# BIOENERGY FOR ELECTRICITY GENERATION

Presented by Jennifer Den

in partial fulfillment of the requirements for completion of the
Polymathic Scholars program in the College of Natural Sciences at
The University of Texas at Austin

Spring 2016

David Eaton, Ph. D.
Supervising Professor
LBJ School of Public Affairs

Date

Rebecca A. Wilcox, Ph.D.
Second Reader
Honors Center, College of Natural Sciences

Date

# Bioenergy for Electricity Generation

| | |
|---|---|
| Jennifer Den | Date |
| Dr. David Eaton, LBJ School of Public Affairs | Date |

# Table of Contents

# List of Tables

# List of Figures

# Acknowledgements

I would like to thank my faculty mentor and professor, Dr. David Eaton, for his guidance and expertise. This thesis would not have been possible without Dr. Eaton's patience and his enthusiastic support, advice, and supervision.

I would also like to thank Dr. Rebecca Wilcox for her time and her sincere and helpful comments. The constant encouragement and instruction throughout the writing process was well appreciated.

# Abstract

Energy from biological materials addresses a number of key energy and environmental issues, including climate change, energy security, and replacement of carbon-intensive energy sources. This thesis assesses the feasibility of using three types of biological material for U.S. electricity generation: wood chips, biofuels, and organic waste. To evaluate economic feasibility, this paper examines system design, feedstock availability, and other advantages and disadvantages of alternative biological feedstocks. It also discusses three cost-benefit studies evaluating wood chips, biofuels, and waste-to-energy. This thesis recommends that the U.S. electricity sector consider investing in additional use of wood chips and organic waste and continue developing research for next-generation biofuel. Wood chips can cost less than heating oil. Municipal solid waste as a fuel could manage and reduce carbon. Although next-generation biofuels are more expensive in terms of capital and operating costs than conventional biofuel and fossil fuels, their use could mitigate food security and environmental concerns. All three technologies are used globally, proving technical feasibility. The availability of wood and waste in the U.S. offers another incentive for feedstock. Additional funding and research remain challenges for next-generation biofuel. Future research in bioenergy could include cost-benefit and carbon emission analyses that incorporate additional production pathways, comparisons to current renewable feedstocks, and recommended sites for the three technologies this paper addresses.

# RENEWABLE ENERGY FOR ELECTRICITY GENERATION

Renewable energy is defined as energy collected from sources that can be replenished continually or annually (International Energy Agency, 2016). It can be used to generate electricity, heat or cool air or water, transport people or materials, or provide off-grid (rural) services (Renewable Energy Policy Network for the 21st Century, 2010). This discusses electricity generation from renewable energy fuels.

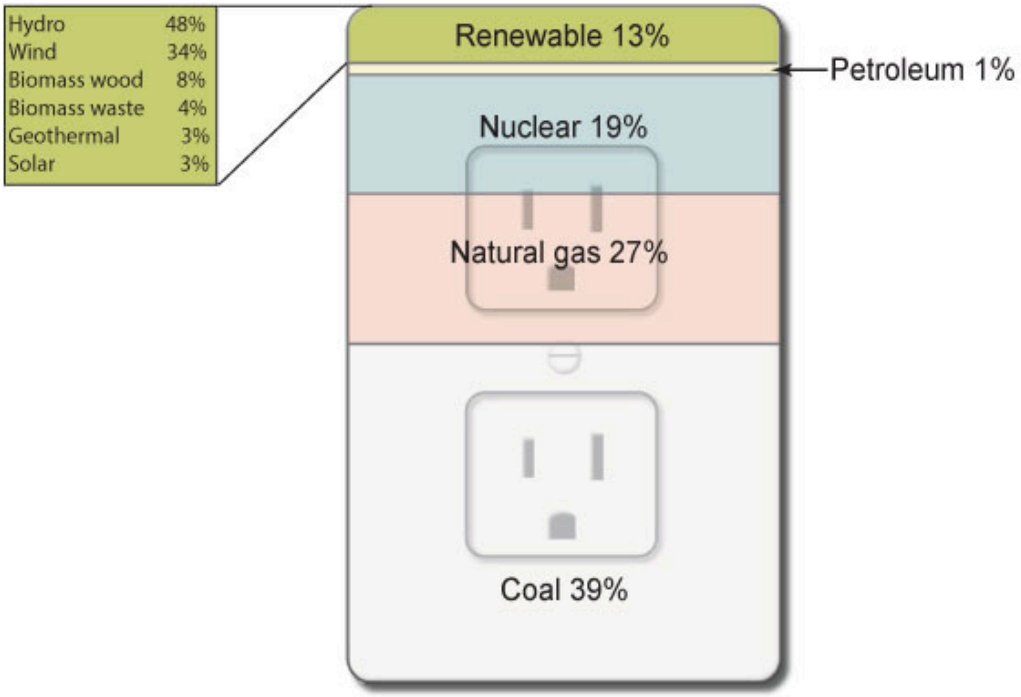
Although fossil fuels remain the primary fuel source to produce electrical power within the U.S. and worldwide, clean and renewable sources, such as hydroelectric, wind, solar, geothermal, and bioenergy, have become more widespread. Some notable U.S. government policies that support this process include the Energy Independence and Security Act (EISA) of 2007, America's Clean Energy and Security Act (ACES) of 2009, and the Recovery and Reinvestment Act (2009). These policies were passed to create clean energy jobs, enable energy independence, promote research, increase energy efficiency and performance, reduce greenhouse gas (GHG) emissions, and transition to a clean energy economy.

Current sources of U.S. electricity generation include coal (39 percent), natural gas (27 percent), nuclear (19 percent), renewables (13 percent), and petroleum (1 percent). Renewables are composed of 48 percent hydro, 34 percent wind, 8 percent wood, 4 percent waste, 3 percent geothermal, and 3 percent solar (see Figure 1) (U.S. Department of Energy, Energy Information Administration, 2015b). This paper will focus on bioenergy, which includes wood, waste, and biofuel.

According to the International Energy Agency (IEA), bioenergy, renewable energy produced by organic matter, provides 10 percent of the world's primary energy supply, making it the largest renewable energy source. In some poor developing countries, biological material remains a common fuel source for heat and space heating (IEA, 2006). However, bioenergy has become a viable and close to carbon neural option for electricity generation in developed countries like the United States. Bioenergy can be converted into different forms (solid, liquid, and gas) from local and often abundant resources. Harvesting and using the many different types of biological material have benefits that range from stabilizing soil fertility to managing waste disposal. Because of these reasons as well as growing interest in this area of research, the utilities sector should consider including more bioenergy into the electrical fuel mix.

Different sources of bioenergy (i.e. wood chips, biofuels, etc.) require distinct technical methods to convert the raw material to electricity. These processes will be discussed for each source. Studies that conduct a cost-benefit analysis will be used to examine economic parameters (cost, resource availability, etc.), technical feasibility (design, potential production scale), and environmental impacts. If the net economic benefits of using one or more of these processes are favorable compared to fossil fuels, bioenergy for electricity generation should be a feasible option.

**Figure 1. U.S. Electricity Generation Mix, 2014**



**Source:** Reprinted from "Electric Power Monthly" by the U.S. Department of Energy, Energy Information Administration, 2015, Retrieved from https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_1_1

# BIOLOGICAL MATERIAL AND BIOENERGY

Biological materials refer to substances derived from living organisms that can be harnessed to produce bioenergy. Bioenergy can be generated through biomass (solid), biogas (gas), or biofuel (liquid). To generate energy, all three undergo thermochemical processes and follow a similar chemical equation (Carnegie Mellon University, 2003):

Biomaterial + Oxygen → Carbon Dioxide + Water + Heat Equation 1

Biomass originates from organic material, which may include wood, manure, crops, garden waste, or other agricultural byproducts (Guo, 2014). The energy in organic materials comes from sunlight harvested via photosynthesis, the process where light energy is used to convert water and carbon dioxide into oxygen and organic compounds. The energy not used in chemical reactions is stored as chemical bonds that can release energy when broken (McKendry, 2002). The process of harnessing energy from biomass can be compared to the generation of heat from burning coal. During combustion, biomaterial and oxygen are combined in a high temperature environment to produce carbon dioxide, water vapor, and thermal energy. The approximate chemical equation for biomass is as follows (Ciolkoszv, 2014):

$CH_{1.44}O_{0.66} + 1.03\ O_2 \rightarrow 0.72\ H_2O + CO_2 + \text{heat}$ Equation 2

The amount of generated heat depends on many factors, such as climate and biomaterial species, although it generally falls within 20 Megajoules of heat energy per kilogram of fuel substrate (Ciolkosz, 2014). Moisture in biomaterial can lower the heat content because fuels burn best when dry. For the best combustion, the water content for biomass should not exceed 20 percent (Ciolkosz, 2014). Processing biomass by grinding or drying material can make it more suitable for combustion. The types of bioenergy used for electricity production may depend on the region, such as forest byproducts in the United States, sugarcane in Brazil, or rice husks in Southeast Asia (Urban, 2011).

Biogas derives from the breakdown of biomass under anaerobic conditions. Biogas sources include agricultural waste in the natural environment, municipal solid waste, landfill, or sewage. Fermentation, another type of anaerobic digestion, can also generate biogas. Biogas contains mostly methane (55-90%) but can include carbon dioxide and hydrogen sulfide depending on its source (Ghenai, 2015). This flammable mixture may be used as a fuel, such as ethanol from sugar canes; it can also be purified to a natural gas equivalent (98% methane). Each cubic meter of methane contains approximately 50 MJ of energy, or 4-7 kWh of heat energy in one cubic meter of biogas (Alveo Water and Sanitation, n.d.). When combusted, the gas or fuel releases this energy for electrical, transportation, heating, or power generation. The following represents the chemical equation for the combustion of methane (Carnegie Mellon University, 2003).

$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + \text{heat}$ Equation 3

Methane is a potent greenhouse gas. However, its extraction from waste such as landfills and its use for electricity generation reduces direct atmospheric emissions (Mohseni, 2011).

Biofuel derives from both biomass and biogas sources and includes biodiesel, methanol, butanol, and ethanol, with the latter two as the most common sources. Although fermentation via lignocellulosic material can produce bioethanol, most biofuels originate or are converted from once-living organisms through agricultural processes or anaerobic digestion (Rubin, 2008). These processes can occur naturally or in a laboratory or industrial setting. Each chemical equation for biofuel varies by the source. For example, ethanol combustion follows (Biofuel.org.uk, 2011):

$C_2H_5OH + 3O_2 \rightarrow 2CO_2 + 3H_2O$ Equation 4

while butanol combustion follows (Biofuel.org.uk, 2011):

$2C_4H_9OH + 5O_2 \rightarrow 8CO_2 + 10H_2O$. Equation 5

The energy content of biofuel varies by fuel source but produces around 20 Megajoules of energy per liter for ethanol and 34 Megajoules per liter for biodiesel, values that change depending on the plant species and their specific energies. Biofuel is widely used for transportation, but this paper only discusses biofuel for electricity production.

Humans have burned biomass such as wood, hay, dung, and straw for space heating, lighting, and cooking as early as 350,000 years ago. Archaeological evidence shows that the habitual use of fire began in Israel's Tabun Cave (Shimelmitz, 2014). Prior to 1840, these biological materials were the predominant energy source around the world. In developing countries today this still holds true, with almost 40 percent of the global population relying on firewood for cooking and space heating (IEA, 2006). Burning wood and raw plant material, however, can release hazardous emissions.

During the Industrial Revolution, fossil fuel energy surpassed bioenergy. Within the last two decades, however, bioenergy has been on the rise (Guo, 2014). While firewood and charcoal consumptions have remained constant, wood chips and pellets for renewable electricity generation have doubled in the last decade and some analysts predict biomass use to increase (Guo, 2014). Commercial production of cellulosic ethanol is also projected to expand, especially under U.S. government regulations (Rubin, 2008). Renewable energy research has sought to optimize biofuel production, identifying plant species with high oil yield potential, parameters and guidelines for producing desired fuel qualities, and determining oil characteristics to control quality. From 2000 to 2013, world production of biodiesel, or biofuel intended as a substitute for diesel, increased from 213 million gallons to 6.29 billion gallons, with Germany, France, Brazil, Spain, and the U.S. as some of the top producing countries (U.S. DOE, EIA, 2014). In 2015, the U.S. produced over one billion gallons of biodiesel (Atadashi, 2011). Further bioenergy research has also focused on recovering energy from waste such as municipal solid waste, food, and sewage.

One can expect to see a trend in new technologies that focus on improving combustion, energy, and production efficiencies of bioenergy. Although current fossil fuel prices do not make bioenergy production economically advantageous, the World Energy Council predicts that bioenergy consumption could increase three-fold by 2050, displacing a quarter of global natural gas consumption and possibly meeting 30 percent of the world's energy demand, a projection that provides reason to enhance research and development of bioenergy (Guo, 2014). The next chapter will explore these technological processes.

# TECHNOLOGIES THAT PRODUCE BIOENERGY

Bioenergy can be produced from many sources of biological material. This section will focus on the technology behind three types of feedstock: wood chips, biofuels, and organic waste.

The process of converting biological material into energy begins with harvesting and processing, followed by a thermochemical procedure where heat energy and chemical catalysts convert biological material into intermediate compounds. There are three common thermochemical processes: (1) combustion, which requires sufficient oxygen for oxidation; (2) gasification, which requires insufficient oxygen to prevent complete oxidation; and (3) pyrolysis, which occurs in the absence of oxygen.

## THERMOCHEMICAL PROCESSES

Combustion of biomass refers to burning fuel in a boiler or stove to produce heat that can be utilized as hot air, hot water, steam or directly as electricity. Burning is the most widely used and simplest technology with a conversion efficiency into electricity at 20 to 30 percent. Wood and municipal solid waste are the most common feedstocks for combustion, although the moisture content must be low for efficiency. Combustion requires high temperatures for ignition, sufficient turbulence to mix the biological components with an oxidant, and time to complete the oxidation reaction (Equation 1). The final products of biomass are hydrogen, carbon monoxide, carbon dioxide, methane, and other hydrocarbons. $CO_2$ and $H_2O$ result from complete combustion, and the burning of solid charcoal releases CO and $CO_2$. The release of hot gases during combustion contain about 85 percent of the fuel’s potential energy; this heat can be used directly or indirectly through a heat exchanger, such as through a boiler to produce steam. Steam can be used to generate electricity, mechanical energy, or heat (Basu, 2010).

Pyrolysis refers to the heating and decomposition of biomass in anaerobic conditions, or conditions without oxygen. It is especially useful in decomposing and fractionating biomass such as cellulosic fibers, lignin, and sugars. Its products include bio-charcoal or gases and bio-oil from the volatile fraction of biomass. The process begins with raising the temperature to release volatiles and form charcoal (Basu, 2010). Once various reactions occur, pyrolysis gas is formed. Slow pyrolysis, which occurs geologically over thousands of years with temperatures that reach 500 degrees Celsius, produces charcoal. Fast pyrolysis, or the rapid heating of material, can occur in anaerobic conditions at 450 to 600 degree Celsius, produces mainly bio-oil (60-75%) with other products including solid charcoal (15-25%) and noncondensable gases (10-20%). However, bio-oils must be further processed to lower oxygen content or filtered for particulates and alkali. Once produced, bio-oil can be used as fuel for combustion or refined into transportation fuel (U.S. DOE, Office of Energy Efficiency and Renewable Energy, 2012).

Gasification is a technique that heats biomass, converting it into combustible gas, volatiles, and ash. The technology behind gasification may vary based on the gasification agent or the reactor, but it is often more demanding because of feedstock specifications. Waste, such as municipal solid waste and agricultural residues, is a common feedstock. Gasification occurs in two endothermic steps. Biomass is first heated to over 700 degrees Celsius, which vaporizes volatiles such as hydrogen, CO, $CO_2$, and other hydrocarbon gases. The byproducts that remain are charcoal and ash. In the second step, the charcoal is gasified when it reacts with oxygen, steam, and hydrogen at high temperatures. The main gasification products include synthesis gas (syngas), bio-charcoal, and tar. The specific amount of each depends on the feedstock, oxidizing agent, and the process conditions (Basu, 2010). Syngas, which consists of CO, $CH_4$, and other hydrocarbons, can be utilized for heating or electricity generation as fuel for a Combined Heat and Power (CHP) generator, as well as production of ethanol, diesel, and chemical feedstocks (U.S. DOE, Office of EERE, n.d.). Because gasification processes have a higher conversion efficiency, they are more suited for 10 MW power plants or larger to achieve full potential.

Combustion, pyrolysis, and gasification have many similarities but differ in their end uses and product ratios. When choosing a suitable mechanism for energy production, one must consider the desired final products, such as gas, bio-char, or only heat, and their end uses, such as electricity generation, heat, or transportation fuel.

The sections below describe commonly used biological materials and the technologies employed to produce bioenergy. The biological materials to be considered are woodchips, biofuel, and organic waste.

## WOOD CHIPS

Woodchipping describes the process of cutting, or chipping, large pieces of wood to produce smaller, solid material of approximately 5-50 mm long. Although this procedure is often associated with mulch for gardening or landscaping, woodchips can also be used as fuel from biomass. In a process that is comparable to pulverizing conventional fossil fuels such as coal, wood chips are burned to produce steam, which powers the turbines that generate electricity. Compared to logs or planks, mechanically chipped wood has a large surface area to volume ratio. This makes the wood easier to feed steadily into a conversion system where it can be burned more uniformly and efficiently.

Wood fuel has several advantages because, as a renewable resource, it originates from a sustainable local supply. Although the combustion process (Equation 2) generates carbon dioxide, biomass in a cycle is generally considered close to carbon neutral. New biomass growth absorbs emitted carbon dioxide, and this life cycle will repeat. Recent studies have indicated that burning biomass may not actually be carbon neutral (McKendry, 2002). However, when compared to fossil fuels, wood fuel emits less carbon dioxide per heating unit during combustion. The entire process is closer to carbon neutral than combustion of oil, natural gas, or coal. Wood fuel does not contain the heavy metals or sulfur associated with coal or heavy oil, which leads to pollution and acid rain. Burning wood fuel from wood wastes prevent methane production, which lower potential greenhouse gas production (Li, 2014).

The production process begins by clearing or collecting raw materials from forest owners or forest management specialists (Figure 2). Raw materials can derive from forest wood, waste wood, pulpwood, or residues from construction, sawmills, logging, or landscaping. Ideally, these materials should be sourced as locally as possible to benefit the local economy. Once harvested, wood is delivered to a combustion site after the material is fed through a woodchipper machine. There are several types of chippers used in the industry, each with its own constraints based on the wood to be processed. These chippers are defined by well-researched factors, including operating parameters (such as angle of the chipper plate and the direction of cutting) and chip geometry (the shape and thickness of the wood chip) (Hellstrom, 2010).

Following the chipping process, the wood chips are delivered to a heating plant. These plants vary in size and may be small-scale, generating 20 to 200 kWh of heat energy, or large-scale. The type of heating plant chosen depends on the location in which electricity will be generated as well as the original raw material. For example, timber products and felled trees are more suitable for small-scale heating plants that power rural locations. In contrast, treetops and construction waste can be sent to large heating plants that power urban cities. These plants use larger feeders that can process and manage rough material and impurities (Small Giant of Bioenergy, n.d.).

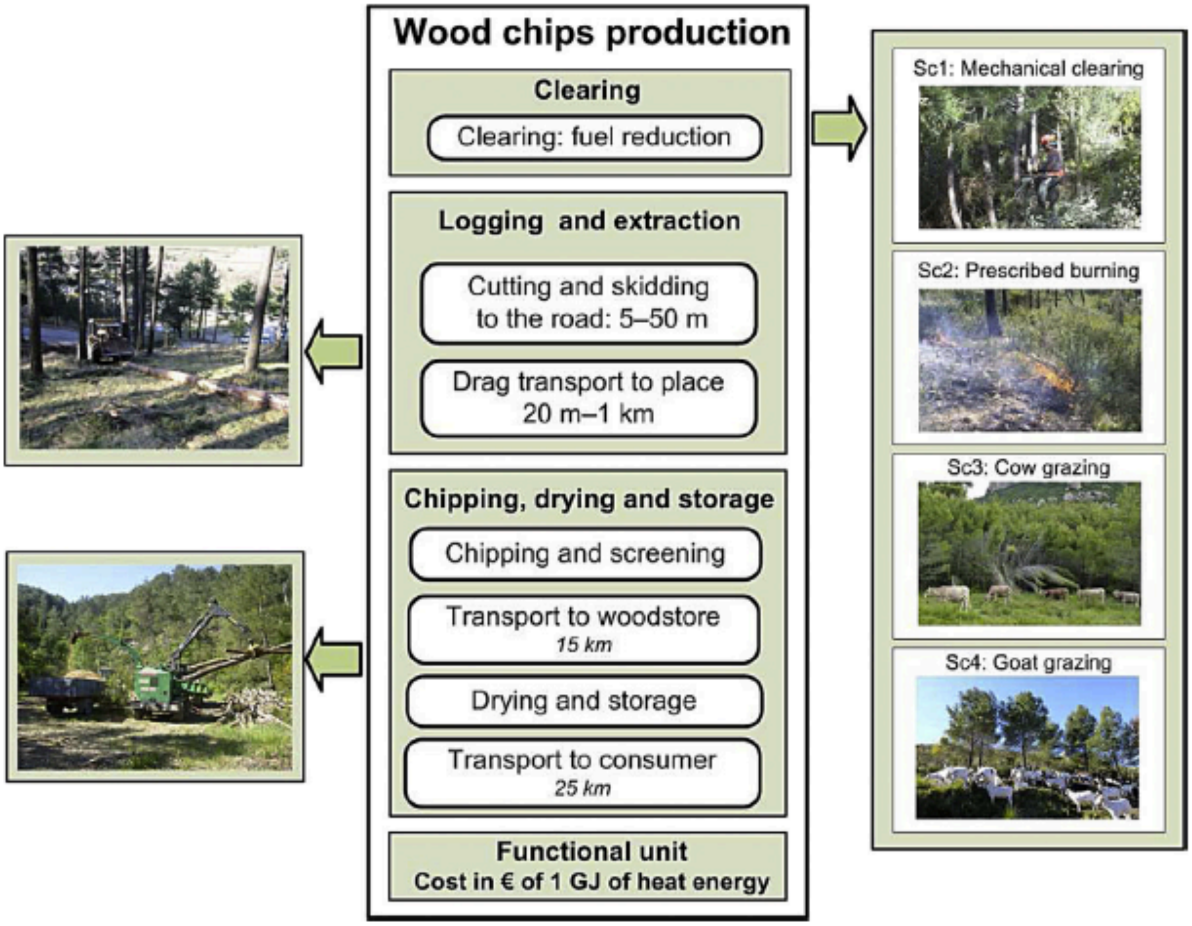
At the heating plant, the chips may be combusted, gasified, cogenerated, or cofired. Combustion (Equation 2) refers to the burning of wood chips, where the heat is transferred to a hot water boiler. Steam turbines then convert the steam to electrical power. Gasification is the heating of wood in an anaerobic environment, which releases pyrolysis gases such as carbon monoxide and hydrogen. This type of wood fuel is used for internal combustion engines, gas turbines, and microturbines. Cogeneration diverges from the traditional steam turbine method by simultaneously producing heat and electricity from wood fuel through a combined heat and power (CHP) system. Cofiring uses biomass as a supplementary energy source in coal plants, a low-cost option that reduces greenhouse gases (USDA Forest Products Laboratory, 2004).

Because of the multiple steps during production, the measurement units for wood chips change by location. Wood merchants that harvest from forest owners describe wood by volume, such as solid or loose cubic meters. To describe the energy potential of fuels, hauling operators use “tons” and heating plants use “MWh” (Central Baltic INTERREG IV A Programme & EU, 2013). A hectare of trees produces approximately 30 $m^3$ of felled trees, 75 $m^3$ of wood chips, 60 MWh of energy, or 6000 liters of fuel oil. A loose cubic meter of wood chips is approximately equal to 0.8 MWh of energy, or 80 liters of fuel oil. A solid cubic meter of felled trees equals 2.5 cubic meters of wood chips and 2 MWh of energy (Small Giant of Bioenergy, n.d.).

Several physical parameters define the efficiency of the woodchipping process. The first one is uniform quality of chips and absence of long thin pieces, or slivers. Wood chips of uniform quality allow for undisturbed function. Slivers could cause bridging or blockage when chips are fed into the system. Another parameter to consider is maximum moisture content. This also affects feed blockages but can play a role in combustion efficiency as well. Depending on the region, fresh-cut trees can have moisture contents of over 50 percent, when the advisable content should not exceed 20 percent (SEAI, n.d.c). Moist wood chips lower the quality of the fuel and the efficiency of the process by requiring a more considerable amount of energy to heat the water associated with the wood. The lower heating efficiency can cause higher energy consumption for the system, higher risk of backburn and discharge, and even problems in preserving fuel for storage (Buchmayr et al., 2015). As a result, fresh-cut material for woodchipping is often left to dry naturally; artificial drying is another option that can be costly because it requires energy expenditure. A third parameter to consider is the level of contaminant content in wood, which may increase emissions. Further parameters of interest are tree species, amount of dust and fungal spores, ash content, and even wood storage. Any of these factors can also affect the quality of the chips and the wood fuel produced (Biomass Energy Centre, n.d.).

Wood chips are traditionally used as solid fuel for electrical power or heating buildings. In some cases, coal power plants have been converted to run on wood chips; this can be a straightforward process because both can use the same type of steam turbine engines. Countries like Sweden and Finland have already increased the use of domestic wood and wood byproducts for electricity production. In Sweden, logging residues are used to generate energy for district heating companies, and the amount of this energy has increased over the years (Central Baltic INTERREG IV A Programme & EU, 2013). Finland—where 76 percent of land is forested—became the global leader in forest bioenergy in 2012, when over 24 percent of its energy consumption came from domestic wood and byproducts. This value was greater than the amount of energy produced from oil, making wood fuel the most used source of energy in Finland for the first time (Statistics Finland, 2013). Finland and Sweden's success with wood chips for fuel shows the potential this process has in the U.S.

**Figure 2. Wood Chip Production Process**



**Source:** Reprinted from "Comparative cost evaluation of heating oil and small-scale wood chips produced from Euro-Mediterranean forests" by B. Esteban, et al., 2015, *Renewable Energy, 74*, p. 568-575.

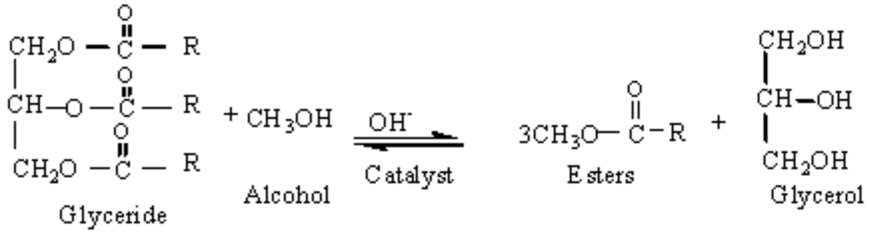
## BIOFUELS

Biofuel is a liquid energy fuel that can be produced from biomass conversion or carbon fixation through photosynthesis. The feedstock comes directly from plants and microalgae or indirectly from agricultural, commercial, or industrial wastes. In contrast, fossil fuels originate through geological processes as plants and animals in the ground decompose over millions of years. The two most popular types of biofuel include bioethanol, alcohol made by fermentation, and biodiesel, oil based from long-chain alkyl esters. Bioethanol derives from crops such as wheat, woody crops, and sweet sorghum, and biodiesel derives from oil crops such as rapeseed and camelina (SEAI, n.d.b).

The most common form of biofuels today are conventional, or first-generation biofuels, made from arable crops that produce sugar, starch, and oils. Corn is the chosen material in the U.S. due to commercial-scale experience with a proven fermentation process and support from government mandates, subsidies, and tariffs. Other methods around the world use different feedstock for biofuel, such as sugarcane in Brazil and biodiesel in Argentina and Europe (U.S. DOE, National Renewable Energy Laboratory, 2015). In the U.S., gasoline is blended with bioethanol. There are multiple ways to produce biofuel, but the process generally includes chemical reactions, fermentation, and heat to break down plant sugars and starch. Products are then refined into a usable fuel.

Biofuel production cycle begins with photosynthesis. Solar energy and carbon dioxide are converted into chemical energy in biomass. Farmers then harvest the crops, which are sent to pre-treatment. There are several conversion processes but the most common are biochemical, thermochemical, and photobiological (U.S. DOE, Office of EERE, 2013).

Biochemical processes use enzyme and microorganisms as catalysts to convert biomass into desirable products. This could include breaking down carbohydrates and cellulose (hydrolysis) or fermenting and distilling sugars into ethanol (Figure 3). Many plant and animal fat oils contain triglycerides that must be separated via transesterification, a process commonly used for biodiesel (Figure 3). Transesterification reacts these triglycerides with alcohol to form esters and glycerols (Equation 6) (University of Strathclyde Engineering, n.d.).



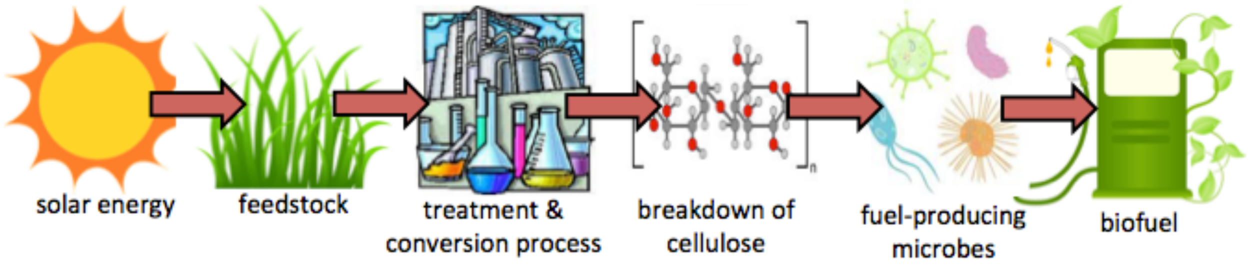
(Equation 6)

Following the breakdown of cellulose, additional microbes ferment sugars into liquid fuels (Figure 3). Remaining coproducts are converted into biobased products, such as plastics, solvents, intermediates, acids, and lubricants. Given the nature of the carbon cycle, the net carbon released during the biofuel production cycle should be close to zero (University of Illinois at Urbana-Champaign, n.d.). However, there are energy inputs throughout the conversion process, such as fossil fuels for fertilization, to power refineries, and for transportation.

Photobiological processes use natural photosynthetic activity to produce biofuels, now termed as advanced, or second-generation biofuels. Second-generation biofuels use diverse sources of biomass, which can include bacteria, algae, agricultural wastes and residues, and lignocellulosic biomass from woody crops and energy grasses such as switchgrass. Lipids converted from sugars can also become biodiesel through chemical reactions such as esterification and hydrogenation (British Petroleum, 2015). Algal biofuel production has become a popular method that both government and private companies have begun funding. The process begins with genetic engineering by selecting choice algae. Once the algae are cultivated, harvested, and separated via chemical solvents, they can be processed and refined into useable products (U.S. DOE, Office of EERE, 2014). Although second-generation biofuels have many positive features, they are not without challenges within the infrastructure and manufacturing process that complicate their integration into the energy economy and market. For example, many high-energy advanced biofuels require labs and technical processes that are costly and complex in order to generate fuel or extract cells, with commercial manufacturing facility costs ranging from $100 million to $300 million (Solecki et al., 2013).

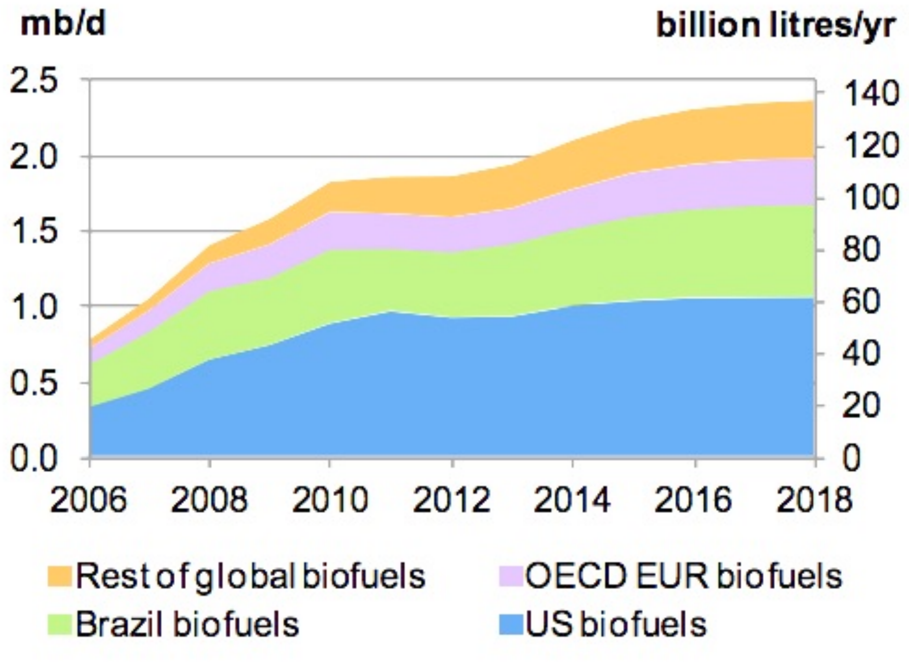
Some governments now encourage biofuel production through economic incentives, policies, mandates, subsidies, or tax credits (U.S. DOE, EIA, 2015c). For example, the U.S. Energy Independence and Security Act (EISA) of 2007 suggests a volumetric expansion to 36 billion gallons per year of renewable fuel by 2022: 15 billion from corn and 21 billion from advanced biofuels (Environmental Protection Agency, 2007). Currently, biofuels provide 3.5 percent of road transport fuels in the world (IEA, n.d.). Global biofuel supply is expected to increase; scientists project that 140 billion liters of biofuel will be produced in 2018 (Figure 4), which would provide 4 percent of global road transport fuel demand (IEA, 2013c). By 2020, biofuels may provide up to 27 percent of world transportation fuel. The uncertainties and risks of biofuel production will be discussed below.

**Figure 3. Classical Approach to Biofuel Production**



**Source:** Jennifer Den at The University of Texas at Austin, 2015, unpublished.

**Figure 4. Global Supply of Biofuel From 2006-2018**



**Source:** Reprinted from "Market Trends and Projections to 2018" by the International Energy Agency, 2013, Retrieved from https://www.iea.org/publications/freepublications/publication/2013MTRMR.pdf

## ORGANIC WASTE (MUNICIPAL SOLID WASTE, SEWAGE, LIVESTOCK MANURE)

Municipal solid waste (MSW), sewage sludge (a byproduct of wastewater treatment), and livestock manure can be sources of biogas energy, and it is unlikely that they will deplete, as there will always be waste generated across any civilization. For example, Americans generated 254 millions ton of garbage, or MSW, and recycled about 87 millions tons in 2013 (Figure 5) (U.S. DOE, EPA, 2016).

Waste-to-energy has become more attractive due to its relatively low air and water pollution rates, useful byproducts, feasibility in both large and small-scale industries, and the production process's allowance of high water content, which is not the case for many conversion technologies such as combustion (IEA, 2013a). The energy conversion process for organic waste uses anaerobic digestion, a biochemical conversion technique. Anaerobic digestion is a naturally occurring microbial method that occurs when organic material decomposes in the absence of oxygen to release biogas. This process converts unstable pathogens and nutrient rich substrates into more stable material. Dried leftover substrate can be used as fertilizer or composted and reused as bedding material. The biogas produced in this process is composed of approximately 65 percent methane, 35 percent carbon dioxide, and the rest as trace gases (Ileleji et al., 2008).

There are four stages to produce biogas from anaerobic digestion: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Figure 6). Hydrolysis is the process where specific bacteria split long chain organic compounds into simple compounds, such as proteins into amino acids or carbohydrates into sugars. The products of hydrolysis are then sent to the acidogenesis phase, where acid-forming bacteria break these products into short chain fatty acids. This process is used in digesting manure. Some of the products from acidogensis include acetic acid, hydrogen, and carbon dioxide, which act as initial products for methane formation.

The third phase is acetogenesis, or the use of acetic-forming bacteria to break down organic acids and alcohols into more acetic acid, hydrogen, and carbon dioxide. The last phase, methanogenesis, also used in manure digestion, converts the acetogenesis products into biogas via mioorogranisms (SEAI, n.d.a). Anaerobic digestion of biomass varies by temperature, which can influence speed and stability of the process. There are two temperature ranges: mesophilic (32-45 degrees Celsius) or thermophilic (50 to 65 degrees Celsius). As optimum growth for methane bacteria occurs at the mesophilic range, many biogas facilities operate at this temperature for high gas yields and process stability. Thermophilic digestion is most advantageous when using animal byproducts or agricultural wastes. Although this temperature produces higher gas yields, the process is more sensitive to disturbances.

Tables 1-4 list some of the many sources of waste material: MSW, agricultural waste, manure, and energy crops and their associated methane yields (Appels et al, 2011). Most sources follow the general process mentioned above, but MSW and manure will be further described, as there are additional techniques involved.

## Municipal Solid Waste

Source separation is an important first step that removes compounds such as heavy metals not suitable for anaerobic digestion to produce a higher quality end product. However, the composition of MSW's organic fraction may vary based on location, season, and the type or quality of waste. For example, rural areas produce higher biodegradable waste, whereas urban areas would have a higher percentage of plastic (Appels et al., 2011).

Anaerobic digestion technology for MSW can be classified according to the content of total solids to be digested in wet or dry digestion. Low solid contents (less than 12 percent) undergo wet digestion, while high solid contents (22-40 percent) undergo dry digestion (IEA, 2013a). Wet digestion, established in Europe during the 1980s, begins with homogenizing material in a mixing unit. A spiral press then separates the material into a liquid and solid phase. The liquid matter goes into digestion, whereas the solid fraction is processed for composting. The main limitation to this technique is the large amount of water used, which results in expensive post-treatment technology and high reactor volume. Wet digesters can operate as co-digestion plants; other liquid or solid material such as sewage sludge can be digested at the same time as MSW (IEA, 2013b).

There are three common dry digestion processes, also developed in the 1980s: Dranco, Kompogas, and Valorga (IEA, 2013a). The Dranco reactor passes feedstock vertically through a reactor and the digestate is recycled. The Kompogas process uses a horizontal flow, where the digester is mixed with a paddle stirrer. The Valorga digester is vertical but the feedstock enters from the bottom (Figure 7).

Following digestion, the MSW can then be treated and converted to energy. The three types of thermochemical procedures can be applied for treatment of waste: combustion, gasification, and pyrolysis. While combustion furnaces are the most commonly used technology, pyrolysis plants exist in both Japan and Germany, demonstrating their potential application in the U.S. For example, approximately 30,000 tons of MSW are treated annually in a pyrolysis plant in Burgau, Germany (IEA, 2013b).

Landfill gas (LFG) contains 50-60 percent methane and 40-50 percent carbon dioxide and is another alternative source of MSW energy that allows facilities to be built nearby or onsite. Landfills are the most widespread method of solid waste disposal in the world, responsible for approximately 8 percent of methane emissions. Waste may take years to decompose and soluble constituents may leach into and pollute soil and groundwater. A common option is waste incineration, but like all combustion processes, it can release harmful gases to the atmosphere, such as nitrogen oxides and carbon dioxide (Tsai, 2007).

Landfill gas (LFG) is created when organic waste in a MSW landfill decomposes. Instead of escaping into air, LFG can be captured and converted into energy (Environmental Protection Agency, n.d.). Collection is accomplished through trenches or wells that are installed into the waste. The gas is then piped to be treated or flared. Flaring removes gas that does not warrant direct use or electricity generation and can also control excess gas extraction spikes. During treatment, impurities, condensates, and particulates are removed from LFG. Treatment systems may be divided into multiple processing systems if the gas will be used for electricity generation: primarily to remove moisture and secondarily to clean up constituents such as sulfur compounds. For electricity generation, gas turbines or internal combustion engines are employed. If the gas is used directly, which usually means within five miles of the landfill, boilers, dryers, or process heaters are used. This process is most similar to that of using natural gas. Although LFG is much cheaper than natural gas, it also holds only half of its heating value (Tsai, 2007).

## Sewage Sludge

Wastewater treatment facilities generate sewage sludge as a byproduct during treatment. By using anaerobic digestion, facilities can treat sludge and reduce almost 40 percent of the overall load of biosolids to be disposed. Anaerobic digestion, now widely considered as both economical and environmentally friendly, stabilizes sludge and reduces pathogenic microorganisms. The anaerobic digestion of sewage sludge is said to yield the highest biogas production capacity worldwide, generating large amounts of methane. However, the methane yield of the sludge depends on its composition (Appels et al., 2011).

There are two phases of wastewater sludge treatment. In the first step, all incoming flows of sludge are combined and the mixture is heated to accelerate biological conversion for 10-20 days. The mixture undergoes further digestion without mixing to promote separation. This process generates its own heat as the digested sludge begins to settle. Following treatment, the sludge is dewatered, thickened, and stabilized to reduce pathogen levels and odors. The entire anaerobic digestion procedure, especially secondary-treatment of sludge, generates biogas by breaking down organic matter into carbon dioxide and methane for energy use (Nazaroff & Alvarez-Cohen, n.d.).

For example, the Albert Lea facility in Minnesota processes 12 million gallons of sewage per day, with 4.5 million gallons treated into sludge. It produces 75,000 cubic feet of biogas and the four microturbines at the facility each generates 30 kW. At peak production, this facility can produce 2,500 kWh/day of energy and 28,000 Btu/day of heat. For a renewable resource, this is a significant portion of energy when one considers that an average residential customer uses approximately 30 kWh/day (Nazaroff & Alvarez-Cohen, n.d.).

## Manure

Key states in the U.S. with large amounts of agricultural residues and manure include Iowa with 31 million tons, Arkansas with 10.3 million tons, Texas with 9.8 million tons, and California with 9.2 million tons. Figure 8 shows the projected agricultural residues and manure availability by county in 2030. The most abundant agricultural residues and manure resources (500,000 to 1.2 million dry tons) are located in the upper Midwest and central California. Several other agricultural regions across America also have potential to produce bioenergy.

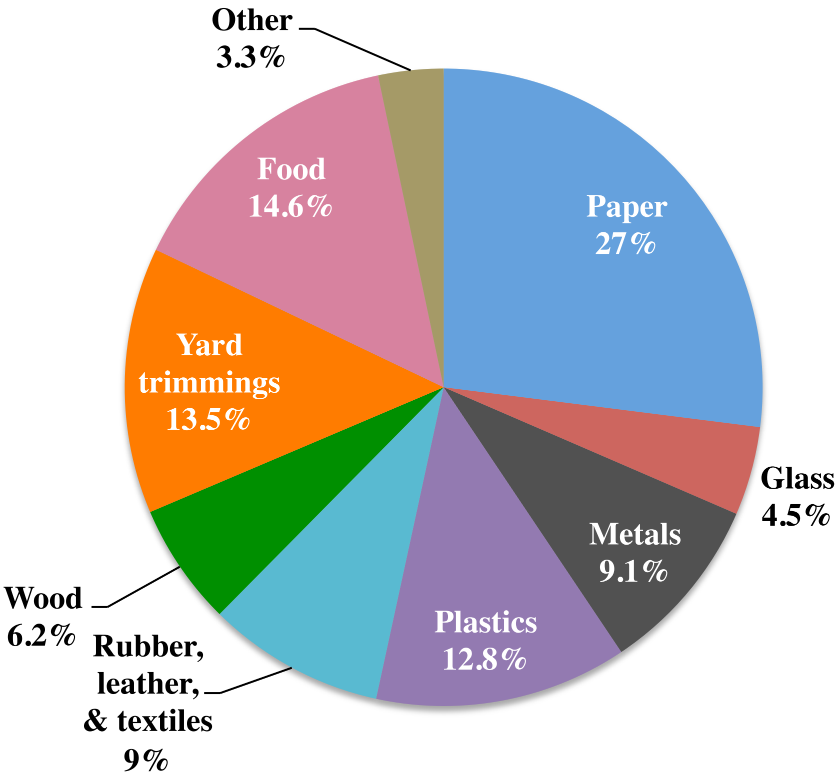
The methane potential of manure includes both the animal feces and the bedding material. Due to its high nitrogen content, manure is suitable for the development of anaerobic microorganisms. Manure is frequently co-digested with other wastes with low nitrogen concentration to reduce ammonia content, which may inhibit the digestion process. Natural degradation of manure leads to uncontrolled methane emission, which has an undesirable effect on the climate. By controlling this degradation via anaerobic digestion in a facility, facilities can reduce methane discharge (Appels et al., 2011).

The general process of anaerobic digestion of manure begins with liquefaction of the organic substrate by bacteria. This is followed by acidogenesis, or acid production via acid-forming bacteria, and methanogenesis, or methane production via methane-producing bacteria (Figure 9). The effluent can often be further separated into solid and liquid fractions. For example, solid fraction from cow manure may be recycled as bedding. Its improved nutrient availability, reduced acidity, and reduced odor also allow digested manure to be used as fertilizer (Illeleji et al., 2008).

Poorly managed waste can produce residuals that can affect human health, environment, and the economy. It often results in downstream costs higher than what it would have cost to manage the waste appropriately from the beginning. Waste can contribute to greenhouse gas emissions from methane release during biodegradation (IEA, 2013b). However, properly managed waste coupled with clean energy or electricity generation is a way to reduce waste and greenhouse gases with one process. Even in developing countries, biogas projects can help small farmers and villages by producing electricity with reduced fuel crops. For example, biogas has long been used in small pig farms in Asian countries and Latin America (IEA, 2013b). Not only does this enhance the incomes of pig farmers, but it also captures methane for on-farm use and treats effluent so there is safe water for irrigation and drinking. The methane can be captured and ignited for cooking and heating. In more developed countries, small-scale or medium-sized operations can also find additional revenue by selling bioenergy to clients or reducing their own on-site energy costs.

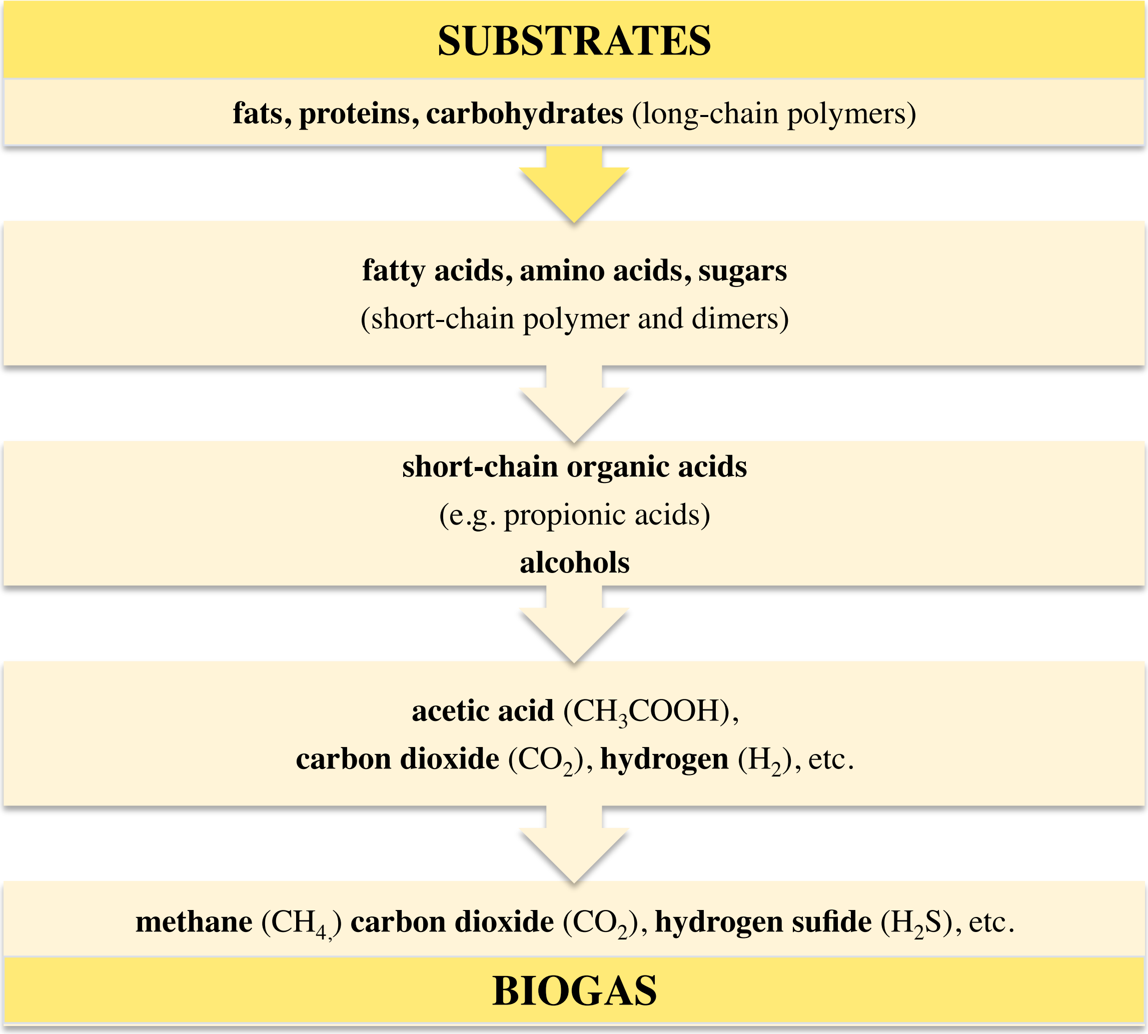
This section shows that through different technologies, bioenergy can be generated from many sources of biological material. These technologies employ thermochemical processes such as combustion, pyrolysis, and gasification, which are techniques that can also vary product ratios and determine a feedstock's end use. Wood chips are harvested, processed and chipped, and heated for energy. Biofuel crops are harvested and treated with enzymes and microorganisms to undergo chemical reactions and biochemical processes. Once cellulosic breakdown has occurred, plant sugars are fermented into liquid fuel. Organic waste comes in many different forms but is processed in one of two ways, using heat (incinerating material) or anaerobic digestion (producing biogas from anaerobic enzymes). The following section will reference three cost-benefit studies that analyze these technologies.

**Figure 5. Total Municipal Solid Waste Generation in 2013 By Material**



**Source:** Reprinted from “Municipal Solid Waste” by the U.S. DOE Environmental Protection Agency, 2014, Retrieved from https://www3.epa.gov/epawaste/nonhaz/municipal/

**Figure 6. Anaerobic Digestion Process**



**Source:** Reprinted from "Four phases to produce biomass" by the Sustainable Energy Authority of Ireland, n.d., Retrieved from http://www.seai.ie/Renewables/Bioenergy/Bioenergy_Technologies/Anaerobic_Digestion/The_Process_and_Techniques_of_Anaerobic_Digestion/

## Table 1. Methane Yield for MSW

| Type of MSW | Methane Yield ($m^3$/kg Organic Dry Substance) |
|---|---|
| Mechanically sorted (fresh) | 0.22 |
| Mechanically sorted (dried) | 0.22 |
| Hand sorted | 0.21 |
| Grass | 0.21 |
| Leaves | 0.12 |
| Branches | 0.13 |
| Mixed Yard Waste | 0.14 |
| Office Paper | 0.37 |
| Corrugated Paper | 0.28 |
| Printed Newspaper | 0.10 |

## Table 2. Methane Yield for Fruit & Vegetable Waste

| Types of Fruit & Vegetable Waste | Methane Yield ($m^3$/kg Organic Dry Substance) |
|---|---|
| Mango peels | 0.37-0.52 |
| Banana peels | 0.24-0.32 |
| Orange peels | 0.46 |
| Orange pressings | 0.50 |
| Mandarin peels | 0.49 |
| Mandarin pressings | 0.43 |
| Whole mandarins (rotten) | 0.50 |
| Lemon pressings | 0.47 |
| Grape pressings | 0.28 |
| Pomegranate peels | 0.31 |
| Tomatoes (rotten) | 0.21-0.38 |
| Onion exterior peels | 0.40 |
| Garden beet leaves | 0.23 |
| Carrot leaves | 0.24 |
| Cabbage leaves | 0.31 |

## Table 3. Methane Yield for Manure

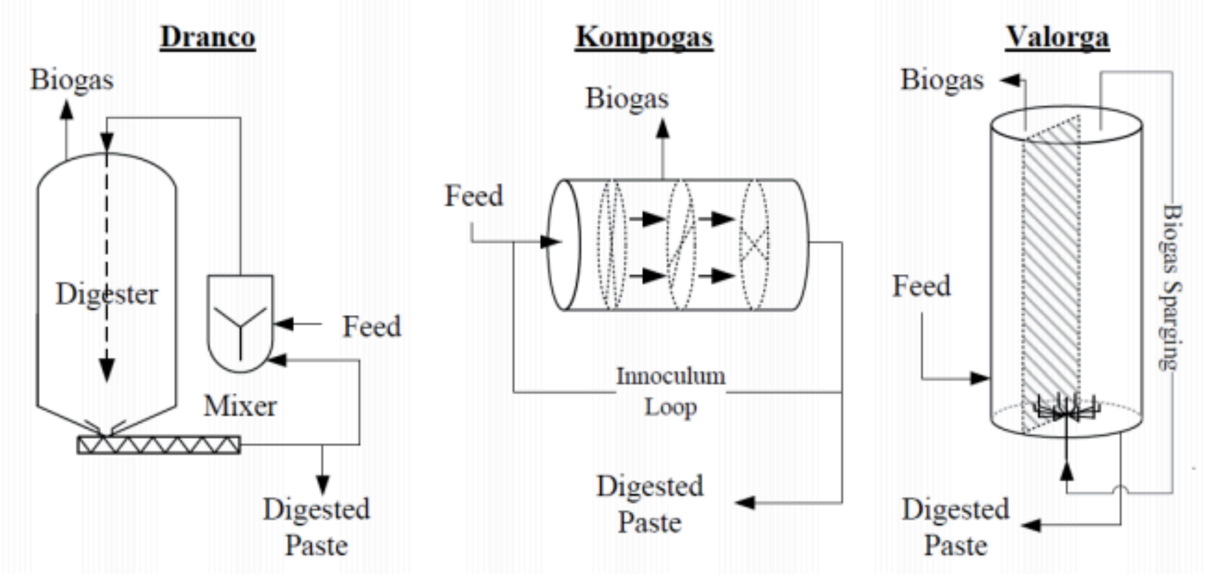
| Type of Manure | Methane Yield ($m^3$/kg Organic Dry Substance) |
|---|---|
| Pig | 0.36 |
| Sow | 0.38 |
| Dairy cattle | 0.15 |

## Table 4. Methane Yield for Energy Crops

| Crop | Crop Yield (ton /hectare) | Methane Yield ($m^3$/kg Organic Dry Substance) |
|---|---|---|
| Sugar beet | 40-70 | 0.39-0.41 |
| Fodder beet | 80-120 | 0.40-0.42 |
| Maize | 40-60 | 0.29-0.34 |
| Corn cob mix | 10-15 | 0.35-0.36 |
| Wheat | 30-50 | 0.35-0.38 |
| Triticale | 28-33 | 0.32-0.34 |
| Sorghum | 40-80 | 0.29-0.32 |
| Grass | 22-31 | 0.29-0.32 |
| Red clover | 17-25 | 0.30-0.35 |
| Sunflower | 31-42 | 0.23-0.30 |
| Wheat grain | 6-10 | 0.37-0.40 |
| Rye grain | 4-7 | 0.30-0.41 |

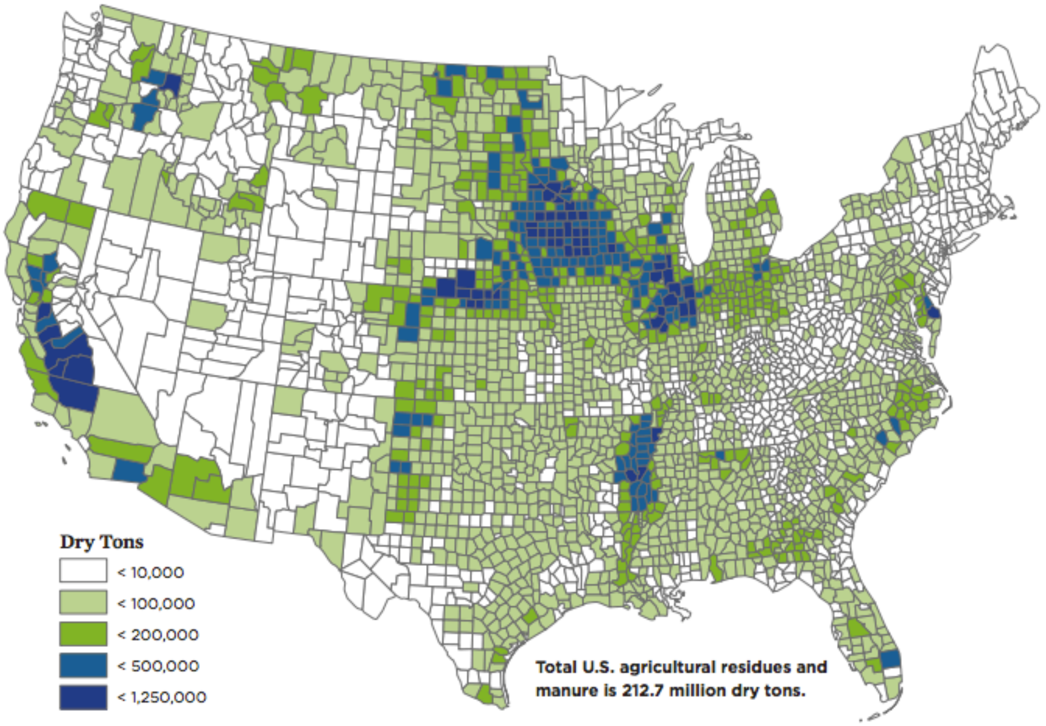
**Source:** Reprinted from “Anaerobic digestion in global bio-energy production: Potential and research challenges” by L. Appels, et al., 2011, *Renewable and Sustainable Energy Reviews, 15*, p. 4295-4301.

**Figure 7. Dry (Solid Waste) Digestion Processes**



**Source:** Reprinted from “Waste to Energy” by the International Energy Agency, 2013, Retrieved from http://www.ieabioenergy.com/wp-content/uploads/2014/03/ExCo71-Waste-to-Energy-Summary-and-Conclusions-28.03.14.html

**Figure 8. Agricultural Residues and Manure Availability by County in 2030**



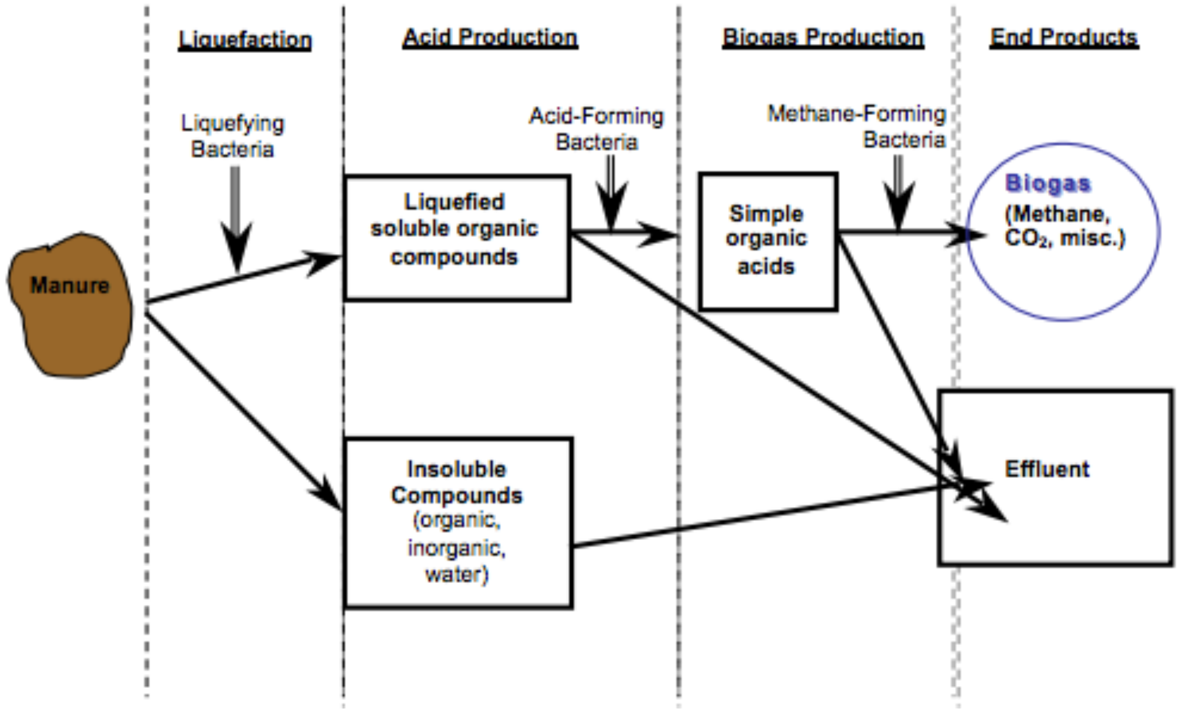
*While the most abundant agricultural residues and manure resources are located in the upper Midwest and central California, agricultural areas around the country can contribute to low-carbon bioenergy production.*

Note: Agricultural residues include corn and small grains, cotton, orchard prunings, and other parts of the plant not needed for food or other uses.

SOURCE: ADAPTED FROM UCS 2012.

**Source:** Reprinted from "Turning Agricultural Residues and Manure into Bioenergy" by the Union of Concerned Scientists, 2014, Retrieved from http://www.ucsusa.org/sites/default/files/legacy/assets/documents/clean_vehicles/Agricultural-Residue-Ranking.html

**Figure 9. Anaerobic Digestion of Manure**



**Source:** Reprinted from "Basics of energy production through anaerobic digestion of livestock manure" by K. Illelji, et al., 2008, Retrieved from https://www.extension.purdue.edu/extmedia/ID/ID-406-W.html

# FEASIBILITY ANALYSES VIA COST-BENEFIT STUDIES

This section discusses three studies that conduct cost-benefit analyses for the three technologies mentioned in this paper (wood chipping, biofuels, and waste-to-energy) to examine biomaterial feasibility for electricity. In addition, the limitations of these studies and additional advantages/disadvantages of each technology will be assessed.

## WOOD CHIPS

In 2014, Esteban and colleagues compared and evaluated the production costs of using heating oil versus small-scale wood chips in the Argencola municipality in northeastern Spain. The feedstock comes from 2200 hectares of forest composed of pine trees, conifers, and oak. In analyzing the energy costs of using wood chips, the researchers studied and integrated a variety of factors, including forest clearing methods, operation costs (clearing, logging, extraction, chipping, drying, and storage), consumption costs, and work hours. The discussion in this sub-section is based on Esteban et al., so each fact or argument that derives from their paper is not individually referenced.

The forest clearing methods were used within a 23-year project to preserve long-term ecosystem functionality and maintain natural ecosystems. They included mechanical fuel reduction (mechanical cutting of small trees and shrubs), prescribed burning (controlled burning of unchecked undergrowth), cow grazing, and goat grazing. Mechanical fuel reduction and prescribed burning are used to reduce biomass stock, which can be used for energy. Cow and goat grazing, as well as the former two methods, are used to reduce wildfire risk. Each clearing strategy is considered a “scenario” for the separate cost analyses. To calculate an energy ratio for each scenario, Esteban and colleagues used energy inputs (work hours and production pathway costs) and energy obtained (Equation 7) (Table 5-7).

$$\text{Energy ratio} = \frac{\text{Energy obtained}}{\sum \text{Energy inputs}} \qquad \text{Equation 7}$$

Esteban and colleagues then compared the cost of wood chips to that of heating oil. Wood chips cost was determined by evaluating production pathway. Based on their calculations, the cost of wood chips range from 5.22 – 11.27 Euros/GJ, about half the price of heating oil. Prescribed burning was the most economical forest clearing method as it requires the least intensive human intervention.

The researchers conducted a sensitivity analysis to evaluate factors that affect each scenario, such as fossil fuel price, annual biomass growth rate, wildfire costs, and wood transportation. The researchers evaluated the effect of fossil fuel prices on wood chips price using three price increments (20%, 50%, and 100%) for diesel and gasoline to determine their influence. They found that the price for wood chips is stable and thus generally independent of fossil fuel price. The researchers also looked at biomass growth rate to determine availability of feedstock. They found that wood stock is highly variable due to climate and forest parameters, such as rainfall variability, forest orientation, or age of the tree species. Based on their calculations, an increased biomass growth rate would lower the production costs for wood chipping.

Esteban and colleagues considered wildfire costs because the area of study often has periods of drought. For each scenario, they analyzed an increase of wildfire probability from 50 to 100 percent. Because managed forests showed a decreased wildfire cost, wood chips presented a more economical opportunity. The researchers also studied wood transportation, which includes transport from chipping place to drying facilities, storage facilities, and consumers. The results showed that a lesser need for transportation has little effect on production costs. However, a larger need would have a significant effect on final production costs.

This cost evaluation of small-scale wood chip production in northeastern Spain showed a reduced cost of wood chip production, especially when compared to traditional oil systems. Although this research study was particular to the specific area analyzed, it can be extended to regions with similar characteristics or locations with on-site consumption of small-scale produced wood chips.

## Discussion and Limitations of the Study

As shown through the study, wood chipping is cost-effective and appropriate in some areas. Production costs for wood chips range from 12.2 to 18.5 Euros/GJ ($13 – 21/GJ). Heating oil costs were approximately 23.9 Euros/GJ ($27/GJ). The comparative advantages for wood chips, a 51 to 77 percent reduction in costs, suggests that wood chips for electricity generation has potential.

There are several other factors that may influence the production costs of wood chips that the study did not mention. These include storage requirements, preparation of wood fuel, and the source, species, and availability of wood. Wood storage is determined by features such as form and moisture content of wood, the need for air-drying, and availability of land (Food and Agriculture Organization of the United Nations, n.d.). Additional costs during preparation may come from collection and handling of raw material, size reduction to achieve uniform particle size, screening to reduce particulates, and densification if wood pellets are produced (Food and Agriculture Organization of the United Nations, n.d.). The prices for alternative fuels and traditional energy sources, which fluctuate based on the market, may also affect wood chip production costs. Economic feasibility can also be influenced by capital cost of equipment and producer and consumer energy requirements. To analyze all of these factors and their economic effects would be beyond the scope of this project. However, the 2014 study by Esteban, B. et al. shows the potential of using wood chips and its reduced production costs, especially when compared to fossil fuels.

## Disadvantages/Challenges of Implementation

When evaluating properties of a combustible material that will be used as fuel, its heating value is an important factor. The heating value indicates the amount of thermal energy that can be obtained when combusting a certain mass unit of this material. For wood, the heating value varies based on the species and part of tree that is being used. Bark tends to have a higher heating value due to its resin content, whereas wood values differ by its softness or hardness. For example, dry woods have a heating value of 23 MJ/kg, whereas softer woods have a slightly lower value of 20 MJ/kg (Food and Agriculture Organization of the United Nations, n.d.). In comparison, coal, crude oil, gasoline, and natural gas have heating values of approximately 23 MJ/kg, 44 MJ/kg, 45 MJ/kg, and 46 MJ/kg, respectively (Oak Ridge National Laboratory, 2011).

The already low heating value for wood can be further affected by additional factors such as moisture content, particle size, type and efficiency of combustion equipment. If the heating value of a species of wood is 19.8 MJ/kg, moisture content can drop this value to 10 MJ/kg, demonstrating moisture effects on overall combustion efficiency (Food and Agriculture Organization of the United Nations, n.d.). Therefore, not only must producers consider the low heating value for wood chips, but they must also apply proper maintenance and preparation techniques to prevent this value from dropping even further.

There can be a misconception that wood waste or residues are free sources of energy. Although they may be free sources of readily available fuel, there are costs in waste handling, treatment and combustion equipment, plant operating costs, and labor. Most mills and plants use fossil fuels for each step of wood chip production, such as cutting and clearing forests, chipping wood, and transporting material.

Some studies argue that there are low benefits from wood fuel in lowering carbon emissions. Although trees absorb carbon dioxide, these absorbed gases are released back into the atmosphere during the combustion process (Li, 2014). In addition, forest owners must also take steps to manage their forests sustainably and prevent major topological changes and deforestation.

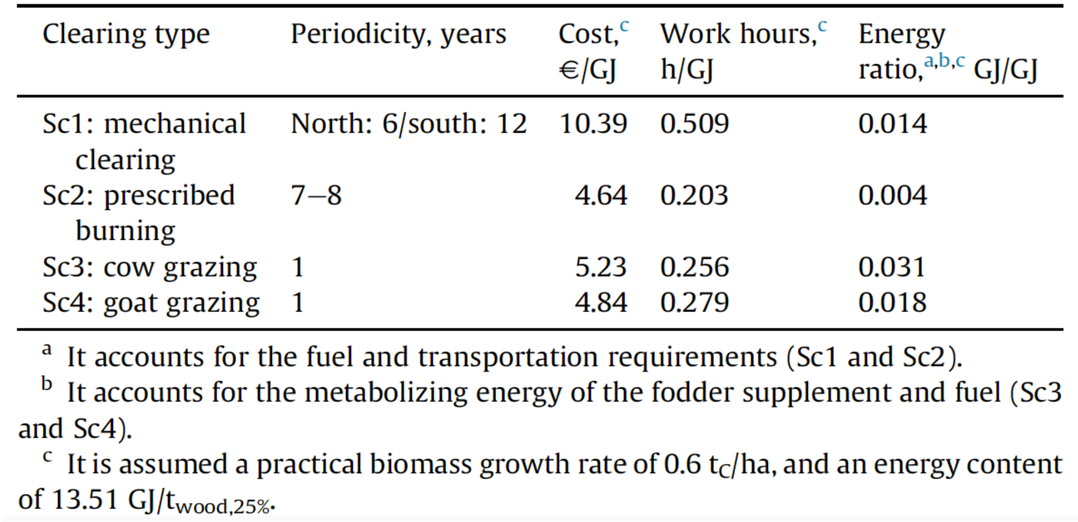
### Advantages

Electricity generation from wood chips is certainly more attractive as traditional fuel prices increase. The availability of wood is also a significant advantage. There are many sources of available wood residue such as forests, mill-site generated wood waste, and manufacturing waste. Producing wood chips that will be used for electricity generation provides an alternative and more efficient way of handling wasted wood. It is also a way to mitigate the effects of climate change, such as preventing forest fires.

Wood chipping is a relatively environmentally friendly option. Although carbon dioxide is emitted during combustion, the same amount of carbon was absorbed while the tree was growing, resulting in a net carbon emission of zero from the fuel source, excluding the fossil fuels used during the production, harvesting, and transport processes. Wood chips can be a sustainable source of energy because as trees are cut down, they can be replaced. However, managing sustainability must be taken into consideration.

Information from the Energy Information Administration (EIA) suggests continued growth for wood chip usage. In the summer of 2013, the U.S. generated 487.4 billion kilowatt-hours of electric power from renewable energy. The total electric power sector generating capacity for renewables was 154.7 GW out of a total 1,029 GW (United States Department of Energy, Energy Information Administration, 2015a). Wood and other biomass made up 3.3 GW of power, or 12.2 billion kilowatt-hours of energy. The Energy Information Administration predicts a 1.8 percent capacity growth for wood and biomass, which will reach 5.5 GW of power by 2040. They also predict a 6.0 percent growth for the total amount of energy generation, with 58.8 billion kilowatt-hours being generated by 2040 (Table 8) (U.S. DOE, EIA, 2015a). Though there are challenges in implementation, it is reasonable to believe that because of its projected growth and its attractive source of readily available heat or power, wood chip production for electricity generation has much potential.

**Table 5. Energy Ratios and Costs Per Forest Clearing Scenario**



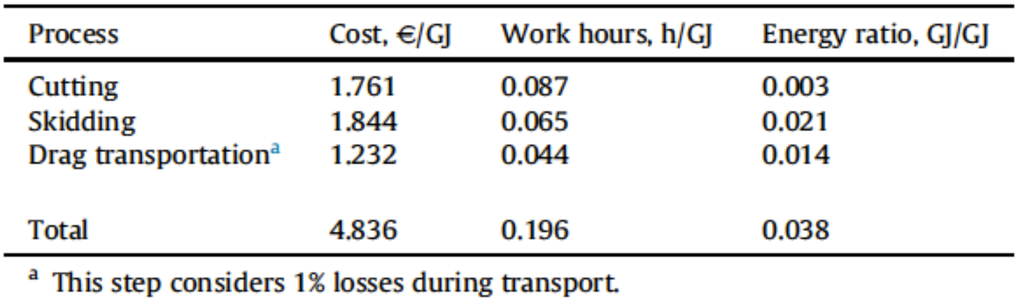
| Clearing type | Periodicity, years | Cost,[c] €/GJ | Work hours,[c] h/GJ | Energy ratio,[a,b,c] GJ/GJ |
|---|---|---|---|---|
| Sc1: mechanical clearing | North: 6/south: 12 | 10.39 | 0.509 | 0.014 |
| Sc2: prescribed burning | 7–8 | 4.64 | 0.203 | 0.004 |
| Sc3: cow grazing | 1 | 5.23 | 0.256 | 0.031 |
| Sc4: goat grazing | 1 | 4.84 | 0.279 | 0.018 |

[a] It accounts for the fuel and transportation requirements (Sc1 and Sc2).

[b] It accounts for the metabolizing energy of the fodder supplement and fuel (Sc3 and Sc4).

[c] It is assumed a practical biomass growth rate of 0.6 $t_C$/ha, and an energy content of 13.51 GJ/$t_{wood,25\%}$.

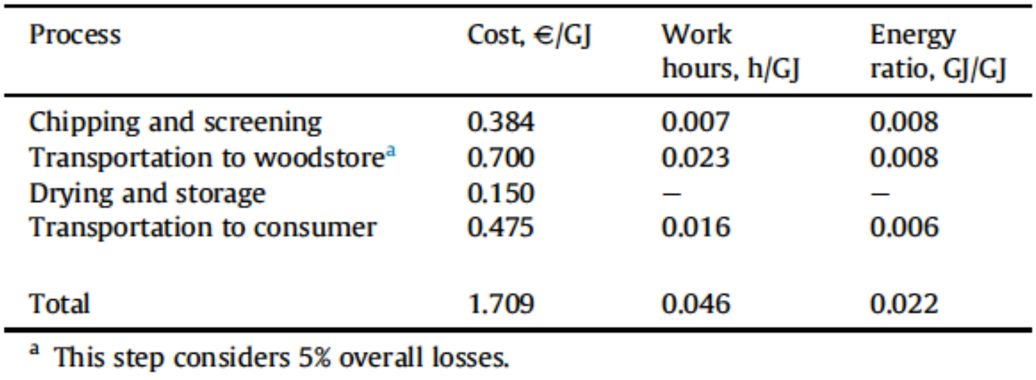
**Table 6. Energy Ratios and Costs for Logging and Extraction of Wood**



| Process | Cost, €/GJ | Work hours, h/GJ | Energy ratio, GJ/GJ |
|---|---|---|---|
| Cutting | 1.761 | 0.087 | 0.003 |
| Skidding | 1.844 | 0.065 | 0.021 |
| Drag transportation[a] | 1.232 | 0.044 | 0.014 |
| Total | 4.836 | 0.196 | 0.038 |

[a] This step considers 1% losses during transport.

**Table 7. Energy Ratios and Costs for Chipping, Drying, and Storing Wood**

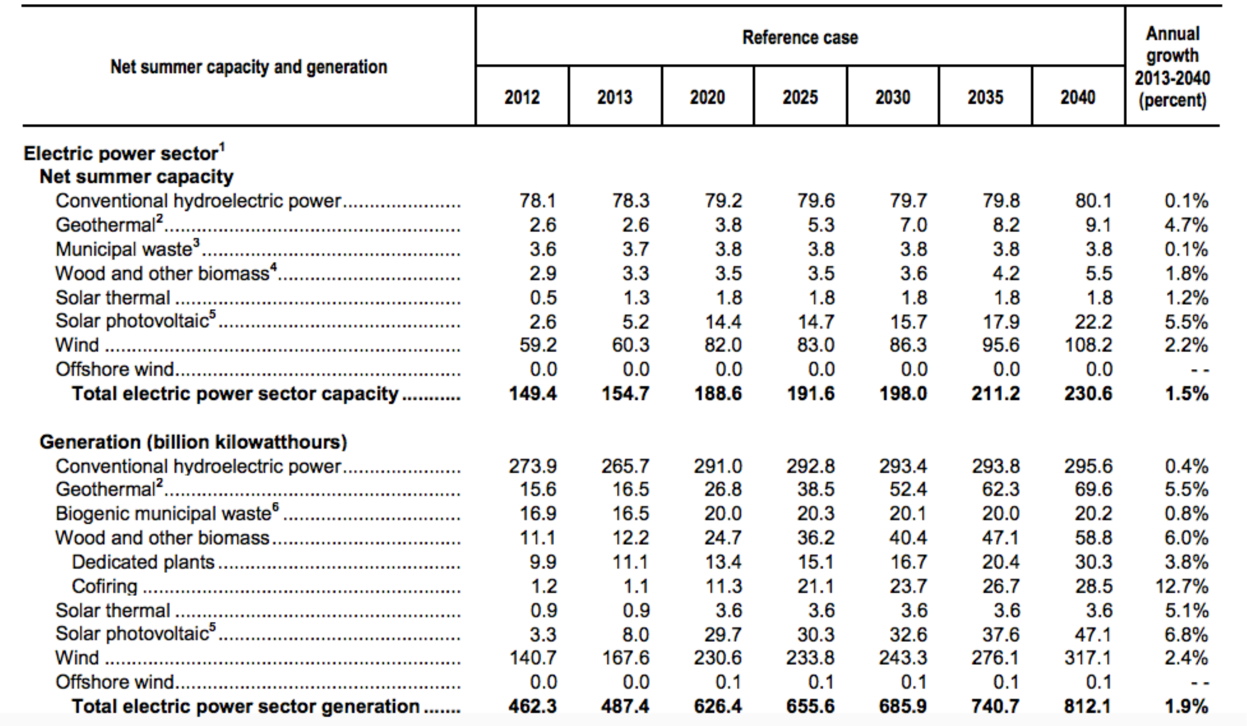


| Process | Cost, €/GJ | Work hours, h/GJ | Energy ratio, GJ/GJ |
|---|---|---|---|
| Chipping and screening | 0.384 | 0.007 | 0.008 |
| Transportation to woodstore[a] | 0.700 | 0.023 | 0.008 |
| Drying and storage | 0.150 | – | – |
| Transportation to consumer | 0.475 | 0.016 | 0.006 |
| Total | 1.709 | 0.046 | 0.022 |

[a] This step considers 5% overall losses.

**Source:** Reprinted from "Comparative cost evaluation of heating oil and small-scale wood chips produced from Euro-Mediterranean forests" by B. Esteban, et al., 2014, *Renewable and Energy, 74*, p. 568-575.

### Table 8. Renewable Energy Capacity and Generation (In Gigawatts unless specified)



| Net summer capacity and generation | Reference case | | | | | | | Annual growth 2013-2040 (percent) |
|---|---|---|---|---|---|---|---|---|
| | 2012 | 2013 | 2020 | 2025 | 2030 | 2035 | 2040 | |
| **Electric power sector[1]** | | | | | | | | |
| **Net summer capacity** | | | | | | | | |
| Conventional hydroelectric power | 78.1 | 78.3 | 79.2 | 79.6 | 79.7 | 79.8 | 80.1 | 0.1% |
| Geothermal[2] | 2.6 | 2.6 | 3.8 | 5.3 | 7.0 | 8.2 | 9.1 | 4.7% |
| Municipal waste[3] | 3.6 | 3.7 | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 | 0.1% |
| Wood and other biomass[4] | 2.9 | 3.3 | 3.5 | 3.5 | 3.6 | 4.2 | 5.5 | 1.8% |
| Solar thermal | 0.5 | 1.3 | 1.8 | 1.8 | 1.8 | 1.8 | 1.8 | 1.2% |
| Solar photovoltaic[5] | 2.6 | 5.2 | 14.4 | 14.7 | 15.7 | 17.9 | 22.2 | 5.5% |
| Wind | 59.2 | 60.3 | 82.0 | 83.0 | 86.3 | 95.6 | 108.2 | 2.2% |
| Offshore wind | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | - - |
| **Total electric power sector capacity** | **149.4** | **154.7** | **188.6** | **191.6** | **198.0** | **211.2** | **230.6** | **1.5%** |
| **Generation (billion kilowatthours)** | | | | | | | | |
| Conventional hydroelectric power | 273.9 | 265.7 | 291.0 | 292.8 | 293.4 | 293.8 | 295.6 | 0.4% |
| Geothermal[2] | 15.6 | 16.5 | 26.8 | 38.5 | 52.4 | 62.3 | 69.6 | 5.5% |
| Biogenic municipal waste[6] | 16.9 | 16.5 | 20.0 | 20.3 | 20.1 | 20.0 | 20.2 | 0.8% |
| Wood and other biomass | 11.1 | 12.2 | 24.7 | 36.2 | 40.4 | 47.1 | 58.8 | 6.0% |
| Dedicated plants | 9.9 | 11.1 | 13.4 | 15.1 | 16.7 | 20.4 | 30.3 | 3.8% |
| Cofiring | 1.2 | 1.1 | 11.3 | 21.1 | 23.7 | 26.7 | 28.5 | 12.7% |
| Solar thermal | 0.9 | 0.9 | 3.6 | 3.6 | 3.6 | 3.6 | 3.6 | 5.1% |
| Solar photovoltaic[5] | 3.3 | 8.0 | 29.7 | 30.3 | 32.6 | 37.6 | 47.1 | 6.8% |
| Wind | 140.7 | 167.6 | 230.6 | 233.8 | 243.3 | 276.1 | 317.1 | 2.4% |
| Offshore wind | 0.0 | 0.0 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | - - |
| **Total electric power sector generation** | **462.3** | **487.4** | **626.4** | **655.6** | **685.9** | **740.7** | **812.1** | **1.9%** |

**Source:** Reprinted from “Annual Energy Outlook 2015” by the U.S. DOE Energy Information Administration, 2015, Retrieved from http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf

## BIOFUELS

In 2010, Vujadin Kovacevic and Justus Wesseler conducted a cost-benefit analysis for algae energy production, a type of next-generation biofuel. Although their focus was on road transportation fuels, their research can be used to understand the general costs due to similarities in algae production and operation costs. All of the information in this sub-section is derived from Kovacevic and Wesseler, so the individual facts from their study are not referenced.

Kovacevic and Wesseler compared private operation and production costs as well as external environmental and socioeconomic costs of diverse feedstocks: algae, fossil fuels (gasoline and diesel), and first generation biofuels (rapeseed). To determine private production costs for algal biodiesel, Kovacevic and Wesseler included the land requirement, favorable conditions (water supply, solar radiation, temperature), system design (mixing, carbon supply, anaerobic digestion, biomass conversion via chemical extraction), and distributing costs. For rapeseed biodiesel, a conventional biofuel, the researchers also used land requirement, design costs, and other production costs, many of which were similar to algal biodiesel. For fossil fuels, the researchers created three different scenarios that vary based on the projected cost for a barrel of oil in 2020. Their results are summarized in Table 9, with the unit for costs as Euros per GJ. In 2008, algal and rapeseed biodiesel production costs were 220.2 Euros/GJ and 125.9 Euros/GJ, respectively. Kovacevic and Wesseler estimated that algal biodiesel costs would be reduced to 86.4 Euros/GJ and rapeseed biodiesel increased to 126.3 Euros/GJ (Table 9). The three fossil fuel cases (A-C) are based on the cost for a barrel of oil. In 2008, they assumed the price was stable ($45 a barrel), thus costing 12.6 Euros per GJ. In 2020, the Euros per GJ varied; Case A assumed a stable barrel price ($45), Case B increased to $100 a barrel, and Case C increased to

$200 a barrel. Fossil fuel production costs were thus cheaper than algal and rapeseed biodiesel for both 2008 and 2020, though costs can increase two to four times based on oil price (Table 9).

Kovacevic and Wessler included external costs (Euros per GJ) to account for each fuel source's impact on the environment (leaching and greenhouse gas and non-GHG emissions), social issues (food vs. fuel), and security of supply (Table 10). A negative value in the table denotes a benefit. For greenhouse gas emissions, the researchers considered land use changes (biofuels only), energy used in production (all fuels), fuel distribution and dispensing (all fuels) and fuel combustion (fossil fuels only). GHG emissions from combustion were considered only for fossil fuels since they release new carbon into the atmosphere. Based on their analysis, Kovacevic and Wessler found that all three types of fuel would release GHG emissions. In analyzing effects of non-GHG emissions (volatile organic compounds or hydrocarbons, particulates, sulfur dioxide, and nitrous oxide emissions), Kovacevic and Wessler looked at information from the European Union, and found that all three fuels negatively affect human health costs, biodiversity, and crops. The food versus fuel dilemma related to conventional biofuels is based on the idea that diverting farmland or crop supply for biofuel use is detrimental to food supply, which increases food prices. Kovacevic and Wesseler calculated land area for different types of conventional biofuel crops and determined their effects on food price, assuming that total land area must be approximately 15.4 Mega hectares to have no effect. They concluded that conventional biofuels have a negative impact on food prices. Leaching via fertilizers and pesticides applies to conventional biofuels, as these crops are fertilized and grown on arable land. Kovacevic and Wessler also incorporated security of supply, or the reliability of energy supply at affordable prices, into their external costs calculations. This factor only applies to fossil fuels as they cannot be readily replaced in a timely manner; it is one of the aspects of oil dependency. The researchers used estimations from the European Union's Joint Research Centre and determined that fossil fuels have a negative effect on security of supply costs. Table 7 lists the external costs using the units "Euros per GJ."

**Discussion and Limitations of the Study**

The results from Kovacevic and Wesseler's 2010 study estimate that production costs for both conventional and next-generation biofuels may remain higher than that of fossil fuels by 2020. Algal biodiesel costs may decrease, eventually becoming a more economical alternative to rapeseed biodiesel, a conventional biofuel. In addition, fossil fuel production costs may be less expensive than both types of biofuel, but can also change dramatically as the market and oil prices fluctuate (Table 9). Furthermore, Kovacevic and Wesseler found that the external costs for algal biodiesel are lower than that of both rapeseed biodiesel and fossil fuels (Table 10). Next generation biofuels produce lower production cycle emissions and have fewer socioeconomic and global effects than do conventional biofuels and fossil fuels.

Kovacevic and Wesseler's study was able to incorporate comparisons among three types of fuel. They demonstrated how next-generation biofuels such as algae have environmental advantages over fossil fuels and conventional biofuels. However, their paper did not include issues related to wastewater treatment, biodiversity, and water, factors that could enhance next-generation biofuels.

Kovacevic and Wesseler's article did not estimate the costs to build large production facilities that contain the proper and often expensive "enzyme cocktails" that are needed to break down the plant cell walls (Klein-Marcuschamer et al., 2011). These facilities must also be specifically designed to provide optimum conditions for the feedstock and to prevent microbrial contaminations. Contamination would reduce end product yield and require expensive cleaning procedures. Kovacevic and Wesseler also did not consider the large volume of feedstock required in order to meet the demands of different sectors, especially the electrical utilities sector (Coyle, 2010).

## Disadvantages/Challenges of Implementation

While next-generation biofuels offer environmental and socioeconomic advantages, they have high operating costs and some uncertainties. Kovacevic and Wesseler's study also describe many of the issues related to conventional biofuels; large-scale biofuel production can lead to deforestation, land impoverishment, loss of biodiversity, water and soil degradation, loss of food sovereignty and security, and dispossession of local communities. Biofuel use could accelerate climate change if production pathways are taken into account, such as fossil fuels used to process crops or nitrous oxide generated from fertilizers, which can be natural gas or petroleum based. Energy crops must also be transported, usually via diesel-powered trucks. Production of corn-based ethanol may require as much energy as the fuel contains (Kovacevic & Wessler, 2010). Additional environmental problems with conventional biofuels include topsoil erosion and runoff. For example, the Dead Zone in the Gulf of Mexico is an area of hypoxic (low oxygen concentration that cannot sustain most animal life) water at the mouth of the Mississippi River. This area can cover up to 6,000 to 7,000 square miles and results in part from upstream runoff of fertilizers, soil erosion, animal waste, and sewage in the farming states in the Mississippi River Valley (Snyder et al., 2001).

Biofuels are also corrosive and can cause cracking in steel, leading to leaked fuel and other hazardous materials. Biodiesel is seven to eight times more biodegradable than traditional diesel. As fatty esters are hydrolyzed by microbes, organic acids and highly corrosive hydrogen sulfide are created. To prevent these issues, biofuels are transported by trucks and rail rather than the traditional pipeline system that gasoline and diesel use, which is less costly and can extend to many areas (Nelson, 2010).

Another challenge to both conventional and next-generation biofuels is their low conversion efficiency and heat content. Photosynthetic efficiency is less than five percent, whereas solar photovoltaic cells are 20-30 percent (Mick, 2008). For energy crops, heat content falls within 17-20 MJ/kg, and for different strains of algae, it can range from 12-40 MJ/kg (Milledge et al., 2014). In comparison, fossil fuels average at around 40 MJ/kg, so biofuel heat content remains an issue to consider.

**Advantages**

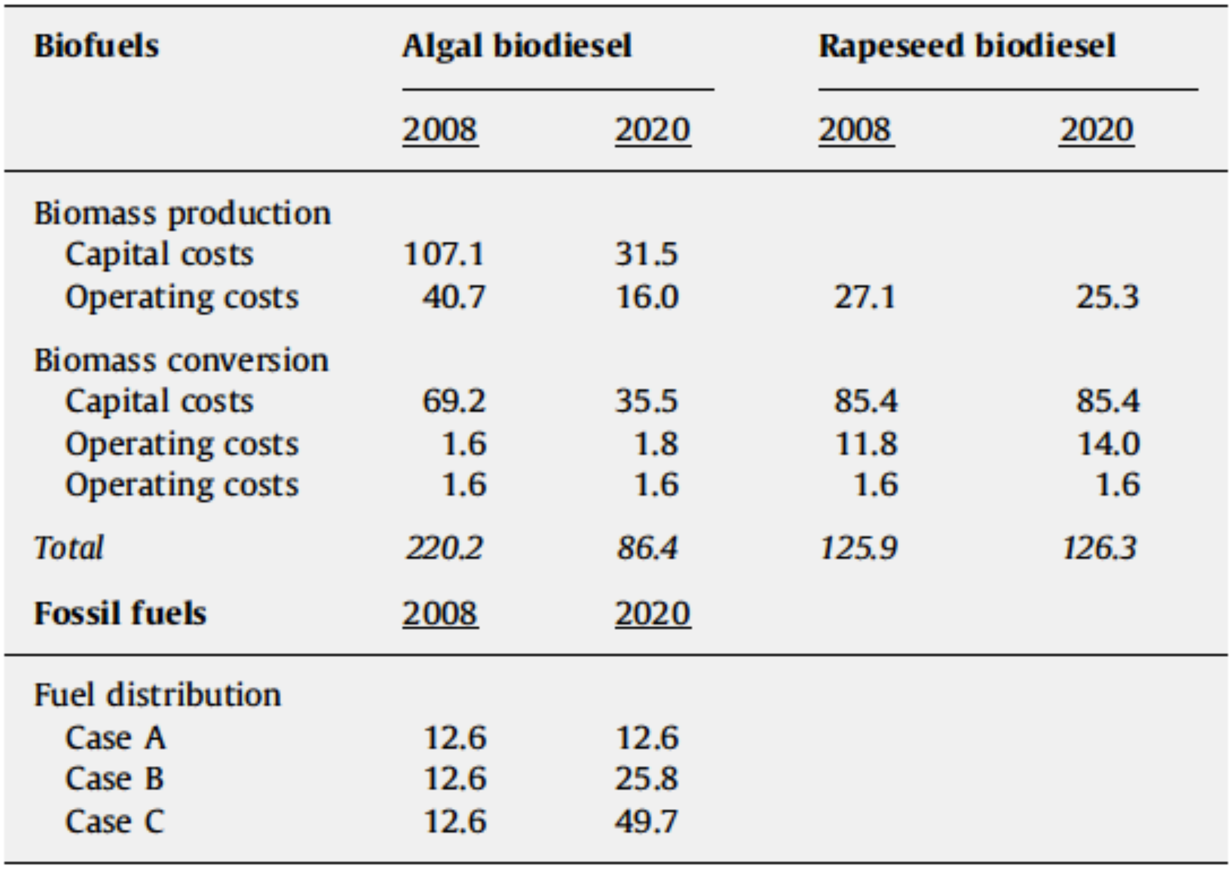
If harvested sustainably, conventional biofuels can prevent widespread deforestation or soil depletion. Harvesting energy crops or growing algae domestically can also strengthen energy security by reducing dependence on foreign oil.

Although many studies do not count the carbon dioxide released when burning biomass, biofuels can help lower carbon emissions, as they do not increase carbon dioxide emissions beyond what would have been released from natural decomposition. When compared to fossil fuels, biofuels have a higher overall cost-benefit, as shown in the study by Kovacevic and Wesseler. If the price for carbon dramatically increases, the production of biofuels may be less costly per energy unit than fossil fuels.

Given the amount of legislation that requires biofuel usage, biofuels, such as corn ethanol, are strongly supported by the U.S. and other governments. For example, the U.S. government offers mandates to consumers to purchase a certain volume of biofuels. It provides subsidies to farmers to grow biomaterial for biofuel production and tax credits to petroleum companies to blend biofuels into traditional fuels. There are tariffs that raise costs of imported biofuels to keep resources domestic. Mandates for producers also create a predictable market that gives incentives to increase production. Agricultural subsidies and tax credits further reduce consumer costs. Strong support from the government is intrinsic to biofuel production due to policies such as the Energy Independence and Security Act of 2007.

Based on Kovacevic and Wesseler's study, it is reasonable to assume a slow but steady growth for both conventional and next-generation biofuels. While conventional biofuels are predicted to increase in production costs, government support as well as improvement in machine efficiencies and production pathways offer opportunity to grow (Table 5). Capital availability and operating costs for facilities and materials remain challenges that affect the commercialization of next generation biofuels. Public funding, financial investments, and research for available yet low-cost feedstock are ways to help drive expansion. While financial investment is crucial, market stability and regulation by the government are also decisive forces. The more certainty there is in regulations and policies, the more likely investors will provide capital for the industry, powering commercialization and growth. Eventually, there may be greater potential for next-generation biofuels to scale in production, providing both environmental and economic opportunities.

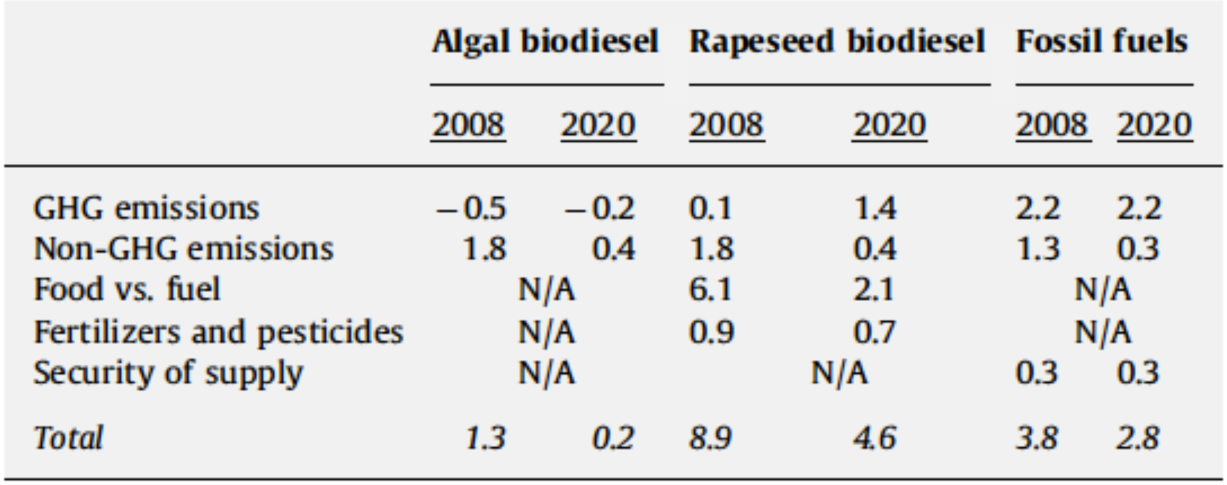
**Table 9. Production Costs for Algal Biodiesel and Rapeseed Biodiesel versus Fossil Fuels**



| Biofuels | Algal biodiesel | | Rapeseed biodiesel | |
|---|---|---|---|---|
| | 2008 | 2020 | 2008 | 2020 |
| Biomass production | | | | |
| Capital costs | 107.1 | 31.5 | | |
| Operating costs | 40.7 | 16.0 | 27.1 | 25.3 |
| Biomass conversion | | | | |
| Capital costs | 69.2 | 35.5 | 85.4 | 85.4 |
| Operating costs | 1.6 | 1.8 | 11.8 | 14.0 |
| Operating costs | 1.6 | 1.6 | 1.6 | 1.6 |
| *Total* | *220.2* | *86.4* | *125.9* | *126.3* |
| **Fossil fuels** | 2008 | 2020 | | |
| Fuel distribution | | | | |
| Case A | 12.6 | 12.6 | | |
| Case B | 12.6 | 25.8 | | |
| Case C | 12.6 | 49.7 | | |

**Source:** Reprinted from “Cost-effectiveness analysis of algae energy production in the EU” by V. Kovacevic & J. Wesseler, 2010, *Energy Policy, 38*, p. 5749-5757.

**Table 10. External Costs and Benefits for Algal Biodiesel and Rapeseed Biodiesel versus Fossil Fuels**



| | **Algal biodiesel** | | **Rapeseed biodiesel** | | **Fossil fuels** | |
|---|---|---|---|---|---|---|
| | 2008 | 2020 | 2008 | 2020 | 2008 | 2020 |
| GHG emissions | −0.5 | −0.2 | 0.1 | 1.4 | 2.2 | 2.2 |
| Non-GHG emissions | 1.8 | 0.4 | 1.8 | 0.4 | 1.3 | 0.3 |
| Food vs. fuel | N/A | | 6.1 | 2.1 | N/A | |
| Fertilizers and pesticides | N/A | | 0.9 | 0.7 | N/A | |
| Security of supply | N/A | | N/A | | 0.3 | 0.3 |
| *Total* | *1.3* | *0.2* | *8.9* | *4.6* | *3.8* | *2.8* |

**Source:** Reprinted from “Cost-effectiveness analysis of algae energy production in the EU” by V. Kovacevic & J. Wesseler, 2010, *Energy Policy, 38*, p. 5749-5757.

## ORGANIC WASTE

In 2010, Jamasb and Nepal presented an economic assessment of waste-to-energy for the UK. They developed a cost-benefit analysis that includes factors such as operating and maintenance (O&M) costs, facility capacities, and $CO_2$ displacement costs compared to coal-fired electricity. The units used are in “tonnes,” also known as a “metric ton.” A tonne is equivalent to 2,240 pounds, whereas an American English “ton” is equal to 2,000 pounds. As all the information discussed in this sub-section is from Jamasb and Nepal, specific citations are not restated.

In 2005 and 2006, the UK produced nearly 29 million tonnes of municipal solid waste (MSW), of which only 2.6 million tonnes, or nine percent, were incinerated for energy (Department for Environmental Food and Rural Affairs, 2007). This percentage is estimated to increase to 25 percent of total MSW by 2020. The UK currently relies on landfill as its primary waste management method, though the Landfill Tax rate is expected to increase from £32 to £48 per tonne, giving additional reason to consider waste-to-energy as an alternative option.

In their study, Jamasb and Nepal used the assumption that 1 tonne of waste generates approximately 2 MWh of heat and 0.65 MWh of electricity. They analyzed different treatment facilities. The facilities most relevant to this paper are incineration for heat and electricity (Incineration H&E), incineration for electricity (Incineration E), and landfill for energy recovery. Jamasb and Nepal also used a scenario that falls in accordance with the European Union Directive’s targets for reducing waste: 62.4, 55.6 and 50 percent of total MSW in a landfill will be used for energy recovery in 2015, 2020, and 2030, respectively. Because the price of carbon affects the desirability of incineration against coal power, Jamasb and Nepal incorporated a low (£13.12 tonnes/$CO_2$) and a high (£62 tonnes/$CO_2$) $CO_2$ costs into their scenario.

If the European Union Directive's targets are fulfilled under a low carbon price, Jamasb and Nepal found that by 2030, incineration for electricity and incineration for electricity and heat would cost 719 million Euros compared to 331 million by a coal-fired plant. However, the two treatments would save 89 million Euros in $CO_2$ displacement costs compared to that of a coal plant (Table 11). Under a high carbon price, costs were similar, but the amount saved in $CO_2$ displacement costs by 2030 increased to 425 million Euros (Table 11). Therefore, as the price of carbon increases, the comparative advantage to generate an equivalent amount of energy from a coal-fired plant will eventually decrease in comparison to facilities that convert waste-to-energy. Jamasb & Nepal also predicted that by 2030, incineration for electricity and incineration for both electricity and heat would also produce 5253 GWh of energy, 2973 GWh from electricity and 2280 from heat. Jamasb and Nepal also noted that costs from coal power may actually be higher than those of incineration plants, due to site-specific damage and drawbacks from using coal, such as scrubber systems that remove particulates from exhaust streams.

Under a low carbon price based on the European Union Directive scenario, a coal-fired plant in 2030 would cost 50 million more Euros than would a landfill that utilizes energy recovery. Under a high carbon price, this difference would increase to nearly 150 million Euros. These results show that the operating and production costs of generating energy from landfill are lower compared to producing the same amount of energy from a coal-powered plant.

Jamasb and Nepal's 2010 study showed that using waste for energy is a cost-effective waste management option if the European Directive targets are met. Although the operating and production costs may be more expensive compared to coal, the cost-effectiveness of waste-to-energy improves substantially with higher carbon prices. Jamasb and Nepal also indicated that additional factors that could increase the cost of coal power plants were not included in their study, such as fossil fuel supply, damages to the environment, or costs of machinery. They predicted that if damages to both environment and machinery were taken into account, coal power costs could increase by 34 percent under the low-carbon price scenario and 14 percent under the high carbon price scenario.

## Discussion and Limitations of the Study

The study shows that under the right conditions and when compared to coal, waste energy for heat or electricity is cost-effective in the long term. Climate change, increasing cost of land, policies such as the European Union Directive, and landfill taxes are all current issues or factors that also make waste energy more appealing. Under high carbon prices of £62 tonnes/$CO_2$, incineration waste for electricity and heat could save 425 million Euros in $CO_2$ costs compared to coal by 2030.

There are other factors that influence the cost of generating energy from waste. As mentioned by the study, plant efficiency, which depends on technology and design specifications, can increase or decrease costs. As research and development, technical progress, and cost reductions increase waste-to-energy, plant efficiency can improve and decrease production costs. Using technologies such as Combined Heat and Power (CHP) can increase efficiency. Another factor that Jamar and Nepal mention that was not included in their study is waste composition, which can affect efficiency and costs. Their assumption that 1 tonne of waste generates approximately 2 MWh of heat and 0.65 MWh of electricity could vary considerably depending on the waste composition and its different calorific values.

This study is limited because of its focus on coal for electricity. Though natural gas also produces greenhouse gases, the decreased costs for production may make it more desirable than waste. Alternative fuel and fossil fuel prices can also affect production costs for using waste to generate energy.

### Disadvantages/Challenges of Implementation

Heating value is a factor in determining the energy output and efficiency of a material, and for wastes, the heating value varies with waste composition. For example, rubber has a high heating value per ton and paper has a low heating value. A study by Fobil et al. found that a typical municipal solid waste heat content has a low range of 14 to 20 MJ/kg with an average conversion efficiency of about 40 percent (Fobil et al., 2005). A finding by the EIA also showed that from 1989 to 2005, heat content for municipal solid waste increased by 14 percent based on the changing composition of waste. Therefore, any material that faces a lower heating value when compared to fossil fuels will face challenges in implementation. MSW composition, which varies by location, can also alter the heat content and overall energy produced.

Waste-to-energy plants can also emit pollutants such as sulfur dioxide, lead, and dioxins (carcinogen), which lead to health and environmental damages (Jamasb & Nepal, 2010). The toxins produced while incinerating waste must be disposed in special landfills and plants must be continuously maintained, both of which cost money. Residents who live near waste-to-energy plants may also perceive the facilities as unsightly and find the odors unpleasant. Methane from landfill gas is a potent greenhouse gas that has a warming potential 25 times higher per ton than that of carbon dioxide (Zafar, 2008). However, one tonne of MSW that is incinerated rather than landfilled could reduce greenhouse gases by about 1.2 tonnes of carbon dioxide (Jamasb & Nepal, 2010). Another alternative is to use landfill methane for electricity generation.

## Advantages

Waste is an inexpensive fuel that can be a reliable resource. Not only does waste-to-energy offer an alternative method to dispose MSW, it reduces the land area used for landfills (IEA, 2013a). Using MSW offers a way to generate renewable energy and a sustainable strategy for waste management. An incinerator that handles 250 tonnes per day can generate 6.5 Megawatts of power per day, with 1 MW powering approximately 1000 homes. Colder states can also use heat from the incinerators for offices and homes located near the plants (Jawasb & Nepal, 2010).

Waste-to-energy plants can have environmental benefits. For every tonne of MSW used to generate energy, the consumption of oil and coal reduces by approximately one barrel and 0.26 tonnes, respectively (Jawasb & Nepal, 2010). As a result, there is a reduction in greenhouse gas emissions. Some researchers consider waste-to-energy a carbon neutral process; when waste is combusted, the amount of carbon dioxide released is equal to that removed from the environment during the original material's production, suggesting less impact on the environment over the product's life cycle. However, the amount of GHG emissions will vary based on the energy inputs during the production pathway, such as collecting and transporting waste (Jawasb & Nepal, 2010).

Areas that do not use landfill methane for electricity generation can also benefit from waste-to-energy facilities. By incinerating MSW, they reduce the amount of organic material going into landfills, which in turn reduces methane emissions. Metals that are part of the MSW composition can also be recycled after becoming ash during incineration.

According to Columbia University's waste map, the U.S. generated over 300 million tonnes of MSW in 2004, of which 28.5 percent was recycled, 64.1 percent was landfilled, and

7.4 percent was incinerated for energy (Environmental Protection Agency, 2016). Based on Table 4, the EIA predicts a slow growth rate for MSW. From 2013 to 2040, electric power capacity and electricity generation are projected to increase by 0.1 percent and 0.8 percent, respectively. In 2013, MSW generated 16.5 billion kilowatt-hours of electricity (3.7 GW capacity) in comparison to a total of 487.4 billion kilowatt hour generated from all renewable energy sources (154.7 GW capacity) (Table 8) (United States Department of Energy, Energy Information Administration, 2015a). By 2040, MSW electric power capacity could increase slightly and electricity generation could increase by 4 billion kilowatt-hours.

Despite a slow projected growth for waste-to-energy, there is reason to believe using MSW for energy has potential due to increased costs of landfilling and concern for climate change. MSW is also a readily available source and a solution for sustainable waste management.

The results from this section show the economic feasibility of using wood chips, biofuels, and organic waste for electricity generation. Under local use, wood chip production costs are less than those of oil, suggesting a cost-effective and appropriate option for areas with high resource availability. Currently, biofuels are hindered by high capital costs and require additional research and funding to lower operating costs. By 2020, next-generation biofuels are projected to reduce negative environmental impacts and decrease production costs. Due to increasing carbon costs, organic wastes for electricity, namely waste-to-energy via incineration, could save millions in carbon costs by 2030.

# Table 11. Total Costs and Carbon Savings for Incineration E, Incineration E&H, and Coal (Under European Union Directive targets)

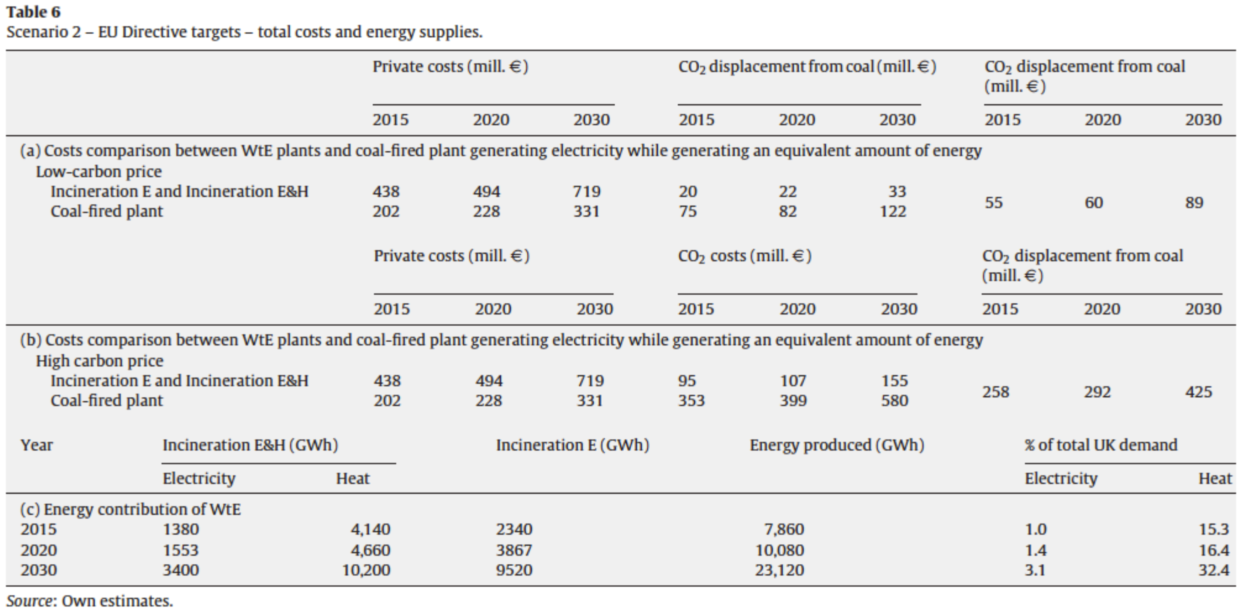


**Table 6**
Scenario 2 – EU Directive targets – total costs and energy supplies.

| | Private costs (mill. €) | | | $CO_2$ displacement from coal (mill. €) | | | $CO_2$ displacement from coal (mill. €) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2015 | 2020 | 2030 | 2015 | 2020 | 2030 | 2015 | 2020 | 2030 |
| (a) Costs comparison between WtE plants and coal-fired plant generating electricity while generating an equivalent amount of energy | | | | | | | | | |
| Low-carbon price | | | | | | | | | |
| Incineration E and Incineration E&H | 438 | 494 | 719 | 20 | 22 | 33 | 55 | 60 | 89 |
| Coal-fired plant | 202 | 228 | 331 | 75 | 82 | 122 | | | |

| | Private costs (mill. €) | | | $CO_2$ costs (mill. €) | | | $CO_2$ displacement from coal (mill. €) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2015 | 2020 | 2030 | 2015 | 2020 | 2030 | 2015 | 2020 | 2030 |
| (b) Costs comparison between WtE plants and coal-fired plant generating electricity while generating an equivalent amount of energy | | | | | | | | | |
| High carbon price | | | | | | | | | |
| Incineration E and Incineration E&H | 438 | 494 | 719 | 95 | 107 | 155 | 258 | 292 | 425 |
| Coal-fired plant | 202 | 228 | 331 | 353 | 399 | 580 | | | |

| Year | Incineration E&H (GWh) | | Incineration E (GWh) | Energy produced (GWh) | % of total UK demand | |
|---|---|---|---|---|---|---|
| | Electricity | Heat | | | Electricity | Heat |
| (c) Energy contribution of WtE | | | | | | |
| 2015 | 1380 | 4,140 | 2340 | 7,860 | 1.0 | 15.3 |
| 2020 | 1553 | 4,660 | 3867 | 10,080 | 1.4 | 16.4 |
| 2030 | 3400 | 10,200 | 9520 | 23,120 | 3.1 | 32.4 |

*Source*: Own estimates.

**Source:** Reprinted from “Issues and options in waste management: A social cost-benefit analysis of waste-to-energy in the UK” by T. Jamasb & R. Nepal, 2010, *Resources, Conservation and Recycling, 54*, p. 1341-1352.

# CONCLUSION

Biological materials have a significant potential for electricity generation. The three types of feedstock mentioned in this paper—wood chips, biofuels, and organic waste—offer more environmental benefits compared to both fossil fuels and other renewables. For example, waste wood that is meant to be burned can be repurposed and combusted in a bioenergy plant to generate heat and electricity. This would reduce greenhouse gas emissions twice—once through reduced burning and again through fossil fuel substitution (Energy and Earth Resources, 2012). Wood chipping and waste-to-energy plants offer alternatives to handling waste and are also more economical than fossil fuels. Esteban and his colleagues' 2014 study showed that wood chips cost less per GJ than heating oil. Jamasb and Nepal's 2010 study concluded that municipal solid waste is more cost-effective than fossil fuels, as it could save the UK over 400 million Euros in carbon costs by 2030. Although biofuels have a more difficult path to large scale production, Kovacevic and Wesseler's 2010 study showed that by 2020, next-generation biofuels could have a lower production cost and carbon footprint compared to that of conventional biofuels and have a lower external cost compared to both conventional biofuels and fossil fuels. However, there are many challenges of implementation for next-generation biofuels that may slow their growth.

In 2011, the U.S. Department of Energy conducted the "Billion-Ton Study" to highlight opportunities for growth and development in bioenergy resources. Taking into consideration resources such as wood waste, logging residues, manure, crop waste, and others, the study found that 1.3 billion tons of biomass could be available each year (U.S. DOE, 2011). If the average biomass energy density is 10 million Btu per ton, 1.3 billion tons of biomass could produce up to 13 quads of energy in the U.S. each year. However, 13 quads is less than one-sixth of the total U.S. annual consumption, which was 95 quads in 2012 (U.S. DOE, EIA, 2015d). These statistics show the possibility of incorporating more bioenergy into the energy sector. However, due to lower heat contents and energy efficiencies, biomass and its interchangeable forms (biogas and biofuel) may not supply significant portions of U.S. energy consumption. This does not mean the many advantages of bioenergy should go unnoticed. Biological materials can be used as a relatively clean and sustainable energy source. The feedstocks are local, abundant, easily replenished, and in principle, interchangeable (biomass, biofuel, biogas), resulting in many different end products. Waste that would otherwise be disposed in a landfill (MSW) or burned (wood waste) can be reused and harnessed for energy. This results in less landfill use and risk of wildfires, saving environmental and economic costs for disposal, damage, and contamination. Because biomass sources are abundant, the energy they produce is reliable and secure. The products themselves (such as biofuels) are biodegradable, whereas petroleum and petrochemicals can pollute both air and ground.

Increasing bioenergy supply can create regional and rural economic development and employment opportunities. Bioenergy can stimulate regional economic growth by providing new, decentralized, and diversified jobs throughout the production pathway: growing/harvesting biomass, transport, handling, construction, and operation/management of plants. Landholders have more market options for agricultural and tree crops. Farmers can make use of livestock waste. There may even be opportunities to grow new crops for energy usage. Even from a global point of view, bioenergy has its advantages; it reduces global GHG emissions, offers energy security, and is a useful energy source for poor developing countries without fuel. A domestic energy source in a rural or regional area can run continuously or be easily increased at peak times.

Producing enough bioenergy that can meet U.S. energy needs will be difficult if some factors do not change. These include carbon prices, fossil fuel prices, energy security, policy, and concerns about climate change. However, as long as there is inexpensive and available feedstock, the use of biological material for electricity generation is a feasible option. Wood and organic waste have significant potential due to their availability. In order to see the advantages of next-generation biofuel, there must be additional research that allows the technology to operate at an industrial scale. For example, researchers can simplify equipment to lower costs, better optimize conditions for fuel yield, and improve enzymes and chemicals. Due to the many environmental and economic advantages as shown throughout this thesis, bioenergy should be more heavily incorporated into the electrical fuel mix. At this time, wood and organic waste are feasible options.

# References

Alveo Water and Sanitation (n.d.). Biogas Treatment. Retrieved from http://www.alveo.co.za/biogas-treatment

Appels, L., Lauwers, J., Degreve, J., Helsen, L., Lievens, B., Willems, K., Van Impe, J., & Dewil, R. (2011). Anaerobic digestion in global bio-energy production: Potential and research challenges. *Renewable and Sustainable Energy Reviews, 15*(9), 4295-4301. doi:10.1016/j.rser.2011.07.121

Atadashi, I.M., Aroua, M.K., Azia, A.R., & Sulaiman, N.M.N. (2011). Refining technolgoies for the purification of crude biodiesel. *Applied Energy, 88,* 4239-4251. doi:10.1016/j.apenergy.2011.05.029

Basu, P. (2010). *Biomass Gasification and Pyrolysis: Practical Design and Theory*. Burlington, MA: Elsevier Inc.

Biofuel.org.uk (2011). *Biofuel Chemistry: How they Burn? Retrieved from* http://biofuel.org.uk/how-do-biofuels-burn.html

Biomass Energy Centre (n.d.). *Wood chips*. Retrieved from http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,18515&_dad=portal&_schema=PORTAL

British Petroleum (2015). Biofuels Technologies. *Next generation biofuels*. Retrieved from http://www.bp.com/en/global/corporate/about-bp/bp-and-technology/lower-carbon-future/biofuels.html

Buchmayr, M., Gruber, J., Hargassner, M., & Hocenauer, C. (2015). Experimental investigation of the primary combustion zone during staged combustion of wood-chips in a commercial small-scale boiler. *Biomass and Bioenergy, 81,* 356-363. doi:10.1016/j.biombioe.2015.07.016

Carnegie Mellon University (2003). *Science Notes: Chemistry of Fossil Fuels*. Retrieved from http://environ.andrew.cmu.edu/m3/s3/09fossil.shtml

Central Baltic INTERREG IV A Programme & European Union. (2013). *Production of Wood Chips* [PowerPoint slides]. Retrieved from http://www.slideserve.com/josiah/production-of-wood-chips

Ciolkosz, D. (2014, March 10). *Introduction to biomass combustion*. Retrieved from http://articles.extension.org/pages/31758/introduction-to-biomass-combustion

Coyle, W.T. (2010). Next-Generation Biofuels: Near-Term Challenges and Implications for Agriculture. Economic Research Service of the United States Department of Agriculture. Retrieved from http://www.ers.usda.gov/media/122837/bio0101.pdf

Energy and Resources (2012). The Benefits of Bioenergy. Retrieved from http://www.energyandresources.vic.gov.au/energy/sustainable-energy/bioenergy/benefits-of-bioenergy

Environmental Protection Agency (2007). *Energy Independence and Security Act*. Retrieved from https://www.gpo.gov/fdsys/pkg/BILLS-110hr6enr/pdf/BILLS-110hr6enr.pdf

Environmental Protection Agency (2016). Municipal Solid Waste. Retrieved from https://www3.epa.gov/epawaste/nonhaz/municipal/

Environmental Protection Agency (n.d.). LFG Energy Projects. Retrieved from https://www3.epa.gov/lmop/faq/lfg.html

Esteban, B., Riba, J., Baquero, G., & Rius, A. (2014). Comparative cost evaluation of heating oil and small-scale wood chips produced from Euro-Mediterranean forests. *Renewable Energy, 74*(2015)*,* 568-575. doi:10.1016/j.renewe.2014.08.038

Fobil, J.N., Carboo, D., Armah, N.A. (2005). Evalulation of municipal solid wastes (MSW) for utilization in energy production in developing countries. *Int. J. Environmental Technology and Management, 5*(1), 76-86.

Food and Agriculture Organization of the United Nations (n.d.). The potential use of wood residues for energy generation. Retrieved from http://www.fao.org/docrep/t0269e/t0269e08.htm

Ghenai, C. & Janajreh, I. (2015). Combustion of renewable biogas fuels. *Journal of Energy and Power Engineering, 9,* 831-843. doi:10.17265/1934-8975/2015.010.001

Guo, M., Song, W., & Buhain, J. (2014). Bioenergy and biofuels: History, status, and perspective. *Renewable and Sustainable Energy Reviews, 42*, 712-725. doi:10.1016/j.rser.2014.10.013

Hellstrom, L. (2010). *On the wood chipping process – a study on basic mechanisms in order to optimize chip properties for pulping* (Doctoral dissertation). Retrieved from DiVA Portal. Mid Sweden University, Sundsvall, Sweden.

Ileleji, K., Martin, C., & Jones, D. (2008, August). Basics of energy production through anaerobic digestion of livestock manure. Retrieved from https://www.extension.purdue.edu/extmedia/ID/ID-406-W.html

International Energy Agency (2006). World Energy Outlook. Retrieved from https://www.iea.org/publications/freepublications/publication/cooking.pdf

International Energy Agency (2013) Waste to Energy. Retrieved from http://www.ieabioenergy.com/wp-content/uploads/2014/03/ExCo71-Waste-to-Energy-Summary-and-Conclusions-28.03.14.html

International Energy Agency (2013). Waste to Energy. Summary and Conclusions from the IEA Bioenergy ExCo71 Workshop.

International Energy Agency (2013) Renewable Energy Medium-Term Market Report. *Market Trends and Projections to 2018*. Retrieved from https://www.iea.org/publications/freepublications/publication/2013MTRMR.pdf

International Energy Agency (2016). About renewable energy. Retrieved from http://www.iea.org/topics/renewables/

International Energy Agency (n.d.) Bioenergy. Retrieved from https://www.iea.org/topics/renewables/subtopics/bioenergy/

Jamasb, T. & Nepal, R. (2010). Issues and options in waste management: A social cost-benefit analysis of waste-to-energy in the UK. *Resources, Conservation and Recycling, 54*(2010), 1341-1352. doi:10.1016/j.resconrec.2010.05.004

Klein-Marcuschamer, D., Oleskowicz-Popiel, P., Simmons, B.A., Blacnh, H.W. (2011). The Challenge of Enzyme Cost in the Production of Lignocellulosic Biofuels. *Biotechnology and Bioengineering 109*(4), 1083-7. doi:10.1002/bit.24370

Kovacevic, V. & Wesseler, J. (2010). Cost-effectiveness analysis of algae energy production in the EU. *Energy Policy, 38*(201), 5749-5757. doi:10.1016/j.enpol.2010.05.025

Li, H. (2014, May 9). Burning wood for energy leads to debate over its carbon emissions. *Unearthed*. Retrieved from https://unearthedmag.wordpress.com/2014/05/09/burning-wood-for-energy-leads-to-debate-over-its-carbon-emissions/

McKendry, P. (2002). Energy production from biomass: overview of biomass. *Bioresource Technology, 83(1)*, 37-46. doi:10.1016/S0960-8524(01)00118-3

Mick, J. (2008, February 19). Solar Cell Makes Hydrogen Via Synthetic Photosynthesis. *Daily Tech*. Retrieved from http://www.dailytech.com/Solar+Cell+Makes+Hydrogen+Via+Synthetic+Photosynthesis/article10735.htm

Milledge, J.J., Smith, B., Dyer, P.W., Harvey, P. (2014). Macroalgae-Derived Biofuel: A Review of Methods of Energy Extraction from Seaweed Biomass. *Energies, 7*, 7194-7222. doi:10.3390/en7117194

Mohseni, F., Magnusson, M., Görling, M., & Alvfors, P. (2012). Biogas from renewable electricity – Increasing a climate neutral fuel supply. *Applied Energy*, *90(1),* 11-16. doi:10.1016/j.apenergy.2011.07.024

Nazaroff & Alvarez-Cohen. *Anaerobic Digestion of Wastewater Sludge* [PowerPoint slides]. Retrieved from http://engineering.dartmouth.edu/~d30345d/courses/engs37/anaerobicdigestion.html

Nelson, B. (2010, June 2). Biodiesel corrosion could cause leaks in fuel infrastructure. *Mother Nature Network*. Retrieved from http://www.mnn.com/earth-matters/energy/stories/biodiesel-corrosion-could-cause-leaks-in-fuel-infrastructure

Oak Ridge National Laboratory (2011). Center for Transportation Analysis. Lower and Higher Heating Values of Gas, Liquid, and Solid Fuels. Retrieved from http://cta.ornl.gov/bedb/appendix_a/Lower_and_Higher_Heating_Values_of_Gas_Liquid_and_Solid_Fuels.pdf

Renewable Energy Policy Network for the 21st Century (2010). Renewables 2010 Global Status Report. Retrieved from http://www.harbortaxgroup.com/wp-content/uploads/2014/07/REN21_GSR_2010_full_revised-Sept2010.pdf

Rubin, E. (2008). Genomics of cellulosic biofuels. *Nature, 454,* 841-845. doi:10.1038/nature07190

Shimelmitz, R., Kuhn, S.L., Jelinek, A.J., Ronen, A., Clark, A.E., & Weinstein-Evron, M. (2014). 'Fire at will': The emergence of habitual fire use 350,000 years ago. *Journal of Human Evolution, 77,* 196-203. doi:10.1016.j.hevol.2014.07.005

Small Giant of Bioenergy (n.d.). *Wood Chips*. Retrieved from http://www.bioenergyadvice.com/bio-fuels/wood-chips/quality/

Snyder, C.S., Howarth, R.W., Winstanely, D., Ferber, D. (2001). Hypoxia, fertilizer, and the Gulf of Mexico. *Science, 292*(5521), 1485-1486. doi:10.1126/science.292.5521.1485b

Solecki, M., Scodel, A., & Epstein, B. (2013). Environmental Entrepreneurs. *Advanced Biofuel Market Report 2013*. Retrieved from http://www.eesi.org/files/E2AdvancedBiofuelMarketReport2013.pdf

Statistics Finland (2013). *Wood fuels became the largest source of energy in 2012*. Retrieved from http://www.stat.fi/til/ehk/2012/ehk_2012_2013-12-12_tie_001_en.html

Sustainable Energy Authority of Ireland (n.d.). *Four phases to produce biomass*. Retrieved from http://www.seai.ie/Renewables/Bioenergy/Bioenergy_Technologies/Anaerobic_Digestion/The_Process_and_Techniques_of_Anaerobic_Digestion/

Sustainable Energy Authority of Ireland (n.d.). *Energy Crops*. Retrieved from http://www.seai.ie/Renewables/Bioenergy/Sources/Biomass/#waste

Sustainable Energy Authority of Ireland (n.d.). *Wood chips*. Retrieved from http://www.seai.ie/Renewables/Bioenergy/Sources/Wood_Energy_and_Supply_Chain/Wood_Chips/

Tsai, W.T. (2007). Bioenergy from landfill gas (LFG) in Taiwan. *Renewable and Sustainable Energy Reviews, 11*(2), 331-344. doi:10.1016/j.rser.2005.01.001

Union of Concerned Scientists (2014). Turning Agricultural Residues and Manure into Bioenergy. Retrieved from http://www.ucsusa.org/sites/default/files/legacy/assets/documents/clean_vehicles/Agricultural-Residue-Ranking.html

United States Department of Agriculture Forest Products Laboratory (2004). *Wood Biomass for Energy*. Retrieved from http://www.fpl.fs.fed.us/documnts/techline/wood-biomass-for-energy.pdf

United States Department of Energy (2011). Department of Energy Releases New ‘Billion-Ton’ Study Highlighting Opportunities for Growth in Bioenergy Resources. Retrieved from http://energy.gov/articles/department-energy-releases-new-billion-ton-study-highlighting-opportunities-growth

United States Department of Energy (2015). Energy Information Administration. Annual Energy Outlook 2015. Retrieved from http://www.eia.gov/forecasts/aeo/pdf/0383(2015).pdf

United States Department of Energy (2015). Energy Information Administration. *Electricity Power Monthl*y.

United States Department of Energy (2015). Energy Information Administration. *Monthly biofuel production report*. Retrieved from http://www.eia.gov/biofuels/biodiesel/production/

United States Department of Energy (2015). Energy Information Administration. What is the United States' share of world energy consumption? Retrieved from https://www.eia.gov/tools/faqs/faq.cfm?id=87&t=1

United States Department of Energy (2016). Location of MSW Combustion Facilities. MSW Generation and Dispostion by State. Retrieved from https://www3.epa.gov/wastes/nonhaz/municipal/wte/plants.html

United States Department of Energy (2015). National Renewable Energy Laboratory. *Biofuels Basics*. Retrieved from http://www.nrel.gov/learning/re_biofuels.html

United States Department of Energy (2012). Office of Energy Efficiency and Renewable Energy. *Technical Information Exchange on Pyrolysis Oil: Potential for a Renewable Heating oil Substitution Fuel in New England*. Retrieved from http://energy.gov/sites/prod/files/2014/04/f14/pyrolysis_workshop_report.pdf

United States Department of Energy (2013). Office of Energy Efficiency and Renewable Energy. *Biofuel Conversion Basics*. Retrieved from http://energy.gov/eere/energybasics/articles/biofuel-conversion-basics

United States Department of Energy (2014). Office of Energy Efficiency and Renewable Energy. *Making algal biofuel production more efficient, less expensive*. Retrieved from http://energy.gov/eere/articles/making-algal-biofuel-production-more-efficient-less-expensive

United States Department of Energy (n.d.). Office of Energy Efficiency and Renewable Energy. *Hydrogen production: biomass gasification*. Retrieved from http://energy.gov/eere/fuelcells/hydrogen-production-biomass-gasification

University of Illinois at Urbana-Champaign (n.d.). Integrated Bioprocessing Research Laboratory. *Six Steps to Biofuel*. Retrieved from http://bioenergy.illinois.edu/assets/downloads/state_fair.pdf

University of Strathclyde Engineering (n.d.). Biodiesel Production. Retrieved from http://www.esru.strath.ac.uk/EandE/Web_sites/02-03/biofuels/what_biodiesel.html

Urban, F. & Mitchell, T. (2011). Climate change, disasters, and electricity generation. *Strengthening Climate Resilience Discussion Paper, 8,* 22-23

Zafar, Salman (2008). Negative impacts of incineration-based waste-to-energy technology. Environment and Sustainability. Retrieved from http://www.alternative-energy-news.info/negative-impacts-waste-to-energy/

# Author Biography

Jennifer Den is a senior at The University of Texas at Austin majoring in Biochemistry, and receiving certificates as a Polymathic Scholars. She plans to receive her B.S.A. degree and her Evidence and Inquiry certificate in Spring 2016.