**Technical assessment for**

**Perennial biomass**

Sector: land use

Agency Level: Farmer and land manager

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# Executive Summary

Biomass feedstock may contribute up to 2% to the world’s energy generation by 2050. Key to this goal are perennial biomass crops, an important alternative to annual cropping system which produces biomass feedstock like maize stalks and wheat straw. Perennial grasses (e.g., miscanthus) and woody plants (e.g., willow) have naturally high productivity, need less fertilizers and irrigation. Perennial crops can reduce climate change by removing carbon dioxide from the atmosphere and storing it in the soils and root systems as they displace fossil fuel use and eliminate fossil fuel greenhouse gas emissions.

Perennials crops are generally defined by their lifetime of three or more years. This study focuses on two types of perennial energy crops: herbaceous crops (in this case mostly giant grasses) and short rotation coppice (SRC), in which re-sprouting woody crops are harvested mechanically on a 2-3-year rotation. There are many advantages of perennial crops. Studies have shown beneficial land use changes when perennial grasses and SRC replace annual crops that have high fertilizer and pesticide requirements. Some studies also indicate that perennial crops planted in degraded lands provide a potential to improve soil carbon and abate erosion and salinity issues. There are also some potential barriers to adoption specifically around low return on investment for biomass.

Total adoption of the perennial biomass in the *Plausible* Scenario is 96.39 million hectares in 2050. Of this, 96.12 hectares are adopted from 2020-2050. The combined carbon sequestration and emissions reduction impact of this scenario is 3.76 gigatons of carbon dioxide-equivalent between 2020-2050. Net profit margin is 724.56 2014 USD.

Total adoption in the *Drawdown* Scenario is 143.55 hectares in 2050, representing 93 percent of the total suitable land. Of this, 143.28 million hectares are adopted from 2020-2050. The combined sequestration and emissions reduction impact of this scenario is 5.58 gigatons of carbon dioxide-equivalent between 2020-2050. Net profit margin is 1091.43 billion 2014 USD.

Total adoption in the *Optimum* Scenario is 154 million hectares in 2050, representing 100 percent of the total suitable land. Of this, 154.06 million hectares are adopted from 2020-2050. The combined sequestration and emissions reduction impact of this scenario is 5.92 gigatons of carbon dioxide-equivalent between 2020-2050. Net profit margin is 1071.92 billion 2014 USD.

# Literature Review

## State of the Practice

Global demand for biomass for bioenergy is increasing, particularly in industrialized countries. Biomass feedstock may contribute up to 2% to the world’s energy generation by 20501[[1]](#footnote-1). Perennial energy crops grown on abandoned and degraded land can replace fossil fuel use and contribute to low carbon future. Perennial biomass energy crops such as willow, poplar, miscanthus have naturally high productivity – high energy output, low greenhouse gas emissions, need less fertilizers and pesticides when compared to annual crops like maize and rapeseed.[[2]](#footnote-2) A study by Zucaro et al[[3]](#footnote-3) clearly shows through a direct comparison of sorghum (annual crop) and giant reed (perennial crop) in the Mediterranean region that the perennial crop resulted in substantially higher environmental beneﬁts than corn due to reduced inputs and emissions from establishing crops, as well as the potential of CO2 sequestration in soil organic matter.

Perennial energy crops considered in this study are of two types:

1. **Herbaceous energy crops**

Herbaceous crops contain no woody tissues and can regrow from their roots without requiring re-planting for long periods of time (>15 years)[[4]](#footnote-4). These crops are mostly harvested like hay at the end of growing season when important nutrients such as nitrogen have been translocated to roots.

1. **Short rotation woody crops or coppice (SRC).**

SRC are fast growing woody plants with great range of adaptability. They have a lifetime of 20-30 years (unlike traditional coppice, which can live for centuries). The total sequestration rates for SRC are higher than the herbaceous crops.

Table 1.1: Common perennial crops used in this study[[5]](#footnote-5),4

|  |  |  |
| --- | --- | --- |
| Type | Examples | Region |
| Herbaceous energy crops | switchgrass (*Panicum virgatum L.*)  giant miscanthus (*Miscanthus spp*.),  giant reed (*Arundo donax*)  cardoon (*Cynara cardunculus*) | North America  East Asia  Europe, Asia  Mediterranean, North Africa |
| Short rotation woody crops (SRC) | poplar (*Populus* spp)  willow (*Salix* spp.)  eucalyptus (*Eucalyptus* spp.)  black locust (*Robinia pseudoacacia*) | USA  North America  Australia  Germany |

**Climate benefits**

*Soil Nitrous Oxide Emissions*

Nitrous oxide emissions have a global warming potential 298 times greater over 100 years than carbon dioxide emissions. Perennial energy crops have in general lower nitrous oxide emissions than annual crops. Drewer et al. (2012), found that mean nitrous oxide emissions from miscanthus and willow cultivation are five time lower than those from annual crops. Use of synthetic nitrogen fertilizer in perennial energy crops causes GHG emissions from soil, for example Gauder et al., 2012 found that nitrous oxide emissions from fertilized fields of miscanthus increased in comparison to unfertilized field however, nitrous oxide emissions were still 30% lower than fertilized maize. Similarly, Yang et al., 2018 found increase in soil nitrous oxide emissions relative to a control unfertilized field, yet this increase lead to an increase of carbon storage in root and in the soil and increase biomass yield. The irrigated and moderate nitrogen addition treatment increased greenhouse gas emissions by 0.77 Mg carbon dioxide equivalents per hectare per year, of which half were nitrous oxide emissions and half were emissions from energy needed for fertilizer manufacturing and application.

## Adoption Path

Based on literature review we estimated that current area used for perennial energy crops is 0.2 million hectares.

### Trends to Accelerate Adoption.

* There is need for policy that provides incentives for bioelectricity generation. In US Several policies have the potential to create markets for the bioenergy feedstocks: (1) the national Renewable Fuel Standard (RFS) with incentives for ethanol derived from cellulosic biomass; (2) a Renewable Portfolio Standard (RPS) for electricity generation (3) a climate policy with a cap on emissions of carbon dioxide (CO2); and (4) a subsidy on bioelectricity (USDA, 2017).
* Perennial energy crops would be grown in regions where they have a comparative yield advantage relative to other crops.
* The Danish Government has included the promotion of growing perennial energy crops in its Green Growth Agreement from June 2009. The government subsidize perennial energy crops and established a preference to plantation of perennial energy crops in areas vulnerable to nitrogen leaching. The agreement also includes initiatives to equalize tax rules for perennial energy crops and annual crops an allows growing perennial energy crops on marginalized areas like buffer-strips alongside streams, ponds and lakes without using fertilizers or pesticides (The Danish Ministry of Agriculture and Fisheries, 2010).

### Barriers to Adoption

* A key barrier in adoption of perennial energy crops is lack of market for large scale use of this resource. The price obtained for dedicated energy crop feedstocks such as switchgrass, miscanthus and willow is too low for farmers.
* Another important barrier is the discussion regarding land usage for food vs. fuel. A recent study[[6]](#footnote-6) has shown that even low levels of bioenergy production of around 5EJ/yr from dedicated land use (which is less than 1% of total world’s energy production in 2014[[7]](#footnote-7)) have contributed to rising food prices. Based in a study by Wirseniu[[8]](#footnote-8), considering the reference scenario developed by FAO projections, only about 5% land expansion of agricultural land area will be needed for food security in 2030 because most of the global increase in biomass comes from raised yields and extraction per unit area rather than expansion of the agricultural area.

### Adoption Potential

Adoption potential of this solution is usually combined with forest plantations rather than projected independently.

## Advantages and disadvantages of Perennial Biomass

Perennial biomass energy crops have naturally high productivity, need fewer fertilizers and pesticides, less water. A study by Zucaro et al3 clearly shows through a direct comparison of sorghum (annual crop) and giant reed (perennial crop) in Mediterranean region that the perennial crop resulted in substantially higher environmental beneﬁts than annual crops due to reduced input and emissions for establishing crops and the potential of carbon sequestration in soil organic matter. In addition, perennial crops can be cultivated on abandoned or degraded land and where they can improve soil carbon and abate erosion and salinity issues[[9]](#footnote-9),[[10]](#footnote-10). A comparison of soil erosion rates, fertilizer and herbicide application rates for annual crop (corn) and perennial crops both herbaceous and SRC are shown in Table 2[[11]](#footnote-11). According to IPCC[[12]](#footnote-12), perennial cropping systems have a medium technical mitigation potential in terms of impacts on greenhouse gas emissions. Beneficial land use changes can also be observed when perennial grasses and short rotation woody crops replace annual crops that have high fertilizer and pesticide requirements.

Table 1.2:Typical fertilizer and herbicide application rates and soil erosion rates for annual and perennial cropping systems11

|  |  |  |  |
| --- | --- | --- | --- |
| Cropping system | Soil erosion rates  (Mg ha-1 yr-1) | N-P-K Application rates  (kg ha-1 yr-1) | Herbicide application rates  (kg ha-1 yr-1) |
| ***Annual crops***  Corn  Soybean | 21.8  40.9 | 135-60-80  20-45-70 | 3.06  1.83 |
| ***Perennial crops***  Herbaceous energy crops  SRC | 0.2  2.0 | 50-60-60  60-15-15 | 0.25  0.39 |

There are also some disadvantages of considering perennial crops for energy.

Herbaceous crops such as switchgrass and miscanthus have limited applications other than for bioenergy production. In United States, it has been suggested that switchgrass could be used as fodder but same cannot be done for miscanthus due to sharp edges on the leaves.[[13]](#footnote-13) However during processing of perennial biomass there is potential of converting leaf protein concentrate from certain types of herbaceous crops into edible protein for humans and livestock.**Error! Bookmark not defined.**

Another disadvantage or barrier to large-scale adoption is the perception of low ﬁnancial returns on investment and lack of robust supply chains as also explained above.

Unlike annual grain crops used for comparison in this report, perennial grasses and SRC cannot be propagated by seeds or and need to be vegetatively propagated. This increases the cost and deters farmers from large scale adoption13.

Other disadvantage of considering any biomass-based electricity generation is the comparison of other renewable electricity generation pathways such as hydropower or wind. It has been shown that GHG emissions from biomass based electricity generation (range of 8.5-130 kg/MWh) is higher than both hydropower (2-20 kg/MWh) and wind (3-41 kg/MWh) when you consider the entire lifecycle[[14]](#footnote-14).

### Similar Solutions

To a certain degree perennial energy crops solution is also similar to biomass energy solution in electricity generation sector, and perennial food crops that sequester carbon and leave soil intact.

### Arguments for Adoption

The solution is based on scientific evidence and are tested in different geographies ( US, Europe, Africa) a both at scientist’s experimental plots as well as on farmers’ plots. They have greenhouse gas emissions reduction potential as well as saving on costs of cultivation and (sometimes), thus proving to be more trustworthy for up scaling at a larger scale.

### Additional Benefits and Burdens

Here this solution is compared with other solutions in the biomass production cluster for farm, ecosystem, and social impacts. Perennial biomass is similar to the other biomass production solutions, but has a shorter period until profitability than afforestation, and poorer ecosystem services than bamboo and forest plantations. Compared to all other land use solutions it has the poorest ecosystem service value.

Table 1.3: Land Use Solutions Comparison: Economic Impacts

**First Cost**: Free is $0**,** Low is $1-100, Medium is $100-500, Expensive is $500+. **Net Profit Margin:** Low is $0-100/ha, Medium is $100-500, High is $500+. **Value of Ecosystem Services:** Set values for very high, high, medium, low. **Timber and Biomass Production:** Decrease indicates restriction of logging where it currently occurs; Increase indicates new commercial biomass production where it does not currently occur.

|  | **First Cost $/ha** | **Net Profit $/ha** | **Value of Ecosystem Services** | **Timber and Biomass Production** |
| --- | --- | --- | --- | --- |
| Afforestation | Expensive | Medium | High | Increase |
| Bamboo | Expensive | Medium | High | Increase |
| Forest Protection | Not calculated | Not calculated | Very high | Decrease |
| Indigenous People’s Forest Management | Not calculated | Not calculated | Very high | Decrease |
| Peatland Protection | Not calculated | Not calculated | Very high | Decrease |
| Perennial Biomass | Expensive | Medium | Medium | Increase |
| Temperate Forest Restoration | Not calculated | Not calculated | High | n/a |
| Tropical Forest Restoration | Not calculated | Not calculated | High | n/a |

Table 1.4: Land Use Solutions Comparison: Social and Climate Impacts

**Carbon Stock Protected:** Low 0-500 Gt CO2-eq, Medium is 500-1000 Gt CO2-eq, high is 1000+ Gt CO2-eq.

**Ecosystem Services** is subjective based on impacts on biodiversity, water quality, etc. **Social Justice Benefits:** Is solution Targeted to disadvantaged producers like smallholders and women, Relevant to them, or Not Applicable (n/a). **Climate Impacts per Hectare:** Low 0-3.7 t CO2-eq/ha/yr (0-1tC),Medium 3.8-11.0 t CO2-eq/yr (1-3 tC), High 11.1-18.0 tCO2-eq/yr (3-5 tC), Very High 18.1 tCO2-eq/yr (5tC+). **Global Adoption Potential:** Low 0-100Mha, Medium 101-500 Mha, High 500+ Mha

|  | **Carbon Stock Protected** | **Social Justice Benefits** | **Climate Impact/ha** | **Global Adoption Potential** |
| --- | --- | --- | --- | --- |
| Afforestation | Medium to High | Relevant | High | Medium |
| Bamboo | Medium | Relevant | High | Medium |
| Forest Protection | High | Relevant | Very High | Medium |
| Indigenous People’s Forest Management | High | Targeted | Very High | Medium to High |
| Peatland Protection | n/a | Relevant | Very High | Medium |
| Perennial Biomass | n/a | Relevant | Low | Medium |
| Temperate Forest Restoration | n/a | Relevant | Medium | Low to Medium |
| Tropical Forest Restoration | n/a | Relevant | High | Medium |

# Methodology

## 2.1 Introduction

Project Drawdown’s models are developed in Microsoft Excel using standard templates that allow easier integration with each other since integration is critical to the bottom-up approach used. The template used for this solution was the Land Model which accounts for sequestration of carbon dioxide from the atmosphere into plant biomass and soil, and reduction of emissions for a solution relative to a conventional practice. These practices are assumed to use land of a specific type that may be shared across several solutions. The actual and maximum possible adoptions are therefore defined in terms of land area (million hectares). The adoptions of both conventional and solution were projected for each of several Drawdown scenarios from 2015 to 2060 (from a base year of 2014) and the comparison of these scenarios with a reference (for the 2020-2050 segment[[15]](#footnote-15)) is what constituted the results.

*Agency Level*

The farmers and land use managers are selected as the agency level for this solution. Though certainly other agents can, do, and should play an important role in this solution, the decision-maker on the ground is the most critical player in implementation.

## 2.2 Data Sources

The FAO Statistical Service is a key dataset used in this study. A total of 83 peer-reviewed studies were used in the model.

## 2.3 Total Available Land

Drawdown’s agricultural production and land use model approach defines the Total Land Area as the area of land (in million hectares) suitable for adoption a given solution. Data on global land is acquired from Global Agro-Ecological Zones database, developed by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA). The Drawdown Land-Use Model categorizes and allocates land according to agro-ecological zones based on the following factors: thermal climate, moisture regimes, soil quality, slope, cover type, and degradation status. These characteristics influence the suitability of different practices, and solution adoption scenarios are restricted by one or more of these factors.

Determining the total available land for a solution is a two-part process. The technical potential is based on: current land cover or land use; the suitability of climate, soils, and slopes; and on degraded or non-degraded status. In the second stage, land is allocated using the Drawdown Agro-Ecological Zone model, based on priorities for each class of land. The total land allocated for each solution is capped at the solution’s maximum adoption in the *Optimum* Scenario. Thus, in most cases the total available land is less than the technical potential. Total available land for this solution is 154 million hectares.

## Adoption Scenarios

Two different types of adoption scenarios were developed: a Reference (REF) Case which was considered the baseline, where not much changes in the world, and a set of 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[[16]](#footnote-16)

Current adoption data for perennial energy crops are available for the bioenergy statistics of the EU Member States, USDA statistics on SRC cultivation and estimated as 0.27 million hectares. Data are lacking for other world regions.

**Project Drawdown Scenarios**

#### Six custom adoption scenarios were developed based on the estimation of average and low, medium, and high adoption rates for the future growth of perennial biomass cultivation within the EU and US and future potential in China, details on each scenario are given below.

1. ***Custom adoption scenario one***: This scenario presents the results based on the average adoption rate. Thus, projecting 50% (38Mha) adoption of the solution by 2050.
2. ***Custom adoption scenario two***: This scenario presents the results based on the average of the “high adoption” growth rate. Thus, projecting 100% adoption of the solution by 2050.
3. ***Custom adoption scenario three***: This is scenario assume that bioenergy crops will be cultivated on 85% of allocated land by 2050.
4. ***Custom adoption scenario four***: This is scenario 1, assuming 70 percent adoption of the will be achieved by 2030.
5. ***Custom adoption scenario five***: This is scenario 3, assuming 70% adoption will be achieved by 2030.

Impacts of increased adoption of *perennial biomass* from 2020-2050 were generated based on three growth scenarios, which were assessed in comparison to a *Reference*Scenario where the solution’s market share was fixed at the current levels.

#### Plausible Scenario - A conservative approach is adopted for the plausible scenario, and future growth of the solution is estimated based on the “average of all” custom adoption scenarios as listed above.

#### Drawdown Scenario – An ambitious approach is adopted for the plausible scenario, and future growth of the solution is estimated based on the “high of all” custom adoption scenarios as listed above.

#### Optimum Scenario – Maximum growth is projected for the optimum scenario, and future growth of the solution is estimated based on “custom adoption scenario 3”, as stated above that assume, 100% adoption of the solution by 2050

## Inputs

### Climate Inputs

Sequestration rates are set at 1.09 tons of carbon per hectare per year, based on 24 data points from 9 sources. We also collected data for nitrous oxide emissions from the fertilizer application and carbon dioxide emissions from on farm operations. These parameters are not considered in the final calculation, because they represent avoided emissions as compared to annual crop systems. Only one study Yang et al., 2018 compare nitrous oxide emissions and carbon dioxide emissions on degraded land only.

Table 2.1: Climate Inputs

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| Carbon dioxide – eq emissions | *t/CO2/ha/yr* | -2.14 - 0.98 | -0.57 | 14 | 6 |
| Biosequestration | *tC/ha/yr* | 0.18 - 1.99 | 1.09 | 24 | 9 |

Note: Project Drawdown data set range is defined by the low and high boundaries which are respectively 1 standard deviation below and above the mean of the collected data points[[17]](#footnote-17).

*Modeling Saturation*

Biosequestration does not have limitless potential. In most cases, there is a maximum amount of carbon that can be stored in soils and aboveground perennial biomass before they become saturated. Biosequestration continues after saturation but is offset by more or less equal emissions. In most cases soils, and biomass can return to their approximate pre-agricultural or pre-degradation levels of carbon. This takes anywhere between 10-50 years in agricultural cases, and sometimes somewhat longer in the case of ecosystems like forests. Data about saturation time is very limited.

The Drawdown land model takes the conservative approach that all land units currently adopted for agricultural solutions (including multistrata agroforestry) have already achieved saturation, and will not be contributing additional sequestration. New adopted land is assumed to sequester for at least 30 years before achieving saturation.

Note that there are some important exceptions to saturation. Certain ecosystems continue to sequester soil carbon for centuries, notably peatlands and coastal wetlands. Some scientists argue that tropical forests can continue to sequester carbon at a slower rate after saturation. The addition of biochar to saturated soils may be able to overcome this constraint, as does the use of biomass from bamboo or afforestation in long-term products like buildings.

### Financial Inputs

The present solution is allocated on degraded land area (grassland). Project Drawdown’s model assumes marginal conventional use of this degraded land areas, principally for grazing. In the absence of sufficient financial data sources documenting the implementation of grazing practices on degraded land, Drawdown’s *perennial biomass* model uses conventional grazing data as a basis for comparison. However, in order to model decreased productivity on degraded land, financial variables for conventional grazing are weighted value based on the proportion of total global grassland area (3514 Mha) that is already degraded (772 Mha), i.e. 21.97%. This calculation is based on Project Drawdown's AEZ values.

First costs of *perennial energy cultivation is*estimated to be US$1294 per hectare, as the cultivation in the first year use an equipment (fertilizers, seeds,) and infrastructure (machinery, fuels) and labor.2 For all conventional agricultural solutions, it is assumed that there is no conventional first cost, as agriculture is already in place on the land. *Operating cost* of the solutions is estimated to be US$599 per hectare. while *net profit* is calculated at US$ 363 per hectare per year for the solution.

Table 2.2 Financial Inputs for Conventional Practice (Grazing on Degraded Lands)

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| First costs (Conventional) | *US$2014/ha* | $0 | $0 | n/a | n/a |
| Net profit (Conventional) | *US$2014/ha* | $69.49-$323.38 | $154.12 | 18 | 16 |
| Operating Cost (Conventional) | *US$2014/ha* | $28.06-$684.58 | $328.42 | 9 | 8 |

Table 2.3:Financial Inputs for Solution

|  | **Units** | **Project Drawdown Data Set Range** | **Model Input** | **Data Points (#)** | **Sources (#)** |
| --- | --- | --- | --- | --- | --- |
| First costs (solution) | *US$2014/ha* | $322 to $2266 | $1294 | 9 | 6 |
| Net profit (solution) | *US$2014/ha* | $305 to $893 | $599 | 11 | 6 |
| Operating Cost (solution) | *US$2014/ha* | $135 to $589 | $363 | 13 | 6 |

### Yield Inputs

Yield data were collected for miscanthus, switch grass, poplar in different geographical regions, including EU, US, Turkey and India. The average yield was estimated to be 17 tons per hectare, 49 data points were collected from 16 sources.

## Assumptions

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

Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

1. It is assumed that the land area for perennial energy crops cultivation will not exceed 74 million hectares of degraded land.
2. In the study, we use input information for miscanthus, switch grass, willow, and poplar cultivation in Europe, US, Turkey and India.
3. In this solution, climate impact of the perennial energy crops only considers carbon sequestrations. Avoided greenhouse gas emissions from fertilizer application and on-farm activities and avoided emissions from fossil fuel replacement are included in the model but not applied. Next version of the model may consider these inputs to expand climate impact of the perennial biomass.
4. The future adoption scenarios were built based on the data available for European countries and US. It was assumed that similar trends will be followed at the global scale.

## Integration

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

*Perennial Biomaas* is part of Drawdown’s Land sector.

***The Agroecological Zone model***

Drawdown’s approach seeks to model integration between and within sectors, and avoid double counting. Several tools were developed to assist in this effort. The Agroecological Zone (AEZ) model categorizes the world’s land by: current cover (e.g. forest, grassland, cropland), thermal climate, moisture regime, soil quality, slope, and state of degradation.  Both Food (supply-side) and Land Use solutions were assigned to AEZs based on suitability. Once current solution adoption was allocated for each zone (e.g. semi-arid cropland of minimal slopes), zone priorities were generated and available land was allocated for new adoption. Priorities were determined based on an evaluation of suitability, consideration of social and ecological co-benefits, mitigation impact, yield impact, etc. For example, *Indigenous peoples’ land management* is given a higher priority than *forest protection* for AEZs with forest cover, in recognition of indigenous peoples’ rights and livelihoods. *Multistrata agroforestry* is highly prioritized in tropical humid climates due to its high sequestration rate, food production, and highly limited climate constraints.

Each unit of land was allocated to a separate solution to avoid overlap between practices. The exception to this are *farmland irrigation*, *nutrient management*, and *women smallholders*, which can be implemented in addition to other practices. The constraint of limited available land meant that many solutions could not reach their technical adoption potential. The AEZ model thus prevents double-counting for adoption of agricultural and land use solutions.

Drawdown’s agricultural production and land use model approach defines the Total Land Area as the area of land (in million hectares) suitable for adoption a given solution. Data on global land is acquired from Global Agro-Ecological Zones database, developed by the Food and Agriculture Organization of the United Nations (FAO) and the International Institute for Applied Systems Analysis (IIASA). The Drawdown Land-Use Model categorizes and allocates land according to agro-ecological zones based on the following factors: thermal climate, moisture regimes, soil quality, slope, cover type, and degradation status. These characteristics influence the suitability of different practices, and solution adoption scenarios are restricted by one or more of these factors.

Determining the total available land for a solution is a two-part process. The technical potential is based on: current land cover or land use; the suitability of climate, soils, and slopes; and on degraded or non-degraded status. In the second stage, land is allocated using the Drawdown Agro-Ecological Zone model, based on priorities for each class of land. The total land allocated for each solution is capped at the solution’s maximum adoption in the *Optimum* Scenario. Thus, in most cases the total available land is less than the technical potential.

***The Yield model***

Drawdown’s yield model calculates total annual global supply of crops and livestock products based on their area of adoption in each of the three scenarios, and global yield impacts of each solution (including both gains due to increased productivity per hectare and losses due to reduction of productive area due to adoption of non-agricultural solutions, e.g., loss of grazing area due to afforestation of grasslands). Grain surpluses in the yield model were also used to set a ceiling for the amount of crops available for use as feedstock for the *bioplastic* Materials solution.

The yield model matches demand and supply as an integrated system. Both *Reference* Scenarios showed a food deficit in the high and medium population scenarios (see *family planning*and *educating girls* solutions). This would require the clearing of forest and grassland for food production, with associated emissions from land conversion.

All three Drawdown scenarios show agricultural production sufficient to meet food demand and provide a surplus that can be used in bio-based industry, for example as feedstock for *bioplastic*production*.*Due to this surplus, no land clearing is necessary, resulting in impressive emissions reduction from avoided deforestation.  Because population change (resulting from *educating girls*and *family planning*),*plant-rich diet*, and *reduced food waste* are the principal drivers of this effect, Drawdown allocates the resulting reduction in emissions from land clearing to these solutions. However, as the impacts of population on yield and food demand are highly complex, we do not include avoided land conversion emissions associated with population change in the final emissions calculations for those solutions.

This solution is adopted on degraded grassland, and as a result displaces grazing, impacting global livestock production.

***The Biomass Model***

Drawdown’s Biomass model begins with projected global biomass demand through 2060, based on FAO historical data and other sources, in categories including sawnwood, other woody biomass, and herbaceous biomass (which includes crop residues). It determines the impact of demand reduction solutions including *clean cookstoves* and *recycled paper*, resulting in an adjusted demand projection through 2060. Biomass supply reductions are modeled as well, which result from protection of forests from *forest protection, Indigenous Peoples’ forest management, mangrove protection,* and *peatland protection*, reducing biomass availability. Biomass supply increases are modeled through the increased adoption of solutions including *afforestation, bamboo, perennial biomass*andagroforestry solutions like *tree intercropping, silvopasture,*and *multistrata agroforestry.*Biomass availability from crop residues, *seaweed farming*, and dedicated biomass crops planted on cropland freed up by *sustainable intensification* is also modeled.

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

## Limitations/Further Development

There are limited data availability on adoption, that is used for developing the future adoption scenario. Current dataset needs to be updated, based on new scientific knowledge.

# Results

## Adoption

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

Total adoption in the *Plausible* Scenario is 96.39 million hectares in 2050, representing 63 percent of the total suitable land. Of this, 96.12 million hectares are adopted from 2020-2050.

Total adoption in the *Drawdown* Scenario is 143.55 million hectares in 2050, representing 93 percent of the total suitable land. Of this, 143.28million hectares are adopted from 2020-2050.

Total adoption in the *Optimal* Scenario is 154.33 million hectares in 2050, representing 100 percent of the total suitable land. Of this, 154.06 million hectares are adopted from 2020-2050.

Table 3.1:World Adoption of the Solution

| **Solution** | **Units** | **Base Year (2014)** | **New Adoption by 2050** | | |
| --- | --- | --- | --- | --- | --- |
| **Plausible** | **Drawdown** | **Optimum** |
| Perennial Biomaas | Mha | 0.27 | 96.12 | 143.28 | 154.06 |
| % Total Land Available | 0.2% | 63% | 93% | 100% |

Figure 3.1:World Annual Adoption 2020-2050 in Mha (a) and as a percentage of TLA (b)

## Climate Impacts

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

Total impact is 4.93, 7.52, and 8.07 gigatons of carbon-dioxide equivalent in the *Plausible, Drawdown,* and *Optimum* Scenarios respectively.

Table 3.2:Climate Impacts

| **Scenario** | **Maximum Annual Emissions Reduction** | **Total Emissions Reduction** | **Max Annual CO2 Sequestered** | **Total Additional CO2 Sequestered** | **Total Atmospheric CO2-eq Reduction** | **Emissions Reduction in 2030** | **Emissions Reduction in 2050** |
| --- | --- | --- | --- | --- | --- | --- | --- |
| *(Gt CO2-eq/yr.)* | *Gt CO2-eq/yr. (2020-2050)* | *(Gt CO2-eq/yr.)* | *Gt CO2-eq/yr. (2020-2050)* | Gt CO2-eq (2020-2050) | (Gt CO2-eq/year) | *(Gt CO2-eq/year)* |
| ***Plausible*** | -0.23 | -3.72 | 0.37 | 7.48 | 3.76 | 0.19 | 0.14 |
| ***Drawdown*** | -0.35 | -5.72 | 0.55 | 11.30 | 5.58 | 0.29 | 0.20 |
| ***Optimum*** | -0.31 | -4.84 | 0.60 | 10.75 | 5.92 | 0.23 | 0.29 |

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

Table 3.3 Impacts on Atmospheric Concentrations of CO2-eq

| **Scenario** | **GHG Concentration Change in 2050** | **GHG Concentration Rate of Change in 2050** |
| --- | --- | --- |
| *PPM CO2-eq (2050)* | *PPM CO2-eq change from 2049-2050* |
| **Plausible** | 0.309 | 0.010 |
| **Drawdown** | 0.456 | 0.013 |
| **Optimum** | 0.495 | 0.022 |

Figure 3.2 World Annual Greenhouse Gas Emissions Reduction

Note that the negative value in the later phase shows the emissions associated with the end of life of the perennial biomass plantation and there is no new adoption.

## Financial Impacts

Below are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary. Note that the financial results have changed from those published in the first edition of the *Drawdown* book.

For the *Plausible* Scenario, cumulative first cost is US$$235.55 billion. Marginal first cost is the same as cumulative first cost. Net operating savings is US$-522.24 billion. Net profit margin is US$522.24 billion, and lifetime profit margin is US$724.56. Lifetime cashflow savings NPV is US$-136.57.

For the *Drawdown* Scenario, cumulative first cost is US$$354.78 billion. Marginal first cost is the same as cumulative first cost. Net operating savings is US$-789.61 billion. Net profit margin is US$789.61 billion, and lifetime profit margin is US$1,091.43 billion. Lifetime cashflow savings NPV is US$-209.07 billion.

For the *Optimum* Scenario, cumulative first cost is US$348.95 billion. Marginal first cost is the same as cumulative first cost. Net operating savings is US$-748.26 billion. Net profit margin is US$ 748.26 billion, and lifetime profit margin is US$1,071.92 billion. Lifetime cashflow savings NPV is $-182.60 billion.

Table 3.4:Financial Impacts

| **Scenario** | **Cumulative First Cost** | **Marginal First Cost** | **Net Operating Savings** | **Net Profit Margin** | **Lifetime Profit Margin** | **Lifetime Cashflow Savings NPV (of All Implementation Units)** |
| --- | --- | --- | --- | --- | --- | --- |
| *2015-2050 Billion USD* | *2015-2050 Billion USD* | *2020-2050 Billion USD* | *2020-2050 Billion USD* | *2020-2050 Billion USD* | *Billion USD* |
| **Plausible** | $235.55 | $235.55 | $-522.24 | $522.24 | $724.56 | $-136.57 |
| **Drawdown** | $354.78 | $354.78 | $-789.61 | $ 789.61 | $1,091.43 | $-209.07 |
| **Optimum** | $348.95 | $348.95 | $-748.26 | $ 748.26 | $1,071.92 | $-182.60 |

Figure 3.3:Net Profit Margin Solution vs. Conventional

# Discussion

In conclusion, perennial energy crops are certainly an important replacement of annual energy crops and fossil fuel. The results in the report suggest that under a conservative optimistic scenario, 154 million hectares of land can be planted under perennial crops for bioenergy use and this will help sequester 8 Gt carbon dioxide equivalents in total. Though these impacts are modest, they must be paired with the emissions reductions from converting a portion of the energy supply from fossil fuels to biomass-based energy. For example, Yang at al., 2018, found climate impact of replacing fossil fuels by perennial energy crops to be 12 megatons per ha per year.

Also as discussed in the report, both herbaceous crops and SRC offer many advantages over annual crops. Some examples of environmental benefits are reduction in fertilizer and pesticide use, reduction in water requirements, improved soil quality through increased carbon sequestration rates.

Overall, although the report is comprehensive in collecting data, there are certainly quite a few gaps and limitations especially related to data on current and future adoptions

## 4.1 Limitations

It would be useful to obtain more data on greenhouse gas emissions from perennial energy crop cultivation on degraded land. Additional data on current and projected adoption needs to be updated annually

## 4.2 Benchmarks

Benchmarks for this solution are unavailable.

# References

Adams, P. W. R., & Lindegaard, K. (2016). A critical appraisal of the effectiveness of UK perennial energy crops policy since 1990. Renewable and Sustainable Energy Reviews, 55, 188–202. <http://doi.org/10.1016/j.rser.2015.10.126>

Adler, P. R., Grosso, S. J. D., & Parton, W. J. (2007). Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems. Ecological Applications, 17(3), 675–691.

Alexander, P., Moran, D., Smith, P., Hastings, A., Wang, S., Sünnenberg, G., … Cisowska, I. (2014). Estimating UK perennial energy crop supply using farm-scale models with spatially disaggregated data. GCB Bioenergy, 6(2), 142–155. <http://doi.org/10.1111/gcbb.12121>

Bangor University. (2010). Growing Miscanthus - Does it pay? Retrieved from <http://www.calu.bangor.ac.uk/Technical%20leaflets/Miscanthus%20-%20does%20it%20payv3.pdf>

Camargo, G. G. T., Ryan, M. R., & Richard, T. L. (2013). Energy Use and Greenhouse Gas Emissions from Crop Production Using the Farm Energy Analysis Tool. BioScience, 63(4), 263–273. <http://doi.org/10.1525/bio.2013.63.4.6>

Coote, C. (n.d.). Costs and Returns of SRC Production. Retrieved from <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.549.7656&rep=rep1&type=pdf>

Danish Ministry. (2010). Perennial energy crops. The Danish Ministry of Food, Agriculture and Fisheries. Retrieved from <http://en.mfvm.dk/fileadmin/user_upload/ENGLISH_FVM.DK/Themes/Bioenergy/Perennial_energy_crops.pdf>

DeCicco, J. M., Liu, D. Y., Heo, J., Krishnan, R., Kurthen, A., & Wang, L. (2016). Carbon balance effects of U.S. biofuel production and use. Climatic Change, 138(3–4), 667–680. <https://doi.org/10.1007/s10584-016-1764-4>

Dhungel, S., & Anex, R. (2011). Life Cycle Comparison of Annual and Perennial Biofuel Cropping System. In Proceedings from the LCA XI International Conference. Chicago, IL, United States. Retrieved from <http://lcacenter.org/lcaxi/final/379.pdf>

El Bassam, N. (2010). Handbook of bioenergy crops: a complete reference to species, development and applications. London ; Washington: Earthscan.

Energy Use and Greenhouse Gas Emissions from Crop Production Using the Farm Energy Analysis Tool. (2013). BioScience, 63(4), 263–273. <http://doi.org/10.1525/bio.2013.63.4.6>

Georgescu, M., Lobell, D. B., & Field, C. B. (2011). Direct climate effects of perennial bioenergy crops in the United States. Proceedings of the National Academy of Sciences, 108(11), 4307–4312.

Hamelin, L., Jørgensen, U., Petersen, B. M., Olesen, J. E., & Wenzel, H. (2012). Modelling the carbon and nitrogen balances of direct land use changes from energy crops in Denmark: a consequential life cycle inventory. GCB Bioenergy, 4(6), 889–907. <http://doi.org/10.1111/j.1757-1707.2012.01174.x>

Hohenstein, W. G., & Wright, L. L. (1994). Biomass energy production in the United States: an overview. Biomass and Bioenergy, 6(3), 161–173.

Immerzeel, D. J., Verweij, P. A., van der Hilst, F., & Faaij, A. P. C. (2014). Biodiversity impacts of bioenergy crop production: a state-of-the-art review. GCB Bioenergy, 6(3), 183–209. <http://doi.org/10.1111/gcbb.12067>

IPCC. (2014). Climate Change 2014: Mitigation of Climate Change: Contribution of Working group II to the Fifth Assessment Report of the Intergovermental Panel on Climate Change. Cambridge, UK: Cambridge University Press.

Kartha, Sivan, & Dooley, Kate. (2016). The risks of relying on tomorrow’s negative emissions’ to guide today’s mitigation action (Working Paper. 2016-08). Stockholm Environment Institute. Retrieved from <https://www.sei-international.org/mediamanager/documents/Publications/Climate/SEI-WP-2016-08-Negative-emissions.pdf>

Lemus, R., & Lal, R. (2005). Bioenergy Crops and Carbon Sequestration. Critical Reviews in Plant Sciences, 24(1), 1–21. <http://doi.org/10.1080/07352680590910393>

Lovett, A., Sünnenberg, G., & Dockerty, T. (2014). The availability of land for perennial energy crops in Great Britain. GCB Bioenergy, 6(2), 99–107. <http://doi.org/10.1111/gcbb.12147>

Lychnaras, V., Rozakis, S., Soldatos, P., Tsiboukas, K., & Panoutsou, C. (2007). Economic analysis of perennial energy crops production in Greece under the current CAP. In Proceedings of the 15th European Biomass Conference and Exhibition (pp. 7–11).

Meehan, T. D., Gratton, C., Diehl, E., Hunt, N. D., Mooney, D. F., Ventura, S. J., … Jackson, R. D. (2013). Ecosystem-Service Tradeoffs Associated with Switching from Annual to Perennial Energy Crops in Riparian Zones of the US Midwest. PLoS ONE, 8(11), e80093. <http://doi.org/10.1371/journal.pone.0080093>

Meyboom, R. H. (1976). [Anaphylaxis after the use of glafenine]. Nederlands Tijdschrift Voor Geneeskunde, 120(21), 926–927.

Monti, A., Fazio, S., & Venturi, G. (2009). Cradle-to-farm gate life cycle assessment in perennial energy crops. European Journal of Agronomy, 31(2), 77–84. <http://doi.org/10.1016/j.eja.2009.04.001>

REN21. (2015). Renewables 2015 Global Status Report. Retrieved from <http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015_Onlinebook_low1.pdf>

SAC. (2008). Willow short rotation coppice: Is it commercially viable? Scotland’s Rural College. Retrieved from http://www.sruc.ac.uk/download/downloads/id/103/willow\_short\_rotation\_coppice\_2008

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., … Yu, T.-H. (2008). Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. Science, 319(5867), 1238–1240. <https://doi.org/10.1126/science.1151861>

Toensmeier, E. (2016). The carbon farming solution: a global toolkit of perennial crops and regenerative agriculture practices for climate change mitigation and food security. White River Junction, Vermont: Chelsea Green Publishing.

Turconi, R., Boldrin, A., & Astrup, T. (2013). Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renewable and Sustainable Energy Reviews, 28, 555–565. <https://doi.org/10.1016/j.rser.2013.08.013>

USDA. (2014). Volume 1 - Geographic Area Series - part 51 (2012 United States Census of Agriculture). Retrieved from <https://www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1,_Chapter_1_US/usv1.pdf>

U.S. Department of Energy. (2016). 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks. (No. ORNL/TM-2016/160) (p. 448). Oak Ridge, TN: Oak Ridge National Laboratory. Retrieved from <http://energy.gov/sites/prod/files/2016/08/f33/BillionTon_Report_2016_8.18.2016.pdf>

Valentine, J., Clifton-Brown, J., Hastings, A., Robson, P., Allison, G., & Smith, P. (2012). Food vs. fuel: the use of land for lignocellulosic “next generation” energy crops that minimize competition with primary food production. GCB Bioenergy, 4(1), 1–19. <http://doi.org/10.1111/j.1757-1707.2011.01111.x>

Wicke, B., Smeets, E. M. W., Akanda, R., Stille, L., Singh, R. K., Awan, A. R., … Faaij, A. P. C. (2013). Biomass production in agroforestry and forestry systems on salt-affected soils in South Asia: Exploration of the GHG balance and economic performance of three case studies. Journal of Environmental Management, 127, 324–334. <http://doi.org/10.1016/j.jenvman.2013.05.060>

Wirsenius, S., Azar, C., & Berndes, G. (2010). How much land is needed for global food production under scenarios of dietary changes and livestock productivity increases in 2030? Agricultural Systems, 103(9), 621–638. <https://doi.org/10.1016/j.agsy.2010.07.005>

Yang Y., Tilman D., Lehman C., Trost J.J (2018) Sustainable intesification of high diversity biomass production for optimatl biofueld benefits. Vol 1., 686-692. Nature Sustainability.

Zucaro, A., Forte, A., Fagnano, M., Bastianoni, S., Basosi, R., & Fierro, A. (2015). Comparative attributional life cycle assessment of annual and perennial lignocellulosic feedstocks production under Mediterranean climate for biorefinery framework: Comparative LCA of Lignocellulosic Feedstocks Production. Integrated Environmental Assessment and Management, 11(3), 397–403. <https://doi.org/10.1002/ieam.1604>

# 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. REN21. (2015). Renewables 2015 Global Status Report. Retrieved from <http://www.ren21.net/wp-content/uploads/2015/07/REN12-GSR2015_Onlinebook_low1.pdf> [↑](#footnote-ref-1)
2. El Bassam, N. (2010). Handbook of bioenergy crops: a complete reference to species, development and applications. London ; Washington: Earthscan. [↑](#footnote-ref-2)
3. Zucaro, A., Forte, A., Fagnano, M., Bastianoni, S., Basosi, R., & Fierro, A. (2015). Comparative attributional life cycle assessment of annual and perennial lignocellulosic feedstocks production under Mediterranean climate for biorefinery framework: Comparative LCA of Lignocellulosic Feedstocks Production. Integrated Environmental Assessment and Management, 11(3), 397–403. <https://doi.org/10.1002/ieam.1604> [↑](#footnote-ref-3)
4. Lemus, R., & Lal, R. (2005). Bioenergy Crops and Carbon Sequestration. Critical Reviews in Plant Sciences, 24(1), 1–21. <http://doi.org/10.1080/07352680590910393> [↑](#footnote-ref-4)
5. Toensmeier, E. (2016). The carbon farming solution: a global toolkit of perennial crops and regenerative agriculture practices for climate change mitigation and food security. White River Junction, Vermont: Chelsea Green Publishing. [↑](#footnote-ref-5)
6. Kartha, Sivan, & Dooley, Kate. (2016). The risks of relying on tomorrow’s negative emissions’ to guide today’s mitigation action (Working Paper. 2016-08). Stockholm Environment Institute. Retrieved from <https://www.sei-international.org/mediamanager/documents/Publications/Climate/SEI-WP-2016-08-Negative-emissions.pdf> [↑](#footnote-ref-6)
7. IES (2016). Key World Energy Trends. Available online at: <http://www.iea.org/publications/freepublications/publication/KeyWorldEnergyTrends.pdf> [↑](#footnote-ref-7)
8. Wirsenius, S., Azar, C., & Berndes, G. (2010). How much land is needed for global food production under scenarios of dietary [↑](#footnote-ref-8)
9. Immerzeel, D. J., Verweij, P. A., van der Hilst, F., & Faaij, A. P. C. (2014). Biodiversity impacts of bioenergy crop production: a state-of-the-art review. GCB Bioenergy, 6(3), 183–209. http://doi.org/10.1111/gcbb.12067 [↑](#footnote-ref-9)
10. Wicke, B., Smeets, E. M. W., Akanda, R., Stille, L., Singh, R. K., Awan, A. R., … Faaij, A. P. C. (2013). Biomass production in agroforestry and forestry systems on salt-affected soils in South Asia: Exploration of the GHG balance and economic performance of three case studies. Journal of Environmental Management, 127, 324–334. http://doi.org/10.1016/j.jenvman.2013.05.060 [↑](#footnote-ref-10)
11. Hohenstein, W. G., & Wright, L. L. (1994). Biomass energy production in the United States: an overview. Biomass and Bioenergy, 6(3), 161–173. [↑](#footnote-ref-11)
12. IPCC. (2014). Climate Change 2014: Mitigation of Climate Change: Contribution of Working group II to the Fifth Assessment Report of the Intergovermental Panel on Climate Change. Cambridge, UK: Cambridge University Press. [↑](#footnote-ref-12)
13. Valentine, J., Clifton-Brown, J., Hastings, A., Robson, P., Allison, G., & Smith, P. (2012). Food vs. fuel: the use of land for lignocellulosic “next generation” energy crops that minimize competition with primary food production. GCB Bioenergy, 4(1), 1–19. <http://doi.org/10.1111/j.1757-1707.2011.01111.x> [↑](#footnote-ref-13)
14. Turconi, R., Boldrin, A., & Astrup, T. (2013). Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. Renewable and Sustainable Energy Reviews, 28, 555–565. <https://doi.org/10.1016/j.rser.2013.08.013> [↑](#footnote-ref-14)
15. For most results, only the differences between scenarios, summed over 2020-2050 were presented, but for the net first cost, the position was taken that to achieve the adoptions in 2020, growth must first happen from 2015 to 2020, and that growth comes at a cost which should be accounted for, hence net first cost results represent the period 2015-2050. [↑](#footnote-ref-15)
16. Current adoption is defined as the amount of land area adopted 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-16)
17. In some cases, the low boundary is negative for a variable that can only be positive, and in these cases the lowest collected data point is used as the “low” boundary. [↑](#footnote-ref-17)