Environmental Impact of
Approving Biomass Conversion Plants in California

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Executive Summary

Generating electricity from biomass is considered to be an alternative energy source due to its promise to reduce the quantity of CO_2 released into the environment, when compared with fossil fuels. However, biomass is considered to be a low-density fuel, because it is believed to be more expensive than fossil fuels to produce, handle, and transport. The purpose of this study was to analyze whether or not exclusive use of feedstocks/technologies that are carbon-neutral would be economically feasible for biomass plant operators, or under what circumstances (i.e., subsidies and/or incentives) economic feasibility could be achieved.

Determining the economic feasibility for the biomass feedstocks available in California involved comparing the average cost of biomass fuel against the cumulative cost of fuel of California's current energy generation technologies. Published data indicates that the majority of electricity produced in the state of California is generated from natural gas. The balance of is produced from nuclear, large hydro, renewables, and coal. Using a weighted average calculation, the cumulative cost of fuel was determined to be $6.56 US dollars per MMBtu. This value was used as the baseline for comparison to determine whether or not an individual biomass feedstock is economically feasible. Based on prior research, a life-cycle analysis methodology that considers carbon emissions throughout the life-cycle of a feedstock was used to calculate the average fuel cost for each feedstocks. This was performed for all feedstocks that are definitively able to provide carbon neutrality or net reductions to carbon emissions. A comparison for each feedstock was then performed against California's current energy cumulative cost.

Findings indicate that most of the first generation feedstocks, which include orchard pruning's and vine removal, field and seed, vegetable trimmings, food processing (rice hulls, shells, and pits), mill residue, logging slash, chaparral, municipal solid waste were determined to have an average fuel cost below $6.56 and therefore do not require a subsidy. Several of the second generation feedstocks, which include loblolly pine, eucalyptus, sugarcane/energycane, sugarcane bagasse, and algae were calculated to have a fuel cost average of $5.96 US dollars per MMBtu, which approaches the limit of $6.56 US dollars per MMBtu for economic feasibility. These biomass feedstocks may require subsidies under circumstances that vary from the analyzed conditions in this report.

The calculation for forest thinnings yielded an average fuel cost of $7.78 US dollars per MMBtu, which is not economically feasible, and would require a subsidy of at least $1.22 US dollars per MMBtu to be competitive. The calculation for animal manure also indicated that it is not economically feasible primarily due to the fact that manure biogas systems are typically very small for gas treatment to be economical.

Section 1 - Introduction

1.1 Purpose and Scope

The purpose of this study was to prepare information for state decisions makers regarding the Environmental Impact of Approving Biomass Conversion Plants in California. The scope of work included the following:

1. Reviewing existing literature on comprehensive life-cycle assessments of biomass-to-energy projects in the Western United States;
2. Identifying feedstocks and/or technologies in current or future use that definitively provide carbon neutrality or net reductions to carbon emissions when all life-cycle emissions are considered;
3. Analyzing whether exclusive use of feedstocks/technologies that are carbon-neutral would be economically feasible for biomass plant operators, or under what circumstances (subsidies/incentives) economic feasibility could be achieved; and
4. Determine whether increased use of biomass conversion to contribute to California's Renewable Portfolio Standard is warranted.

1.2 Background

The generation of electricity from biomass is considered by some to be an alternative source of energy production due to its ability to reduce the amount of CO_2 released into the environment when compared against fossil fuels. However, biomass is a considered to be a low-density fuel, meaning that it is considered to be more expensive than fossil fuels in production, handling, and transportation. Another factor differentiating biomass fuels from fossil fuels is that emissions from biomass to the biosphere are reversible whereas those from fossil fuel sources are not (Sedjo, 2011). The primary sources of biomass found throughout the State of California include agricultural, forestry, and municipal. As a whole, the sources of biomass energy feedstocks are considered to be scarcer and more dispersed when compared to fossil fuels. In addition, the existing biomass power generating facilities are relatively small when compared to fossil fuel energy production facilities. Therefore, the generation of electricity from biomass appears to be at a disadvantage (Morris, 1999). According to Morris, the value of the environmental services associated with biomass energy production in the United States is 14.1¢/kWh (Morris, 1999). The calculation Morris uses to generate this value takes into consideration both electric and non-electric benefits. His methodology includes the development of the economy in rural, including related employment and the increase of energy generation diversification and security provided by biomass energy production.

According to Morris, there have been a number of policies that have been proposed to enhance the viability of biomass energy generation in California. These policy goals focus upon providing enough incentives to preserve and expand the production of renewable biomass energy in California (Morris, 2002). Prior research indicates that the establishment of payments would cover the cost associated with "establishing" these crops (i.e., clearing, planting, and seeding) within a project area (Stubbs 2010).

Federal congressional support for biopower has aimed to promote energy security and has generally assumed that biopower is carbon neutral (Bracmont, 2011). However, determining whether or not biopower is carbon neutral depends on the following (Bracmont, 2011):

- feedstock type
- electricity generation technology used, and
- time frame examined.

Furthermore, energy production activities are generally classified as carbon neutral if they do not produce or do not increase the amount of greenhouse gas (GHG) emissions when the entire life-cycle is considered. This calculation considers the carbon flux, which is the CO_2 emission and sequestration at each phase of the biopower pathway. The carbon flux varies considering the specific site and method used to produce electricity. In work completed by Miner, he states the following regarding the carbon neutrality of biomass energy (Miner 2010):

- Biomass energy is carbon neutral because biomass is naturally carbon neutral;
- Biomass energy is neutral if the activity removes as much CO2 as was emitted into the atmosphere;
- Biomass energy is neutral only if the net life-cycle emissions are zero; and
- Biomass energy is neutral if it achieves lower net increases in atmospheric GHG's when compared to alternative energy activities.

In order to evaluate the economic feasibility of producing energy with biomass a Life Cycle Analysis (LCA) is needed that calculates the environmental footprint and includes the carbon flux of a particular biopower pathway. This requires following each biomass fuel sources from a point of origin to the point where electrical energy is generated. Bracmort argues that only an LCA for each biopower operation can truly determine whether biopower generation is carbon neutral and a complete LCA will measure carbon flux for each phase of the biopower pathway and incorporates the replenishment of the individual biomass feedstock. A standard approach in performing a biopower LCA ensures uniformity in carbon accounting across the biopower sector (Bracmort, 2011).

Section 2 - Existing Biomass Technologies and Plants in California

2.1 Existing Biomass Technologies

There are many technologies that can be employed to convert biomass feedstocks to electric energy. The primary technologies include combustion, co-firing, gasification, pyrolysis, and anaerobic digestion. Each of these processes is summarized below.

2.1.1 Combustion

Combustion is the burning of biomass in a power plant. The biomass is burned to heat a boiler and create steam. The steam powers a turbine, which is connected to a generator to produce electricity. Existing plant efficiencies are in the low 20% range, although methods could be employed to advance efficiency above 40%. Efficiency refers to that percentage of a feedstock that is actually converted to electricity (i.e., electricity energy output/feedstock energy input). Approximately 180 combustion units across the United States for biomass are in operation using wood and agricultural residues as the feedstock (Bracmort, 2010).

2.1.2 Co-firing

Co-firing is the simultaneous firing of biomass with coal in an existing power plant; it is considered to be the most cost-effective biopower technology (Bracmont 2010). Co-firing with biomass uses existing equipment and is less expensive than constructing a new biopower plant. Although existing plants require retrofitting to accept the biomass entering the plant, certain air particulates associated with coal combustion are reduced with co-firing, as less coal is being burned. Co-fired plants have efficiencies ranging from 33% to 37%, while coal-fired plants have efficiencies ranging from 33% to 45%. Approximately seventy-eight (78) co-fired biomass units that use wood or other agricultural residues as feedstocks are in operation throughout the United States (Bracmort, 2010).

2.1.3 Gasification

Gasification is the heating of biomass into a synthetic gas, known as syngas, in an environment with limited oxygen. Syngas is a mixture of hydrogen and carbon monoxide, which is highly flammable. Syngas can then be used in a combined gas and steam turbine to generate electricity with efficiencies ranging from 40% to 50%. One challenge for gasification is feedstock logistics (e.g., cost to ship or transport the feedstock to the power plant). A wide variety of feedstocks could undergo gasification, including wood chips, sawdust, bark, agricultural resides, and waste; however, there are currently no gasification systems for biomass at any scale (Bracmort, 2010).

2.1.4 Pyrolysis

Pyrolysis is the chemical breakdown of a substance under extremely high temperatures in the absence of oxygen. These temperatures range from 400°C to 500°C. There are currently two types of pyrolysis technologies, fast and slow. Fast pyrolysis technologies can be used to generate electricity by producing a liquid product from a biomass feedstock; this pyrolysis oil or bio-oil can be readily stored and transported. The bio-oils produced from these technologies are suitable for use in boilers for electricity generation. A major challenge for the pyrolysis technology is that the bio-oil produced tends to be of lower quality relative to what is needed for power production. Feedstock types for pyrolysis include a variety of wood or agricultural resources. Currently, there are no commercial-scale pyrolysis facilities utilizing biomass in the United States (Bracmort, 2010).

2.1.5 Anaerobic digestion

Anaerobic digestion is a biological conversion process that breaks-down a feedstock (e.g., manure, landfill waste) in the absence of oxygen to produce methane and other gases that can be captured and used as an energy source to generate electricity. Anaerobic digestion systems have historically been used for comparatively smaller-scale energy generation in rural areas. Feedstocks suitable for digestion include brewery waste, cheese whey, manure, grass clippings, restaurant wastes, and the organic fraction of municipal solid waste, among others. Generation efficiency ranges from 20% to 30% (Bracmort, 2010).

2.1.6 Commercial Bioenergy routes

The Figures 2-1 and 2-2 (Chum, H. et. al. 2011) graphically display a variety of bioenergy conversion routes and their associated lifecycle CO_2 emissions.

For example, as shown in Figure 2-1, the conversion of Oil Crops to energy can follow two conversion routes leading to the generation of liquid fuels such as biodiesel and renewable diesel. Through the conversion path of transesterification or hyrdogenenation, either biodiesel of renewable diesel can be generated. In addition, when oil crops are combined with lignocellulosic biomass through the combustion conversion route, either heat and/or power can be generated.

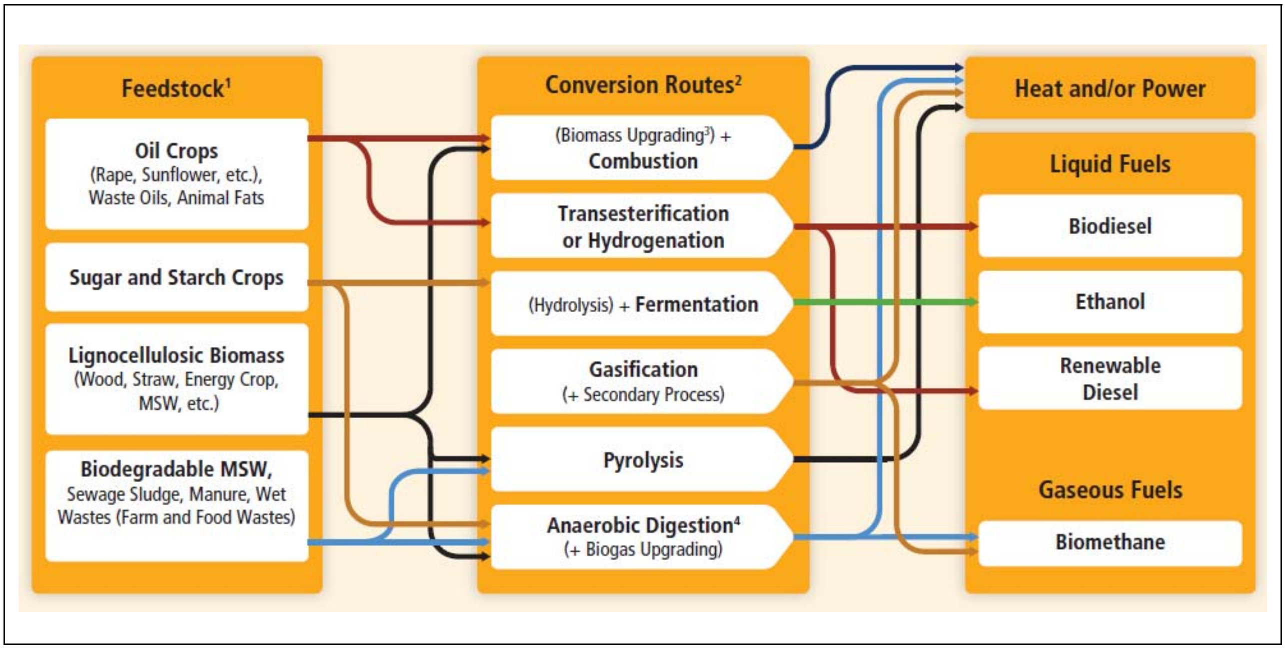


Figure 2-1 - Commercial Bioenergy routes (***Chum, H. et. al. 2011)***

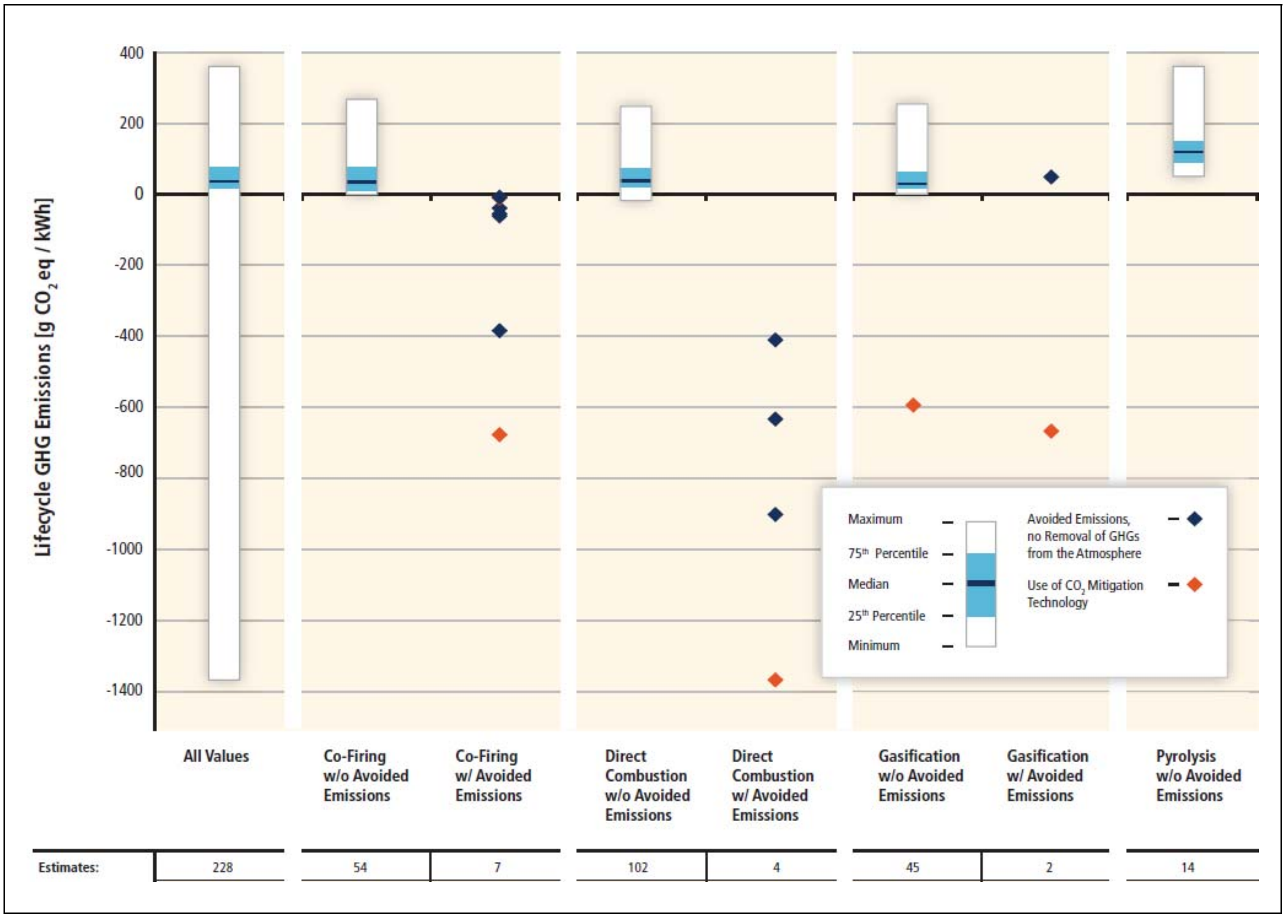


Figure 2-2 - Lifecycle CO_2 Emissions (*Chum*, ***H. et. al. 2011)***

2.2 Existing Biomass Energy Plants in California

There are currently thirty-three (33) active and operating energy plants generating electricity from biomass feedstocks located throughout California. Figure 2-3 (Mayhead, 2012) graphically displays the location and capacity of these plants.

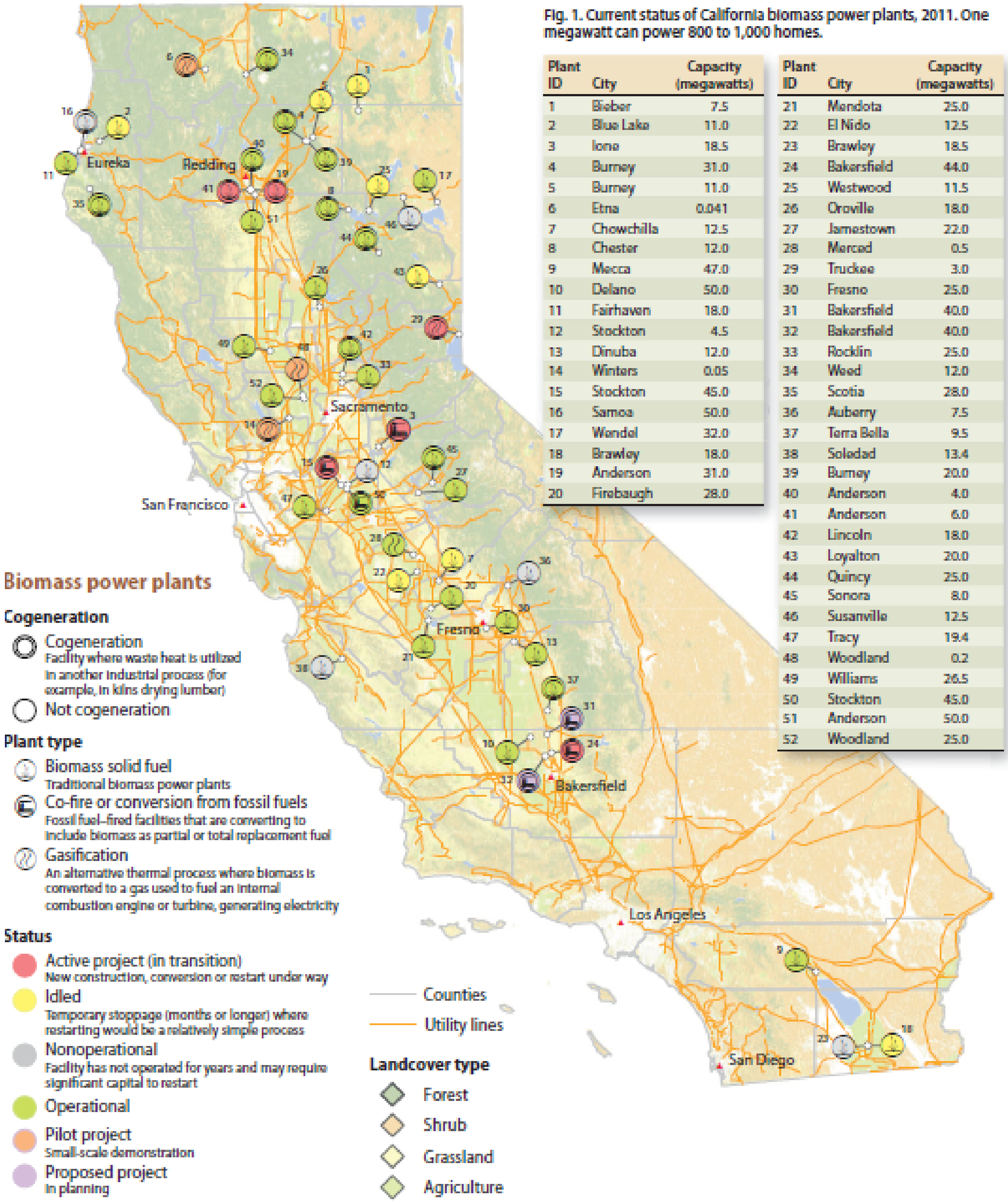


Fig. 1. Current status of California biomass power plants, 2011. One megawatt can power 800 to 1,000 homes.

Plant ID	City	Capacity (megawatts)
1	Bieber	7.5
2	Blue Lake	11.0
3	Ione	18.5
4	Burney	31.0
5	Burney	11.0
6	Etna	0.041
7	Chowchilla	12.5
8	Chester	12.0
9	Mecca	47.0
10	Delano	50.0
11	Fairhaven	18.0
12	Stockton	4.5
13	Dinuba	12.0
14	Winters	0.05
15	Stockton	45.0
16	Samoa	50.0
17	Wendel	32.0
18	Brawley	18.0
19	Anderson	31.0
20	Firebaugh	28.0
21	Mendota	25.0
22	El Nido	12.5
23	Brawley	18.5
24	Bakersfield	44.0
25	Westwood	11.5
26	Oroville	18.0
27	Jamestown	22.0
28	Merced	0.5
29	Truckee	3.0
30	Fresno	25.0
31	Bakersfield	40.0
32	Bakersfield	40.0
33	Rocklin	25.0
34	Weed	12.0
35	Scotia	28.0
36	Auberry	7.5
37	Terra Bella	9.5
38	Soledad	13.4
39	Burney	20.0
40	Anderson	4.0
41	Anderson	6.0
42	Lincoln	18.0
43	Loyalton	20.0
44	Quincy	25.0
45	Sonora	8.0
46	Susanville	12.5
47	Tracy	19.4
48	Woodland	0.2
49	Williams	26.5
50	Stockton	45.0
51	Anderson	50.0
52	Woodland	25.0

Reference: *Mayhead, 2012*

Figure 2-3 - Map of Existing Biomass Plants in California (Mayhead, 2012)

Section 3 - Survey of Existing Biomass Feedstocks

Biomass feedstocks are generally divided into two categories, first and second generation. Those feedstocks that are widely grown and used for some form of production are known as first generation feedstocks. Second generation feedstocks generally refers to crops that have a high potential yield of biofuel, but that may not be widely cultivated, or may not be cultivated as an energy crop.

3.1 First Generation Feedstocks

First generation feedstocks represent biomass that is currently available. Tables 3-1 and 3-2 were generated by consolidating data from several sources. As shown, California produces an estimated eight-six (86) million tons of biomass annually (Moller, 2005). Approximately thirty-three and two-thirds (33.6) million tons is estimated to be technically feasible to be collected and used in producing renewable electricity, fuels, and biomass-based products (Moller, 2005). About 30% of this amount could come from agriculture, 40% from forestry, and another 30% could be recovered from municipal sources, including landfill gas and biogas (methane) from wastewater treatment.

Table 3-1 - Estimated Quantity and Potential Energy Value of First Generation Feedstocks

First Generation Feedstocks	Total Biomass Produced (million dry tons/yr)	Biomass That Can Effectively Be Utilized (million dry tons/yr)	Energy Value Btu/lb (dry)	Average Energy Value $kJ/kg\ (dry)^1$
Reference	*Moller, 2005*	*Moller, 2005*	*Appendix A, Table 13*	*Appendix A, Table 13*
First Generation Feedstocks	**86.0**	**33.6**	**7,929**	**18,443**
Agricultural	**21.6**	**9.6**	**8,125**	**18,898**
Animal Manure	11.8	4.5	8,500	19,771
Orchard Pruning & Vine Removal	2.6	1.8	7,825	18,200
Total Field and Seed	4.9	2.4	7,825	18,200
Total Vegetable	1.2	0.1	7,825	18,200
Total Food Processing	1.0	0.8	8,650	20,120
Forestry	**26.8**	**14.3**	**8,570**	**19,934**
Mill Residue	6.2	3.3	8,570	19,934
Forest Thinnings	7.7	4.1	8,570	19,934
Logging Slash	8.0	4.3	8,570	19,934
Chaparral	4.9	2.6	8,570	19,934
Municipal	**37.6**	**9.7**	**7,093**	**16,498**

Notes:

1) BTU/lb = 2.326 KJ/kg conversion factor

References:

Moller, 2005; Appendix A, Fuel Analysis Spreadsheet

3.2 Second Generation Feedstocks

As stated above, second generation feedstocks include crops that have high potential yields of biofuels, but that may not be widely cultivated, or may not be cultivated as an energy crop. These feedstocks include grasses, trees, and algae. The table below lists second generation feedstocks and their corresponding energy value in Btu/lb dry and KJ/kg dry.

Table 3-2 - Quantity and Energy Value of Second Generation Feedstocks

Second Generation Feedstocks	Average Energy Value Btu/lb (dry)	Average Energy Value $KJ/kg\ (dry)^1$
Loblolly Pine	8,560	19,911
Eucalyptus	8,303	19,313
Unmanaged Hardwood	6,150	14,305
Switchgrass	8,670	20,166
Miscanthus	8,250	19,189
Sugarcane/Energycane	7,900	18,374
Wheat Straw	6,840	15,910
Sugarcane Bagasse	7,900	18,374
Algae (algal mass)	9,000	20,934
Algae (algal oil and lipids)	16,000	37,216

Notes:
1) BTU/lb = 2.326 KJ/kg conversion factor

References:
Appendix A, Fuel Analysis Spreadsheet

Section 4 - Feedstock Analysis

Using federal and state government databases, we identified feedstocks and technologies that provide carbon neutrality and/or net reductions to carbon emissions when all life-cycle emissions are considered. We organized these feedstock and technologies by focusing upon net carbon emissions when the entire life cycle of the process is considered. Finally, we determined the carbon neutrality/net reduction to carbon emission factors for each phase of the biomass pathway.

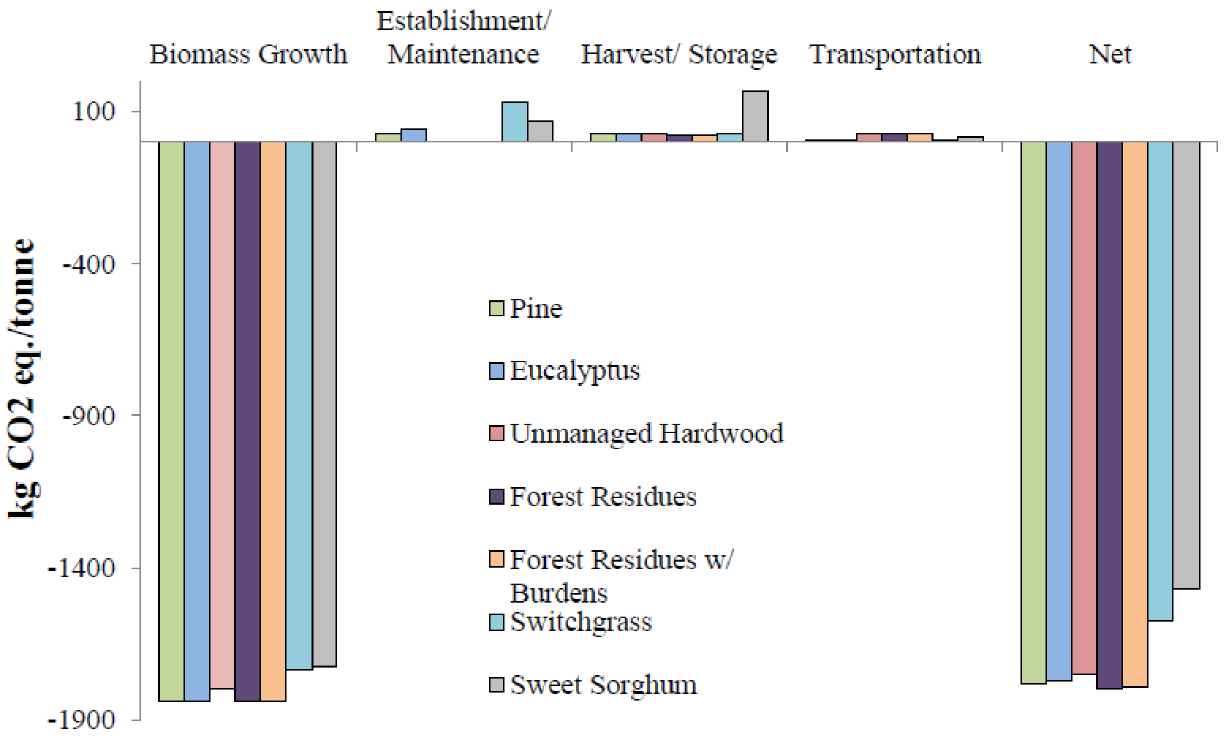
The Society of Environmental Toxicology and Chemistry defines a Life Cycle Analysis (LCA) as "an objective process to evaluate the environmental burdens associated with a product, process, or activity by identifying energy and materials used and wasted released to the environment, and to evaluate and implement opportunities to affect environmental improvements (Consoli et al. 1993)," (USDA, 2005). LCA can be used to assess environmental impacts associated with all the stages of a product's life from cradle-to-grave (i.e., from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling). A LCA can function as a tool to avoid a narrow outlook on environmental concerns by utilizing calculations in the environmental footprint, including the carbon flux of a particular biopower pathway. Carbon neutrality for biopower can be most accurately calculated based on the carbon flux (CO_2 emission or sequestration) of several parameters of a specified time period. In this report, we focused on the following five (5) phases of the biopower pathway (with each phase representing a stage in time with different CO_2 emissions):

- Phase 1: Feedstock Type
- Phase 2: Management and Procurement
- Phase 3: Feedstock Transportation
- Phase 4: Energy Generation Technology
- Phase 5: Time to Replenish Feedstock

The following subsections summarize our findings using LCA for both first and second generation feedstocks and focus upon identifying feedstocks available in California that definitively provide carbon neutrality or net reductions to carbon emissions when all life-cycle emissions are considered.

4.1 Phase 1: Feedstock Types

The biomass feedstock type is often the most important contributor to the net reductions in carbon emissions over the biopower pathway. Figure 4-1 illustrates the greenhouse gas emissions per dry ton in different phases of the biopower pathway [including biomass growth (Phase 1), establishment/maintenance and harvest/storage (Phase 2), and transportation (Phase 3)] for a diverse range of feedstocks. Notice that the “Biomass Growth” column is the largest input to the net reduction in carbon emissions. The negative estimates within the terminology of lifecycle assessments presented in this report refer to avoided emissions, without consideration of energy generation (which is included in Table 4-4). Figure 4-1 only represents Phase 1, 2 and 3 of the biopower pathway and does not include net emissions for Phase 4 and Phase 5 of the biopower pathway defined previously in the report.



***Reference**: Daystar, J., Reeb, C., Gonzalez, R., Venditti, R., Kelley, S. (2012).*

Figure 4-1 – GHG Emissions per dry ton (Daystar, 2012)

The values in Figure 4-1 are used as a guideline for the biomass feedstocks analyzed in this report. The feedstocks listed in Table 4-1 were examined in order to identify feedstocks and/or technologies that definitively provide carbon neutrality or net reductions to Carbon emissions when all life-cycle emissions are considered. The feedstock types include both first and second generation feedstocks and were selected 1. on existing biomass availability in the state of California and 2. on future biomass potential in California. Table 4-1 lists the net reduction to CO_2 emissions consistent with the values given in Figure 4-1.

Table 4-1 – CO$_2$ Emissions for Phase 1: Feedstock Types (from Figure 1)

Feedstock Types	CO$_2$ Emissions for Phase 1 (kg CO$_2$eq./ton)
TOTAL Biomass Feedstocks	**-34,051**
First Generation Feedstocks	**-16,201**
Agricultural Biomass	**-7,200**
Animal Manure	-1,800[2]
Orchard Pruning's and Vine Removal	-1,800[2]
Field and Seed	-1,800[2]
Vegetable	*negligible*[3]
Food Processing (rice hulls, shells, and pits)	-1,800[2]
Forestry Biomass	**-7,202**
Mill Residue	-1,800[2]
Forest Thinnings	-1,800[1]
Logging Slash	-1,800[2]
Chaparral	-1,800[2]
Municipal Biomass	**-1,800**
Municipal Solid Waste	-1,800[2]
Second Generation Feedstocks	**-17,849**
Loblolly Pine	-1,800[1]
Eucalyptus	-1,800[1]
Unmanaged Hardwood	-1,750[1]
Switchgrass	-1,700[1]
Miscanthus	-1,800[2]
Sugarcane/Energycane	-1,800[2]
Wheat Straw	-1,800[2]
Sugarcane Bagasse	-1,800[2]
Algae (algal mass)	-1,800[2]
Algae (algal oil and lipids)	-1,800[2]

Notes:

1. Direct value from Integrated Supply Chain NC State University, (Daystar, J. et. al. 2012)
2. Assumed value based on Integrated Supply Chain NC State University, (Daystar, J. et. al. 2012)
3. Vegetable crop residues are considered negligible for purposes of this report because the total biomass that can effectively be utilized (million dry tons/yr) is only 0.1 as represented in Table 1. "Vegetable crop residues are not generally considered for off-field utilization and are commonly incorporated into the soil," (Moller, 2005).

Reference: *Daystar, J., Reeb, C., Gonzalez, R., Venditti, R., Kelley, S. (2012).*

4.2 Phase 2: Management and Procurement

Management and procurement includes CO_2 emissions associated with the establishment, maintenance, harvest and storage of the feedstock. The state of California has relatively low CO_2 emissions associated with the management and procurement of biomass feedstocks because the biomass energy industry is already well established for agricultural biomass throughout the Central Valley and for forestry biomass in Northern California. Table 4-2 shows a small increase to CO_2 emissions during the Phase 2: Management and Procurement stage based upon the values given in Figure 4-1.

Table 4-2 - CO_2 Emissions for Phase 2: Management and Procurement (Establishment/Maintenance and Harvest/Storage from Figure 4-1)

Feedstock Types	CO_2 Emissions for Phase 2 (kg CO_2 eq./ton)
TOTAL Biomass Feedstock	**705**
First Generation Feedstocks	**185**
Agricultural Biomass	**75**
Animal Manure	*15*
Orchard Pruning's and Vine Removal	*15*
Field and Seed	*15*
Vegetable	$negligible^2$
Food Processing (rice hulls, shells, and pits)	*15*
Forestry Biomass	**60**
Mill Residue	*15*
Forest Thinnings	15^1
Logging Slash	*15*
Chaparral	*15*
Municipal Biomass	**50**
Municipal Solid Waste	*50*
Second Generation Feedstocks	**520**
Loblolly Pine	40^1
Eucalyptus	50^1
Unmanaged Hardwood	15^1
Switchgrass	115^1
Miscanthus	*50*
Sugarcane/Energycane	*50*
Wheat Straw	*50*
Sugarcane Bagasse	*50*
Algae (algal mass)	*50*
Algae (algal oil and lipids)	*50*

Notes:

1. Direct value from Integrated Supply Chain NC State University, (Daystar, J. et. al. 2012)
2. Vegetable crop residues are considered negligible for purposes of this report because the total biomass that can effectively be utilized (million dry tons/yr) is only 0.1 as represented in Table 4-1. "Vegetable crop residues are not generally considered for off-field utilization and are commonly incorporated into the soil," (Moller, 2005).

Reference: *Appendix A, Phase 2 Calculations*

4.3 Phase 3: Transportation

Transportation includes CO_2 emissions associated with transporting the biomass fuel to the energy generation plant. The state of California has relatively low CO_2 emissions associated with transportation of biomass feedstocks because the biomass energy industry is already well established for agricultural biomass throughout the Central Valley and for forestry biomass in Northern California. Table 4-3shows a small increase in CO_2 emissions during the Phase 3: Transportation stage based upon the values given in Figure 4-1.

Table 4-3 - CO_2 Emissions for Phase 3: Transportation (from Figure 4-1)

Feedstock Types	CO_2 Emissions for Phase 3 (kg CO_2 eq./ton)
TOTAL Biomass Feedstocks	**215**
First Generation Feedstocks	**160**
Agricultural Biomass	**50**
Animal Manure	*10*
Orchard Pruning's and Vine Removal	*10*
Field and Seed	*10*
Vegetable	*10*
Food Processing (rice hulls, shells, and pits)	*10*
Forestry Biomass	**60**
Mill Residue	*15*
Forest Thinnings	15[1]
Logging Slash	*15*
Chaparral	*15*
Municipal Biomass	**50**
Municipal Solid Waste	*50*
Second Generation Feedstocks	**55**
Loblolly Pine	5[1]
Eucalyptus	5[1]
Unmanaged Hardwood	10[1]
Switchgrass	5[1]
Miscanthus	*5*
Sugarcane/Energycane	*5*
Wheat Straw	*5*
Sugarcane Bagasse	*5*
Algae (algal mass)	*5*
Algae (algal oil and lipids)	5

Notes:

1. Direct value from Integrated Supply Chain NC State University, (Daystar, J. et. al. 2012)

Reference: *Appendix A, Phase 3 Calculations*

4.4 Phase 4: Energy Generation Technology

4.4.1 Fuel Analysis Approach for Estimating CO_2 Emissions:

Using the Fuel Analysis Equation shown below, which was developed from the Environmental Protection Agency (EPA, 2008), we calculated CO_2 emissions for different energy generation technologies.

Fuel Analysis Equation

$$\boldsymbol{CO_2}\ \textbf{Emissions} = \boldsymbol{Fuel * HC_{avg} * CC * FO * \frac{CO_2}{C}}$$

Where:

Fuel = Mass or Volume of Fuel Type Combusted

HC_{avg} = Average Higher Heating Value of Fuel Type $(\frac{energy}{mass\ or\ volume\ of\ fuel})$

CC = Carbon Content Coefficient of Fuel Type $(\frac{mass\ C}{energy})$

FO = Fraction Oxidized of Fuel Type

CO_2 = Molecular weight of CO_2

C = Molecular weight of Carbon

Figure 4-2 – Basis for Fuel Analysis Calculations

Step 1: Determine the amount of fuel combusted. This is an assumed value based on fuel used during each phase of the biomass pathway.

Step 2: Convert the amount of fuel combusted into energy units. The amount of fuel combusted is measured in terms of physical units, (mass or volume). This needs to be converted to amount of fuel used in terms of energy units in order to apply the default carbon content coefficients. The heat content of various biomass fuels is provided in Tables 3-1and 3-2 columns titled ‘Average Energy Value’.

Step 3: Estimate carbon content of fuels consumed. To estimate the carbon content, multiply energy content for each fuel by fuel-specific carbon content coefficients (mass C / energy). U.S. average default carbon content coefficients are provided in Figure 4-1.

Step 4: Estimate carbon emitted. When fuel is burned, most of the carbon is eventually oxidized into CO_2 and emitted into the atmosphere. To account for the small fraction that is not oxidized and remains trapped in the ash, multiply the carbon content by the fraction of carbon oxidized. The amount of carbon oxidized is assumed to be 100% unless specific supplier information is available.

Step 5: Convert to CO_2 emitted. To obtain total CO_2 emitted, multiply carbon emissions by the molecular weight ratio of CO_2 (44) to Carbon (12), (44/12).

Table 4-4 summarizes the results of the calculations of CO_2 emissions based on co-firing, direct combustion, and gasification technologies. Each technology is calculated both with, and without, avoided emissions considered. The term “w/o avoided emissions” refers to the amount of CO_2 emissions that would be generated if conventional fuels were used; “w/avoided emissions refers to the decrease in CO_2 emissions by using biofuels in lieu of conventional fuels. Refer to Section 5.1, Net Reduction to CO_2 emissions, for more detailed information on the effect of considering energy generation technologies both with, and without, avoided emissions. Equation 1: Fuel Analysis Approach is used to calculate total $\mathrm{CO_2}$ emissions based on a fuel content of 1 kg.

Table 4-4 – CO_2 Emissions for Co-Firing, Direct Combustion and Gasification Technologies

Energy Generation Technology	Step 1	Step 2		Step 3	Step 4	Step 5	TOTAL
	Biomass Fuel	Average Heat Content		CC	FO	CO_2 / C	CO_2 Emissions for Phase 4
	kg	kJ/kg (dry)	kWh/kg (dry)	Kg CO_2/ kWh	ratio	Ratio (44/12)	kg CO_2 eq. / ton
Co-Firing w/o Avoided Emissions	1.0	18,443	5	30,000	1.0	3.67	621
Co-Firing w/ Avoided Emissions	1.0	18,443	5	-675,000	1.0	3.67	-13,977
Direct Combustion w/o Avoided Emissions	1.0	18,443	5	30,000	1.0	3.67	621
Direct Combustion w/ Avoided Emissions	1.0	18,443	5	-1,380,000	1.0	3.67	-28,575
Gasification w/o Avoided Emissions	1.0	18,443	5	20,000	1.0	3.67	414
Gasification w/ Avoided Emissions	1.0	18,443	5	-650,000	1.0	3.67	-13,459
Reference	*Value of 1kg*	*Avg. HC (Table 1)*	1 KJ/kg = 3600 kWh/kg	*Figure 4-1*	*U.S. EPA, 2008*	*U.S. EPA, 2008*	*Appendix A*

Without avoided emissions considered, the highest value for CO_2 emissions is 621 kg CO_2 eq./ton. With avoided emissions considered, the highest value for CO_2 emissions is -13,459 kg CO_2 eq./ton. Using the highest value of CO_2 emissions for both scenarios allows for a conservative calculation of emissions throughout the biopower pathway.

4.5 Phase 5: Timeframe to Replenish Feedstock

If feedstocks are collected without regard to replenishment, or in an otherwise unsustainable manner, biopower enterprises may lead to natural resource deterioration such as soil erosion or the depletion of forested land, (Bracmort, 2010). The recognition of biomass as a renewable resource means that biomass is considered by some to be a continuous feedstock that may be replenished in a short time frame (Bracmort, 2012). The timeframe to replenish biomass feedstocks can vary depending upon market fluctuations and weather variability. A wide range of values, ranging from three (3) months to forty (40) years, has been selected for different feedstocks to consider high variability from one year to the next. The Table 4-5 lists the timeframe to replenish a feedstock and the average timeframe in years.

Table 4-5 – CO_2 Emissions for Phase 5: Timeframe to Replenish Feedstock

Feedstock Types	Timeframe to Replenish Feedstock	Average Timeframe (years)
TOTAL Biomass Feedstock's (average)	**3.5 years**	**3.5**
First Generation Feedstock's (average)	**6 months**	**0.5**
Agricultural Biomass (average)	**3 months**	**0.25**
Animal Manure	*Not available, assume 1 yr*	*1.0*
Orchard Pruning's and Vine Removal	*3 months*[2]	*0.25*
Field and Seed	*3 months*[2]	*0.25*
Vegetable	*3 months*[2]	*0.25*
Food Processing (rice hulls, shells, and pits)	*3 months*[2]	*0.25*
Forestry Biomass (average)	**1 year**	**1.0**
Mill Residue	Highly variable[1], assume 1 yr	1.0
Forest Thinnings	1 year[2]	1.0
Logging Slash	1 year[2]	1.0
Chaparral	1 year[2]	1.0
Municipal Biomass (average)	**Not available, assume 1 yr**	**1.0**
Municipal Solid Waste	*Not available, assume 1 yr*	*1.0*
Second Generation Feedstocks (average)	**6.5 years**	**6.5**
Loblolly Pine	*20 – 40 years*[1]	*30.0*
Eucalyptus	*20 – 40 years*[2]	*30.0*
Unmanaged Hardwood	*Highly variable*[2]*, assume 1 yr*	*1.0*
Switchgrass	*3 months*[2]	*0.25*
Miscanthus	*3 months*[2]	*0.25*
Sugarcane/Energycane	*6 months*[2]	*0.5*
Wheat Straw	*6 months*[2]	*0.5*
Sugarcane Bagasse	*6 months*[2]	*0.5*
Algae (algal mass)	*Not available*[1]*, assume 1 yr*	*1.0*
Algae (algal oil and lipids)	*Not available*[1]*, assume 1 yr*	*1.0*

Notes:
1. Direct value from Bracmort 2010, Appendix A
2. Assumed value from Bracmort 2010, Appendix A

Reference: Bracmort 2010

4.6 CO_2 Emissions of the Biopower Pathway

Carbon emissions for each phase of the biopower pathway are summarized in Table 4-6. Note that avoided emissions are represented as “A.E.”

Table 4-6 – CO_2 Emissions of the Biopower Pathway (kg CO_2 eq./ton)*

Feedstock Types	Phase 1	Phase 2	Phase 3	Phase 4 (w/A.E.)	Phase 4 (w/o A.E.)	Phase 5	TOTAL (w/A.E.)	TOTAL (w/o A.E.)
TOTAL Biomass Feedstocks	**-34,501**	**705**	**215**	**-13,459**	**621**	**N/A**	**-586,654**	**-36,595**
First Generation Feedstocks	**-16,201**	**185**	**160**	**-13,459**	**621**	**N/A**	**-327,854**	**-18,094**
Agricultural Biomass	**-7,200**	**75**	**50**	**-13,459**	**621**	**N/A**	**-251,778**	**-12,418**
Animal Manure	*-1,800*	*15*	*10*	*-13,459*	*621*	*1.0*	*-15,234*	*-1,154*
Orchard Pruning's and Vine Removal	*-1,800*	*15*	*10*	*-13,459*	*621*	*0.25*	*-60,936*	*-4,616*
Field and Seed	*-1,800*	*15*	*10*	*-13,459*	*621*	*0.25*	*-60,936*	*-4,616*
Vegetable	*negligible*	*15*	*10*	*-13,459*	*621*	*0.25*	*-53,736*	*2,584*
Food Processing	*-1,800*	*15*	*10*	*-13,459*	*621*	*0.25*	*-60,936*	*-4,616*
Forestry Biomass	**-7,202**	**60**	**60**	**-13,459**	**621**	**N/A**	**-60,917**	**-4,597**
Mill Residue	*-1,800*	*15*	*15*	*-13,459*	*621*	*1.0*	*-15,229*	*-1,149*
Forest Thinnings	-1,800[1]	15[1]	15.0[1]	*-13,459*	*621*	*1.0*	*-15,229*	*-1,149*
Logging Slash	*-1,800*	*15*	*15*	*-13,459*	*621*	*1.0*	*-15,229*	*-1,149*
Chaparral	*-1,800*	*15*	*15*	*-13,459*	*621*	*1.0*	*-15,229*	*-1,149*
Municipal Biomass	**-1,800**	**50**	**50**	**-13,459**	**621**	**N/A**	**-15,159**	**-1,079**
Municipal Solid Waste	*-1,800*	*50*	*50*	*-13,459*	*621*	*1.0*	*-15,159*	*-1,079*
Second Generation Feedstocks	**-17,849**	**520**	**55**	**-13,459**	**621**	**N/A**	**-258,800**	**-18,501**
Loblolly Pine	-1,800[1]	40[1]	5.0[1]	*-13,459*	*621*	*30.0*	*-507*	*-38*
Eucalyptus	-1,800[1]	50[1]	5.0[1]	*-13,459*	*621*	*30.0*	*-507*	*-37*
Unmanaged Hardwood	-1,750[1]	15[1]	10.0[1]	*-13,459*	*621*	*1.0*	*-15,185*	*-1,105*
Switchgrass	-1,700[1]	115[1]	5.0[1]	*-13,459*	*621*	*0.25*	*-60,153*	*-3,833*
Miscanthus	*-1,800*	*50*	*5*	*-13,459*	*621*	*0.25*	*-60,817*	*-4,497*
Sugarcane/Energycane	*-1,800*	*50*	*5*	*-13,459*	*621*	*0.5*	*-30,407*	*-2,247*
Wheat Straw	*-1,800*	*50*	*5*	*-13,459*	*621*	*0.5*	*-30,408*	*-2,248*
Sugarcane Bagasse	*-1,800*	*50*	*5*	*-13,459*	*621*	*0.5*	*-30,409*	*-2,249*
Algae (algal mass)	*-1,800*	*50*	*5*	*-13,459*	*621*	*1.0*	*-15,205*	*-1,125*
Algae (algal oil and lipids)	*-1,800*	*50*	*5*	*-13,459*	*621*	*1.0*	*-15,204*	*-1,124*
Reference	*Table 3*	*Table 4*	*Table 5*	*Table 6*	*Table 6*	*Table 7*	*Add Phase 1-4 and divide by Phase 5*	

1) Daystar, J. et. al. 2012

* There are two Totals for Table 4-6, the Total CO2 Emissions with Avoided Emissions and the Total CO2 Emissions without Avoided Emissions. The Total CO2 Emissions with Avoided Emissions is calculated by adding the total CO2 Emissions from Phase 1, Phase 2, Phase 3, Phase 4 with Avoided Emissions, and dividing the sum by Phase 5. Similarly, the Total CO2 Emissions without Avoided Emissions is calculated by adding the total CO2 Emissions from Phase 1, Phase 2, Phase 3, Phase 4 without Avoided Emissions and dividing the sum by Phase 5. The method described above is true for each individual feedstock presented in Table 4-6 (every line item that is not bold).

In order to calculate the total CO2 Emissions from a group of feedstocks, (every line item that is bold in Table 4-6), the total from the individual feedstocks is added together for that category. For example, the total for Agricultural Biomass is the sum of the totals for each individual feedstock: Animal Manure, Orchard Pruning's and Vine Removal, Field and Seed, Vegetable and Food Processing. The Total for First Generation Feedstocks is the sum of the totals from Agricultural Biomass, Forestry Biomass and Municipal Biomass. The “TOTAL” Biomass Feedstock at the top of Table 4-6 is the sum of the totals from First Generation Feedstocks and Second Generation Feedstocks.

Section 5 - Net Reduction to CO2 emissions and Economic Feasibility

Using the carbon neutral feedstocks, the economic feasibility was determined using the feedstocks/technologies for biomass plants. Our analysis included consideration of subsidies that would increase the economic feasibility. Life-cycle economic factors included costs associated with feedstock type, management and procurement, transportation, energy generation technology, and timeframe to replenish the feedstock. In 2010, California produced 71% of its own electricity; the balance was imported from the Pacific Northwest (8%) and the U.S. Southwest (21%). Natural gas is the main source for electricity generation at 53.4% of the total in-state electric generation system power (CEC, 2011). California's in-state electricity generation is represented in the Table 5-1.

Table 5-1 - California In-State Electricity Generation

California In-State Electricity Generation Source	Percentage of California In-State Electricity Generation	Cost as an input for Electricity Generation
Natural Gas	53.4%	\$11.32 dollars per 1,000 cubic feet*, (U.S. Energy Information Administration, 2012)
Nuclear	15.7%	\$0.38 per million BTU, (Combs, S. 2005)
Large Hydro (larger than 30 MW)	14.6%	No cost as an input for generating electricity, (Combs, S. 2005)
Coal	1.7%	\$2.44 dollars per million BTU, (U.S. Energy Information Administration, 2012)
Renewable (includes biomass, geothermal, small hydro, wind, and solar generation)	14.6%	\$2.91 per million BTU (assumed value based on biomass consumption), (U.S. Energy Information Administration, 2012) Note that geothermal, small hydro, wind, and solar have no fuel cost as an input for generating electricity.
****Conversion factor: 1,000 cubic feet is about 1 million BTU***		

Table 5-2 calculates the cumulative fuel cost associated with the type of electricity produced in California based upon the fuel costs shown in Table 5-1.

Table 5-2 Cumulative Fuel Cost Calculation based on % Electricity Produced by California

Electric Power Generation	Fuel Cost Calculation based on % Electricity Produced in California (in dollars per million BTU)
Natural Gas	53.4% × \$11.32 = \$6.04
Nuclear	15.7% × \$0.38 = \$0.06
Large Hydro	14.6% × \$0 = \$0
Coal	1.7% × \$2.44 = \$0.04
Renewable	14.6% × \$2.91 = \$0.42
Cumulative Fuel Cost	\$6.56

Table 5-3 lists the results of the calculation for the economic feasibility based upon average fuel cost in US dollars per million Btu.

Table 5-3 – Economic Feasibility

Feedstock Types	Fuel Cost Average (US dollars / MMBtu)	Economically Feasible? Compared with cumulative fuel cost of $6.56/MMBtu	Subsidy Required? (US $ / MMBtu)
First Generation Feedstocks			
Agricultural Biomass			
Animal Manure	N/A[1]	N/A[1]	N/A[1]
Orchard and Vine Removal	$2.84[2]	Yes	No
Field and Seed	$2.84[2]	Yes	No
Vegetable	$2.84[2,3]	Yes[3]	No[3]
Food Processing	$2.84[2]	Yes	No
Forestry Biomass			
Mill Residue	$1.69[4]	Yes	No
Forest Thinnings	$7.78[5]	No	Yes, $1.22
Logging Slash	$2.92[6]	Yes	No
Chaparral	$2.92[6]	Yes	No
Municipal Biomass			
Municipal Solid Waste	$1.47[7]	Yes	No
Second Generation Feedstocks			
Loblolly Pine	$5.96[8]	Yes	No
Eucalyptus	$5.96[8]	Yes	No
Unmanaged Hardwood	$1.47[7]	Yes	No
Switchgrass	$3.51[8]	Yes	No
Miscanthus	$3.51[9]	Yes	No
Sugarcane/Energycane	$5.96[8]	Yes	No
Wheat Straw	$4.57[2]	Yes	No
Sugarcane Bagasse	$5.96[8]	Yes	No
Algae (algal mass)	$5.96[8]	Yes	No
Algae (algal oil and lipids)	$5.96[8]	Yes	No
Reference: U.S. Environmental Protection Agency Combined Heat and Power Partnership (2007).	*Table 10, Cumulative Fuel Cost*	*Compares each fuel to Table 10, Cumulative Fuel Cost*	*Difference*

Notes:

1. Manure biogas systems are typically too small for gas treatment to be economical (US EPA Combined Heat and Power Partnership, 2007, Chapter 4).
2. Average values for crop residues, (US EPA Combined Heat and Power Partnership, 2007, Chapter 3).
3. Vegetable trimmings are not carbon neutral when avoided emissions are not considered, (reference Table 8)
4. Average value for mill residues, (US EPA Combined Heat and Power Partnership, 2007, Chapter 3).
5. Average value for forest thinnings, (US EPA Combined Heat and Power Partnership, 2007, Chapter 3).
6. Average value for forest residues, (US EPA Combined Heat and Power Partnership, 2007, Chapter 3).
7. Average value for urban wood waste, the second largest component of the MSW in 1996, (US EPA Combined Heat and Power Partnership, 2007, Chapter 4). The University of Malaysia presented a value of $0.09 US $ / MMBtu for MSW used for the production of electricity, (Rosli, 2012).
8. Average values for energy crops. Since most second generation feedstocks are not currently used as biomass in the state of California, a conservative value for energy crops has been selected based on the data provided for hybrid poplars.
9. Miscanthus and switchgrass have similar feedstock properties, the value for switchgrass has been used.

5.1 Net Reduction to CO_2 emissions

A net reduction to CO2 emissions of approximately 586,654 kg CO2 eq./ton can be achieved in the state of California when all life-cycle emissions are considered. This assumes the biomass feedstocks analyzed in this report are utilized in the manner presented in Table 4-6, and includes avoided emissions.

The most significant factors influencing CO_2 emissions occur in Phases 1 and 4:

Phase 1, Feedstock Type is the most important contributor to CO_2 emission reductions. The feedstock type for first generation feedstocks includes fuel that currently exists, but is not currently utilized for energy production. For second generation feedstock's, the fuel is easily cultivated to be utilized for energy production. In both cases, CO_2 emissions from biomass feedstocks are significantly lower than CO_2 emissions generated from fossil fuels. The negative values for Phase 1 feedstocks represent avoided CO_2 emissions.

Phase 2, Management and Procurement, and Phase 3, Transportation are very low contributors to CO_2 emissions in the state of California. This can most likely be attributed to the various biomass plants that exist throughout the Central Valley of California.

Phase 4, Energy Generation Technology is arguably the most important contributor to CO_2 emissions. Energy generation technologies for 1kg of fuel can emit up to 621 kg CO_2 eq./ton for co-firing, and combustion technologies without considering avoided emissions. However, these same technologies with avoided CO_2 emissions can reduce CO_2 emissions as much as 13,459 kg CO_2 eq./ton. This report considers energy generation technologies both with, and without, avoided emissions to better understand the effect of energy generation technologies in the biopower pathway.

Phase 5, Time to Replenish Feedstock assumes a value over time to completely regrow the biomass feedstock so that the carbon can be recaptured and returned to the biosphere.

The calculated CO_2 emissions from Phases 1, 2, 3 & 4 are added together and divided by the feedstocks replenish time. This calculates an overall CO_2 emissions value (kg CO_2 eq./ton/year) for the entire biopower pathway for each feedstock. CO_2 emissions both with, and without, avoided emissions have been considered. The only scenario that results in positive CO_2 emissions is a feedstock of vegetable trimmings without considering avoided emissions. All other feedstocks analyzed in this report result in negative CO_2 emissions both with, and without, consideration of avoided emissions.

The values used in Phases 1-5 can vary depending on climate, location, and transportation methods available. Appendix A: Fuel Analysis Spreadsheet provides a methodology for calculating CO_2 emissions during different phases of the biomass pathway for different feedstocks. The methodology can be applied to feedstocks that were not analyzed in this report. The unknown values required to calculate CO_2 emissions from a specific fuel include:

- Energy Value: Btu/lb (dry) or KJ/kg
- Fuel consumed: million dry tons/yr (average)
- Carbon Content of Fuel Consumed: kg Carbon / MMBtu

These unknown values are highlighted in yellow in Appendix A, Fuel Analysis Spreadsheet and hypothetical values are used as placeholders.

5.2 Economic Feasibility

Economic feasibility of biomass feedstocks is analyzed by comparing the average cost of biomass fuel to the cumulative cost of fuel from California's current energy generation technologies. The majority of electricity produced in the state of California, (54%) comes from natural gas, at a cost of $11.32 US dollars per MMBtu, (Table 5-1). Other sources of electricity come from nuclear, large hydro, renewable and coal. The percentage of each electricity source is multiplied by the fuel cost of that electricity source in order to produce a cumulative cost of fuel that considers all of California's current technologies. The cumulative cost of fuel, $6.56 US dollars per MMBtu is used as the baseline to determine whether or not biomass feedstocks are economically feasible based on the fuel cost of each biomass feedstock.

Most of the first generation feedstocks, including orchard pruning's and vine removal, field and seed, vegetable trimmings, food processing (rice hulls, shells, and pits), mill residue, logging slash, chaparral, municipal solid waste were determined to have an average fuel cost below $6.56 and therefore did not require a subsidy.

Several of the second generation feedstocks, including loblolly pine, eucalyptus, sugarcane/energucan, sugarcane bagasse, and algae were calculated to have a fuel cost average of $5.96 US dollars per MMBtu, which approaches the limit of $6.56 US dollars per MMBtu for economic feasibility. These biomass feedstocks may require subsidies under circumstances that vary from the analyzed conditions in this report.

Forest thinnings are not economically feasible because the average fuel cost is $7.78 US dollars per MMBtu. A subsidy of at least $1.22 US dollars per MMBtu is required in order for the fuel cost of forest thinnings to be competitive with the cumulative cost of fuel, $6.56 US dollars per MMBtu.

Animal manure is not economically feasible because manure biogas systems are typically too small for gas treatment to be economical, (US EPA Combined Heat and Power Partnership, 2007, Chapter 4).

The following table summarizes biomass feedstocks and whether a subsidy may be required:

Table 5-4 – Carbon Neutral Biomass Feedstocks and Subsidies

No Subsidy Required	Subsidy May Be Required	Subsidy Required

• Orchard Pruning's and Vine Removal
• Field and Seed
• Vegetable Trimmings
• Food Processing (rice hulls, shells, and pits)
• Mill Residue
• Logging Slash
• Chaparral
• Municipal Solid Waste
• Unmanaged Hardwood
• Switchgrass
• Miscanthus
• Wheat Straw
	• Loblolly Pine
	• Eucalyptus
	• Sugarcane/Energycane
	• Sugarcane Bagasse
	• Algae (algal mass)
	• Algae (algal oil and lipids)
		• Forest thinning's
		  • $1.22 US dollars / MMBtu
		• Animal manure
		  • Subsidy unknown

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APPENDIX A – Calculation Spreadsheets

Fuel Analysis Spreadsheet

$$CO_2 \text{ Emissions} = Fuel * HC_{avg} * CC * FO * \frac{CO_2}{C}$$

Fuel type & source	Step 1							Step 2			Step 3			Step 4		Step 5		
	Biomass Fuel (that can be effectively utilized in CA) 1 short ton = 907.19kg 1kg = 2.20462 lb							Energy Units of Fuel Combusted (1 therm= 100,000 Btu) (1 therm = 0.1mmBtu)			Carbon Content of Fuel Consumed			Calculate Carbon Emitted		Convert CO2 Emitted to Tons		
	Btu/lb (dry)	kJ/kg (dry)	million dry tons/yr (avg)		dry tons/yr	kg/yr	lb/yr	Btu	Therm	mmBtu	kg Carbon/mmBtu	kg Carbon/kJ	kg Carbon	Fraction Oxidized	kg Carbon	kg CO2/kg C = (44/12)	kg CO2	Metric Tons of CO2
TOTAL Biomass Feedstocks	**8,343**	**19,406**	**144.7**		**54,584,084**	**49,518,134,986**	**109,168,670,752**	**838,223,913,305,989**	**8,382,239,133**	**838,223,913**	**18.98**	**1.80E-05**	**15,040,082,456**	**1.0**	**15,040,082,456**	**3.67**	**55,197,102,614**	**60,844,038**
First Generation Feedstocks	**7,929**	**18,443**	**99.4**		**54,503,984**	**49,445,469,067**	**109,008,470,013**	**836,884,671,333,585**	**8,368,846,713**	**836,884,671**	**18.65**	**1.77E-05**	**15,015,424,987**	**1.0**	**15,015,424,987**	**3.67**	**55,106,609,704**	**60,744,287**
Agricultural Biomass	**8,125**	**18,898**	**10**		**9,600,000**	**8,709,024,000**	**19,200,088,491**	**157,631,426,504,133**	**1,576,314,265**	**157,631,427**	**16.16**	**1.53E-05**	**2,575,853,233**	**1.0**	**2,575,853,233**	**3.67**	**9,453,381,364**	**10,420,509**
Animal Manure (7, 3, 12)	8,500	19,771	4.5		4,500,000	4,082,355,000	9,000,041,480	76,500,352,580,850	765,003,526	76,500,353	17.00	1.61E-05	1,300,505,994	1.0	1,300,505,994	3.67	4,772,856,998	5,261,144
Orchard Pruning's and Vine Removal (9, 3, 11)	7,825	18,200	1.8		1,800,000	1,632,942,000	3,600,016,592	28,168,329,824,417	281,683,298	28,168,330	15.23	1.44E-05	429,003,663	1.0	429,003,663	3.67	1,574,443,444	1,735,517
Field and Seed (hulls, shells, prunings), (9, 3, 11)	7,825	18,200	2.4		2,400,000	2,177,256,000	4,800,022,123	37,557,773,099,223	375,577,731	37,557,773	15.23	1.44E-05	572,004,884	1.0	572,004,884	3.67	2,099,257,925	2,314,022
Vegetable (hulls, shells, prunings), (9, 3, 11)	7,825	18,200	0.1		100,000	90,719,000	200,000,922	1,564,907,212,468	15,649,072	1,564,907	15.23	1.44E-05	23,833,537	1.0	23,833,537	3.67	87,469,080	96,418
Food Processing (hulls, shells, prunings & pits), (9, 3, 11)	8,650	20,120	0.8		800,000	725,752,000	1,600,007,374	13,840,063,787,176	138,400,638	13,840,064	18.10	1.72E-05	250,505,155	1.0	250,505,155	3.67	919,353,917	1,013,408
Forestry Biomass	**8,570**	**19,934**	**14**		**14,300,000**	**12,972,817,000**	**28,600,131,815**	**245,103,129,650,608**	**2,451,031,297**	**245,103,130**	**25.60**	**2.43E-05**	**6,274,640,119**	**1.0**	**6,274,640,119**	3.67	**23,027,929,237**	**25,383,800**
Mill Residue (6, 3, 1)	8,570	19,934	3.3		3,300,000	2,993,727,000	6,600,030,419	56,562,260,688,602	565,622,607	56,562,261	25.60	2.43E-05	1,447,993,874	1.0	1,447,993,874	3.67	5,314,137,516	5,857,800
Forest Thinnings (6, 3, 1)	8,570	19,934	4.1		4,100,000	3,719,479,000	8,200,037,793	70,274,323,885,839	702,743,239	70,274,324	25.60	2.43E-05	1,799,022,691	1.0	1,799,022,691	3.67	6,602,413,278	7,277,873
Logging Slash (6, 3, 1)	8,570	19,934	4.3		4,300,000	3,900,917,000	8,600,039,637	73,702,339,685,148	737,023,397	73,702,340	25.60	2.43E-05	1,886,779,896	1.0	1,886,779,896	3.67	6,924,482,218	7,632,891
Chaparral (6, 3, 1)	8,570	19,934	2.6		2,600,000	2,358,694,000	5,200,023,966	44,564,205,391,020	445,642,054	44,564,205	25.60	2.43E-05	1,140,843,658	1.0	1,140,843,658	3.67	4,186,896,225	4,615,236
Municipal Biomass	**7,093**	**16,498**	**30.6**		**30,603,984**	**27,763,628,067**	**61,208,249,708**	**434,150,115,178,844**	**4,341,501,152**	**434,150,115**	**14.20**	**1.35E-05**	**6,164,931,636**	**1.0**	**6,164,931,636**	3.67	**22,625,299,102**	**24,939,979**
Municipal Solid Waste, (MSW) (9, 7, 4, 1)	7,093	16,498	30.6		30,603,984	27,763,628,067	61,208,249,708	434,150,115,178,844	4,341,501,152	434,150,115	14.20	1.35E-05	6,164,931,636	1.0	6,164,931,636	3.67	22,625,299,102	24,939,979
	Btu/lb (dry)	kJ/kg (dry)	dry tons/acre/yr (avg)	acres (assumed value for CA)	dry tons/yr	kg	lb	Btu	Therm	mmBtu	kg Carbon/mmBtu	kg Carbon/kJ	kg Carbon	Fraction Oxidized	kg Carbon	kg CO2/kg C = (44/12)	kg CO2	Metric Tons of CO2
Second Generation Feedstocks	**8,757**	**20,369**	**45.3**	**12500**	**80,100**	**72,665,919**	**160,200,738**	**1,339,241,972,404**	**13,392,420**	**1,339,242**	**19.31**	**1.83E-05**	**24,657,469**	**1.0**	**24,657,469**	**3.67**	**90,492,911**	**99,751**
Loblolly Pine (7, 7, 1)	8,560	19,911	5.0	1000	5,000	4,535,950	10,000,046	85,600,394,522	856,004	85,600	25.95	2.46E-05	2,221,330	1.0	2,221,330	3.67	8,152,282	8,986
Eucalyptus (9, 8, 1)	8,303	19,313	13.0	2000	26,000	23,586,940	52,000,240	431,757,989,920	4,317,580	431,758	25.95	2.46E-05	11,204,120	1.0	11,204,120	3.67	41,119,120	45,326
Unmanaged Hardwood (6, 10, 1)	6,150	14,305	0.5	1000	500	453,595	1,000,005	6,150,028,345	61,500	6,150	25.75	2.44E-05	158,363	1.0	158,363	3.67	581,193	641
Switchgrass (6, 7, 5)	8,670	20,166	6.5	3000	19,500	17,690,205	39,000,180	338,131,558,407	3,381,316	338,132	13.50	1.28E-05	4,564,776	1.0	4,564,776	3.67	16,752,728	18,467
Miscanthus (2, 7, 5)	8,250	19,189	5.5	2000	11,000	9,979,090	22,000,101	181,500,836,515	1,815,008	181,501	11.50	1.09E-05	2,087,260	1.0	2,087,260	3.67	7,660,243	8,444
Sugarcane/Energycane (7, 7, 11)	7,900	18,374	10.0	1000	10,000	9,071,900	20,000,092	157,990,728,160	1,579,907	157,991	11.95	1.13E-05	1,887,989	1.0	1,887,989	3.67	6,928,920	7,638
Wheat straw (6, 7, 5)	6,840	15,910	2.6	1500	3,900	3,538,041	7,800,036	53,352,245,894	533,522	53,352	13.50	1.28E-05	720,255	1.0	720,255	3.67	2,643,337	2,914
Sugarcane bagasse (7, 7, 5)	7,900	18,374	2.2	1000	2,200	1,995,818	4400020.3	34,757,960,195	347,580	34,758	15.00	1.42E-05	521,369	1.0	521,369	3.67	1,913,426	2,109
Algae (algal mass) (7, 7, 12)	9,000	20,934	N/A	N/A	1,000	907,190	2,000,009	18,000,082,960	180,001	18,000	22.00	2.09E-05	396,002	1.0	396,002	3.67	1,453,327	1,602
Algae (algal oil and lipids) (7, 7, 12)	16,000	37,216	N/A	N/A	1,000	907,190	2000009.2	32,000,147,485	320,001	32,000	28.0	2.65E-05	896,004	1.0	896,004	3.67	3,288,335	3,625

Unknowns (hypothetical values used)

Fuel type & source	Step 1						Step 2			Step 3			Step 4		Step 5		
	Biomass Fuel (that can be effectively utilized in CA)						Energy Units of Fuel Combusted			Carbon Content of Fuel Consumed			Calculate Carbon Emitted		Convert CO2 Emitted to Tons		
	Btu/lb (dry)	kJ/kg (dry)	million dry tons/yr (avg)	dry tons/yr	kg	lb	Btu	Therm	mmBtu	kg Carbon/mmBtu	kg Carbon/kJ	kg Carbon	Fraction Oxidized	kg Carbon	kg CO2/kg C = (44/12)	kg CO2	Metric Tons of CO2
Feedstock 1	10	23	10.0	10,000,000	9,071,900,000	20,000,092,178	200,000,921,780	2,000,009	200,001	10.00	9.48E-06	2,000,009	1.0	2,000,009	3.67	7,340,034	8,091
Feedstock 2	20	47	20.0	20,000,000	18,143,800,000	40,000,184,356	800,003,687,120	8,000,037	800,004	20.00	1.90E-05	16,000,074	1.0	16,000,074	3.67	58,720,271	64,728
Feedstock 3	30	70	30.0	30,000,000	27,215,700,000	60,000,276,534	1,800,008,296,020	18,000,083	1,800,008	30.00	2.84E-05	54,000,249	1.0	54,000,249	3.67	198,180,913	218,456

References: (x, y, z) represent the column in Step 1 (Btu/lb), the column in Step 1 (million dry tons/yr (avg)), and the column in Step 3 (kg Carbon/MMBtu)

For Municipal Solid Waste, (w, x, y, z) represents the column in Step 1 (Btu/lb), the column in Step 1 (million dry tons/yr (avg)), the column in Step 1 (lb) and the column in Step 3 (kg Carbon/MMBtu)

❶ *United States Environmental Protection Agency, "Direct Emissions from Stationary Combustion Sources," Office of Air and Radiation, 2008.*
❷ *Clarke, S., Eng, P., Preto, F. "Biomass Burn Characteristics: Factsheet." Order No. 11-033. AGDEX 737-120. June 2011.*
❸ *Moller, Rosa. California Research Bureau, "Brief on Biomass and Cellulosic Ethanol." December 2005.*
❹ *1,643 lbs/person/year (Biomass Feedstocks for Biopower: Background and Selected Issues") multiplied by California population of 37,253,956 (http://worldpopulationreview.com/population-of-california-2012/)*
❺ *Ciferno, J., Marano, J. "Benchmarking Biomass Gasification Technologies for Fuels, Chemicals and Hydrogen Production: Table 2. Potential Biomass Gasifier Feedstocks." U.S. Department of Energy . National Energy Technology Laboratory. June 2002.*
❻ *EPA Combined Heat and Power Partnership, Chapter 3. Biomass Resources.*
❼ *Bracmort, Kelsi. "Biomass Feedstocks for Biopower: Background and Selected Issues." Congressional Research Service, October 6, 2010.*
❽ *Gonzalez, R., Wright, J., Saloni, D. "The Business of Grwogin Eucalyptus for Biomass." Biomass Magazine 4, pg. 52. 2010.*
❾ *Appendix A: Heat Content Ranges for Various Biomass Fuels (dry weight basis) with English and Metric Units. Retrieved from: cta.ornl.gov/.../Heat_Content_Ranges_for_Various_Biomass_Fuels.xl...Similar*
❿ *Brink, Steven. "The Value of Actively Managed Forestlands, Wood Products, and Biomass for Electricity Generation for California's CO2 Emissions Reduction Goals."*
⓫ *Jenkins, B.M., Baxter, L.L., Miles Jr., T.R., Miles, T.R. "Combustion Properties of Biomass." Elsevier Fuel Processing Technology 54 (1998) 17-56.*
⓬ *Estimates not available. These values are predicted based on all resources included in report.*

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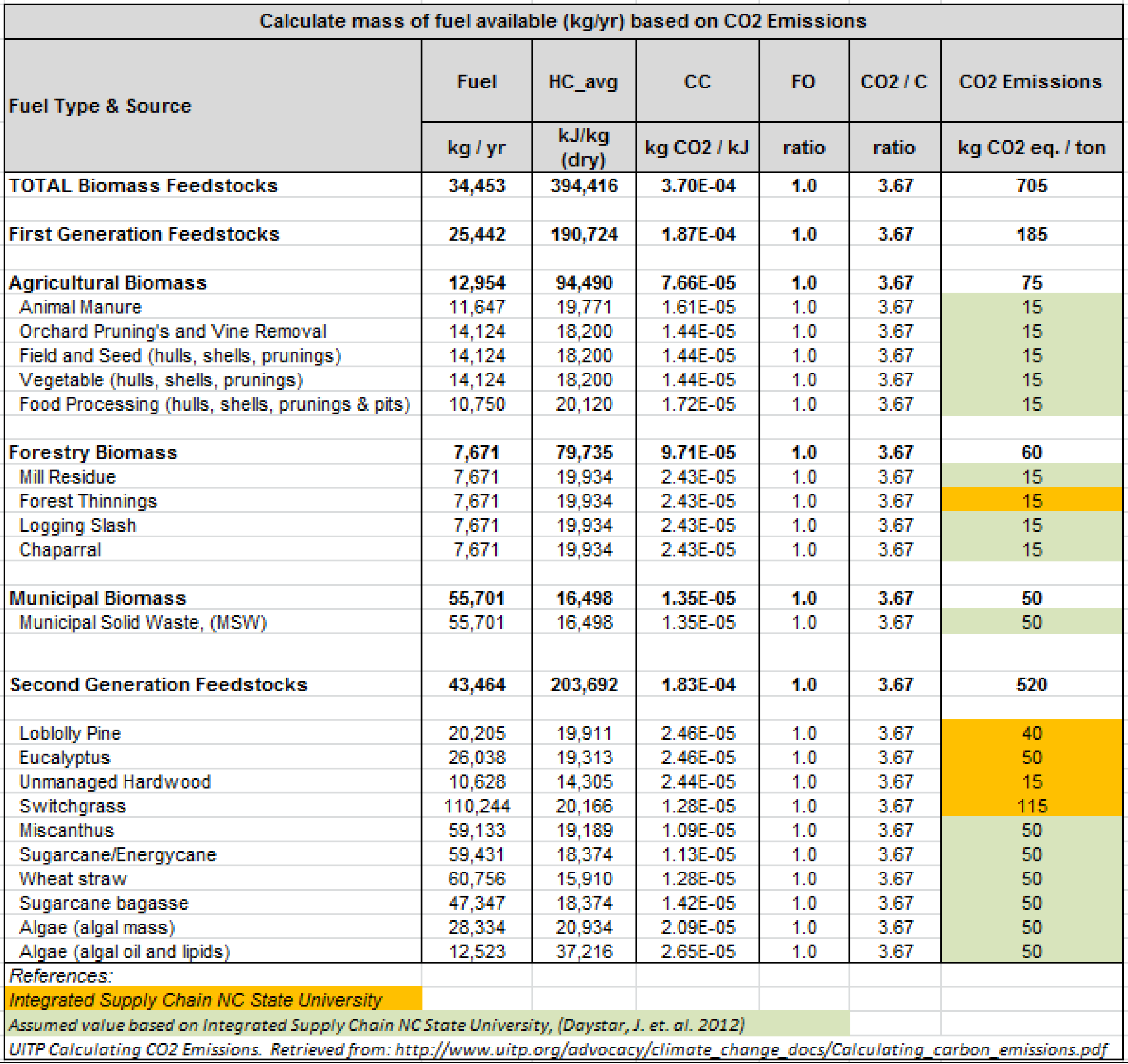
Phase 2 Calculation Spreadsheet

$$CO_2 \text{ Emissions} = Fuel * HC_{avg} * CC * FO * \frac{CO_2}{C}$$



Calculate mass of fuel available (kg/yr) based on CO2 Emissions

Fuel Type & Source	Fuel	HC_avg	CC	FO	CO2 / C	CO2 Emissions
	kg / yr	kJ/kg (dry)	kg CO2 / kJ	ratio	ratio	kg CO2 eq. / ton
TOTAL Biomass Feedstocks	**34,453**	**394,416**	**3.70E-04**	**1.0**	**3.67**	**705**
First Generation Feedstocks	**25,442**	**190,724**	**1.87E-04**	**1.0**	**3.67**	**185**
Agricultural Biomass	**12,954**	**94,490**	**7.66E-05**	**1.0**	**3.67**	**75**
Animal Manure	11,647	19,771	1.61E-05	1.0	3.67	15
Orchard Pruning's and Vine Removal	14,124	18,200	1.44E-05	1.0	3.67	15
Field and Seed (hulls, shells, prunings)	14,124	18,200	1.44E-05	1.0	3.67	15
Vegetable (hulls, shells, prunings)	14,124	18,200	1.44E-05	1.0	3.67	15
Food Processing (hulls, shells, prunings & pits)	10,750	20,120	1.72E-05	1.0	3.67	15
Forestry Biomass	**7,671**	**79,735**	**9.71E-05**	**1.0**	**3.67**	**60**
Mill Residue	7,671	19,934	2.43E-05	1.0	3.67	15
Forest Thinnings	7,671	19,934	2.43E-05	1.0	3.67	15
Logging Slash	7,671	19,934	2.43E-05	1.0	3.67	15
Chaparral	7,671	19,934	2.43E-05	1.0	3.67	15
Municipal Biomass	**55,701**	**16,498**	**1.35E-05**	**1.0**	**3.67**	**50**
Municipal Solid Waste, (MSW)	55,701	16,498	1.35E-05	1.0	3.67	50
Second Generation Feedstocks	**43,464**	**203,692**	**1.83E-04**	**1.0**	**3.67**	**520**
Loblolly Pine	20,205	19,911	2.46E-05	1.0	3.67	40
Eucalyptus	26,038	19,313	2.46E-05	1.0	3.67	50
Unmanaged Hardwood	10,628	14,305	2.44E-05	1.0	3.67	15
Switchgrass	110,244	20,166	1.28E-05	1.0	3.67	115
Miscanthus	59,133	19,189	1.09E-05	1.0	3.67	50
Sugarcane/Energycane	59,431	18,374	1.13E-05	1.0	3.67	50
Wheat straw	60,756	15,910	1.28E-05	1.0	3.67	50
Sugarcane bagasse	47,347	18,374	1.42E-05	1.0	3.67	50
Algae (algal mass)	28,334	20,934	2.09E-05	1.0	3.67	50
Algae (algal oil and lipids)	12,523	37,216	2.65E-05	1.0	3.67	50

References:

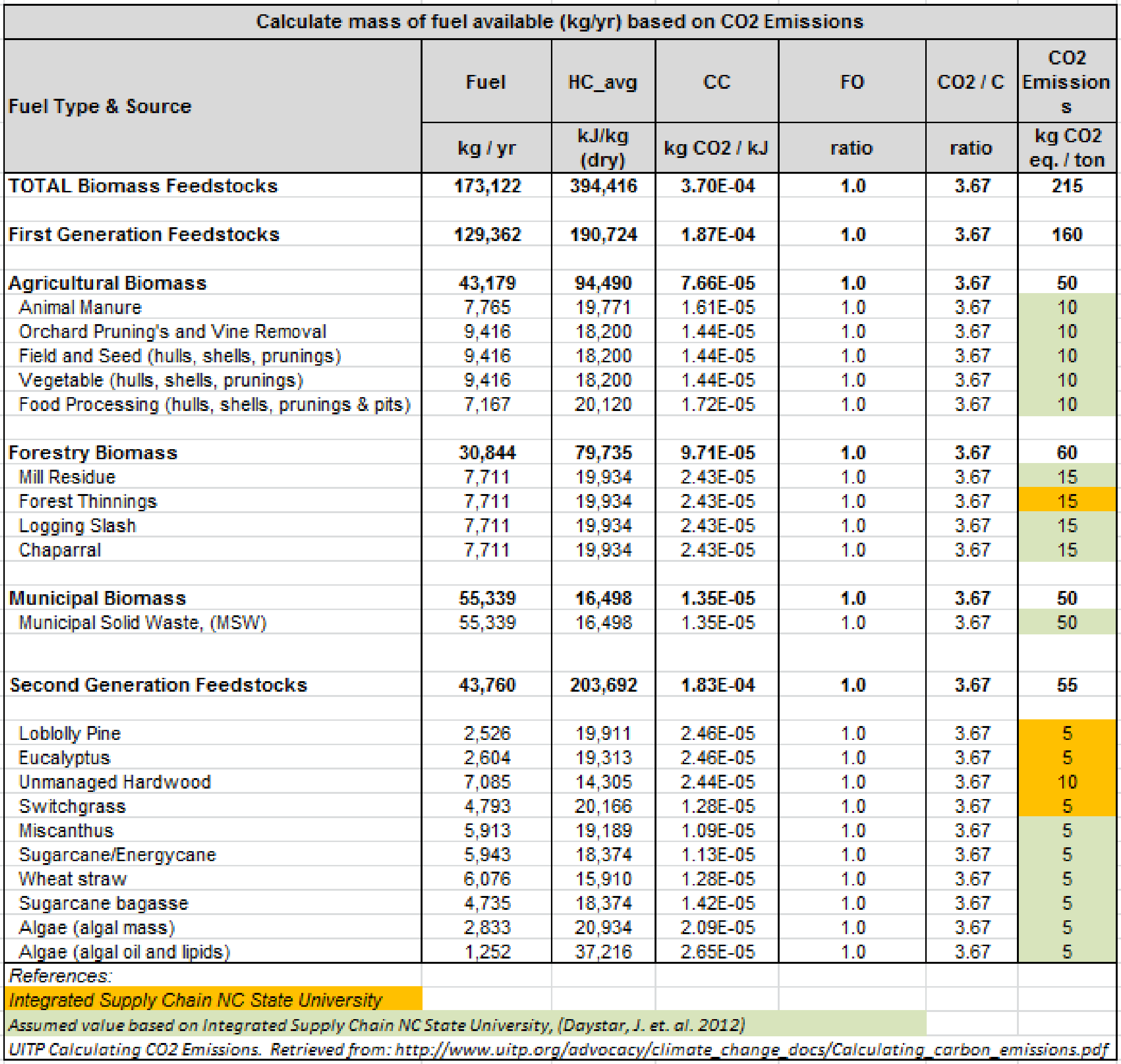
Integrated Supply Chain NC State University

Assumed value based on Integrated Supply Chain NC State University, (Daystar, J. et. al. 2012)

UITP Calculating CO2 Emissions. Retrieved from: http://www.uitp.org/advocacy/climate_change_docs/Calculating_carbon_emissions.pdf

Phase 3 Calculation Spreadsheet

$$CO_2 \text{ Emissions} = Fuel * HC_{avg} * CC * FO * \frac{CO_2}{C}$$



Calculate mass of fuel available (kg/yr) based on CO2 Emissions						
Fuel Type & Source	Fuel	HC_avg	CC	FO	CO2 / C	CO2 Emissions
	kg / yr	kJ/kg (dry)	kg CO2 / kJ	ratio	ratio	kg CO2 eq. / ton
TOTAL Biomass Feedstocks	**173,122**	**394,416**	**3.70E-04**	**1.0**	**3.67**	**215**
First Generation Feedstocks	**129,362**	**190,724**	**1.87E-04**	**1.0**	**3.67**	**160**
Agricultural Biomass	**43,179**	**94,490**	**7.66E-05**	**1.0**	**3.67**	**50**
Animal Manure	7,765	19,771	1.61E-05	1.0	3.67	10
Orchard Pruning's and Vine Removal	9,416	18,200	1.44E-05	1.0	3.67	10
Field and Seed (hulls, shells, prunings)	9,416	18,200	1.44E-05	1.0	3.67	10
Vegetable (hulls, shells, prunings)	9,416	18,200	1.44E-05	1.0	3.67	10
Food Processing (hulls, shells, prunings & pits)	7,167	20,120	1.72E-05	1.0	3.67	10
Forestry Biomass	**30,844**	**79,735**	**9.71E-05**	**1.0**	**3.67**	**60**
Mill Residue	7,711	19,934	2.43E-05	1.0	3.67	15
Forest Thinnings	7,711	19,934	2.43E-05	1.0	3.67	15
Logging Slash	7,711	19,934	2.43E-05	1.0	3.67	15
Chaparral	7,711	19,934	2.43E-05	1.0	3.67	15
Municipal Biomass	**55,339**	**16,498**	**1.35E-05**	**1.0**	**3.67**	**50**
Municipal Solid Waste, (MSW)	55,339	16,498	1.35E-05	1.0	3.67	50
Second Generation Feedstocks	**43,760**	**203,692**	**1.83E-04**	**1.0**	**3.67**	**55**
Loblolly Pine	2,526	19,911	2.46E-05	1.0	3.67	5
Eucalyptus	2,604	19,313	2.46E-05	1.0	3.67	5
Unmanaged Hardwood	7,085	14,305	2.44E-05	1.0	3.67	10
Switchgrass	4,793	20,166	1.28E-05	1.0	3.67	5
Miscanthus	5,913	19,189	1.09E-05	1.0	3.67	5
Sugarcane/Energycane	5,943	18,374	1.13E-05	1.0	3.67	5
Wheat straw	6,076	15,910	1.28E-05	1.0	3.67	5
Sugarcane bagasse	4,735	18,374	1.42E-05	1.0	3.67	5
Algae (algal mass)	2,833	20,934	2.09E-05	1.0	3.67	5
Algae (algal oil and lipids)	1,252	37,216	2.65E-05	1.0	3.67	5

References:

Integrated Supply Chain NC State University

Assumed value based on Integrated Supply Chain NC State University, (Daystar, J. et. al. 2012)

UITP Calculating CO2 Emissions. Retrieved from: http://www.uitp.org/advocacy/climate_change_docs/Calculating_carbon_emissions.pdf