**Technical assessment for**

**Landfill Methane Capture**

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Table of Contents

[List of Figures 4](#_Toc44379358)

[List of Tables 4](#_Toc44379359)

[Acronyms and Symbols 5](#_Toc44379360)

[Executive Summary 7](#_Toc44379361)

[1. Literature Review 9](#_Toc44379362)

[1.1 State of Landfill Methane Capture 9](#_Toc44379363)

[1.1.1 Landfill gas technologies 10](#_Toc44379364)

[1.1.2 Emerging methods and technologies 11](#_Toc44379365)

[1.1.3 The effectiveness of landfill gas capture 11](#_Toc44379366)

[1.2 Adoption Path 11](#_Toc44379367)

[1.2.1 General Trends 11](#_Toc44379368)

[1.2.2 Percentage of Waste used and Methane Mitigated 12](#_Toc44379369)

[1.2.3 Landfill Gas to electricity adoption 13](#_Toc44379370)

[1.3 Advantages and disadvantages of Landfill Methane Capture 14](#_Toc44379371)

[1.3.1 Similar Solutions 14](#_Toc44379372)

[1.3.2 Arguments for Adoption 14](#_Toc44379373)

[1.3.3 Additional Benefits and Burdens 15](#_Toc44379374)

[2. Methodology 19](#_Toc44379375)

[2.1 Introduction 19](#_Toc44379376)

[2.2 Data Sources 20](#_Toc44379377)

[2.3 Total Addressable Market 21](#_Toc44379378)

[2.4 Adoption Scenarios 23](#_Toc44379379)

[2.4.1 Reference Case / Current Adoption 23](#_Toc44379380)

[2.4.2 Landfill Methane Adoption Prognostications 24](#_Toc44379381)

[2.4.3 Project Drawdown Scenarios 24](#_Toc44379382)

[2.5 Inputs 26](#_Toc44379383)

[2.5.1 Climate Inputs 26](#_Toc44379384)

[2.5.2 Financial Inputs 29](#_Toc44379385)

[2.5.3 Technical Inputs 30](#_Toc44379386)

[2.6 Assumptions 31](#_Toc44379387)

[2.7 Integration 33](#_Toc44379388)

[2.8 Limitations / Further Developments 33](#_Toc44379389)

[2.8.1 Use of Thermal Energy from Landfill Carbon Capture 33](#_Toc44379390)

[2.8.2 Model the Solution with a Reduction in Landfilling over Time 34](#_Toc44379391)

[3. Results 35](#_Toc44379392)

[3.1 Adoption 35](#_Toc44379393)

[3.1.1 Electricity Generation from Landfill Methane Capture 35](#_Toc44379394)

[1.3.4 Tons of Waste 36](#_Toc44379395)

[3.1.2 Climate Impacts 36](#_Toc44379396)

[3.2 Financial Impacts 38](#_Toc44379397)

[4. Discussion 39](#_Toc44379398)

[4.1 Benchmarks 40](#_Toc44379399)

[5. References 41](#_Toc44379400)

[6 Glossary 45](#_Toc44379401)

# List of Figures

[Figure 1.1 Methane mass balance (Bogner et al., 2007) 10](#_Toc44379343)

[Figure 1.2 Estimation of Landfill Type by Country from the EPA's MAC Report (Ragnauth et al, 2013). 13](#_Toc44379344)

[Figure 1.3 Hierarchy of solid waste disposal (IPCC, 2014) 15](#_Toc44379345)

[Figure 1.4 Hierarchy of solid waste disposal (Themelis et al., 2013) 16](#_Toc44379346)

[Figure 1.5 Hierarchy of solid waste disposal (Hoornweg and Bhada-Tata, 2012) 17](#_Toc44379347)

[Figure 3.1 World Annual Adoption 2015-2060 36](#_Toc44379348)

[Figure 3.2 World AnnualGreenhouse Gas Emissions Reduction 38](#_Toc44379349)

[Figure 3.3 Operating Costs Over Time for the three PD scenarios 39](#_Toc44379350)

# List of Tables

[Table 2.2 Financial Inputs for Conventional Technologies 29](#_Toc44379351)

[Table 2.3 Financial Inputs for Solution 30](#_Toc44379352)

[Table 2.4 Technical Inputs Conventional Technologies 30](#_Toc44379353)

[Table 2.5 Technical Inputs Solution 31](#_Toc44379354)

[Table 3.1 World Adoption of the Solution 35](#_Toc44379355)

[Table 3.4 Financial Impacts 38](#_Toc44379356)

[Table 4.1 Benchmarks 40](#_Toc44379357)

# 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

Project Drawdown defines landfill methane as: the process of capturing methane generated from anaerobic digestion of municipal solid waste in landfills and incinerating the captured biogas to generate electricity. This solution replaces conventional electricity-generating technologies such as coal, oil, and natural gas power plants.

Landfill methane capture is most effective in closed and engineered landfills, achieving 85 percent efficiency or more; it is least effective in open dumps, where the collection efficiency is approximately 10 percent and capture is typically not seen as an economically favorable decision. As a waste treatment solution, from a climate perspective, *landfill methane* is generally seen as preferable only to landfilling without methane capture. However, where landfills exist it is an important solution for mitigating greenhouse gases. This analysis models the impacts of the adoption of landfill methane for electricity generation and gas flaring. The total addressable market for landfill methane is based on projected global electricity generation in terawatt-hours from 2020-2050.

Current adoption (in 2018) is considered to be 26.9 terawatt-hours, or 0.12 percent of total electricity generated worldwide (IRENA, 2016). Total adoption estimates vary widely between different future adoption prognostications, due to the fact that different sources place a different value on biomass and waste for energy adoption. Impacts of increased adoption of landfill methane from 2020-2050 were generated based on three growth scenarios derived from the evaluation of several global energy system modeling scenarios. These scenarios were assessed in comparison to a Reference Scenario where the solution’s market share was fixed at the current levels. The sources used do not clearly depict landfill methane and biogas technologies for electricity generation adoption pathways; instead, their results combine biomass and waste for electricity generation. Therefore, a few assumptions were made to determine future adoption: biogas represents around 18 percent of total electricity generation from bioenergy worldwide, and biogas from landfills covered within this solution represents 30 percent of total biogas. The remaining 70 percent is covered by methane capture from agriculture, manure, and wastewater. Due to landfill methane’s low priority in waste management ranking, the Plausible Scenario is built upon an average of four conservative scenarios based on International Energy Agency World Energy Outlook (2019), The Institute of Energy Economics (2019), Japan Outlook and Equinor (2018). Using a medium growth trajectory, the Plausible Scenario foresees landfill methane capture reaching 0.17 percent of the market share in 2050. The Drawdown Scenario and the Optimum Scenario follows the same adoption projections, both reducing to 0.0 percent by 2050. In each of these scenarios, the conservative adoption is bounded by the total waste available for landfill methane capture from the waste integration model. As landfill methane solution is the last priority within the waste integration model, as more aggressive measures are being taken to reduce and reuse waste, less waste is available for landfill methane solution in each PDS Scenario.

Landfill methane emission rates are estimated using the first-order decay method recommended by the Intergovernmental Panel on Climate Change (IPCC), in order to estimate both total emissions reductions for landfill gas-to-electricity generation and an increase in landfill gas flaring. The results for the Plausible Scenario show that through the advanced adoption of landfill methane, the net first costs compared to the Reference Scenario would be US$3.3 billion in savings from 2020-50 and approximately US$20.35 billion in operational savings over the same period. Increasing the use of landfill methane to 0.17 percent of world electricity generation by 2050 would require an estimated US$37.24 billion in cumulative first costs. Under the Plausible Scenario, landfill methane’s increased use could reduce 6.69 gigatons of carbon dioxide-equivalent greenhouse gas emissions from 2020-2050. Both the Drawdown and Optimum Scenarios are more conservative in the growth of landfill methane due to the combination with other waste management solutions, with impacts on greenhouse gas emission reductions over 2020-2050 of 0.96 and addition of 3.0 gigatons of carbon dioxide-equivalent, respectively.

Landfill methane solutions are a net benefit for the climate. From a financial perspective, while some up-front costs are required for landfill gas-to-electricity technologies, the long-term return on investment is significant, and therefore these technologies are a sound investment. While it is clearly a ‘second-best’ waste management strategy, as long as landfills are being created it is still a viable and important solution for climate mitigation. Aside from the significant climate benefits and long-term cost savings shown by this study, landfills which capture methane are safer and less of a public health hazard than those which do not. Therefore, as landfills move globally from open dumps or basic landfills to engineered sanitary landfills, the percentage of landfills which use landfill methane capture can and should be expected to increase.

# Literature Review

## State of Landfill Methane Capture

Global waste generation today is estimated to be somewhere between 1.8-2.1 billion tons of waste per year and (Hoornweg & Bhada-Tata, 2012; Hoornweg *et al.,* 2015; Kaza *et al.* 2018) and is expected to increase to about 3.4 billion tons per year in 2050 (Kaza *et al*., 2018). Much of this waste ends up, and will continue to end up in landfills if no specific measures for reducing food waste, improve recycling collection and others, are fostered. This can be shown by the fact that even in places like Europe which have arguably made the most concerted efforts to reduce waste landfilling, over 50% of waste still ends up in landfills (Powell *et al.*, 2016).

Landfills become anaerobic within months following the placement of municipal waste as oxygen is rapidly depleted by aerobic bacteria (Goldsmith *et al*., 2012). Organic material then degrades through anaerobic processes, generating carbon dioxide (CO2), water, heat and methane (CH4). The CH4 emissions contribute to climate change and the significance at a rate of between 28 and 84 times that of CO2, depending on the time period over which they are considered (100 years or 20 years, respectively) (Myhre *et a*l., 2013). The amount and rate of CH4 release depends on the waste composition, the climate, pH and moisture levels in the waste and the design and management of the landfill.

Landfill methane capture systems reduce the emissions of greenhouse gases (GHGs) from landfilling by directing the flow of landfill methane to a centralized source and either flaring it to convert the methane to CO2 and H2O, lowering the overall GHG output from the landfill, using it directly as a fuel for thermal energy, or incinerating it and converting it to electricity.

However, it is not possible to capture all landfill gas and some is inevitably lost to the atmosphere. A methane mass balance calculates the different pathways for CH4 emissions in a landfill by summing landfill gas collected, methane oxidized by the landfill cover soils and the methane lost as emissions to the atmosphere (Goldsmith *et al*., 2012) (Figure 1.1).

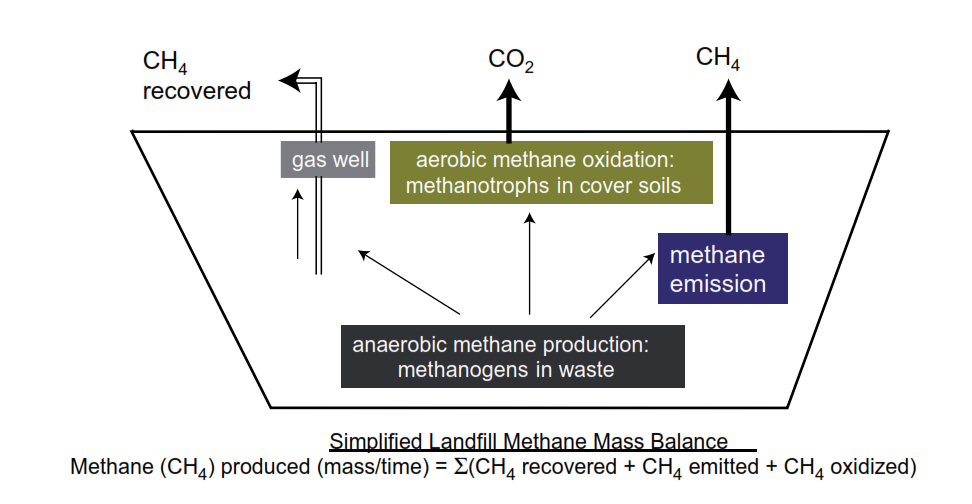


Figure 1.1 Methane mass balance (Bogner et al., 2007)

### Landfill gas technologies

Landfills can be broadly classified in three categories:

* Open dumps, common in areas with limited or no centralized waste management, are un-compacted piles of waste and tend to be shallow, which results in a greater degree of aerobic biodegradation.
* Basic or controlled landfills compact and cover waste but do not include additional engineered solutions.
* Engineered sanitary landfills are engineered to contain waste until it is stabilized biologically, chemically and physically; they generally include systems for gas and leachate collection.

A landfill gas collection system can be applied to any of the three types of landfills, however a landfill in which the gas is more contained will result in a more effective landfill gas capture system. A landfill gas capture system consists of extraction wells, a system of lateral and header piping to convey the gas, a condensate management system, a blower and flare system, monitoring devices and system controls (EPA, 2012). An active landfill gas collection system uses a vacuum to extract the gas from the landfill, whereas a passive system relies on the natural flow of the gas.

Once landfill gas is collected, it can either be flared or collected for use as a fuel. In North America and Europe, landfill gas has been transported in pipelines and used in place of natural gas, fuel oil or coal for more than 30 years. Landfill gas can be used in boilers to produce steam or hot water and the steam can then generate electricity by driving a turbine. Other options for producing electricity include internal combustion engines, gas turbines and combined heat and power, which generates both electricity and captures waste heat for thermal energy.

### Emerging methods and technologies

Technologies and methods which increase methane capture over the life of a landfill are expected to grow, particularly for use in open landfills. Using temporary, low-permeability covers in open landfills is one option which shows promise to increasing capture efficiency.

With respect to energy generation from methane capture, in a more complex and expensive process, landfill gas can be purified by increasing the CH4 content and decreasing CO2, nitrogen, oxygen and moisture to produce the equivalent of natural gas, compressed natural gas or liquefied natural gas, which can then be used for industrial purposes or to fuel vehicles. Landfill gas can potentially be used in a pyrolysis furnace, a type of low-temperature waste incineration used to destroy semi-volatile organic compounds.

### The effectiveness of landfill gas capture

The effectiveness of landfill gas capture also depends on the type of system used. According to a EPA study, open landfills only capture 10% of emissions, while basic landfills and sanitary engineered landfills capture 75% and 85%, respectively (Ragnauth *et al*., 2013).

A 2016 study in Nature Climate Change measured the efficiency of landfill gas capture from all landfills in the US which are required to report data on landfill gas efficiency, accounting for over 90% of the waste landfilled in the US (Powell *et al.*, 2016). These are primarily sanitary engineered landfills. The study found the average efficiency for landfills which were still open was 17% lower than landfills which had been closed and therefore were able to better direct the flow of methane. A chart depicted in the study shows that open landfills have an efficiency of approximately 65% and closed landfills have an efficiency of approximately 82%. The analysis also showed that 91 +/- 0.5% of methane emissions by mass come from open landfills according to data from 2010-2013 (ibid).

## Adoption Path

### General Trends

The US and many EU nations have had laws mandating that landfill methane capture is performed for decades (Powell *et al.*, 2016). Therefore, the vast majority of all large landfills in the US and EU use landfill methane capture of some form.

In developing nations, current adoption of landfill methane capture is less clear, and sources estimating total adoption are few and far between. When they are available, they are often based on specific case studies. In many instances landfill methane capture projects are enacted in developing countries under the Clean Development Mechanism (CDM), one of the three mechanisms under the Kyoto Protocol used for allowing industrialized countries to get credit for emissions reduction projects in developing countries. While today, many of these projects seem to prioritize electricity generating systems, it is likely that landfill methane capture of all forms will spread to developing countries. As landfill technology changes in developing countries from open dumps which are common today to sanitary landfills, landfill methane capture will become necessary for health and safety reasons and is likely to be quickly adopted.

In Asia, due to different climate and moisture characteristics, it is difficult to directly transfer technology for landfill gas generation that was developed for western climates and waste streams. Therefore, adoption in Asia has been slow, and many areas have been developing slightly different landfill methane capture solutions and methane reduction technologies, including semi-aerobic landfill designs to encourage increased aerobic reactions with the waste and reduce overall GHG emissions (Ishigaki *et al.*, 2011). This may in the end be a better low cost solution for methane reduction in tropical climates in Asia than landfill capture gas flaring.

### Percentage of Waste used and Methane Mitigated

Specific estimates on adoption rates of methane capture are few and far between, and oftentimes obfuscated behind other data. However, a few studies give an indication which can be used to understand the magnitude of landfill methane capture overall potential.

A large study undertaken by the EPA in 2013 to estimate the marginal abatement cost of waste diversion solutions uses one approach to estimate total potential adoption of landfill methane capture technologies. Using estimations for CH4 emissions from landfills given the “BAU” scenario for landfill technology (based on current technologies and policy measures), the report estimates the potential adoption and resulting CH4 emissions reductions globally based on projections for landfill type and waste composition in landfills. It estimates that given current technology, it is possible to reduce 61% of all projected emissions, 7-8% of which could be done in a way that is cost effective with today’s energy prices (Ragnauth *et al*., 2013).

Another useful piece of information in this study is the estimate of the percentage of each type of landfill (open, basic, engineered) by country, projected to 2030, shown in Figure 1.2 below. The report states that “these shares were developed using expert judgment after reviewing existing literature on waste disposal trends and abatement opportunities provided through various studies by the World Bank, USEPA’s LMOP program, and the Global Methane Initiative (GMI)” (Ragnauth *et al.*, 2013, p. III-17). This information can be used to discern a reasonable estimate of the percentage of waste and CH4 emissions which can be expected to adopt landfill methane capture. Engineered landfills are likely to already have some form of landfill methane capture built into their design, even if it may be only flaring the gas. Basic landfills are able to have landfill methane capture added, but are likely to have a lower adoption rate than engineered landfills. Open dumps can sometimes add landfill methane capture, but not in a way that is likely to be economically viable. Therefore, the adoption rate for these landfills can be assumed to be very low (ibid).

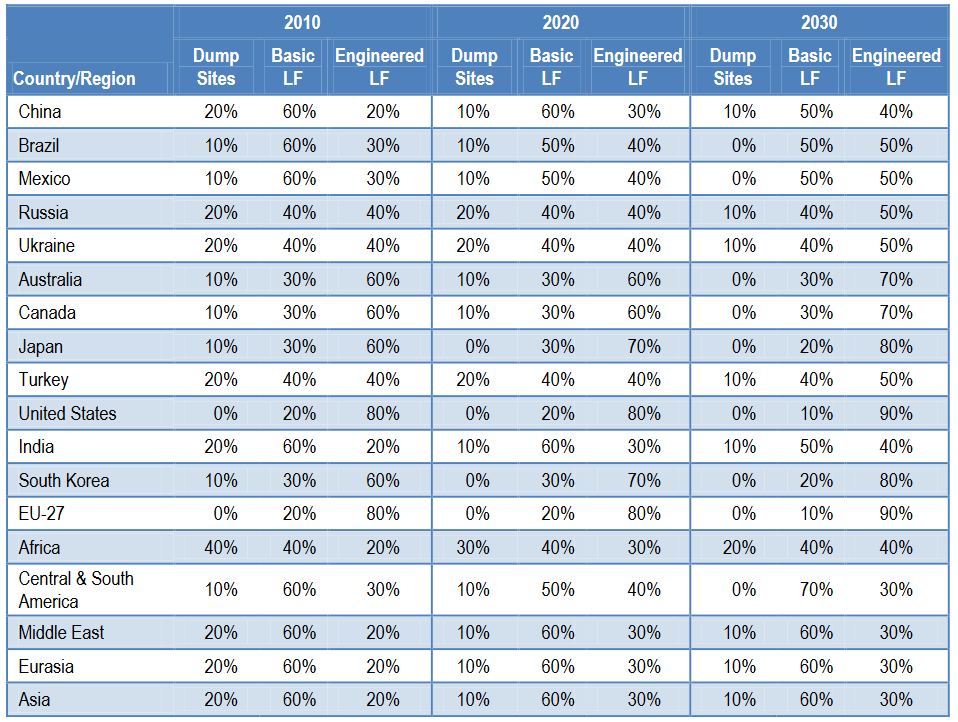


Figure 1.2 Estimation of Landfill Type by Country from the EPA's MAC Report (Ragnauth et al, 2013).

### Landfill Gas to electricity adoption

Global and regional estimates of landfill gas to electricity adoption are reported with more frequency than total landfill methane capture adoption rates or landfill gas flaring rates. However, their adoption is often reported together with biogas created from other sources, such as agriculture and waste water. Therefore, assumptions about percentage adoption of each source need to be made in order to separate the landfill gas prognostications from the total biogas prognostications.

Current adoption of landfill gas to electricity is heavily focused on global estimates. Future prognostications vary significantly across sources, likely based on the fact that different sources had different goals and value judgements when making the prognostications.

## Advantages and disadvantages of Landfill Methane Capture

### 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 landfill methane capture 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:

* **Large Methane Digesters:** large methane digesters associated with agriculture, manure, and wastewater facilities that produce biogas to be used for electricity generation in dedicated biogas or combined heat and power plants.
* **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

Landfills which were created within the past 15 years are still emitting methane into the environment, so even without any new landfills being created, the methane from current landfills is polluting our environment. Landfill methane capture is the only solution widely used to mitigate methane from landfills which are already in place, and therefore is often a wise environmental decision for landfills which are emitting methane today. Additionally, it is highly unlikely that a switch from landfilling to other waste diversion practices will happen overnight. Therefore, in the short term it is inevitable that emissions of methane from landfills will continue to be a problem to which landfill methane capture is well-suited.

In addition to reducing landfill methane emissions, landfill methane capture can also provide benefits to public health and safety. Burning of the landfill gas not only destroys the methane, but also most of the other non-methane organic components, many of which are hazardous air pollutants and volatile organic compounds (VOCS) which can be dangerous to health. Additionally, as gas builds up in landfills, they present a risk to explosions from accumulation in structures on or near the landfill (US EPA, 2016). Originally landfill methane capture was developed not as a climate change mitigation tool, but as a prevention of explosions in the area near the landfill.

Furthermore, landfill methane capture solutions which recover energy from the methane in the form of electricity or thermal energy directly offset emissions from fossil fuels, further increasing the positive environmental impact of the solution. In many countries, this energy is considered renewable energy, since it is mainly the biomass portions of the waste which are producing the methane. Unlike many sources of renewable energy, it provides a continuous supply of energy which can be used to balance out the variable supply of sources such as wind and solar. While not commonly done due to increased costs, it can even be processed and refined into a gas which can be transported and stored as a natural gas replacement.

### Additional Benefits and Burdens

While landfill methane capture is preferable to other types of landfilling, in most reports it is rated lower than all other alternative waste diversion options. Universally, solutions which reduce the amount of waste generated in the first place or recycle or compost the waste are seen as environmentally preferable solutions. Landfill methane capture is typically seen as preferable only if there is no other way to prevent the waste from going to the landfill and reaching its end of life in the first place. Three different waste hierarchies are shown in Figure 1.3, Figure 1.4, and Figure 1.5 below. The first, from the IPCC, places landfill with methane recovery and use just above treatment (most likely incineration) of waste without any energy recovery. Landfill with Methane Flared is only rated higher than other landfill solutions. (Figure 1.3).

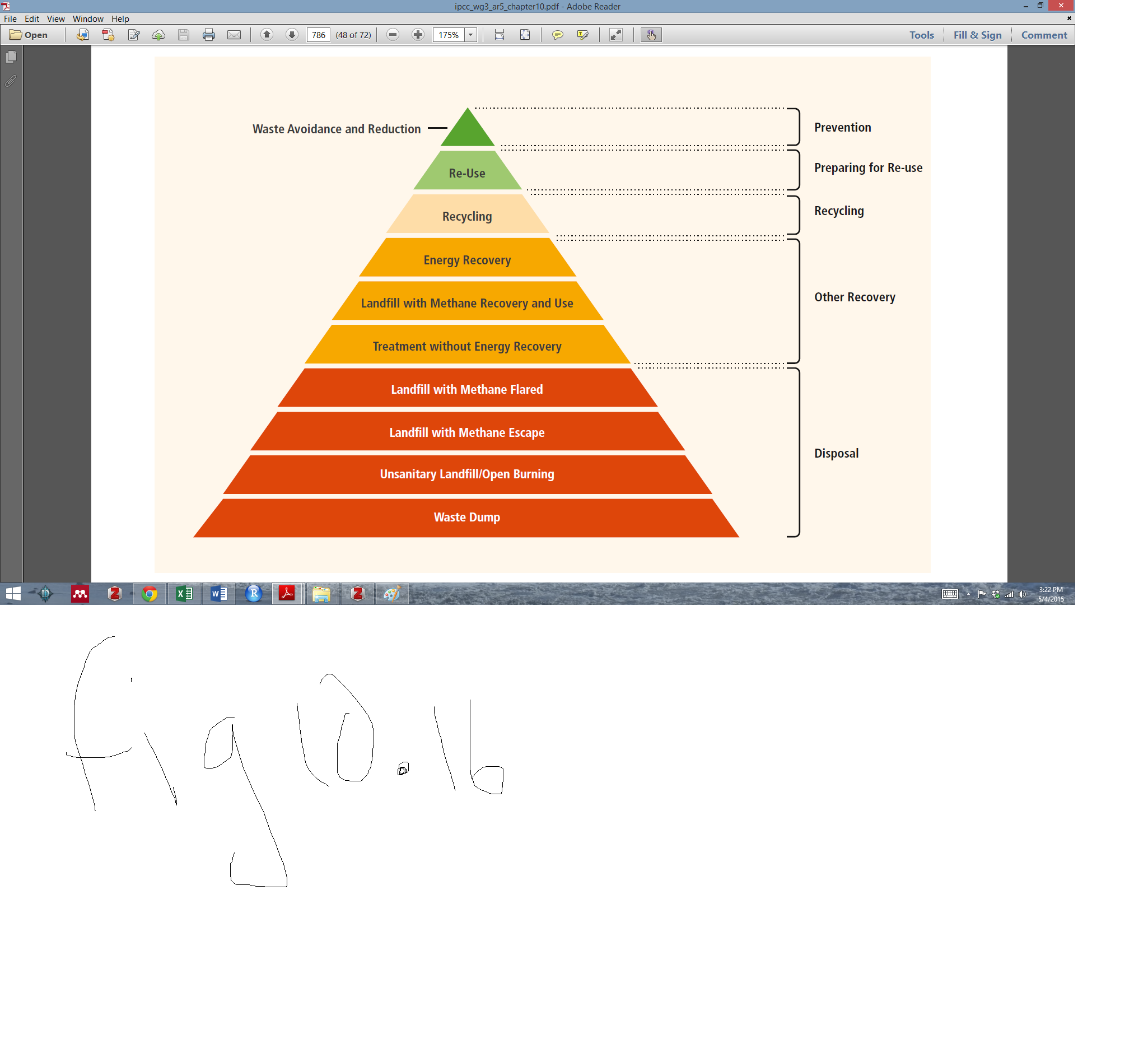


Figure 1.3 Hierarchy of solid waste disposal (IPCC, 2014)

The second figure places landfill methane recovery below all solutions aside from landfilling without methane capture (Figure 1.4). Unlike the first figure it also includes composting as a waste disposal option. It is commonly argued that if biomass materials were habitually composted rather than sent to the landfill, very little methane would be emitted from a landfill as the majority of landfill methane comes from biomass. However, this hierarchy specifies that the composting should be aerobic, as many composting sites can cause anaerobic breakdown of the waste and also emit methane. Some larger sites even capture it and use it to generate electricity for their facility (Powell et al, 2016). Therefore, the design of the composting site is very important to determining the magnitude of its benefits relative to landfill methane capture.

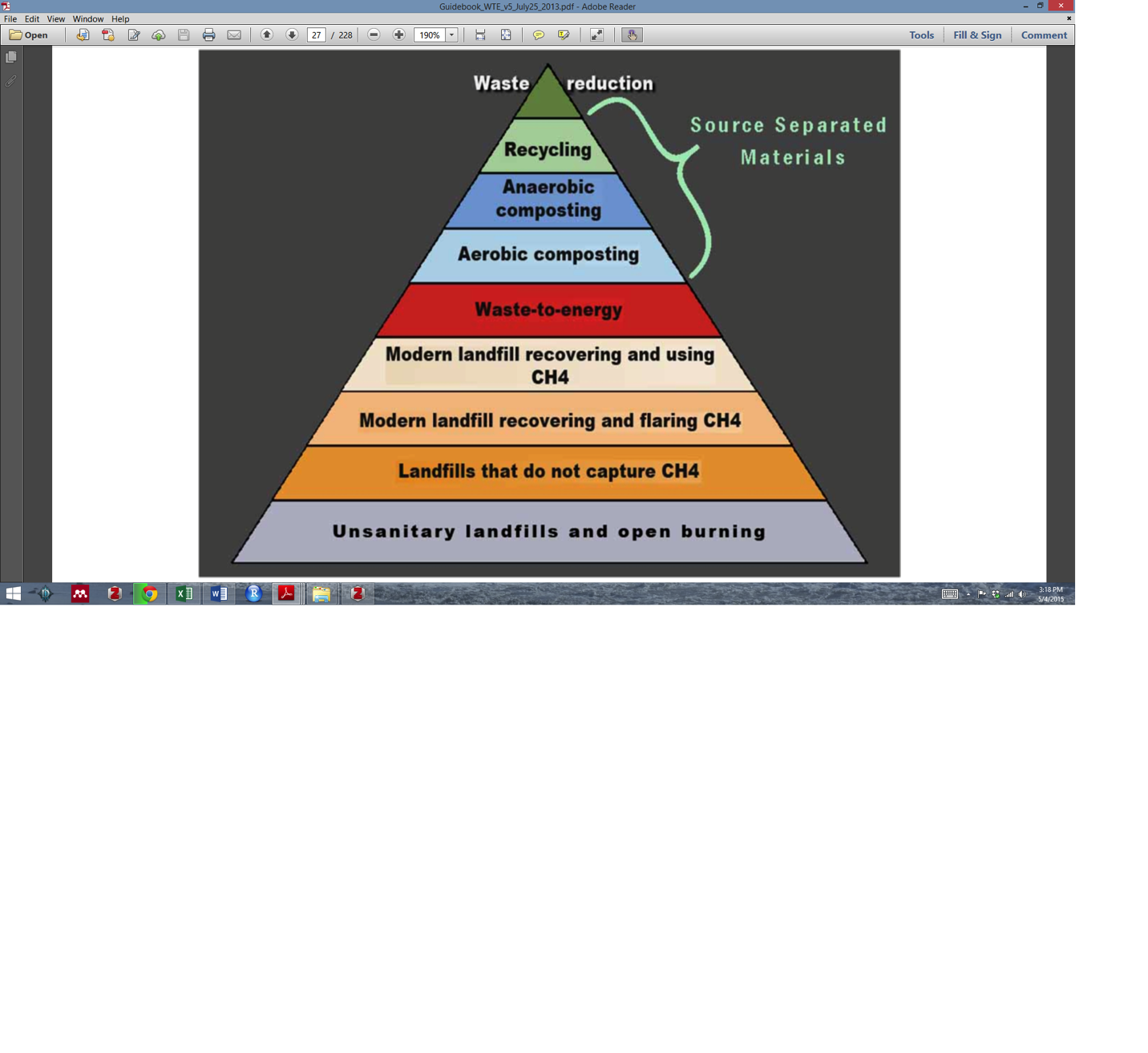


Figure 1.4 Hierarchy of solid waste disposal (Themelis et al., 2013)

The third hierarchy is slightly less clear and places landfill above incineration, though only by a dotted line, and their waste disposal category is not visually separated, as the others in the diagram are. This depiction reflects a more developing-world conscious view of the study’s authors, staff at The World Bank, who probably recognize that low-cost incineration is not likely a strategy they should advocate to many readers of World Bank reports (Figure 1.5).

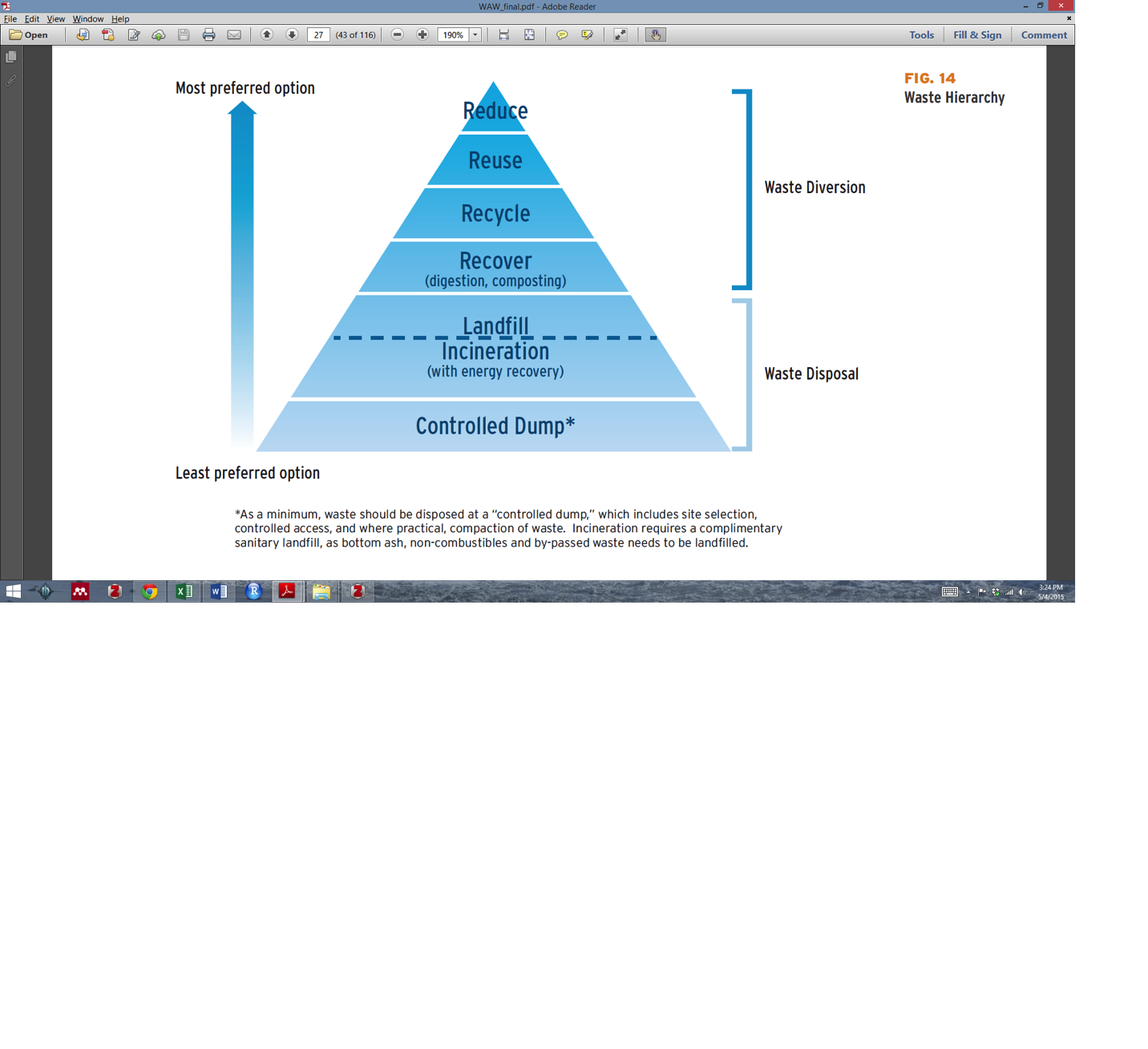


Figure 1.5 Hierarchy of solid waste disposal (Hoornweg and Bhada-Tata, 2012)

As the waste hierarchies above highlight, there is wide agreement that it is a ‘second best’ or even a ‘last resort’ waste management strategy, even though it can have substantial benefits. Its proponents’ arguments live or die on the assumption that some landfill-bound MSW is unavoidable. As progressive cities begin to more aggressively pursue zero-waste strategies, this assumption will be tested.

While waste to energy/incineration is clearly a close competitor with landfill methane capture, there are a few reasons that landfill methane capture is often ranked lower. First, even in engineered landfills, 17-35% of methane emissions are unable to be captured and still pollute the environment (Powell *et al*., 2016). Second, due to the fact that methane emissions tend to peak and then sharply decline, the electricity generation potential from a landfill varies significantly over time. This makes it difficult to size an engine, since engine efficiency varies with load. Therefore, the engine is typically either under-sized and unused landfill gas is flared, or it is sized to the peak load and operates at lower than peak efficiency for much of its life. Either way, this reduces the effective efficiency and total energy output from landfill gas to electricity solutions when compared to waste to energy. Along a similar vein, some of the energy potential in the waste is not recovered through landfill methane capture, as fossil fuel-based wastes such as plastics and textiles which can be burned in waste to energy plants do not typically degrade and produce methane in landfills. Another large disadvantage compared to many other waste diversion solutions is that landfill methane capture still requires a vast portion of land to hold the waste, destroying landscapes and habitats and removing other potential uses for the land and resources.

Another issue with landfilling in general is the potential for landfill fires. The likelihood of fires from landfills is thought to even be increased by adding landfill methane capture systems which encourage airflow throughout the landfill and can oxidize the waste, though this is a bigger issue at landfills that are open and still accepting waste rather than closed landfills. Between 2004 and 2010, 839 unique landfill fires occurred in the US alone 25% of which were at landfills which had already had a fire at least once before. Of the landfills with active landfill gas collection systems, 46% of them had at least one fire between 2004 and 2010. These fires are sometimes difficult to extinguish, lasting for months or years (Powell et al, 2016). These fires are also damaging to health, safety, and environment, presenting a significant downside to landfilling of any kind. The risk and impact of fires may increase further in developing countries which have less stringent access controls, as illicit disposal of materials is a common cause of fires (ibid).

# 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 (Landfill Methane Capture) 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 landfill methane capture systems. The model used for this analysis constructs both alternative ambitious adoption pathways (PD scenarios) and a Reference scenario (REF) for Landfill Methane Capture. 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 26.9 terawatt-hours, or 0.12 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 landfill methane capture use is extrapolated to model several alternative adoptions. The landfill methane capture solution in RSS encompasses only electricity generation from landfill methane. 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 landfill methane capture 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 landfill methane capture 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 12 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 landfill gas to electricity systems. First cost data from several sources was collected. First, USAID’s *Grid-Connected Energy Generation Toolkit,* a collection of presentations made to help “USAID mission staff and national policy makers understand and assess the relevance of policies and programs that have been used successfully in support of large, grid-connected renewable energy (RE) development” (Hamrin, 2016). It is a comprehensive source detailing cost and other parameters for a wide range of renewable energy sources, including landfill gas. While the information is gathered from a series of peer-reviewed data sources, it is often not clear which source relates to which data point, and what year the data was gathered, as it appears to be updated over time. However, low and high estimates for first cost of electricity generation from landfill gas appear to be relatively in line with other sources. EPA (2016 and 2020) study on landfill gas to energy is also used, where first cost estimates are shown to vary greatly between end generation technology (microturbine, small internal combustion engine, large internal combustion engine, gas turbine). Data from IRENA (2012), EESI (2013), and IPCC 4th Assessment Waste Management Report (2003) is also collected into the RRS model.

Fixed operation and maintenance (FOM) costs are estimated from sources like EPA (2016 and 2020) which estimate operating costs for each type of electricity generation technology (microturbine, small internal combustion engine, large internal combustion engine, gas turbine) and Ragnauth *et al.* (2013). Data from IRENA (2012) and EESI (2013) is also included.

These estimates were used to calculate total operating costs of landfill methane capture 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. World Bank (2005); Ragnauth et al. (2013); EPA (2016); Chandel et al. (2012); GMI (2013); Ahmed *et al.(*2008); Cooley *et al.* (2013).

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 landfill methane capture systems for electricity generation and the avoided methane emissions using flaring. 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.

While the RRS model is used and the primary TAM is based on electricity generation, the landfill methane capture adoption parameters are also limited by the total waste available in landfills for landfill methane capture. Therefore, total landfilled waste can be seen as a “secondary” TAM, representing the waste side of the technology. Because the landfill methane capture solution includes both landfill gas to electricity systems and landfill methane capture and flaring, this is particularly important in bounding the adoption characteristics for non-electricity based technologies.

In the RRS model, this TAM for waste comes directly from global waste generation prognostications. The waste generation data is a blended solution which takes the average of 4 different waste to energy sources, common to all drawdown waste solutions. The IEA Annex 1 (IEA, 2016) is taken by interpolating from the regional waste estimates for 2013 and 2050. World Bank’s What a Waste 2.0 (2016) reports global waste for 2016 and projections for 2030, and 2050 which are interpolated and extrapolated to make future projections used as a second reference. Some of the same authors from the World Bank report produced another set of future waste prognostications in 2015, which are also used as a source (Hoornweg *et al.*, 2015). Finally, a UNEP 2015 report on Global Waste Management Outlook is used to generate MSW generation per capita, which is multiplied by UN total urban population projections. Based on the calculated markets for *composting, household & commercial recycling,* and *recycled paper*, MSW is separated into three classifications: organic, recyclable, and remainder. Within these categories, the impact of each solution is quantified according to the following prioritization:

1.     *Reduced food waste*

2.     *Bioplastic*

3.     *Composting*

4.     *Household and Commercial (HH&C)* *recycling*

5.     *Recycled paper*

6.     *Waste-to-energy solutions:*

1. Waste to Energy

2. Landfill Methane Capture

## 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 landfill methane capture systems has been kept constant throughout the study period to 2050. As the market grows, the total number of landfill methane capture 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.

### Landfill Methane Adoption Prognostications

For the global adoption scenarios, six 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 landfill methane 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 landfill methane 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 landfill methane solutions in all bioenergy was equal to 5.34%.
2. Since no better information is available for landfill methane for electricity generation, future adoption was obtained applying the previous calculated share of biogas from landfill methane 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 represents an incremental growth of renewable energy solutions using a conservative adoption trajectory to 2050. For this solution, Due to *landfill methane’s* low priority in waste management ranking, the *Plausible* Scenario is built upon four conservative scenarios from the IEEEJ Outlook Advanced Technology Scenario (2019), IEA WEO Stated Policies Scenario (2018), IEA ETP Reference Technology Scenario (2017), and Equinor Reform Scenario (2018). The average of these four cases is also bounded by the available waste allocated to the landfill methane capture solution from the integration model. As mentioned above, the landfill methane solution is at the bottom of the pyramid of solid waste disposal, therefore it is the last solution to get integrated during the waste integration. The resulting Plausible Scenario is therefore determined by taking the minimum value of the average of the four conservative cases or the available waste from and foresees landfill methane capture reaching 0.17 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 uses the same methodology of the Plausible Scenario where the average of the four conservative adoption scenarios are bounded by the available waste allocated to landfill methane capture solution from integration. In this scenario the solutions reduces its market share in 2050 to 0.0 percent.

#### Optimum Scenario

This scenario represents the most optimistic case, and is based on the average of the four conservative adoption scenarios are bounded by the available waste allocated to landfill methane capture solution from integration. This scenario depicts 0.0 percent of the total electricity generation in 2050.

Although the Plausible, Drawdown and Optimum scenario are all built upon an average of the conservative adoption data sources and bounded by the available waste allocated to landfill methane capture from the integration model, it is important to note that each scenario will have completely different results. As mentioned previously, the MSW TAM is impacted by the calculated markets for other solutions and the waste-to-energy solution is quantified as the lowest priority with landfill methane capture being the last waste mitigation option. Therefore for each scenario, waste diversion solutions are adopted at more aggressive levels and therefore less waste remains for the waste to energy solutions. The final landfill methane capture adoption for each scenario is therefore bounded by less waste than the previous scenario, where the Plausible scenario has the largest amount of waste available and the Optimum has the lowest amount of waste available for landfill methane solution. If the landfill methane adoption scenario was less than the total available waste, then the adoption held true. However, if the adoption was greater than the waste available, then the adoption was bounded by the total waste available.

## 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 landfill methane capture for electricity generation was estimated globally and regionally 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.

The second emissions reduction impact is generated from the displacement of CH4 from landfills. Estimates for this are described below. This displacement happens regardless of whether the landfill methane capture solution produces electricity. IPCC waste guidelines are used to calculate methane avoided per year based on the amount of waste used in landfill methane capture. The following method is used:

* 1. Calculate Amount of Carbon in Waste
     1. As a prerequisite to estimating the avoided methane emissions from landfill, the carbon in MSW streams is estimated using data from the IPCC waste guidelines on the carbon content of waste types (IPCC, 2006b)
     2. The degradable organic carbon (DOC) fraction is taken from the value calculated in the Waste to Energy Drawdown solution, which uses a waste composition from the IPCC’s waste composition estimates as reported in Annex 9 of the World Bank’s What a Waste report (Hoornweg and Bhada-Tata, 2012). It is assumed that these values are acceptable to use for both solutions even though the compositions may be slightly different between the two solutions, as waste composition only has a minor effect on the DOC fraction value.
  2. Avoided methane from waste decomposition (see: IPCC guidelines, below)
     1. Methane emissions in this are calculated only for Drawdown regions, in line with the IPCC waste guidelines using a first order decay model. IPCC default values for methane generation factors are used across the board, and the solid waste disposal emissions guidelines should be reviewed for a detailed explanation of the methodology (IPCC, 2007). This estimate is highly sensitive to choices in k-value which depend on particular landfill climate, waste composition, and landfill design. Therefore, while this is an approximation, there is likely to be a wide range of local variations in methane generation not taken into account by this model.

In this solution methane capture is assumed to begin immediately once waste begins generating methane. It is assumed that the first few months of a landfill’s life in which methane is being emitted in minor amounts but methane capture is not installed will have small enough emissions that they can be ignored for the sake of this analysis. It is also assumed that all landfill methane capture is installed in new landfills, rather than landfills which are already generating considerable methane emissions. This is likely to be the most accurate method for calculating methane emissions each year, and therefore it is the one used in the calculations. Emissions avoided are therefore calculated using the following equation:

where:

* is the CO2-eq emissions reduction associated with the additional generation provided by landfill methane to electricity conversion in the PDS scenario.
* is the total generation of electricity generation from landfill methane 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 landfill methane capture systems over their lifetime.
* is the total methane reduction associated with all landfill capture technologies (flaring and electricity) per TWh. Multiplying this value by the CH4 GWP of 84 converts it to CO2 equivalent.
* is the CO2-eq emissions generated by combusting landfill gas. This is comprised of CO2, CH4, and N2O.

In the RRS model, is the same value used for all Drawdown Electricity Replacement solutions. In LCAs for landfill methane capture systems, indirect emissions estimates are typically lacking. Therefore, these emissions are assumed to be small enough to not affect the overall system, and is set to 0 in the model. Estimates for calculated using the first order decay model recommended by the IPCC to convert tons of waste adopted to total CH4 emissions from landfills where this waste is disposed. Efficiency of methane capture is estimated over time by type of landfill. In 2015, efficiency of landfill methane capture in engineered landfills is calculated using the empirical data from climate reporting of landfills in the US, which show that 90% of landfill emissions are come from open engineered landfills at 65% capture efficiency, and 10% of landfill emissions come from closed engineered landfills at 82% capture efficiency (Powell et al., 2016). A weighted average of this data estimates overall capture efficiency at landfills of 66.7% in 2015. However, it is also indicated that technology developments are likely to increase capture efficiency at landfills over time (ibid). Therefore, efficiency at engineered landfills is estimated to increase linearly from 66.7% in 2015 to 82% around 2050. Basic landfills are estimated in the EPA’s MAC report to have 10% lower efficiency of capture than engineered landfills (Ragnauth *et al*, 2013). In our model, we assume this relationship maintains constant over time.

Capture efficiencies are multiplied by estimates for CH4 output from landfills using methane capture. This gives a value for methane emissions mitigated in each region each year. These are summed to estimate the total global methane emissions mitigated between 2015 and 2050 and divided by the total net electricity output during the same time period to develop and average estimate for tCH4 per TWh that is used in the final emissions calculations.

Estimates of CO2-eq from combustion are calculated as follows. For CO2 emissions, a mass-balance is done to convert the CH4 emissions saved from landfill to CO2 emissions caused by burning. The atomic mass of CO2 is 2.74 times that of CH4. Therefore, CH4 emissions saved are multiplied by 2.74 over 84 (the CH4 GWP) to estimate CO2 emissions caused from burning. CH4 and N2O emissions are calculated using the IPCC’s default emissions values for combustion of natural gas, and dividing by a gas to electricity efficiency of .33 to estimate the total emissions. Total CO2eq/TWh estimates are generated by summing the combustion emissions estimates for CO2, CH4, and N2O. IPCC’s 20-year GWP values are used for both CH4 and N2O.

Several other custom calculations estimating reduction in methane emissions are included in the RRS model for reference. These sources are likely to produce higher estimates for CH4 mitigated, because they consider the total CO2-eq impact over the life of the landfill, whereas the first order decay calculations consider methane emissions which would have happened within the time period of 2015-2050.

One set of these custom calculations are taken by aggregating and averaging data from several literature sources which cite estimates for m3 landfill gas per ton of waste (Rajaram et al., 2011; Surroop et al., 2011). This can be converted to tons of CH4 using a conversion factor based on the relative atomic masses of CH4 and CO2, given that landfill gas is approximately 50% CH4 and 50% CO2 on a molar basis (Rajaram et al, 2011). An average of sources found estimating kWh output per m3 of landfill gas is used to convert these values to total energy output in the gas (Rajaram et al., 2011; UCF, 2012). When combined with estimates for gas collection efficiency and engine efficiency the total kWh per ton of waste or tCH4 per kWh electricity is estimated.

### Financial Inputs

The RRS model constructs PDS adoption scenarios for landfill methane capture electricity generation globally and regionally 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. As above-mentioned, the landfill methane capture solution in RRS model encompasses not only electricity generation from landfill methane, but also landfill methane flaring to reduce CH4 emissions. These cost values only encompass the electricity generation portion of the solution. Electricity costs for landfill methane flaring are estimated to be approximately half that of landfill gas to electricity systems (Damgaard *et al*., 2011) and are also added into the final calculations. A lifetime capacity of 111,755 hours (around 16 years) was calculated depending on the average powerplant annual use.

No first cost learning rate is applied since this solution is already a mature technology (IRENA, 2013). Nevertheless, a technology development is taken into account through the increase in efficiency of the system modeled in the adoption and climate data.

For the solution (*i.e.* landfill methane capture), 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 landfill methane capture systems which results in a total first cost of US$ 2,110 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* | 1,617 – 2,603 | 2,110 | 16 | 6 |
| Fixed Operation and Maintenance Costs (Solution) | *US$2014/kW* | 153.5 – 349.9 | 251.7 | 16 | 5 |
| Variable Operation and Maintenance Costs (Solution) | *US$2014/kWh* |  |  |  |  |
| Learning Rate Factor (Solution) | % |  |  |  |  |

### Technical Inputs

Lifetime capacity data is consistent across a several sources at 15 to 20 years being the average time methane is produced at a landfill. Capacity factor varies from 74% to 85%, 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* | 97,785 – 125,724 | 111,755 | 5 | 5 |
| Average Annual Use (Solution) | *hours* | 6,598 – 7,371 | 6,985 | 3 | 3 |

## 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. 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 29.8% while the remaining (70.2%) are produced from wastewater and agricultural activities and used in Large digesters solution.

1. This solution only covers biogas production from landfills 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 landfills is equal to 29.8%. The remainder is allocated to large digester solutions.
2. Since no better information is available for biogas for electricity generation, future adoption was obtained applying the previous calculated share of biogas from landfill methane capture (5.36%) 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 landfill methane capture is linked to other waste management solutions as among others, waste to energy, methane biodigesters, 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 landfill capture and technologies used for landfill capture are uniform across regions. While there are some indications that in tropical areas 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.
6. Our descriptions for engineered landfill, basic landfill, and open landfill is characteristic of the general landscape for landfill technology. This is consistent with the assumptions made in the EPA’s 2013 MAC report, which is one of the most comprehensive estimates which has been done on global landfill methane capture potential. However, it does exclude sustainable landfilling technologies designed specifically for the increase of methane in order to recover it.
7. Methane emissions are uniform across types of landfills. No change in methane emissions are estimated based on the design of the landfill and whether or not it encourages aerobic or anaerobic digestion.

## 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

### Use of Thermal Energy from Landfill Carbon Capture

A share of landfill gas capture opportunities will be used to provide heat, displacing alternative or equivalent fuel use. In the case that this is an equivalent fuel, in other words, natural gas, there would be a reduction in upstream GHG emissions and this reduction has not been included in the calculations. The current RRS model does not automatically allow for a calculation of emissions reduction from displacement of fossil fuel sources used for heating.

### Model the Solution with a Reduction in Landfilling over Time

The current model assumes that the percentage of waste going to landfills will remain constant over time. From a climate perspective, this is less than ideal, as landfilling and even landfill methane capture is the least preferable method of waste disposal. While it may reduce the total estimates for landfill methane capture, future research which includes practical reductions in the percentage of waste going to landfills 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 Landfill Methane Capture technologies for electricity generation as compared to conventional technologies and other landfill methane capture alternatives.

## Adoption

### Electricity Generation from Landfill Methane Capture

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 landfill methane capture systems. As a result of this exercise, the Plausible Scenario (PDS1) projects 0.17 percent of total electricity generation worldwide coming from landfill methane capture systems by 2050. In the Drawdown (PDS2) and Optimum Scenarios (PDS3), the market share reduces to 0.0 percent for both. 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 landfill methane capture systems.

Table . World Adoption of the Solution

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Solution** | **Units** | **Base Year (2014)** | **World Adoption by 2050** | | |
| **Plausible** | **Drawdown** | **Optimum** |
| *Landfill Methane Capture* | *Electricity Generation (TWh)* | 26.89 | 79.47 | 0.00 | 0.00 |
| *(% market)* | 0.12% | 0.17% | 0.0% | 0.0% |

Figure 3.1 World Annual Adoption 2015-2060

Note: As waste diversion solutions are adopted at more aggressive levels in each scenario, less waste remains for the landfill methane capture solution. Therefore, the Optimum WTE scenario will have less global electricity generation in comparison to the Plausible Scenario.

### Tons of Waste

In order to compare the waste allocated to landfill methane capture from the Waste integration model to the electricity-based scenarios, values given in tons of waste were converted to TWh of electricity produced from landfill methane capture. A rough approximation can be made separating tons of waste used for electricity generation from other end uses based on data already calculated in the model. In calculating CH4 outputs, literature sources were used to estimate TWh per tons of waste, and a tonnage conversion of 0.199 TWh/ MMT waste was used. This figure is then multiplied by the tons of waste used in the each scenario to determine total TWh electricity potential in that waste.

### 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 6.69 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, however bounded by less available waste, with impacts on greenhouse gas emissions reductions over 2020-2050 of 0.96 gigatons of carbon dioxide-equivalent and ad addition of 3.0 gigatons of carbon dioxide-equivalent respectively. 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*** | 0.34 | 6.69 | 0.18 |
| ***Drawdown*** | 0.21 | 0.96 | -0.37 |
| ***Optimum*** | 0.11 | -3.0 | -0.27 |

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 6.67 gigatons of carbon dioxide-equivalent in the PDS1 - Plausible scenario, 0.96 gigatons of carbon dioxide-equivalent for the Drawdown Scenario and a negative impact of -3.0 gigatons 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** | 0.54 | 0.01 |
| **Drawdown** | 0.02 | -0.04 |
| **Optimum** | -0.28 | -0.02 |

Figure 3.2 World AnnualGreenhouse Gas Emissions Reduction

## Financial Impacts

The financial impacts incurred by replacing conventional grid electricity sources with landfill methane capture systems are significant. The Plausible scenario presents US$3.30 billion in in savings from marginal first costs and over US$20.35 billion of net operating cost savings are projected over 2020 to 2050. Both PDS2 and PDS3 have zero marginal first costs and 3.38 billions of net operating savings and 15.7 net operating costs, respectively over the same period.

The capital costs for PDS adoption of landfill methane capture systems will require significant investments, as the cumulative capital costs are over $37.2 billion under the Plausible Scenario. 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** | 37.24 | 3.3 | 20.35 | 4.08 |
| **Drawdown** | - | - | 3.38 | - |
| **Optimum** | - | - | -15.68 | - |

Figure 3.3 Operating Costs Over Time for the three PD scenarios

# Discussion

This study models a scenario where landfill methane capture could significantly reduce future GHG emissions and help drawdown the amount of carbon in the atmosphere by 0.54 ppm by 2050. This is an important decrease, and is less than the true total amount possible, as it was chosen to use reference climate mitigation scenarios estimations for landfill gas to electricity adoption, under the assertion that ambitious adoption of landfill gas to electricity is less ideal than diverting waste to alternate disposal options.

Overall, landfill methane capture solutions are a net benefit for the climate. From a financial perspective, while some up-front costs are required for landfill gas to electricity technologies, the long term return on investment is significant and therefore these technologies are a sound investment.

The overall climate and financial impact varies significantly based on a few key assumptions. First, the model only calculates CH4 emissions impacts which take place during the 2020-2050 timeframe. If the emissions from the entire lifetime savings of the landfill are taken into account, the overall GHG reduction is almost double. Perhaps even more significant is the variation in adoption data depending on whether the reference, conservative, or ambitious scenarios are chosen.

While it is clearly a ‘second-best’ waste management strategy, as long as landfills are being created it is still a viable and important solution for climate mitigation. Aside from the significant climate benefits and long term cost savings shown by this study, landfills which capture methane are safer and less of a public health hazard than those which do not. Therefore, as landfills move globally from open dumps or basic landfills to engineered sanitary landfills, adoption can and should be expected to continue to increase.

## 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 landfill methane capture solution results. There are no direct comparable benchmarks to the landfill methane capture solution, therefore these references can be used to bound the adoption of the landfill methane capture 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)** | **79.47** | **0.17%** |
| **Project Drawdown – Drawdown Scenario (PDS2)** | **0.00** | **0.0%** |
| **Project Drawdown – Optimum Scenario (PDS3)** | **0.00** | **0.0%** |
| 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)