INL/EXT-15-36869

Procter & Gamble Technology Process Assessment for Bioenergy Production

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January 2016

The INL is a U.S. Department of Energy National Laboratory
operated by Battelle Energy Alliance

INL/EXT-15-36869

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Prepared for
Procter & Gamble
Box Elder Plant
Tremonton, Utah

EXECUTIVE SUMMARY

Procter & Gamble intend to replace much of their current heat and power with renewable energy sources. For 2014, Procter & Gamble's total energy, including electricity, natural gas, and steam, is approximately 1,540,000 MMBTU annually. The biomass and waste around a Procter & Gamble facility can be grouped into six categories: (1) agriculture residue and grass, (2) refuse solid material, (3) food waste, (4) organic waste stream, (5) livestock manure, and (6) wastewater and sludge. The six feedstock sources theoretically can provide a total energy of 3,520,000 MMBTU per year, among which agriculture residue is the biggest fraction with about 67%, followed by livestock manures at 27%. The practical estimation of bioenergy would be about 2,840,000 MMBTU annually. Therefore, the available energy sources around a Procter & Gamble facility are enough to meet their energy needs.

These energy feedstocks would be treated by two processes: (1) anaerobic digestion for biogas and, subsequently, for heat and power and (2) thermochemical processes (e.g., combustion, pyrolysis, and gasification) for heat and power. For anaerobic digestion, a one-stage complete mixing digester is preferable; fluidized bed reactors are favorable for the thermochemical process.

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ACRONYMS

AD	anaerobic digestion
CO_2	carbon dioxide
COD	chemical oxygen demand
CRP	Conservation Reserve Program
IEA	International Energy Agency
P&G	Procter & Gamble
VS	volatile solids

Procter & Gamble Technology Process Assessment for Bioenergy Production

1. PROJECT SCOPE

Based on all unspecified biomass and waste resources available for Procter & Gamble's (P&G's) Box Elder facility, located in Tremonton, Utah, a set of biomass and waste conversion options are proposed to meet the basic heat and power needs of P&G's Box Elder facility.

2. OVERALL BIOMASS, WASTE, AND CONVERSION ROUTES

2.1 Types of Biomass and Waste

According to the International Energy Agency (IEA), fossil fuels accounted for up to 81% of the world's primary energy supply in 2007 (IEA 2010), whereas renewable energy sources only contributed 13% (shown in Figure 1), with 77% coming from the bioenergy generated from biomass and waste. In order to mitigate carbon dioxide (CO_2) emissions, renewable resources will play an important role. In this regard, bioenergy from biomass and waste is seen as one of the most dominant future renewable energy sources due to three aspects: (1) a sustainable local supply can guarantee continuous stable power generation; (2) biomass and waste do not compete with food crops in agricultural land usage; and (3) biomass and waste need to be treated at a cost while they are an energy source that can be converted to energy via various technologies to offset the costs related to treatment.

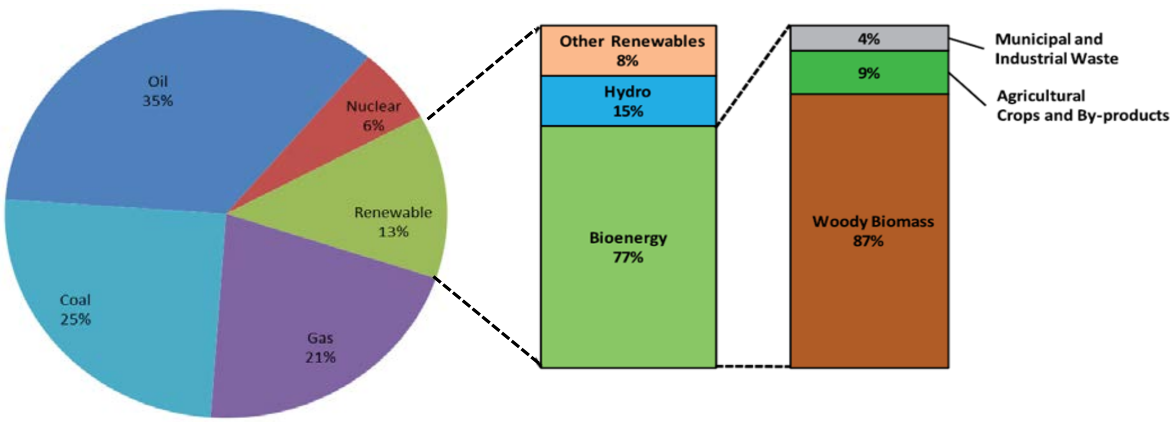


Figure 1. Share of bioenergy in the world energy mix (IEA 2010).

Biomass consists of any organic matter of vegetable or animal origin. It is available in many forms and from many different sources (e.g. forestry products such as biomass from logging, residue, process and residues such as sawdust and black liquor; agricultural products such as crops, harvest residues, food processing waste, and animal dung; and municipal and other waste such as waste wood, sewage sludge, and organic components of municipal solid waste).

2.2 Conversion Technologies

Different biomass and waste can be utilized via different technologies to produce different energy forms (see Figure 2 and Figure 3). For example, taking agriculture residue, wheat straw can be directly burned to produce heat and power and it can be utilized for production of syngas via gasification process or biodiesel from pyrolysis (Figure 2). These conversion processes can be subdivided into three categories: (1) thermochemical, (2) biochemical, and (3) physicochemical (Figure 3). A brief description of three conversion technologies (i.e., anaerobic digestion [AD], pyrolysis, and gasification) is provided in the following subsections.

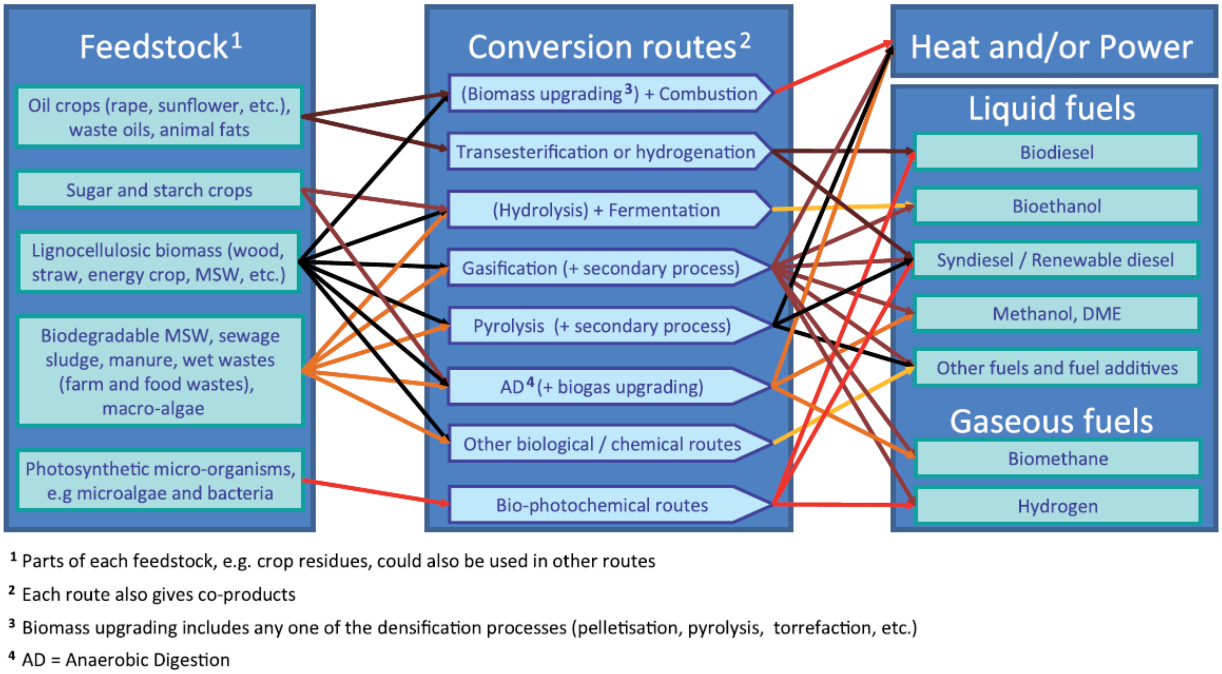


Figure 2. Overall conversion routes of biomass and waste to bioenergy (source: IEA Bioenergy 2009).

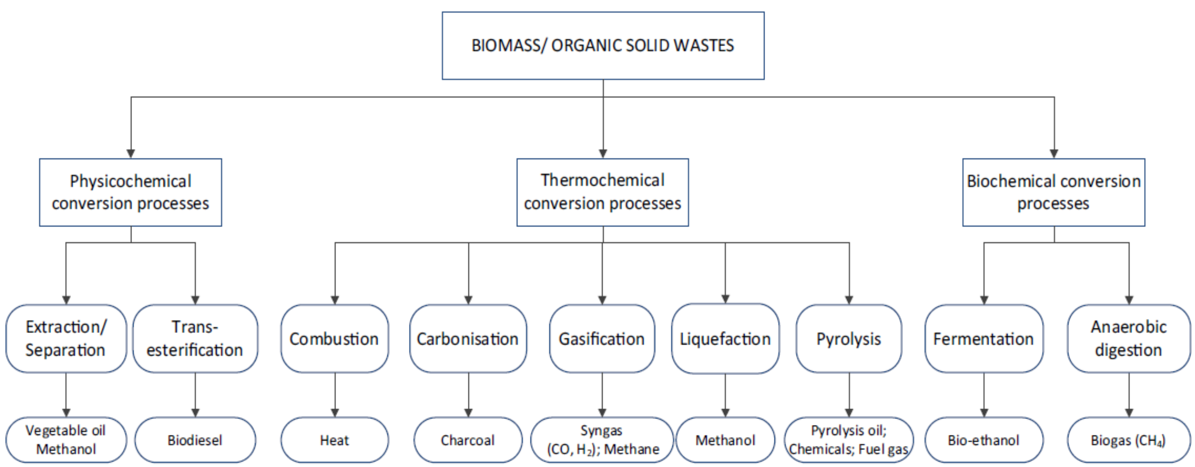


Figure 3. Overall conversion routes of biomass and waste to bioenergy (Appels et al. 2011).

2.2.1 Anaerobic Digestion

AD is a robust biochemical conversion process using microorganisms to degrade organics in aqueous solution in absence of oxygen to produce biogas, which typically consists of 65% CH_4, 35% CO_2, trace H_2S, H_2, N_2, and water vapor. The decomposition of biowaste occurs in four stages in sequence: (1) hydrolysis, (2) acidogenesis, (3) acetogenesis, and (4) methanogenesis (Figure 4). Various biomass and waste can be used as feedstock in AD for production of biogas, including farm waste (i.e., manure), food waste (e.g., food manufacture waste and food processing waste/wastewater), organic fraction of municipal solid waste, energy crops, agriculture waste, waste oils and fat, wastewater, and sludge.

Different feedstocks have different organic contents, which result in different biogas or methane yields, expressed in m^3 methane per kilogram of degraded chemical oxygen demand (COD).

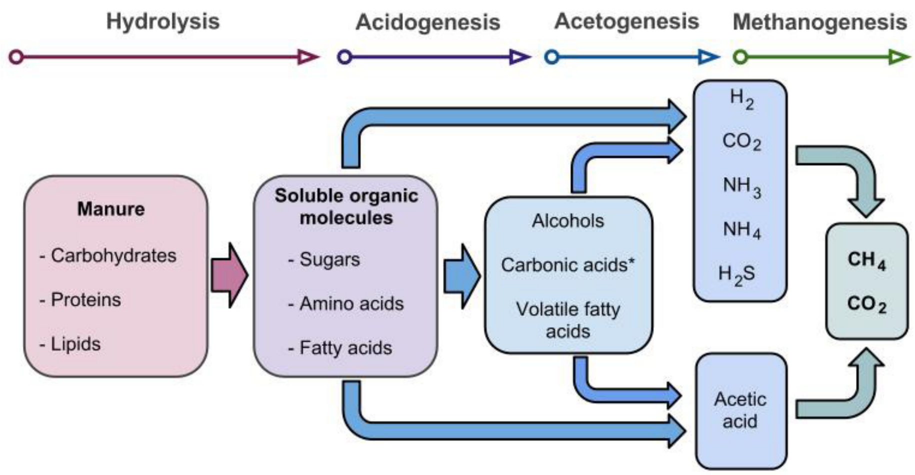


Figure 4. Conceptual degradation stages of AD process (Girard et al. 2013).

COD is used to quantify the amount of organic matter in waste streams and predict the potential for biogas production. COD conversion is the basis for estimating the methane yield from various feedstocks. Different feedstocks for AD have different COD values. For example, 1 g carbohydrates (sugar is a typical example) is equal to 1.07 g COD; 1 g protein provides 1.5 g COD; and 2.91 g COD is produced from 1 g lipid (Zeeman and Gerbens 2011). If the COD value is not available for some waste, the volatile solids (VS) content, with a factor adjustment, can be used as an approximation of COD. The ratio of COD/VS could be 1 to 2. In this report, the methane yield is taken as 0.35 m^3 CH_4 per kg COD that is degraded based on several references (Zeeman and Gerbens 2011; Moriarty 2013; Cornell University 2004; USDA 2007).

There are a wide variety of digesters; the most common digester types are covered lagoon, completer mixed digester, and plug flow digester. AD is widely applied throughout the world. For commercial-scale livestock facilities, more than 6,800 digesters are currently operating in Germany, while 157 projects are operating in the United States (C2ES 2015, EPA 2010). As illustrated in Table 1, about half of the operating digester projects in the United States use plug flow digesters. Complete mix systems are the second most common digester type (i.e., 23%), followed closely by covered lagoons (i.e., 19%). Plug flow digesters are prevalent because the technology is commonly used for scraped manure systems at dairies and dairy farms currently represent almost 80% of the digester projects in the United States.

Table 1. Numbers of operating ADs by animal type in the United States.

Farm	Total Digester	Plug Flow	Complete mix	Covered Lagoon	Others
Dairy	126	74	27	16	9
Swine	24	2	5	15	2
Poultry	5	1	4	0	0
Beef	2	2	0	0	0
Total	**157**	**79**	**36**	**31**	**11**

2.2.2 Pyrolysis

Pyrolysis is the controlled thermal decomposition of biomass occurring at about 500°C to produce a liquid bio-oil: a mixture of gas (i.e., syngas) and solid charcoal (i.e., biochar). Like AD, pyrolysis operates in anaerobic environments (i.e., in the absence of oxygen). Based on the residence times in the reactor, there are two main types of pyrolysis processes (i.e., fast and slow), leading to different proportions of the liquid, gas, and solid fractions. Slow pyrolysis favors the production of bio-char, which can be substituted in any applications using coal; on the other hand, fast pyrolysis maximizes the production of bio-oil, which makes this process more attractive and suitable for industrial applications (Figure 5).

The essential features of fast pyrolysis are (1) very high heating and heat transfer rates, which usually requires a finely ground biomass feed; (2) a carefully controlled pyrolysis reaction temperature of around 500°C in the vapor phase, with short vapor residence times of typically less than 2 seconds; and (3) rapid cooling of the pyrolysis vapors to give the bio-oil product. The main product (i.e., bio-oil) is a miscible mixture of polar organics (about 75 ±80 wt%) and water (about 20 ± 25 wt%). Its yield is up to 80 wt% on dry feed, together with by-product char and gas that can be used within the process so there are no waste streams.

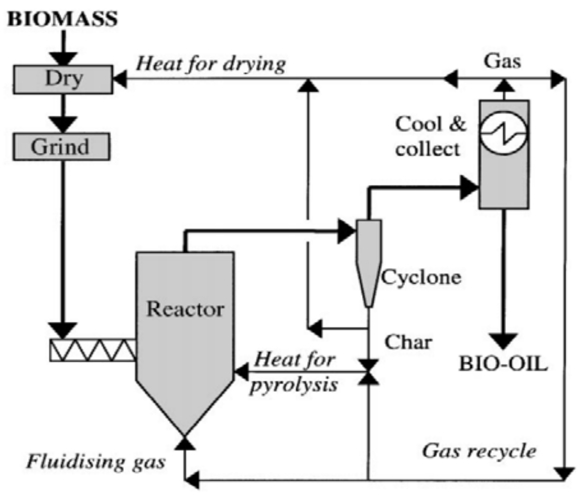


Figure 5. Conceptual fluid bed fast pyrolysis process (Bridgewater et al. 1999).

2.2.3 Gasification

Biomass gasification of biomass occurs by partial oxidation into a gaseous product (i.e., syngas), which consists primarily of hydrogen and carbon monoxide, with lesser amounts of CO_2, water, methane, and nitrogen (N_2). The reactions are carried out at elevated temperatures (i.e., 500 to 1400°C) and atmospheric or elevated pressures up to 33 bar. The oxidant used is essential for the gasification processes and can be air, pure oxygen, steam, or a mixture of these gases. Air-based gasifiers typically produce a product gas containing a relatively high concentration of nitrogen with a low heating value between 4 and 6 MJ/m^3 (107 to 161 Btu/ft^3). Oxygen and steam-based gasifiers produce a product gas containing a relatively high concentration of hydrogen and carbon monoxide with a heating value between 10 and 20 MJ/m^3 (268 to 537 Btu/ft^3).

Biomass gasification proceeds primarily via a two-step process (i.e., pyrolysis followed by gasification) (Figure 6). Pyrolysis, which is also known as devolatilization as described above, is endothermic and produces 75 to 90% volatile materials in the form of gaseous and liquid hydrocarbons. The remaining non-volatile material that contains high carbon content is referred to as biochar. The volatile hydrocarbons and char are subsequently converted to syngas in the second step (i.e., gasification). Pyrolysis partially removes carbon from the feed but does not add hydrogen. Gasification, on the other hand, requires a gasifying medium like steam, air, or oxygen to rearrange the molecular structure of the feedstock to convert the solid feedstock into gases or liquids; it can also add hydrogen to the product.

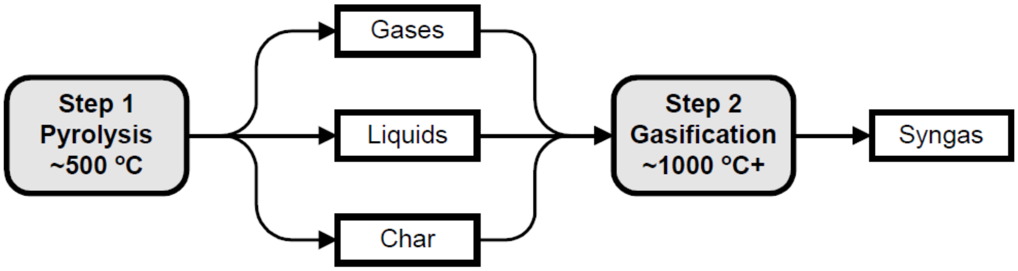


Figure 6. Gasification steps (Ciferno and Marano 2002).

3. BASIC HEAT AND POWER NEEDS OF PROCTER & GAMBLE

P&G provided their basic heat and power needs in Table 2, which are in the following three forms: electricity, natural gas, and steam. P&G's intention is to replace much of heat and power with renewable energy sources. As for electricity, it is converted to thermal energy in MMBTU for easier calculation, assuming the efficiency of converting thermal energy into electricity is 30%. For steam, it is assumed that it is typically saturated steam at 3.5 bar and 148°C. Consequently, the total thermal energy for 2014, 2018, and 2025 are estimated at approximately 1,540,000 MMBTU; 2,900,000 MMBTU; and 4,400,000 MMBTU, respectively.

Table 2. Average energy consumption of P&G in 2014 and expectation for future.

	Unit	**2014**	**2018**	**2025**
Electricity[a]	1,000x kWh/month	8,976	17,951	26,927
	MW	12.06	24.13	36.19
	MMBTU/month[d]	102,083	204,166	306,250
Natural Gas[b]	1,000x CF/month	8,720	10,464	21,801
	MMBTU/month	8,956	10,747	22,390
Steam[c]	lb/hour	19,971	29,957	43,936
	MMBTU/month	17,203	25,805	37,847
Total	MMBTU/month	128,242	240,718	366,487
	MMBTU/year	1,538,904	2,888,616	4,397,844

a. Assuming the efficiency of converting thermal energy to electricity is 30%.
b. Natural Gas: 1,027 BTU/ft^3
c. Steam: assuming it is typical saturated steam at 3.5 bar and 148°C; its specific enthalpy is 1,180 BTU/lb.
d. 365 days/year, 24 hours/day, 30.4 day/month; 1 kWh = 3,412 BTU.

4. TOTAL BIOMASS AND ENERGY AVAILABILITY FOR PROCTER & GAMBLE FACILITY

The total biomass and waste energy sources around a P&G facility are subdivided into six groups: (1) agriculture residue and energy or wild grass; (2) refuse solid materials (e.g., cardboard, dirty plastics, and pallets); (3) wastewater and sludge; (4) organic waste streams (e.g., dairy processing wastewater); (5) livestock waste (i.e., manure); (6) food waste (from individual household, food manufactures, and processing companies). The amount of biomass and waste were from Bonner and Wright's report (2015).

4.1 Agriculture Residue and Grass

Stover and straw are the main components of agriculture residue, which provides 150,000 tons of biomass per year. These amounts of biomass can contribute more than 2 million MMBTU per year, which is 30% more than the 2014 energy needs of P&G. Bear River Refuge and the Conservation Reserve Program (CRP) may provide an additional 28,000 tons of wild grass per year (i.e., 318,000 MMBTU/year), even though they are not presently harvestable. The total energy from agriculture residues would be 2,350,000 MMBTU/year (Table 3).

Table 3. Biomass and energy available from agriculture residues.

Source	Waste	Unit	Unit Ton/Year	Energy BTU/lb-dry[c]	Moisture %	Total Energy MMBTU/Year
Primary agriculture	Stover and straw	150,000 ton/year	150,000	7,500	10	2,025,000
	Barley hulls	50 ton/month	600	7,500	10	8,100
	Grass in CRP[a]	—	18,000	7,500	20	243,000
Bear River Refuge	Phragmites[b]	12,000 acres	10,000	7,500	50	75,000
Total			**178,600**			**2,351,100**

a. Cannot currently be harvested for commercial use.

b. These *Phragmites* are 50+% moisture and not presently harvestable. Assuming a yield of 0.83 ton/acre/year for 12,000 acres (Bonner and Wright 2015).

c. http://www1.eere.energy.gov/biomass/feedstock_databases.html.

4.2 Refuse Solid Materials

Refuse solid materials from around the area are shown in Table 4. For waste from Schrieber, the waste density is assumed to be 50 to 100 lb/yd^3 (CalRecycle 2015). The total energy from refuse materials averages 30,000 MMBTU per year.

Table 4. Biomass and energy available from refuse wastes.

Source	Waste	Unit	Unit Ton/Year	Energy BTU/lb-Dry[a]	Moisture %	Total Energy MMBTU/Year[b]
Mom's/Post	Plastics	8 tons/week	416	14,000	15	9,901
	Cardboard	4 to 5 tons/week	208 to 260	7,000		2,475 to 3,094
Schrieber	Blotched products, cardboard, dirty plastics, and pallets	30 yd^3/day[c]	274 to 548	10,000	15	4,658 to 9,316
Loft House	Food-contaminated paper and plastics	60 to 90 tons/month	720 to 1,080	7,000	15	8,568 to 12,852
Total			**1,618 to 2,304**			**25,602 to 35,163**

a. Themeilis et al. 2011.

b. Assuming 15% moisture for all refuse waste.

c. Waste density is assumed to be 50 to 100 lb/yd^3 (CalRecycle 2015).

4.3 Waste Water and Sludge

The wastewater and sludge streams are low solid and low energy content, which can be treated by AD to produce a total energy of 4,000 MMBTU/year (Table 5). Please note that the yield is methane yield and, not biogas. These wastewaters could be used as carriers for co-digestion with other high-strength waste.

Table 5. Biomass and energy available from wastewater and sludge.

Source	Waste	Unit gal/year[a]	TS %	VS/TS %	VS/COD %	Conversion of COD %[b]	CH_4 Yield m^3/year[c]	Total Energy MMBTU/year[c]
JB's	Sewage sludge	12,000 tons/year	10	70	100	50	133,329	4,835
Schrieber Foods	Sludge	2.19 million	3	80	100	50	38,300	1,389
Total							**119,172**	**4,322**

a. Assuming the density of the waste stream is 1.1 kg/L.
b. USDA 2007.
c. CH_4 yield is taken as 0.35 m^3-CH_4/kg COD (Zeeman and Gerbens 2011), 1,027 BTU/ft^3-CH_4.

4.4 Organic Waste Stream

Organic waste streams are mainly from dairy or food processing plants. They are high in COD content and easily degradable. As for JB's paunch waste, pretreatment (such as size reduction) will be conducted first and they will be co-digested with other waste streams. The total energy from organic waste is about 100,000 MMBTU per year (Table 6) via AD processes.

Table 6. Biomass and energy available from organic waste.

Source	Waste	Unit gal/year	TS %	VS/TS %[a]	VS/COD[b,d]	Conversion of COD %[c]	CH_4 Yield m^3/year[c]	Total energy MMBTU/year[c]
Schrieber Foods	Whey (high lactose, cream cheese)	2.19 million	8	90	1.7[c,d]	80	312,527	11,335
	Yogurt	104,000	30	90	1.7	80	55,656	2,019
	Cream cheese	31,200	30	90	1.7	80	16,697	606
JB's	Paunch (fat)	28,080 ton/year	20	90	1.7	80	2,182,146	79,143
Mom's Post	Sugar waste water	2.19 million	250 g/gal	90	1	80	137,970	5,004
Loft House	Sugar (some fat)	1.1 to 2.2 million	6%	90	1	80	69,255	2,512
Total							**2,774,250**	**100,617**

a. The VS/TS is 99% in Lipp and Schmit 2013. In this report, 90% is used for safety.
b. Lebrato et al. 1990.
c. USDA 2007.
d. CH_4 yield is taken as 0.35 m^3-CH_4/kg COD (Zeeman and Gerbens 2011), 1,027 BTU/ft^3-CH_4.

4.5 Animal Manure

Manure is one of the main sources for bioenergy due to its high energy content, huge amounts available, and the mandatory regulations on waste and nutrient management by governments. Idaho has about 580,000 milking cows, with more than 70% of these being located in the Magic Valley region of southern Idaho. This makes Idaho the fourth largest milk-producing state in 2015 (Statista 2016). A portion of the generated manure in Idaho and Utah are usually spread over lands as fertilizer supplement, especially for beef cow manure. However, some consequences from land application of manure include the loss of NH_3, which plays a big role in the formation of fine secondary aerosol particulates (PM2.5), and runoff of nutrients such as nitrate/nitrogen and phosphorous that cause eutrophication of surface waters and contamination of groundwater (Leytem et al. 2009). The dairy farm industry is recognized as the sector with the highest ammonia emissions in Idaho (Sheffield and Louks 2007). Consequently, a permit by rule was made effective on July 1, 2006, by the Idaho Department of Environmental Quality requiring dairy farms with cows or animal units above the specified threshold numbers (i.e., about 2000 heads) to implement industry best management practices to control ammonia emission. More and more farmers shift their usage of manure from land application to various best management practices.

Treatment of manure using AD is popular in Europe, with about 6,800 digesters operating in Germany alone, while less than 200 digesters operate in U.S. farms (C2ES 2015). There are 107,000 head of cattle in the four counties around the P&G facility, which contribute to a total energy of 950,000 MMBTU per year (Table 7). However, the amount of energy may be reduced when considering the potential transportation difficulty resulting from the varying distance between the cattle farms, the P&G facility, and the other uses of manure (such as land application). Because dairy cows are normally kept in cow shelters most of the time, the manure is relatively easy to collect and transport. This leaves the assumption that 75% of the manure is available for P&G use. On the other hand, 25% is assumed to be available from beef cattle because beef cattle are commonly in an open ranch. These assumptions result in a total energy of 601,594 MMBTU annually from cow manure.

Table 7. Biomass and energy available from cattle/cow manure.

County	Animal Type	Heads[a]	kg COD/ Head/ Day[b]	% Manure Collected[b]	Conversion of COD %[b,c]	CH_4 Yield m^3/year	Total Energy MMBTU/year
Box Elder	Beef	37,644	2.4			3,635,620	131,857
	Dairy	9,238	11.5			4,275,110	155,051
Cache	Beef	10,441	2.4	90	35	1,008,381	36,572
	Dairy	15,646	11.5			7,240,568	262,602
Weber	Beef	6,825	2.4			659,152	23,906
	Dairy	4,582	11.5			2,120,432	76,904
Franklin	Beef	9,319	2.4			900,020	32,642
	Dairy	13,857	11.5			6,412,665	232,576
Total		**107,552**				**26,251,947**	**952,111**

a. USDA 2012 census.
b. USDA 2007.
c. Zeeman and Gerbens (2011) estimated that 50% is convertible. Therefore, the number in here is estimated based on the two studies.
d. CH_4 yield is taken as 0.35 m^3-CH_4/kg COD (Zeeman and Gerbens 2011), 1,027 BTU/ft^3-CH_4.

4.6 Food Waste

Food waste can be collected from food processing industries or individual families. Currently, we do not have data for food manufacturing or processing plants. In this document, the food waste from individual household is used to represent the whole amount of food waste. From Table 8, total food waste from the four counties is about 47,000 tons/year, among which the COD is around 14,000 tons. The total energy from food wastes is estimated at 86,000 MMBTU per year (Table 8). The characteristics of food waste are summarized in Table 9.

Table 8. Biomass and energy available from food waste.

County	Population[a]	kg COD/ capita/year	% Waste Collected	Conversion of COD %[b]	CH_4 Yield m^3/year[b]	Total Energy MMBTU/year[b]
Box Elder	51,518	34[b]	80	60	294,271	10,673
Cache	118,343				675,975	24,516
Weber	240,475				1,373,593	49,818
Franklin	13,021				74,376	2,697
Total	**423,357**				**2,418,215**	**87,704**

a. U.S. Census Bureau 2014.
b. Busby and Hyman (2012) estimated that 0.3 kg of food/capita/day was wasted, which is equal to 34 kg COD/capita/year, considering the TS, VS, and COD contents.

Table 9. Characteristics[a] of food waste.

	Unit	Value
Moisture content	%	70
Total solid	%	30
VS/TS	%	88
VS/COD		1.2
Energy content	BTU/lb	1,500 to 3,000
Density	lb/yd^3	2,000
CH_4 yield	m^3-CH_4/kg COD	0.35[a,b,c,d]

a. Moriarty 2013.
b. Cornell University 2004.
c. USDA 2007.
d. Zeeman and Gerbens 2011. The CH_4 yield is averaged from the references of a, b, c, and d.

4.7 Summary and Adjustment of Total Availability of Bioenergy for Practical Estimation

The energy content from the six biomass and waste streams is summarized in Table 10 and Figure 7. These feedstocks can provide a total energy of 3,520,000 MMBTU per year, which is more than two times higher than the energy needs of P&G in 2014 and even 20% higher than the needs of 2018 (Table 10). Among these available energy sources, agriculture biomass provides the biggest portion at 67%. Manure can contribute another 27%, while the other four resources together, including organic waste, food waste, refuse, and wastewater/sludge supply the final 6% of the total energy (Figure 7).

However, because some biomass and waste are not practically available at present conditions (e.g., the grass in CRP) and others might be underestimated due to limited information, adjustment could be made to reflect this situation. As for agriculture, the energy value is reduced to 2 million MMBTU per year after removing the currently non-harvestable grass in CRP and *Phragmites* in the Bear River Refuge. From the discussion in Section 4.5, the energy from manure could be reduced to 600,000 MMBTU per year, considering the difficulty in transportation and collection and other usage of manure. The numbers for organic waste and solid refuse are conservative and could be kept the same. As for food waste, only individual family waste is considered here; waste from food processing companies and supermarkets (e.g., Walmart) is not included. Therefore, it is reasonable to increase the total to 100,000 MMBTU per year by adjusting 14%. Only two wastewater streams are included in this report for AD. However, any wastewater theoretically can be treated by AD, even wastewater from pulp and paper industries are treated using digesters (Meyer and Edwards 2014; Kamali and Khodaparast 2015). Therefore, energy from wastewater can be increased to 10,000 MMBTU per year. Thus, the total energy for current conditions is approximately 3,000,000 MMBTU per year (Table 10).

Table 10. Summary and adjustment of total availability of bioenergy for P&G.

	Agriculture Residue	**Livestock Manure**	**Organic Waste Stream (Sugar, Cheese)**	**Food Waste**	**Refuse Solid**	**Wastewater and Sludge**	**Total**
Ton/year	178,600		28,000	47,000	1,900	12,000	
Gal/year	—	—	5,543,000	—	—	2,190,000	
MMBTU/year	2,350,000	950,000	100,000	86,000	30,000	4,000	3,520,000
%	66.76	27.00	2.84	2.44	0.85	0.11	100
Practical estimation							
MMBTU/year	*2,000,000*	*600,000*	*100,000*	*100,000*	*30,000*	*10,000*	*2,840,000*
%	66.67	25.33	3.33	3.33	1	0.34	100

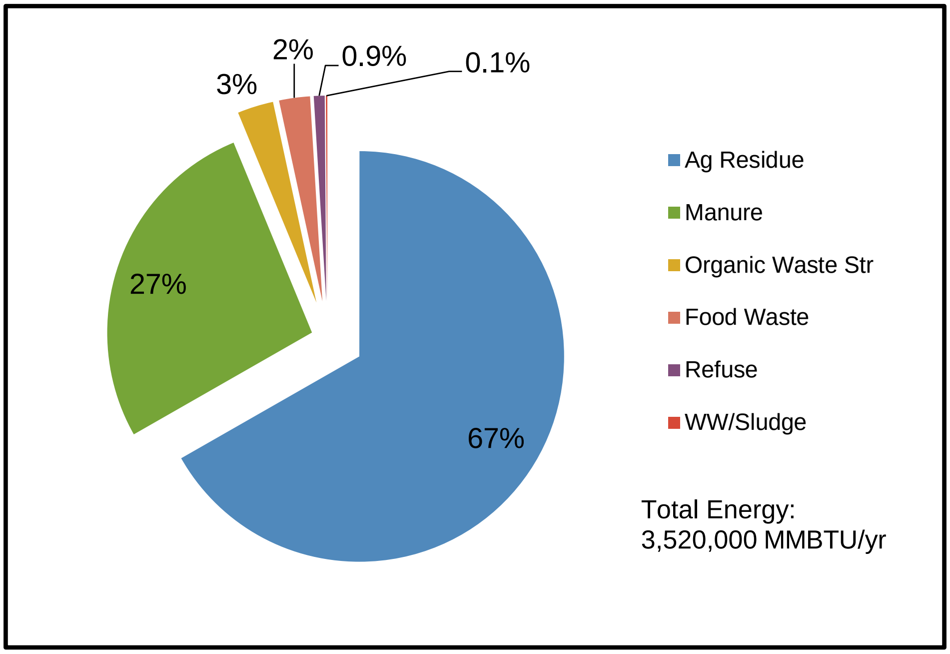


Figure 7. Distribution of theoretical availability of bioenergy for P&G (total energy: 3,520,000 MMBTU/year).

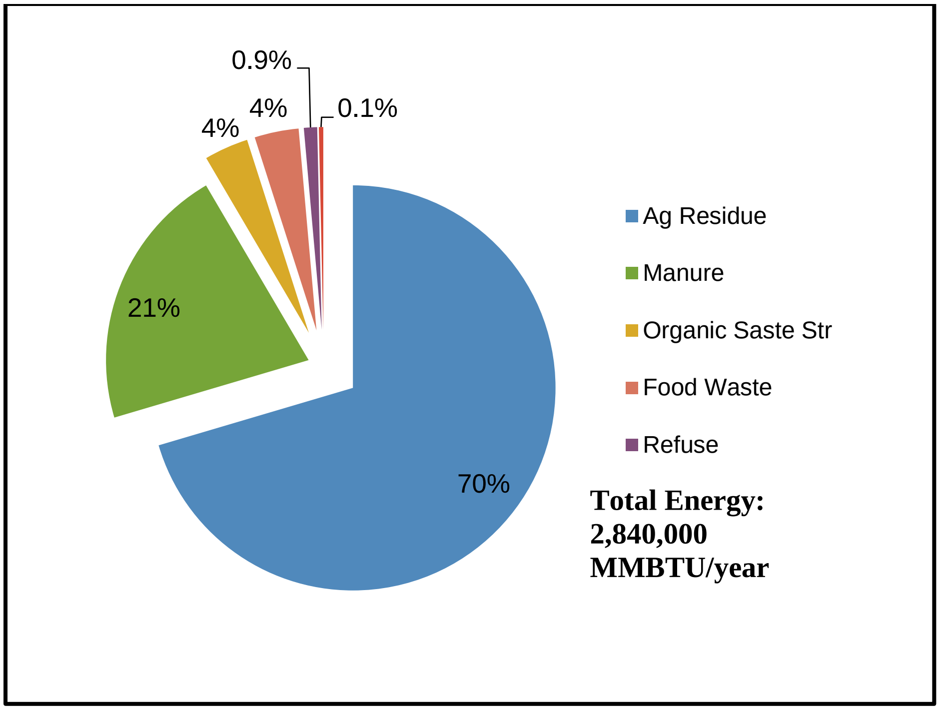
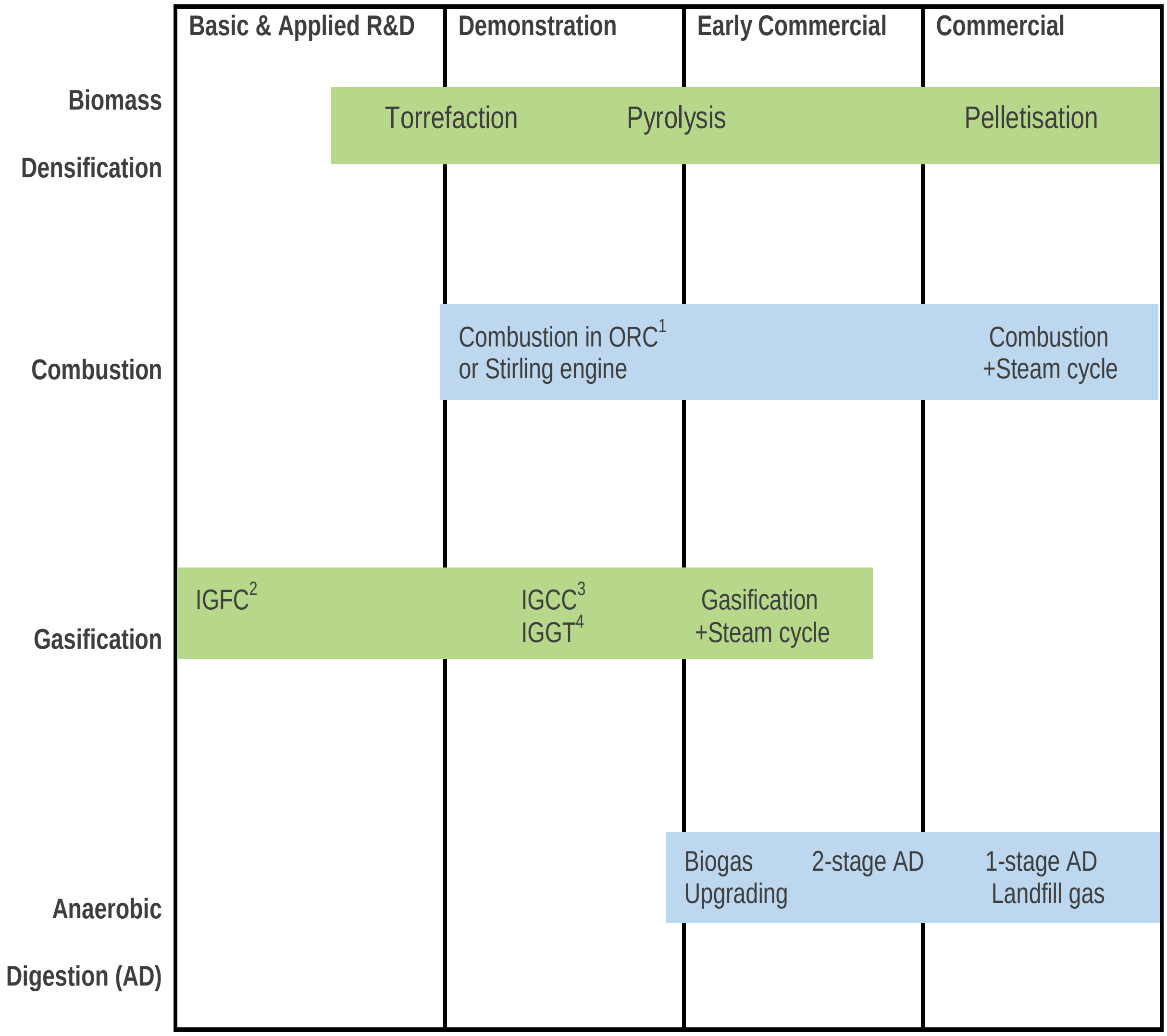


Figure 8. Distribution of practical estimation of bioenergy for P&G (total energy: 2,840,000 MMBTU/year).

5. BIOMASS CONVERSION PROCESSES FOR PROCTER & GAMBLE

As for the various conversion routes of biomass and waste into bioenergy (shown in Figure 2 and Figure 3), their development statuses are different as demonstrated in Figure 8. A couple of processes are applied commercially (such as combustion combining with the steam cycle and one stage of AD), while some processes, including gasification and pyrolysis, are in an early commercial stage after successful demonstration. However, some processes (e.g., integrated gasification fuel cell and bio-photochemical) are still in the early research stage. Considering the feedstocks available for the P&G facility, four processes have high potentials to be applied in P&G: (1) combustion, (2) gasification, (3) pyrolysis, and (4) AD. Their combined application in the P&G facility is demonstrated in Figure 9.

After pretreatment, agriculture residue biomass and refuse solid waste can be converted through thermochemical processes (e.g., biomass combustion boiler, a gasifier, and/or a pyrolysis reactor) to heat and/or power. On the hand other, the livestock manure, organic and food waste, and wastewater/sludge would be treated in an AD for biogas production, which can be further converted to hear and/or power. As shown in Figure 10, AD can generate a total energy of 1,140,000 MMBTU per year, while 2,380,000 MMBTU per year can be provided through a thermochemical process. Each process is described in the following subsections (see Figures 11 and 12).



[1] Organic Rankien Cycle; [2]Integrated gasification fuel cell, [3/4]Integrated gasification combined cycle (CC)/gas turbine (GT)

Figure 1. Development status of some conversion processes (IEA Bioenergy 2009).

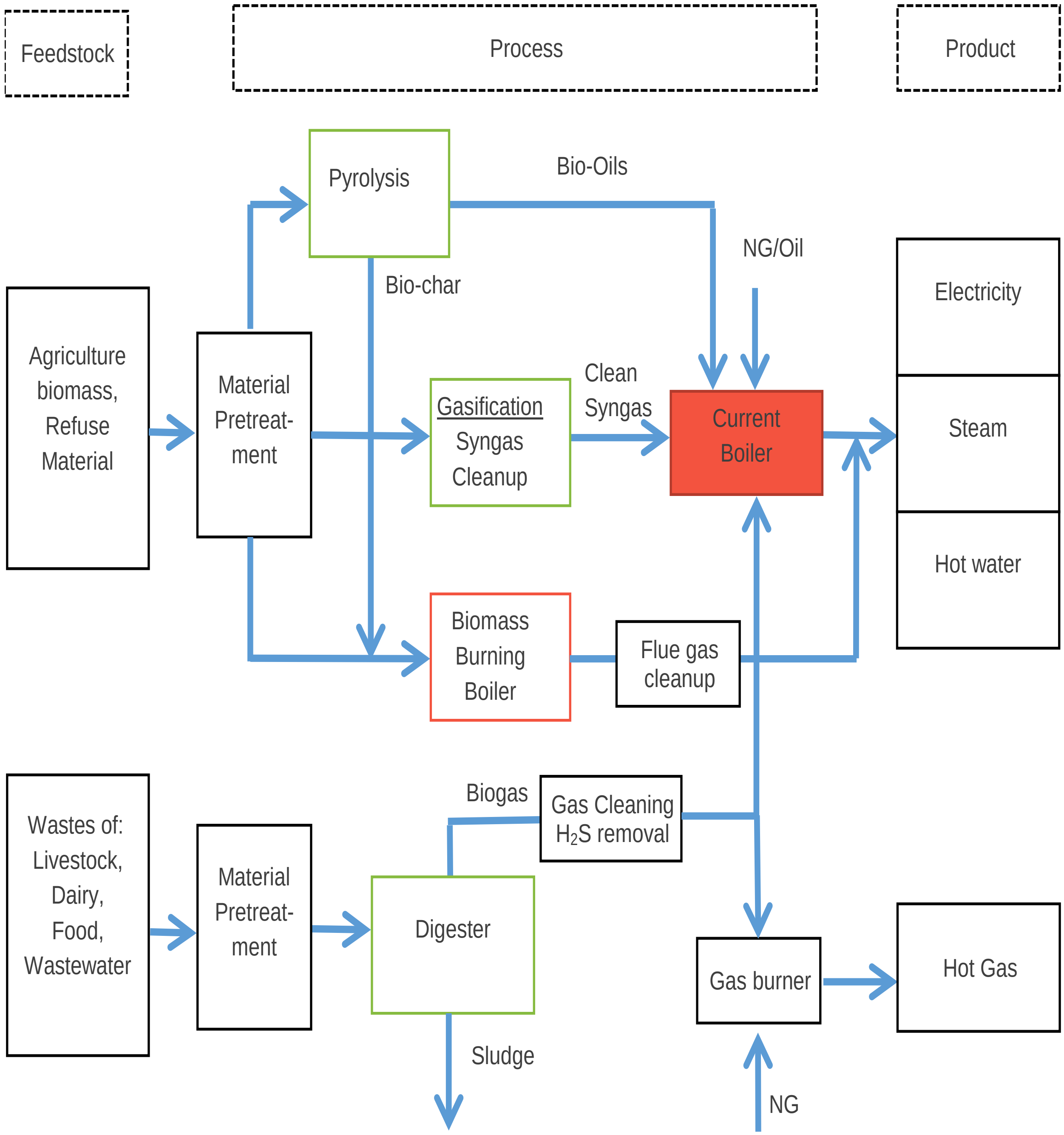


Figure 2. Overall biomass conversion processes for P&G.

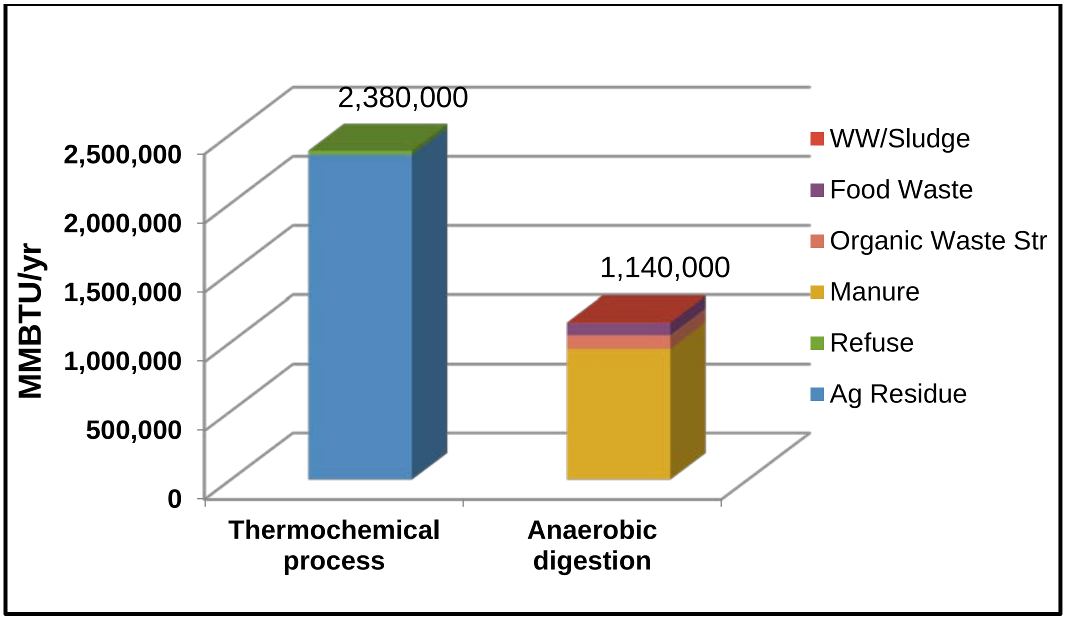


Figure 11. Allocation of theoretical availability of bioenergy for P&G between AD and the thermochemical process.

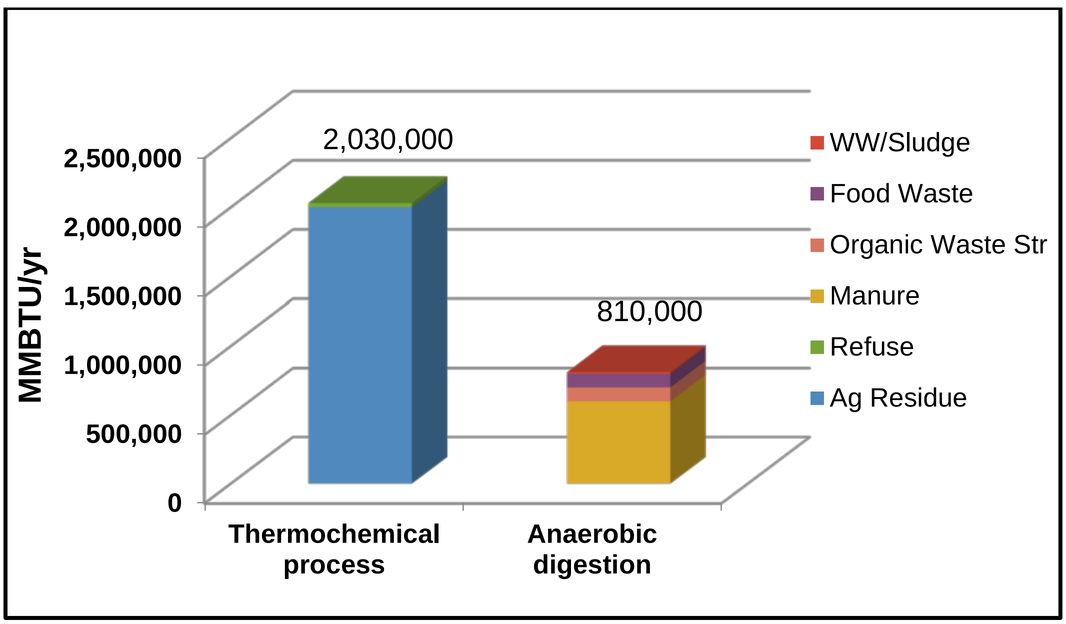


Figure 12. Allocation of practical estimation of bioenergy for P&G between AD and the thermochemical process.

5.1 Anaerobic Digestion

AD is desirable for high-moisture content feedstock because this process occurs in an aqueous environment. The waste feedstock will go through a pretreatment process to remove non-degradable solids, including plastics, rocks, and glass and to reduce the size of organic materials such as food, vegetables, and fats. Considering the varying COD contents of different waste (e.g., wastewater/sludge has much lower COD value compared to fats, oils, and grease), various waste would mix and add together into the digester for co-digestion because a too low or too high organic loading would be negative for the performance of a digester. The optimal organic loading rate would range from 0.7 to 0.8 kg COD/day/m^3-reactor for a well operated digester, while it is different for the start-up process. The main product of a digester is biogas, which typically consists of 65% CH_4 and 35% CO_2, with a trace of H_2S, H_2, N_2 and water vapor. In order to keep the emission standard, H_2S must be removed through a gas cleaning process. CO_2 can also be removed from the biogas in some cases where higher energy content is required. Then the clean biogas/methane can replace the purchased natural gas and be burned in the current boiler to produce heat/steam and power if a generator is included. In addition, the biogas can be utilized in a second gas burner to generate hot gas, which is used for drying paper. The digester could generate 1,140,000 MMBTU annually for the P&G facility by treating various waste streams.

The AD process can be designed into a one-stage or two stage-system. For the one-stage system, the four steps of AD shown in Figure 4 all occur in one reactor. This system has a relatively lower capital cost due to the simple design and it is more technologically ready than a two-stage system as shown in Figure 8. On the other hand, a two-stage system separates the four steps in two reactors (i.e., the hydrolysis and acidogenesis in the first reactor and the acetogenesis and methanogenesis in the second reactor). A two-stage system could optimize parameters for each phase; however, it requires more capital cost and is still in an early commercial development stage.

As for digester type, presently, there are more plug flow digesters operated on livestock farms in the United States, because they are more suitable for scrapped dairy manure. However, the feedstock for the potential AD process in the P&G facility is a wide range, including wastewater and organic and food waste, which are more suitable to be digested using completely mixed systems. Thus, a one-stage complete mixed digester is more preferable for P&G when considering all factors mentioned above.

5.2 Thermochemical Processes

Thermochemical processes in this report refer to combustion, gasification, and pyrolysis. The feedstock, either agriculture biomass or refuse materials, needs to be treated before going into the reactors. Pretreatment of feedstock mainly involves sizing and drying. Achieving the correct feedstock sizing for the thermochemical reactors (especially for gasification) is important. Smaller particles have a larger surface area to volume ratio and the thermochemical reaction occurs faster when there is a larger biomass surface area. Smaller particles can also be suspended in gas flows more readily and, if very small, the particles may act like a fluid, which is especially important for a fluidized gasifier or combustion boiler. A screening process is often used to ensure any remaining larger particles and extraneous materials are removed.

For solid feedstock, thermochemical processes prefer a moisture content in the 10 to 20% range. The heat for drying can be provided externally or extracted from the gasifier syngas or biogas from the digester. Reactor efficiency increases with drier biomass; however, drying costs also increase quickly below 10% moisture.

After sizing and drying, feedstock could be divided into three steams. First, half of the total feedstock could be fed into a combustion boiler, either a conventional stoker boiler or a modern fluidized bed combustion boiler that offers multiple benefits (i.e., compact boiler design, fuel flexibility, higher combustion efficiency, and reduced emission of noxious pollutants such as SOx and NOx). The flue gas needs to be cleaned to meet national emission standards.

Second, fast pyrolysis could treat one quarter of the total feedstock for generation of liquid fuel (i.e., bio-oil). A wide range of reactor configurations have been investigated and operated, which can be grouped into three methods of achieving the fast pyrolysis:, (1) ablative hydrolysis, (2) fluid bed or circulating fluid bed hydrolysis, and (3) vacuum hydrolysis. Among the various reactor configurations, fluid beds are the most popular due to ease of operation and ready scale up as depictured in Figure 2. The by-products of gas and char are utilized to provide processing heat. The characteristics of produced bio-oils vary considerably according to feedstock and pyrolysis process parameters. They are highly oxygenated with a HHV (dry basis) of 22.5 MJ/kg. The bio-oils can be directly burned in the boiler for heat or used in an engine or turbine for electricity.

Third, another quarter of the total feedstock could be gasified in a gasifier to generate syngas. The gasifier has mainly three types: (1) fixed bed (also called moving bed) gasifiers, including down and updraft design; (2) fluidized bed reactors, including bubbling fluidized beds and circulated fluidized beds; and (3) entrained-flow gasifiers. Of these reactor configurations, fluidized beds are most popular because of their multiple advantages: (1) smaller reactor volume due to high heat exchange and reaction rates resulted from intense mixing of the fluidized bed; (2) wider range of acceptable feedstock conditions; (3) more scalable and applicable for large installations; (4) more uniform and narrow temperature profile without hot spots; and (5) higher conversion rates. With minor cleanup, the produced syngas can be directly burned in a boiler for steam/heat generation or a turbine for electricity. The choice of gasifying the medium affects the composition and heating values of the produced syngas. Air, steam, and oxygen are the main gasifying agents used for gasification. Oxygen gasification has the highest heating value, while steam gasification generates a syngas having the highest H/C ratio.

It is worth noting that ThermoChem Recovery International, LLC (TRI) has developed a proprietary biomass gasification process. TRI gasifiers employ a deep steam fluidized bed that is indirectly heated with pulsed combustion heat exchangers (PC heaters) that are fully submerged inside the fluid bed to convert any carbonaceous feedstock, including liquid into high quality syngas (TRI 2015). Since 2003, a TRI gasifier has been in commercial-scale operation, gasifying black liquor from pulp and paper mills in Canada. In addition, TRI has also proved their ability to successfully gasify a wide range of feedstocks (e.g., woody biomass, agricultural residues, refuse derived fuel, lignite, and subbituminous coal) into a consistent and reliable medium-calorific (300 to 350 BTU/ft^3) syngas. Therefore, gasification could provide reliable energy for the P&G facility.

6. SUMMARY

P&G intends to replace much of their current heat and power with renewable energy sources. For 2014, P&G’s total energy, including electricity, natural gas, and steam, is approximately 1,540,000 MMBTU annually. The biomass and waste around the P&G facility can be grouped into six categories: (1) agriculture residue and grass, (2) refuse solid material, (3) food waste, (4) Organic waste stream, (5) livestock manure, and (6) wastewater and sludge. The six feedstock sources can provide a total energy of 3,520,000 MMBTU per year, with agriculture residue being the biggest fraction at about 67%, followed by livestock manure at about 27%. Therefore, the available energy sources around the P&G facility are enough to meet the facility’s energy needs.

These energy feedstocks would be treated by two processes: (1) AD for biogas and for heat and power and (2) thermochemical process (i.e., combustion, pyrolysis, and gasification) for heat and power. For AD, a one-stage complete mixing digester is preferable; fluidized bed reactors are favorable for the thermochemical process.

7. REFERENCES

Appels. L, J. Lauwers, et al., 2011, “Anaerobic digestion in global bioenergy production: potential and research challenges,” *Renewable and Sustainable Energy Reviews* 15: 4295-4301.

Bonner, I., B. Heath, and C. T. Wright, 2015, *Procter & Gamble Bioenergy Resources Assessment*, INL/EXT-15-36570, Idaho National Laboratory.

Bridgewater, A. V., D. Meier, and D. Radlein, 1999, “An overview of fast pyrolysis of biomass,” *Organic Geochemistry* 30: 1479-1493.

Buzby, J. and J. Hyman, 2012, “Total and per capita value of food loss in the United States,” *Food Policy* 37: 561-570.

C2ES, Center for Climate and Energy Solutions, http://www.c2es.org/technology/factsheet/anaerobic-digesters, accessed September 2015.

CalRecycle, 2015, California Department of Resources Recycling and Recovery, http://www.calrecycle.ca.gov/lgcentral/library/dsg/irecycl.htm, accessed at September 2015.

Ciferno, J. P. and J. J. Marano, 2002, "Benchmarking biomass gasification technologies for fuels, chemicals, and hydrogen production," DOE NETL.

Cornell University, 2004, http://www.manuremanagement.cornell.edu/Pages/General_Docs/Fact_Sheets/Codigestion_factsheet.pdf.

EPA AgStar, 2010, "U.S. Anaerobic Digester Status Report," http://www.epa.gov/outreach/agstar/documents/digester_status_report2010.pdf.

IEA, 2010, International Energy Agency, World Primary Energy Supply.

IEA Bioenergy, 2009, "Bioenergy: a sustainable and reliable energy sources; a review of status and prospects," ExCo IEA Bioenergy.

Kamali, M. and Z. Khodaparast, 2015, "Review on recent developments on pulp and paper mill wastewater treatment," *Ecotoxicology and Environmental Safety* 114: 326-342.

Girard M., J.H. Palacios, M. Belzile, S. Godbout, and F. Pelletier, 2013, "Biodegradation in animal manure management", http://cdn.intechopen.com/pdfs-wm/45120.pdf.

Lebrato J., J. L. Perez Rodriguez, C. Maqueda, and E. Morillo, 1990, "Cheese factory wastewater treatment by anaerobic semicontinuous digestion," *Resources Conservation and Recycling* 3: 193-199, http://digital.csic.es/bitstream/10261/62125/1/Cheese%20factory%20wastewater%20treatment%20by%20anaerobic%20semicontinuous%20digestion.pdf.

Leytem, A. B., D. L. Bjorneberg, R. E. Sheffield, and M. E. de Haro, 2009, "Case study: on-farm evaluation of liquid dairy manure application methods to reduce ammonia losses," http://www.extension.uidaho.edu/nutrient/wastemanagement/pdf/ars1343.pdf.

Lipp, B. and C. Schmit, 2013, "Anaerobic respirometery studies of fats, oils and grease," http://www.sdstate.edu/weerc/projects/completed/upload/Anaerobic-Respirometry-Studies-of-FOGs-report.pdf.

Meyer, T. and E. A. Edwards, 2014, "Anaerobic digestion of pulp and paper mill wastewater and sludge," *Water Research* 65: 321-349.

Moriarty, K., 2013, "Feasibility study of anaerobic digestion of food waste in St. Bernard, LA," NREL/TP-7A30-57082.

Statista, 2016, http://www.statista.com/statistics/194962/top-10-us-states-by-number-of-milk-cows/, accessed January 2016.

Sheffield, R. E. and B. Louks, 2007, "Dairy ammonia control practices," http://www.cals.uidaho.edu/edComm/pdf/CIS/CIS1138.pdf.

Themeilis, N. J., M. J. Castaldi, J. Bhatti, and L. Arsova, 2011, "Energy and economic value of non-recycled plastics (NRP) and municipal solid wastes (MSW) that are currently landfilled in the fifty states," Columbia University Earth Engineering Center, http://www.seas.columbia.edu/earth/wtert/sofos/ACC_Final_Report_August23_2011.pdf.

TRI, 2015, "TRI Biomass gasification technology," http://www.tri-inc.net/pdfs/TRI%20How%20It%20Works%20Overview.pdf.

U.S. Census Bureau, 2014, http://quickfacts.census.gov/qfd/states/49/49003.html ; http://quickfacts.census.gov/qfd/states/16/16041.html.

USDA, 2007. "An analysis of energy production costs from anaerobic digestion systems on U.S. livestock production facilities," USDA Natural Resources Conservation Service, Technical Note No.1, October 2007. http://www.agmrc.org/media/cms/manuredigesters_FC5C31F0F7B78.pdf.

USDA, 2012, 2012 Census: County Level Data, http://www.agcensus.usda.gov/Publications/2012/Full_Report/Volume_1,_Chapter_2_County_Level/Utah/st49_2_011_011.pdf.

Zeeman, G. and S. Gerbens, 2011, "CH_4 Emissions from Animal Manure," Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories, http://www.ipcc-nggip.iges.or.jp/public/gp/bgp/4_3_CH4_Animal_Manure.pdf.