

# TECHNICAL ASSESSMENT FOR BIOMASS POWER

SECTOR: ELECTRICITY GENERATION

AGENCY LEVEL: UTILITIES, COMMUNITIES

KEYWORDS: BIOENERGY, PERENNIAL BIOMASS,  
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\*Note: For some of the technical reports, the result section is not yet updated. Kindly refer to  
the model for the latest results.

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## ACRONYMS AND SYMBOLS

- AC - Alternating Current
- AMPERE – Assessment of Climate Change Mitigation Pathways and Evaluation of the Robustness of Mitigation Cost Estimates
- BFB – Bubbling fluidized bed
- BIOSEQ – Drawdown Bio Sequestration Model
- BOS - Balance-Of-System
- CCS - Carbon Capture and Storage
- CFB - Circulating Fluidized Bed
- CH<sub>4</sub> – Methane
- CHP – Combined Heat and Power
- CIGS - Copper Indium Gallium Selenide
- CO – Carbon Monoxide
- CO<sub>2</sub> – Carbon Dioxide
- CO<sub>2</sub> eq. - Carbon Dioxide equivalent
- CO<sub>2</sub> eqv - Carbon Dioxide equivalent
- COP- Conference of Parties (UNFCCC)
- CPUC – California Public Utilities Commission
- DC- Direct Current
- DCF – Discounted Cash Flow
- DC - Direct Current
- DOE – Department of Energy (US)
- DS – Degree Scenario
- EIA – Energy Information Administration (US)
- EJ – Exajoule
- EPBT - Energy Payback Time
- EPIA - European Photovoltaic Industry Association
- EROI – Energy Returned on Energy Invested
- ETOI - Energy Return On Investment
- ETP – Energy Technology Perspectives
- EU – European Union
- EV – Electric Vehicles
- GaAs – Gallium Arsenide
- GCV – Gross Calorific Value
- GEM-E3 – General Equilibrium model for Economy, Energy and Environment
- GHG – Greenhouse Gases
- Gt — Gigatons
- GTM - Greentech Media
- GW - Gigawatts
- H<sub>2</sub>- Hydrogen
- IEA - International Energy Agency
- IEEJ – The Institute of Energy Economics, Japan
- IGCC – Integrated Gasification Combined Cycle

- IMAGE/TIMER – Integrated Model to Assess the Global Environment/The Targets IMage Energy Regional model
- IPCC – Intergovernmental Panel on Climate Change
- IRENA – International Renewable Energy Agency
- JRC – Joint Research Center
- kW – Kilowatt
- kWp – Kilowatt (Peak)
- LCA – Life Cycle Assessment
- LCOE - Levelized Cost of Electricity
- LED – Light Emitting Diode
- LUT -Lappeenranta University of Technology
- MESSAGE-MACRO – Model for Energy Supply Strategy Alternatives and their General Environmental impact with macroeconomic feedback
- MIT – Massachusetts Institute of Technology
- MNRE — Ministry of New and Renewable Energy, Govt of India.
- MSW – Municipal Solid Waste
- MW – Megawatt
- MWp – Megawatt (Peak)
- NAFU - Net Annual Functional Units
- NAIU - Net Annual Implementation Units
- NO<sub>x</sub> - Nitrogen Oxides
- NPV – Net Present Value
- NREL - National Renewable Energy Laboratory (US)
- O&M - Operation and Maintenance
- OECD – Organization for Economic Co-operation and Development
- PD – Project Drawdown
- PDS - Project Drawdown Scenario
- PM<sub>2.5</sub> - Particulate Matter ( 2.5µm)
- PPA - Power Purchase Agreement
- PPB – Parts Per Billion
- PPM – Parts Per Million
- PV – Photovoltaic
- R&D – Research and Development
- REF – Reference Case
- REmap – Renewable Energy Roadmap (IRENA)
- REN21 – Renewable Energy Policy Network for the 21st century
- RES — Renewable Energy Sources
- ROR -Run of River
- RPO – Renewable Purchase Obligation
- RRS – Reduction and Replacement Solutions
- SCADA - Supervisory Control and Data Acquisition
- SEIA - Solar Energy Industries Association
- SO<sub>2</sub> - Sulfur Dioxide
- SPM – Suspended Particulate Matter
- SPV – Solar Photovoltaic
- SRC – Short Rotation Coppice

- TAM - Total Addressable Market
- TWh - Terawatt-Hours
- UK – United Kingdom
- US – United States
- USD – United States Dollars
- WEO – World Energy Outlook (IEA)
- WtE – Waste to Energy

## EXECUTIVE SUMMARY

Project Drawdown defines the “*Biomass*” solution as: the use of perennial biomass feedstock for dedicated electricity generation and combined heat and power generation. This solution replaces fossil fuel based electricity and is considered a “bridge solution” to a 100% clean renewable energy system, where biomass for power and heat might not be needed.

It is important to consider the development and deployment of perennial crops as an alternative to annual “bioenergy” (i.e. biomass energy) crops. Through various life cycle assessment studies performed on annual bioenergy crops such as corn, it has been shown that they are not much better than fossil fuel energy sources in terms of climate and energy impacts. Perennial biomass with its 2/3 year life-cycle has a higher productivity, needs fewer chemicals and water, and is not a food crop; hence, many governments worldwide are choosing perennials as future energy farming systems. The present analysis focuses on perennial biomass, and models both woody and herbaceous plants as the main source of feedstock for dedicated electricity generation. The total addressable market (TAM) for electricity generation is based on projected global electricity generation in terawatt-hours (TWh) from 2020-2050. At a level of an estimated value of 73 TWh in 2018, the current adoption of this solution is 0.32% of global generation.

Impacts of increased adoption of *biomass* from 2020-2050 were generated based on three growth scenarios, derived from the evaluation of scenarios from two global systems models. These three scenarios were assessed in comparison to a *Reference* Scenario where the solution’s market share was fixed at the current levels. A *Plausible* Scenario that follows a medium growth trajectory derived from the biomass and waste electricity generation projections of IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; and Equinor (2018) renewal Scenario using a medium growth trajectory. The share of biomass from these values of biomass and waste is estimated to be 77.8 percent, of which 20.2 percent is assumed to use perennial biomass as a feedstock. This scenario results in a 1.00 percent market share for *biomass* within the electricity-generation technologies mix in 2050. The *Drawdown* and *Optimum* Scenarios consider the high growth trajectory based on the same scenarios used on the *Plausible* scenario. On these scenarios, similar calculations to the *Plausible* Scenario were considered for the share of electricity generated from perennial crops.

The results for the *Plausible Scenario* show that the marginal first costs compared to the Reference Scenario would be US\$56 billion from 2020-50, with just over US\$119 billion in savings from the energy-generating biomass plants installed in the same period. Increasing the use of this solution from approximately 0.32 percent in 2018 to 1.0 percent of world electricity generation by 2050 would require an estimated US\$257 billion in cumulative first costs. Under the *Plausible Scenario*, this solution could reduce 2.6 gigatons of carbon dioxide-equivalent greenhouse gas emissions from 2020-2050, compared to a Reference Scenario where the solution is fixed at current adoption. The *Drawdown* and *Optimum* scenarios results depict similar result with 3.6 gigatons avoided. This is due to assumptions made regarding adoption trajectories, system dynamic analysis, and integration with other solutions. For the same reasons but especially due to the assumption on later scenario of no nuclear power by 2050, all renewable energy sources are increasingly needed to meet the estimated demand for electricity.

While the carbon savings may not be tremendous, the model did not account for electricity generation technologies with carbon capture and storage. Despite the robust adoption projections for total biomass and waste, the mix of electricity-generating technologies (co-firing or dedicated biomass, pure electricity or co-generation) or fuels (wood pellets, agricultural residues, municipal solid waste, synthetic gas, biogas), and the share of perennial crops used, bring significant levels of uncertainty.



## LITERATURE REVIEW

### 1.1 STATE OF BIOMASS ELECTRICITY GENERATION TECHNOLOGIES

#### 1.1.1 What is Biomass?

Biomass broadly refers to organic plant and animal material, in which all energy has been stored, either directly (in the case of plants) or indirectly (in the case of animals, including humans), from photosynthesis. Biomass can come from a variety of sources, whether woody or non-woody plant sources, or human or animal sources. Biomass is most frequently sourced from forestry, agriculture, and waste sources. The chemical energy contained in biomass can be converted to useful energy through multiple paths, including combustion, pyrolysis, torrefaction, gasification, anaerobic digestion, fermentation, transesterification, and electrochemical oxidation. The end result of these energy conversions may be useful heat output, thermal power generation, and biodiesel, liquid biofuel or biogas production. This report only considers those processes which result in the end use of producing electricity from perennial biomass. Currently, fossil fuels are the dominant source for production of electricity – making up 64.9% of global electricity production in 2017 (IEA, 2018). Biomass has the potential to displace a part of these fossil fuels, and depending on the technologies used, also to displace some of the associated greenhouse gas emissions released during the combustion of those fuels. Because plant biomass is approximately 45% carbon by weight, and plants grow over relatively short timespans as compared to their creation, plant biomass has the potential to circulate existing atmospheric and biogenic carbon rather than releasing it into the atmosphere. Biomass from humans and animals is generally in the form of waste– usually sewage, manure, or municipal solid waste (MSW) and can this form can easily displace fossil fuels without impacting other systems.

#### 1.1.2 History of Biomass

Since the advent of civilization, biomass has been used to provide heat and light, and in more recent times, has been converted to electricity, often to provide the same services. Despite advances in biomass power generation, “traditional” uses are still most common, making up 54-60% of total bioenergy over the last few years. All uses of biomass accounted for 10% of the global total primary energy supply in 2012 (IEA; 2012). Though biomass is still an important energy source throughout the world, other sources have gained greater shares of global supply in the hundreds of thousands of years since humans first discovered how to make fire. Coal was first burned for heat and cooking in China roughly 4,000 years ago, and two thousand years later, petroleum was first used to light lamps. Roughly two centuries later, waterwheels were invented in Europe, and eight centuries after that, the first windmills were developed in Persia. Coal rose to

dominance in the 17th and 18th centuries in Europe and North America, fueling the economic transition from agriculture to industry. The first half of the 19th century saw the drilling of the first natural gas and oil wells. The second half of that century saw the development of the first solar energy generator and first use of geothermal energy to heat buildings.

### **1.1.3 Perennial Biomass**

1.4% of world's electricity in 2050 could come from perennial biomass based feedstock (IEA, 2017b). In anticipation of this large change, it is important to consider the development and deployment of perennial crops as an alternative to annual bioenergy crops. Through various life cycle assessment studies (Searchinger (2008); DeCicco (2016)) performed on annual bioenergy crops such as corn, it has been shown that they are not much better than fossil fuel energy sources in terms of climate and energy impacts, sometimes even worse off than fossil fuels. Perennial grasses on the other hand have naturally high productivity, need fewer chemicals and water and are not food crops : hence many governments worldwide are choosing them as future energy farming systems (El Bassam (2010). A study by Zucaro *et al.* (2015) clearly shows through a direct comparison of Sorghum (annual crop) and Giant Reed (perennial crop) in the Mediterranean region that the perennial cultivation resulted in substantially higher environmental benefits than annual crops due to reduced inputs and emissions for establishing crops and the potential of CO<sub>2</sub> sequestration in soil organic matter.

Perennials are generally defined by their lifetime of 3 or more years. For this study the focus is on two types of perennial energy crops: herbaceous crops and short rotation coppice (SRC). 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. Current estimates put the total land area under perennial crops to be at least 153 million hectares which is 11% of world's cropland, but out of this area only a small fraction of the land is used for energy crops (Toensmeier, 2016).

### **1.1.4 Biomass electricity generation technologies**

Electric applications of biomass can also be described as a form of thermal power applications. Thermal power applications rely on combustion or gasification of biomass, but only as a first step in a more complex series of conversions to produce electricity.

### Direct Combustion

Combustion is the oldest technology for biomass conversion, especially for generating heat and steam from woody biomass. A biomass combustion facility can produce steam, electricity, or both (Combined Heat and Power - CHP). Direct combustion is classified by different types of boiler furnaces that are used for burning the biomass. Steam created during burning is passed through a steam-turbine generator to convert a portion, or all of the thermal energy into electricity. Being the oldest technology, combustion is also the most mature and also the lowest-cost biomass-to-energy technology to construct and operate, especially for woody fuels (Yakima County, 2003). Different types of biomass-fuel can be burned in the combustion boilers (e.g. dry manure and waste or mixtures of two or more fuels) to generate the heat energy.

Fluidized-bed boilers are the most common type of boilers recommended for biomass (Crawford, 2012). Boiler engineers can choose between two main types of fluidized-bed boilers—bubbling fluidized bed (BFB) and circulating fluidized bed (CFB). The fluidized bed system is also versatile and can easily deal with different types of biomass feedstocks and moisture content of up to 55%. The basis for a fluidized bed system is a bed of an inert material such as sand or limestone through which air is blown from below. The air is pumped through the bed in sufficient volume and at a high enough pressure to catch the small particles of the bed material so that they behave in a similar manner as a fluid. The combustion chamber of a fluidized bed plant is shaped so that above a certain height the air velocity drops below that which is necessary to entrain the particles. This helps retain the bulk of the entrained bed material towards the bottom of the chamber. Once the bed becomes hot, combustible material introduced into it will burn, generating heat in a manner similar to that of a conventional furnace (UNEP, 2007).

### Co-firing with Coal

The co-firing of biomass with coal in existing large power station boilers has proved to be one of the most cost effective large-scale means of converting biomass to electricity mainly because it makes use of existing infrastructure of a coal fired power plant (IEA, 2012). This approach also profits from the comparatively higher conversion efficiencies of these large-scale coal plants. Biomass co-firing may be able to reduce NO<sub>x</sub> emissions as compared to coal since biomass has a lower nitrogen content. Lower proportion (5-10%) of biomass needs to be used for simple co-firing by mixing solid biomass and coal and injecting them together into the boiler without any major modifications. Higher co-firing rates require some modifications, such as to the fuel pre-treatment (milling) plant which can increase capital cost. The alternative options, designed to avoid these problems are indirect and parallel co-firing, where fuel is fed individually into the boiler through separate burners. Though they are more capital intensive than direct co-firing (IEA 2012). Even though co-firing approach has the potential to reduce climate impacts by replacing part of coal, it still

falls short of the larger Drawdown goal that can be achieved by gasification or direct combustion with the benefits of higher efficiency.

### Gasification

Biomass gasification is the most advanced approach amongst the three technologies discussed here. It involves incomplete combustion of biomass (in restricted oxygen) resulting in a mix of combustible gases consisting of carbon monoxide (CO), hydrogen (H<sub>2</sub>) and traces of methane (CH<sub>4</sub>). This mixture is called producer-gas (Rajvanshi, 1986). The output gas can be used to generate electricity directly through gas engines or by using gas turbines which offer higher efficiencies than steam turbines. This is especially of small-scale plants between the capacities of 5 to 10 MW (IEA, 2012). At larger scales (e.g. above 30 MW), gasification-based systems can be coupled with combined gas and steam turbines providing higher efficiency levels as compared to direct combustion systems.

Integrated gasification combined cycle (IGCC) plants can run syngas (which is somewhat similar to producer gas) through a purification process and then a combustion turbine to produce electricity. The heat from the exhaust gas then goes through a heat recovery steam generator, producing steam that is run through a steam turbine like in a conventional thermal power station to generate additional electricity. The steam coming out of the turbine can then be fed back into the gasifier to produce more syngas. Biomass gasification thus promises higher efficiencies and could offer the best option for future biomass-based generation systems.

### Anaerobic Digestion

This is a specific biological process in which the biodegradable portion of the biomass is broken down with the help of microorganisms. This action is conducted in absence of oxygen and results in production of biogas – comprised mainly of methane and carbon dioxide along with some trace compounds. The methane gas can be put to a number of heat and power generation applications. It can be burned in boilers to produce steam which can then be deployed in heat applications or to generate electricity. With advancement in technologies, this methane can also be fed directly into microturbines, gas engines and also fuel cells to generate electricity.

### Pyrolysis

This process involves heating the biomass feedstock in absence of oxygen to very high temperatures (typically in the range of 300°C to 550°C). At these high temperatures, the organic material gets converted into volatile organic compounds in the form of volatile liquids, gases and some char. These compounds

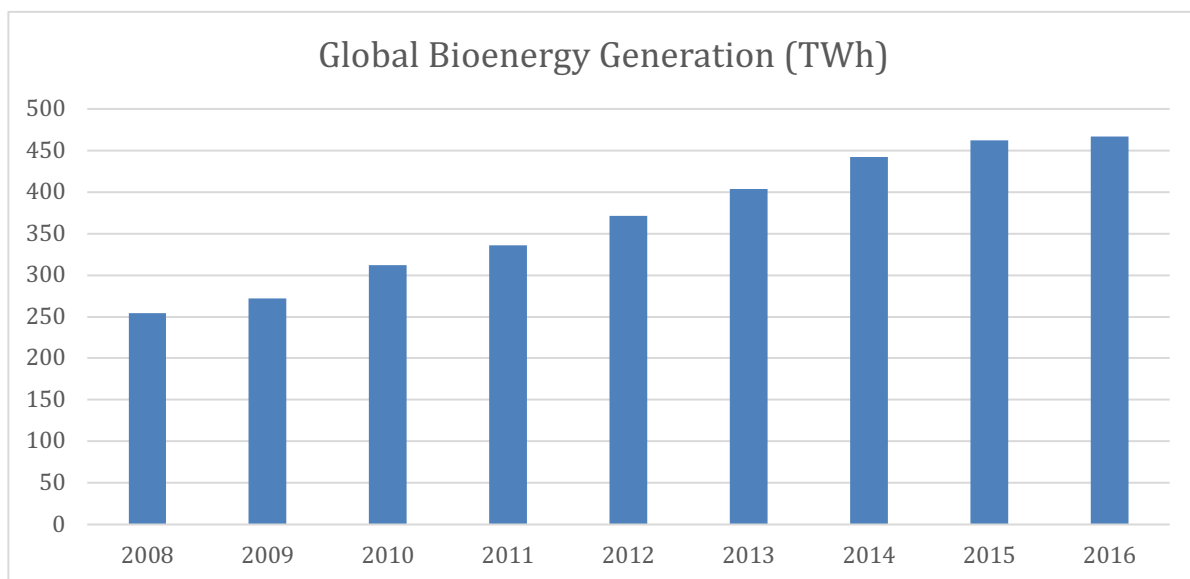
form what is known as pyrolysis oil which can be used in conventional power and heat generating systems with a bit of processing.

Amongst the range of available technologies, the direct combustion, CHP, anaerobic digestion, gasification and co-firing with coal technologies are established technologies whereas pyrolysis is still at the stage of demonstration and pre-commercialization.

## 1.2 ADOPTION PATH

### 1.2.1. Current Adoption

According to the International Renewable Energy Agency (IRENA), 466TWh of energy was produced globally from various forms of biomass. Figure 1.1 shows the trend of growth of total bioenergy from all sources for the period 2008 to 2016.



*Figure 1.1 Global bioenergy generation ( Data source : IRENA, 2018)*

The International Renewable Energy Agency (IRENA) divides the total bioenergy into three constituents:-

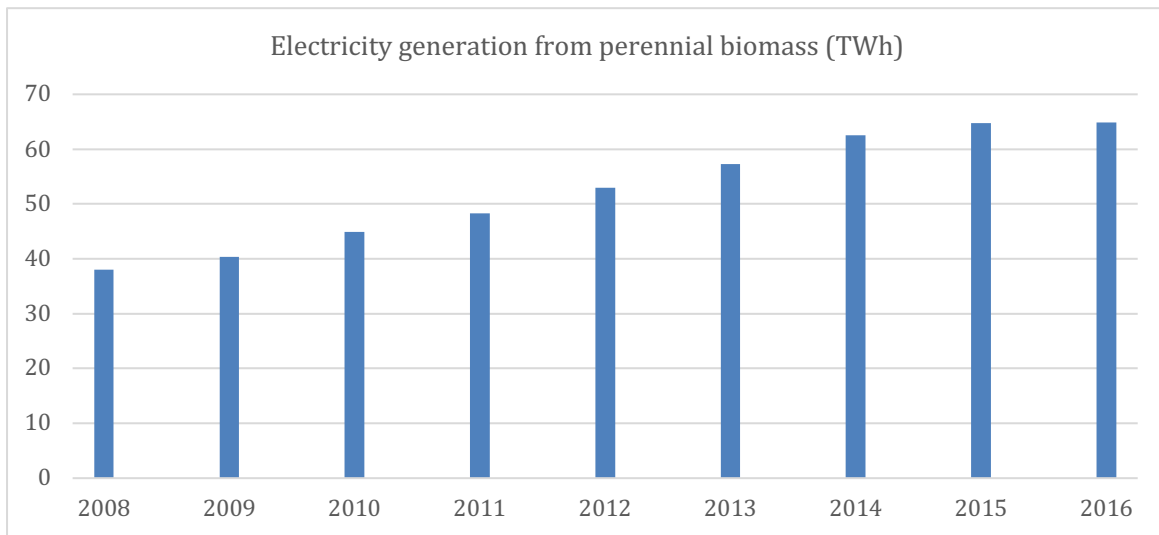
- i) Solid biofuels and renewable waste
- ii) Liquid biofuels and
- iii) Biogas

The solid biofuels and renewable waste component is further broken up into three components :

- a) Renewable municipal waste
- b) Bagasse and

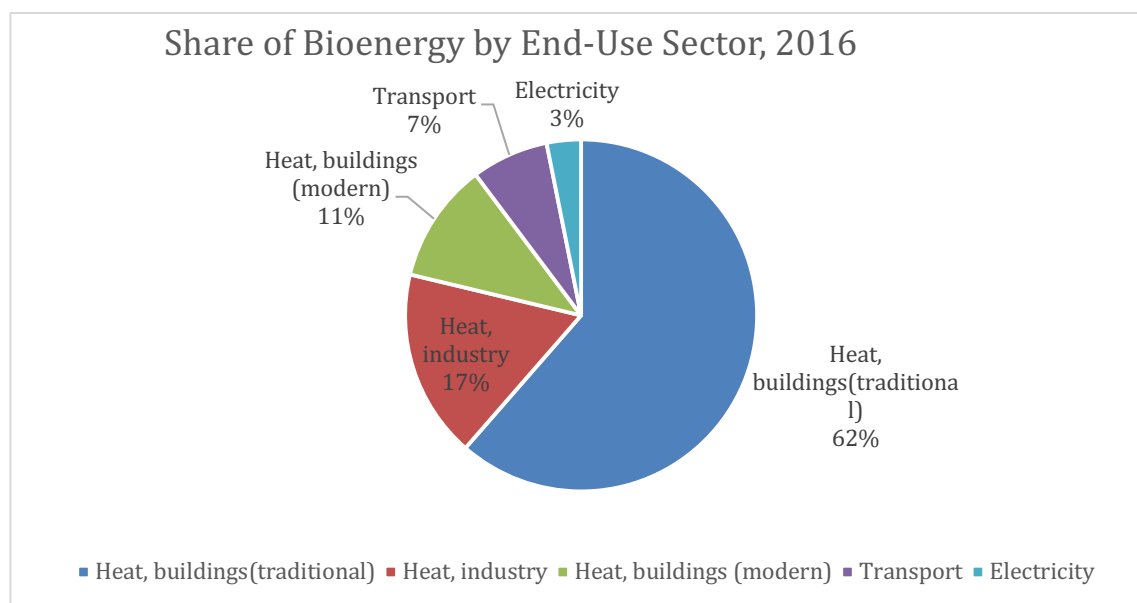
### c) Other solid biofuels

To arrive at the component of electricity generation from “perennial” portion of the biomass, historical factor was used. This historical factor has been derived from the share of perennial biomass in total biomass through modeling studies based on LCA models/studies of NREL, World Bank and BioSEQ (NREL, 2016; World Bank, 2016; Bassam, 2010). By applying these factors to the generation data from IRENA (IRENA, 2018), the trend of global electricity generation from perennial biomass was arrived at. This is depicted in the following figure.



*Figure 1.2 Trend of electricity generation from perennial biomass (Data source: IRENA, 2018)*

According to the Renewable Energy Policy Network for the 21<sup>st</sup> century (REN21, 2018), biomass contributed an estimated 46.4 EJ or 12.8% of the global total final energy consumption in 2016. Modern bioenergy (excluding the traditional use of biomass) contributed 5% to global final energy consumption. The following chart shows the share by end-use of different sectors of biomass energy (i.e. bioenergy).



*Figure 1.3 Share of End-Use Sector in Bioenergy (Data Source: REN21, 2018)*

In the electricity generation sector, the global bio-energy capacity was estimated by REN21 to be 122 GW with global generation at 555 TWh in 2017. China overtook the United States as the largest bio-electricity producing country at an estimated 79.4 TWh from an installed capacity of 14.9 GW. Generation of bio-electricity in the US, on the other hand, remained “relatively flat” around 69 TWh despite new capacity of 268 MW being added during 2017.

In the United States, several states have renewable portfolio standards (LBNL, 2016) that mandate a percentage of energy consumption to come from renewable sources within a given timeframe. The percentages, definitions of renewable energy, and compliance dates vary between states, but where biomass qualifies, renewable portfolio standards targets have driven utilities to invest in dedicated biomass, co-firing, and conversions. In other cases, utilities can purchase credits from industrial facilities using biomass for heat and/or power. Such facilities include lumber and paper mills, agricultural and livestock facilities, and landfill operations, where biomass resources are abundant and in close proximity.

As a region, Europe remained the leader with a 11% rise in generation during 2017. This was largely driven by the Renewable Energy Directive. Within Europe, Germany led the field with large increases in biogas, biomethane and sewage gas capacities. The United Kingdom’s generation from bioenergy rose 6% in 2017 to 31.8 TWh with Finland, Ireland, Poland and Sweden also closely following. In the South American region, Brazil led the way with bioenergy capacity rising 5% in 2017 to 14.6 GW. In Asia, apart from China, Japan and India also showed rapid increases of over 10% in bioenergy capacity (REN21, 2018).

While traditional uses of biomass in Asia and Africa have been driven by necessity, the growth of modern applications is a result of resource availability and low-cost, as well as efforts to curb greenhouse gas emissions. South America is seeing increased biomass demand for the same reasons, particularly Brazil, as previously mentioned.

### **1.2.2. Trends to Accelerate Adoption**

For biomass energy technologies to take off worldwide there will need to be a number of political, financial, social, and technological shifts that take place. Current mandates for renewable energy that specify biomass as a renewable resource are a strong first step to driving demand, but still more stringent standards will be necessary. So long as fossil fuels remain the lowest cost, and in the absence of other financial drivers or compliance requirements, utilities will continue with business as usual. Specification of biomass as a renewable resource and escalation of renewable mandates on shorter timescales will create the urgency for adoption, as well as reduce financial risk and create a stable investment environment.

Removal of subsidies for fossil fuels will have a similar effect from the other direction, making fossil fuels more expensive and less preferable provided that biomass resources can consistently be procured cost-competitively. It is already the case that for many heat applications, particularly where demand is steady and wastes and residues are utilized, biomass is cost-competitive with fossil fuels. There are also import and export tariffs currently in place in certain geographies that add costs to biomass fuels. Removal of such tariffs can further improve the competitiveness of biomass with fossil fuels, though in many cases, the existence of tariffs is for the very purpose of protecting domestic fossil fuel interests.

Additional subsidies for biomass facilities, at least in the short-term, could further accelerate adoption, particularly for electricity generation, where fossil fuels are still the more cost-effective choice. These incentives could come in the form of investment and production tax credits for facilities producing heat and electricity, or as loans or grants for facility construction, as well as for research and development of improved technologies. Incentives could be phased out over time as biomass gains marketplace traction and can stand on its own. Technologies in need of further R&D investment include improved efficiency combustion, torrefaction, pyrolysis, gasification, absorption cooling (which can use waste heat to cool air or water), and carbon capture and sequestration. International collaboration could lead to mutually beneficial technology breakthroughs, particularly for standardized biomass plant design. At present, biomass facilities tend to be custom-designed, but “off-the-shelf” plans, coupled with increased demand for biomass, could reduce capital costs.

Sustainable fuel supply is perhaps the single most important factor for the future success of biomass at the global scale. As world energy demand grows, energy crop plantations do not seem likely to be able to



provide enough supply. Should plantations be used to source fuel, coppicing and short/fast-rotation practices should be favored to maintain a closer balance between carbon uptake from new growth and emissions from combustion. Crop rotation and crop sequencing can also help maintain soil health and increase the productivity of both energy and food crops. On the other hand, climate change may adversely affect growth rates and productivity. Of course, proximity of resource supply is a key to the carbon impact of biomass facilities. Ideally, such facilities should only be built in regions where there is abundant, low-cost supply, or where such supply can be transported with minimal energy input. Eastern Africa, South America, and Eastern Europe have abundant land area suited for biomass production and are projected to be major future suppliers for the world, though again, appropriate technology uptake and infrastructure development will be necessary.

The global push towards cleaner sources of energy with lesser GHG emissions provides another push to global adoption of bioenergy, like other sources of renewable energy. An important difference between bioenergy and other forms of renewable energy like solar and wind energy is that all forms of bioenergy do not result in a reduction of GHG. Many processes and sources associated with bioenergy in fact add to the GHG load in the atmosphere rather than reducing it. Here one has to be very careful in assessing that the feedstock from which bioenergy is sourced should be produced in a sustainable and (at least) a carbon neutral manner. It is for this reason that Project Drawdown extracts the “perennial” component from the whole envelop of biomass energy to arrive at the sustainable and carbon neutral portion of the bioenergy. At the current levels, this component of perennial biomass is derived to be 20.2% of the total biomass which can be used for bioenergy production.

An unlikely but strong push towards accelerating greater adoption of biomass energy technology is the recent local pollution hazard in Asia created by the burning of biomass stubble in the farmers’ fields at the end of harvesting season. Rather than physically removing the stubble, many farmers are adopting the easier, cheaper and much quicker method of burning the stubble in the field itself so as to prepare the field in time for the next crop. This indiscriminate burning of left-over biomass in the field itself is creating unprecedented levels of atmospheric pollution (especially in SPM levels) in vast adjoining areas creating the phenomenon of “brown haze” so often seen nowadays in many parts of Asia. It is not unusual for the pollution levels to reach critical levels and remain there for weeks during the harvesting seasons.

As countries scramble to tackle this health emergency, generating electricity from this biomass is getting a lot of attention and many regions are taking up this technology which provides the double benefit of cleaning up the environment as well as generating power. As more and more farmers adopt this technology, the graph of adoption of biomass technology is only set to rise further. Though annual crops are not counted among perennial sources of biomass in Project Drawdown, large scale adoption of this technology will only

help develop and disseminate this technology which can equally be sustainably used for perennial biomass as well.

At the institutional level, the area of biomass energy has been getting a lot of attention and support at the international fora. A Global Bioenergy Partnership (GBEP) was launched in 2006 under the aegis of the UN Commission for Sustainable Development “to support wider, cost effective, biomass and biofuels deployment, particularly in developing countries where biomass use is prevalent” (GBEP, 2019). Similarly, Brazil launched the BioFuture Platform along with 20 major biomass-endowed countries at COP-22 for policy dialogue and collaboration among leading countries, organizations, academia and the private sector to dramatically accelerate the transition to an advanced, low carbon and global “bioeconomy” (BioFuture Platform, 2019).

### **1.2.3. Barriers to Adoption**

In their report “Bioenergy in Europe: Opportunities and Barriers”, Fagernas *et al* (2006) have given a detailed account of the different types of barriers which face the bioenergy sector in Europe. There is a whole range of barriers faced in the development and deployment of biomass energy. The barriers are both technical as well as non-technical in nature. On the whole, the non-technical barriers predominate but rather than one major barrier, biomass energy faces a web of many interrelated barriers that it is required to overcome in order to be widely adopted.

Among the non-technical group are placed the economic, financial, policy and supply side barriers whereas on the technical side there are constraints of R&D in developing new systems, materials and processes for heat and power which can bring the whole range of technologies from the lab to the field and make them commercially viable. The prominent ones are listed below.

#### *1.2.3.1 Non-Technical Barriers*

- Security of sustainable biomass supply
- Lack of legislation to support biomass energy
- Higher financial risks involved with biomass projects
- Uncertainty of long term financial policies
- Insufficient incentives and subsidies
- Procedural barriers related to bank finance and investments
- Non-availability of sustainably grown biomass
- Competing demand from food crops
- Barriers related to biodiversity and long-term effects of biomass production

- Social barriers : public perception/opposition to bioenergy development
- Poor applications of biomass production chains for local conditions

#### *1.2.3.2 Technical Barriers*

- Higher technical risks involved with (as yet developing) biomass technologies
- Lack of cost-effective harvesting technologies
- Extraction, transportation, handling, logistics and storage problems
- 5 to 10% limit for co-firing,
- Conversion of high-ash biomass in gasification : Slag, fouling and corrosion problems
- Inability to handle multiple types of feedstock
- Inadequate emissions control in WtE processes : gasification, pyrolysis and co-combustion
- Inadequate feedstock and fuel standards [*Adapted from* (Fagernas, 2006)]

The major problem is with relation to GHG emissions while considering any biomass based electricity generation project in comparison to alternate renewable electricity generation pathways such as hydropower or wind. Here, it has been shown that GHG emissions from biomass based electricity generation (in the range of 8.5-130 kg CO<sub>2</sub> eq/MWh) is higher than both hydropower (2-20 kg CO<sub>2</sub> eq/MWh) and wind (3-41 kg CO<sub>2</sub>-eq/MWh) when the entire lifecycle is considered (Turconi , 2013). However, when compared to energy sourced from fossil fuels, the GHG reduction offered by sustainably grown biomass is substantial and needs to be adopted while taking care of the major barriers listed above.

### **1.3 ADVANTAGES AND DISADVANTAGES OF BIOMASS POWER SYSTEMS**

#### **1.3.1 Similar Solutions**

There are several solutions in the electricity generation sector that can replace conventional electricity-generating technologies such as coal, oil, and natural gas power plants which could be considered as similar/analogous solutions. Technologies similar to biomass systems for electricity generation that also use bioenergy are waste to energy, landfill methane. These differ from this solution in the way the technologies work and the bioenergy type.

#### Cogeneration

Cogeneration is a complementary form of technology that captures excess heat produced during electricity generation (from any fuel) and puts this waste energy to use. Through the cogeneration process, this thermal energy is used either to produce additional electricity or for heating applications.

### Waste Solutions

Under this category, there are three Drawdown solutions which can be considered as solutions which compete with perennial biomass to varying degrees. These are i) Waste to Energy, ii) Large Digesters and iii) Landfill Methane. In many of these, the biological processes are somewhat similar in that these involve biodegradation and oxidation of biomass from different sources and under different levels of oxygen which produce largely methane and a few other combustible products which can be deployed for production of energy. Hence, all these three solution can be considered as similar solution to an extent that they also replace fossil fuel based electricity and are based on processes that convert biomass into combustible gases like methane.

#### **1.3.2 Arguments for Adoption**

What has driven fuel source switching throughout history? There are a few key drivers. Ease of extraction reduces the necessary energy investment for fuel sources. All over the world, biomass has generally been abundant, though with growing populations and the accompanying demand for energy, deforestation has in many cases limited the availability of forest sector resources, while energy crops may lose out to food crops, and waste from humans and animals and residues from agriculture may be ungainly to collect. Early discoveries of coal, petroleum, and natural gas, on the other hand, uncovered huge and easily accessible deposits. Fuels with high energy content increase the energy return of fuel sources. Coal, petroleum, natural gas, and especially uranium (the fuel for nuclear power) all have greater energy content per unit of mass than biomass. The benefits of other renewable sources, namely solar, wind, hydro, and geothermal, is that they do not require any fuel input.

In more recent times, energy return on investment (EROI, the ratio of usable energy obtained from an energy resource to the energy expended to acquire that resource) has not necessarily been the only determinant of preferred energy sources, while climate impacts and energy security have become more prominent points of concern. New technologies allow for the production of biomass fuels in solid, liquid, and gaseous forms, which can be easily stored and transported and are flexible in combustion applications. Biomass is a renewable resource, and furthermore, reforestation and afforestation efforts have contributed to greater supply in certain key regions of the globe, particularly the United States. At the same time, new agricultural developments in crop sequencing can increase the productivity of both energy and food crops. In markets where biomass is sourced locally, it can reduce reliance on costly fuel imports, providing energy security, and feedstock prices can be relatively low compared to fossil fuels (though they may vary considerably depending on type, location, and purchase quantity). In thermal power applications, biomass offers baseload stability that is currently lacking for solar and wind power in the absence of large-scale,

cost-effective energy storage and smart grid technologies (IEA, 2012). To elaborate, the sun does not always shine and the wind does not always blow, making power output from these sources intermittent, while wood fuels can be consistently burned to meet minimum around-the-clock energy demand. That being said, there is not a choice to be made between biomass and other renewable energy technologies; rather, all these avenues should be pursued in tandem. As the enabling technologies to make intermittent sources viable for baseload applications continue to be developed and improved, biomass can provide a more favorable carbon profile in the transition away from fossil fuels. Biomass energy also does not come with the safety or cost issues associated with nuclear energy.

### **1.3.3 Additional Benefits and Burdens**

Of late, with higher levels of variable wind and solar energy being injected into the grid, questions of predictability and variability of supply as well as stability of the grid have come to the fore. Levels of 20% injection of solar /wind power are giving rise to numerous problems for the grid operations. Under these circumstance, bioenergy can play an important role by providing flexible, predictable and dispatchable levels of complementary generation thus offsetting the drawbacks associated with wind and solar generation. Where feedstock costs are low, bioenergy can be a source of low cost generation and what is important from the future point of view is that bioenergy can also be linked to carbon capture and storage systems which are gaining importance in a carbon-constrained world.

At the same time, biomass is not without its unique disadvantages. Growing energy demand, coupled with slow forest growth rates, can lead to deforestation and substantial alteration of landscapes, resulting in loss of wildlife habitat, soil erosion and nutrient depletion, and reduced water storage capacity. In modern context, biomass crops purposefully planted as energy resources can create competition for land where competing uses might be conservation areas, wildlife habitat, timber production, pastureland, agricultural production, or urban development. This competition can drive up prices for food, feed, and forest products. Furthermore, intensively managed energy crop plantations may put pressure on groundwater resources, which in certain regions of the world, are becoming increasingly limited. Land-use change can result in indirect greenhouse gas emissions. Finally, there is the question of the carbon neutrality of biomass energy. There is still no scientific consensus on this issue, so only objective claims from both sides of the argument shall be presented here.

The question of whether the biomass employed in producing energy is “sustainable” is always at the back of the mind when evaluating projects that produce biomass based energy. As stated earlier, there are many studies that find that biomass projects do not do as well on the scale of sustainability and GHG emissions when compared to other renewable energy projects (Turconi 2013). A perception gets created now and then

that a majority of biomass projects have a deleterious effect on the environment and that they add to GHG emissions and are beset with problems of unsustainability including deforestation, water stress etc. The burden of sustainability of bioenergy persists and to overcome this burden, an expert international body called the Global Bioenergy Partnership (GBEP) has prepared a table of 24 indicators. These fall into three categories of environmental, social and economic indicators and help in facilitating the assessment and monitoring of bioenergy for sustainability at the country level.

Other challenge of biomass based electricity generation is the wide variation in the sizes of the biomass as it is received. This calls for an additional process of appropriate sizing of the biomass. The sizing in combination with multi-fuel combustion of biomass is the biggest reason for low efficiency of biomass based electricity generation (JRC, 2012). Compared to coal based power plants, biomass based power plants operate with higher heat rate (low efficiency) due to poor fuel quality (high moisture and low GCV), lack of optimization of boiler parameters and the turbine parameters (such as optimization of excess air and steam parameters).

Specifically, perennial energy crops have naturally high productivity, need fewer chemicals and water and are not food crops, hence many governments worldwide are choosing them as future energy farming systems. A study by Zucaro *et al.* (2015) clearly shows through a direct comparison of Sorghum (annual crop) and Giant Reed (perennial crop) in Mediterranean region that the perennial cultivation resulted in substantially higher environmental benefits than annual crops due to reduced input and emissions for establishing crops and the potential of CO<sub>2</sub> sequestration in soil organic matter. According to IPCC (2014), perennial cropping systems have a medium technical mitigation potential in terms of impacts on GHG 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. Some studies also indicate that perennial crops planted in degraded lands provide a potential to improve soil carbon and abate erosion and salinity issues (Immerzeel *et al.*, 2014). Table 1.1. presents a comparison of selected pros and cons of the solution with others in the same sector and with the same energy source.

*Table 0.1 Bioenergy solutions versus conventional electricity generation technologies*

Parameter	Conventional Electricity Generation Technologies	Perennial Biomass	Large Digesters	Landfill Methane Capture	Waste to Energy
<i>Greenhouse Gas Emissions</i>	Extremely High	Medium	Low	Medium	High
<i>Land Requirement</i>	Medium	Large	Low	Medium	Medium
<i>Air Pollution</i>	Extremely High	High	Low	Medium	Very High
<i>Electricity Generation Flexibility</i>	Very High	High	High	High	High
<i>Resource Extractive Drawbacks</i>	Extremely High	Low	Low	Low	Low
<i>End of life Disposal Drawbacks</i>	Very High	Low	Low	Medium	Medium
<i>Gestation Period<sup>1</sup></i>	Very High	Medium	Low	Medium	Medium
<i>Modular Scalability<sup>2</sup></i>	Low	Very High	Very High	High	Very High
<i>Environment/Health Benefits</i>	Very Low	Very High	Very High	Very High	Medium
<i>Operation and Maintenance Costs</i>	High to Very High	Low	Low	Low	Low

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<sup>1</sup> Gestation period means the time it takes to actually set up the project once the investment decision is made.

<sup>2</sup> Scalability means how easily can we upgrade the size of the plant by adding more modules or turbines.

## 2 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 replacement of conventional electricity generation technologies (i.e. coal, oil, natural gas) and related emissions for an alternative solution (see the Drawdown RRS Model Framework and Guide for more details). These technologies are assumed to compete in markets to supply the final functional demand which is exogenous to the model, but may be shared across several solution models. The adoption and markets are therefore defined in terms of functional units (TWh), and for investment costing, adoptions are also converted to implementation units (TW). The adoption of both conventional technologies and the present solution for electricity generation (Biomass from Perennial crops) were projected for each of several scenarios from 2015 to 2050 and the comparison of these scenarios (for the 2020-2050 segment) is what constitutes the results.

For this solution, the approach was to analyze the impacts of increased adoption of biomass for electricity generation using only perennial crops. The model used for this analysis constructs both alternative ambitious adoption pathways (PD scenarios) and a Reference scenario (REF) for biomass perennial. Following project Drawdown methodological assumptions (further description available on the Drawdown RRS Model Framework and Guide), and in order to grasp the total impact of an increased adoption of the solution during the assessed time frame, the REF scenario assumes the future rate of adoption of electricity generated from biomass technologies using perennial crops feedstocks remains fixed at the current adoption (i.e. 2018) level of the Total Addressable Market (TAM), estimated at 0.32 percent of electricity generation. The TAM for this solution is based on the common project Drawdown projected global electricity generation in terawatt-hours till 2050 (Section 2.3.).

The developed alternative PDS scenarios, draw on existing adoption scenarios from bioenergy feedstocks electricity generation to model several alternative adoptions. The RRS model contains both financial and climate analyses in order to model the global and regional impacts of adoption in the PDS scenarios compared to the REF scenario. What the model thus prognosticates is the total financial costs and benefits of adoption cases for biomass power, as well as the contribution this adoption can make to annual and cumulative emissions reduction.



## 2.2. DATA SOURCES

This section presents key data sources utilized in the model to evaluate the adoption of perennial biomass feedstock used for electricity generation. Data inputs for the model come from a variety of sources, primarily from peer-reviewed publications and from institutional reports. For all variable inputs, a variable meta-analysis of existing literature was conducted to create low, high, and mean estimates. For each solution variable, a sensitivity analysis of, on average, 25 data points reported in the literature was conducted. In some cases as many as 75 data points were considered. This allowed a robust and reliable analysis of financial, technological and climate parameters. These represent both optimistic and conservative estimates for the future costs and benefits of adopting this solution.

Several reports provide first installed costs for biomass plants for electricity generation. The costs vary significantly depending on the region, technology and size, therefore several sources/regions, technologies (dedicated power plants, incineration and gasification plants, CHP systems) and sizes were included in this analysis to determine the average capital cost of biomass systems installations (e.g. IPCC, 2011; WEC, 2013, JRC, 2014; Ram et al., 2017, Tsiropoulos, 2018; EIA US, 2016, REN21, 2018; IRENA, 2018).

Biomass powerplants depict a much higher install first cost than some other renewables and conventional technologies. On the other hand, this technology deployment is highly region and resource dependent. Cost estimates for fixed and variable operation and maintenance (O&M) of biomass plants were collected from several sources (e.g. IEA, 2012; JRC, 2014; Lazard, 2017; IRENA, 2018; EIA, 2016; Johansson, 2018). These estimates were used to calculate total operating costs of biomass adoption, which, combined with capital costs for installation, represent the total financial costs of adopting this solution in the PD scenarios. Fixed operation and maintenance costs for both renewable and conventional generation technologies can include expenses such as day-to-day preventative and corrective maintenance, labor costs, asset and site management, and maintaining health and safety, among others (Lo, 2014). Average fuel price was calculated considering average prices for coal, oil and natural gas from 2005-2014 using IEA data (IEA, 2016a). Prices for different biomass feedstocks (wood chips, straw, wood pellets, short cycle crops, crop residues) were extensively collected in the RRS model, but only short cycle crops data points were used for the calculations.

In order to compare capital and O&M costs of biomass systems adoption in the PD scenarios with that of conventional generation technologies, the cost data was obtained for fossil fuel-based electricity generating sources from the IPCC 5<sup>th</sup> Assessment Report (IPCC, 2014) which has conducted its own sensitivity

analysis of a number of sources from the literature<sup>3</sup>, and other sources such as OECD (2015), and Lazard (2016). In all, variables for conventional electricity generation sources, data for coal, oil and natural gas (primarily pulverized coal and combined cycle gas turbine technologies) were included and a weighted average obtained. These weights are based on the percentage, for each fuel on the total global electricity generation for 2014 (World Bank, 2015).

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

Though the average annual use of conventional generating technologies is lower than that of biomass technologies, the range of capacity factors for different conventional generating sources can still vary based on type of technology and location. For this reason, data was collected from a range of different sources (EIA, 2016; IEA, 2016b; Lazard, 2016) that represent most of the regions contained in this analysis. The lifetime of biomass systems for electricity generation that has been presented in the literature shows a wide variation (from 20 to around 40), which may be derived by the type of technology being depicted. According to Ram (2017), the lifetime of these technologies before replacement is 25 years whereas (Johansson, 2018) presents a higher lifetime of 40 years. Also a wide variation is considered in the literature with capacity factors varying from a low of 26% to 86% of annual use for higher values (IRENA, 2018b; IRENA, 2018c).

The model's analysis of the climate impacts of adoption are primarily derived from the direct emissions factor associated with the replacement of conventional generating technologies with biomass plants. This methodology is explained in greater detail in Drawdown RRS model framework and guidelines. In order to account for indirect emissions from conventional technologies and biomass systems—primarily those lifecycle emissions associated with manufacturing, transporting, installing and other non-generation activities. Many life cycle assessment (LCA) studies have been performed to evaluate the environmental impact of biomass derived electricity generation (Alexander (2015); Pehnt (2006); Masanet (2013);

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<sup>3</sup> The IPCC's 5<sup>th</sup> Assessment Report analyzes the following sources: Coal: Black and Veatch (2012), DEA (2012), IEA/NEA (2010), IEA (2013a), IEA-RETD (2013), Schmidt et al. (2012), US EIA (2013). Gas Combined Cycle: Black and Veatch (2012), DEA (2012), IEA/NEA (2010), IEA (2011), IEA (2013a), IEA-RETD (2013), Schmidt *et al.* (2012), US EIA (2013).

Perilhon (2012); Evans, (2010); Shen (2015); Liu (2014); EIA (2016); Gu (2017); Yang (2018)). An attempt was made to gather data for only the studies that focus on using perennial feedstock. Also in order to avoid double counting of climate impacts, data from upstream operations and fuel cycles i.e. production of biomass was discounted. This part of the lifecycle was evaluated separately in the Perennial biomass production BIOSEQ model.

Turconi (2013) performed a meta-analysis of LCAs of various electricity generation technologies including biomass based technologies. The studies that use perennial feedstock and use either direct combustion or gasification technology have been used for gathering direct and indirect emission data. Same strategy has been applied to Alexander (2015).

### **2.3. TOTAL ADDRESSABLE MARKET**

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

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

The Ambitious Project Drawdown TAM Scenario is constructed from the average of yearly values of four scenarios: the IEA (2017) 2D Scenario, the IEA (2017) B2D scenario, Renewal Scenario from Equinor (2018), and IEA (2018) WEO SD scenario. The Conservative Project Drawdown TAM Scenario follows the average yearly values of the IEA (2018) WEO New Policy scenario (NPS); Reform Scenario from Equinor. (2018), IEEJ Outlook (2018) Advanced Tech scenario, and IRENA (2019b) Roadmap 2050 REmap case. The Baseline Project Drawdown TAM Scenario is built by the average of the Equinor (2018) Rivalry Scenario, IEEJ Outlook (2018) Reference Scenario, IEA (2017) Reference Case and IEA (2018)

WEO Current policies Scenario (CPS). These three Project Drawdown TAM scenarios show an estimated range of electricity generation from 45,286TWh to 49,706TWh by 2050. Baseline TAM is used for PD Plausible scenario assessment.

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

## **2.4. ADOPTION SCENARIOS**

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

### **2.4.1 Reference Case / Current Adoption**

For the Reference (REF) case scenario, adoption is fixed at the current adoption<sup>4</sup> (in percentage terms) of the market. That is, the current percentage of total electricity generation (TWh) provided by biomass power systems assumed to use perennial crops, has been kept constant throughout the study period to 2050. As the market grows, the total number of biomass plants adopted grows equally to maintain the percent adoption at its current value in 2018. It is acknowledged that this, in reality, may not be a “business as usual” trajectory considering the changes taking place worldwide, but it allows a sort of measure to evaluate the impact of recent and even more aggressive policies to reverse global warming.

### **2.4.2 Project Drawdown Scenarios**

Three Project Drawdown scenarios (PDS) were developed for each solution, to compare the impact of an increased adoption of the solution to a reference case scenario. Integration with Project Drawdown Biomass model to evaluate the available feedstock for each scenario is explained in Section 2.7. The scenarios developed to assess biomass for electricity generation using perennial crops feedstock are:

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<sup>4</sup> Current adoption is defined as the amount of functional demand supplied by the solution in 2018. This study uses 2014 as the base year due to the availability of global adoption data for all Project Drawdown solutions evaluated.

### *Plausible Scenario*

This scenario represents an incremental and plausible growth of renewable energy solutions using medium to high growth trajectories to 2050 depending on the current maturity levels of the technology, and bounded by existing ambitious projections from other global energy systems models. For biomass electricity generation, this scenario is based on the evaluation of yearly averages of four ambitious scenarios: IEA (2017) Energy Technology Perspectives 2DS and B2DS scenarios; IEA (2018) World Energy Outlook SDS; and Equinor (2018) renewal Scenario using a medium growth trajectory. The share of biomass from these values is estimated to be 77.8 percent, of which 20.2 percent is assumed to use perennial biomass as a feedstock.

### *Drawdown Scenario*

This scenario is optimized to reach drawdown by 2050 using more ambitious projections from existing sources. The scenario projects a 100% adoption of non-fossil fuel-based technologies in 2050; mainly RES but also includes several technologies that are considered transitional solutions (as nuclear energy) (See section 6). For biomass for electricity generation using perennial crops feedstock, this scenario is based on the yearly average values of the same scenarios and sources depicted above, while following a high growth trajectory. The share of biomass from these values is estimated to be 77.8 percent, of which 20.2 percent is assumed to use perennial biomass as a feedstock.

### *Optimum Scenario*

This scenario represents the most optimistic case, in which clean, renewable energy solutions such as wind, solar, and other renewable energy sources capture 100% of electricity generation by 2050, with both fossil fuels and transitional solutions fully phasing out by 2050. This scenario for electricity generated from perennial crops is based on the yearly average values of the same scenarios used for the previous scenarios scenario, with a high growth trajectory.

## **2.5. INPUTS**

### **2.5.1 Climate Inputs**

In order to calculate the climate impacts of the project Drawdown scenarios, in terms of maximum annual emissions reduction, total emissions reduction, and PPM equivalent, the electricity generation from perennial biomass was estimated globally and regionally from 2020-2050. Thereafter, the emissions reductions due to the replacement of conventional electricity generation sources with the solution were

calculated. The detailed methodology of these calculations is available at the Project Drawdown Integration Methodology report.

While being a renewable energy technology, biomass plants do not have direct emissions attributable to combustion of fossil fuels and greenhouse gas emissions from biomass feedstocks are not accounted in international statistics. However, Project Drawdown modeling exercise considers the analysis of indirect emissions related to the different factors that indirectly contribute to GHG emissions from the lifecycle of biomass systems. The lifecycle emissions biomass for electricity generation adoption in the scenarios, a fixed value (t CO<sub>2</sub>-eq per TWh) was used factoring in information from several biomass technologies rather than using a weighted average for different types of biomass systems in use. The climate results would therefore be expected to be more conservative than would have been the case if a decreasing average lifecycle emissions value for this solution was assumed.

*Table 2.1 Climate Inputs*

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Indirect CO <sub>2</sub> Emissions (Solution)	t CO <sub>2</sub> -eq/TWh	4,000 to 237,775	112,226	15	7

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<sup>5</sup>.

## 2.5.2 Financial Inputs

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

The financial calculations examine the first cost in US\$ per kW and the operating cost in US\$ per kW (fixed costs) and US\$ per kWh (variable costs). For this, many inputs estimating annual output and lifetime output per biomass electricity generation technologies, along with first costs (per functional unit), were calculated.

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<sup>5</sup> 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.

A lifetime capacity of 166,297 hours (around 28 years) was calculated depending on the average powerplant annual use.

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

Fuel prices for conventional technologies are derived from IEA (2019) data, averaging 2007-2018 historical registries for oil, coal and natural gas used for electricity generation and calculated through a weighted average by fuel from the current electricity generation mix. An average cost of biomass from short cycle crops of 0.0143 US\$2014 per kWh is considered.

A mean value of the data set range collected is assumed for installation costs of biomass systems which results in a total first cost of US\$ 3,386 per kilowatt<sup>6</sup>. A first cost learning rate was considered. Estimates in the literature for the learning rate for this solution range from 0 to 24 percent (Elshurafa, 2018). An average learning rate of 7.56% was used in the calculations; and this has the effect of reducing the installation cost to US\$2,871 per kilowatt in 2030 and to US\$2,669 in 2050, compared to US\$1,786 (in 2014) per kilowatt for the conventional technologies (i.e. coal, natural gas, and oil power plants). Tables 2.2. and 2.3 depict the dataset ranges and the model inputs for the conventional and solution technologies.

*Table 2.2 Financial Inputs for Conventional Technologies*

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Conventional)	US\$2014/kW	470.5 – 3,101	1,786	24	8
Fixed Operation and Maintenance Costs (Conventional)	US\$2014/kW	3.44 – 65.86	32.95	18	4
Variable Operation and Maintenance Costs (Conventional)	US\$2014/kWh	0.0014 – 0.0079	0.0048	22	7
Fuel Price (Conventional)	US\$2014/kWh		0.0492		1
Learning Rate Factor (Conventional)	%		2.00%		

*Table 2.3 Financial Inputs for Solution*

<sup>6</sup> All monetary values are presented in US\$2014

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
First costs (Solution)	<i>US\$2014/kW</i>	1,305 – 5,466	3,386	73	16
Fixed Operation and Maintenance Costs (Solution)	<i>US\$2014/kW</i>	55.59 – 127.18	91.39	26	12
Variable Operation and Maintenance Costs (Solution)	<i>US\$2014/kWh</i>	0.002 – 0.029	0.012	24	12
Learning Rate Factor (Solution)	%	0 - 24%	7.56%	12	6
Biomass Feedstock Price	<i>US\$2014/kWh</i>	0 – 0.024	0.014	20	9

### 2.5.3 Technical Inputs

In order to characterize biomass technologies for electricity generation compared to conventional technologies, several technical inputs are considered in the RRS as capacity factors and lifetime (Table 2.4 and 2.5).

*Table 2.4 Technical Inputs Conventional Technologies*

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity (Conventional)	<i>hours</i>	121,807 – 222,351	172,079	12	6
Average Annual Use (Conventional)	<i>hours</i>	3,337– 6,587	4,962	23	4

*Table 2.5 Technical Inputs Solution*

	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Lifetime Capacity (Solution)	<i>hours</i>	166,297– 209,753	166,297	18	12
Average Annual Use (Solution)	<i>hours</i>	3,855 – 8,155	6,005	71	12



## 2.6 ASSUMPTIONS

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that infrastructure required for solution is available and in-place, policies required are already in-place, no carbon price is modeled, all costs accrue at the level of agency modeled, improvements in technology are not modeled, and that first costs may change according to learning. Full details of core assumptions and methodology are available on the Project Drawdown Reduction and Replacement Solutions (RRS) Model Framework and Guide report. Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

**Assumption 1:** This solution only focuses on “perennial” biomass as feedstock for electricity generation and available data for adoption assumes all types of feedstocks including waste. Hence to reflect the correct share in adoption data, information from 3 literature sources (NREL, 2011; Greenpeace, 2015; El Bassam, 2010) was used along with the current adoption as calculated in the Project Drawdown BIOSEQ model for perennial biomass production. These sources provided an average value of 20.2% as the share of perennial feedstock out of all biomass for electricity generation. Some of the sources also provide aggregate current adoption data for electricity generation in TWh under the combined head of “bioenergy” or “bioelectricity”. Based on historical data from IRENA (2018) for the years from 2008 to 2016, a historical average split ratio of 14.34% was derived as the component of biomass in total bioenergy. Using this value, the biomass share was calculated and to the resultant figure was applied the factor of 20.2% (described before) to ascertain the component of “perennial” portion from the total biomass generation.

**Assumption 2:** When performing a global analysis across several solutions and sectors, Project Drawdown can identify a realistic allocation of biomass for each solution and sector. This enables the estimation of the maximum potential for perennial Biomass contribution to Electricity generation adoption. For the Plausible scenario 608.8MMT of perennial biomass by 2050 is the maximum use; 839.9MMT for the Drawdown scenario and 1031.1MMT on the Optimum scenario.

**Assumption 3:** Same operating conditions for biomass electricity generation are applicable for all types of feedstocks including perennials and no special considerations have been made for efficiency, capacity factors, lifetime or annual use.

**Assumption 4:** Direct and indirect emission values for perennial feedstock production were excluded from the climate calculations to avoid overlap with the Project Drawdown BIOSEQ model.

**Assumption 5:** Calculations on the RRS model for this solution does not assume electricity generation with carbon capture and storage options.

**Assumption 6:** Biomass electricity generation technologies using direct combustion and gasification are included in the study, co-firing and combined heat and power technologies are excluded from the analysis but data is collected in the RRS model if in the future that is an option.

## 2.7 INTEGRATION

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

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

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

Biomass availability for this solution was provided from the integration with the Drawdown 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 sawn wood, other woody biomass, and herbaceous biomass (which includes crop residues). It determines the impact of demand reduction solutions including *clean cookstoves* and *recycled paper*, resulting in an adjusted demand projection through 2060. Biomass supply reductions are modeled as well, which result from protection of forests, reducing biomass availability. Biomass supply increases are modeled through the increased adoption of solutions

including *afforestation*, *bamboo*, *perennial biomass* and agroforestry solutions like *tree intercropping*, *silvopasture*, and *multistrata agroforestry*. Biomass availability from crop residues, *seaweed farming*, and dedicated biomass crops planted on cropland freed up by *sustainable intensification* is also modeled.

Surplus biomass is allocated to climate solutions that require biomass as feedstock. These include *biochar*, *biomass electricity*, *bioplastic*, *2<sup>nd</sup> 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.

## 2.8 LIMITATIONS / FURTHER DEVELOPMENTS

The first, and most prominent, limitation which is associated with biomass systems is the perception regarding their sustainability aspect. Since many a time these systems are run on locally available biomass, the feedstock is not always sustainably grown. This brings a bad name to the technology as a whole which gets branded as “unsustainable” as a whole. Cases are known where in order to keep the systems running, the local communities have even fallen back upon long-standing forests and mangroves (NRDC, 2018). As such, it becomes very important to ensure that the feedstock is sustainably grown and that it does not result in any deforestation or loss of floral/faunal species. To that extent, the definition of “perennial” biomass adopted by Project Drawdown is the way for future development.

The second limitation is in the nature of emissions which are produced as a result of the biomass conversion process. In direct combustion, the emissions are large and unless the feedstock and process is monitored and controlled, incomplete combustion would only add to GHG emissions and pollutants. For this, it is important to control both the feedstock and the process so as to ensure minimal emissions.

To overcome the problem of emissions, the technology is shifting from direct combustion to i) gasification and ii) anaerobic digestion. Both these developments are where the technology is headed and systems tailored to specific feedstock and ambient conditions need to be designed and employed in a far wider manner. More research and monitoring of these emissions is also necessary to ensure that emissions do not become a cause of setback for the technology.

Biomass systems offer great opportunities of working in hybrid systems in tandem with solar and wind energy systems especially in remote and isolated locations like islands which do not have grid power. When working in tandem with wind or solar systems, the biomass systems help overcome the limitations of variability and dispatchability which beset the solar and wind systems.

Of late, large portions of many countries like India and China have been facing severe air pollution problems due to indiscriminate burning of crop stubble. Though annual crops do not count as perennial biomass for

the purpose of Project Drawdown, there is a strong movement toward deploying biomass based technologies at scale to curb this critical problem. The resultant R&D effort towards modernization and upgradation of the associated technologies can only augur a bright future of all biomass systems which would help them overcome their drawbacks.

All in all, it needs to be stressed that biomass technologies have been punching much below their weight. The criticism of non-sustainability has prevented the adoption of the technology at rates equal to those at which other renewable technologies like wind and solar are being taken up. But once the emission issues and the source of feedstock can be taken care of, there is no reason why this technology will not move up to the front line of the renewable energy movement.

The RRS model for biomass electricity generation has a few limitations mainly from data perspective. In all the financial evaluations, it has been assumed that replacing existing feedstocks used with perennials especially herbaceous energy crops will not have any impact on efficiency, capacity or annual use of the plant. This assumption was made due to lack of data but if data becomes available could change some of the final results. Another assumption made for evaluating adoption data was based on average global value of electricity generation from waste as previously explained. Considering regional values will be more accurate.

### 3. RESULTS

In the following section selected results derived from the RRS model are depicted evaluating the impact of increased adoption of biomass technologies for electricity generation using perennial crops as compared to conventional technologies.

#### 3.1 ADOPTION

A comparison of the results from the three modeled scenarios to the Reference Scenario allows an estimation of the climate and financial impacts of increased adoption of biomass systems. As a result of this exercise, the Plausible Scenario (PDS1) projects 1.1 percent of total electricity generation worldwide coming from perennial biomass feedstock power systems by 2050. In the Drawdown (PDS2) and Optimum Scenarios (PDS3), the market share reaches 0.86 percent. Below in Table 3.1 are shown the adoptions of the solution in 2050 in functional units and percentage terms. Figure 3.1 depicts the long term pathway trajectories for the different scenarios of in-stream hydro plants.

*Table 3.1 World Adoption of the Solution*

Solution	Units	Base Year (2014)	World Adoption by 2050		
			Plausible	Drawdown	Optimum
Biomass (Perennial) electricity generation systems	<i>Electricity Generation (TWh)</i>	55	499	608	608
	<i>(% market)</i>	0.25%	1.09%	0.86%	0.86%

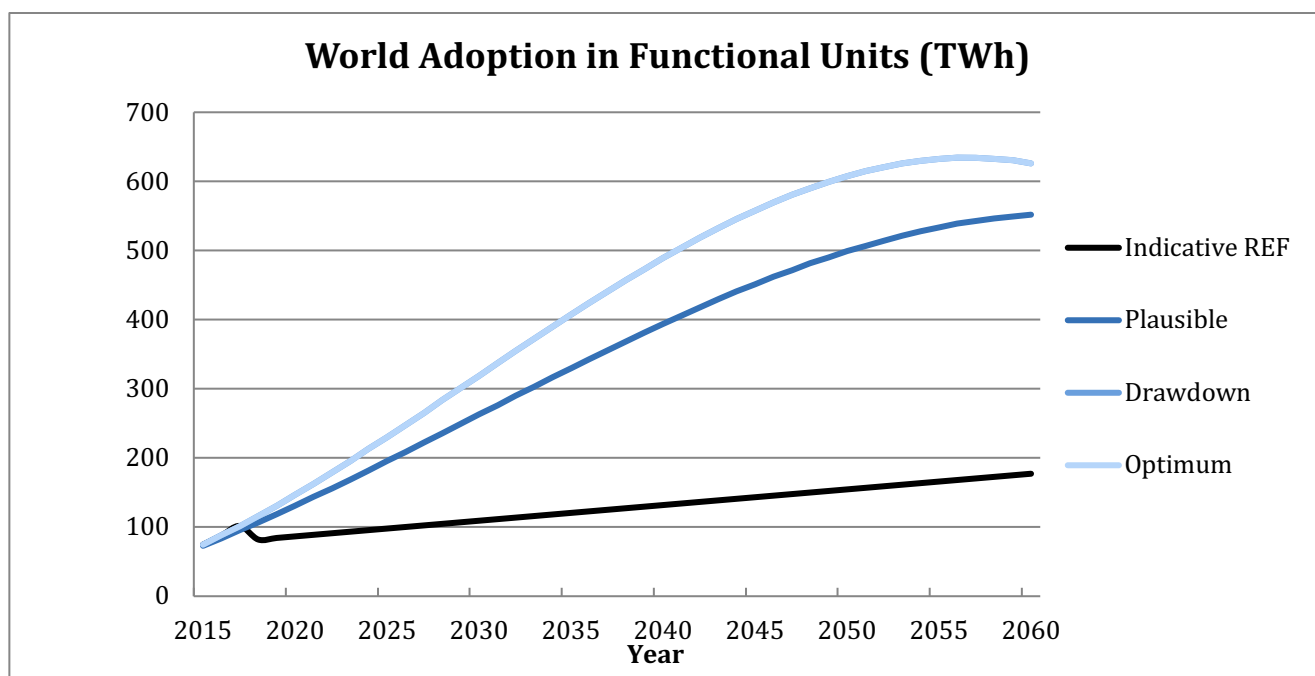


Figure 3.1 World Annual Adoption 2015-2060

### 3.2. CLIMATE IMPACTS

Below are the emissions results of the analysis for each scenario which include total emissions reduction and atmospheric concentration changes. For a detailed explanation of each result, please see the glossary (Section 6). The Plausible Scenario results in the avoidance of 2.69 gigatons of carbon dioxide-equivalent greenhouse gas emissions between 2020-2050. The Drawdown and Optimum Scenarios results in a higher growth of biomass power technologies, with impacts on greenhouse gas emissions reductions over 2020-2050 of 3.64 gigatons. Tables 3.2 and 3.3. provide additional information on the climate impacts of the solution adoption.

Table 3.2 Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Emissions Reduction in 2050
	(Gt CO <sub>2</sub> -eq/yr.)	Gt CO <sub>2</sub> -eq/yr. (2020-2050)	(Gt CO <sub>2</sub> -eq/year)
<i>Plausible</i>	0.14	2.69	0.14
<i>Drawdown</i>	0.18	3.64	0.18
<i>Optimum</i>	0.18	3.64	0.18

The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the models. This is due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined). After integration, the impact on emission reduction for this solution suffered minor changes with a total impact of 2.61 gigatons of carbon dioxide-equivalent avoided in the *Plausible* scenario, 3.58 gigatons of carbon dioxide-equivalent for the *Drawdown* Scenario and 3.57 gigatons of carbon dioxide-equivalent for the *Optimum* Scenario. Figure 3.2. show the world annual emissions reduction trajectories for the different scenarios for the long term.

Table 3.3 Impacts on Atmospheric Concentrations of CO<sub>2</sub>-eq

Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	PPM CO <sub>2</sub> -eq (2050)	PPM CO <sub>2</sub> -eq change from 2049-2050
<b>Plausible</b>	0.22	0.01
<b>Drawdown</b>	0.30	0.01
<b>Optimum</b>	0.30	0.01

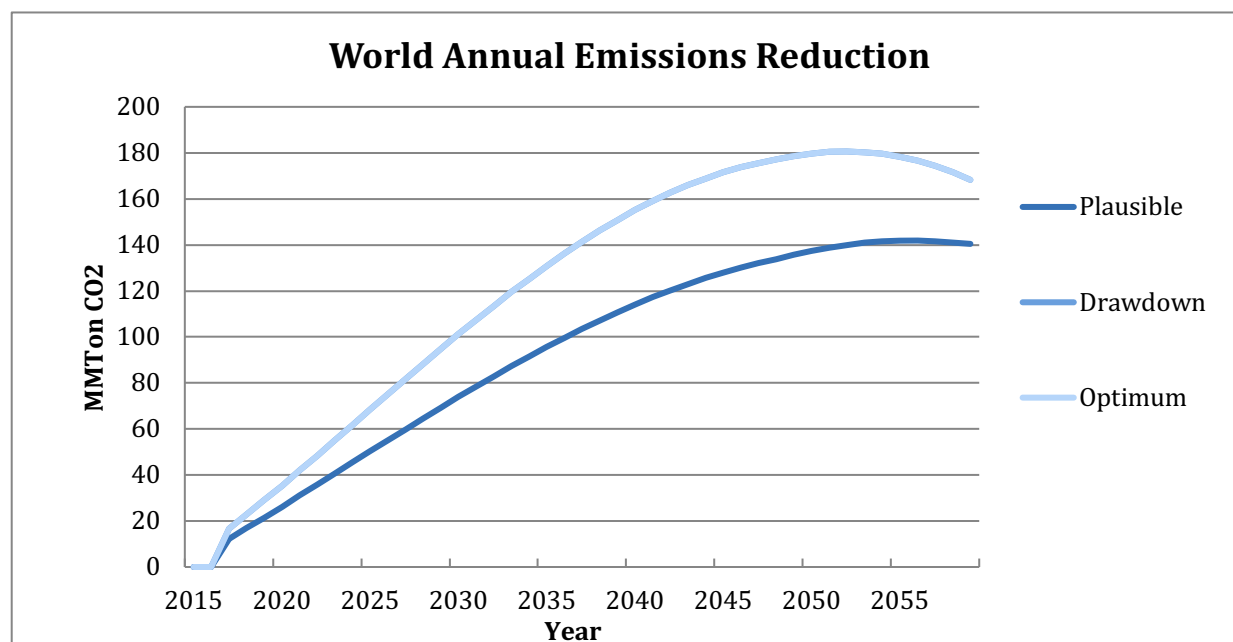


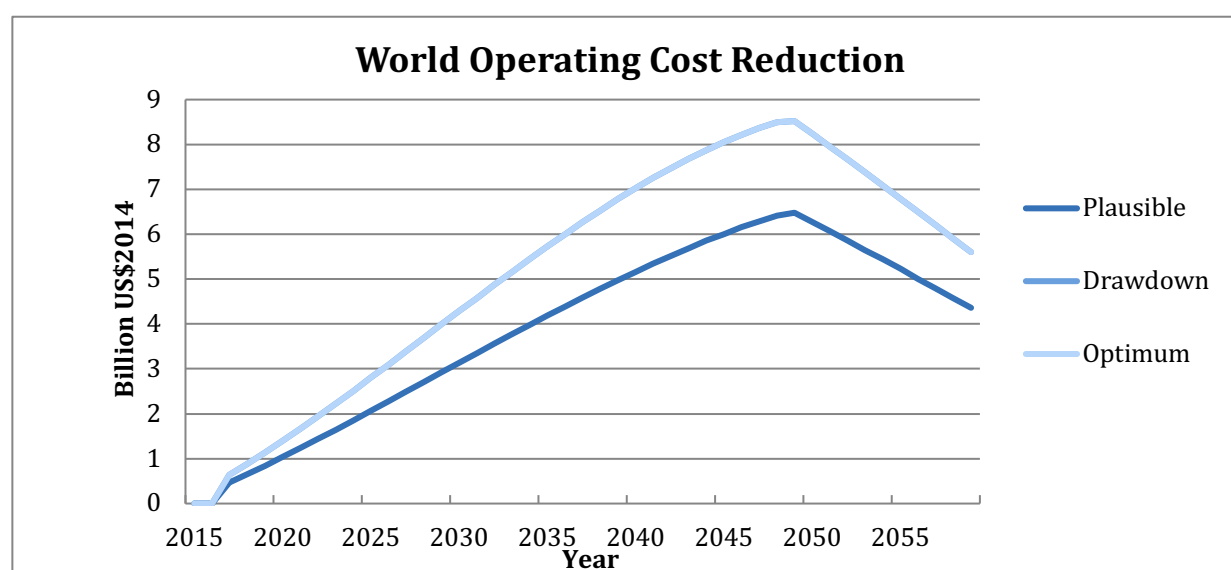
Figure 3.2 World Annual Greenhouse Gas Emissions Reduction (2015-2060)

### 3.3. FINANCIAL IMPACTS

The financial impacts incurred by replacing conventional grid electricity sources with biomass powered systems are significant. The Plausible scenario presents US\$58 billions of marginal first costs and over US\$119 billions of net operating cost savings are projected over 2020 to 2050. PDS2 and PDS3 present US\$68.5 billions of marginal first costs and US\$161.3 of net operating savings for the same period. Below in Table 3.4 and Figure 3.3. are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary (Section 6).

*Table 3.4 Financial Impacts*

Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Savings	Lifetime Cashflow Savings NPV (of All Implementation Units)
	2015-2050 Billion USD	2015-2050 Billion USD	2020-2050 Billion USD	Billion USD
<b>Plausible</b>	256.71	55.76	119.30	9.42
<b>Drawdown</b>	315.13	68.53	161.34	14.15
<b>Optimum</b>	315.13	68.53	161.34	14.15



*Figure 3.3 - World operating costs reduction (2015-2060)*



## 4 DISCUSSION

Overall the study provides a comprehensive look at perennial biomass based electricity generation as replacement for conventional technologies such as coal and natural gas. Based on the model results, biomass feedstock adoption from perennial crops for power generation might have a promising future. Keeping in mind the portfolio of other renewable energy technologies available, around 1% is still a significant portion of global electricity demand. While the carbon savings may not be big, the model was run without accounting for electricity generation technology with carbon capture and storage. There will be significant upfront investments required as demonstrated by marginal first cost of near \$300 to 500 billion, but with also high operation cost savings.

The adoption projections in terms of TWh are robust, having made use of fourteen different highly reliable data sources, with most also represent regional data. On the other hand, these projections do not provide further insight into the mix of generating technologies (co-firing versus dedicated biomass, pure electricity versus co-generation etc.) or fuels (wood pellets, agricultural residues, MSW, syngas, biogas, etc.). This is especially of interest when for all other parameters; every effort has been made to exclude co-firing technologies and cogeneration technologies from the current analysis. The capital costs of different generating technologies and the operating costs based on fuel can vary widely, making the financial projections somewhat ambiguous. Uncertainty in the financial projections also stems from the fact that perennial biomass market is at a very early stage and cost for biomass especially herbaceous is not well established. Furthermore, the financial inputs do not account for cost reductions as perennial biomass becomes more widespread and technology and efficiency improves. Further data on how generating technologies and the fuels to feed them may be adopted over time, as well as how costs may change, would greatly improve the accuracy of the financial projections.

Future adoption of carbon capture and storage (CCS) in biomass plants is left unconsidered in this study. The data used for biomass adoption included possible adoption scenarios for CCS that with a dynamic modeling approach could provide a more nuanced climate analysis. For CCS as well as other pre-commercial or niche technologies, more detailed cost estimates could further inform the financial analysis.

### 4.1 BENCHMARKS

Table 4.1 depicts a benchmark of Project Drawdown results for 2050 of the biomass electricity generation solution, on the three developed scenarios to other six publicly available scenarios from IEA (2016b) and Greenpeace (2015). Due to a lack of specific information on generation of electricity from “perennial” biomass crops, some historical factors and average trends have been used (Ref Para 2.6 – Assumptions) to

derive the share of the generation from perennials from the total biomass/generation. Some of the benchmarked results account for all biomass and waste power electricity generation projected for the year 2050 while others portray values estimated just for perennial crops.

*Table 4.1 Benchmarks*

Source and Scenario	Electricity Generation 2050 (TWh)	Market Share in 2050 (%)
<b>Project Drawdown – Plausible Scenario (PDS1)</b>	<b>498.9*</b>	<b>1.00%</b>
<b>Project Drawdown – Drawdown Scenario (PDS2)</b>	<b>607.6*</b>	<b>0.86%</b>
<b>Project Drawdown – Optimum Scenario (PDS3)</b>	<b>607.6*</b>	<b>0.86%</b>
IEA Energy Technologies Perspectives (2016) – 6DS	2,061 <sup>7</sup>	4.00%
IEA Energy Technologies Perspectives (2016) – 4DS	2,460 <sup>7</sup>	5.26%
IEA Energy Technologies Perspectives (2016) – 2DS	3,470 <sup>7</sup>	8.35%
Greenpeace Energy [R]evolution (2015) – Reference Scenario	1,577 <sup>7</sup>	3.15%
Greenpeace Energy [R]evolution (2015) – Energy Revolution Scenario	3,039 <sup>7</sup>	6.10%
Greenpeace Energy [R]evolution (2015) – Advanced Energy Revolution Scenario	3,193 <sup>7</sup>	4.73%
IEA, World Energy Outlook (2018), Current Policies	207.1*	0.38%
IEA, World Energy Outlook (2018), New Policies	268.1*	0.53%
IEA, World Energy Outlook (2018), Sustainable Development Scenario	404.4*	0.79%
IRENA (2018a), Roadmap-2050, Reference Case	172.6*	0.33%
IRENA (2018a), Roadmap-2050, REmap Case	249.0*	0.60%
Ram et al. (2017) 100% RE Scenario	270.6*	0.49%

<sup>7</sup> Accounts for total biomass and waste systems electricity generation.

\* Figures for electricity generation exclusively from perennial biomass

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## 5 GLOSSARY

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

**Approximate PPM Equivalent** – the reduction in the atmospheric concentration of CO<sub>2</sub> (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

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

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

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

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

**Discount Rate**- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis takes into account, not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the

higher the discount rate. Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

**Emissions Factor**– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO<sub>2</sub>e/kWh.

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

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

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

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

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

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

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

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

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

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

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

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

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

**Operating Costs** – the average cost to ensure the operation of an activity (conventional or solution) which is measured in 2014\$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve

the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

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

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

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

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

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

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

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

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

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

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