**Technical assessment for**

**Improved Manure Management**

Sector: Avoided Methane

Agency Level: Farm

Keywords: Livestock, Slurry, Pit, Anaerobic lagoon, Manure Storage, Daily Spread

June 2021

**Prepared by:**

Senorpe Hiablie, Research Fellow

Jay Barlow, Research Fellow

Kristina Colbert, Research Fellow

Mamta Mehra, Senior Research Fellow



[info@drawdown.org](mailto:info@drawdown.org) [www.drawdown.org](http://www.drawdown.org)

Table of Contents

[List of Figures 4](#_Toc81904026)

[List of Tables 4](#_Toc81904027)

[Acronyms and Symbols 5](#_Toc81904028)

[Executive Summary 6](#_Toc81904029)

[1 Literature Review 8](#_Toc81904030)

[1.1. State of Manure Management 8](#_Toc81904031)

[1.2. Adoption Path 13](#_Toc81904032)

[1.2.1 Current Adoption 13](#_Toc81904033)

[1.2.2 Barriers to Adoption 13](#_Toc81904034)

[1.2.3 Trends to Accelerate Adoption 14](#_Toc81904035)

[1.3. Advantages and Disadvantages of Improved Manure Management 15](#_Toc81904036)

[1.3.1 Similar Solutions 15](#_Toc81904037)

[1.3.2 Adoption Burdens 16](#_Toc81904038)

[1.3.3 Arguments for Adoption 16](#_Toc81904039)

[2 Methodology 18](#_Toc81904040)

[2.1 Introduction 18](#_Toc81904041)

[2.2. Data Sources 18](#_Toc81904042)

[2.3 Total Addressable Market 19](#_Toc81904043)

[2.4 Adoption Scenarios 22](#_Toc81904044)

[2.4.1 Reference Case / Current Adoption 23](#_Toc81904045)

[2.4.2 Project Drawdown Scenarios 24](#_Toc81904046)

[2.5 Model Inputs 26](#_Toc81904047)

[2.5.1 Climate Inputs 26](#_Toc81904048)

[2.5.2 Financial Inputs 27](#_Toc81904049)

[2.6 Assumptions 27](#_Toc81904050)

[2.7 Integration 28](#_Toc81904051)

[2.8 Limitations/Further Development 28](#_Toc81904052)

[3 Results 29](#_Toc81904053)

[3.1 Adoption 29](#_Toc81904054)

[3.2 Climate Impacts 30](#_Toc81904055)

[3.3 Financial Impacts 33](#_Toc81904056)

[4 Discussion 34](#_Toc81904057)

[4.1 Benchmarks 35](#_Toc81904058)

[5 References 37](#_Toc81904059)

[6 Glossary 42](#_Toc81904060)

# List of Figures

[Figure 1‑1 Contributions of livestock manure by type and region or production 3](#_Toc81407736)

[Figure 1‑2 A schematic representation of the sources of methane and nitrous oxide from the manure management continuum (Source: Chadwick et al., 2011) 5](#_Toc81407737)

[Figure 2‑1 Percentage of manure in management system type by species and region 15](#_Toc81407737)

[Figure 3‑1 World Annual Adoption 2015-2050 22](#_Toc81407738)

[Figure 3‑2 World AnnualGreenhouse Gas Emissions Reduction in a) Covered Anaerobic Lagoons and b) Reduced Storage 24](#_Toc81407739)

# List of Tables

[Table 1‑1 Definitions of manure management systems and their methane emission factors 2](#_Toc76842591)

[Table 1‑2 Manure management techniques and practices for non-CO2 mitigation (adapted from Gerber, 2013) 4](#_Toc76842592)

[Table 2‑1 Conversion factors used to derive manure production associated with livestock products 12](#_Toc76842593)

[Table 2‑2 Methane emission Factors (kg of CH4 per head/year) by livestock type and region. 13](#_Toc76842594)

[Table 2‑3 Proportions of current manure management systems by region and TAM available for adoption scenarios 15](#_Toc76842595)

[Table 3‑1 World Adoption of the Solution (Covered Anaerobic Lagoons) 20](#_Toc76842596)

[Table 3‑2 Climate Impacts Covered Anaerobic Lagoons 22](#_Toc76842597)

[Table 3‑3 Impacts on Atmospheric Concentrations of CO2-eq 22](#_Toc76842598)

[Table 3‑4 Financial Impacts 24](#_Toc76842599)

[Table 4‑1 Benchmarks 27](#_Toc76842600)

# Acronyms and Symbols

* BAU – Business as Usual
* CH4 – Methane
* CO2 – Carbon Dioxide
* CO2-eq - Carbon Dioxide Equivalent
* EU – European Union
* FAO – Food and Agricultural Organization of the United Nations
* GHG – Greenhouse Gases
* GLEAM – Global Livestock Environmental Assessment Model
* Gt – Gigatonnes
* GWP – Global Warming Potential
* IEA – International Energy Agency
* IPCC – Intergovernmental Panel for Climate Change
* IRENA – International Renewable Energy Agency
* LCA – Life Cycle Assessment
* MWh – Megawatt hour
* N2O – Nitrous Oxide
* OECD – Organization for Economic Co-operation and Development
* PD – Project Drawdown
* PDS – Project Drawdown Scenario
* REF – Reference Case
* RRS – Reduction and Replacement Solutions
* TAM – Total Addressable Market
* TWh – Terawatt hour
* USD – United States Dollars
* USEPA – United States Environmental Protection Agency
* VOCS – Volatile Organic Compounds
* VS – Volatile Solids

# Executive Summary

Project Drawdown defines *Improved Manure Management* as a set of strategies that lower manure methane emissions in cattle and pig production systems. The solution specifically focuses on two strategies in liquid manure management, namely, *Reduced Storage* and *Covering Anaerobic Lagoons*. These are modeled as two separate sub solutions. These solutions replace the business-as-usual (conventional) long-term storage in manure pits and slurry systems and uncovered anaerobic lagoons. About 0.7 Gt-CO2eq in annual methane emissions are estimated to come from global livestock manure. With increasing intensification in livestock production and associated moves toward liquid manure systems, the global manual methane emissions are expected to increase. Methane has a global warming potential (GWP) of 28 to 36 times that of between CO2 for a 100-year timescale. The higher GWP and relatively shorter lifespan of methane in the atmosphere provides opportunities to limit global warming on the short term, thus achieving temperature reduction targets more quickly (Collins et al., 2018). Furthermore, acting to reduce manure methane footprints could help avert negative environmental impacts beyond methane emissions alone.

Among mitigation strategies in manure management systems, those that reduced both methane and nitrous oxide emissions were selected for this assessment due to their impacts on overall emissions. The adoption of covered anaerobic lagoons and reduced storage systems were modeled under different scenarios. These strategies as with many other manure methane mitigation strategies are influenced by the types of livestock species, production system, agroclimatic zone, operation size, and socio-economics status. Data on emissions from business-as-usual and solution implementation were obtained from peer-reviewed literature, published reports, and global-scale datasets. The Global Livestock Environmental Assessment Model (GLEAM) and the FAOSTAT database were particularly useful and so were the IPCC’s classification of regional manure management systems and associated emissions factors.

The impacts of increased adoption of the two improved manure strategies were modelled for three adoption scenarios based on two reference (business as usual) cases. *Reference 1* assumed business as usual population projection while *Reference 2* accounted for the population impacts of the *Drawdown Family Planning* and *Educating Girls* solutions. The Project Drawdown Scenarios; PDS1, PDS2, and PDS3 assumed conservative, progressive, and ambitious adoption approaches. The Total Addressable Market (TAM) for the livestock manure management solutions were based on projected total production of meat and milk from grazing and non-grazing cattle and pigs from the *Drawdown Food Supply Model*. The amount of manure used in the *Large Methane Digestors* *Model*[[1]](#footnote-1)was deducted. It was assumed that livestock types, production system types, machinery requirements, and land use did not change during the years simulated.

Results of the assessments showed that the combined total emissions reduction by both manure management solutions under PDS1, PDS2 and PDS3 were 2.76, 5.05, and 7.33 Gt CO2-eq/yr from 2020 to 2050. The share of manure managed in covered anaerobic lagoons was projected to increase from 20 MMT in the reference case in 2014 to about 968 MMT, 1,380 MMT, and 1,8000 MMT by 2050 under the PDS1, PDS2, and PDS3 projections, respectively. These represent 5.2%, 7.4%, and 9.6% growth under PDS1, PDS2, and PDS3 adoption scenarios. The amount of manure managed under the reduced storage solution was expected to increase from about 1,830 MMT in the reference scenario to about 2,800 MMT, 3,500 MMT, and 4,200, respectively by 2050 under the PDS1, PDS2, and PDS3 scenarios. This would be a result of anticipated 15%, 19%, and 22% world adoption of reduced manure storage under PDS1, PDS2, and PDS3, respectively.

The result of the limited financial modeling showed that the combined first costs for both manure management solutions were 28.1, 45.3, and 62.5 bn USD under PDS1, PDS2, and PDS3, respectively. The cumulative first costs nearly doubled between 2015 and 2050 (from 10.7 to 20 USD bn) under PDS1 and PDS3 scenarios for the covered lagoon solution. The reduced storage solution had higher first costs under the different modeled scenarios ranging from 17 to 42.6 bn USD under PDS1 and PDS3 scenarios, respectively. It is expected that coproducts including nutrients for fertilizer (for both solutions) and gas for energy and solid material for bedding (covered lagoon solution) will generate revenues to offset expenses in the adoption of the solutions.

The estimates of the climate impacts modeled were close to other reports. Whereas the current solutions focused on manure storage and treatment strategies to reduce methane from cattle and pigs, opportunities for further reduction may be found in improving overall livestock production efficiency. This would include *improved feed quality* (a solution Project Drawdown has modeled) improved health and reduced mortality, and improved cattle genetics, as well as.

# Literature Review

## State of Manure Management

The global livestock value chain contributes an estimated 14.5% of anthropogenic greenhouse gas emissions in the form of carbon dioxide (CO2), methane (CH4) and nitrous oxide (N2O) through direct and indirect emissions (Gerber et al., 2013). Of the estimated 7.1 gigatonnes CO2 equivalents (Gt CO2 eq) total annual emissions, feed production and processing, enteric fermentation, and manure storage and processing represent 45%, 39%, and 10%, respectively (Gerber et al., 2013). Animal products’ processing and transportation contribute the remaining 6% of emissions. Greenhouse gas reduction strategies are therefore needed at all stages of the livestock supply chain. Although manure emissions appear to be a relatively small fraction of the total emissions, it offers significant opportunities for mitigating emissions of potent greenhouse gases, methane and nitrous oxide.

Livestock manure, composed of feces, urine, and bedding material may be stored as liquid, semi solid/slurry, or solid. The decomposition of manure produces gases including methane and nitrous oxide whose emissions can occur during manure storage, treatment, land application, or from direct disposal on pasture and grazing land by livestock. During storage, emissions are influenced by environmental conditions such as aeration, temperature, and pH. In land disposal, timing, quantity, and mode of application also influence gas emissions. Additionally, the characteristics of the manure itself such as nitrogen, sulfur, and solid contents influenced by the animal type, its rate of growth, and diet also affect emissions during land application (Kebreab et al., 2006). Managing conditions for storage, treatment, and land application therefore present opportunities for reducing methane and nitrous oxide emissions from manure (Petersen et al., 2013; Robertson & Vitousek, 2009).

.

The main manure management systems used globally are defined in Table 1-1 below. They may be broadly classified under dry or wet systems (Wolf et al., 2017). Dry management systems such as pasture, rangelands, paddock, dry lot, solid storage, daily spread, manure burned for fuel, or pit storage of less than one month occur mainly under aerobic conditions which are not conducive for methanogenesis (Chadwick et al., 2011; Petersen et al., 2013). This is evidenced by their relatively low methane emission intensities (Table 1-1). Aerobic conditions in dry systems may however promote nitrous oxide emissions (Brown et al., 2000; Hao et al., 2001). As the main focus of this assessment is the avoidance of methane emissions, solutions will be formulated for wet manure management systems (liquid/slurry, pits, and uncovered anaerobic lagoons).

Table 1‑1 Definitions of manure management systems and their methane emission factors[[2]](#footnote-2)

|  |  |  |
| --- | --- | --- |
| **System** | **Definition (see reference for full definitions)** | **Average global emission factors of CH4/head -year[[3]](#footnote-3)** |
| **Pasture/ Range / Paddock** | Manure is deposited by animals on pasture/rangeland and is not managed. | 0.01 – 0.58 |
| **Burned for fuel** | Dung and urine are excreted on fields and sun-dried dung are burned for fuel. | 0.15 – 2.83 |
| **Daily spread** | Manure is removed from a confinement facility and applied to cropland or pasture within 24 hours of excretion. | 0.01 – 0.03 |
| **Dry lot** | Manure is accumulated in an open confinement area without any significant vegetative cover and may be removed periodically. | 0.02 – 2.08 |
| **Solid storage** | Manure with bedding or dried by evaporation, is stored for several months in unconfined piles or stacks. | 0.04 – 5.05 |
| **Liquid/Slurry** | Manure is stored as excreted or with some minimal addition of water in either tanks or earthen ponds outside the animal housing, usually for periods less than one year. | 0.95 – 3.55[[4]](#footnote-4)  1.13 – 30.66[[5]](#footnote-5) |
| **Pit storage** | Manure is collected or stored with little or no added water typically below a slatted floor in an enclosed animal confinement facility. Storage usually lasts for less than one year. |
| **Uncovered anaerobic lagoon** | Manure is flushed into a liquid storage waste stabilization and system. Storage could be up to a up to a year or more depending on the climate, volatile solids loading rate, and other operational factors. The water from the lagoon may be recycled as flush water in the associated confinement facilities or used to irrigate and fertilize fields. | 1.12 – 9.84 |
| **Anaerobic digester** | Manure with or without straw is collected and anaerobically digested in a containment vessel or covered lagoon. Digestion stabilizes waste by microbial breakdown of complex organic material into carbon dioxide and methane. The methane may be captured and flared or used as fuel. Lagoon supernatant is usually used to flush manure from the associated confinement facilities to the lagoon. | - |

Among livestock species, cattle and pigs produce 85% of methane emissions according to estimates from the GLEAM data (FAO, 2017). Manure storage and processing were found to contribute 0.7 Gt CO2-eq in global annual emissions (Gerber et al., 2013). Based on GLEAM data, (FAO, 2017), manure contributed 0.33 Gt CO2-eq in methane emissions annually. Of this, pigs, dairy cattle and beef cattle made up 58%, 25%, and 17%, respectively (Figure 1-1).

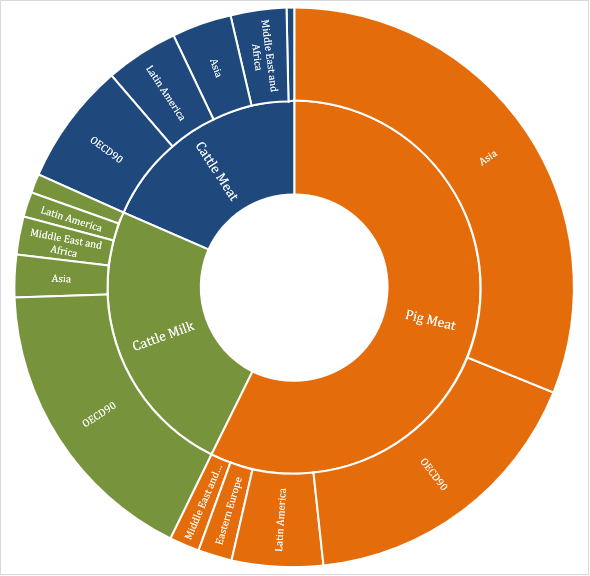


Figure 1‑1 Contributions of livestock manure by type and region or production

Figure 1-1 also shows that in terms of regions, the OECD 90, Asia, and Latin America contributed the most to manure methane emissions. Contributions were influenced by livestock numbers and emission entities of the manure management systems.

Many technologies and practices could contribute to methane reduction in manure management systems to varying degrees (Clemens et al., 2006; Gerber et al., 2013; Hristov et al., 2013; Montes et al., 2013; Niles & Wiltshire, 2019; Sommer et al., 2009). Those that have the clearest effects on methane reduction without increasing nitrous oxide emissions in dairy, non-dairy (beef), and pig (swine) systems were modeled (Table 1-2). These were anaerobic digestion, sealed cover with flare, and decreased storage time. Sealed cover with flare is a form of anaerobic digestion applied to uncovered anaerobic lagoons or other suitable open systems.

Table 1‑2 Manure management techniques and practices for non-CO2 mitigation (adapted from Gerber, 2013)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  | Potential mitigating effect[[6]](#footnote-6) | | |
| Practice/Technology | **Species[[7]](#footnote-7)** | **N2O** | **CH4** | **NH3** |
| Housing |  |  |  |  |
| Manure system | DC, BC, P | High | Unknown | High |
| Manure storage |  |  |  |  |
| Decreased storage time | DC, BC, P | High | High | High |
| Storage cover with straw | DC, BC, P | High | Increase? | High |
| Aeration during liquid manure storage | DC, BC, P | Medium to High | Increase? | Unknown |
| Composting | DC, BC, P | High | Unknown | Increase |
| Sealed storage with flare | DC, BC, P | High | High | Unknown |
| Manure treatment |  |  |  |  |
| Anaerobic digestion | DC, BC, P | High | High | Increase? |
| Manure acidification | DC, BC, P | High | ? | High |
| Manure application |  |  |  |  |
| Manure injection vs surface application | DC, BC, P | No effect to Increase? | No effect to Increase? | High |

Decreased storage time has high potential mitigation effects on methane and nitrous oxide (Weerden et al., 2014) and is applicable to the livestock types found relevant to this assessment (dairy and beef cattle and pigs). The practice of decreased storage time may occur in the form of daily spreading or storage of less than one month (Table 1-1). Project Drawdown’s improved manure management solution for business-as-usual slurry and pit manure systems are daily spreading or reduced storage of less than one month. For uncovered anaerobic lagoons, tightly sealed impermeable covering was selected. In covering existing anaerobic lagoons, methane gas produced may be flared which converts it to CO2 before emission into the atmosphere or it could be captured and utilized. This solution focused on the net methane emissions resulting from covering existing anaerobic lagoons. Globally, flared methane gas contributes approximately 1%[[8]](#footnote-8) of anthropogenic atmospheric CO2 emissions and about 90% of this comes from upstream exploration and production facilities as a by-product of oil extraction (Elvidge et al., 2018).

Daily spreading or reduced storage may be suitable for smaller operations or those that have enough land area for application of the removed manure. Application of manure on land introduces nutrients in the form of nitrogen and phosphorus which are of benefit to crops. As equipment may already be in place for manual removal, additional capital investments may not be a requirement for the adoption of the solution however, increased labor may be needed. Installing a cover over an existing lagoon may require that it has the capability of being filled and emptied without displacing the cover (ICF, 2013). Lagoons without primary settling ponds would accumulate sludge that need to be removed periodically (Pal, 2017, Niles & Wiltshire, 2019). Methane gas accumulated in the sealed lagoons could be flared or captured for use as energy. Energy production was not modeled in the current manure management solutions. Future updates may consider integrating potential energy production into Project Drawdown’s energy solutions models.

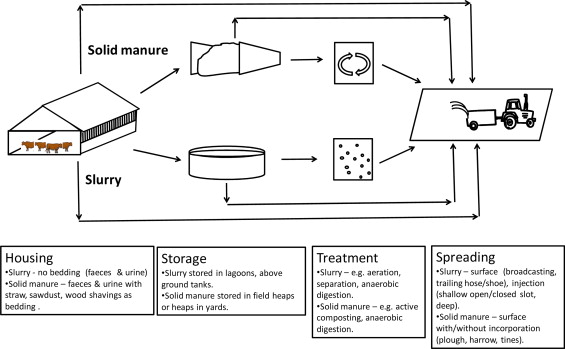


Figure 1-2. A schematic representation of the sources of methane and nitrous oxide from the manure management continuum (Source: Chadwick et al., 2011)

## 1.2. Adoption Path

### 1.2.1 Current Adoption

Globally data on farms practicing daily manure spreading and reduced storage were not easily available. Average values on regional animal waste management systems for cattle and pigs were obtained from estimates (*IPCC*, 2019). Inclusion of global livestock numbers (FAO, 2017) and associated manure excretion rates helped estimate global adoption. It was estimated that 11.5% of manure worldwide, 18.4% of manure in Asia, 14.4% in the OECD and 6.1% in Eastern Europe were treated in reduced storage systems as defined in this assessment. Details of these percentages are shown by species, management system type, and regions in Figure 2-1. Less than 1% of farms collectively in Latin America, and the Middle East and Africa practiced reduced storage likely due to the fact that majority of operations in these regions were grazed or practiced other forms of treatment such as burning manure for fuel.

Data on the number of farming operations covering lagoons with impermeable material was not readily available either. According to the USEPA (2021), about 4% of digesters use this practice in the United States. Given the capital and technological needs of this practice, it was assumed that adoption will be concentrated in the OECD 90. The 4% value was applied to current adoption of digesters for electricity generation in the Large Methane Digesters solution of Project Drawdown leading to an estimated 0.13% in the world and 0.2% in the OECD. The rest of the world was at less than 1% adoption.

### 1.2.2 Barriers to Adoption

Technological and non-technological barriers may reduce adoption rates of both improved manure management solutions (ICF, 2013). In terms of covering existing lagoons, technological barriers in the form of specialized equipment needed to keep lagoon sealed, maintaining the right level of biogas formed, flaring captured gas, and land disposal of digestate and effluent may pose barriers. In cooler climates, lower mitigation potential exists due to reduced anaerobic activity during low temperature seasons (Sommer et al., 2004). Legal barriers may also exist in regions where special permits are required for lagoon modification in consideration of potential contamination of groundwater resources due to leakage.

The main barriers to the adoption of reduced storage may be due to limitations in land availability for daily spreading. This will be the case in large intensive operations without enough land area for manure application. Agronomic considerations and environmental regulations and limit how much manure can be safely deposited on land. Environmental regulations limiting land application of manure nutrients may also be causing smaller dairy farms to store manure longer rather than spread it daily (USEPA, 2017). For example, although majority of cattle farms in China (95.4%) can be considered as small farms (maintaining 1 – 49 heads), policy barriers to individual ownership may present challenges to frequent land application (Zhao et al., 2019).

Regulations limiting manure application rates and timing (for example, prohibition of winter application in parts of the United States) due to environmental concerns may also present challenges to adoption. Areas with geological constraints such as shallow water table, karst aquifers, and highly porous soils, or nearness to vulnerable ecosystems may limit frequent manure application.

### 1.2.3 Trends to Accelerate Adoption

Methane is receiving attention as a potent greenhouse gas whose global emissions are increasing (Wolf et al., 2017). In the United States, methane emissions from manure management increased by over 78% between 1990 and 2015 (USEPA, 2017). Increasing population growth, rising income levels, increasing intensification in livestock management systems, legislation changes, and policy incentives are trends that are likely to accelerate the use of liquid manure management systems particularly in dairy cows and pigs. The need to mitigate methane produced in liquid systems will call for adoption of solutions.

Population growth and rising income levels particularly in developing countries is driving rapid increasing demand for animal protein. In China, the world's most populous country, for example, there is a strong and increasing demand for pork. The country registered 55 million tons in production over the 10-year period between 2007 and 2017 (Zhao et al., 2019). At the same time, non-profitability of smaller farms is driving consolidation into larger facilities. A 150% increase in farms producing over 10, 000 heads annually was reported in the same 10-year period (McOrist et al., 2011; Zhao et al., 2019). The United States also reports a shift to larger operations in which liquid systems are used (USEPA, 2017). The intensification of dairy cattle and pig production systems are leading to the general adoption of liquid systems (USEPA, 2017). Projections are that livestock production in the future will occur mostly in confined animal feeding operations where higher GHGs and methane emissions are likely (Petersen et al., 2013). Intensive systems are also seen as being well-positioned to fund facility and treatment technologies due to increased cash flow (Petersen et al., 2013).

Due to the increasing attention on the environmental impacts of GHG’s and methane, resources are being dedicated to solutions. Methane capture and use and energy production from livestock waste is an example of mitigation options being focused on for technical innovations and incentives. Technological innovations and policy instances that reduce barriers to adoption may play significant roles in pig and dairy manure management according to the 2011 projections of the USDA Economic Research Service (2011) (Key et al., n.d.). These would be feasible in regions such as the OECD-90 and Asia with significant amounts of wet manure management systems. In the Middle East, Africa, Latin America and Eastern Europe, nearly 80% or more of manure were found to be managed in dry systems (Figure 2-1).

## 1.3. Advantages and Disadvantages of Improved Manure Management

### Similar Solutions

Project Drawdown has modeled GHG reduction solutions focusing on feed production and processing and more recently, methane from enteric fermentation which addresses livestock production. The current solution focuses on methane mitigation in livestock manure as part of a cluster of “avoiding methane” solutions. Similarities between this solution and other Project Drawdown Solutions are as follows.

Avoiding Methane - The solutions under this cluster are i) Improved Cattle Feed Quality ii) Avoiding Methane Leaks and iii) Improved Manure Management. These three solutions aim to reduce global methane emissions. Through improved cattle feed, enteric fermentation which is a significant source of methane emissions in livestock can be reduced. Sealing leaks in natural gas infrastructure also provides opportunities for significantly reducing methane emissions. Although the current solution is part of a cluster, it can be seen as being unique in its role. It may however be affected by the feed solution. Some feed types and additives have been proposed as reducing both enteric fermentation and manure sources of methane (Cardenas et al., 2007). It has also been demonstrated that feeding strategies can help lower manure methane emissions (Li et al., 2012; Mathot et al., 2012).

Waste Solutions **-** Under this cluster of solutions, the i) Waste to Energy and ii) Large Methane Digesters may be similar to the Covering Anaerobic Lagoon solution. Both the current solution and the Large Methane Digester solution utilize manure as feedstocks. **To avoid double counting, manure that may have gone into the Large Methane digester solution was deducted from the total addressable market of the current solution. Biogas is a coproduct of both solutions from which energy could be obtained. For the methane digester solution, the energy produced was electricity to replace fossil sources. The current solution does not model electricity production, but the methane gas captured could be used onsite or offsite.**

### Adoption Burdens

The disadvantages of the proposed solutions include the following;

1. Covered lagoon systems require regular monitoring and maintenance to function properly. For example, the aerating fans need to be well-maintained particularly in hot weather (ICF, 2013). Wastewater from lagoons may need to be treated before disposal. Also, the lagoons may need to be emptied periodically to remove sludge build-up ((Niles & Wiltshire, 2019). Without CO2 price incentives, covered lagoon systems need to be large (about 5,000 dairy head) to have a 0 USD break-even price (ICF, 2013).
2. For both solutions, the absence of uniformity of manure constituents applied, and uniformity of application on land may be a concern as manure produced is not always uniform due to changing diets. This calls for the need for high quality manure analysis program, up-to-date soil tests, analysis of crop needs, and knowledge of the amount of manure to be produced. The impact on changing planting dates could also cause operational challenges. Soil compaction due to manure application, increased weeds and disease are additional considerations (Iowa State Extension, 2007[[9]](#footnote-9)).

### Arguments for Adoption

With projected increases in livestock populations come management needs for the manure that will be produced. The current solutions are the first one to assess methane reductions from manure management systems. Moreover, these solutions have many core benefits which are listed below.

1. Nutrient value – The coproducts of digestion in covered anaerobic lagoons include liquid and solid or semi solid digestate. These as well as manure from slurry and pits have nutrient value. When applied on land they could serve as nutrient sources. These nutrients retain revenue on the farm which would have otherwise been used to purchase fertilizer. If sold, additional revenue could potentially be brought to the farm.
2. Avoiding indirect emissions – Synthetic fertilizer production is energy intensive therefore replacements with manure and digestates will reduce GHG impacts of a farm and its products.
3. Reduced fugitive methane emissions from the storage of manure – Covering anaerobic lagoons with impermeable sealed covers reduces fugitive emissions.
4. Odor and pathogen reduction – Covered anaerobic lagoons have been used to reduce odor from farms. Additionally, the condition for digestion reduces pathogen load of manure thereby protecting the environments, surface water and groundwater.
5. Energy production – Captured methane from biogas produced could be used as a natural gas alternative if further cleaned to required standards. It may also be used for electricity generation or directly on site for heating.

The improved manure management solutions in addition to reducing methane emissions, offer opportunities for the recycling of nutrient and materials back onto the farm, presenting a form of circularity.

# Methodology

## 2.1 Introduction

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

## 2.2. Data Sources

Data collected covered animal census, manure management system types, environmental impacts, and financial data. These were collected from inventories and databases belonging to inter-governmental and national agencies, non-governmental and academic institutions, as well as industry, and peer-reviewed journal publications.

Global animal census data was obtained from the statistics database of the Food and Agriculture Organization (FAOSTAT, 2021). Data availability (current, historical, and projected) on the proportions of manure managed in each manure systems was limited globally. For this analysis, classifications in IPCC (2019), Global Livestock Environmental Assessment Model (GLEAM) reference documentation (FAO, 2017) and Gerber et al.2013) and Wolf et al. (2017), were referenced for the definitions of manure management systems (Table 1) and to determine the proportions of manure treated in each system.

Environmental impact data, primarily, methane emissions reported in CO2,eq was obtained for both the business-as-usual (business as usual) functional and solution functional units (MMT of manure). Emission intensities from manure management systems by region, climate, and livestock species were obtained from the guidelines of the IPCC (2019) and GLEAM data (FAO, 2017). Additional data came from literature sources, extension publications, and reports produced by national agencies including the USEPA AgSTAR database of livestock anaerobic digesters. The model’s analysis of the climate impacts of adoption were derived from the direct emissions related to the replacement of business-as-usual liquid and slurry manure storage with reduced storage and covering of uncovered anaerobic systems. The Drawdown RRS model framework and guidelines provides more details on this methodology.

Financial data, primarily first costs, fixed costs and variable costs were obtained from published reports and peer-reviewed publications where available. A key source for the solution of covering anaerobic lagoons was ICF International (2013). First costs for the reduced storage solution included the acquisition of manure hauling and spreading equipment. Variable costs for this solution included repairs and maintenance and operational expenses such as loading, hauling, and manure application. Together, these would help estimate the total cost of adoption for the reduced storage solution. For the covered lagoon solution, first costs included the cost of cover and flaring equipment. Variable costs were primarily the operational and maintenance costs. These capital and operations and maintenance costs helped estimate the cost of adoption for this solution.

## 2.3 Total Addressable Market

The Total Addressable Market was calculated based on projections for global annual animal protein production in the Project Drawdown Food Supply Model. The Food Supply Model integrates solutions in the food demand, food production, and land use sectors and estimates the annual global supply of crops and livestock products based on the model’s assumption that all demand for livestock protein will be met through 2050. The Food Supply Model is based on five scenarios, two references and three solution scenarios. The reference scenarios (REF1 and REF2) simulate business-as-usual (BAU) projections in the global demand for livestock products. Reference 2 includes the population impacts of the Project Drawdown Family Planning and Educating Girls solutions. The three solution scenarios, (Project Drawdown Scenarios; PDS), PDS1, PDS2, and PDS3 incorporate changes in food demand based on the Plant-rich Diet and Reduced Food Waste solutions.

The amount of manure production associated with meat (cattle and pigs) and milk (cattle) under the different scenarios was calculated on an annual basis. To estimate the available TAM for adoption of these solution, manure allocated to the Project Drawdown Large Methane Digester solution was deducted. The Large Methane Digester solution estimated that the total share of biogas from all biofuels was 18% of which biogas produced from large bio-digesters contributed 70.2%. Furthermore, animal manure made up 20% of bioenergy feedstock in the large bio-digesters under the baseline scenario in 2016.

Given their relatively small, combined contributions, small ruminant livestock, buffalo, and poultry where excluded from this analysis. The conversion of animal product to manure in million metric tonnes (MMT) was based on literature sources (see footnotes) and standards as shown in Table 2.1. The milk or meat yield per live weight of animal was determined. The amount of manure excreted per live animal annually was estimated and the recoverable manure was taken as 85% for dairy cattle and 80% for non-dairy cattle and pigs.

Table 2‑1 Conversion factors used to derive manure production associated with livestock products

|  |  |  |  |
| --- | --- | --- | --- |
|  | Dairy Cattle | non-Dairy cattle | Pig |
| Milk yield (liters milk/year-animal)[[10]](#footnote-10) | 2514 |  |  |
| Meat to live weight (fraction)[[11]](#footnote-11) | 0.50 | 0.50 | 0.65 |
| Live weight (global average) (kg)[[12]](#footnote-12) | 423 | 337 | 74 |
| Live weight (kg) |  |  |  |
| Asia (Sans Japan) | 362 | 276 | 69 |
| Eastern Europe | 550 | 389 | 77 |
| Latin America | 508 | 329 | 81 |
| Middle East and Africa | 278 | 314 | 72 |
| OECD90 | 576 | 394 | 72 |
| Manure (t/day-animal)[[13]](#footnote-13) | 0.068 | 0.038 | 0.007 |
| Recoverable manure (%)10 | 85.0% | 80.0% | 80.0% |

The amounts of manure produced globally in association with each animal product under the five Project Drawdown Food Supply Model scenarios described above were allocated to regions and manure management systems using GLEAM data (FAO, 2017; Gerber et al., 2013), IPCC (2019), and Wolf et al. (2017) as the main sources. *Figure 2-1* shows a breakdown of manure by management system type, species and region. In all regions, majority of cattle were managed dry systems. Dry management systems consisted of dry lots, pasture/range, solid manure, daily spread, manure burned for fuel, and pit storage of less than one month. Globally, 64% of the livestock manure were estimated to be managed in dry systems. In non-dry systems, estimates were as follows, liquid and deep pit systems (23%), lagoons (6%), and digestors and other systems (7%). According to the estimates, nearly all manure were managed in dry systems in Middle East and Africa while this value was 88% in Latin America and 79% in Eastern Europe. About half, 54% and 52%, respectively of manure belonged in dry systems in the OECD 90 and Asia. In Asia, the livestock numbers contributing this majority were pigs while in the OECD, cattle were predominant. Methane emission factors were calculated by country for each livestock species, agroclimatic zone, and production systems .and consolidated into regional averages (Table 2.2)

Table 2‑2 Methane emission Factors (kg of CH4 per head-year) by livestock type and region (IPCC, 2019[[14]](#footnote-14))

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Livestock type | System type | Asia (Sans Japan) | Eastern Europe | Latin America | Middle East and Africa | OECD90 |
| Dairy | High Productivity System | 7.30 | 8.79 | 3.28 | 6.22 | 34.17 |
| Uncovered anaerobic lagoon | 0.00 | 0.00 | 0.00 | 0.00 | 5.85 |
| Solid storage | 1.72 | 5.05 | 0.67 | 2.09 | 1.78 |
| Drylot | 1.33 | 0.00 | 2.03 | 2.08 | 0.00 |
| Pasture/Range/Paddock | 0.30 | 0.16 | 0.58 | 0.52 | 0.34 |
| Daily Spread | 0.00 | 0.01 | 0.00 | 0.00 | 0.02 |
| Digester | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Burned for fuel | 2.83 | 0.00 | 0.00 | 1.53 | 0.00 |
| Liquid/Slurry, Pit storage > 1 month | 1.13 | 3.57 | 0.00 | 0.00 | 26.19 |
| Non-Dairy (Meat) | High Productivity System | 2.75 | 31.09 | 0.82 | 2.95 | 6.62 |
| Uncovered anaerobic lagoon | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Solid storage | 1.00 | 0.23 | 0.17 | 0.88 | 0.74 |
| Drylot | 0.59 | 0.00 | 0.11 | 0.94 | 0.02 |
| Pasture/Range/Paddock | 0.16 | 0.20 | 0.54 | 0.34 | 0.36 |
| Daily Spread | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 |
| Digester | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Burned for fuel | 1.00 | 0.00 | 0.00 | 0.78 | 0.00 |
| Liquid/Slurry, Pit storage < 1 month | 0.00 | 30.66 | 0.00 | 0.00 | 5.51 |
| Pig | High Productivity System | 4.02 | 1.40 | 5.25 | 4.09 | 6.15 |
| Uncovered anaerobic lagoon | 7.12 | 1.12 | 1.17 | 1.32 | 9.84 |
| Liquid/Slurry, Pit storage < 1 month | 2.59 | 1.28 | 3.11 | 3.55 | 0.95 |
| Solid storage | 0.07 | 0.60 | 0.22 | 0.25 | 0.04 |
| Drylot | 0.04 | 0.00 | 0.09 | 0.10 | 0.02 |
| Pasture/Range/Paddock | 0.02 | 0.00 | 0.01 | 0.01 | 0.00 |
| Daily Spread | 0.00 | 0.00 | 0.01 | 0.02 | 0.03 |
| Digester | 0.01 | 0.00 | 0.03 | 0.04 | 0.00 |
| Burned for fuel | 0.22 | 0.00 | 0.15 | 0.17 | 0.00 |
| Liquid/Slurry, Pit storage > 1 month | 5.28 | 3.46 | 6.30 | 6.92 | 2.69 |

The methane emission factors (Table 2.2) were multiplied with the proportion of cattle maintained in each system and region (Figure 2-1). Weighting these values by the quantity of livestock products gave estimates of the total methane produced globally in association with the various livestock products and manure management systems.

Figure 2‑1; Percentage of manure in management system type by species and region

## 2.4 Adoption Scenarios

Two different types of adoption scenarios were developed: a Reference (REF) Case which served as the baseline under which there was business as usual (BAU), and a set of Project Drawdown Scenarios (PDS) with varying levels of ambitious adoption of the solution. Published results comparing one PDS to the REF show changes in the world relative to a baseline. This report includes an REF scenario based on the current adoption of management systems which maintains the same rate of use from 2020 and 2050 and a set of PDS scenarios based on aggressive growth adoption between 2020 and 2050. The adoption scenarios considered variability in regional practices and constraints were set based on limits of the TAM and considerations of region-specific practicality such as land availability due to existing ownership policies.

### 2.4.1 Reference Case / Current Adoption

The REF scenarios were maintained at their current percentages of the total market over the next thirty years. The number of systems managed under the REF scenarios were assumed to grow equally with the projected increases in livestock numbers at constant percentage adoptions. Although this may not reflect the reality of the BAU, it allowed the evaluation of the relative impact of more aggressive scenarios.

The current adoption of the covered anaerobic lagoon solution was modeled as 4% of the corresponding adoption of the Drawdown Large Methane Digester solution. This was based on the USEPA (2021) report that covered lagoons made up 4% of anaerobic digesters. The quantity of manure corresponding to the electricity generated (TWh) in the Large Methane Digester Model was estimated as the current adoption.

The current adoption of the reduced storage solution was taken as being represented by the practices of daily spread of manure and storage of less than one month as reported in IPCC (2019) and FAO (2017). Table 2-3 shows the current adoption of the improved manure management solutions in each region and the TAM available for adoption scenarios.

Table 2‑3 Proportions of current manure management systems by region and TAM available for adoption scenarios

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  |  | Current Solution Adoption / Reference (%) | | TAM available for solution adoption (%) | |
| Region | Manure managed in region (%) | Covered Anaerobic Lagoons | Reduced Storage | Covered Anaerobic Lagoons | Reduced Storage |
| Asia (Sans Japan)[[15]](#footnote-15) | 30.6% | 0.01% | 18.4% | 26.7% | 5.0% |
| Eastern Europe | 7.5% | 0% | 6.1% | 0% | 21.4% |
| Latin America[[16]](#footnote-16) | 17.5% | 0% | 0.4% | 12.2% | 0.3% |
| Middle East and[[17]](#footnote-17) Africa | 7.4% | 0% | 0% | 0% | 0.5% |
| OECD 90 | 37.0% | 0.20% | 14.4% | 10.0% | 32.0% |
| World[[18]](#footnote-18) | 100% | 0.13% | 11.5% | 6% | 23.3% |

### 2.4.2 Project Drawdown Scenarios

Three custom PDS scenarios were developed based on a linear interpolation of the current adoption and consideration of growth within limits set by existing practices and the available TAM. For the reduced storage solution, projected adoption was kept stagnant at 50% of the current adoption in Latin America and the Middle East and Africa resulting in the low values of 0.15% and 0.25%, respectively. These were due to the low quantities of manure managed in non-dry systems in these regions according to available data. Adoption projections for reduced storage were kept stagnant at 5% in Asia for all scenarios owing to anticipated limited land availability for spreading manure particularly in China (the world’s largest pork producer) where current policies restrict private land ownership. The remaining TAM in Asia was allocated under the covered anaerobic lagoon solution.

In view of these limitations, seven custom scenarios for future projections were developed for each manure management solution at various levels of linear adoption. The seven custom scenarios for the covered anaerobic lagoon solution were based on incremental levels of added adoption between 6.5% and 12.5% to the highest current adoption reported for a region of the world. The scenarios do not include increased adoption in the Middle East and Africa or Eastern Europe. Middle East and Africa manage nearly all manure in "dry systems" while there is reportedly low utilization of anaerobic lagoons in Eastern Europe. Thus, custom adoption scenarios for the solution were not modeled in these regions.

*Custom Scenarios 1, 2, and 3*: Assume increased solution adoption of 6.50%, 10%, and 7.5%, respectively by uncovered systems in Asia, Latin America and the OECD 90.

*Custom Scenario 4*: Assumes increased solution adoption of 12.50% by uncovered systems in Asia and Latin America and 6.50% in the OECD 90.

*Custom Scenario 5*: This scenario assumes increased solution adoption of 7.50% by uncovered systems in Asia and Latin America and 6.50% in the OECD 90.

*Custom Scenario 6*: This scenario assumes increased solution adoption of 6.50% by uncovered systems in Asia and Latin America and 7.50% in the OECD 90.

*Custom Scenario 7:* Assumes an increased solution adoption of 6.50% by uncovered systems in Asia and Latin America and 7.50% in the OECD 90.

The seven custom adoption scenarios of the reduced storage solution were built under projections of increases of half, twice and two-and-half times the current adoption in the region with the highest reported adoption. The current adoption is 6.1% and 14.4% of farms managing liquid and slurry pits in Eastern European and the OECD 90, respectively. Details of the custom scenario are below. The scenario does not include increased adoption in the Middle East and Africa or Latin America. These two regions manage at least 95% of their manure in "dry systems". Due to limitations in land availability in Asia (predominantly in China where most of the intensive systems are), only 5% of solution adoption is modeled and the rest of the available TAM is addressed in the covered anaerobic lagoon solution.

*Custom Scenarios 1, 2, and 3*: Assumes an increased solution adoption of 50%, 2 times, and 2.5 times, respectively above the highest current regional adoption for farms managing liquid and slurry pits in Eastern European and the OECD 90.

*Custom Scenario 4*: This scenario assumes an increased solution adoption of 2.5 times that of the highest current regional adoption by farms managing liquid and slurry pits in Eastern European and the OECD 90.

*Custom Scenario 5:* This scenario assumes an increased solution adoption of 2.5 times that of the highest current regional adoption by farms managing liquid and slurry pits in the OECD 90 and 50% in Eastern Europe.

*Custom Scenario 6:* This scenario assumes an increased solution adoption of 50% times that of the highest current regional adoption by farms managing liquid and slurry pits in the OECD 90 and twice in Eastern Europe.

*Custom Scenario 7:* This scenario assumes an increased solution adoption of 2 times that of the highest current regional adoption by farms managing liquid and slurry pits in the OECD 90 and 50% in Eastern Europe. EE.

With the solutions being modeled separately, modifications or development of improved adoption trends for each solution may be more easily implemented as more data is obtained.

The averages of the moderate, low (with standard deviation subtracted), and high (with standard deviation added) levels of the custom adoption scenarios were estimated to be PDS1, 2, and 3, respectively. These scenarios are further defined as follows:

PDS1 follows a conservative growth rate to 2050 based on baseline projections. The adoption rates of the solution were set at the lower bound over the 30-year time-period.

PDS2 follows a progressive growth rate to 2050 based on baseline projections. The adoption rates of the solution were set at the average of the moderate scenarios over the 30-year time-period.

PDS3 follows an ambitious growth rate to 2050 based on baseline projections. The adoption rates of the solution were set at the upper bound of the higher custom scenarios over the 30-year time-period.

## 2.5 Model Inputs

### 2.5.1 Climate Inputs

The climate impacts due to improved manure management were calculated from emissions avoided from the adoption of the solutions. The inputs were in the form of methane emissions from the business as usual management systems and the solutions. The reduced or captured emissions as a result of the solutions’ implementation were calculated based on the functional unit of a million metric tonnes (MMT) of manure.

Inputs included emission intensities reported for each manure management system by livestock type, climate, and region. These were multiplied by the corresponding quantities of manure managed. There were high levels of uncertainties associated with the percentages of manure reported to be managed in each system at regional levels. These uncertainties may reduce as data availability improves particularly for developing nations.

In addition to methane, nitrous oxide emissions data was obtained when available for the management systems. The system boundary was set as the farmgate and climate impacts from products of the solutions such as manure for fertilizer and biogas for offsite use were not modeled. Revenue from these products were however noted as they would impact the costs and affect adoption decisions by the implementing agency, the farm.

The subcategories of manure management solutions are suitable under diverse environments, contribute different climate impacts, and are undergoing diverse levels of adoption. Under some circumstances, covers on storage systems could serve as solutions to methane emissions for business as usual long-term manure as was simulated for Asia in this assessment.

### 2.5.2 Financial Inputs

The model relied on peer-reviewed literature, published reports, and extension publications for financial data. These were mostly available for North America and Europe. First costs for the reduced storage solution included the acquisition of manure hauling and spreading equipment.

The first cost for lagoon cover considered only transiting from existing systems and included lagoon cover and flaring equipment. The costs of business as usual slurry and pit storage systems and uncovered anaerobic lagoons were challenging to find and so were forecasted prices for both business as usual and solution cases. A first cost learning rate of 2% was applied and based on reports, the lifetime capacity of 22 years was used for the reduced storage solution, and 15 years for the covered lagoon solutions.

Co-products such as nutrientsnayak from manure and methane extracted from biogas could be put to beneficial use onsite. Revenue gains from these products may also help to offset the costs of adoption. A more robust assessment of the value of manure and biomethane co-produced could be done in the future.

## 2.6 Assumptions

Seven overarching assumptions are made by Project Drawdown 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. Assumptions specific to these models are below.

1. The covering anaerobic lagoon solution was modeled for existing lagoons only and did not consider first costs related to new lagoon constructions
2. The Food Supply Model was the source of animal protein projections.
3. The current adoption for covering anaerobic lagoon solutions was 4% of the adoption of the Large Methane digesters but future projections did not follow the same trajectory
4. Other than ensuring that manure emission factors for the various manure management systems, livestock species, and regions were allocated their protein equivalences, no weighting was done.
5. Manure from slurry and pits systems in Asia were modeled under covered anaerobic lagoons solutions due to the practical feasibility of limitations in land available for manure disposal particularly in China for which majority of the pigs raised in slurry and pit systems was reported
6. Cow and pig manure had the similar bioenergy content per tonne[[19]](#footnote-19)
7. Livestock types, production system types, machinery requirements, and land use remained unchanged during the 30-years of the solution was modeled

## 2.7 Integration

The improved manure solutions are kept as separate sub-solutions. This will allow easier accounting and integration into the Project Drawdown System of models. Manure considered available for the adoption of both solutions excluded that used in the Large Methane Digester solutions and the TAM was adjusted accordingly. Methane produced under the covered anaerobic lagoons if not flared, may have several end uses. This includes electricity generation, use on site for heat, or a compressed natural gas alternative that is injected for pipeline injection. Energy generation was not modeled as part of the current manure management solution.

The TAM for both solutions were aligned with the proportions of manure produced in their corresponding business as usual systems in each region. The TAM of the Food Supply model was used to determine the TAMs for the projections for global annual animal protein production for each solution.

## 2.8 Limitations/Further Development

The limited availability of accurate estimates of the proportion of manure managed in each system across regions was a major challenge. As the size of an operation influences the physical and financial feasibility of the adoption of a solution, animal census data showing the representative sizes of operations within regions will be beneficial. Regional financial data describing the costs of adoption (first costs, capital, and variable) and forecasts would also enhance the accuracy of the costs estimated. As more data becomes accessible, the uncertainty in estimates could be reduced.

# Results

Results on world adoption, climate impacts, and financial impacts which were derived from the Drawdown RRS model of the covered anaerobic and reduced storage management solutions are presented below from the years 2014 to 2050. The growth of the two solutions were modeled to follow a linear trend over the simulated period.

## 3.1 Adoption

Table 3-1 and Figures 3-1a and b show simulated values of the world’s adoption in functional units and percentages for the two sub-solutions from year 2014 to 2050 under the three Project Drawdown scenarios. With a higher current adoption, the reduced storage solution consistently maintained 40% higher adoption than the covered anaerobic lagoon solution.

The amount of manure managed in covered anaerobic lagoons was projected to increase from 20 MMT to about 968 MMT or 1,8000 MMT by 2050 under the conservative (PDS1) or aggressive (PDS3) scenarios, respectively. These represent 5.2% growth under PDS1 and 9.6% growth for PDS3 scenario of the covered lagoon solution. The current adoption was based on 4% that of the Large Methane Digesters. This low level of adoption put constrains on the available TAM. Due to projection data limitations for manure management, the future years’ projection was based on seven scenarios built on increments of adoption between 6.5% and 12.5% adoption in regions of the world where the business as usual systems were reported. Under PDS1 and PDS3 scenarios, manure managed under the reduced storage solution is expected to increase from about 1,830 MMT to 2,800 MMT and 4,200, respectively from the years 2014 to 2050. This would be a result of anticipated 15% and 22% adoption of the reduced storage solution under PDS1 and PDS3, respectively.

Table 3‑1 World Adoption of the Solution (Covered Anaerobic Lagoons)

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Solution** | **Units** | **Current Year (2014)** | **World Adoption by 2050** | | |
| **PDS1** | **PDS2** | **PDS3** |
| Covered Anaerobic Lagoons | MMT Manure | 20.79 | 967.78 | 1,383.97 | 1,800.16 |
| *(% Market)* | 0.1% | 5.2% | 7.4% | 9.6% |
| Reduced Storage | MMT Manure | 1,833.32 | 2,803.46 | 3,501.58 | 4,199.69 |
| *(% Market)* | 11.5% | 14.9% | 18.6% | 22.4% |

Figure 3‑1 World Annual Adoption 2015-2050

## 3.2 Climate Impacts

Associated with the simulated adoption scenarios are the climate impacts presented below. Table 3.2 and 3.3 show emissions reductions and changes and impacts on atmospheric concentrations. The glossary (Section 6) gives detailed descriptions of each of these measures. The anticipated total emissions reduction between the years 2020 and 2050 through the adoption of covered lagoons under the modeled scenarios ranged between 1.52 to 2.75 *Gt CO2-eq.* For reduced storage, this value ranged between 1.24 to 4.58 *Gt CO2-eq.* As explained earlier, limitations on the available TAM such as only 4% that of the Large Methane Digesters solution going to covered anaerobic lagoons and predominantly (80% and greater) dry manure management systems in the Middle East, Africa, Latin America and Eastern Europe limited adoption solution levels.

Table 3‑2 Climate Impacts Covered Anaerobic Lagoons

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
|  | **Scenario** | **Maximum Annual Emissions Reduction** | **Total Emissions Reduction** | | **Emissions Reduction in 2050** |
|  | *(Gt CO2-eq/yr.)* | *Gt CO2-eq. (2020-2050)* | | *(Gt CO2-eq/year)* |
| ***Covered Anaerobic Lagoon*** | ***PDS1*** | 0.08 | 1.52 | 0.08 | |
| ***PDS2*** | 0.11 | 2.14 | 0.11 | |
| ***PDS3*** | 0.15 | 2.75 | 0.15 | |
| ***Reduced Storage*** | ***PDS1*** | 0.07 | 1.24 | 0.03 | |
| ***PDS2*** | 0.16 | 2.91 | 0.07 | |
| ***PDS3*** | 0.25 | 4.58 | 0.11 | |
| ***Combined Results*** | ***PDS1*** | 0.08 | 2.76 | 0.11 | |
| ***PDS2*** | 0.16 | 5.05 | 0.18 | |
| ***PDS3*** | 0.25 | 7.33 | 0.26 | |

These solutions when integrated with other Drawdown solutions may have different emissions than individually reported here due to adjustments that would be made. By keeping these sub-solutions separate, allocations of the inputs and their impacts many be easier to track.

Table 3‑3 Impacts on Atmospheric Concentrations of CO2-eq

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Scenario** | **GHG Concentration Change in 2050** | **GHG Concentration Rate of Change in 2050** |
|  | *PPM CO2-eq (2050)* | *PPM CO2-eq change from 2049-2050* |
| ***Covered Anaerobic Lagoon*** | ***PDS1*** | 0.13 | 0.006 |
| ***PDS2*** | 0.18 | 0.009 |
| ***PDS3*** | 0.23 | 0.011 |
| ***Reduced Storage*** | ***PDS1*** | 0.10 | 0.005 |
| ***PDS2*** | 0.24 | 0.012 |
| ***PDS3*** | 0.38 | 0.019 |
| ***Combined Result*** | ***PDS1*** | 0.23 | 0.011 |
| ***PDS2*** | 0.42 | 0.021 |
| ***PDS3*** | 0.61 | 0.030 |

Figure 3‑2 World AnnualGreenhouse Gas Emissions Reduction in a) Covered Anaerobic Lagoons and b) Reduced Storage

## Financial Impacts

Based on data limitations, only cumulative first costs were modeled for both solutions. For PDS1, 2, and 3, the combined solutions first costs were 28.1, 45.3, and 62.5, respectively. These costs nearly doubled between 2015 and 2050 (from 10.7 bn to 20 USD bn) under PDS1 and 3 scenarios for the covered lagoon solution (Table 3-2). The reduced storage solution had higher first costs under the different modeled scenarios ranging from 17 to 42.64 under the three scenarios. Reduced storage practices such as daily spread would require more labor and may contribute to higher costs.

Table 3‑4 Financial Impacts

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Scenario** | **Cumulative First Cost** | **Marginal First Cost** | **Net Operating Cost Savings** | **Lifetime Operating Cost Savings** | **Lifetime Cashflow Savings NPV (of All Implementation Units)** |
| *2015-2050 Billion USD* | *2015-2050 Billion USD* | *2020-2050 Billion USD* | *2020-2050 Billion USD* | *Billion USD* |
| **Covered Anaerobic Lagoon** | | | | | |
| ***PDS1*** | 10.70 | - | - | - | - |
| ***PDS2*** | 15.31 | - | - | - | - |
| ***PDS3*** | 19.87 | - | - | - | - |
| **Reduced Storage** | | | | | |
| ***PDS1*** | 17.43 | - | - | - | - |
| ***PDS2*** | 30.04 | - | - | - | - |
| ***PDS3*** | 42.64 | - | - | - | - |

# Discussion

Livestock manure management has long been a cause for concern for various environmental, ecological, and social reasons. This will continue to be so as demand for livestock protein is driven by population growth and lifestyle changes in developing countries. The growth of the livestock industry is expected to continue to meet increasing demand and associated with it, larger volumes of manure to manage. Increased intensification is also projected to be the trend as smaller operations consolidate into larger ones. Larger systems tend to use liquid manure management options. Regions with high livestock densities but have limited land for recycling the nutrients have historically produced surplus manure. Due to its bulkiness, transport of manure over long distances are untenable.

The current solutions were selected based on their ability to reduce both methane and nitrous oxide emissions at the farm level. They also do not involve introducing chemical compounds that may pose additional hazards. These two solutions though modeled separately, may feed into each other. Covers for instance, could be introduced onto existing manure slurry storage systems and pits. Removal of the liquid from the anaerobic storage systems while not akin to daily spreading may serve as a form of reduced storage due to the relatively shorter storage times. The advantages of both solutions are that they offer co-products such as nutrients, gas, and solid material that could be used as fertilizer, energy source, or bedding, respectively onsite or offsite to help offset costs of adoption. Furthermore, this would reduce indirect emissions and the associated GHG footprints of the farm.

Recycling of the co-products also introduce efficiency which is important in manure methane management solutions. Other solutions such as improved feed quality may have impacts on the quantity and constituents of the manure produced and improve efficiency (Hristov et al., 2013). Improved forages and certain new feed additives including 3-nitrooxypropanol (3-NOP) targeted at enteric fermentation reduction have been reported to reduce methane emissions in manure while improving productivity. Improvements in genetics may also promote increased nutrient use efficiency resulting in faster growth rates and reduced age-to-slaughter and subsequently, the amounts of manure produced per animal over a lifespan. This would mean that fewer livestock are maintained to meet demands of the human population.

As manure management systems change, it is likely that solutions would grow to reflect the manure management types employed. The higher levels of adoption of the PDS scenarios relative to the reference case as modeled may be possible if costs associated with adoption are lowered, supporting policies are in place and technologies are available. Costs may be reduced from revenue from co-products, government incentives, and reductions in acquisition costs as applicable technologies become more widely available. In the United States for example, government grants have supported some manure management programs.

Uncertainties in this model were associated with determining accurately, the proportion of manure managed in the different systems worldwide. The historical and future use of the various manure management systems were also not readily available. Most of the data for this assessment came from developed nations where data was more available. Model improvements should consider incorporating data sources from non-OECD regions. Animal census data showing the size of representative operations, and typical manure management practices for example, would be beneficial as well. Finance data from worldwide sources to serve us model inputs would help provide robust estimates of the financial outcomes of the adoption of these solutions. This data should include the current costs of acquisition, operations, and maintenance as well as future projections where possible.

In conclusion, this assessment showed that methane emissions reductions are possible for large or small operations. The costs and land availability will influence adoption. Importantly, these solutions yield co-products through which nutrients could be recycled on the farm or could serve as additional farm revenue. In continuing to add more high-quality input data, the models’ projections would improve.

## 4.1 Benchmarks

Table 4.1 presents benchmarks related to methane reductions measured or estimated in peer-reviewed literature and reports. The projected mitigation impacts of the two solutions are also presented. While the other sources might not offer direct comparisons, they are useful for judging the expected impacts of the proposed solutions.

Table 4‑1 Benchmarks

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Source and Scenario** | **Practice** | **Mitigation impact**  **(Gt CO2e)** | | |
| **at time of study** | **2030** | **2050** |
| Project Drawdown (PDS1) | Covering existing anaerobic lagoon |  |  | 0.08 |
| Project Drawdown (PDS2) | Covering existing anaerobic lagoon |  |  | 0.11 |
| Project Drawdown (PDS3) | Covering existing anaerobic lagoon |  |  | 0.15 |
| Project Drawdown (PDS1) | Reduced storage |  |  | 0.03 |
| Project Drawdown (PDS2) | Reduced storage |  |  | 0.07 |
| Project Drawdown (PDS3) | Reduced storage |  |  | 0.11 |
| US EPA (2019) | Large scale covered lagoon without engine |  | 0.02 |  |
| US EPA (2019) | Large scale covered lagoon with engine |  | 0.02 |  |
| Herrero et al. (2016) | Mitigation potential of manure management techniques |  | 0.08 | |
| Nayak et al. (2015) | Anaerobic digestion of manure | 0.06 |  | |

# References

Amon, B., Kryvoruchko, V., Fröhlich, M., Amon, T., Pöllinger, A., Mösenbacher, I., & Hausleitner, A. (2007). Ammonia and greenhouse gas emissions from a straw flow system for fattening pigs: Housing and manure storage. *Livestock Science*, *112*(3), 199–207. https://doi.org/10.1016/j.livsci.2007.09.003

Brown, H. A., Wagner-Riddle, C., & Thurtell, G. W. (2000). Nitrous Oxide Flux from Solid Dairy Manure in Storage as Affected by Water Content and Redox Potential. *Journal of Environmental Quality*, *29*(2), 630–638. https://doi.org/10.2134/jeq2000.00472425002900020034x

Cardenas, L. M., Chadwick, D., Scholefield, D., Fychan, R., Marley, C. L., Jones, R., Bol, R., Well, R., & Vallejo, A. (2007). The effect of diet manipulation on nitrous oxide and methane emissions from manure application to incubated grassland soils. *Atmospheric Environment*, *41*(33), 7096–7107. https://doi.org/10.1016/j.atmosenv.2007.04.055

Chadwick, D., Sommer, S., Thorman, R., Fangueiro, D., Cardenas, L., Amon, B., & Misselbrook, T. (2011). Manure management: Implications for greenhouse gas emissions. *Animal Feed Science and Technology*, *166–167*, 514–531. https://doi.org/10.1016/j.anifeedsci.2011.04.036

Clemens, J., Trimborn, M., Weiland, P., & Amon, B. (2006). Mitigation of greenhouse gas emissions by anaerobic digestion of cattle slurry. *Agriculture, Ecosystems & Environment*, *112*(2), 171–177. https://doi.org/10.1016/j.agee.2005.08.016

Elvidge, C. D., Bazilian, M. D., Zhizhin, M., Ghosh, T., Baugh, K., & Hsu, F. C. (2018). The potential role of natural gas flaring in meeting greenhouse gas mitigation targets. Energy strategy reviews, 20, 156-162.

FAO. 2017. Global Livestock Environmental Assessment Model. Model Description Version 2.0

http://www.fao.org/fileadmin/user\_upload/gleam/docs/GLEAM\_2.0\_Model\_description.pdf

FAO. 2019. Global dairy platform; Global Agenda for Sustainable Livestock, Dairy Sustainability Framework. FAO, Rome. http://www.fao.org/publications/card/en/c/CA2929EN/ FAOSTAT. (2021). FAOSTAT Database. Food and Agriculture Organization of the United Nations (FAO). http://www.fao.org/faostat/

Gerber, P. J., Hristov, A. N., Henderson, B., Makkar, H., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A. T., Yang, W. Z., Tricarico, J. M., Kebreab, E., Waghorn, G., Dijkstra, J., & Oosting, S. (2013). Technical options for the mitigation of direct methane and nitrous oxide emissions from livestock: A review. *Animal*, *7*, 220–234. https://doi.org/10.1017/S1751731113000876

Haeussermann, A., Hartung, E., Gallmann, E., & Jungbluth, T. (2006). Influence of season, ventilation strategy, and slurry removal on methane emissions from pig houses. *Agriculture, Ecosystems & Environment*, *112*(2), 115–121. https://doi.org/10.1016/j.agee.2005.08.011

Hao, X., Chang, C., Larney, F. J., & Travis, G. R. (2001). Greenhouse gas emissions during cattle feedlot manure composting. *Journal of Environmental Quality*, *30*(2), 376–386. https://doi.org/10.2134/jeq2001.302376x

Herrero, M., Henderson, B., Havlík, P., Thornton, P. K., Conant, R. T., Smith, P., Wirsenius, S., Hristov, A. N., Gerber, P., Gill, M., Butterbach-Bahl, K., Valin, H., Garnett, T., & Stehfest, E. (2016). Greenhouse gas mitigation potentials in the livestock sector. *Nature Climate Change*, *6*(5), 452–461. https://doi.org/10.1038/nclimate2925

Hristov, A.N., Oh, J., Lee, C., Meinen, R., Montes, F., Ott, T., Firkins, J., Rotz, A., Dell, C., Adesogan, A., Yang, W., Tricarico, J., Kebreab, E., Waghorn, G., Dijkstra, J. & Oosting, S. 2013. Mitigation of greenhouse gas emissions in livestock production – A review of technical options for non-CO2 emissions. Edited by Pierre J. Gerber, Benjamin Henderson and Harinder P.S. Makkar. FAO Animal Production and Health Paper No. 177. FAO, Rome, Italy

ICF (2013). Greenhouse Gas Mitigation Options and Costs for Agricultural Land and Animal Production within the United States. Prepared for: U.S. Department of Agriculture Climate Change Program Office Washington, DC

IEA. (2020). Outlook for biogas and Prospects for organic growth World Energy Outlook Special Report biomethane. https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth

IPCC (2019) *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories—*https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/

Kebreab, E., Clark, K., Wagner-Riddle, C., & France, J. (2006). Methane and nitrous oxide emissions from Canadian animal agriculture: A review. *Canadian Journal of Animal Science*, *86*(2), 135–157. https://doi.org/10.4141/A05-010

Key, N., McBride, W. D., Ribaudo, M., & Sneeringer, S. (n.d.). *Trends and Developments in Hog Manure Management:* 39.

Li, C., Salas, W., Zhang, R., Krauter, C., Rotz, A., & Mitloehner, F. (2012). Manure-DNDC: A biogeochemical process model for quantifying greenhouse gas and ammonia emissions from livestock manure systems. *Nutrient Cycling in Agroecosystems*, *93*(2), 163–200. https://doi.org/10.1007/s10705-012-9507-z

Mathot, M., Decruyenaere, V., Stilmant, D., & Lambert, R. (2012). Effect of cattle diet and manure storage conditions on carbon dioxide, methane and nitrous oxide emissions from tie-stall barns and stored solid manure. *Agriculture, Ecosystems & Environment*, *148*, 134–144. https://doi.org/10.1016/j.agee.2011.11.012

McOrist, S., Khampee, K., & Guo, A. (2011). Modern pig farming in the People’s Republic of China: Growth and veterinary challenges. *Revue Scientifique Et Technique (International Office of Epizootics)*, *30*(3), 961–968. https://doi.org/10.20506/rst.30.3.2091

Montes, F., Meinen, R., Dell, C., Rotz, A., Hristov, A. N., Oh, J., Waghorn, G., Gerber, P. J., Henderson, B., Makkar, H. P. S., & Dijkstra, J. (2013). SPECIAL TOPICS — Mitigation of methane and nitrous oxide emissions from animal operations: II. A review of manure management mitigation options1. *Journal of Animal Science*, *91*(11), 5070–5094. <https://doi.org/10.2527/jas.2013-6584>

Nayak, D., Saetnan, E., Cheng, K., Wang, W., Koslowski, F., Cheng, Y. F., ... & Smith, P. (2015). Management opportunities to mitigate greenhouse gas emissions from Chinese agriculture. Agriculture, Ecosystems & Environment, 209, 108-124.

Niles, M. T., & Wiltshire, S. (2019). Tradeoffs in US dairy manure greenhouse gas emissions, productivity, climate, and manure management strategies. *Environmental Research Communications*, *1*(7), 075003. https://doi.org/10.1088/2515-7620/ab2dec

Petersen, S. O., Blanchard, M., Chadwick, D., Del Prado, A., Edouard, N., Mosquera, J., & Sommer, S. G. (2013). Manure management for greenhouse gas mitigation. *Animal*, *7*, 266–282. https://doi.org/10.1017/S1751731113000736

Robertson, G. P., & Vitousek, P. M. (2009). Nitrogen in Agriculture: Balancing the Cost of an Essential Resource. *Annual Review of Environment and Resources*, *34*(1), 97–125. https://doi.org/10.1146/annurev.environ.032108.105046

Schade, G.W. 2020. The problem with natural gas flaring. A Texas A&M atmospheric scientist says routine flaring is wasteful, polluting and undermeasured. For the Conversation. https://today.tamu.edu/2020/08/03/the-problem-with-natural-gas-flaring/

Sommer, S. G., Olesen, J. E., Petersen, S. O., Weisbjerg, M. R., Valli, L., Rodhe, L., & Béline, F. (2009). Region-specific assessment of greenhouse gas mitigation with different manure management strategies in four agroecological zones. *Global Change Biology*, *15*(12), 2825–2837. https://doi.org/10.1111/j.1365-2486.2009.01888.x

Sommer, S. G., Petersen, S. O., & Møller, H. B. (2004). Algorithms for calculating methane and nitrous oxide emissions from manure management. *Nutrient Cycling in Agroecosystems*, *69*(2), 143–154. https://doi.org/10.1023/B:FRES.0000029678.25083.fa

USEPA (2021). AgSTAR: Biogas Recovery in the Agriculture Sector. https://www.epa.gov/agstar

USEPA. (2019). Global Non-CO2 Greenhouse Gas Emission Projections and Mitigation: 2015-2050. United States Environmental Protection Agency Washington (DC). https://www.epa.gov/sites/production/files/2019-09/documents/epa\_non-co2\_greenhouse\_gases\_rpt-epa430r19010.pdf

USEPA. (2017). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015. Chapter 5. Agriculture. https://www.epa.gov/sites/production/files/2017-02/documents/2017\_chapter\_5\_agriculture.pdf

Value of Manure Nutrients (B1-65). (2007). Iowa State University Extension. https://www.extension.iastate.edu/agdm/livestock/pdf/b1-65.pdf

Weerden, T. van der, Luo, J., Dexter, M., & Rutherford, A. J. (2014). Nitrous oxide, ammonia and methane emissions from dairy cow manure during storage and after application to pasture. *New Zealand Journal of Agricultural Research*, *57*(4), 354–369. https://doi.org/10.1080/00288233.2014.935447

Wolf, J., Asrar, G. R., & West, T. O. (2017). Revised methane emissions factors and spatially distributed annual carbon fluxes for global livestock. *Carbon Balance and Management*, *12*(1), 16. https://doi.org/10.1186/s13021-017-0084-y

Zhao, Q., Axelsson, C., Artois, J., Robinson, Timothy. p, & Gilbert, M. (2019). Distribution and trends of pig production in China 2007-2017. *Frontiers in Veterinary Science*, *6*. https://doi.org/10.3389/conf.fvets.2019.05.00051

# Glossary

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

**Approximate PPM Equivalent** – the reduction in atmospheric concentration of CO2 (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

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

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

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

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

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

**Emissions** **Factor**– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO2e/kWh.

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

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

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

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

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

**Learning Rate/Learning Curve** - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experienced is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for calculating how costs change due to learning. A 2% learning rate means that the cost of producing a *good* drops by 2% every time total production doubles.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

1. In its modeled solution, Project Drawdown defines Large Methane Digestors as industrial-scale anaerobic bio-digester systems that produce biogas from agriculture and wastewater sludge and are linked to biogas plants to produce electricity and/or heat.

   [↑](#footnote-ref-1)
2. IPCC (2019). Table 10.18. Emission factors included for systems reporting values other than 0. [↑](#footnote-ref-2)
3. Project Drawdown estimates for high productivity systems based on region-specific emission factors, volatile solids excretion rates and live weights IPCC (2019) [↑](#footnote-ref-3)
4. Liquid/Slurry, Pit storage < 1 month [↑](#footnote-ref-4)
5. Liquid/Slurry, Pit storage > 1 month [↑](#footnote-ref-5)
6. High = ≥ 30% mitigating effect; Medium = 10 to 30 % mitigating effect; Low = ≤ 10% mitigating effect. Mitigating effects refer to

   percentage change over a “standard practice”, i.e. study control that was used for comparison and based on combination of study data and judgement by Gerber et al., (2013).

   ? = Uncertainty due to limited research, variable results or lack of/insufficient data on persistency of the effect. [↑](#footnote-ref-6)
7. DC = Dairy cattle, BC = Beef cattle, P = Pig [↑](#footnote-ref-7)
8. https://folk.universitetetioslo.no/roberan/img/GCB2019/PNG/s21\_2019\_CO2growthbars\_category.png as in Schade (2020) [↑](#footnote-ref-8)
9. Value of Manure Nutrients (B1-65). (2007). Iowa State University Extension. https://www.extension.iastate.edu/agdm/livestock/pdf/b1-65.pdf [↑](#footnote-ref-9)
10. FAO, 2019. Climate change and the global dairy cattle sector – The role of the dairy sector in a low-carbon [↑](#footnote-ref-10)
11. https://extension.sdstate.edu/how-much-meat-can-you-expect-fed-steer [↑](#footnote-ref-11)
12. Table 10A.5 of the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [↑](#footnote-ref-12)
13. ASAE D384.2: Manure Production and Characteristics (2005). Swine Average, 7 ~ (5 kg (per head gestating sow) + 12 kg (per head lactating sow) + 3.8 kg (per head boar))/3 [↑](#footnote-ref-13)
14. Project Drawdown calculations using Tables 10.A6-10.A9, 10A.5, 10.13A, and 10.14 of the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories [↑](#footnote-ref-14)
15. Dairy cattle, TAM considered under covered lagoon solution due to land limitations in Asia [↑](#footnote-ref-15)
16. 100% of dairy and 99% of non-dairy TAM are in dry systems [↑](#footnote-ref-16)
17. 100% of dairy, 100% non-dairy, and 94% Pig TAM are in dry systems [↑](#footnote-ref-17)
18. Mostly applied to dairy and pig manure management [↑](#footnote-ref-18)
19. IEA (2020). Outlook for biogas and Prospects for organic growth World Energy Outlook Special Report biomethane [↑](#footnote-ref-19)