



# **Technical Summary of Bioenergy Carbon Capture and Storage (BECCS)**

**Report Prepared for the Carbon Sequestration Leadership Forum (CSLF)  
Technical Group**

**By the Bioenergy Carbon Capture and Storage (BECCS) Task Force**

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This report represents a review of the current status and potential for Bioenergy with Carbon Capture and Storage and does not necessarily represent the views of individual contributors or their respective employers.

## EXECUTIVE SUMMARY

At the Carbon Sequestration Leadership Forum (CSLF) Meeting held in London, United Kingdom in June 2016, the CSLF Technical Group formally moved forward with a task force to identify commercial status, technology options and pathways, resource assessments and emission profiles, as well as an economic analysis for Bioenergy Carbon Capture and Storage (BECCS). This effort supplements carbon capture and storage (CCS) technologies that have been the main focus of CSLF efforts since its inception in 2003.

The term BECCS refers to the concept of combining bioenergy applications (including all forms of power, heat, and fuel production) with CCS. BECCS projects have the potential to be negative emissions technologies (NETs) that can remove CO<sub>2</sub> emissions from the atmosphere by either stimulating natural carbon uptake and increasing terrestrial and aquatic carbon sinks or applying engineering approaches. One of the strengths of BECCS is that it can be applied to a wide range of technologies with varying amounts of CO<sub>2</sub> emissions, e.g., dedicated or co-firing of biomass in power plants, combined heat and power plants (CHPs), pulp and paper mills, lime kilns, ethanol plants, biogas refineries, and biomass gasification plants.

BECCS has the technical potential to mitigate up to 3.3 GtC per year. However, deployment of BECCS at the technical potential as a major climate mitigation solution will necessitate planting bioenergy crops on approximately 430-580 million hectares of land. This is approximately one-third of the arable land on the planet or about half of the U.S. land area. Clearing this amount of land for bioenergy crops will be associated with its own direct and indirect emissions as a result of: (1) land cover change, (2) loss of forests and native grasslands, (3) soil disturbance, and (4) increased use of fertilizer. Although the direct CO<sub>2</sub> emissions from biogenic feedstock conversion broadly correspond to the amount of atmospheric CO<sub>2</sub> sequestered through the growth cycle of bioenergy production, the extent of negative emissions will ultimately depend on the total life cycle emissions, which include emissions from the biomass supply chain, energy penalties, time horizon, etc.

Further areas of uncertainty exist in understanding whether biomass energy can serve as an important tool for mitigating carbon emissions. Research, experimentation, and modeling approaches have the potential to narrow some areas of uncertainty and provide the much-needed data to de-risk technological solutions. For biomass conversion and wide-scale deployment of bioenergy to reduce greenhouse gas (GHG) emissions or achieve negative emissions, the processes must be integrated with carbon capture, utilization and storage (CCUS). Today, there is limited practical and research experience of dedicated BECCS technologies at scales necessary for climate mitigation, but lessons learned from the deployment of CCUS technologies apply to BECCS as well. Currently, the majority of major BECCS projects are located at ethanol fermentation plants. And half of those projects use the CO<sub>2</sub> for enhanced oil recovery (EOR), highlighting the importance of CO<sub>2</sub>-EOR as a driver for commercializing BECCS and utilizing EOR as an early economic driver.

Along with the lack of commercial use, there are several barriers to large scale deployment of BECCS technologies. Some of these barriers arise from technical, economical, governmental, perception, land use, resource availability, and other developmental hurdles. To overcome these obstacles, there is an

urgent need for not only research and development, but financial mechanisms, incentives, government support, and policies to promote the benefits associated with BECCS.

To advance technical issues, there is a need for establishing research programs exploring BECCS concepts. These research programs should focus on outlining a way to achieve the commercial deployment of BECCS for each industrial application and at various scales. These programs should include:

- Evaluating the impact of CO<sub>2</sub> capture on plant operations and competitiveness: The capture of CO<sub>2</sub> from ethanol plants is less energy intensive than capturing CO<sub>2</sub> from cement or pulp/paper mill flue gases. Systematic evaluation of the impacts on production cost, operational costs is needed for all BECCS approaches.
- Studying the impact of gas stream impurities on CO<sub>2</sub> capture technologies that were developed for the power generation industries: The types and composition of impurities in gas streams from biomass co-firing, ethanol, biomass-to-liquids plants, cement, and waste incineration plants is different from those encountered in gas streams in power plants. For instance, waste incineration plant flue gas may require pretreatment to remove chlorine, dioxins, and other compounds before the CO<sub>2</sub> separation step.
- Exploring novel means to recover waste heat from industrial processes and integrate this with the CO<sub>2</sub> capture and compression step: Part of the steam required for CO<sub>2</sub> capture from paper and pulp and cement gas streams can be recovered from flue gas waste heat. Studies on the heat/process integration between the CO<sub>2</sub> capture process and the production plant are needed to gauge what level would be most optimal.
- Exploring the diverse incentives and opportunities that drive the adoption of BECCS: With the exception of pulp and paper, most other processes (co-firing, liquefaction, ethanol, cement, waste to energy) are driven by incentives and regulations such as renewable energy portfolio standards, industry GHG standards, high waste disposal fees, and production and/or investment tax credits. These factors determine the economic feasibility of the capturing and storing of biomass-derived CO<sub>2</sub>.

Recommendations developed by the BECCS Task Force include:

- Inform policymakers with respect to the benefits of BECCS market opportunities, opportunities for EOR and negative carbon emissions.
- Develop a common framework for lifecycle assessment to facilitate accurate accounting of BECCS carbon footprint.
- Perform research to develop and identify biomass feedstocks that require limited processing.
- Perform continued research to develop and identify new capture technologies that will have a substantially lower capital and energy cost affecting the cost of electricity.
- Develop regional organizations to track and monitor feedstock availability to insure sufficient quantities can be provided for continuous power generation.
- Incentivising the double benefit of BECCS can help avoid direct investment competition with other abatement options. Concerted efforts, e.g., global forest protection policies, carbon stock

incentives, and bioenergy/renewable energy incentives, are necessary to avoid undesirable land use change (LUC) emissions.

- Early BECCS projects should aim to use mainly “additional” biomass and 2<sup>nd</sup> generation biofuel crops to avoid adverse impacts on land use and food production. However, additional biomass may be costlier or have other adverse impacts.
- BECCS options that optimize water use and carbon footprint need to be identified through careful selection of crops, location, cultivation methods, pre-treatment processes, and biomass conversion technologies. Sustainable biomass feedstocks will require avoidance of unsustainable harvesting practices, e.g., exceeding natural replenishment rates. Using “additional biomass” to avoid sustainability issues also helps improve public acceptance.
- Sustainability needs to be ensured across the whole BECCS chain. Improving pre-treatment processes for biomass (i.e., densification, dehydration, and pelletisation) will make biomass transport more efficient and remove geographical limitations of biomass supply.
- BECCS project developers and advocates should focus more on building up trust with the general public and local communities, instead of just providing educational information.
- Stronger collaboration and exchange of ideas between stakeholders of the CCUS, bioenergy, and BECCS industries would also be beneficial and are recommended.

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# 1 Introduction

## 1.1 CSLF Purpose

The CSLF is a Ministerial-level international climate change initiative that is focused on the development of improved cost-effective technologies for the separation and capture of CO<sub>2</sub> for its transport and long-term safe storage. The mission of the CSLF is to facilitate the development and deployment of such technologies via collaborative efforts that address key technical, economic, and environmental obstacles. The CSLF also promotes awareness and champion legal, regulatory, financial, and institutional environments conducive to such technologies.

The CSLF comprises a Policy Group and a Technical Group. The Policy Group governs the overall framework and policies of the CSLF and focuses mainly on policy, legal, regulatory, financial, economic, and capacity building issues. The Technical Group reports to the Policy Group and focuses on technical issues related to CCUS and CCUS projects in member countries.

The Technical Group has the mandate to identify key technical, economic, environmental, and other issues related to improving technological capacity and establishing and regularly assessing potential research and technology gaps.

At the CSLF Meeting held in London, United Kingdom in June 2016, the CSLF Technical Group formally moved forward with a task force to identify commercial status, technology options and pathways, resource assessments and emission profiles, as well as an economic analysis for BECCS. This effort supplements CCUS technologies that have been the main focus of CSLF efforts since its inception in 2003.

## 1.2 Task Force Mandate

The United States proposed to serve as chairperson and lead a Technical Group Task Force that is focused on identifying the commercial status, technology options and pathways, resource assessments and emission profiles, as well as an economic analysis for BECCS. The Task Force will develop a report that will:

- Identify the existing projects, government programs, market drivers for BECCS deployments, barriers to large-scale BECCS demonstration and deployment, and opportunities and recommendations for overcoming barriers progress;
- Provide an overview of BECCS technology options and pathways: (power; fuels and chemicals production; industrial sources; summary of technical challenges and R&D opportunities);
- Summarize resource assessments and emissions profiles: existing reports and analyses; biomass and carbon storage resource assessments; direct and indirect GHG emissions; summary of life cycle assessments; identification of gaps in analyses and future opportunities;
- Summarize economic analyses for BECCS concepts;
- Include findings and recommendations for consideration by CSLF and its member countries.



### 1.3 Overview of BECCS and Bio-CCS

The terms BECCS and Bio-CCS both refer to the concept of combining bioenergy applications with CCS. CCS describes processes that separate a relatively pure stream of CO<sub>2</sub> from industrial or power plants and store the conditioned and compressed gas in suitable geological formations (IPCC, 2005).

Throughout the published literature, terminology and definition of BECCS and Bio-CCS are not entirely consistent, and both are used alternatively. Definitions of Bio-CCS can be as simple as “[...] CCS, in which the feedstock is biomass (IPCC, 2005) or as comprehensive as “[...] processes in which CO<sub>2</sub> originating from biomass is captured and stored. These can be energy production processes or any other industrial processes with CO<sub>2</sub>-rich process streams originating from biomass feedstocks. The CO<sub>2</sub> is separated from these processes with technologies generally associated with CCS for fossil fuels. Biomass binds carbon from the atmosphere as it grows; but with the conversion of the biomass, this carbon is again released as CO<sub>2</sub>. If, instead, it is captured, transported to a storage site and permanently stored deep underground, this would result in a net removal of CO<sub>2</sub> from the atmosphere” (ZEP and EMTP, 2012). Figure 1 shows the general concept of coupling bioenergy with CCS.

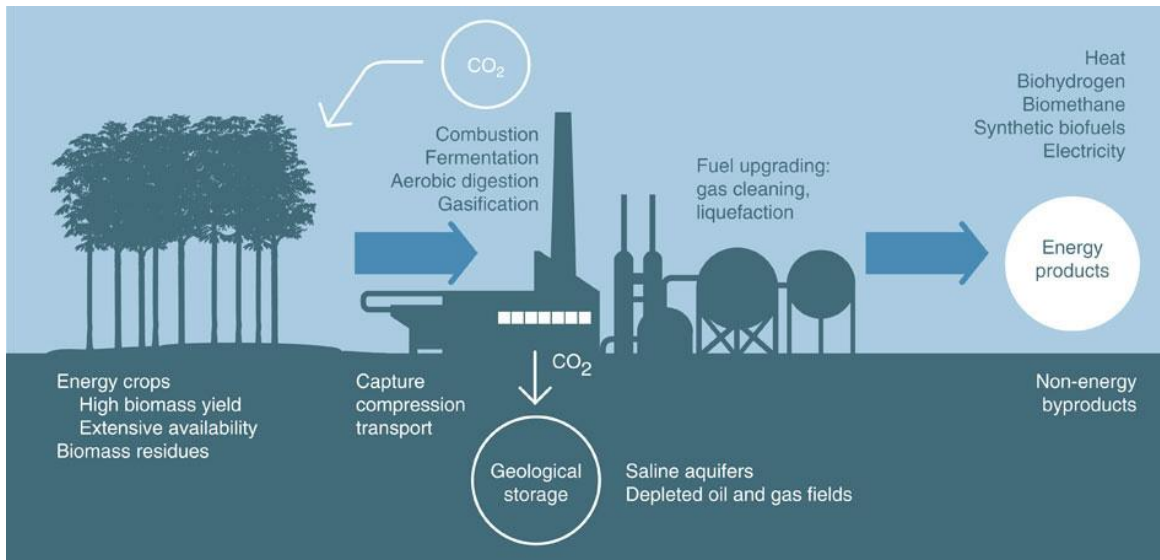


Figure 1: Concept of Bio-CCS (Canadell & Schulze, 2014)

Although some references use BECCS in the broad sense as an application of CCUS to bioenergy conversion processes (IPCC, 2014), some use it to refer to the process of biomass combustion for energy with subsequent CCUS only, especially in the power sector. Bio-CCS, on the other hand, appears generally in a wider context of sequestration, i.e., includes using the captured biogenic CO<sub>2</sub> as a feedstock to produce algae, plastics, transport fuels, animal feed, or other materials/chemicals (Gough & Upham, 2010). Thus, Bio-CCS usually has a broader definition that includes BECCS technologies if these are defined to cover only biomass combustion processes. This report will be using the term BECCS, assuming it includes all forms of power, heat, and fuel production.

BECCS projects have the potential to be negative emissions technologies (NETs) that can remove CO<sub>2</sub> emissions from the atmosphere by either stimulating natural carbon uptake and increasing terrestrial

and aquatic carbon sinks or applying engineering approaches. The portfolio of proposed NETs often includes land and ocean-based CO<sub>2</sub> mineral sequestration (mineral carbonation), large-scale afforestation, soil carbon sequestration, direct air capture and storage (DACs), BECCS, and the more speculative approach of iron fertilization of the oceans to promote biomass growth (Williamson, 2016). As a NET, BECCS can lead to a net removal of CO<sub>2</sub> from the atmosphere (IEA, 2011; IEAGHG, 2011). Like the terms BECCS and Bio-CCS, the definition of NETs is not clear at times due to partially overlapping definitions, e.g., with mitigation. Although the direct CO<sub>2</sub> emissions from biogenic feedstock conversion broadly correspond to the amount of atmospheric CO<sub>2</sub> sequestered through the growth cycle of bioenergy production, the extent of negative emissions will ultimately depend on the total life cycle emissions, which include emissions from the biomass supply chain, energy penalties, time horizon, etc.

#### 1.4 Challenges and Benefits of BECCS

BECCS is one of the few technologies that have the potential to enable the world to limit warming to 2°C or below by 2100 (Azar, Lindgren, Larson, & Möllersten, 2006; van Vliet, den Elzen, & van Vuuren, 2009; Krey, Luderer, Clarke, & Kriegler, 2014; Kriegler, et al., 2014; IPCC, 2014; Tavoni & Socolow, 2013). One of the strengths of BECCS is that it can be applied to a wide range of technologies with varying amounts of CO<sub>2</sub> emissions, e.g., dedicated or co-firing of biomass in power plants, combined heat and power plants (CHPs), pulp and paper mills, lime kilns, ethanol plants, biogas refineries and biomass gasification plants (Karlsson & Byström, 2011). BECCS also provides a technology pathway for countries to surpass the target emission reduction values in the near-term within the mitigation scenarios (IPCC, 2014). In addition, BECCS can provide a buffer to tackle emissions in sectors where reductions are harder to achieve due to economic, political, or technical constraints (e.g., aviation, shipping, iron and steel making, etc.).

As a technological solution, deploying BECCS will be essential to address broader issues related to both CCUS and bioenergy. Several studies have already addressed the technical and economic challenges of CCUS technologies (e.g. Gibbins & Chalmers, 2008; Pires, Martins, Alvim-Ferraz, & Simoes, 2011; Nykvist, 2013; Boot-Handford, et al., 2014; Leung, Caramanna, & Maroto-Valer, 2014). When considering the application of BECCS in bioenergy, sustainability at scale and engineering challenges for large-scale biomass conversion remain knowledge and R&D gaps.

## 2 Summary of Resource Assessments and Emissions Profiles

### 2.1 Biomass and Carbon Storage Resource Assessments

#### 2.1.1 Biomass

Biomass is any organic matter that can be renewable and available as a feedstock for bioenergy, which can come from agricultural crops, forestry products, municipal and other waste (WBDG, 2016), and microalgae and bacteria. Primary bioenergy uses farmland or forests to produce biomass and the other biomass can come from residue generated as a by-product of food or wood production throughout the supply-consumption chain (IRENA, 2014). Biomass accounts for 10% of global primary energy used for heat and electricity (IEA, 2017) and is also utilized for industrial processes (for example, the production of chemicals and pharmaceutical products) and to make transportation fuels. The United States leads

the world in biomass-generated electricity, followed by Germany, China, and Brazil (NEB, 2017). Biomass resource assessment includes the technically available, economically recoverable, and sustainable potential for biomass resources and their projected change over time. Today, an upper estimated 1.2 billion hectares (ha) of surplus land is available for bioenergy crop production (FAO, 2014; IRENA, 2014), approximated by subtracting land demand for non-energy uses from potentially available, but without considering sustainability or economic feasibility factors. Estimates of bioenergy land availability are sensitive to key variables, such as agricultural productivity and demand and population growth. Low estimates (approximately 1/3 of the current energy supply) of global biomass supply to drive bioenergy deployment assume that there is limited land available for bioenergy crops and the limitation are driven by high demand for food, but little expansion of agriculture into forested landscapes and limits to productivity increases (Lewis & Kelly, 2014). Midrange estimates (approximately half of the current global primary energy supply) assume that agricultural productivity can keep pace with population growth and high estimates (more than current global primary energy supply) assume that agricultural yields outpace demand for food and that land mass the size of China becomes available for bioenergy crop production (Slade, Saunders, Gross, & Bauen, 2011).

Sustainability indicators for biomass energy vary, but the Global Bioenergy Partnership (GBEP) inter-governmental initiative of 50 national governments and 26 international organizations was established to implement uniform sustainability indicators and, as of 2015, has been implemented in six countries. The goal of GBEP is to support national and regional bioenergy policy-making and market development within a sustainability framework and facilitate bioenergy integration into energy markets by addressing the market barriers within countries and across regions. These goals rely on robust methodologies to address the policy and market impacts of deploying bioenergy widely and include life cycle assessments for GHG emissions from bioenergy production. Life cycle assessments address which GHGs are included, the sources of biomass, land use changes due to bioenergy production, biomass feedstock production, transport of biomass, processing into fuel, by-products and co-products, transport of fuel, fuel use, and comparison of the GHG associated with those steps with replaced fuels.

Along with GHG assessments, bioenergy sustainability also includes impacts on soil quality, biomass quality, harvest levels, water use and efficiency, water quality, and impacts on biological diversity in the landscape where bioenergy production is proposed. There are also social impacts to consider, including allocation of land for bioenergy crops, the impacts on the price and supply of other commodities (with larger impacts in developing nations), jobs in the bioenergy sector, and associated changes in the work force. Bioenergy crops and agricultural resources are often produced using the same land resources and as bioenergy demand increases, competition for land and market dynamics are expected to put those sectors at odds with each other. In countries with insufficient resource bases to cover both demands for bioenergy and food production, food production is expected to be prioritized (IRENA 2014). The benefits of shifting to bioenergy in developing countries include adding value to traditional use of biomass for energy, diversifying the energy landscape, building capacity and flexibility, and training the workforce (GBEP, 2011).

### 2.1.2 Carbon Dioxide Utilization and Storage

For biomass conversion and wide-scale deployment of bioenergy to reduce GHG emissions or achieve negative emissions, the processes must be integrated with CCUS (IEAGHG, 2014). Carbon sequestration can be used to describe both natural and technology-driven processes to remove CO<sub>2</sub> from the atmosphere or divert CO<sub>2</sub> emissions to long-term storage sites in the ocean, in soils or sediments, or in geologic formations. Because the natural CO<sub>2</sub> uptake mechanisms are insufficient to offset the pace of emissions from human activities, there is a need to enhance natural and deliberate uptake mechanisms and utilize long-term CO<sub>2</sub> storage. To reach the less than 2°C goal set forth by the Intergovernmental Panel on Climate Change (IPCC) and agreed upon at COP21, global annual CO<sub>2</sub> emissions must be reduced from the current level of ~54 Gt CO<sub>2</sub>-eq/year to approximately 42 Gt CO<sub>2</sub>-eq/year by 2030 and 22 Gt CO<sub>2</sub>-eq/year by 2050 (Rogelj et al., 2016), while global population and energy use continue to grow. Carbon removal and storage will be a critical component for achieving these ambitious carbon emission reduction targets.

Terrestrial carbon sequestration includes afforestation, wildfire and disease outbreak suppression, soil conservation, and enhanced weathering. The world's forests present one potential carbon sink estimated to be 2.4GtC/year (Pan, et al., 2011; Ni, Eskeland, Giske, & Hansen, 2016) which would require a combination of planting and replanting programs and drastically reducing global deforestation rates. The wood (biomass is 50% carbon) can be collected and combusted with CCUS (BECCS) or stored in bulk storage facilities or utilized in long-lasting applications (Scholz & Hasse, 2008). The scale of potential in carbon storage varies geographically (Kraxner, Nilsson, & Obersteiner, 2003), but tropical regions have the highest potential for storing carbon in forests (Ni, Eskeland, Giske, & Hansen, 2016) and though boreal peatlands hold vast amounts of carbon, they are rapidly warming, accelerating the release of that stored carbon back into the atmosphere. Thus, land management practices and the potential to disrupt other present-day activities like agriculture and urban development play critical roles in the capacity of terrestrial carbon sequestration to offset carbon emissions.

Oceanic natural carbon uptake is currently net 2 GtC/year (Solomon, et al., 2007) but the potential to enhance natural uptake in the oceans is limited because the oceans become more acidic as more CO<sub>2</sub> reacts with sea water, with negative effects on marine organisms that form carbonate skeletons and shells (Orr, et al., 2005, Hofmann et al., 2010). Overcoming the issues of ocean acidification is possible but would require increasing alkalinity to enhance ocean-based mineral carbonation. Though technically feasible using a variety of engineering approaches, the potential cost and unintended consequences cannot be ignored (Ravel, et al., 2005).

Geologic carbon sequestration holds the potential to store vast amounts of CO<sub>2</sub>. When CO<sub>2</sub> is captured from a point source, such as a power plant or industrial facility, it is piped and injected 1-4km below the land surface into porous rock formations, where it can remain for millions of years. The capacity for geologic storage varies geographically and is constrained by the volume and distribution of storage sites. For example, CO<sub>2</sub> can be stored in depleted oil and gas reservoirs, unmineable coal beds, and saline aquifers. In the U.S. alone, between 900-3400 GtC can be stored in deep geologic reservoirs (NETL, 2015), orders of magnitude more storage than could be produced from burning our fossil energy resources.

## 2.2 Direct GHG emissions

Greenhouse gases (GHGs) include CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, and halocarbons (organic compounds that contain chlorine, bromine, or fluorine) – these gases are emitted from human activities directly or indirectly (IPCC, 2007). Direct emissions are emissions that can be attributed to a point source in a sector, technology, or activity (for example, emissions from a coal-fired power plant). Indirect emissions are attributed to an end-use sector (for example, emissions from growing bioenergy crops for BECCS).

In December 2016, the average CO<sub>2</sub> concentration in the atmosphere was 404.48 ppm, a dramatic increase relative to the pre-industrial level of 280ppm (ESRL, 2017). The energy sector contributed 68% of the global anthropogenic GHGs and fossil energy resources accounted for 82% of the global total primary energy supply in 2014. CO<sub>2</sub> emissions from energy supply came from two sectors: electricity and heat generation. Transportation and industry accounted for an additional 42% of CO<sub>2</sub> emissions in 2014 (IPCC). The six largest emitting countries/regions in 2015 were China (29%), the United States (14%), the EU (10%), India (7%), the Russian Federation (5%), and Japan (3.5%) (ESRL, 2017).

Global GHG emissions in 2010 were estimated to be 48 Gt CO<sub>2</sub>-eq/year and are expected to reach approximately 65 Gt CO<sub>2</sub>-eq/year if no climate policies are enacted (Rogelj, et al., 2016). Reaching global emissions targets set forth during COP21 will require bringing annual global emissions below 20 Gt CO<sub>2</sub>-eq/year and mitigating upwards of 600 Gt of CO<sub>2</sub> over the 20<sup>th</sup> century. This level of emission reductions may necessitate wide deployment of NETs like BECCS, which can be applied to reduce emissions from electricity and heat generation as well as some industrial processes, largely those where combustion of fossil fuels such as coal and natural gas can be replaced with biomass and CO<sub>2</sub> can be captured at the stack.

BECCS has the potential to mitigate up to 3.3 GtC per year (Smith, et al., 2016). However, deployment of BECCS as a climate mitigation solution will necessitate planting bioenergy crops on approximately 430-580 million hectares of land (approximately one-third of the arable land on the planet or about half of the U.S. land area (Williamson, 2016)). Clearing this amount of land for bioenergy crops will be associated with its own direct and indirect emissions as a result of (1) land cover change, (2) loss of forests and native grasslands, (3) soil disturbance, and (4) increased use of fertilizer. When these emissions are considered, BECCS is estimated to be able to remove 391 Gt of CO<sub>2</sub> by the end of the century (IPCC RCP2.6 scenario) if bioenergy crops are planted on abandoned land only (Williamson, 2016). But if large forested areas are converted to bioenergy croplands, the result will be a net release of 135 Gt of CO<sub>2</sub> by 2100 (Williamson, 2016). If BECCS is deployed alongside with other NETs or if alternative feedstocks (such as ocean biofuels and algae) are utilized in place of bioenergy crops, the impacts associated with land use may be much lower, although the effects of wide scale harvesting of these resources is uncertain at this point (IEAGHG, 2011).

Over and above uncertainty about the size and direction of emission reductions associated with BECCS, there are gaps in our understanding of how bioenergy crops will respond to future climate conditions, including the increased climate variability, coupled with increased water scarcity. Droughts, fires, and pests are all expected to become bigger problems in the 2<sup>nd</sup> half of the 20<sup>th</sup> century (IPCC, 2014) and these will directly and indirectly impact bioenergy crops.

### 2.3 Indirect GHG emissions

Indirect emissions are attributed to an end-use sector (for example, emissions from the generation of purchased electricity, heat or steam, production of purchased materials and fuels, transport-related activities in vehicles not owned or controlled by the reporting entity, outsourced activities, waste disposal, among others).

Indirect emissions associated with BECCS can come from land use change, soil disturbance, and emissions from processes associated with growing bioenergy crops and these indirect emissions can be estimated using Life Cycle Assessments (LCAs, next section). Despite their wide use, LCA results can vary substantially based on the sources of data, the scope of the analyses, and the required assumptions. LCA analyses often lack real-world data because there are so few projects in operation today. Within the LCA analysis framework, bioenergy crops and fuels should be evaluated based on their specific carbon emissions criteria, both direct and indirect. This context of accounting for both direct and indirect emissions is necessary to label a particular technology or process as carbon neutral or negative and may be the simplest and most transparent means of setting standards for sustainability and responsible production.

### 2.4 Summary of Life Cycle Assessments

#### Life Cycle Assessment Methods:

Life cycle assessment methods (LCAs) have been developed to complete a mass balance and to identify and evaluate risks of unintended consequences such as leakage. LCAs may be attributional (dominated by process chain analysis) - seeking to establish burdens associated with the existing production and use of a product, or with a specific service or process at a point in time. LCAs may also be consequential (utilizing input/output methods) - seeking to identify the consequences of a pending decision or a proposed change in a system. All assessments, regardless of scope, face data constraints.

In general, CCUS technologies, including BECCS, have the potential to reduce life cycle emissions (Singh, et al., 2012, Schakel, et al., 2014). Life cycle emissions of BECCS can vary depending on type of biomass feedstock, geographic region covered in the study, time frame, scale, and biomass production methods. The scope of the analysis can include construction, resource extraction or production, operation, post-project dismantling, upstream and downstream waste disposal for all components and capture-specific upstream and downstream processes, fuel (for combustion processes), and resultant GHG emissions. The definition of the boundaries in life cycle emission analyses strongly influence the final reported emissions. For LCAs to be useful, boundaries must be clear and justifiable.

Biomass feedstock options with low life cycle emissions have already been identified and include, e.g., sugarcane, miscanthus, short rotation coppices (SRC), fast-growing tree residues (residues can include agricultural and wood residues) and wastes (biogenic wastes that are not cultivated, including manure, organic waste, and sludge) (Clarke, et al., 2014, Smith, et al., 2014). Emissions reductions are also possible for options that have been perceived as less sustainable in the past, like corn ethanol. Measures include improvement in ethanol production technologies, increase in corn yields and advances in corn production methods. Innovations in the farming sector can directly result in a decrease in indirect land use change (iLUC) and related emissions (Flugge, et al., 2017). The majority of

emissions can also come from land use change (LUC) and fossil fuel use for biomass production and pre-treatment (IPCC, 2014), so these areas provide ample opportunity for improvement.

Key areas of uncertainty in both attributional and consequential analyses include dealing with indirect versus direct emissions and their impacts on policies, regulations, and carbon crediting systems. Some analyses seek to allow these measures to be flexible – ostensibly to identify optimal strategies - while others treat them as fixed and report on the consequences. The following subsections will provide examples of recent approaches to deal with indirect versus direct emissions and highlight the confusion that can arise when the treatment of these two key uncertainties is not explicit.

The International Organization for Standardization (ISO) has published a series of consensus standards that are focused on principles and practices for LCAs.<sup>1</sup> ISO standards are presented as guidelines and collections of best practices and refer to four components (BSI, 2011; WRI, 2011):<sup>2</sup>

- Goal definition and scoping: Define and describe the product, process, or activity being studied. Establish the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment.
- Inventory analysis: Identify and quantify energy, water, and materials usage and environmental releases (e.g., air emissions, solid waste disposal, waste water discharges).
- Impact assessment: Assess the potential human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis.
- Interpretation: Evaluate the results of the inventory analysis and impact assessment to select the preferred product, process, or service with a clear understanding of the uncertainty and the assumptions used to generate the results.

These four ISO components are not highly restrictive, and boundaries can be drawn narrowly to focus the analysis close to an individual location or broadly, as is often the case for GHG mitigation analyses.

LCA analyses often suffer from uncertainties associated with incomplete data or knowledge of inputs and outputs (IEAGHG, 2014). When used properly and described clearly, LCAs can provide valuable data for use in Integrated Assessment Models. However, many aspects of LCA practice and methodology are overlooked or misunderstood (Curran, 2013). These include:

- Goal setting and definition of the functional unit;
- Allocating environmental burdens across co-products from a process;
- Giving credit for avoided burden;

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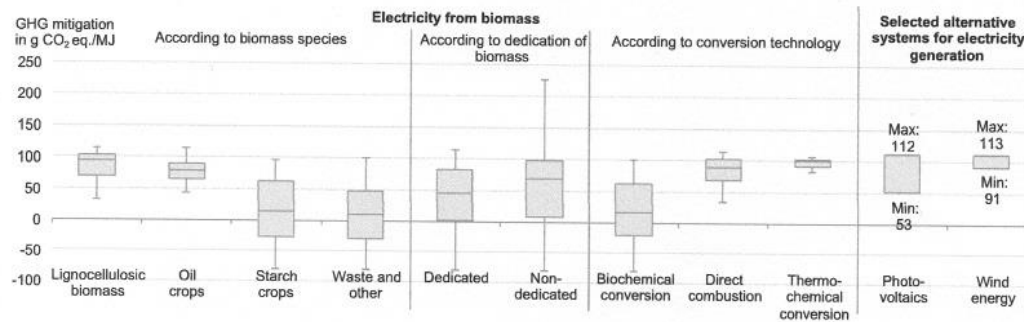
<sup>1</sup> Principles and procedures that can be applied to perform life cycle assessments (LCA) are part of the [ISO 14000](#) environmental management standards: in ISO 14040:2006 and 14044:2006. Additional standards are available which clarify the procedures or that serve as examples for specific industries.

<sup>2</sup> International Standards Organization. 1997: Environmental Management - Life Cycle Assessment - Principles and Framework ISO 14040; International Standards Organization. 1998. Life Cycle Assessment - Impact Assessment ISO 14042; and International Standards Organization. 1998b. Environmental Management - Life Cycle Assessment - Life Cycle Interpretation ISO 14043.

- Understanding the difference between attributional and consequential LCAs;
- Availability of inventory data and transparency of that data;
- Assessing data uncertainty;
- Differentiating life cycle risk assessment and other risk assessment;
- Reporting qualitative as well as quantitative data (but identifying each as what it is);
- Acknowledging that LCA may not define the "best" option; and,
- Recognizing LCAs are iterative in nature and may be better used as a comparative tool.

Studies assessing the life cycle emissions:

LCA results can indicate the amount of CO<sub>2</sub> that is avoided using biomass and the additional reduction that arises when the emitted CO<sub>2</sub> is captured. They can also show that not all sources of biomass yield similar GHG benefits when CCUS is added. A paper by Muench (2015) compares the mitigation potential for various biomass fuels by species and purpose (waste versus dedicated crop) when these are utilized for power and for transportation. The comparative results are shown in Figure 2 below.



**Figure 2: Global Warming Mitigation Potential of Biomass Electricity (Muench, 2015)**

Not all sources of biomass or conversion technology are carbon neutral. Similarly, adding CCUS will result in different overall negative emissions.

Comparing various combustion options, including co-firing and dedicated biomass combustion, the net life cycle CO<sub>2</sub> emissions appear to depend on biomass type and the combustion method (Weisser, 2007; Odeh & Cockrell, 2007; Cai, et al., 2014; Schakel, et al., 2014). The net life cycle CO<sub>2</sub> emissions also depend on the data, LCA methodology, and analysis assumptions, and in many cases, the data and assumptions are inaccurate or out of date (Schakel, et al., 2014).



**Table 1: Life-cycle CO<sub>2</sub> emissions comparing combustion technology and biomass content (See Schakel, Meerman, Talaei, Ramirezrez, & Faaij, 2014 for Study references)**

Study (citation number)	Technology	Biomass Type	Co-firing Ratio (%)	Capacity (MW)	Life-cycle CO <sub>2</sub> emissions (g/kWh)	Net Life-cycle CO <sub>2</sub> emissions (g/kWh)
Spath and Mann (1)	Co-firing	Urban waste – energy crops	15	600	270	43
Corti & Lombardi (2)	BIGCC <sup>(a)</sup>	Poplar	100	205	70-130	-410
Carpentieri et al. (3)	BIGCC <sup>(a)</sup>	Poplar	100	191	227	-594
NETL (4)	IGCC <sup>(b)</sup>	Switch grass	30 (weight)	451-654	Not reported	-6 to -105
NETL (5)	Super-critical coal co-firing plant	Hybrid poplar	30	550	Not reported	38
Cuellar (6)	Coal co-firing plant	Forest residues	20	141.5	Not reported	-129.5
Schakel (7)	PC <sup>(c)</sup>	Wood pellets/straw pellets (residue)	30	550	281-291	-67 to -72
Schakel (7)	IGCC <sup>(b)</sup>	Wood pellets/straw pellets (residue)	30	550	253-262	-81 to -85
(a) Biomass gasification combined cycle; (b) Integrated gasification combined cycle; (c) pulverized coal-fired						

## 2.5 Identify Gaps in Analyses and Future Opportunities

Key areas of uncertainty exist in understanding whether biomass energy can serve as an important tool for mitigating carbon emissions. Research, experimentation, and modeling approaches have the potential to narrow some areas of uncertainty and provide the much-needed data to de-risk technological solutions. When considering the potential for bioenergy from forestry, global land cover datasets provide an important starting point - differences in estimates of land cover among global datasets can be upwards of 35% (Thomson, et al., 2010), a key piece of uncertainty that limits the ability to accurately model BECCS potential globally. Planting trees for energy generation or carbon sequestration must not endanger food security (DeFries and Rosenzweig, 2010; Smith, et al., 2013) and put further restraints on the potential for afforestation and bioenergy. Many least costly options for enhancing carbon sequestration in forestry projects are in Africa, South America, and Asia; but these are contingent upon risk profiles and within-country volatility (Benitez & Obersteiner, 2006). Although afforestation can cost less than deployment of BECCS technologies, both afforestation and BECCS options offer promise for effective mitigation options (Humpenöder, et al., 2014). The relative merits of each vary with policy choices and the length of time that these CO<sub>2</sub> mitigation approaches are pursued. The standalone and combined mitigation potential of afforestation and BECCS depends on trade-offs like competition for land or path dependencies constrained by earth system responses and cumulative emission budgets, bioenergy potential, CCUS capability, and significant political and socio-economic

factors. Variations in the potential of biomass energy to mitigate carbon emissions rely on land area availability relative to food production along with forestry practices, and thus constitute a key uncertainty, especially when combined with changing water resources, direct and indirect land use change, biodiversity, social acceptability and policy frameworks (Azar, et al., 2010; Bonsch, et al., 2014; van Vuuren and Riahi, 2011). Today, CCUS technology is in the demonstration phase and uncertainty is diminishing. There is limited practical and research experience of dedicated BECCS technologies, but lessons learned from the deployment of CCUS technologies apply to BECCS as well.

A transparent and readily understood system to account for carbon emissions can assist in the deployment of BECCS technologies. It may also help define what kinds of fuels are preferable if the goal is carbon emission reductions and could be demonstrated as carbon saved or removed and/or produced.

Although carbon accounting of the combination of CCUS with bioenergy is possible, there are some uncertainties in ensuring the process delivers genuine net 'negative' emissions. When biomass is used to generate electricity, GHG reductions vary depending upon the type of biomass used and not all scenarios lead to GHG reductions (Muench, 2015). Addition of CCUS to biomass energy systems should result in net GHG reductions in all cases, but the relative value of the combined technologies can vary. For BECCS to be a useful mitigation technology, global participation and widespread deployment would be required to significantly impact projected atmospheric concentrations of carbon dioxide later in this century (Tilman, et al., 2009).

### 3 Commercial Status of BECCS Technology Deployment

#### 3.1 Planned and Existing Projects

A complete list of BECCS projects can easily turn out to be a very comprehensive one, as the technology is suitable in a variety of facilities from different sectors, e.g., power, heat, industrial. In addition, there is a potential overlap with coal-CCUS and gas-CCUS projects if a project would decide to switch all or part of their fuel supply to biomass. Table 2 provides a list of existing, planned, completed and cancelled projects where information was available. The table shows select key characteristics, such as status, CO<sub>2</sub> capacity, source, and sink.

There are currently five BECCS projects in operation, which capture approximately 1.85 MtCO<sub>2</sub>/yr (see Table 2). The Norwegian Government has set a goal to construct at least one full-scale carbon capture demonstration plant by 2020. The Ministry of Petroleum and Energy has supported three feasibility studies in 2016, of which two are BECCS: The Klemetsrud Waste-to-Energy Plant and the NORCEM cement plant. Based on the result from the studies, Gassnova recommends that all three should continue preparing for the front end engineering design (FEED) phase (GASSNOVA, 2016).

In the United States, the Illinois Industrial CCS Project (IL-ICCS) is capturing 1 MtCO<sub>2</sub>/yr. It became operational in April 2017 and is now the largest operating BECCS project. This is an important milestone for CCUS and will put this BECCS project on par with other large-scale projects, including Boundary Dam with 1 MtCO<sub>2</sub>/yr, Petra Nova with 1.4 MtCO<sub>2</sub>/yr, and many industrial gas processing facilities providing 1 MtCO<sub>2</sub>/yr (including Quest, Lost Cabin, Whiting Petroleum, etc.). The majority of major BECCS projects are located at ethanol fermentation plants. CO<sub>2</sub> capture from ethanol production is a commercially

tested and proven technology. The application of BECCS to ethanol plants in Table 2 is dominant because the fermentation process supplies a stream of relative pure CO<sub>2</sub>, making its capture relatively simple, only requiring dehydration and compression of the product stream. Half of the projects use the CO<sub>2</sub> for EOR, highlighting the importance of CO<sub>2</sub>-EOR as a driver for commercializing BECCS and utilizing EOR as an early economic driver. The U.S. IL-ICCS project is injecting its CO<sub>2</sub> into the Mount Simon saline bearing sandstone over a mile below the facility and is planning to claim 45Q tax credits from the U.S. government, highlighting the importance of government incentives for early adoption of the technology. Furthermore, planned projects are clustered in certain regions, e.g., North America, Japan, Scandinavia, and other specific European locations. Though the number of BECCS projects that are either operational or underway is encouraging, significantly more CCUS projects will be necessary to achieve the required CO<sub>2</sub> emission reductions and to build up operational knowledge and confidence in the technology at large/commercial scale.

Table 2: Summary of global BECCS projects (Kemper 2015)

Project name	Location	Status	CO <sub>2</sub> capacity MtCO <sub>2</sub> /yr	CO <sub>2</sub> source	CO <sub>2</sub> sink
<i>Operational projects</i>					
IL-ICCS project	Decatur, IL, USA	2 <sup>nd</sup> phase operating since April 2017	1.0	Archer Daniels Midland ethanol plant, other	Saline storage, Mount Simon sandstone
Arkalon	Liberal, KS, USA	Operating since 2009	0.18-0.29	Conestoga's Arkalon ethanol plant	EOR, Booker and Farnsworth oil fields, TX
Bonanza	Garden City, KS, USA	Operating since 2011	0.10-0.15	Conestoga's Bonanza BioEnergy ethanol plant	EOR, Stuart oil field, KS
RCI/OCAP/ROAD	Rotterdam, NL	Operating since 2011	0.1 (Abengoa) 0.3 (Shell)	Shell's Pernis refinery, Abengoa's ethanol plant, Maasvlakte power plant, various other	Nearby greenhouses, TAQA's P18-4 gas reservoir after 2015
Husky Energy	Lloydminster, SK, CA	Operating since 2012	0.09-0.1	Ethanol plant	EOR, Lashburn and Tangleflags oil fields
<i>Planned projects / projects under evaluation</i>					
Klemetsrud	Oslo, NO	Planned start in 2022	0.3	Waste-to-energy plant, 50-60% biomass	Smeaheia, North Sea
Norcem	Brevik, NO	Planned start in 2022	0.4	Cement plant, >30% biomass	Smeaheia, North Sea
Mikawa power plant	Omuta, Fukuoka, JP	Planned start in 2020, pilot-scale CO <sub>2</sub> capture since 2009	0.18	Mikawa power plant (coal and/or biomass)	Not yet identified
C.GEN North Killingholme Power Project	North Killingholme, UK	Evaluating, planned start in 2019, now likely cancelled	2.5	Biomass co-fired IGCC power plant	Southern North Sea
Södra	Värö, SE	Identifying and evaluating	0.8	Pulp and paper mill	Skagerrak, North Sea
Domsjö Fabriker	Domsjö, SE	Identifying and evaluating	0.26	Black liquor gasification pulp mill	Saline aquifer, North or Baltic Sea
Lantmännen Agroetanol	Norrköping, SE	Identifying and evaluating	0.17	Ethanol plant	Saline aquifer, North Sea
CPER Artenay project	Artenay and Toury, FR	Identifying and evaluating	0.045-0.2	Tereos ethanol plant	Dogger and Keuper saline aquifers, Paris Basin,
Sao Paulo	Sao Paulo state, BR	Identifying and evaluating	0.02	Ethanol plant	Saline aquifer
Biorecro/EERC	ND, USA	Identifying and evaluating	0.001-0.005	Gasification plant	Saline aquifer
Skåne	Skåne, SE	Identifying and evaluating	0.0005-0.005	Biogas plant	Saline aquifer
<i>Completed projects</i>					
Russel EOR research project	Russel, KS, USA	Completed 2005	0.004 (0.007 in total)	Ethanol plant	EOR, Hall-Gurny-Field
Norcem	Brevik, NO	Testing 2014-2016, CO <sub>2</sub> capture only	Small-scale	Cement plant, >30% biomass-fueled	N/A
IBDP	Decatur, IL, USA	First phase completed in 2014, now monitoring	0.3 (1.0 in total)	Archer Daniels Midland ethanol plant	Mount Simon sandstone
<i>Cancelled projects</i>					
White Rose CCS Project	Selby, UK	Cancelled	2.0	Drax power station, biomass (co)-firing	Bunter sandstone
Rufiji cluster	TZ	Cancelled	5.0-7.0	Sekab's ethanol plants	Saline aquifer
Greenville	Greenville, OH, USA	Cancelled in 2009	1.0	Ethanol plant	Saline aquifer, Mount Simon sandstone
Wallula	Wallula, WA, USA	Cancelled	0.75	Boise Inc's pulp mill	Saline aquifer
CO <sub>2</sub> Sink	Ketzin, DE	Cancelled	0.08		Saline aquifer

## 3.2 Projects in Operation

### 3.2.1 Illinois Basin Decatur Project / Illinois Industrial CCS project

The most relevant BECCS project is the Illinois Basin Decatur Project (IBDP). The world's first large-scale BECCS project has been operational since November 2011. The U.S. Department of Energy (USDOE) funds the project under their Regional Carbon Sequestration Partnership programme (RCSP). The CO<sub>2</sub> in this project comes from the Archer Daniels Midland (ADM) ethanol plant in Decatur, Illinois, with a production capacity of around 350 million gallons per year. The ethanol fermentation process produces a high CO<sub>2</sub> concentration, high water content but low-pressure exhaust gas. This gas is then compressed, dehydrated to around 200 ppm (H<sub>2</sub>O) and transported 1.6 km by pipeline for injection into a deep saline formation, the Mount Simon sandstone. The Midwest Geological Sequestration Consortium (MGSC), one of the seven regional partnerships under the RCSP, extensively monitors the subsurface injection aspects of the project. The project reached its primary goal of injecting a total of 1 MtCO<sub>2</sub> (i.e. 0.33 MtCO<sub>2</sub>/yr) underground in November 2014 and continues with a 3-year post-closure monitoring programme (Finley, 2014; Jones & McKaskle, 2014).

The Illinois Industrial CCS (IL-ICCS) project now succeeds the IBDP, again with USDOE support. The project expands the CO<sub>2</sub> storage capability to that of a commercial-scale operation, i.e., 1 MtCO<sub>2</sub>/yr. ADM has integrated the IBDP compression and dehydration facilities with the new facilities constructed under the IL-ICCS project upon completion of IBDP injection operations in autumn 2014 (GCCSI, 2017; NETL, 2015). The main aim is to inject 1 MtCO<sub>2</sub>/yr (Gollakota & McDonald, 2012) and the project became operational in April 2017.

### 3.2.2 Rotterdam Climate Initiative

Since 2011, the Organic Carbon Dioxide for Assimilation of Plants (OCAP) project in Rotterdam, Netherlands, has been delivering nearly 0.1 Mt/yr of biogenic CO<sub>2</sub> from the Abengoa ethanol plant and 0.3 Mt/yr of fossil CO<sub>2</sub> from Shell's Pernis refinery to greenhouses nearby, which use the CO<sub>2</sub> as fertiliser (RCI, 2011; Mastop, de Best-Waldhober, Hendriks, & Ramirez, 2014). As it effectively does not store the CO<sub>2</sub>, the project is not strictly bio-CCS but rather bio-CCU (biomass with carbon dioxide capture and utilisation). The OCAP project is part of the bigger efforts of the Rotterdam Climate Initiative (RCI), which is planning to develop a CCUS hub, connecting additional CO<sub>2</sub> suppliers to reach demonstration stage capacities. The CO<sub>2</sub> in the Rotterdam hub will include a mixture of biogenic and fossil sources related to the power and industry sector and will involve utilisation as well as storage of CO<sub>2</sub>.

Abengoa, an international bioethanol producer, has an ethanol production capacity of approximately 480 million litres per year in the Port of Rotterdam, equivalent to more than 2% of the road transport fuel demand in 2010 of 418 PJ (Mastop, de Best-Waldhober, Hendriks, & Ramirez, 2014). Abengoa is currently working on other projects in the U.S. and France that involve utilization of captured CO<sub>2</sub> for beverage carbonation and refrigeration applications. However, no detailed information about the status of those bio-CCU, or other bio-CCS, activities is available at present.

### 3.2.3 Norcem

This project investigates CO<sub>2</sub> capture from a cement plant operated by Norcem in Brevik, Norway. Gassnova is funding the project through the CLIMIT programme. The plant's year of construction dates back to 1919, but after refurbishment, it can handle alternative fuels, such as coal mixtures and biomass shares of more than 30%. The flue gas contains approximately 20% CO<sub>2</sub>, with fluctuating levels of SO<sub>2</sub>. The project involves testing of mature as well as early stage CO<sub>2</sub> capture technologies, such as amines, solid sorbents, membranes, and regenerative calcium cycles. It is a key objective to obtain information about the performance of the different processes when adapted from power plant to cement plant application. The project focuses on the capture step, so will not include any assessment of transport and storage for now. Norcem carried out first estimations showing that conventional amine systems with waste heat utilisation could capture around 30 – 40% of the CO<sub>2</sub> at the Brevik plant, which corresponds to 0.3 – 0.4 MtCO<sub>2</sub>/yr (Bjerge & Brevik, 2014; GCCSI, 2017).

### 3.3 Government Programs

Currently, there is very little direct government support for BECCS projects anywhere in the world. That said, there are several programs related to bioenergy and to fossil CCUS that can support BECCS projects both directly and indirectly. For example, bioenergy R&D programs and commercialization incentives can increase supply of biogenic emissions for future BECCS projects, and CCUS programs aimed at fossil-fueled power and/or industrial systems can help reduce the costs of both capture and storage for BECCS projects. For example, bio-CCS research has been funded through the EU Framework Programme for Research and Innovation's Horizon 2020 Program since 2014.

It is through these existing bioenergy and/or CCUS government programs that BECCS projects have gained support to date. For example, in the United States, the ADM ethanol BECCS project in Decatur, IL, has secured funding from the DOE's existing CCUS program (Massachusetts Institute of Technology, 2016) and has recently received additional funding to explore further ethanol capture and saline storage demonstrations (Lusvardi, 2016). In Norway, the Klemetsrud partial-BECCS facility at a municipal solid waste plant is receiving support from the City of Oslo government (Engen, 2016) and the Ministry of Petroleum and Energy through the CLIMIT program.

In addition, there have been a number of proposed government programs in the United States that would support BECCS projects. The most important of these proposed incentives is an expansion of section 45Q in the U.S. tax code that increased tax credits to \$50/tCO<sub>2</sub> for saline storage and \$35/tCO<sub>2</sub> for utilization, which could lead to increased ethanol BECCS projects for both EOR and saline aquifer storage in the U.S. (NEORI, 2016). In addition, the California Air Resource Board (ARB) is in the process of determining how CCUS can contribute towards the state's cap-and-trade and low carbon fuel standard regulations, both of which could drive BECCS projects (CEPA, 2016). Lastly, there was language in the version of the Energy Bill passed by the U.S. Senate in 2016 that authorized \$22M/yr for five years to support a partial BECCS co-fired biomass + coal power project in the southeastern United States (CCR, 2016), and the U.S. Department of Energy's Advanced Projects Research Agency-Energy (ARPA-E) has also explored launching a program dedicated to BECCS innovation in the near future (Stark, 2016).

### 3.4 Market Drivers for BECCS Deployments (e.g., Policies, Regulatory, etc.)

The most significant driver for BECCS projects today is policy support. In particular, government incentives for biofuels and/or CCUS are critical for making BECCS projects economic. This is because biofuels are currently more expensive than fossil fuel alternatives in most markets globally, and markets for compressed CO<sub>2</sub> are relatively small and low-priced.

In the United States, EOR can help drive some demand for ethanol BECCS projects to a moderate degree. However, ethanol facilities will need to address challenging economics in the near future with oil prices and relatively small volumes compared to the needs by EOR operators, although the 45Q tax credits and credits for low carbon fuels such as in California can help to drive additional BECCS projects. There is some niche demand for CO<sub>2</sub> from biogenic sources in food and beverage and other manufacturing applications, but the potential to drive new, large-scale BECCS projects using this demand source is limited. Increased demand for CO<sub>2</sub> utilization in novel applications such as cements, plastics, etc., is also unlikely to drive many BECCS projects outside of the ethanol industry, given the lower-cost and widespread availability of CO<sub>2</sub> from fossil-fueled anthropogenic sources.

On the regulatory side, there are several ongoing efforts in the United States that could help advance BECCS projects. For one, clarifying the U.S. Environmental Protection Agency's (EPA) Class VI underground injection permitting process and/or approving state primacy applications could help advance projects both on the fossil and biogenic capture side. To date, there are very few Class VI permits that have been issued by the U.S. EPA.

Corporate demand for BECCS projects is also very low. Awareness of the value of BECCS among corporate buyers of renewable energy is low, and these buyers are often constrained to purchase market-competitive contracts, which BECCS projects are unlikely to deliver in most locations. The biggest potential hurdle with BECCS projects for corporate buyers is on the GHG accounting side. Without widely accepted biofuel and CCUS accounting frameworks, corporations are exposed to negative public perception of BECCS as an effective climate strategy. Having wide-scale acceptance of GHG accounting protocols for the sustainable growth of biofuels and the long-term safe and reliable geologic sequestration of CO<sub>2</sub> are critical for boosting corporate demand for BECCS projects.

Lastly, finance is an important factor for BECCS projects. The cost of capital is high for early generation BECCS projects, given technology and regulatory uncertainty, as well as the variability inherent in standard CO<sub>2</sub> off-take agreements (as CO<sub>2</sub> suppliers sell to EOR operators on an oil-priced-indexed contracts). To address these concerns, regulatory programs such as loan guarantees, extending master limited partnership (MLP) tax structures for BECCS projects, and offering government-backed price-stabilization contracts for CO<sub>2</sub> off-take can enable faster and wider market adoption of BECCS projects.

### 3.5 Barriers to Large-scale BECCS Demonstration and Deployment

There are many barriers to large-scale BECCS deployment. This section provides a brief discussion of where challenges exist and some ways of overcoming them.

#### 3.5.1 Technical

Some of the technical barriers are related to the biomass combustion/conversion process, e.g., dealing with the high moisture content, diversity, variability, and impurities of biomass, which can lead to increased corrosion, slagging, and fouling (Pourkashanian, et al., 2016). Further, biomass co-firing in excess of 20% requires increasing levels of biomass pre-treatment and boiler modifications (Gough and Upham, 2010).

Despite these challenges, BECCS applications are among the most mature technologies in the NET portfolio and allow for a relatively smooth integration into current energy systems. Research, development, and demonstration (RD&D) into the less mature options, like large scale biomass gasification, should be pursued. Research is needed to identify feedstocks that require limited processing, compatibility with existing boiler and pollution control equipment, and reduction in processing equipment costs, and associated energy costs. The specific processes adapted to every biomass source (vegetal, waste, etc.) and use (power and heat, paper, cement, etc.) require a considerable amount of research focusing on the heat integration of the capture unit, which is so important for the overall efficiency and costs of capture.

#### 3.5.2 Economics and Incentives

Despite the relatively robust technical potential of several BECCS options that vary from 3-20 GtCO<sub>2</sub>/yr uptake (Azar, et al., 2010; Woolf, et al., 2010; IEAGHG, 2011; IEAGHG, 2013; McLaren, 2012; van Vuuren, et al., 2013; Arasto, et al., 2014; Caldecott, et al., 2015; NRC, 2015), the economic potential lags. Considering the cost of resources relative to a fossil fuel reference technology, the economic potential is often only a fraction of the technical potential.

In this regard, price, reliability and sustainability of biomass supply will have a profound effect on the eventual economic feasibility of BECCS. Current economic assessment uncertainties make it difficult to predict which sectors/applications will be able to deploy BECCS in the most profitable way. Small-scale BECCS in the power sector will likely increase electricity costs (IPCC, 2005). Currently, CO<sub>2</sub> price signals are weak and there is no incentive for CCUS or even BECCS. In addition, land and biomass supply limitations could cause a substantial increase in BECCS costs when the biomass removal rate reaches large-scale deployment, i.e., about 12 GtCO<sub>2</sub>/yr (Kriegler, et al., 2013; Lackner, 2010). Financing BECCS projects continues to be difficult because there are not enough operational large-scale, whole-chain projects that could provide the necessary investor confidence.

Bioenergy incentives have the potential to lead to land conversion and result in LUC and related emissions (Wise, et al., 2009; Reilly, et al., 2012) if biomass production does not adhere to sustainability standards. Finally, BECCS deployment could suffer from other limitations, especially when competing with low-cost sustainable biomass feedstocks, confronted with limiting land resources, affordable CO<sub>2</sub> storage capacity and funding/investment resources.



To overcome these economic obstacles, there is an urgent need for financial mechanisms and incentives to promote the benefits associated with BECCS. Many studies identified setting a price of CO<sub>2</sub> as one of the main drivers for BECCS deployment (IEAGHG, 2011; IEAGHG, 2013). An advantage of BECCS, and other NETs, is to compensate for residual emissions from sectors where abatement is more expensive. Along those lines, a BECCS plant in the power sector might provide a double benefit: producing low-carbon electricity and negative emissions at the same time (Dooley, 2012). Economies of scale can bring down the cost of BECCS substantially (IPCC, 2005) and for some industrial sectors, BECCS might be the decarbonisation option with the lowest cost (Meerman, et al., 2013). Integrated assessment models (IAMs) project that carbon abatement will be significantly costlier if NETs, especially BECCS and DAC, are unavailable (Rose, et al., 2013). In addition, BECCS technologies allow for overshoot scenarios, which postpone the costs of mitigation, i.e., it presents a financial opportunity for discounting (Azar, et al., 2013; Lomax, et al., 2015). IAMs themselves need improvement and refinement to represent BECCS pathways adequately (The Secretary of Energy Advisory Board (SEAB) Task Force on CO<sub>2</sub> Utilization, 2016).

Early opportunities for BECCS are co-firing of biomass in fossil-CCUS plants and bioethanol plants (Gough and Upham, 2010; Lomax, et al., 2015). Currently, co-firing biomass in heat and power plant appears to be the most efficient way in terms of GHG reduction targets in a cost-effective manner (REN21, 2013; Junginger, et al., 2014; Sterner and Fritsche, 2011). When several BECCS projects are co-located, the cluster structures with shared infrastructure provide huge opportunities not only for BECCS but also for CCUS deployment in general.

### 3.5.3 Policies, Regulations, and Accounting

Many low-carbon policies and GHG accounting frameworks do not appropriately recognise, attribute, and reward BECCS and negative emissions in general, especially regional cap-and-trade schemes (IEAGHG, 2014; Zakkour, et al., 2014). As a result, there are no incentives to capture and store biogenic emissions over zero emissions, e.g., from dedicated biomass firing without CO<sub>2</sub> storage. The political processes involved in designing accounting schemes are complex and the timelines lengthy, interfering with a rapid implementation of BECCS. Without strong policy support, weak or patchy GHG accounting rules can lead to carbon leakage and undermine the potential for BECCS and other technological solutions to be considered negative emissions technologies and more broadly, the potential carbon neutrality of bioenergy. Even when those would be aligned, the direction and immediacy of returns remains a challenge. For example, long growth times of biomass could delay return of revenues, thus acting as a disincentive for BECCS projects, especially if other options with faster returns are available (e.g., renewables) (Thomas, et al., 2010).

Incentivising the double benefit of BECCS can help avoid direct investment competition with other abatement options. Concerted efforts, e.g., global forest protection policies, carbon stock incentives, and bioenergy/renewable energy incentives, are necessary to avoid undesirable LUC emissions (Wise, et al., 2009; Clarke, et al., 2014). Large-scale bioenergy development, together with strict forest management, can increase food and water prices by exacerbating land competition (Popp, et al., 2011). Thus, forest and land management activities can be optimized to address multiple-use scenarios. In

addition, different policies can have diverse impacts on CO<sub>2</sub> prices, food prices, electricity prices, and GHG emissions (Sands, et al., 2017).

The European Directive on the geological storage of CO<sub>2</sub> (2009/31/EC), known as the 'CCS Directive', has established a legal framework for the geological storage of CO<sub>2</sub>. Potential BECCS projects fall under this Directive and must follow the four Guidance Documents (GDs) that have been produced (EU, 2016).

A variety of approaches have been implemented to enable carbon markets. For example, clean development mechanism (CDM), joint implementation (JI), and emission trading systems (ETS) are a few examples of functioning carbon markets that have been moderately effective (Smith, et al., 2014). Several studies show that the CDM can provide significant incentives for renewable energy deployment in developing countries, including BECCS (Restuti and Michaelowa, 2007; Bodas Freitas, et al., 2012; Hultman, et al., 2012). However, direction and timing of returns need to be addressed at the same time to avoid project failures.

#### 3.5.4 Public Perception

Public perception of BECCS is influenced by two main parts: 1) image of biomass/bioenergy and 2) CCUS. Bioenergy, as a renewable energy, and especially if produced from biomass waste, tends to be seen mostly favourable. Biomass for bioenergy is seen as competing with food supplies land use, while half of the population think the land can be used more productively (ETI, 2016). Public perception of BECCS varies with location and social/cultural background and it can be either a driver or a barrier. The public perception of CCUS is well studied (e.g., Ashworth, et al., 2013; Dowd, et al., 2014) but research focussing on BECCS is limited. BECCS generally has a lower profile than fossil-CCUS and appears to lack support among external as well as its own stakeholders (Dowd, et al., 2015). When competing with other mitigation options, such as other renewable energy and energy efficiency, fossil-CCUS and BECCS are usually perceived as non-favourable (TNS 2003). The negative public perception of CCUS can adversely affect BECCS (Mander, et al., 2011). In fact, public opposition has led to several CCUS and bioenergy projects being cancelled in the past.

To overcome these issues, BECCS project developers and advocates should focus more on building up trust with the general public and local communities via dialogues and site visits (Upham and Roberts, 2010) instead of just providing educational information. Stronger collaboration and exchange of ideas between stakeholders of the CCUS, bioenergy, and BECCS industries would also be beneficial.

#### 3.5.5 Land Demand and Land Use Change (LUC: dLUC and iLUC)

A critical issue related to sustainable bioenergy production for BECCS is LUC. Direct LUC (dLUC) is a change in the use or management of land caused by humans that leads to a change in land cover (IPCC, 2000). Indirect LUC (iLUC) means a change in land use triggered by diversion of land to replace another product or service (IPCC, 2014).

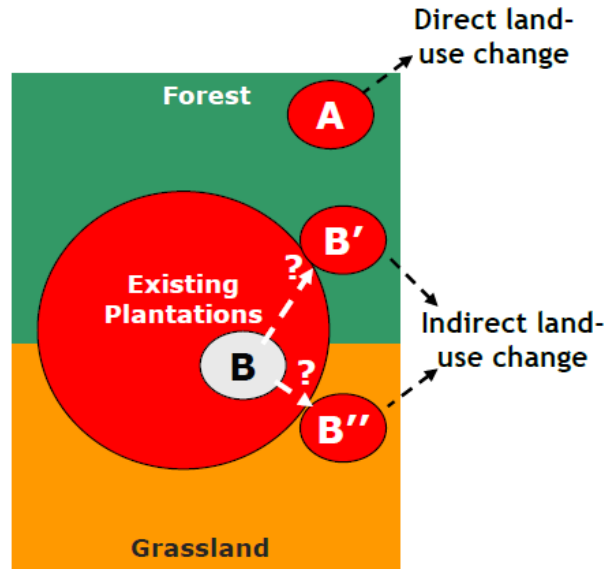


Figure 3: Concept of direct and indirect land use change (Hamelinck, 2014)

dLUC occurs when additional biomass feedstock demand leads to the cultivation of new areas (see circle A in Figure 3) for biomass production. iLUC, in contrast, can occur when existing production areas cover the additional feedstock demand (see B), displacing the previous production function of the land, which can trigger expansion of land to new areas (e.g., to B' and/or B''). The balance between LUC and association emissions is critical as it may render any zero emissions, negative emissions, or double benefit assumption invalid (Kemper, 2015). Additionally, the time delay between carbon emission and carbon uptake by natural systems (plants, soils, and oceans) makes it difficult to calculate the carbon balance.

To limit the negative effects of LUC and land competition for bioenergy with land for crops, BECCS can use semi-perennial crops, perennial grasses or woody biomass that need less fertiliser and grow on marginal or carbon-depleted land (Harper, et al., 2010; Sterner and Fritsche, 2011; Sochacki, et al., 2012). For example, miscanthus outperforms yields and GHG savings of switchgrass and corn, and can grow on low-quality soil (Brandao, et al., 2011; Dwivedi, et al., 2015). Other means to avoid or reduce LUC emissions are the use of sustainable biomass, wastes/residues and 2<sup>nd</sup> generation crops (Davis, et al., 2011; Scown, et al., 2012).

### 3.5.6 Resource Limitations

In the end, BECCS and other bioenergy applications might experience a limitation of feedstock to truly “additional” biomass. “Additional” refers to biomass that does not negatively affect sustainability and food security and includes e.g., winter cover crops, timber processing wastes, urban waste wood, landfill wastes, and forest/crop residues (Searchinger and Heimlich, 2015). It also includes only biomass grown in excess of that which would be grown anyway or biomass that would otherwise decompose (EEA, 2011). In addition, there might be competition for biomass and land resources between several sectors/players and competition for CO<sub>2</sub> storage resources between different mitigation options (Clarke, et al., 2014; Gough and Upham, 2010; Gough and Upham, 2011; McLaren, 2012).

Early BECCS projects should aim to use mainly “additional” biomass and 2<sup>nd</sup> generation biofuel crops to avoid adverse impacts on land use and food production (Smith, et al., 2014). However, additional biomass is likely to be costlier due to, for example, increased irrigation. BECCS options that optimize water use and carbon footprint need to be identified through careful selection of crops, location, cultivation methods, pre-treatment processes, and biomass conversion technologies. Sustainable biomass feedstocks will require avoidance of unsustainable harvesting practices, e.g., exceeding natural replenishment rates (IPCC, 2014b). Using “additional biomass” to avoid sustainability issues also helps improve public acceptance (Searchinger and Heimlich, 2015).

### 3.5.7 Supply Chain Development

Lack of infrastructure (i.e., for biomass, natural gas, and CO<sub>2</sub> as well as CO<sub>2</sub> storage/utilization) could be a showstopper for BECCS projects. BECCS already depends on CCUS scalability, deployment, infrastructure, and timeframe, which could be up to half a century for a CCUS roll-out of 8-16 GtCO<sub>2</sub> (Azar, et al., 2010). The timeline for CCUS deployment could be the most important cost barrier for BECCS (Edenhofer, et al., 2010; Tavoni, et al., 2012; Krey, et al., 2014; Kriegler, et al., 2014; Riahi, et al., 2014). Large-scale biomass supply chains and trade need further development.

Sustainability needs to be ensured across the whole BECCS chain. Improving pre-treatment processes for biomass (i.e., densification, dehydration, and pelletisation) will make biomass transport more efficient and remove geographical limitations of biomass supply (Hamelinck, et al., 2005; Luckow, et al., 2010).

### 3.5.8 Other Issues in the Food-Water-Energy-Climate Nexus

The food, energy, water nexus interacts with climate and assessing these interactions will likely necessitate new and integrated approaches. General barriers associated with BECCS include impacts on emissions from LUC, competition for land with other services, water demand and biodiversity (Kemper, 2015). One issue of great concern is how to avoid food price increases due to land use competition. However, there is a multitude of other factors that influence food prices (e.g., fossil fuel prices, stockpiles, demand, speculation, trade liberalisation, subsidies, climate change, weather, currency fluctuations, inflation, social unrest) and the complexity of the food system make it difficult to predict the influence of increasing bioenergy crops. Bioenergy applications require disproportionately high amounts of water, especially when compared to other energy production options (WEC, 2010). As water becomes more limiting, questions about water allocation are likely to become central. Irrigation of bioenergy crops is likely to be very costly and to compete with other uses. In addition, fertiliser use might negatively affect the economics of BECCS (Crutzen, et al., 2008) and offset the CO<sub>2</sub> emissions reductions through an increase in N<sub>2</sub>O emissions (Robertson, et al., 2000; Brown, et al., 2004; Li, et al., 2005; Smith, et al., 2012). Furthermore, particulate matter (PM) emissions of biomass co-firing are significantly higher than of dedicated coal combustion (NETL, 2012, Schakel, et al., 2014).

Improvements in crop yield increases, food waste reduction, and demand side changes could help free land for bioenergy production (Thomson et al., 2010). Increased PM emissions of BECCS can be addressed through optimal design of the whole BECCS chain, e.g., improvement of the biomass pre-treatment and transport processes, especially via fuel switching.

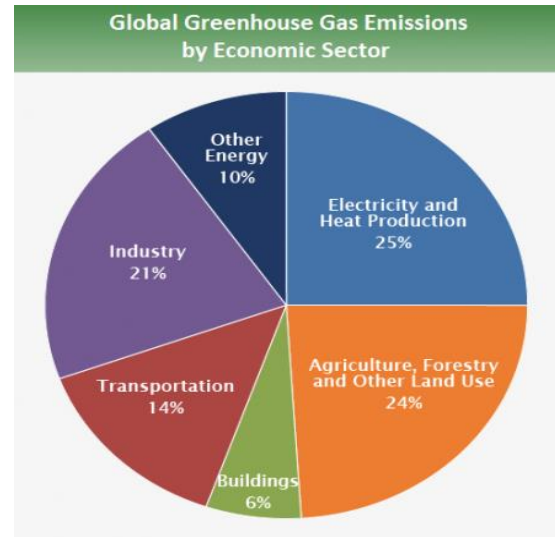
## 4 Overview of BECCS Technology Options and Pathways

### 4.1 Power Generation

The power generation economic sector emitted, which is comprised of the electricity and heat production industry, is a large contributor to global CO<sub>2</sub> emissions (Figure 4). Fossil fuel based steam power generation plants typically burn conventional hydrocarbon-based fuels such as coal, gas, and oil to create steam to drive the turbines that produce electricity. Biomass firing and co-firing with conventional fuels can substantially reduce GHG emissions in the production of electric power (IRENA, 2012). In general, there are three pathways for the use of biomass as fuel for power generation plants (IEA, 2012):<sup>1</sup>

- Development of new power generation plants that utilize biomass. The plants can involve combustion or gasification of biomass. The combustion plants typically require designs that use grate-fired or fluidized bed boilers. Gasification of biomass can occur using a gasifier producing a syngas that is used for combustion in a boiler of gas turbine.
- Co-firing of biomass with a conventional fuel such as coal at an existing or new power plant.
- Conversion of an existing pulverized coal boiler in a coal plant to instead burn biomass.

CCUS technology can be added to biomass or co-fired plants to capture CO<sub>2</sub> emissions from the power generation. A BECCS power plant involves the use of biomass as fuel and may utilize pre-combustion, post-combustion, or oxy-fuel technology in the capture of CO<sub>2</sub>. BECCS technology applications in the steam power generation sector fall into 2 categories: 1) Combustion & Co-Firing and 2) Thermal Gasification.



**Figure 4:** Source: EPA Global Greenhouse Gas Emissions Data. IPCC (2014) based on global emissions from 2010. Details about the sources included in these estimates can be found in the *Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*

#### 4.1.1 Combustion & Co-Firing

##### Fuels

The burning of hydrocarbon fuels with oxygen in combustion boilers to create steam and electricity results in substantial CO<sub>2</sub> and GHG emissions. Coal-based electrical generation in the United States represented approximately one-third of the total U.S. generation and more than 70% of CO<sub>2</sub> emissions emitted by the power generation sector in 2015 (USEIA, 2016; Figure and Figure 66). In 2016, the use of natural gas surpassed coal as the primary fuel source in the U.S. power generation sector. Globally, coal is the second largest energy source as stated by the International

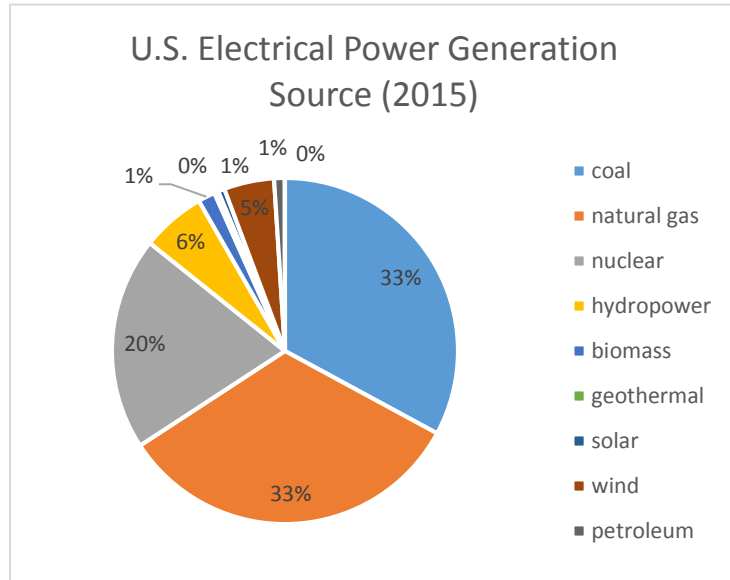


Figure 5: U.S. Electrical Power Generation Sources (EIA, 2016)

Energy Outlook (EIA, 2016). The top three coal-consuming countries are China, the United States, and India, which together account for more than 70% of world coal use (EIA, 2016). In the United States, total CO<sub>2</sub> emissions from combustion power plants have been estimated to be 1,925 million metric tons, or about 37% of the total U.S. energy-related CO<sub>2</sub> emissions (5,271 million metric tons) in 2015 (EIA, 2016). Increasing the use of biomass and co-firing of biomass in pulverized coal power plants for electricity production has the potential to reduce overall GHG from the power sector.

Biomass has been successfully used to supplement pulverized coal, but the use of biomass currently represents a very small portion of overall electricity generation in the United States (EIA, 2016). Other countries with large forestry reserves, such as Finland, utilize biomass for electricity generation to a greater extent

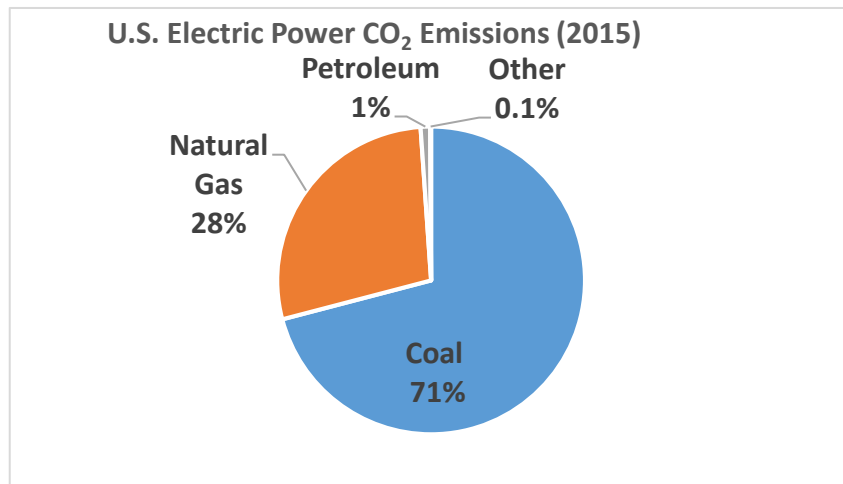


Figure 6: Carbon Dioxide Emissions from US Electric Power Plants

(Karhunen, Ranta, Heinimö, & Alakangas, 2014). The biomass industry supplies about 52 gigawatts of global power generation capacity, mostly using wood products, municipal solid waste, and agricultural

waste (Block, 2009). The United States supplies approximately 20% of the world’s biomass for power production (Shah, 2011) and a substantial portion of the wood pellets from the United States are used to fuel the Drax Power station in the United Kingdom (IER, 2015).

The preferred biomass fuel for use in pulverized coal-fired boilers is pelletized wood, including wood chips, pellets, and sawdust, which are combusted or gasified to generate electricity (WBDG, 2016) as depicted in Table 3.

**Table 3: Biofuel Types (IEA, 2016)**

<b>Agricultural</b>	<b>Forestry products</b>	<b>Domestic and municipal wastes</b>	<b>Energy crops</b>
<b>Harvesting residues</b> <ul style="list-style-type: none"> <li>• Straws</li> <li>• Corn stalks</li> </ul>	<b>Harvesting residues</b> <ul style="list-style-type: none"> <li>• Forestry residues</li> </ul>	<b>Domestic / industrial</b> <ul style="list-style-type: none"> <li>• MSW / RDF/ SRF</li> <li>• Scrap tyres</li> <li>• Wood wastes</li> <li>• Sewage sludges</li> </ul>	<b>Wood</b> <ul style="list-style-type: none"> <li>• Willow</li> <li>• Poplar</li> </ul>
<b>Processing residues</b> <ul style="list-style-type: none"> <li>• Rice husks</li> <li>• Sugarcane bagasse</li> <li>• Olive/palm oil/sunflower husks and residues</li> <li>• Fruit residues</li> <li>• Cereal straws and residues</li> </ul>	<b>Primary Processing residues</b> <ul style="list-style-type: none"> <li>• Bark</li> <li>• Sawdusts</li> <li>• Offcuts</li> <li>• Wood pellets</li> </ul>	<b>Urban green wastes leaves</b> <ul style="list-style-type: none"> <li>• Grass and hedge cuttings</li> </ul>	<b>Grasses etc.</b> <ul style="list-style-type: none"> <li>• Switch grass</li> <li>• Reed Carry Grass</li> <li>• Miscanthus</li> </ul>
<b>Animal wastes</b> <ul style="list-style-type: none"> <li>• Poultry litter</li> <li>• Tallow</li> <li>• Meat and bone meal</li> </ul>	<b>Secondary process wastes</b> <ul style="list-style-type: none"> <li>• Sawdusts</li> <li>• Offcuts</li> </ul>		

The use of torrefaction, a process in which the biomass fuel is heated between 200°C and 300°C in the absence of oxygen and converted into char, has been successfully implemented to improve biomass feedstock characteristics (IEA, 2012). Typically, torrefaction of wood results in pellets that have 25-30% higher energy density than conventional wood pellets (IEA, 2012). The product has properties closer to those of coal, with similar handling, storage, and processing.

## Combustion

### ***Biomass Combustion Power Plants***

Several power generation plants using biomass as the primary energy source are operating worldwide. Typical biomass power plant sizes are based upon availability of local feedstocks and range between 10 and 50 MWe in size (IEA, 2012). However, converted pulverized coal power plants that utilize 100% biomass fuels are much larger. The power generation efficiencies of plants in the 10-50 MWe size without CCUS range between 10-33%, lower than plants that burn natural gas or coal (IEA, 2012).

Biomass combustion produces acid gases such as sulfur oxides (SO<sub>x</sub>), nitrogen oxides (NO<sub>x</sub>), and hydrogen chloride (HCl) but at levels that are lower than those for most coals. However, the flue gas must still be treated with conventional particulate control equipment. The use of limestone injection in the boiler fluidized bed and typical wet, lime, or limestone based flue gas desulfurization technology is used to capture sulfur dioxide and hydrogen chloride. NO<sub>x</sub> emissions are controlled using low NO<sub>x</sub> burners, two stage combustion, selective catalytic reduction (SCR), and selective non-catalytic reduction

(SNCR) similar to plants that are burning coal as fuel. Trace metals such as mercury are present in flue gas from biomass plants at levels dependent upon the type of biomass that is used. Mercury emissions can be reduced when co-firing with biomass if halogens are present in the biomass. (Cao, et al., 2008). In general, biomass such as wood has lower mercury levels as compared to coal (Rohr, et al., 2013), (Tweed, 2013) and will result in lower mercury emissions. Other biomass fuels such as poultry litter that could be used in co-firing, for example, can contain higher levels of lead, arsenic, copper, iron, zinc, and mercury and may require additional treatment when used as a biofuel in power generation applications (Ewall, 2007).

### **Fuel Unloading & Storage**

The biomass fuel (wood chips, sawdust, or pellets) storage system at a power generating facility will typically use both a bunker for short-term storage and an outside fuel yard for larger storage. Bulk handling and conveying equipment with pneumatic transport and other equipment including control system, stackers, dust collection, bins, bucket elevators, reclaimers, front-end loaders, and augers are used to store and transfer the biomass fuel from the unloading area to the mills.

### **Combustion / Steam Turbine**

Wood chip-fired electric power systems generally consume approximately one dry ton of biomass per megawatt-hour of electricity production (WBDG, 2016). This is a high-level approximation typical of wet wood systems and the actual value varies with system efficiency. For comparison, this approximation is equivalent to 20% HHV efficiency with 17 MMBtu/ton wood (WBDG, 2016).

In a direct combustion system, biomass is burned in a combustor or furnace to generate hot gas, which is fed into a boiler to generate steam. The steam is then expanded through a steam turbine or steam engine to produce mechanical or electrical energy.

Typical biomass boilers are the stoker or fluidized bed type (WBDG, 2016). Stoker boilers burn fuel on a grate to produce hot flue gases that are used to produce steam. The ash from the combusted fuel is removed continuously (WBDG, 2016). Fluidized bed boilers suspend fuels on upward blowing jets of air during the combustion process. Circulating fluidized bed boilers (CFB) separate and capture fuel solids entrained in the high velocity exhaust gas and return them to the bed for complete combustion (WBDG, 2016).

### **Biomass Co-firing**

The co-firing of biomass at pulverized coal power generation plants is well established and cost-effective (IEA, 2016). Biomass co-firing equipment can be installed with relatively minor modifications and capital investment to an existing pulverized coal plant. The addition of storage, drying, pre-treatment, and feed systems can be done at a relatively low cost. The use of biomass co-firing provides co-benefits in reducing flue gas cleaning as acid gases such as SO<sub>x</sub>, HCl, and NO<sub>x</sub> are typically reduced in the flue gas (IEA, 2016).

Different approaches to co-firing of biomass at pulverized coal power plants that have been used at several locations in North America and Europe (IEA, 2016):



- Milling of 100% biomass through one or more of the existing coal mills and firing systems involves modification to both the plant milling and firing systems (IEA, 2016). The approach involves firing of both coal and biomass, each from dedicated systems, into the boiler.
- Pre-mixing of the biomass and coal in the coal handling and conveying system, with use of the existing milling and firing systems, is the simplest design and requires 5-10% biomass with coal (IEA, 2016).
- Milling of the biomass to sizes suitable for suspension firing and the direct injection in the pulverized coal firing system results in the highest capital cost investment, but results in greater co-firing ratios. Biomass can be co-fired with the coal based upon heat input (IEA, 2016).
- Gasification of the biomass in a separate gasifier to form a gas which is combined with air and injected into the pulverized coal boiler for combustion (IEA, 2016).

### Biomass Co-firing Projects

The successful demonstration of biomass co-firing has reduced the technical risk and improved the technology dramatically. Co-firing ratios of biomass to coal have ranged between 5-50% (IEA, 2016). In Europe, electricity generation from biomass peaked between 2005-2006 due to government subsidies (IEA, 2016) and again between 2010-2012. But without subsidies, a sharp reduction in electrical generation with biomass can occur, as it did in the Netherlands (IEA, 2016).

Table 4: Worldwide Biomass Projects (Source: IEA, 2016)

Power Station	Country	Unit	Owner	Plant Output (MWe)	Plant Output (MWth)	Direct Co-firing percentage (heat)
Studstrupvaerket	Denmark	4	Dong Energy	350	455	7
Studstrupvaerket	Denmark	3	Dong Energy	350	455	0-100
Amagar	Denmark	1	HOFOR	80	250	0-100
Avedore	Denmark	1	Dong Energy	215	330	100
Avedore main boiler	Denmark	2	Dong Energy	365	480	100
Avedore straw boiler	Denmark	2	Dong Energy			100
Grenaa Co-Generation Plant	Denmark	1	Verdo (from 2017 Grenaa Vermevaerk)	19	60	50
Herningvaert	Denmark	1	Dong Energy	95	174	100
Randers Co Gen Plant	Denmark	1	Verdo	52	112	100
Ensted biomass boilers	Denmark	3	Dong Energy	630	95	100
Skaerbaekvaerket	Denmark	3	Dong Energy	392	444	100
Maasvlake	Netherlands	1	E.On	531	-	10
Maasvlake	Netherlands	2	E.On	531	-	10

Power Station	Country	Unit	Owner	Plant Output (MWe)	Plant Output (MWth)	Direct Co-firing percentage (heat)
Amer Centrale	Netherlands	8	Essent	600	250	10-12
Gelderland	Netherlands	13	Electrabel	602	-	25
Borssele	Netherlands	12	EPZ	403	-	10-15
Amer Centrale	Netherlands	9	Essent	600	350	27 + 5
Drax Power	United Kingdom	1-3	Drax Power Group	TBD	TBD	TBD
Ironbridge Power Station	United Kingdom	TBD	TBD	TBD	TBD	TBD
Tilbury Power Station	United Kingdom	TBD	TBD	TBD	TBD	TBD
New Hope Power Partnership	United States	1	NHPP	140	-	100
Les Awirs	Belgium	TBD	TBD	TBD	TBD	TBD
Atikokan Generating Station	Canada	TBD	Ontario Power Generation	TBD	TBD	TBD
Thunder Bay Generating Station	Canada	TBD	Ontario Power Generation	TBD	TBD	TBD
Port Hawkesbury	Canada	TBD	Nova Scotia Power	TBD	TBD	TBD

**Notes:**

1. This is a partial list
2. Several projects have been taken out of service in 2016-2017
3. Capacity is included in the figure for the main boiler
4. From 2017
5. Conversion to pellets decided in 2015
6. Biomass boilers supplied steam corresponding to 40 MWe out of block unit total 630 MWe
7. Biomass boilers to supply steam corresponding to 90 MWe and 320 MWth out of this from 2017

**Large Coal Conversion to Biomass Combustion Power Plant Projects**

Several successful demonstrations of pulverized coal power generation plants converted to 100% biomass plants exist today (IEA, 2016). The Drax Power (Drax Group) plant in Yorkshire, UK, completed a conversion of three 660 MWe pulverized coal units to 100% biomass wood pellet fuel during the period of 2010-2015 (IEA, 2016). The project included a significant upgrade to include biomass reception, storage, and handling, allowing up to 9 million tonnes of biomass per year (IEA, 2016).

Though now closed, the Ironbridge Power Station located in Shropshire, England, is owned by E.ON. The plant includes two 500 MWe pulverized coal-fired units and was successfully converted to 100% biomass in 2013 (IEA, 2016). The Tilbury power station near London, England, converted three 300 MWe pulverized coal boilers to biomass wood pellet fuel for approximately 2 years prior to closure (IEA, 2016). In Belgium, the 80 MWe Les Awirs plant and the 250 MWe Max Green plant were both converted from coal to 100% biomass. The DONG Energy Avedøre Unit 1 & 2 plant in Denmark was converted to 100% wood pellet biomass in 2014 (IEA, 2016).

In North America, Canada has installed 61 bioenergy plants with a total of 1,700 MWe generating capacity (IEA, 2016). The Ontario Power Generation (OPG) Atikokan Generating Station was converted from a pulverized coal plant and is now the largest power generation facility in North America using 100% biomass with generating capacity of 200 MWe. The OPG Thunder Bay Generating Station was converted from coal to advanced biomass in February, 2015 (IEA, 2016).

In the United States, biomass is used primarily in co-generation plants for the pulp and paper industry (Haq, 2002). However, one exception is the New Hope Power Partnership plant located in Tampa, Florida (Power Technology, 2014). The New Hope Power Partnership biomass power plant burns sugar cane and wood and has electrical generating capacity of approximately 140 MWe (Power Technology, 2014).

#### 4.1.2 Thermal Gasification

Similar to coal, biomass can be utilized in a thermal gasification process (Figure 7) in which solid feedstock is transformed into a combustible synthetic fuel gas containing hydrogen (IEA, 2012). The

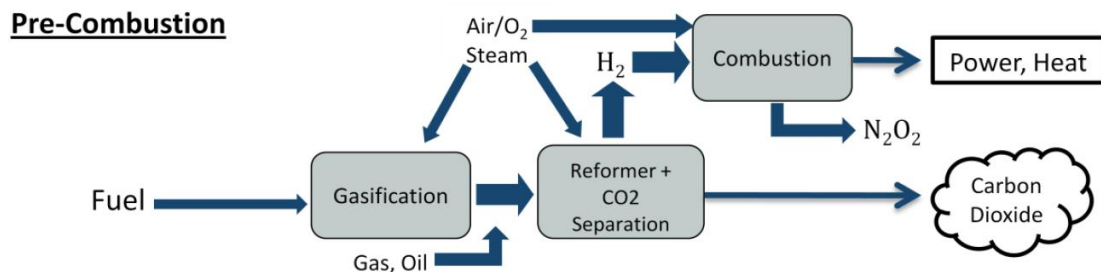


Figure 7: Pre-combustion steps (Source: Global CCS Institute: Global Status of BECCS Projects 2010)

synthetic gas with hydrogen can then be used to produce electricity with gas combustion turbines at higher efficiency than with a turbine in a steam cycle (EERE, 2017). The process involves heating the biomass with less oxygen than is needed for complete combustion. The gasification process involves operation at high temperatures (>700°C) with a defined amount of oxygen and/or steam to convert the biomass into carbon monoxide, hydrogen, and carbon dioxide (EERE, 2017). The carbon monoxide then reacts with water (steam) to form carbon dioxide and additional hydrogen using a water-gas shift reaction. Separation of the hydrogen from this gas stream is performed leaving a pure stream of carbon dioxide. The gasification of biomass does not occur as easily as with coal and an extra reforming step is needed in the presence of a catalyst to reform the remaining hydrocarbon compounds that have not been fully converted. Another shift reaction with steam again converts the produced carbon monoxide to carbon dioxide.

New developments in biomass power generation include the biomass integrated gasification combined cycle (BIGCC) concept. Further research in this area is needed to determine optimal efficiency. In addition, the Vaskiluodon Voima Oy power generating plant in Finland is one of the largest bio-gasification plants (140 MWe) to produce a gas that is burned in the existing power plant pulverized coal boiler to reduce coal consumption by approximately one half.

## Pyrolysis

Pyrolysis is a process in which the biomass is heated to 400°C and 600°C in the absence of oxygen (IEA, 2012). The products of pyrolysis are charcoal, liquid pyrolysis oil, and a product gas which can be used in the heat and power generation plants. Further work to determine whether mixing of the pyrolysis oil with conventional crude oil in refineries is feasible (IEA, 2012).

## 4.2 Fuels and Chemicals Production

### 4.2.1 Ethanol/Fermentation processes

The global consumption of fuels and chemicals is steadily rising. Currently, there are over 60 bio-refinery projects around the world producing alcohols, hydrocarbons, and intermediate chemicals from biomass like 1,4-butanediol (BDO) (Warner, Schwab, & Bacovsky, 2016).

Global demand for biofuels grew at 5% per year between 2010 and 2015. It is projected to further grow at 3.6% per year over the next two decades (74.2 million tonnes of oil equivalent (MTOE) in 2015 to 129.7 MTOE by 2035). Global demand for ethanol grew at 5.6% per year from 2011 to 2014 (BP, 2017). Ethanol and bio-butanol represent a significant part of that demand growth (BP, 2017). Ethanol is commonly made by fermenting sugars from agricultural feedstocks such as corn, beets, and sugar cane or through gasification of biomass and converting the syngas to ethanol by catalytic or bio-based approaches (e.g., LanzaTech's gas-to-ethanol technology). Further, ethanol can also be made from lignocellulosic feedstock such as woodchips, short-rotation woody crops, grasses, sugarcane bagasse, and corn stover.

The steps in producing ethanol from corn include grinding the feedstock to a coarse flour (meal), cooking the meal into a hot slurry, and adding enzymes to produce a "mash"; and fermenting the mash by adding yeast to produce ethanol, CO<sub>2</sub>, and solids from the grain and yeast, known as fermented mash. The fermented mash is distilled to produce ethanol and water, and a residue called "stillage". The ethanol is distilled to remove the water and the co-products include distiller's grains, CO<sub>2</sub>, and soluble syrup. Capturing CO<sub>2</sub> from fermentation is relatively facile compared to separating CO<sub>2</sub> from power plant flue gases because the fermentation gas stream is almost pure CO<sub>2</sub>.

Cellulosic ethanol is mainly made by acid or enzymatic pre-treatment of the woody biomass, followed by using enzymes to convert the complex polysaccharides to simple sugars and fermenting the simple sugars to ethanol, producing CO<sub>2</sub> and solid fuel (lignin). Fermentation from corn-ethanol plants represents the largest single-sector CO<sub>2</sub> source for the U.S. CO<sub>2</sub> market. The CO<sub>2</sub> is sold and utilized in the beverage industry, to create dry ice, in metal welding, the production of chemicals, pH reduction, EOR, and CO<sub>2</sub> in hydraulic fracturing applications. Raw CO<sub>2</sub> from ethanol fermentation contains trace sulfur compounds and acetaldehyde that must be removed before the gas is supplied for CO<sub>2</sub> utilization or storage. Typical corn-ethanol plants in the United States can supply approximately 390 to 725 tonnes of CO<sub>2</sub> per day (Rushing, 2015) and CO<sub>2</sub> sourced from corn-ethanol plants can displace sources with higher emissions and/or capture costs (Mueller, 2017). There are around 210 ethanol plants in the United States that together are emitting an estimated 100,000 T CO<sub>2</sub>/d (Wittig, 2016). Of these, CO<sub>2</sub> is stored or used for EOR at three plants:

- The ADM Decatur plant currently injects CO<sub>2</sub> to a saline aquifer for storage, previously injecting approximately 1 million tons of carbon over 3 years and now has the capability to store 1.1 million tons of carbon annually,
- The Bonanza BioEnergy CCUS EOR project in Garden City, Kansas (Conestoga Energy) captures ~100,000 T/y for EOR. At the Bonanza BioEnergy project, the raw fermenter gas contains more than 99% CO<sub>2</sub> and is dehydrated, compressed to 1500 psi and transported 15 miles to an oilfield where it is injected at depths around 4800' (Wittig, 2016),
- Conestoga Energy Holdings' Arkalon ethanol plant near Liberal, Kansas produces ~269,000 T/y (14 MMCF/d) CO<sub>2</sub> for EOR (Texas, Oklahoma panhandles).

#### 4.2.2 Synthesis Processes (e.g., Fischer-Tropsch [FT])

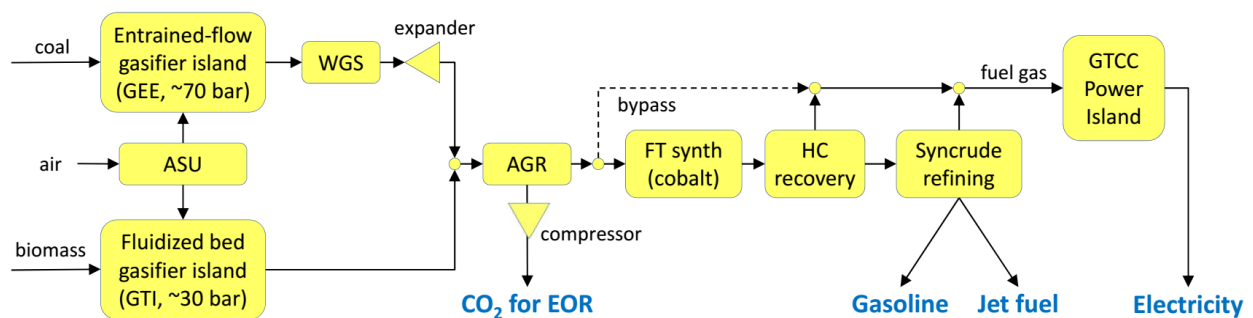


Figure 8: Block flow diagram of one potential coal-and-biomass-to-liquids (CBTL) plant. Source: (Larson, Liu, Li, Williams, & Wallace, 2013)

Biomass can be converted to fuels using heat and chemical-based approaches. Non-food/lignocellulosic feedstocks are dried, ground, and converted to a gas using oxygen and/or steam. Biomass can represent the sole source of carbon for the fuel synthesis, or it may be gasified in a plant along with conventional fossil fuels such as coal or petroleum coke. The product gas from the gasifiers is cooled and cleaned and can be used to produce fuels and chemicals such as hydrogen, substitute natural gas (SNG) via methanation, diesel, gasoline, jet fuel through Fischer-Tropsch (F-T) and refining steps, and methanol, which can be further processed to dimethyl ether, gasoline, plastics, and formaldehyde. The biomass synthesis gas does not have enough hydrogen molecules to produce chemicals and needs to be "shifted" or further processed. The proportion of hydrogen to carbon monoxide in the gas is adjusted using the water-gas shift reaction, which produces CO<sub>2</sub> and H<sub>2</sub> from CO and H<sub>2</sub>O. The CO<sub>2</sub> is separated from the shifted synthesis gas using pre-combustion CO<sub>2</sub> capture technologies such as physical solvent absorption (Selexol, Rectisol).

CO<sub>2</sub> capture from biomass-based F-T fuel production is required as a part of the synthesis process. Process CO<sub>2</sub> emissions vary from 4.4 to 4.9 kg CO<sub>2</sub> per kg of F-T product (~0.59 t-CO<sub>2</sub>/bbl F-T product) (Carbo, Smit, & van der Drift, 2010; NETL, 2013). A 100% biomass-fed F-T facility with a capacity of 10,000 bbl/d (1192 t F-T products/d) could capture up to 2 million t/y (Carbo, Smit, & van der Drift, 2010).

Conventional crude-based jet fuel life cycle GHG emissions amount to 87.4 g-CO<sub>2</sub>e/MJ (LHV basis) (Skone, 2011). Coal-based jet fuel produced under conditions when the captured CO<sub>2</sub> is used for EOR has life cycle GHG emissions of ~92 g-CO<sub>2</sub>e/MJ. CBTL jet fuel configurations with 31% switchgrass (thermal input) result in 15 to 28% reductions in life cycle CO<sub>2</sub> equivalent emissions when compared to petroleum jet fuel, but net emissions depend on whether the CO<sub>2</sub> is used for EOR or stored in saline aquifers. Larger extent of life cycle GHG emission reductions (over 50% compared to baseline jet fuel emissions) can be obtained by natural gas-biomass-to-liquids (GBTL) configurations both without (65% biomass, 35% natural gas) and with (30% biomass) CO<sub>2</sub> capture (Haq & Gupte, 2014).

### 4.3 Industrial sources

#### 4.3.1 Pulp and paper

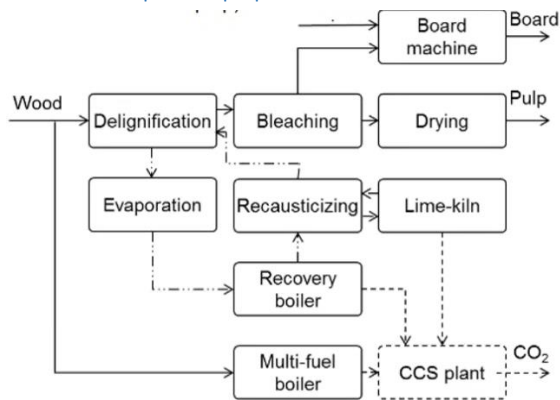


Figure 9: Block flow diagram of CO<sub>2</sub> capture applied to the pulp and paper manufacturing process (IEAGHG, 2016).

Integrated paper-and-pulp facility produces paper as the primary product. Pulp and paper production (Figure 139) consists of preparing the wood, separating the cellulosic fibers in the wood from the wood matrix (pulping) using mechanical and/or chemical means, washing the pulp and recovering chemicals for the pulping process, pulp screening, bleaching and treating the pulp to form paper (papermaking). There are three main chemical pulping processes – kraft, soda, and sulfite pulping, which use different reagents to remove cellulose fibers from the wood matrix.

Of these, kraft pulping is the most common process used for virgin (i.e., not previously used) fiber. Liquor (pulping reagent) preparation and recovery represents a major source of CO<sub>2</sub> emissions in pulp and paper making. It consists of black liquor concentration, combustion of the black liquor, and causticizing and calcining steps.

**Black liquor concentration:** The dilute (12-15% solids) weak black liquor (consisting of wood lignin, organic materials, oxidized inorganic compounds, sodium sulfate Na<sub>2</sub>SO<sub>4</sub>, sodium carbonate Na<sub>2</sub>CO<sub>3</sub>) is concentrated using a series of multiple-effect evaporators (MEEs) to increase the content of the solids to 50% (EPA, 2010). This step helps to improve the heating value of the liquor when it is burned in a recovery furnace to produce steam.

**Recovery furnace:** Organic components in the black liquor are burnt in the recovery furnace and the inorganic chemicals are recovered in a molten state. The steam generated in the furnace is used for cooking wood chips, concentrating black liquor, preheating air, and drying pulp and paper. The process steam is supplemented by burning wood or coal in power boilers.

**Causticization and calcining:** The smelt from the recovery furnace is dissolved to form the green liquor (primarily Na<sub>2</sub>S and Na<sub>2</sub>CO<sub>3</sub>, with insoluble unburned carbon, inorganic impurities), which is clarified and causticized (i.e., Na<sub>2</sub>CO<sub>3</sub> is converted to NaOH forming CaCO<sub>3</sub>) using slaked lime Ca(OH)<sub>2</sub> to produce

white liquor for the pulping process. Lime mud collected from the white liquor clarifier is burnt in a lime kiln to regenerate lime for the caustization process.

**Biogenic CO<sub>2</sub> capture from pulp and paper making:** Unlike the cement industry, most of the CO<sub>2</sub> emissions in pulp and paper production is biogenic (i.e., CO<sub>2</sub> emitted by the combustion of plant material) (Kangas, 2016). For example, the biogenic CO<sub>2</sub> emissions from a standalone kraft pulp mill would be roughly 23 times the emissions from fossil fuels used in the kiln or for supplemental firing (2.59 tonne per tonne of air-dry ton of pulp [t CO<sub>2</sub>/adt], vs. 0.11 t CO<sub>2</sub>/adt) (IEAGHG, 2016). For a typical pulp mill, roughly half of the incoming wood is converted to fiber (i.e., paper products) and tall oil. The other half is eventually burnt in the boiler, resulting in biogenic CO<sub>2</sub> emissions. Recovery boilers represent the biggest source of CO<sub>2</sub> in the pulp and paper industry (Kangas, 2016). The quantity of biogenic CO<sub>2</sub> emissions from the recovery boiler are 3.8 times the emissions from the multi-fuel boiler and the lime kiln (IEAGHG, 2016). Standalone kraft mills or integrated pulp and board mills produce excess steam and power and between 666-1127 kWh of electricity can be exported from a typical pulp and board mill and kraft pulp mill per air-dry ton of pulp respectively (Kangas, 2016). The flue gas streams from the recovery boiler, calciner, and black liquor concentration can be fed to a carbon capture system, removing the CO<sub>2</sub>. Amine solvent CO<sub>2</sub> capture and compression consumes electricity and steam, and CO<sub>2</sub> capture from the pulp mill alone requires additional steam to be extracted from the steam turbines to supply the CO<sub>2</sub> reboiler load. Because it requires additional power compared to the pulp making process, paper or board making would lower the amount of electricity exported from integrated mills compared to standalone pulp mills. Therefore, capturing CO<sub>2</sub> from an integrated pulp and paper/board mill would require an auxiliary boiler to supply the steam required for solvent regeneration. Starting in 2018, CO<sub>2</sub> Solutions Inc. will capture up to 30 t CO<sub>2</sub>/d from a softwood kraft pulp mill in Quebec, Canada. The captured CO<sub>2</sub> will be transported and used at a vegetable greenhouse (Healy, 2016). BECCS for pulp and papermaking can result in negative CO<sub>2</sub> emissions of the order of 2.3 t CO<sub>2</sub>/air-dried tonne [adt] pulp (IEAGHG, 2016).

#### 4.3.2 Waste Incineration

The composition of solid waste varies geographically. It can include food waste, garden (yard) and park waste, paper and cardboard, wood, textiles, diapers, rubber and leather, plastics, metal, and glass wastes. It includes the wastes collected and treated by municipalities but may or may not include wastes sludge), from municipal sewage sludge), municipal construction and demolition (World Bank, 2012). The energy generated by burning municipal solid waste (MSW) depends on the ratio of the biogenic to non-biogenic components of the waste stream. Typically, combustible non-biogenic materials (e.g., plastics) have higher heat content. The biogenic component of MSW is higher on a volume-basis (e.g., 63% of the U.S. MSW in 2014 (EPA, 2016)), however, because its energy content is around three-fifths of the non-biogenic (e.g., plastics) fraction, biogenic MSW contributes 51% of the energy generated in U.S. waste-to-energy (WtE) plants (EIA, 2014). The approximate energy content of MSW combusted for energy recovery ranges from 10 to 12 MJ/kg (Themelis & Mussche, 2014). WtE plants recover part of this energy as steam and/or electricity. Incineration or gasification of the MSW also reduces its volume and reduces the emissions that would be emitted if the waste was landfilled. WtE is of particular interest in countries with growing population, decreasing availability of landfills, or

high landfill tipping fees. The percent of total MSW that is burnt for energy recovery varies significantly across the world, from 70% in Japan, 53% in Norway, 26% in UK, to 13% in the United States (EIA, 2014). 74 WtE facilities in the United States with a combined heat and power capacity of 2,769 MW processed ~26 Mt/y of MSW in 2014, and generated ~14TWh of electricity (536 kWh<sub>e</sub>/t MSW). In the United States, ~1 kg of biogenic CO<sub>2</sub> and 0.7 kg non-biogenic (fossil) CO<sub>2</sub> emissions are emitted per kWh of electricity generated from WtE plants in 2014 (EIA, 2014; EPA 2014).<sup>3</sup> According to the Confederation of European Waste-to-Energy Plants (CEWEP), 88.4 Mt of waste were thermally treated in Europe in 2014 in 455 plants, generating 38 TWh of electricity and 88 TWh of heat, and corresponding to an equal amount of CO<sub>2</sub> emissions being emitted to the atmosphere (approximately 64.6 Mt CO<sub>2</sub>; IPCC, 2011).<sup>4</sup> The amount of waste being landfilled in the EU varies widely. In 2014, only 6.5% (88.4 Mt) of the waste treated in EU was incinerated and more than two-fifths (43.6%, or 593 Mt) of the waste was landfilled. If a considerable portion of the landfilled waste (593 Mt) was used for WtE, it could result in additional electricity and heat generation which could expand the market for CO<sub>2</sub> capture from waste incineration. There is, therefore, a large potential for applying CCUS to both retrofit and greenfield commercial projects for the WtE sector within the short term. Globally, over 1600 WtE plants, with an installed electric generating capacity of 11,311 MW converted 228 Mt/y MSW (WTER, 2013). Therefore, the global potential is much larger, particularly in populated countries with high growth rate. For example, China had 223 WtE plants at the end of 2015, and plans to double that number in the next three years, increasing the amount of waste burned by 2.5 times to 500,000 tonnes per day by 2020 (Stanway, 2016). This scenario would lead to an estimated emission of 166 Mt CO<sub>2</sub> (biogenic and fossil-based) from WtE plants in China every year.

Currently, there are two pilot-scale demos of CO<sub>2</sub> capture from waste incineration power plants. The emissions reduction technologies that would be normally installed on a WtE power plant may be sufficient to clean up the flue gas prior to CO<sub>2</sub> capture. However, data from large scale tests is needed to confirm this. In 2013, Toshiba installed an amine CO<sub>2</sub> capture system at the Saga MSW incineration plant in Japan. The MSW incineration plant handles 220 t/d waste, of which 70% is derived from biomass. CO<sub>2</sub> emissions (without capture) from the power plant are 220 t-CO<sub>2</sub>/d. In 2016, the company started selling the captured CO<sub>2</sub> (10 t-CO<sub>2</sub>/d) from the incinerator flue gas and supply the CO<sub>2</sub> for crop cultivation and algae culture (Toshiba, 2016). The captured CO<sub>2</sub> is transported in the gas phase via a 200 meter pipeline to a 2 hectare algae cultivation facility producing astaxanthin, a fine chemical used in cosmetics and as a nutritional supplement (Tanaka, 2016). Aker Solutions' solvent CO<sub>2</sub> capture technology is being tested at a WtE plant in Klemetsrud, Norway at the pilot scale. 60 percent of the

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<sup>33</sup> Note that neither the EPA nor the IPCC enumerate biogenic CO<sub>2</sub> emissions in plant-, or country-level total estimates. The biogenic emissions were obtained from the GHG reporting program data for the WtE facilities with CO<sub>2</sub> emissions exceeding 25,000 t/y. Only considering reported estimates of kg-CO<sub>2</sub> would lead to erroneous results as they might not account for the biogenic CO<sub>2</sub> emissions from the combustion of biological components of MSW.

<sup>4</sup> The IPCC and other reporting frameworks do not account for biomass CO<sub>2</sub> emissions, only fossil CO<sub>2</sub> emissions. Biomass emissions are considered neutral, which is sufficient from a reporting perspective, but accurate biomass CO<sub>2</sub> inventory is nevertheless important when designing a CO<sub>2</sub> capture system – these emissions would also need to be captured. This is the main drawback in applying CO<sub>2</sub> emission factors from reporting frameworks such as the IPCC to MSW incineration (or related technologies). The actual CO<sub>2</sub> emissions end up being underestimated.



waste material handled at Klemetsrud is biogenic waste (Engen, 2016). The flue gas contains around 10% CO<sub>2</sub> and (Harvey, 2016). The WtE plant at Klemetsrud emits ~0.3 Mt-CO<sub>2</sub>/y. Amine and oxy-combustion options for capturing CO<sub>2</sub> from WtE plants are further discussed by Helsing (2015).

### 4.3.3 Cement

#### **Modern cement production process**

Modern Portland cement production involves countercurrent heating of the limestone raw meal in cyclone preheaters, a fired pre-calciner, and a fired rotary kiln. Lime formed by the calcination of limestone reacts with silica (SiO<sub>2</sub>) and alumina (Al<sub>2</sub>O<sub>3</sub>) forming calcium aluminosilicates (clinker). Clinker produced in the kiln is cooled by air and is stored before being milled to fine particle sizes in cement mills where other additives such as fly ash can also be added.

**Bio-derived fuels in cement production and CO<sub>2</sub> capture:** CO<sub>2</sub> in cement plants is emitted both from limestone calcination and from fuel combustion (e.g., coal, biomass, rubber tires) to supply the heat for the endothermic calcination reaction. Members of the World Business Council for Sustainable Development (WBCSD) Cement Sustainability Initiative pledged to reduce CO<sub>2</sub> emissions by 20-25% by 2030 - a reduction of 1 Gt versus the business as usual scenario (Guenioui, 2015). The Cement Action Plan is part of WBCSD's Low Carbon Technology Partnerships initiative (LCTPi) and includes scaling up the use of alternative fuels and raw materials (AFR) in the cement-making process. The use of alternative fuels and refuse in cement production and downstream CO<sub>2</sub> capture and storage reduces the emissions from cement plants and reduces any emissions that would have been emitted from solid waste incinerators or landfills (WBCSD, 2016). CO<sub>2</sub> in cement production is mostly generated in the calciner and the kiln.

Biomass is one category of AFR that can be used in a cement plant instead of conventional fuels. The type and quantity of bio-derived fuels which are typically co-fired with coal in the kiln varies geographically and include olive waste, wood chips, sugar cane refuse, and refuse-derived fuels such as Subcoal®. Agricultural, organic, diaper waste, and charcoal represents almost 30% of the biomass used globally for cement production, followed by wood and non-impregnated saw dust (14%), animal meal (13%), and dried sewage sludge (~8%) [The rest of the biomass used in cement production does not have a specific category (34%)] (WBCSD, 2014). The use of biomass is challenging because of the lower energy content of the unprocessed biomass (e.g., raw wood has 30% the calorific value of coal), and because of the high initial moisture content, which would create large amounts of steam, leading to reduction in kiln (clinker) throughput due to the higher volume of combustion products generated per unit of clinker. Furthermore, the lower energy content and higher moisture content can lead to reduced flame temperatures and longer flame in the kiln, adversely impacting clinker reactivity (De Raedt, Kline, & Kline, 2015). AFRs vary in homogeneity, energy content, and particle sizes. Typically, high-energy content, homogenous material of less than 30 mm is required for the main burner (kiln), whereas the preheater calciners can handle particle sizes up to 80 mm (Streinik, 2016). Further, the main burner-grade solid-recovered fuel (SRF) typically has a higher energy content (19 to 22 GJ/t fuel) compared to calciner-grade SRF (16 to 19 GJ/t) (Roberts & Jennissen, 2015). Compared to biomass or MSW incineration, the high temperatures and longer residence time of cement kilns allows for a more complete combustion of fuel, thus reducing air emissions. Unlike incineration, the cement

manufacturing process produces limited residual waste, as nearly all non-combusted material is incorporated into the clinker (The Pembina Institute and Environmental Defence, 2014).

CO<sub>2</sub> emissions from fuels depend on the CO<sub>2</sub> intensity of the fuel (amount of CO<sub>2</sub> per unit energy content of fuel) and the amount of thermal energy required for a unit of cement or clinker. In 2014, the weighted-average thermal energy consumed in global cement production was 3500 MJ/t clinker (grey clinker). The amount of biomass co-fired in cement plants (~6% of total thermal input) is small when compared to quantities of fossil fuels (~84%) and fossil and mixed waste (~10%) used (WBCSD, 2014). On the other hand, industry data also show that the fraction of thermal energy supplied by biomass grew almost seven times, from 2000 to 2014, which indicates increasing world-wide adoption of biomass as a fuel in cement production. The carbon intensity of the fuel mix has decreased from 89.6 g-CO<sub>2</sub>/MJ (for producing grey clinker) in 2000 to 85.8 g-CO<sub>2</sub>/MJ in 2014 (WBCSD, 2014).<sup>5</sup> Increased use of biomass in cement plants would further lower the carbon intensity because biomass CO<sub>2</sub> emissions are considered neutral under the IPCC and CO<sub>2</sub> and energy accounting reporting standards for the cement industry (WBCSD, 2011). The fuel-CO<sub>2</sub> emissions (accounting for fossil waste and fossil fuels) for cement production would be roughly 300 kg-CO<sub>2</sub>/t clinker, which is 36% of the gross CO<sub>2</sub> emissions (842 kg-CO<sub>2</sub>/t clinker). Increasing the biomass used in cement from the global average of 6% to 15% would increase the amount of CO<sub>2</sub> emitted per unit of clinker (while reducing the 'reported' CO<sub>2</sub> emissions, which considers biomass emissions to be neutral) from ~305 kg-CO<sub>2</sub>/t clinker to 313 kg-CO<sub>2</sub>/t clinker.<sup>6</sup> Therefore, the CO<sub>2</sub> capture unit would need to capture slightly larger quantity of CO<sub>2</sub> with increasing biomass co-firing.

CO<sub>2</sub> capture from cement plants with biomass co-firing would be largely similar to the case without biomass co-firing. Post-combustion CO<sub>2</sub> capture technologies can be retrofitted to existing cement plants to capture CO<sub>2</sub> in the flue gas exiting the stack. Because there is no large steam boiler on-site, a separate steam boiler is needed if using steam to strip CO<sub>2</sub> from adsorbents or absorbents. Amines can be used for capturing CO<sub>2</sub> from cement plants, however, FGD and SCR units are needed upstream of the CO<sub>2</sub> capture process. Furthermore, the oxygen content of cement plant stack gas at the exit of the preheater cyclone strings is approximately 2-5% (dry basis) and 7-12% in the stack (ECRA, 2009). Only solvents and sorbents tolerant to oxidative degradation at high temperatures in the CO<sub>2</sub> stripper or membranes systems are recommended.

Four CO<sub>2</sub> capture technologies (amine, solid sorbent, membrane, and regenerative calcium cycle) were tested using real flue gas at the Norcem cement plant in Brevik, Norway (Bjerge & Brevik, 2014), with a goal of evaluating technologies for capturing 400,000 t CO<sub>2</sub>/y (around 50% of the plant's total CO<sub>2</sub> emissions). NO<sub>x</sub> and SO<sub>x</sub> in the cement flue gas at Norcem's Brevik plant are removed before CO<sub>2</sub>

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<sup>5</sup> The CO<sub>2</sub> intensity of solid biomass is higher than that from fossil fuels. The IPCC default emission factor for solid biomass is 110 g-CO<sub>2</sub>/MJ. Wood waste has an emission factor of 112 g-CO<sub>2</sub>/MJ, and the biomass fraction of MSW has an emission factor of 100 g-CO<sub>2</sub>/MJ (on a lower heating value basis). CO<sub>2</sub> from biomass is not accounted for in typical protocols and standards, but the quantities are relevant when designing a CO<sub>2</sub> capture and storage/utilization system to handle the CO<sub>2</sub>. [[http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2\\_Volume2/V2\\_2\\_Ch2\\_Stationary\\_Combustion.pdf](http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf)]

<sup>6</sup> This assumes 110 g-CO<sub>2</sub>/MJ for solid biomass and 85.8 g-CO<sub>2</sub>/MJ for fossil waste and fossil fuels.

removal. By 2030, Norcem plans to achieve zero-life cycle CO<sub>2</sub> emissions from its concrete products through a combination of CCUS and the use of biomass energy for cement production (around 30% of the fuel used at Norcem is derived from biomass) (Bergsli, 2017). CO<sub>2</sub> capture at the Norcem cement plant is one of the three industrial CCUS projects selected by Norway for detailed concept/front end engineering and design (FEED) studies.

#### 4.4 Summary of Economic Analyses

**Co-firing:** The total installed costs of biomass power generation and co-firing technologies varies significantly by technology, feedstock price, location, and country. As such, costs for co-firing biomass at low levels have also been reported in the range of \$400-600/kW with investment costs ranging between \$140-850/kW (IRENA, 2012).

In 2014, 487 billion kWh of electricity was produced worldwide from waste and biomass, nearly 40% in the EU-27 countries (EIA, 2016). This represents an opportunity to deploy BECCS technologies in the EU-27 countries. Retrofitting existing pulverized coal power plants to co-fire biomass increases both capital (additional equipment needed for handling biomass) and operational (e.g., biomass fuel) costs. The co-firing of 10% biomass (by heat content) in a 550 MW power plant is estimated to increase the cost of electricity by 31% for hybrid poplar co-firing, and 14% for co-firing forest residues (Skone & James, 2012). The operating and maintenance (O&M) cost of fuel is the biggest contributor to the increase in the cost of electricity, based on a cost of \$1.64/GJ (Illinois No. 6 bituminous coal, 2007\$) and hybrid poplar cost of \$4.27/GJ and forest residue cost of \$1.73/GJ (Skone & James, 2012). The ratio of the costs of coal and forest residue (0.95) compares well with the ratio of average price of coal to the price of wood and waste for electric power generation (~0.88 in 2014, 1.05 in 2013) in the United States (EIA data). The additional capital expenditure required for the biomass co-firing was estimated to be \$230/kW (2007\$).

**Fischer-Tropsch fuels:** CBTL configurations with CO<sub>2</sub> capture require the selling price (RSP) of the F-T products (e.g., jet fuel) to be more than the spot price of conventional jet fuel (DOE/NETL-2012/1563; DOE/NETL-2015/1684)<sup>7</sup>. For example, the average RSP for jet fuel from a CBTL plant fueled by Montana Rosebud sub-bituminous coal and southern pine biomass (11.7% heat input) was estimated to be \$138/bbl compared to \$98/bbl for conventional jet fuel and \$135/bbl for a CTL (0% biomass) configuration (Skone, Marriott, Shih, & Cooney, 2012). Higher levels of biomass input further increase the product cost. The use of torrefied biomass lowered the RSP, whereas gasifying the biomass in a separate gasifier increased the RSP.

**Ethanol:** The cost of capturing CO<sub>2</sub> from the ethanol fermentation step is low because the gas stream consists of just CO and moisture and needs to be only dried and compressed. The range of estimated costs of capturing and compressing CO<sub>2</sub> emissions from the ethanol fermentation process is 10/t CO<sub>2</sub> to

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<sup>7</sup> RSP is the minimum price at which the products need to be sold to recover the annual revenue requirement of the plant, which includes the operating costs, debt service (interest), and revenue to provide the expected rate of return for the investors. It is assumed that 50% of the project capital costs were financed by debt service at an interest rate of 8%. The internal rate of return on equity was assumed to be 20% in the DOE/NETL-2012/1563 report.

\$22/t CO<sub>2</sub> depending on the relative size of the ethanol facility and associated capital and operating expenses. These estimates do not include the costs of transportation and storage. (IEAGHG, 2011).

**Pulp and paper:** Biogenic CO<sub>2</sub> emissions are considered neutral under the EU's emissions trading system (ETS). Industrial facilities emitting biogenic CO<sub>2</sub> are not required to purchase CO<sub>2</sub> credits to offset their biogenic CO<sub>2</sub> emissions. On the flip side, EU facilities also do not receive preferential credits for capturing the biogenic CO<sub>2</sub>. Studies indicate that the cost of avoiding CO<sub>2</sub> emissions from a kraft pulp mill would be around \$56 to \$84/metric tonne of CO<sub>2</sub> respectively (IEAGHG, 2016). For an integrated kraft pulp and board mill, the avoided CO<sub>2</sub> emission costs for capture would be \$75 to \$85/t CO<sub>2</sub> respectively (IEAGHG, 2016). These are significant costs, because the break-even cost of pulp production is increased by around 30% in the case of capturing 90% of CO<sub>2</sub> emissions from a standalone kraft pulp mill.

**Cement:** From a plant operator's perspective, the use of biomass in cement plants is affected by market conditions. When there is abundant supply of cement, a plant can afford to lose some production to minimize energy costs. However, when the market is sold-out, any loss in clinker output would negatively impact the plant profitability, negating the advantage of using alternative fuels with higher moisture and lower energy content (Abbas & Jun, 2015). For cement plants already co-firing biomass, the costs of installing a CO<sub>2</sub> capture system would be mostly similar to cases without biomass co-firing. The cost of retrofitting a cement plant in Norway with amine-based post-combustion CO<sub>2</sub> capture was estimated to be around \$51/t CO<sub>2</sub> (Barker, 2013).

**Waste incineration:** Waste can either be landfilled or incinerated. In countries with low landfill tipping fees, it would not be feasible to add the costs of CO<sub>2</sub> capture to an already expensive WtE plant without receiving some credits or revenues from the captured CO<sub>2</sub>. Tang, Ma, Lai, and Chen (2013) showed by LCA of MSW combustion scenarios in China that oxy-fuel capture has both better efficiency and environmental impacts than MEA-based post-combustion capture. Klein, Zhang, and Themelis estimated the costs of oxycombustion-based CO<sub>2</sub> capture on a WtE plant, and found that the breakeven landfill tipping fee for the project to be feasible was around \$59/ton of MSW.

An overview of this section is provided in Table 5.

**Table 5: Summary of costs of technologies considered in this report**

Technology	Type	Capital cost	CO <sub>2</sub> partial pressure in the inlet gas, kPa	CO <sub>2</sub> capture cost	Other
Biomass co-firing	Retrofit	\$140-\$850/kW	10-15		
Fischer-Tropsch fuels	CBTL plant, sub-bituminous coal + southern pine (11.7%)		460-500		RSP of fuel: \$138/bbl vs. \$98/bbl for jet fuel
Ethanol	Fermentation CO <sub>2</sub> emissions		~95	\$5-\$10/t to \$22/t	
Pulp and paper	Amine CO <sub>2</sub> separation		10-15		Avoided cost: \$70-\$72/t for pulp mill
Cement			14-21	\$51/t	
Waste incineration			10-15		Breakeven tipping fee for oxycombustion CCS: \$59/t-MSW, or ~\$ 65/t-CO <sub>2</sub>

#### 4.5 Summary of Technical Challenges and R&D Opportunities

The technical challenges are summarized below.

**Table 6: Technical Challenges**

Challenge	Co-firing	F-T fuels	Ethanol	Pulp and paper	Cement	Waste incineration
Can steam from process supply all/part of steam required (for CO <sub>2</sub> capture)?	Yes	Yes	NA	Yes	Yes	Yes
Is flue gas pretreatment required (before CO <sub>2</sub> capture)?	Yes	Yes	No, minimal gas scrubbing	Yes	Yes	Yes
Can a large part of captured CO <sub>2</sub> be biogenic?	Yes, varies with amount of biomass	No, 10-15%	Yes	Yes	No	Yes, varies with MSW (50-60%)
Energy requirement for CCS	Moderate	Low	Minimal	Moderate	Moderate	Moderate

#### R&D Opportunities

There is a need for establishing research programs exploring BECCS concepts in several sectors. Unlike the power sector, there are no well-defined research programs that outline a way to achieve the commercial deployment of BECCS for most of the industries discussed in this report by successive RD&D efforts at several scales. Current RD&D projects for specific industries were discussed previously in this section. Some of the common research issues to be addressed include:

- Evaluating the impact of CO<sub>2</sub> capture on plant operations and competitiveness: The capture of CO<sub>2</sub> from ethanol plants is less energy intensive than capturing CO<sub>2</sub> from cement or pulp/paper mill flue gases. Systematic evaluation of the impacts on production and operational costs is needed.
- Studying the impact of gas stream impurities on CO<sub>2</sub> capture technologies that were developed for the power generation industries: The types and composition of impurities in gas streams from biomass co-firing, ethanol, biomass-to-liquids plants, cement, and waste incineration plants is different from those encountered in gas streams in power plants. For instance, waste incineration plant flue gas may require pretreatment to remove chlorine, dioxins and other compounds before the CO<sub>2</sub> separation step.
- Exploring novel means to recover waste heat from industrial processes and integrate this with the CO<sub>2</sub> capture and compression step: Part of the steam required for CO<sub>2</sub> capture from paper and pulp and cement gas streams can be recovered from flue gas waste heat. Studies on the heat/process integration between the CO<sub>2</sub> capture process and the production plant are needed to gauge what level would be most optimal.
- Exploring the diverse incentives and opportunities that drive the adoption of BECCS: With the exception of pulp and paper, most other processes (co-firing, XTL, ethanol, cement, WtE) are driven by incentives and regulations such as renewable energy portfolio standards, industry GHG standards, high waste disposal fees, and production and/or investment tax credits. These factors determine the economic feasibility of the capturing and storing biomass-derived CO<sub>2</sub>.

## 5 Findings and Recommendations

The following section provides a summary of the findings that are highlighted in recent sections of this document, and the recommendations for further work in the area of BECCS development and deployment.

### 5.1 Report Summary Findings

A summary of the primary findings described in the Technical Summary of Bioenergy Carbon Capture and Storage that are provided by the Technical Group Task Force are as follows:

#### **Challenges and Benefits of BECCS**

- BECCS development and implementation in both the power generation and industrial sectors faces some of the same challenges and hurdles that must be addressed in plants which burn coal, gas, and oil. That is, the high capital cost and energy penalty associated with CCUS results in an unfavorable economic condition for the deployment of new BECCS projects without the intervention of government in the form of subsidies and regulations.
- When considering the application of BECCS in bioenergy, sustainability of available feedstocks and efficiency of the whole bioenergy conversion system remain to be issues that must be addressed.

### **Biomass and Carbon Storage Resource Assessment**

- Biomass accounts for 10% of global primary energy used for heat and electricity (IEA, 2017) and is also utilized for industrial processes. The United States leads the world in biomass-generated electricity, followed by Germany and China (IEA, 2015).
- Some of the important factors that will affect bioenergy sustainability include: impact on soil quality, biomass quality, harvest levels, water use and efficiency, water quality, social impacts including allocation for land for bioenergy crops, price and supply of other commodities, and biological diversity in the landscape where bioenergy production is proposed.
- For biomass conversion and wide-scale deployment of bioenergy to reduce GHG emissions or achieve negative emissions, the processes must be integrated with CCUS (IEAGHG, 2014).

### **Direct and Indirect GHG emissions**

- GHG can be in the form of direct and indirect emissions. Reaching global emissions targets set forth during COP21 will require bringing annual global emissions below 20 Gt CO<sub>2</sub>-eq/year and mitigating upwards of 600 Gt of CO<sub>2</sub> over the 20th century. BECCS has the potential to mitigate up to 3.3 GtC per year (Smith, 2016).
- Deployment of BECCS as a climate mitigation solution will necessitate planting bioenergy crops on approximately 430-580 million hectares of land (approximately one-third of the arable land on the planet or about half of the U.S. land area (Williamson, 2016).

### **Life Cycle Assessments**

- Comparing various combustion options, including co-firing and dedicated biomass combustion, the net life cycle CO<sub>2</sub> emissions appear to depend on biomass type and the combustion method (Weisser, 2007; Odeh & Cockrell, 2007; Cai, et al., 2014; Schakel et al., 2014).
- The net life cycle CO<sub>2</sub> emissions also depend on the data, LCA methodology, and analysis assumptions and in many cases, the data and assumptions are inaccurate or out of date (Schakel et al., 2014).
- The lowest net life cycle CO<sub>2</sub> emissions involve the use of poplar biomass using Biofuel IGCC technology with co-firing percentage of 100% (See Schakel, Meerman, Talaei, Ramirezrez, & Faaij, 2014 for Study references).

### **Commercial Status of BECCS Technology Development**

- The majority of BECCS projects are located at ethanol fermentation facilities.
- The Illinois Basin Decatur and now the Illinois Industrial CCS Project (IL\_ICCS) Archer Daniel Midland (ADM) ethanol plant is now capturing a total of 1 MtCO<sub>2</sub>/yr and is the largest operational BECCS project in the world.
- There are currently five additional BECCS projects in operation, which capture approximately 0.85 MtCO<sub>2</sub>/yr. Conestoga's Arkalon and Bonanza ethanol plants, RCI/OCAP plant in Rotterdam, NL on Shell's Pernis refinery and Abengoa's ethanol plant, Maasvlakte power plant, Huskey energy's ethanol plant, Saga City waste to energy plant. Significantly more CCUS projects will be necessary to achieve the required CO<sub>2</sub> emission reductions.

## **Government Programs**

- Government support for BECCS projects is extremely important in the future deployment of these projects. In the United States, the US Department of Energy has provided a portion of the funding for the ADM BECCS project to support construction and operation of the facility.
- Another important government program in the United States that would support BECCS is the an expansion of the section 45Q in the U.S. tax code which increases tax credits to \$50/tCO<sub>2</sub> and saline storage and \$35/tCO<sub>2</sub> for utilization. These could lead to increased ethanol BECCS projects for both saline storage and associated storage during EOR, respectively (NEORI, 2016)
- The California Air Resource Board (ARB) is in the process of determining how CCUS can contribute towards the state's cap-and-trade and low carbon fuel standard regulations, both of which could drive BECCS projects by providing a framework to account for stored CO<sub>2</sub> to reduce the carbon footprint of low carbon transportation fuels sold into the California market (CEPA, 2016).
- Language in the U.S Senate version of the Energy Bill introduced in 2016 authorized \$22M/yr for 5 years to support a partial BECCS co-fired biomass + coal power project in the southeastern United States (CCR, 2016), and the U.S. Department of Energy's Advanced Projects Research Agency-Energy (ARPA-E) has also explored launching a program dedicated to BECCS innovation in the near future (Stark, 2016). Bio-CCS research has been funded through the EU Framework Programme for research and Innovation's Horizon 2020 Program since 2014.
- In Norway, the Klemetsrud partial-BECCS facility at a municipal solid waste plant is receiving support from the City of Oslo government (Engen, 2016) and the Ministry of Petroleum and Energy through the CLIMIT program.

## **Market Drivers for BECCS Deployments**

- The most significant driver for BECCS projects today is policy support.
- In the United States, EOR can help drive some of the demand for ethanol BECCS projects if either co-located near existing oil fields or CO<sub>2</sub> pipeline. Regional clusters of bioenergy plants such as in the Midwest United States would benefit from a dedicated CO<sub>2</sub> pipeline gathering systems to transport CO<sub>2</sub> to EOR markets.
- Corporate demand for BECCS projects is very low. The biggest potential hurdle with BECCS projects for corporate buyers is on the GHG accounting side. Corporations are exposed to potential negative public perception of BECCS as an effective climate strategy.
- Finance is an important factor for BECCS projects. The cost of capital is high for early generation BECCS projects. Programs such as loan guarantees, extending master limited partnership tax structures for BECCS projects, and offering government-backed price-stabilization contracts for CO<sub>2</sub> off-take can enable faster and wider market adoption of BECCS projects.

## **Barriers to Large scale BECCS Demonstration and Deployment**

### **Technical**

- There are many barriers to large-scale BECCS deployment which the industry will need to address prior to wide scale adoption of the technology.



- Technical barriers are related to the biomass combustion/conversion process which can lead to slagging, increased corrosion, and fouling (Pourkashanian. et al., 2016).
- Further research is needed to identify feedstocks that require limited processing, compatibility with existing boiler and pollution control equipment, and reduction in cost of processing equipment costs and associated energy costs.

### **Economics and incentives**

- There is no incentive for CCUS or even BECCS, besides limited government support.
- A BECCS plant in the power sector might provide a double benefit: producing low-carbon electricity and negative emissions at the same time (Dooley, 2012).
- Co-firing biomass in heat and power plant appears to be the most efficient way in terms of GHG reduction targets in a cost-effective manner (REN21 2013; Junginger, et al., 2014; Sterner and Fritsche, 2011).
- Many low-carbon policies and GHG accounting frameworks do not appropriately recognise, attribute, and reward BECCS and negative emissions in general, especially regional cap-and-trade schemes (IEAGHG, 2014; Zakkour, et al., 2014). As a result, there are no incentives to capture and store biogenic emissions over zero emissions, e.g., from dedicated biomass firing without CO<sub>2</sub> storage.
- Public perception of BECCS is composed of two parts: 1) image of biomass/bioenergy and 2) CCUS. Public perception of BECCS varies with location and social/cultural background and it can be either a driver or a barrier. BECCS generally has a lower profile than fossil-CCUS and appears to lack support among external, as well as its own, stakeholders (Dowd, et al., 2015). When competing with other mitigation options, such as renewable energy and energy efficiency, fossil-CCUS and BECCS are usually perceived as non-favourable (TNS 2003).

### **Land Demand and Land Use Change (LUC: dLUC and iLUC)**

- A critical issue related to sustainable bioenergy production for BECCS is LUC. LUC can be direct or indirect. The balance between LUC and association emissions is critical as it may render any zero emissions, negative emissions, or double benefit assumption invalid (Kemper 2015).
- Lack of infrastructure (i.e., for biomass, natural gas, and CO<sub>2</sub> as well as CO<sub>2</sub> storage/utilization) could be a showstopper for BECCS projects. The timeline for CCUS deployment could be the most important cost barrier for BECCS (Edenhofer, et al., 2010; Tavoni, et al., 2012; Krey, et al., 2014; Kriegler, et al., 2014; Riahi, et al., 2014). Large-scale biomass supply chains and trade need further development. One issue of great concern is how to avoid food price increases due to land use competition. Improvements in crop yield increases, food waste reduction, and demand side changes could help free land for bioenergy production (Thomson, et al., 2010).

### **Water Usage**

- Bioenergy applications require disproportionately high amounts of water, especially when compared to other energy production options (WEC, 2010). Irrigation of bioenergy crops is likely to be very costly and to compete with other uses. Research into high energy yield crops with reduced water demand are required for wide-scale deployment.

### **BECCS Technology Options and Pathways**

- The power generation sector, which is comprised of the electricity and heat production industry, is a large contributor to global CO<sub>2</sub> emissions and contributes approximately 25-35% of the global GHG emissions (IPCC, 2014).
- Biomass firing and co-firing can substantially reduce GHG emissions in the production of electrical power (IRENA, 2012). A BECCS power plant may utilize pre-combustion, post-combustion, or oxy-fuel technology in the capture of CO<sub>2</sub>.
- Biomass has been successfully used to supplement pulverized coal in power generation. The biomass industry supplies about 52 GW of global power generation capacity, mostly using wood pellets, municipal solid waste, agricultural waste (Block, 2009).
- Wood pellets are the preferred source of biomass used for BECCS in power generation (WBDG, 2016). Other types of biomass have been used including straws, grasses, animal wastes, forestry residues, and other agricultural processing residues (IEA, 2016).
- Typical biomass power plant sizes are based upon availability of local feedstocks and range between 10 and 50 MWe in size (IEA, 2012). The power generation efficiencies of plants in the 10-50 MWe size without CCUS range between 10-33%, lower than plants that burn natural gas or coal (IEA, 2012).
- Biomass combustion produces acid gases such as SO<sub>x</sub>, NO<sub>x</sub>, and HCl, but at levels that are lower than those for most coals. Trace metals such as mercury are present in flue gas from biomass plants at levels dependent upon the type of biomass that is used.
- Mercury emissions from pulverized coal plants can be reduced when co-firing with biomass if halogens are present in the biomass. (Cao, et al., 2008).
- Biomass fuels such as poultry litter that could be used in co-firing, for example, can contain higher levels of lead, arsenic, copper, iron, zinc, and mercury and may require additional treatment when used as a biofuel in power generation applications (Ewall, 2007).

### **Biomass Co-firing**

- The co-firing of biomass at pulverized coal power generation plants is well established and cost-effective (IEA, 2016). The use of biomass co-firing provides co-benefits in reducing flue gas cleaning as acid gases such as SO<sub>x</sub>, HCl, and NO<sub>x</sub> are typically reduced in the flue gas (IEA, 2016).
- Different approaches to co-firing of biomass at pulverized coal power plants that have been used at several locations in North America and Europe (IEA, 2016). Co-firing ratios of biomass to coal have ranged between 5-50% (IEA, 2016). Co-firing can occur by gasification of the biomass in a separate gasifier to form a gas which is combined with air and injected into the pulverized coal boiler for combustion (IEA, 2016).
- In Europe, electricity generation from biomass peaked between 2005-2006 due to government subsidies (IEA, 2016) and again between 2010-2012. But without subsidies, a sharp reduction in electrical generation with biomass can occur, as it did in the Netherlands (IEA, 2016).

### **Large Coal to Biomass Conversions and Biomass Combustion Power Plant Projects**

- Several successful demonstrations of pulverized coal power generation plants involving conversion to 100% biomass plants (IEA, 2016). The Drax Power (Drax Group) plant in Yorkshire,

UK, the Ironbridge Power Station located in Shropshire, England, the Tilbury power station near London, England, the Les Awirs plant and the Max Green plant with DONG Energy in Belgium were all high profile power projects that converted their fuel source to biomass (IEA, 2016). The fuel for this facility is sourced from southeast United States, demonstrating the challenges of regional fuel supply.

- In North America, Canada installed 61 bioenergy plants through 2016 with a total of 1,700 MWe generating capacity (IEA, 2016).
- The Ontario Power Generation (OPG) Atikokan Generating Station was converted from a pulverized coal plant and is now the largest power generation facility in North America using 100% biomass with generating capacity of 200 MWe.

### **Thermal Gasification**

- Similar to coal, biomass can be utilized in a thermal gasification process in which solid feedstock is transformed into a combustible synthetic fuel gas containing hydrogen (IEA, 2012). New developments in biomass power generation include the biomass integrated gasification combined cycle (BIGCC) concept. The Vaskiluodon Voima Oy power generating plant in Finland is one of the largest bio-gasification plants (140 MWe) to produce a gas that is burned in the existing power plant pulverized coal boiler to reduce coal consumption by approximately one half (C Breitholtzs, 2011).
- Pyrolysis is a process in which the biomass is heated in the absence of oxygen (IEA, 2012). The products of pyrolysis are charcoal, liquid pyrolysis oil, and a product gas which can be used as fuel in heat and power generation plants. Further work to determine whether mixing of the pyrolysis oil with conventional crude oil in refineries is feasible (IEA, 2012).

### **Fuels and Chemicals Production**

- Currently, there are over 60 bio-refinery projects around the world producing alcohols, hydrocarbons, and intermediate chemicals from biomass like 1,4-butanediol (BDO) (Warner, Schwab, & Bacovsky, 2016).
- Global demand for biofuels grew between 2010 and 2015 and is projected to further grow over the next two decades. Global demand for ethanol grew from 2011 to 2014 (BP, 2017). Ethanol and bio-butanol represent a significant part of that demand growth (BP, 2017). Fermentation from corn-ethanol plants represents the largest single-sector CO<sub>2</sub> source for the U.S. CO<sub>2</sub> market.
- Raw CO<sub>2</sub> from ethanol fermentation contains trace sulfur compounds and acetaldehyde that must be removed before the gas is supplied for CO<sub>2</sub> utilization or storage. CO<sub>2</sub> sourced from corn-ethanol plants can displace sources with higher emissions and/or capture costs (Mueller, 2017). There are around 210 ethanol plants in the United States that together emit an estimated 100,000 T CO<sub>2</sub>/d (Wittig, 2016). Of these, CO<sub>2</sub> is stored in saline formations or used for EOR, resulting in associated storage, at three plants:
  1. The ADM Decatur plant currently injects CO<sub>2</sub> to a saline aquifer for storage,

2. The Bonanza BioEnergy CCUS EOR project in Garden City, Kansas (Conestoga Energy) project captures ~100,000 T/y for EOR.
3. Conestoga Energy Holdings' Arkalon ethanol plant near Liberal, Kansas produces ~269,000 T/y (14 MMCF/d) CO<sub>2</sub> for EOR (Texas, Oklahoma panhandles).

### **Synthesis Processes**

- Biomass can be converted to fuels using heat and chemical-based approaches.
- Biomass can be used to produce fuels and chemicals such as hydrogen, substitute natural gas (SNG) via methanation, diesel, gasoline, jet fuel through F-T and refining steps, and methanol, which can be further processed to dimethyl ether, gasoline, plastics, and formaldehyde.
- The CO<sub>2</sub> is separated from the shifted synthesis gas using pre-combustion CO<sub>2</sub> capture technologies such as physical solvent absorption (Selexol, Rectisol).
- CO<sub>2</sub> capture from biomass-based F-T fuel production is required as a part of the synthesis process
- Coal-based jet fuel produced under conditions when the captured CO<sub>2</sub> is used for EOR has life cycle GHG emissions of ~92 g-CO<sub>2</sub>e/MJ. CBTL jet fuel configurations with 31% switchgrass (thermal input) result in 15 to 28% reductions in life cycle CO<sub>2</sub> equivalent emissions when compared to petroleum jet fuel, but net emissions depend on whether the CO<sub>2</sub> is used for EOR or stored in saline aquifers (Skone, 2011).
- Larger extent of life cycle GHG emission reductions (over 50% compared to baseline jet fuel emissions) can be obtained by natural GBTL configurations both without (65% biomass, 35% natural gas) and with (30% biomass) CO<sub>2</sub> capture (Haq & Gupte, 2014).

### **Pulp and paper**

- Liquor (pulping reagent) preparation and recovery represents a major source of CO<sub>2</sub> emissions in pulp and paper making. Most of the CO<sub>2</sub> emissions in pulp and paper production is biogenic (i.e., CO<sub>2</sub> emitted by the combustion of plant material) (Kangas, 2016). Recovery boilers represent the biggest source of CO<sub>2</sub> in the pulp and paper industry (Kangas, 2016). The flue gas streams from the recovery boiler, calciner, and black liquor concentration can be fed to an amine solvent-based CO<sub>2</sub> absorber to remove the CO<sub>2</sub>. Capturing CO<sub>2</sub> from an integrated pulp and paper/board mill would require an auxiliary boiler to supply the steam required for solvent regeneration.

### **Waste Incineration**

- The composition of solid waste varies geographically. It can include food waste, garden (yard) and park waste, paper and cardboard, wood, textiles, diapers, rubber and leather, plastics, metal, and glass wastes.
- The energy generated by burning MSW depends on the ratio of the biogenic to non-biogenic components of the waste stream. The approximate energy content of MSW combusted for energy recovery ranges from 10 to 12 MJ/kg (Themelis & Mussche, 2014). Waste to Energy (WtE) plants recover part of this energy as steam and/or electricity. Incineration or gasification

of the MSW also reduces its volume and reduces the emissions that would be emitted if the waste was landfilled.

- WtE is of particular interest in countries with growing population, decreasing availability of landfills, or high landfill tipping fees. The percent of total MSW that is burnt for energy recovery varies significantly across the world, from 70% in Japan, 53% in Norway, 26% in UK, to 13% in the United States (EIA, 2014).
- There are 74 WtE facilities in the United States with a combined heat and power capacity of 2,769 MW processed ~26 Mt/y of MSW in 2014, and generated ~14 TWh of electricity (536 kWh<sub>e</sub>/t MSW). In the United States, ~1 kg of biogenic CO<sub>2</sub> and 0.7 kg non-biogenic (fossil) CO<sub>2</sub> emissions are emitted per kWh of electricity generated from WtE plants in 2014 (EIA 2014, EPA 2014).<sup>8</sup>
- According to the Confederation of European Waste-to-Energy Plants (CEWEP) 88.4 Mt of waste were thermally treated in Europe in 2014 in 455 plants, generating 38 TWh of electricity and 88 TWh of heat, and corresponding to an equal amount of CO<sub>2</sub> emissions being emitted to the atmosphere (IPCC, 2011). The amount of waste being landfilled in the EU varies widely. In 2014, only 6.5% (88.4 Mt) of the waste treated in the EU was incinerated and more than two-fifths (43.6%, or 593 Mt) of the waste was landfilled. If a considerable portion of the landfilled waste (593 Mt) was used for WtE, it could result in additional electricity and heat generation which could expand the market for CO<sub>2</sub> capture from waste incineration.
- There is a large potential for applying CCUS to both retrofit and greenfield commercial projects for the WtE sector within the short term. Globally, there are over 1600 WtE plants, with an installed electric generating capacity of 11,311 MW converted 228 Mt/y MSW (WTERT, 2013). The global potential is much larger, particularly in populated countries with high growth rate.
- Currently, there are two pilot-scale demos of CO<sub>2</sub> capture from waste incineration power plants.
- Aker Solutions' solvent CO<sub>2</sub> capture technology is being tested at a WtE plant in Klemetsrud, Norway at the pilot scale. 60% of the waste material handled at Klemetsrud is biogenic waste (Engen, 2016). The flue gas contains around 10% CO<sub>2</sub> and (Harvey, 2016). The WtE plant at Klemetsrud emits ~0.3 Mt-CO<sub>2</sub>/y. Amine and oxy-combustion options for capturing CO<sub>2</sub> from WtE plants are further discussed by (Helsing, 2015)

## Cement

- CO<sub>2</sub> in cement plants is emitted both from limestone calcination and from fuel combustion (e.g., coal, biomass, rubber tires) to supply the heat for the endothermic calcination reaction. CO<sub>2</sub> in cement production is mostly generated in the calciner and the kiln.
- Members of the WBCSD Cement Sustainability Initiative pledged to reduce CO<sub>2</sub> emissions by 20-25% by 2030 (Gueniou, 2015).

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<sup>88</sup> Note that neither the EPA nor the IPCC enumerate biogenic CO<sub>2</sub> emissions in plant-, or country-level total estimates. The biogenic emissions were obtained from the GHG reporting program data for the WtE facilities with CO<sub>2</sub> emissions exceeding 25,000 t/y. Only considering reported estimates of kg-CO<sub>2</sub> would lead to erroneous results as they might not account for the biogenic CO<sub>2</sub> emissions from the combustion of biological components of MSW.

- The use of alternative fuels in cement production and downstream CO<sub>2</sub> capture and storage reduces the emissions from cement plants, as well as reduces any emissions that would have been emitted from solid waste incinerators or landfills (WBCSD, 2016). Biomass is one category of alternate fuels and raw materials (AFR) that can be used in a cement plant instead of conventional fuels.
- The lower energy content and higher moisture content can lead to reduced flame temperatures and longer flame in the kiln, adversely impacting clinker reactivity (De Raedt, Kline, & Kline, 2015).
- Compared to biomass or MSW incineration, the high temperatures and longer residence time of cement kilns allows for a more complete combustion of fuel, thus reducing air emissions. Unlike incineration, the cement manufacturing process produces limited residual waste, as nearly all non-combusted material is incorporated into the clinker (The Pembina Institute and Environmental Defence, 2014).
- The amount of biomass co-fired in cement plants (~6% of total thermal input) is small when compared to quantities of fossil fuels (~84%) and fossil and mixed waste (~10%) used (WBCSD, 2014).
- Industry data also show that the fraction of thermal energy supplied by biomass grew almost seven times, from 2000 to 2014, which indicates increasing world-wide adoption of biomass as a fuel in cement production.
- The carbon intensity of the fuel mix has decreased from 89.6 g-CO<sub>2</sub>/MJ (for producing grey clinker) in 2000 to 85.8 g-CO<sub>2</sub>/MJ in 2014 (WBCSD, 2014).<sup>9</sup> Increased use of biomass in cement plants would further lower the carbon intensity because biomass CO<sub>2</sub> emissions are considered neutral under the IPCC and CO<sub>2</sub> and energy accounting reporting standards for the cement industry (WBCSD, 2011).
- Four CO<sub>2</sub> capture technologies were tested using real flue gas at the Norcem cement plant in Brevik, Norway (Bjerge & Brevik, 2014), with a goal of evaluating technologies for capturing 400,000 t CO<sub>2</sub>/y (around 50% of the plant's total CO<sub>2</sub> emissions).
- By 2030, Norcem plans to achieve zero-life cycle CO<sub>2</sub> emissions from its concrete products through a combination of CCUS and the use of biomass energy for cement production (around 30% of the fuel used at Norcem is derived from biomass) (Bergsli, 2017).
- CO<sub>2</sub> capture at the Norcem cement plant is one of the three industrial CCUS projects selected by Norway for detailed concept/front end engineering and design (FEED) studies.

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<sup>9</sup> The CO<sub>2</sub> intensity of solid biomass is higher than that from fossil fuels. The IPCC default emission factor for solid biomass is 110 g-CO<sub>2</sub>/MJ. Wood waste has an emission factor of 112 g-CO<sub>2</sub>/MJ, and the biomass fraction of MSW has an emission factor of 100 g-CO<sub>2</sub>/MJ (on a lower heating value basis). CO<sub>2</sub> from biomass is not accounted for in typical protocols and standards, but the quantities are relevant when designing a CO<sub>2</sub> capture and storage/utilization system to handle the CO<sub>2</sub>. [[http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2\\_Volume2/V2\\_2\\_Ch2\\_Stationary\\_Combustion.pdf](http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_2_Ch2_Stationary_Combustion.pdf)]

## 5.2 Summary of Economic Analyses

### Co-firing

- The total installed costs of biomass power generation and co-firing technologies varies significantly by technology, feedstock price, location, and country.
- As such, costs for co-firing biomass at low levels have also been reported in the range of \$400-600/kW with investment costs ranging between \$140-850/kW (IRENA, 2012).
- Retrofitting existing pulverized coal power plants to co-fire biomass increases both capital (additional equipment needed for handling biomass) and operational (e.g., biomass fuel) costs.
- The co-firing of 10% biomass (by heat content) in a 550 MW power plant is estimated to increase the cost of electricity by 31% for hybrid poplar co-firing, and 14% for co-firing forest residues (Skone & James, 2012). The O&M cost of fuel is the biggest contributor to the increase in the cost of electricity (Skone & James, 2012).
- The additional capital expenditure required for the biomass co-firing was estimated to be \$230/kW (2007\$) (Skone & James, 2012).

### Fischer-Tropsch fuels

- CBTL configurations with CO<sub>2</sub> capture require the selling price (RSP) of the F-T products (e.g., jet fuel) to be more than the spot price of conventional jet fuel (DOE/NETL-2012/1563; DOE/NETL-2015/1684)<sup>10</sup>.
- Higher levels of biomass input further increase the product cost. The use of torrefied biomass lowered the RSP, whereas gasifying the biomass in a separate gasifier increased the RSP.

### Ethanol

- The cost of capturing CO<sub>2</sub> from the ethanol fermentation step is low because the gas stream needs to be only dried and compressed (no amine capture unit is needed).
- The range of estimated costs of capturing fermentation CO<sub>2</sub> emissions is \$10/t CO<sub>2</sub> to \$22/t CO<sub>2</sub> (without transportation and storage costs) (IEAGHG, 2011).

### Pulp and paper

- Biogenic CO<sub>2</sub> emissions are considered neutral under the European Union's ETS.
- Industrial facilities emitting biogenic CO<sub>2</sub> are not required to purchase CO<sub>2</sub> credits to offset their biogenic CO<sub>2</sub> emissions. On the flip side, EU facilities also do not receive preferential credits for capturing the biogenic CO<sub>2</sub>.
- Studies indicate that the cost of avoiding 69-90% of CO<sub>2</sub> emissions from a kraft pulp mill would be around \$72 to \$70/metric tonne of CO<sub>2</sub> respectively (IEAGHG, 2016).
- For an integrated kraft pulp and board mill, the avoided CO<sub>2</sub> emission costs for 62% to 74% capture would be \$91 to \$98/t CO<sub>2</sub> respectively (IEAGHG, 2016). These are significant costs,

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<sup>10</sup> RSP is the minimum price at which the products need to be sold to recover the annual revenue requirement of the plant, which includes the operating costs, debt service (interest), and revenue to provide the expected rate of return for the investors. It is assumed that 50% of the project capital costs were financed by debt service at an interest rate of 8%. The internal rate of return on equity was assumed to be 20% in the DOE/NETL-2012/1563 report.

because the break-even cost of pulp production is increased by around 30% in the case of capturing 90% of CO<sub>2</sub> emissions from a standalone kraft pulp mill.

### **Cement**

- From a plant operator's perspective, the use of biomass in cement plants is affected by market conditions. When there is abundant supply of cement, a plant can afford to lose some production to minimize energy costs. When the market is sold-out, any loss in clinker output would negatively impact the plant profitability, negating the advantage of using alternative fuels with higher moisture and lower energy content (Abbas & Jun, 2015).
- For cement plants already co-firing biomass, the costs of installing a CO<sub>2</sub> capture system would be mostly similar to cases without biomass co-firing.
- The cost of retrofitting a cement plant in Norway with amine-based post-combustion CO<sub>2</sub> capture was estimated to be around \$51/t CO<sub>2</sub> (Barker, 2013).

### **Waste incineration**

- Waste can either be landfilled or incinerated. In countries with low landfill tipping fees, it would not be feasible to add the costs of CO<sub>2</sub> capture to an already expensive WtE plant without receiving some credits or revenues from the captured CO<sub>2</sub>.
- Tang, Ma, Lai, and Chen (2013) showed by LCA of MSW combustion scenarios in China that oxy-fuel capture has both better efficiency and environmental impacts than MEA-based post-combustion capture. (Klein, et al., Klein, Zhang, & Themelis, 2003)
- Klein, et al. (Klein, Zhang, & Themelis, 2003) estimated the costs of oxycombustion-based CO<sub>2</sub> capture on a WtE plant, and found that the breakeven landfill tipping fee for the project to be feasible was around \$59/ton of MSW.

## **5.3 Study Recommendations**

A summary of the Recommendations developed by the Technical Group Task Force arriving from the Technical Summary of Bioenergy Carbon Capture and Storage document:

- Focus resources on education of policy makers with respect to the benefits of BECCS market opportunities, opportunities for EOR and negative carbon emissions.
- Perform research to develop and identify biomass feedstocks that require limited processing.
- Perform continued research to develop and identify new capture technologies that will have a substantially lower cost of electricity and address the unique flue gas compositions from bioenergy applications.
- Support regional organizations to track and monitor feedstock availability to insure sufficient quantities can be provided for continuous power generation.
- Incentivising the double benefit of BECCS can help avoid direct investment competition with other abatement options. Concerted efforts, e.g., global forest protection policies, carbon stock incentives, and bioenergy/renewable energy incentives, are necessary to avoid undesirable LUC emissions (Wise, et al., 2009; Clarke, et al., 2014).



- Early BECCS projects should aim to use mainly “additional” biomass and 2<sup>nd</sup> generation biofuel crops to avoid adverse impacts on land use and food production (Smith, et al., 2014). However, additional biomass is likely to be costlier due to, for example, increased irrigation.
- BECCS options that optimize water use and carbon footprint need to be identified through careful selection of crops, location, cultivation methods, pre-treatment processes, and biomass conversion technologies. Sustainable biomass feedstocks will require avoidance of unsustainable harvesting practices, e.g., exceeding natural replenishment rates (IPCC, 2014). Using “additional biomass” to avoid sustainability issues also helps improve public acceptance (Searchinger and Heimlich, 2015).
- Sustainability needs to be ensured across the whole BECCS chain. Improving pre-treatment processes for biomass (i.e., densification, dehydration, and pelletisation) will make biomass transport more efficient and remove geographical limitations of biomass supply (Hamelinck, et al., 2005; Luckow, et al., 2010).

### **Public Perception**

- BECCS project developers and advocates should focus more on building up trust with the general public and local communities (Upham and Roberts, 2010) instead of just providing educational information.
- Stronger collaboration and exchange of ideas between stakeholders of the CCUS, bioenergy, and BECCS industries would also be beneficial and are recommended.

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