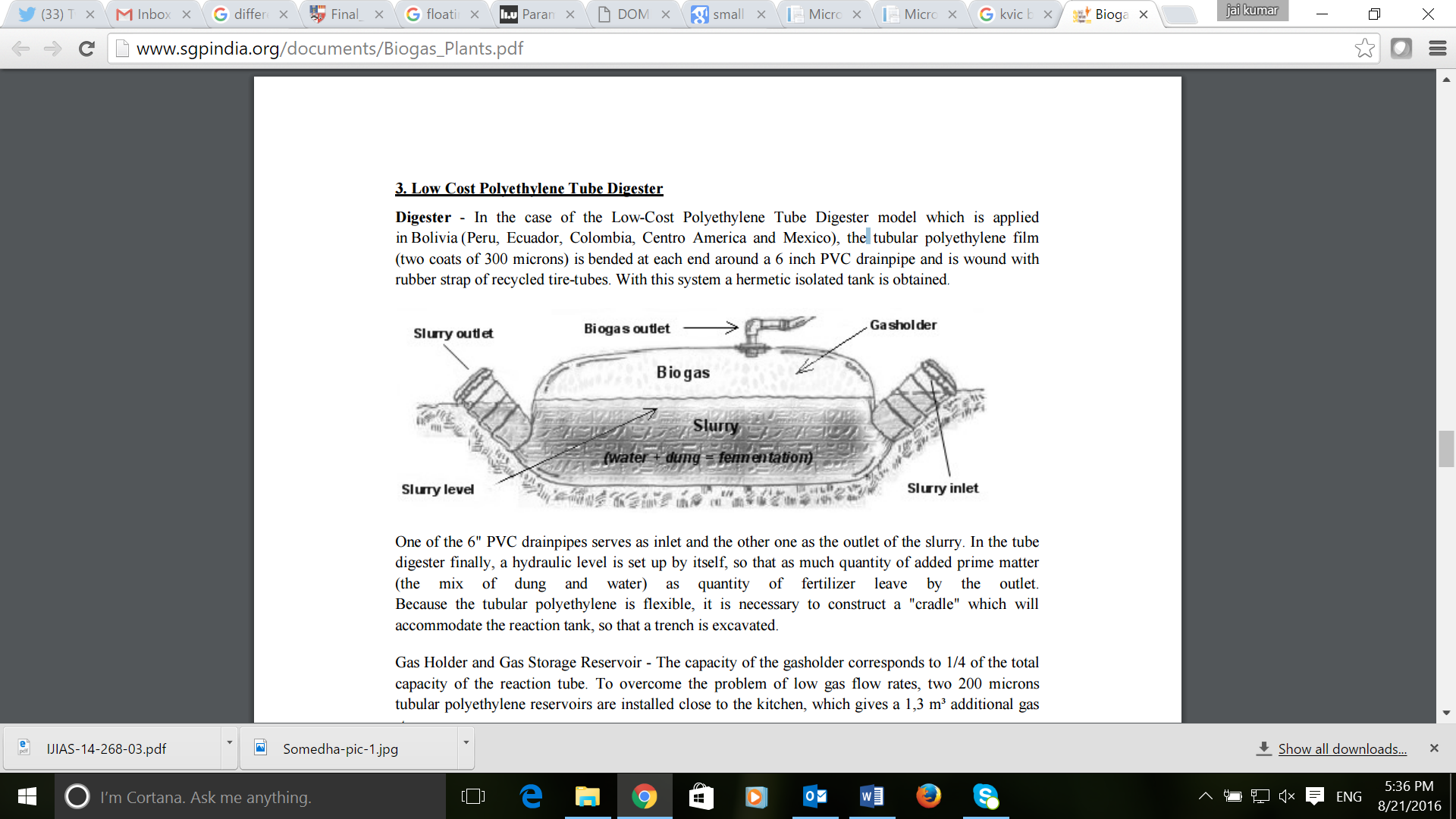


Figure 8 - Polyethylene Tube Digesters (Source: Giraldo et al., 2013)

## Adoption Path

### General Trends For Large Bio-Digesters with Biogas Plants

In 2014, the U.S. agricultural sector was responsible for 9 percent of total U.S. greenhouse gas emissions. GHG emissions from agriculture have increased by approximately 11 percent since 1990 (U.S. EPA, 2016b). One driver for this increase has been the growth in combined CH4 and N2O emissions from livestock manure management systems, reflecting the increased use of emission-intensive liquid systems over this time period.

Of all GHG emissions in the US, manure management emissions represented only 1.15%, agricultural soil management represented 4.6%, and wastewater treatments just over 0.28% of all GHG emissions. Though when assessing methane and nitrous oxides emissions, manure management was responsible for about 13.7 percent of methane emissions and wastewater treatment for 14.7 percent. Regarding N2O emissions, agricultural soil management represented 79 percent, manure management 4% and waste water treatment 1% (U.S. EPA, 2016b).

According to U.S. EPA (2016a) there were 242 operational biogas projects associated with livestock manure in the U.S. (May, 2016) including 196 Dairy, 39 Hog, 7 Poultry, 7 Beef, 7 Mixed and in 2015 these led to direct and indirect GHG emissions avoided of around 3.0 MMTCO2e and generated 981 million kWh equivalent of electricity which is around 123 MW considering 24 hours per day and 330 days of operation. There are also 1241 biogas systems in water resource recovery facilities and 636 capturing landfill gas. According to USDA (2014) only in the US the potential for biogas is over 13000 systems.

The EPA estimated that 62% of CH4 emissions from dairy and 70% of CH4 emissions from hogs could potentially (technical potential) be eliminated by use of AD (Baylis and Paulson, 2011). Applying economic feasibility to AD on US dairy farms, even at relatively modest carbon prices (*i.e*., $15/metric ton CO2-equivalent) could result in almost half of possible manure CH4 emissions from dairy farms being captured using AD (Baylis and Paulson, 2011). Doing a similar analysis, the USDA (2011) found that 44% of manure CH4 emissions could be captured at $26/metric ton CO2-eq.

In EU28, the agricultural sector represented around 10% of GHG emissions, but with a different path when compared to US, since it declined almost a quarter since 1990. The reduction in agricultural emissions of GHG may, at least in part, be attributed to an overall reduction in livestock numbers, more efficient farming practices, the reduced application of nitrogen-based [fertilisers](http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Fertiliser), as well as better forms of manure management. Manure management represented 1.73 percent of all GHG emissions in 2012 (Eurostat, 2016).

There is a great range in the CH4 emissions per animal, depending on how manure is managed, type of livestock, and temperature. Hogs for market can range from 1-23 kg CH4 per head per year; dairy cattle can range from 1-110 kg CH4 per head per year (IPCC, 2006).

The implementation process requires that manure management practices change. Changes in manure management practices from aerobic (dry lot, daily spread on fields) to anaerobic (lagoon, digester) will increase CH4 emissions and decrease N2O emissions. This effect will be particularly high in currently-low livestock CH4 emission regions like Africa, the Middle East and Latin America.

Significant development has also been made in AD processes from sewage sludge, which the wastewater industry has in abundance (Mills et al., 2014). Drying sludge post digestion has been common practice across Europe for over 20 years, especially in Germany where dried sludge is frequently used in coal-fired power stations and cement kilns (Kelessidis and Stasinakis 2012). Advanced energy recovery processes such as syngas pyrolysis and gasification are fast becoming feasible options post drying (Cao and Pawłowski 2012) that could displace conventional AD with electricity generation.

In Europe, anaerobic digesters are used to convert agricultural, industrial, and municipal wastes into biogases that can be upgraded to 97 percent pure methane as a natural gas substitute or to generate electricity. Biogas is also used in residential heating applications. In Europe, it is used increasingly to provide heat for both buildings (space) and industry (processes), often in conjunction with electricity production via CHP (REN21, 2016).

Europe has moved more aggressively to develop digesters than the U.S., and many European digesters have been designed as centralized units to serve the typically small farms (USDA, 2008). The advanced rate of adoption effectively means that each year, the output from another 15 million head of livestock become captured in digester systems. Historic rates of adoption have varied around the world. The US has realized digester growth of 11%-22% per year over the last years at dairy farms, equivalent to 35000 - 300000 head per year (U.S. EPA a, 2016).

In Europe, over half 50% of the total biogas produced was used to generate electricity. More than 14560 biogas power plants were operating in Europe, with total capacity approaching 10.5 GW. Germany accounted for half of this capacity (almost 4.97 GW) followed by Italy (1.39 GW) and Switzerland (1.45GW). In Europe, biogas is derived from agricultural waste, manure, and energy crops (accounting for 4.8 GW of power production capacity) (IRENA, 2016). However, in Germany biogas power capacity growth was limited in 2015 due to reductions in financial support for biogas plants. The biogas market grew strongly in the United Kingdom, with the fastest growth of any country in Europe, stimulated by an attractive feed-in-tariff rate (REN21, 2016).

Currently, biogas represents 20% of total electricity generation from bioenergy worldwide; 1.5% from all RES electricity generation and just 0.33% of total electricity generated in 2014. From total biogas generation in 2014, Europe has the highest share (74.2%) followed by North America (18.4%). The remaining 7% are split in Asia (but no China) (3%), Oceania (2.4%), Eurasia (1.3%) and South America (0.6%) (Figure 9) (IRENA, 2016). Anaerobic digestion plants are being deployed more widely to treat liquid effluents and wastes in Asia, notably in Thailand and Indonesia, where a range of waste materials – including effluents from cassava starch production, palm oil processing and ethanol production, as well as MSW – are being used as feedstocks. There are signs in Africa of increasing activity in biogas production, particularly waste-based projects that involve landfill gas, MSW and agricultural residues (REN21, 2016).

This generation was provided in 2006 by 5429MW, growing to 14020 MW of biogas capacity in 2014, with an average annual increase of around 21% (IRENA, 2016).

Figure 9 – Electricity generation from Biogas plants (2006-2014) (IRENA, 2016)

### General Trends for Small Bio-Digesters

Smaller-scale methane digesters have been widely installed in Asia, using fixed dome designs in Bangladesh, Nepal, and other countries (SNV, 2016). Asia leads the world in the use of small-scale biogas digesters to produce gas for cooking and space heating. At the end of 2014 China ranked first in the number of biogas installations with 43,000,000, followed by India with 4,750,000, Nepal with 300,000, Vietnam 182,805 and Bangladesh with 37,059. More than 100 million people in rural China and 4.83 million people in India have access to digester gas (REN21, 2016). The country wise installed capacity along with source of information is provided in the tables below:

Table 1 - Installed capacity in Asian countries excluding Japan

|  |  |  |
| --- | --- | --- |
| **Installed capacity in Asian countries excluding Japan** | | |
| **Country** | **Small biogas digesters (units)** | **Sources** |
| **Afghanistan** | 2000 | <http://unfccc.int/resource/docs/natc/afgnc1.pdf> |
| **Bangladesh** | 150000 | <https://bangladesheconomy.wordpress.com/2011/12/19/150-000-biogas-plants-in-rural-areas-by-2016/> |
| **Bhutan** | 1420 | http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015\_Onlinebook\_low1.pdf |
| **Cambodia** | 23219 | http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015\_Onlinebook\_low1.pdf |
| **China** | 28000000 | <https://energypedia.info/wiki/Biogas_Technology_in_China> |
| **India** | 4750000 | <http://mnre.gov.in/file-manager/UserFiles/faq_biogas.htm> |
| **Indonesia** | 15892 | http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015\_Onlinebook\_low1.pdf |
| **Lao DPR** | 2888 | http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015\_Onlinebook\_low1.pdf |
| **Nepal** | 250000 | http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015\_Onlinebook\_low1.pdf |
| **Pakistan** | 5360 | http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015\_Onlinebook\_low1.pdf |
| **Vietnam** | 182805 | http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015\_Onlinebook\_low1.pdf |

Table 2 -Installed Capacity in Africa and Middle East

|  |  |  |
| --- | --- | --- |
| **Installed Capacity in Africa and Middle East** | | |
| **Country** | **Small biogas digesters (units)** | **Sources** |
| **Benin** | 107 | http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015\_Onlinebook\_low1.pdf |
| **Burkina Faso** | 5462 | http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015\_Onlinebook\_low1.pdf |
| **Cameroon** | 302 | http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015\_Onlinebook\_low1.pdf |
| **Kenya** | 14112 | http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015\_Onlinebook\_low1.pdf |
| **Ethiopia** | 12000 | http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015\_Onlinebook\_low1.pdf |
| **Rwanda** | 12500 | http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015\_Onlinebook\_low1.pdf |
| **Tanzania** | 11103 | http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015\_Onlinebook\_low1.pdf |
| **Uganda** | 5695 | http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015\_Onlinebook\_low1.pdf |

Table 3 - Installed capacity in Latin America

|  |  |  |
| --- | --- | --- |
| **Installed capacity in Latin America:** | | |
| **Country** | **Small biogas digesters (units)** | **Sources** |
| **Bolivia (Plurinational State of)** | 6000 | <https://www.researchgate.net/publication/293646897_Household_anaerobic_digesters_for_biogas_production_in_Latin_America_A_review> |
| **Peru** | 10000 | <https://www.researchgate.net/publication/293646897_Household_anaerobic_digesters_for_biogas_production_in_Latin_America_A_review> |

In developing countries, small-scale anaerobic digesters are used to meet the heating and cooking needs of individual rural communities, rather than coupled with a generator to create electricity. These digesters can serve 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 2000 hogs.

Biogas installation in Africa has been less widespread than in Asia, but is increasing, largely in the domestic energy sector, due to national domestic biogas programs in Rwanda, Tanzania, Kenya, Uganda, Ethiopia, Cameroon, Benin and Burkina Faso, each with national targets of over 10000 domestic systems to be installed in the next five years (Smith et al., 2013).

## Advantages and disadvantages of Landfill Methane Capture

Bio-digesters also have some disadvantages: if AD do not completely digest all the waste, the resulting digestate may not meet government standards; poor feedstock used in the AD process can result in the production of unusable or contaminated by products (if high in metals as mercury). The combustion of biogas produces nitrogen oxides, which are associated with respiratory problem; AD plants generate lots of waste water high in nitrites and the plants may cause environmental problems such as odor, dust and pollutants due to the burning of methane for power generators (Friends of the Earth, 2002).

### Similar Solutions

There are several solutions in the electricity generation sector that can replace conventional electricity-generating technologies such as coal, oil, and natural gas power plants which could be considered as similar/analogous solutions. Solutions similar to large bio-digesters can be the ones also using the waste stream for electricity generation. These differ from this solution in the way the technologies work or the type of input. These are:

* **Landfill Methane Capture:** the process of capturing methane generated from anaerobic digestion of municipal solid waste in landfills and incinerating the captured biogas to generate electricity.
* **Waste to Energy:** the combustion of waste and conversion to electricity and usable heat in waste-to-energy plants. Waste-to-energy reduces greenhouse gas emissions in many cases, though the magnitude of that reduction varies substantially depending on the baseline used for comparison. Key considerations in waste-to-energy’s case include: the caloric content of combusted waste; its methane generation potential (where it would be landfilled); likely alternative waste disposal pathways; and the emissions intensity of electricity and/or heat being displaced by that generated by the waste-to-energy process.

### Arguments for Adoption

Biogas systems provide economic, energy, and environmental benefits for farms, businesses, and communities. These systems enable the capture and use of methane while also addressing waste management and nutrient recovery needs.

Biogas production have several advantages: it can reduce the pollution potential in wastewater by converting oxygen demanding organic matter that could cause low oxygen levels in surface waters (Wilkie, 2015). The anaerobic digestion eliminates the release of harmful pollutants, including fecal coliform bacteria, into the water supply from feedlot operations (U.S. EPA, 2016). Nutrients, like nitrogen and phosphorous are conserved in biogas effluents and can be used to displace fertilizers in crop production (Wilkie, 2015). Anaerobic digesters plants can be small and unobtrusive making them suitable for locations within towns (Friends of the Earth, 2002).

Larger complete-mix and centralized anaerobic digesters can also realize several revenue streams and cost savings for owners. Potential additional financial benefits include:

* Avoided electricity costs. By employing the generator-set to create electricity, that electricity can be used locally to avoid purchase from the local utility.
* Electricity sales. Any excess electricity not used on site can then be sold back to the grid, at whatever is the prevailing $/kWh agreement with the utility.
* Organics “tipping fees”. Tipping fees are payments made by waste haulers to dispose of material at landfills and recycling facilities. In this case, haulers are bringing organic material to digesters to avoid even higher tipping fees at the landfill.
* Fiber solids sales and/or avoided bedding expenses. After livestock waste digestion, the solids that are left from livestock waste digestion are typically high-cellulose, fibrous material that is often suitable for livestock bedding. This offsets farm costs for straw and other bedding materials, and can be made available for sale to surrounding farms.
* Offset fertilizer costs. Similar to the fiber solid benefits above, the liquid portion of digester effluent is an effective fertilizer.
* Production credits for renewable energy generation. Some states and nations provide incentives for methane digester electricity generated, as it is considered a form of renewable energy.

Other environmental benefits include:

* On-site renewable energy. Digesters that incorporate an engine-generator set and that have access to the electricity grid can sell the electricity outputs to the utility and potentially offer additional greenhouse gas benefit by displacing grid electricity. This substitution reduces SO2, NOx, particulate matter (PM), and CO2 emissions associated with burning fossil fuels. Though depending on the power supply replaced and the technology used for land fill gas capture, net NOx emissions may rise, but the avoidance of methane and other pollutants more than offsets this increase (U.S. EPA, 2016). Smaller-scale systems, typically in developing countries, burn biogas for heat and cooking use, displacing propane, kerosene, cookstove wood and\or other fuels (U.S. EPA, 2016). The World Health Organization estimates 1.3 million people die each year from indoor burning of solid biomass.
* Reduced deforestation. Well-functioning biogas plants can replace the entire consumption of firewood or charcoal of individual households by biogas. In macro-economic cost-benefit analyses the amount of firewood or charcoal saved is often directly translated into hectares of forest lost. The monetary benefit of biogas would then be reflected in re-afforestation costs (Energypedia, 2016).
* Reduced fugitive CH4 emissions in manure storage. Methane losses from manure management are 12–41% of total agricultural CH4 emissions for most countries (Chadwick et al., 2011).
* Reduced N2O emissions in application of digested manure on cropland (Massé et al., 2011).
* Manures from livestock production systems are estimated to contribute 30 to 50% to the global N2O emissions from agriculture.
* Reduced pathogens, odor, and viability of weed seeds in manure that is to be used on cropland (Chadwick et al., 2011)
* Reduced NH3 volatilization in application of digested manure on cropland (Massé et al., 2011).

According to Mills et al (2014), the use of the biogas from the bio-digesters for electricity generation displacing grid electricity also presents a better solution than the impact of injecting bio-methane into the gas grid.

### Burdens

Bio-digesters also have some disadvantages: if AD do not completely digest all the waste, the resulting digestate may not meet government standards; poor feedstock used in the AD process can result in the production of unusable or contaminated by products (if high in metals as mercury). The combustion of biogas produces nitrogen oxides, which are associated with respiratory problem; AD plants generate lots of waste water high in nitrites and the plants may cause environmental problems such as odor, dust and pollutants due to the burning of methane for power generators (Friends of the Earth, 2002).

# 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 replacement of conventional electricity generation technologies (i.e. coal, oil, natural gas) and related emissions for an alternative solution (see the Drawdown RRS Model Framework and Guide for more details). 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 (TWh), and for investment costing, adoptions are also converted to implementation units (TW). The adoption of both conventional technologies and the present solution (Large Bio-Digesters) were projected for each of several scenarios from 2015 to 2050 and the comparison of these scenarios (for the 2020-2050 segment) is what constitutes the results.

For this solution, the approach was to analyze the impacts of increased adoption of large methane digester systems. The model used for this analysis constructs both alternative ambitious adoption pathways (PD scenarios) and a Reference scenario (REF) for Large Methane Digester electricity generation. Following project Drawdown methodological assumptions (further description available on the Drawdown RRS Model Framework and Guide), and in order to grasp the total impact of an increased adoption of the solution during the assessed time frame, the REF scenario assumes the future rate of adoption of this solution remains fixed at the current adoption (i.e. 2018) level of the Total Addressable Market (TAM), estimated at 63.3 terawatt-hours, or 0.28 percent of total electricity generated worldwide (IRENA, 2019). The TAM for this solution is based on the common project Drawdown projected global electricity generation in terawatt-hours till 2050 (Section 2.3.).

The developed alternative PDS scenarios, draw on existing adoption scenarios for waste and biomass generation, and large methane digester use is extrapolated to model several alternative adoptions. The large methane digester solution in RSS encompasses only electricity generation from large bio- digesters (by use of biogas produced from sewage sludge and agriculture activities). The RRS model contains both financial and climate analyses in order to model the global and regional impacts of adoption in the PDS scenarios compared to the REF scenario. What the model thus prognosticates is the total financial costs and benefits of adoption cases for large bio-digesters for electricity generation, as well as the contribution this adoption can make to annual and cumulative emissions reduction.

## Data Sources

This section presents key data sources utilized in the mode to evaluate the adoption of large methane digester technologies for electricity generation. Data inputs for the model come from a variety of sources, primarily from peer-reviewed publications and from institutional reports. For all variable inputs, a variable meta-analysis of existing literature was conducted to create low, high, and mean estimates. For each solution variable, a sensitivity analysis of collected data points reported in the literature was conducted. In some cases as many as 13 data points were considered. This allowed a robust and reliable analysis of financial, technological and climate parameters. These represent both optimistic and conservative estimates for the future costs and benefits of adopting this solution.

Financial data sources are primarily available for large methane digester systems to electricity systems. First cost data from several sources was collected. First cost estimates are shown to be similar across resources. Sources used to collect this information into the RRS model included IEA (2015), Alberta Government Agriculture and Forestry (2008), US EPA/DOE (2015), Biogas Association (2013), Energynet (2012), EWG/LUT by Ram et. al (2019), and Zaks et al (2011) among others.

Fixed operation and maintenance (FOM) costs are estimated from sources like JRC (2013), EWG/LUT by Ram *et. al.* (2019), NREL (2019), Alberta Government Agriculture and Forestry (2008), Energynet (2012), Kang *et al.* (2014), and Zaks *et al.* (2011).

These estimates were used to calculate total operating costs of large methane digester adoption, which, combined with capital costs for installation, represent the total financial costs of adopting this solution in the PD scenarios. Fixed operation and maintenance costs for both renewable and conventional generation technologies can include expenses such as day-to-day preventative and corrective maintenance, labor costs, asset and site management, and maintaining health and safety, among others (Lo, 2014). Average fuel price was calculated considering average prices for coal, oil and natural gas from 2005-2014 using IEA data (IEA, 2016a).

Technical parameters used in the RRS model for the financial calculations such as average annual use and lifetime capacity are retrieved from e.g. JRC (2013), Energynet (2012), BIOGASIN (2011), NREL (2019), Zaks et al (2011), Kang et al (2014), and Ram et al (2019).

In order to compare capital and O&M costs of landfill methane capture systems adoption in the PD scenarios with that of conventional generation technologies, the cost data was obtained for fossil fuel-based electricity generating sources from the IPCC 5th Assessment Report (IPCC, 2014) which has conducted its own sensitivity analysis of a number of sources from the literature[[1]](#footnote-2), and other sources such as OECD (2015), Lazard (2016), Schmidt *et al.* (2012), and USE EIA (2013). In all, variables for conventional electricity generation sources, data for coal, oil and natural gas (primarily pulverized coal and combined cycle gas turbine technologies) were included and a weighted average obtained. These weights are based on the percentage, for each fuel on the total global electricity generation for 2014 (World Bank, 2015).

In order to calculate the total impacts and benefits of increased solution adoption (for the PDS scenarios), technical data was also integrated, including average annual use, plant lifetime, and average efficiencies. All three of these are key to determining the variable O&M costs and the total fuel costs for conventional generation sources, as these costs are determined by the average number of hours the power plant is generating electricity, as well as the average price of fuel inputs and the average efficiency rate. Average plants efficiency is calculated from several global sources (IPCC, 2014; IEA, 2010), as well as from the U.S. EIA (2015).

The model’s analysis of the climate impacts of adoption are primarily derived from the direct emissions factor associated with the replacement of conventional generating technologies with large methane digester systems for electricity generation. This methodology is explained in greater detail in Drawdown RRS model framework and guidelines.

## Total Addressable Market

Solutions assessed in the Electricity Generation Sector share a common market for future adoption defined by the total terawatt-hours (TWh) of generation demanded from 2015-2060. This shared total addressable market (TAM) is used to bound this sector technologies rollout over time. The TAM is determined based on the assessment of estimations of current and future electricity generation from a combination of models and scenarios from different sources, including Greenpeace (2015); International Energy Agency (IEA) - Energy Technology Perspectives (IEA, 2017); IEA World Energy Outlook (WEO) (IEA, 2018); Equinor (2018); Ecofys (2018); The Institute of Energy Economics Japan (IEEJ) Outlook 2019 (2018) and Ram et al. (2019). See Project Drawdown report - Assessing the Total Addressable Market and Major Assumptions for more details on the methodology used to develop the electricity TAM. The updated 2019 study follows the same methodological approach with the inclusion of newer sources.

Four prognostications of the TAM for this assessment were derived by using comparable scenarios from each of the above-mentioned sources which were categorized by expected climate mitigation scenarios (i.e. Ambitious, Conservative, and Baseline) and the scale of deployment of renewable energy sources (RES) (i.e. 100% RES scenarios). The sources used mostly provide results at a decadal level, which were interpolated to provide annual values for Project Drawdown calculations.

The Ambitious Project Drawdown TAM Scenario is constructed from the average of yearly values of four scenarios: the IEA (2017) 2D Scenario, the IEA (2017) B2D scenario, Renewal Scenario from Equinor (2018), and IEA (2018) WEO SD scenario. The Conservative Project Drawdown TAM Scenario follows the average yearly values of the IEA (2018) WEO New Policy scenario (NPS); Reform Scenario from Equinor. (2018), IEEJ Outlook (2018) Advanced Tech scenario, and IRENA (2019b) Roadmap 2050 REmap case. The Baseline Project Drawdown TAM Scenario is built by the average of the Equinor (2018) Rivalry Scenario, IEEJ Outlook (2018) Reference Scenario, IEA (2017) Reference Case and IEA (2018) WEO Current polices Scenario (CPS). These three Project Drawdown TAM scenarios show an estimated range of electricity generation from 43,120TWh to 52,001TWh by 2050. Baseline TAM is used for PD Plausible scenario assessment.

An ambitious TAM scenario for a 100% RES by 2050, which is aligned to Project Drawdown Optimum and Drawdown scenarios, utilizes the Greenpeace (2015) Advanced [R]evolution Scenario, Ram *et al* (2019) analysis and Ecofys (2018) 1.5ºC degree scenario were considered. The estimated electricity generation for this TAM reaches 70,942 TWh by 2050.

## Adoption Scenarios

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

### Reference Case / Current Adoption

For the Reference (REF) case scenario, adoption is fixed at the current adoption[[2]](#footnote-3) (in percentage terms) of the market. That is, the current percentage of total electricity generation (TWh) provided by large methane digester systems has been kept constant throughout the study period to 2050. As the market grows, the total number of large methane digester systems adopted grows equally to maintain the percent adoption at its starting value in 2018. It is acknowledged that this, in reality, may not be a “business as usual” trajectory considering the changes taking place worldwide, but it allows a sort of measure to evaluate the impact of recent and even more aggressive policies to reverse global warming.

### Large Bio-Digesters Adoption Prognostications

For the global adoption scenarios, five sources were collected that provided data on Bioenergy: International Energy Agency (IEA) Energy Technologies Perspectives (2017) and IEA World Energy Outlook (2018), The Institute of Energy Economics Japan Outlook (2019), Equinor Energy Perspective (2018), and Greenpeace Energy Revolution (2015). From these, 13 different scenarios were included to show a wide range of results projecting the role of large methane digester technologies on the future global electricity generation mix. These assessments relate specifically to different climate mitigation pathways or RES adoption. These sources do not clearly depict large methane digester technologies for electricity generation adoption pathways, thus a few assumptions were considered to obtain future adoption:

1. Current historical global adoption share of biogas in all Bioenergy for electricity generation was calculated from IRENA Renewable Energy Statistics (2019) and averaged over the years 2014-2017, and equal to 17.9%. However, electricity generated from biogas can be attributed to landfill methane solutions or to large methane digester solutions. Using data from IREA (2019), US Energy Information Administration (2018), and Scarlat *et al.* (2018), a split of 29.8% of biogas generated was allocated to landfill methane solutions while the remaining 70.2% of biogas generated was allocated to methane digester solutions. Therefore, total biogas generated from large methane digester solutions in all bioenergy was equal to 12.6%.
2. Since no better information is available for large bio-digesters for electricity generation, future adoption was obtained applying the previous calculated share of biogas from large bio-digesters of total bioenergy for global and applied to the results of the sources and scenarios mentioned above.

### Project Drawdown Scenarios

Three Project Drawdown scenarios (PDS) were developed for each solution, to compare the impact of an increased adoption of the solution to a reference case scenario. These are:

#### Plausible Scenario

This scenario represent scenarios where current policies remained fixed over time. The scenarios included here used medium growth with an average of ambitious adoption scenarios based on the IEA WEO SDS Scenario (2019), IEA ETP 2DS Scenario and Beyond 2DS Scenario (2017), and Equinor Renewal Scenario (2018). The resulting Plausible Scenario foresees large bio-digesters reaching 0.85 percent of the market share in 2050.

#### Drawdown Scenario

This scenario is optimized to reach drawdown by 2050 using more ambitious projections from existing sources. The scenario used was based on 100% Renewables using Greenpeace Advanced Energy Revolution Scenario (2015) with a medium growth. This scenario reaches a market share in 2050 of 0.57 percent.

#### Optimum Scenario

This scenario represents the most optimistic case, using medium growth and based on 100% Renewables using Greenpeace Advanced Energy Revolution Scenario (2015). This scenario depicts 0.57 percent of the total electricity generation in 2050.

## Inputs

### Climate Inputs

In order to calculate the climate impacts of the project Drawdown scenarios, in terms of maximum annual emissions reduction, total emissions reduction, and PPM equivalent, the large bio-digesters for electricity generation was estimated globally from 2020-2050. Thereafter, the emissions reductions due to the replacement of conventional electricity generation sources with the solution were calculated. The detailed methodology of these calculations is available at the Project Drawdown Integration Methodology report.

Several hundred life cycle assessments (LCAs) have been conducted for power technologies across the globe over the last 30 years (*e.g.* Pehnt *et al.,* 2006; Masanet, *et al*., 2013) and some addressing specifically alternatives for sludge and agricultural treatment. LCAs determine the environmental impacts of products and technologies throughout their full lifetime, from raw material extraction and processing; to manufacturing and distribution; to use and maintenance; to disposal or recycling. LCAs include estimates of total greenhouse gas (GHG) emissions and other environmental impacts and resources used (*e.g.* water and land use, air pollutants emissions). Despite the large plethora of papers addressing LCA for electricity generating technologies, large bio-digesters with biogas plants are not always accounted in those comparative studies. We draw our numbers on emissions from Pehnt et al. (2006), Fusi et al (2016), Distefano et al (2009), Moller et al (2009), Whiting et al (2014), Timonen et al (2019), and Bacenetti et al (2016). Fusi et al presented estimated life cycle data based on five different plants with varying feedstocks that produce electricity from biogas produced by anaerobic digestion.

Emissions are further categorized from the life cycle studies as direct and indirect emissions from large bio-digesters. Direct emissions are related to generating electricity, while indirect emissions are related to upstream and downstream activities such as plant construction, feedstock handling, transportation, and operation.

### Financial Inputs

The RRS model constructs PDS adoption scenarios for large methane digester electricity generation globally for each year until 2050. It has modelled both the capital costs and the fixed O&M costs associated with the alternative scenarios compared to those of the REF scenario. A detailed description of the methodology used is available in the Drawdown RRS Model Framework and Guide.

The financial calculations examine the first cost in US$ per kW and the operating cost in US$ per kW (fixed costs) and US$ per kWh (variable costs). For this, many inputs estimating annual output and lifetime output per landfill methane capture electricity generation, along with first costs (per functional unit), were calculated. A lifetime capacity of 180,256 hours (around 22 years) was calculated depending on the average powerplant annual use. A first cost learning rate is applied at 2%.

For the solution (*i.e. large bio-digesters*), the conventional current mix of fossil fuel electricity generation technologies (coal, gas, and oil) replaced were identified. Costs and operation for both generation technologies (solution and conventional) were considered to obtain the differential result.

Fuel prices for conventional technologies are derived from IEA (2019) data, averaging 2007-2018 historical registries for oil, coal and natural gas used for electricity generation and calculated through a weighted average by fuel from the current electricity generation mix.

A mean value of the data set range collected is assumed for installation costs of large methane digester systems which results in a total first cost of US$ 5,564 per kilowatt[[3]](#footnote-4). Additionally, a discount rate is fixed at 9.68 percent appropriate for utility-scale projects and use across all Drawdown electricity generation solutions with this level of agency. Tables 2.2. and 2.3 depict the dataset ranges and the model inputs for the conventional and solution technologies.

Table 2.2 Financial Inputs for Conventional Technologies

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| First costs (Conventional) | *US$2014/kW* | 470.5 – 3,101 | 1,786 | 24 | 8 |
| Fixed Operation and Maintenance Costs (Conventional) | *US$2014/kW* | 3.44 – 65.86 | 34.65 | 18 | 4 |
| Variable Operation and Maintenance Costs (Conventional) | *US$2014/kWh* | 0.0016 – 0.008 | 0.0048 | 22 | 8 |
| Fuel Price (Conventional) | *US$2014/kWh* |  | 0.0492 | - | 1 |
| Learning Rate Factor (Conventional) | % |  | 2.00% |  |  |

Table 2.3 Financial Inputs for Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| First costs (Solution) | *US$2014/kW* | 3,168 – 7,960 | 5,564 | 26 | 15 |
| Fixed Operation and Maintenance Costs (Solution) | *US$2014/kW* | 35.0 – 174.6 | 104.8 | 7 | 4 |
| Variable Operation and Maintenance Costs (Solution) | *US$2014/kWh* | 0.0035 – 0.0783 | 0.0409 | 14 | 10 |
| Learning Rate Factor (Solution) | % |  | 2.00% |  |  |

### Technical Inputs

Lifetime capacity data is consistent across a several sources at 20 to 30 years being the average time large-bio-digesters produce electricity. Capacity factor varies from 56% to 98%, though data is centered entirely in the US and Europe.

Table 2.4 Technical Inputs Conventional Technologies

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| Lifetime Capacity (Conventional) | *hours* | 122,186 – 223,043 | 172,615 | 12 | 6 |
| Average Annual Use (Conventional) | *hours* | 3,337– 6,587 | 4,962 | 23 | 4 |

Table 2.5 Technical Inputs Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| Lifetime Capacity (Solution) | *hours* | 138,803 – 197,917 | 168,360 | 11 | 8 |
| Average Annual Use (Solution) | *hours* | 6,426 – 8,691 | 7,559 | 8 | 7 |

## 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 are available on the Project Drawdown Reduction and Replacement Solutions (RRS) Model Framework and Guide report. Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution since all the sources used for adoption do not explicitly depict landfill methane capture technologies for electricity generation adoption pathways. Their results usually combine biomass and waste for electricity generation. These assumptions are detailed below.

1. Large bio-digesters are defined as systems that produce biogas from agriculture and wastewater sludge and are linked to biogas plants to produce electricity and/or heat.
2. Historical global adoption share of Biogas in all Bioenergy for electricity generation was calculated from IRENA Renewable Energy Statistics (2019) and averaged over the years 2014-2017, and equal to 17.9%. This share was assumed to be constant over time.

Data from IRENA (2019) indicated that the total share of global biogas production was heavily accounted for from USA and Europe, contributing 16.1% and 72.9% respectively. In addition, according to the US Energy Information Administration (EIA 2018), in 2018, the US was generating 89% of their biogas production from landfill methane. In 2018, Europe was generating 17% of their biogas from landfill methane (Scarlat *et al.,* 2018). Assuming that the total global biogas split would follow that of the US and Europe, a weighted average was taken. A final share of biogas to be considered within the scope of this solution is 70.2% are produced from wastewater and agricultural activities and used in Large bio-digesters solution while the remaining (29.8%) is allocated to landfill methane capture solution.

1. This solution only covers biogas production from large bio-digesters and therefore we needed to extract biogas from large bio-digesters from wastewater and agriculture activities from landfills that is being considered in the *Landfill Methane Capture* solution. We estimate total share of biogas from all biofuels is 18%. Then the share of biogas produced from large bio-digesters is equal to 70.2%. The remainder is allocated to landfills.
2. Since no better information is available for biogas for electricity generation, future adoption was obtained applying the previous calculated share of biogas from large bio-digesters (12.5%) of total bioenergy for global and regional levels and applied to the results of all our adoption sources which include three selected scenarios from IEA WEO (2018) (Current Policies, Stated Policies, SDS), three scenarios from IEEJ Outlook (2019) (No Coal Plants, Reference, Advanced Technology), three scenarios from IEA ETP (2017) (Reference Technology, Beyond 2DS, 2DS), three scenarios from Equinor (2018) (Rivalry, Reform, Renewal), and to the results of Greenpeace (2015) Advanced Energy Revolution.
3. The uncertainty associated with the future adoption of large bio-digesters capture is linked to other waste management solutions as among others, reduced food waste, waste to energy, landfill methane capture, recycling or composting that could affect the balance between the available waste for each solution.
4. The results from the different sources are given for every 5 or 10 years. To determine annual generation values, data interpolation methods were used to create best fit trends (i.e. 3rd polynomial trends applied between reported data). In cases where there are spikes, stepwise interpolation with one or more of the outlier datapoint(s) removed are performed to smooth out the trend, and complete the data for the missing years.
5. This analysis assumes that efficiency of large bio-digesters are uniform across regions. While there are some indications that different technology choices will be made, the fidelity of data in literature is not high enough to develop credible estimates for different technology costs and efficiencies on a regional basis.

## Integration

The complete Project Drawdown integration documentation with details on how all solution models in each sector are integrated, and how sectors are integrated to form a complete system is available at [www.drawdown.org](http://www.drawdown.org). Those general notes are excluded from this document but may be referred to 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.

The data derived from individual solution models was fed into sector-level integration models to generate the final results for all solutions within a global system. The interlinkage between this sector and all the others is important, but major interactions of this sector occur with energy demand-side sectors like Transport and Buildings and Cities.

Through the process of integrating concentrated solar power with other solutions, the total addressable market for electricity generation technologies was adjusted to account for reduced demand resulting from the growth of more energy-efficient technologies (for example LED lighting and heat pumps) as well as increased electrification from other solutions like electric vehicles and high-speed rail. Grid emissions factors were calculated based on the annual mix of different electricity generating technologies over time. Emissions factors for each technology were determined through a meta-analysis of multiple sources, accounting for direct and indirect emissions.

## Limitations / Further Developments

### Model the Solution with a Change of Large Bio-Digester over Time

The current model assumes that the percentage of waste going to large bio-digesters will remain constant over time. Future research should include in the percentage of waste going to large bio-digesters over time would be a valuable addition.

# Results

In the following section selected results derived from the RRS model are depicted evaluating the impact of increased adoption of Large Bio-Digester technologies for electricity generation as compared to conventional technologies and other alternatives.

## Adoption

### Electricity Generation from Large Bio-Digesters

A comparison of the results from the three modeled scenarios to the Reference Scenario allows an estimation of the climate and financial impacts of increased adoption of large bio-digesters systems. As a result of this exercise, the Plausible Scenario (PDS1) projects 0.85 percent of total electricity generation worldwide by 2050. In the Drawdown (PDS2) and Optimum Scenarios (PDS3), the market share for both reaches 0.57 percent. Below in Table 3.1 are shown the adoptions of the solution in 2050 in functional units and percentage terms. Figure 3.1 depicts the long term pathway trajectories for the different scenarios of large bio-digester systems.

Table 3.1 World Adoption of the Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Solution** | **Units** | **Base Year (2014)** | **World Adoption by 2050** | | |
| **Plausible** | **Drawdown** | **Optimum** |
| *Large Bio-Digesters* | *Electricity Generation (TWh)* | 63.34 | 389.21 | 407.00 | 407.00 |
| *(% market)* | 0.28% | 0.85% | 0.57% | 0.57% |

Figure 3.1 World Annual Adoption 2015-2060

Note: Drawdown and Optimum Scenarios have the same global adoption for this solution and therefore the operation costs reduction over time for both scenarios are overlaid in the figure.

### Climate Impacts

Below are the emissions results of the analysis for each scenario which include total emissions reduction and atmospheric concentration changes. For a detailed explanation of each result, please see the glossary (Section 6). The Plausible Scenario results in the avoidance of 5.53 gigatons of carbon dioxide-equivalent greenhouse gas emissions between 2020-2050. Both the Drawdown and Optimum Scenarios are more ambitious in the growth of CSP technologies, with impacts on greenhouse gas emissions reductions over 2020-2050 of 6.32 gigatons of carbon dioxide-equivalent. Tables 3.4 and 3.5 provide additional information on the climate impacts of the solution adoption.

Table 3.4 Climate Impacts

|  |  |  |  |
| --- | --- | --- | --- |
| **Scenario** | **Maximum Annual Emissions Reduction** | **Total Emissions Reduction** | **Emissions Reduction in 2050** |
| *(Gt CO2-eq/yr.)* | *Gt CO2-eq/yr. (2020-2050)* | *(Gt CO2-eq/year)* |
| ***Plausible*** | 0.29 | 5.53 | 0.29 |
| ***Drawdown*** | 0.31 | 6.32 | 0.31 |
| ***Optimum*** | 0.31 | 6.32 | 0.31 |

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). After integration, the impact on emission reduction for this solution is 5.46 gigatons of carbon dioxide-equivalent in the PD Plausible scenario, 6.30gigatons of carbon dioxide-equivalent for the Drawdown Scenario and 6.30gigatons of carbon dioxide-equivalent for the PD Optimum scenario. Figure 3.2. show the world annual emissions reduction trajectories for the different scenarios for the long term.

Table 3.5 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** | 0.46 | 0.02 |
| **Drawdown** | 0.52 | 0.02 |
| **Optimum** | 0.52 | 0.02 |

Figure 3.2 World AnnualGreenhouse Gas Emissions Reduction

Note: Drawdown and Optimum Scenarios have the same global adoption for this solution and therefore the operation costs reduction over time for both scenarios are overlaid in the figure.

## Financial Impacts

The financial impacts incurred by replacing conventional grid electricity sources with large bio-digester systems are significant. The Plausible scenario presents US$141.14 billion in in savings from marginal first costs and over US$28.87 billion of net operating cost savings are projected over 2020 to 2050. Both PDS2 and PDS3 have similar numbers with US$183.1 billions of marginal first costs and US$32.83 billions of net operating savings over the same period.

The capital costs for PDS adoption of large bio-digesters systems will require significant investments, as the cumulative capital costs are over $324.31 billion under the Plausible Scenario and $357.98 billion for the other two more ambitious PD scenarios. Below in Table 3.4 are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary (Section 6).

Table 3.4 Financial Impacts

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Scenario** | **Cumulative First Cost** | **Marginal First Cost** | **Net Operating Savings** | **Lifetime Cashflow Savings NPV (of All Implementation Units)** |
| *2015-2050 Billion USD* | *2015-2050 Billion USD* | *2020-2050 Billion USD* | *Billion USD* |
| **Plausible** | 324.31 | 141.14 | 28.87 | -17.40 |
| **Drawdown** | 357.98 | 183.10 | 32.83 | -28.52 |
| **Optimum** | 357.98 | 183.10 | 32.83 | -28.52 |

Figure 3.3 Operating Costs Over Time for the three PD scenarios

Note: Drawdown and Optimum Scenarios have the same global adoption for this solution and therefore the operation costs reduction over time for both scenarios are overlaid in the figure.

# Discussion

The conversion of waste material in bio digesters into fertilizer and biogas have several financial and environmental positive impacts for different levels of stakeholders (farmers, industries, municipalities and governments).

Appropriate feedstock for both electricity-generating biogas plants and small digesters is available in adequate quantity across the world from sewage sludge and agriculture systems. Currently, industrialized countries represent the lion share of adoption of larger bio digester systems for electricity generation, mainly located in EU (e.g. Germany) and the USA. Only very few small and medium sized biogas plants are used for electricity generation in Africa, Latin America and even Asia.

The electricity generation component of a biogas power plant does not require much more know-how and effort for maintenance than a normal generator set for fossil fuels with a well-functioning biogas fermentation process as an indispensable prerequisite (Energypedia, 2016). Under rising prices from fossil fuels and annual variability of hydro power, electricity from biogas can economically compete with conventional fossil fuel electricity generation and hydro systems in several countries. Though there are still some barriers to a stronger adoption of large scale bio-digesters such as; high upfront costs, lack of financing, uncertain and long payback period, unfamiliarity with technology in some world regions, and lack of supporting policy and incentives. Barriers and challenges related to the interconnections to the electrical and gas grid and the lack of a guaranteed price for heat and power are still high worldwide. Therefore, establishing ambitious RES portfolio standards, tax credits and other subsidies, and/or a firm price on carbon, disseminate anaerobic digestion technological models for farms with different modernization levels and sizes, and foster related research could be key to overcame many of these barriers and accelerate biogas capture and utilization.

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

Our model for large bio-digesters is also based on the critical assumption that the share of biogas within biomass and waste use projections for electricity generation from the used sources is constant. We acknowledge that it could change considerably over the period of analysis if policies, financial instruments or changes in important technological parameters like the capital costs of biogas plants or of competing alternative solutions. Our model could also improve regional and country level adoptions but currently this bottom up approach is difficult being presented only rather coarse estimates. An increase level of detail by country will be necessary to help local policy makers and project developers of the specific benefits of methane digesters when compared to other electricity generation technologies and waste management practices. Since producing high quality fertilizer can be done in other, cheaper ways such as composting which are even closer to traditional techniques. 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.

## Benchmarks

Table 4.1 depicts a benchmark of Project Drawdown results for 2050 on the three developed scenarios to six other publicly available scenarios from IEA (2017) and Greenpeace (2015). The benchmarked results account for total electricity generation projected for the year 2050 from Biomass and Renewable Waste, while project Drawdown results account for the specific large bio-digester solution results. There are no direct comparable benchmarks to the large bio-digester solution, therefore these references can be used to bound the adoption of the large bio-digesters solution among other solutions. The values reported below are raw data points from the sources.

Table 4.1 Benchmarks

|  |  |  |
| --- | --- | --- |
| **Source and Scenario** | **Electricity Generation in 2050 (TWh)** | **Market Share in 2050 (%)** |
| **Project Drawdown – Plausible Scenario (PDS1)** | **389.21** | **0.85%** |
| **Project Drawdown – Drawdown Scenario (PDS2)** | **407.00** | **0.57%** |
| **Project Drawdown – Optimum Scenario (PDS3)** | **407.00** | **0.57%** |
| IEA Energy Technologies Perspectives (2017) – World Reference Technology Scenario | 2,198 | 4.68% |
| IEA Energy Technologies Perspectives (2017) – 2DS | 2,939 | 6.91% |
| IEA Energy Technologies Perspectives (2017) – Beyond 2DS | 3,589 | 8.10% |
| Greenpeace Energy [R]evolution (2015) – Reference Scenario *(includes Electricity + CHP* | 1,577 | 11.30% |
| Greenpeace Energy [R]evolution (2015) – Energy Revolution Scenario *(includes Electricity + CHP* | 3,039 | 24.57% |
| Greenpeace Energy [R]evolution (2015) – Advanced Energy Revolution Scenario *(includes Electricity + CHP* | 3,193 | 19.83% |

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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 the 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 the high growth of the solution.

**Approximate PPM Equivalent** – the reduction in the 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, the total number of passenger-km driven by a hybrid vehicle in a year depends on the country and the 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 by the lifetime use 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 the 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 is 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 the 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 the 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 the adoption of the solution against which all **PDS scenarios** are compared.

**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 the world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

**Total Emissions Reduction** – the sum of the 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. The IPCC’s 5th Assessment Report analyzes the following sources: Coal: Black and Veatch (2012), DEA (2012), IEA/NEA (2010), IEA (2013a), IEA-RETD (2013), Schmidt et al. (2012), US EIA (2013). Gas Combined Cycle: Black and Veatch (2012), DEA (2012), IEA/NEA (2010), IEA (2011), IEA (2013a), IEA-RETD (2013), Schmidt *et al.* (2012), US EIA (2013). [↑](#footnote-ref-2)
2. Current adoption is defined as the amount of functional demand supplied by the solution in 2018. This study uses 2014 as the base year due to the availability of global adoption data for all Project Drawdown solutions evaluated [↑](#footnote-ref-3)
3. All monetary values are presented in US$2014 [↑](#footnote-ref-4)