PDHonline Course E359 (4 PDH)

Biomass Power Generation

Instructor: Lee Layton, PE

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5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

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Biomass Power Generation

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The photograph on the cover page is of the Surin MGP power plant located in Prasat Surin, Thailand. The 10 MW plant is fueled by rice husks from area farms.

Photograph courtesy of Mungcharoen Green Power Co. Ltd.

Introduction

Biomass energy is the energy from plants and plant derived materials and has been used since people began burning wood to cook food and keep warm. Wood is still the largest biomass energy resource today, but there are other sources of biomass. These include food crops, grassy and woody plants, residues from agriculture or forestry, oil-rich algae, and the organic component of municipal and industrial wastes. Even the methane from landfills can be used as a biomass energy source.

Bio-energy is renewable energy made from any organic material from plants or animals. Sources of bio-energy are called *biomass*, and include agricultural and forestry residues, municipal solid wastes, industrial wastes, and terrestrial and aquatic crops grown solely for energy purposes. Biomass is an attractive petroleum alternative because it is a renewable resource that is more evenly distributed over the Earth's surface than finite energy sources, and may be exploited using more environmentally friendly technologies. Today, biomass resources are used to generate electricity and power, and to produce liquid transportation fuels, such as ethanol and biodiesel. Ethanol is the most widely used liquid transportation fuel, or bio-fuel. Currently, a majority of ethanol is made from corn, but new technologies are being developed to make ethanol from a wide range of agricultural and forestry resources. Ethanol may be used as an alternative fuel, for example, in E-85 for flex fuel vehicles, and may also be used as an octane-boosting, pollution-reducing additive to gasoline.

Biomass can be used for fuels, power production, and products that would otherwise be made from fossil fuels. In such scenarios, biomass can provide an array of benefits. For example:
The use of biomass energy has the potential to greatly reduce greenhouse gas emissions. Burning biomass releases about the same amount of carbon dioxide as burning fossil fuels. However, fossil fuels release carbon dioxide captured by photosynthesis millions of years ago - an essentially "new" greenhouse gas. Biomass, on the other hand, releases carbon dioxide that is largely balanced by the carbon dioxide captured in its own growth.

The use of biomass can reduce dependence on foreign oil because bio-fuels are the only renewable liquid transportation fuels available.

Biomass has played a relatively small role in terms of the overall U.S. energy picture, supplying 5.0 quadrillion BTU of energy out of a total of 101 quadrillion BTU. The majority of it is used in the pulp and paper industries, where residues from production processes are combusted to produce steam and electricity. Industrial cogeneration accounts for almost 3.0 quadrillion BTU of the biomass used in power generation. Outside the pulp and paper industries, only a small amount of biomass is used to produce electricity. There are power plants that combust biomass exclusively to generate electricity and facilities that mix biomass with coal (biomass co-firing plants). About 1.2 quadrillion BTU of biomass is used to generate electricity. The remaining biomass is consumed in residential and commercial applications in the form of wood consumption for heating buildings. To put these numbers in perspective, approximately14 quadrillion BTU of coal and 30 quadrillion BTU of natural gas are consumed to generate electricity.

On a broader scale, biomass currently provides about 10% of the world's primary energy supplies, most being used in developing countries as fuel wood or charcoal for heating and cooking. It is estimated that the world biomass resource potential is over 240 quadrillion BTU's per year. Figure 1 shows the location of the world's biomass. The North American continent has almost 40 quadrillion BTU's of biomass potential.

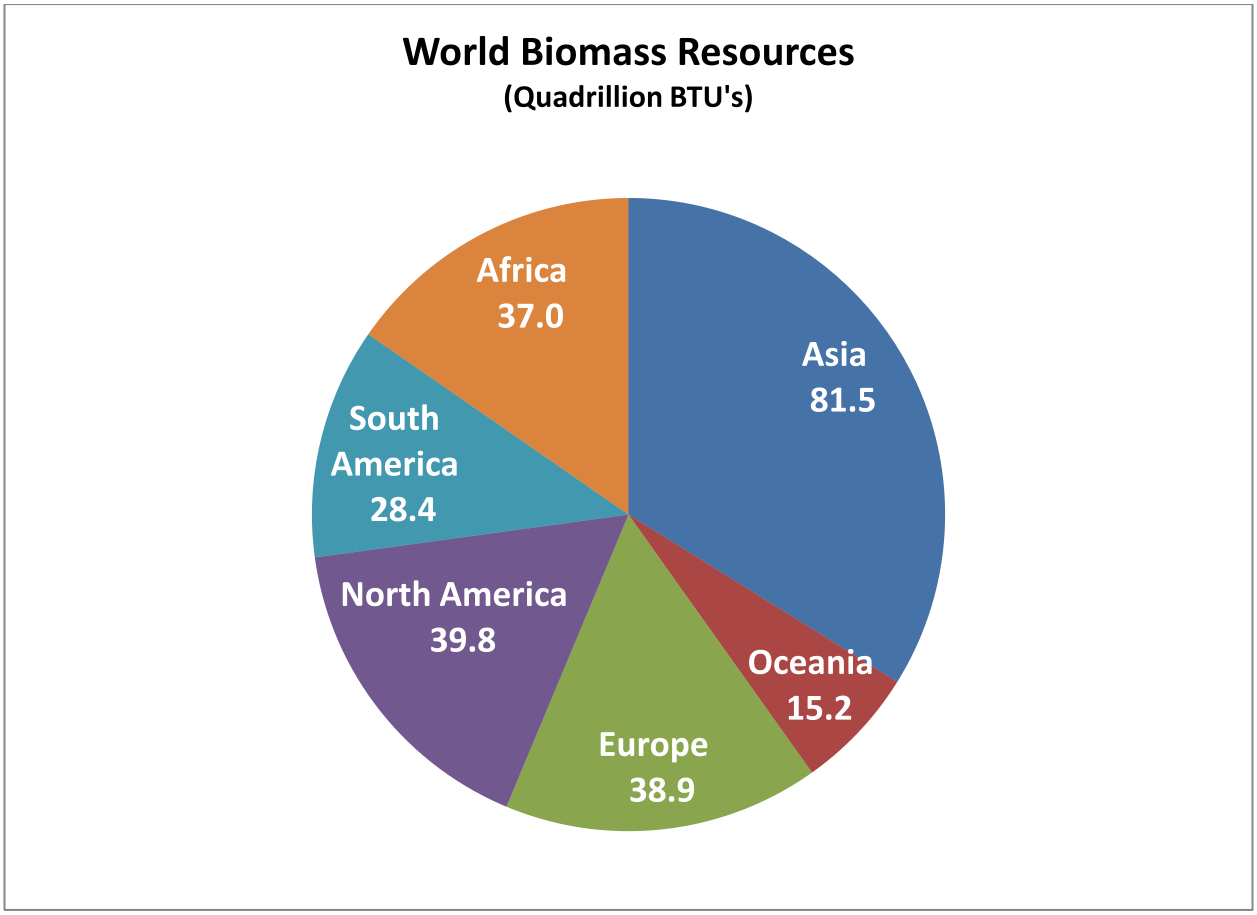


Figure 1

Unlike other renewable energy sources, biomass can be converted directly into liquid fuels, called *bio-fuels*, and are used to help meet transportation fuel needs. The two most common types of bio-fuels in use today are ethanol and biodiesel. Ethanol is an alcohol and is most commonly made by fermenting any biomass high in carbohydrates through a process similar to beer brewing. Ethanol is made from starches and sugars. Ethanol can also be produced by a process called gasification. Gasification systems use high temperatures and a low-oxygen environment to convert biomass into synthesis gas, a mixture of hydrogen and carbon monoxide. The synthesis gas or *syngas* can then be chemically converted into ethanol and other fuels. Ethanol is mostly used as blending agent with gasoline to increase octane and cut down carbon monoxide and other smog-causing emissions. Biodiesel is made by combining alcohol (usually methanol) with vegetable oil, animal fat, or recycled cooking grease. It can be used as an additive to reduce vehicle emissions or in its pure form as a renewable alternative fuel for diesel engines.

In the current environment of low cost fossil fuel supplies biomass power generation may be unable to compete. The inherent cost of power generation from biomass is high for two principal reasons:

1. Biomass is a low-density fuel, so fuel production, handling, and transportation are more expensive than for fossil fuels; and

2. Because of the dispersed nature of the resource, biomass power generating facilities tend to be small, so they cannot capture the economies of scale typical of fossil fuel-fired generating facilities. These characteristics leave biomass generation at a distinct disadvantage in a market that is increasingly driven by cost.

Processes

Bio-power, or biomass power, is the use of biomass to generate electricity. Bio-power system technologies include direct-firing, co-firing, gasification, pyrolysis, and anaerobic digestion. Most bio-power plants use direct-fired systems. They burn biomass feedstocks directly to produce steam. This steam drives a turbine, which turns a generator that converts the power into electricity. In some biomass industries, the spent steam from the power plant is also used for manufacturing processes or to heat buildings. Such combined heat and power systems greatly increase overall energy efficiency. Paper mills, the largest current producers of biomass power, generate electricity or process heat as part of the process for recovering pulping chemicals. Co-firing refers to mixing biomass with fossil fuels in conventional power plants. Coal-fired power plants can use co-firing systems to significantly reduce emissions, especially sulfur dioxide emissions.

Gasification systems use high temperatures and an oxygen-starved environment to convert biomass into synthesis gas, a mixture of hydrogen and carbon monoxide. The synthesis gas, or *syngas*, can then be chemically converted into other fuels or products, burned in a conventional boiler, or used instead of natural gas in a gas turbine. Gas turbines are very much like jet engines, and have high efficiencies. High-efficiency to begin with, they can be made to operate in a *combined cycle*, in which their exhaust gases are used to boil water for steam, a second round of power generation, and even higher efficiency. Using a similar thermo-chemical process but different conditions (totally excluding rather than limiting oxygen, in a simplified sense) will pyrolyze biomass to a liquid rather than gasify it. As with syngas, pyrolysis oil can be burned to generate electricity or used as a chemical source for making fuels, plastics, adhesives, or other bio-products.

The natural decay of biomass under anaerobic conditions produces methane, which can be captured and used for power production. In landfills, wells can be drilled to release the methane from decaying organic matter. Then pipes from each well carry the methane to a central point, where it is filtered and cleaned before burning. This produces electricity and reduces the release of methane (a very potent greenhouse gas) into the atmosphere.

Gasification, anaerobic digestion, and other biomass power technologies can be used in small, modular systems with internal combustion or other generators. These could be helpful for providing electrical power to villages remote from the electrical grid—particularly if they can use the waste heat for crop drying or other local industries. Small, modular systems can also fit well with distributed energy generation systems.

Biomass Fuel or Feedstock

The main biomass feedstocks for power are paper mill residue, lumber mill scrap, and municipal waste. For biomass fuels, the most common feedstocks used today are corn grain (for ethanol) and soybeans (for biodiesel). In the near future agricultural residues such as corn stover and wheat straw will also be used. Long-term plans include growing and using dedicated energy crops, such as fast-growing trees and grasses, and algae. These feedstocks can grow sustainably on land that will not support intensive food crops.

Corn *stover* is the stalks, leaves, and husks of the plant.

Biomass can be purpose-grown as fuel or it can be the byproduct of, or residual from, another process. The advantage of purpose-grown biomass is the stability of supply of biomass fiber and increased efficiency in harvesting the biomass. The main disadvantage of purpose-grown biomass is that it can compete with other uses for the land or the product. For example, using some types of roundwood as a fuel source would take that supply "out of circulation" for the lumber and pulp/paper industries. Using residual biomass is typically less expensive and competes less directly with the primary use for that biomass. This is especially important for agricultural products. However residual biomass, such as corn stover and tree branches, is not always harvested with the primary material, making collection difficult.

Biomass fuel can also be "raw" or pelletized. The process of pelletizing the fuel typically increases the BTU content by removing moisture from the biomass. It also standardizes the fuel's size and shape. However, pelletizing the biomass is typically energy intensive and requires the capital cost of the pellet plant as well as drying and pelletizing equipment.

Biomass Benefits

Because biomass technologies use combustion processes to produce electricity, they can generate electricity at any time, unlike wind and most solar technologies, which only produce when the wind is blowing or sun is shining. Biomass power plants are the second largest amount of renewable energy in the nation. The contribution of biomass power generation is second only to that of hydropower among the renewables to the national energy supply. Biomass has always been used to generate power in the forest products industry, but its widespread use for supplying power to the U.S. grid is a relatively recent phenomenon. Today independent biomass power generators supply 71 billion kWh annually to the national electricity grid.

Energy production from biomass entails emissions during a variety of energy conversion processes, while avoiding the emissions associated with the production of a like amount of energy from fossil fuels. At the same time, disposal in biomass energy facilities avoids the environmental impacts associated with alternative disposal fates for the residues used as fuel, such as landfill burial or open burning. The latter effects constitute the most important source of environmental benefits associated with the production of energy from biomass resources.

In this course we will look at the potential biomass fuel market in detail and discuss the conversion technologies to extract the energy of biomass into electrical energy. Finally, we will look at the environmental issues associated with biomass energy.

Chapter 1
Biomass Feedstock

Biomass resources include agricultural residues; animal manure; wood wastes from forestry and industry; residues from food and paper industries; municipal green wastes; sewage sludge and dedicated energy crops. Dedicated energy crops include three to fifteen year short-rotation coppice, grasses, sugar crops (sugar cane, beet, and sorghum), starch crops (corn, wheat) and oil crops (soy, sunflower, palm oil). Organic wastes and residues have been the major biomass sources, but energy crops are gaining importance and market share. With re-planting, biomass combustion is virtually a carbon-neutral process as the CO_2 emitted has previously been absorbed by the plants from the atmosphere. Residues, wastes, bagasse (sugar cane dry pulp) are primarily used for heat & power generation. Sugar, starch and oil crops are primarily used for fuel production.

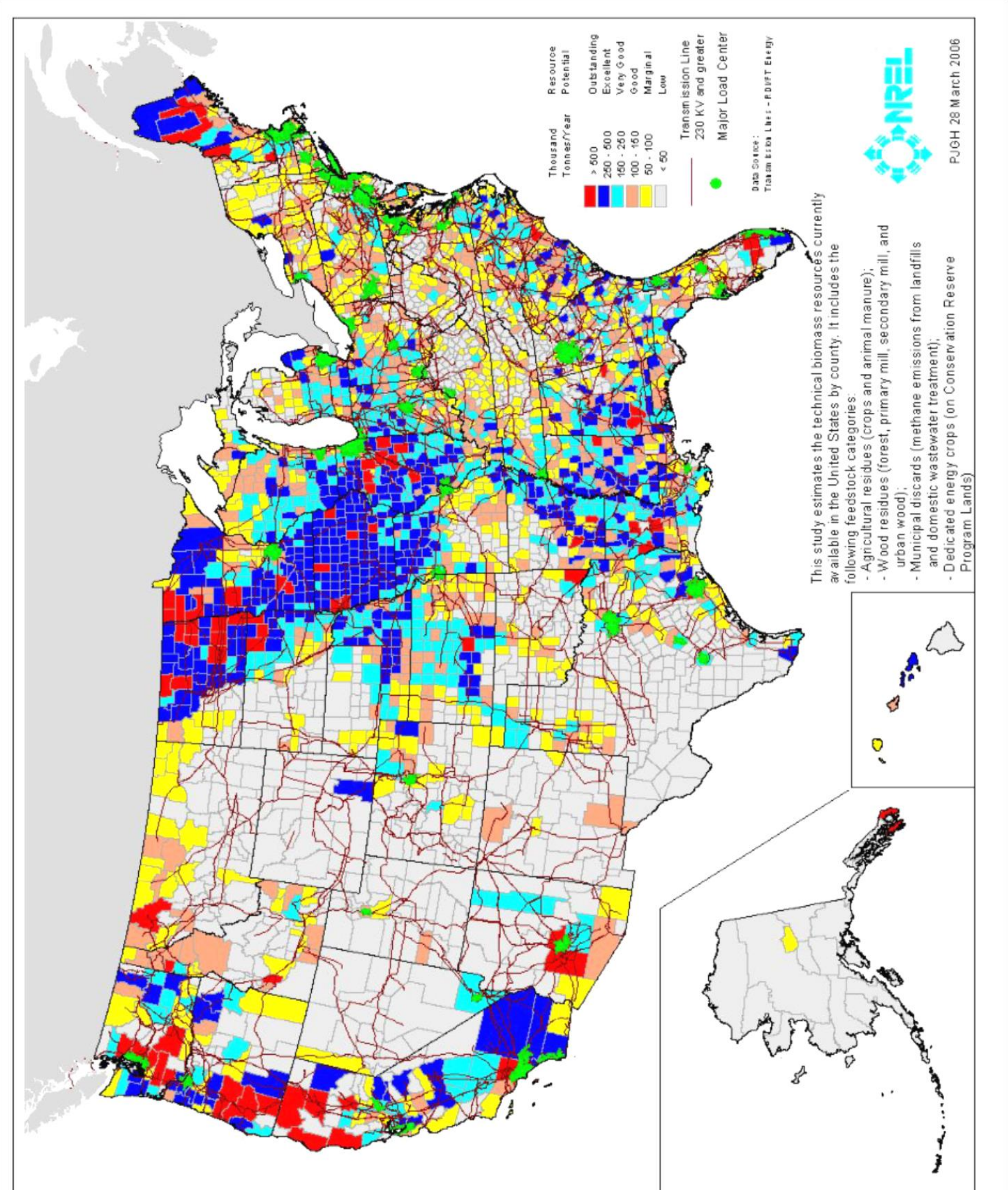
Coppice is small trees such as eucalyptus, poplar, and willow.

Cheap, high-quality biomass (e.g., wood waste) for power generation may become scarce as it is also used for heat production and in the pulp & paper industry. New resources based on energy crops have larger potential but are more expensive. Technologies and cost of power and heat generation from biomass depend on feedstock quality, availability and transportation cost, power plant size, conversion into biogas. If sufficient biomass is available, bio-power and CHP plants are a clean and reliable power source suitable for base-load service.

Estimates of biomass resources show that there is 590 million wet tons of biomass available in the United States on an annual basis. Historically, biomass consumption for energy use has remained at low levels, although it is the largest non-hydroelectric renewable source of electricity in the United States. The main impediment has been the cost of obtaining the feedstock. Of the estimated total resource of 590 million wet tons, only 20 million wet tons - which is enough to supply about 3 gigawatts of capacity - is available at competitive prices for energy production.

Biomass fuels are sometimes reported in terms of green tons, and other times as *bone dry ton* (bdt) equivalents, which is a measure of the fiber content of the material. *Green tons* are used in this text, unless indicated otherwise. A bone dry ton is approximately 54% of a green ton.

Figure 2 on the next page is from an NREL report that shows the biomass potential in the United States from agricultural wastes, forestry and urban wood wastes, municipal wastes (including landfill methane) and energy crops.



This study estimates the technical biomass resources currently available in the United States by county. It includes the following feedstock categories:

- Agricultural residues (crops and animal manure);
- Wood residues (forest, primary mill, secondary mill, and urban wood);
- Municipal discards (methane emissions from landfills and domestic wastewater treatment);
- Dedicated energy crops (on Conservation Reserve Program Lands)

Figure 2

As you can see from Figure 2, the West Coast States have excellent biomass potential. The upper Midwest also has good potential for biomass and to a lesser extent; the Southern States have good biomass potential. New England, with the exception of Maine, has only fair biomass potential. However, Maine has excellent biomass potential. Texas and most of the Western States have poor biomass potential.

Chemical composition

Biomass is carbon, hydrogen and oxygen based. Nitrogen and small quantities of other atoms, including alkali, alkaline earth and heavy metals can be found as well. Some metals, such as magnesium, are also found in biomass. Plants in particular combine water and carbon dioxide into sugar building blocks. The required energy is produced from light via photosynthesis based on chlorophyll. On average, between 0.1% and 1.0% of the available light is stored as chemical energy in plants. The sugar building blocks are the starting point for the major fractions found in all terrestrial plants, lignin, hemicellulose and cellulose.

Feedstock Uncertainties

It is difficult to estimate the amount of biomass feedstock available. Numerous uncertainties exist concerning the availability of biomass feedstock. The uncertainties include,

- The value of competing uses of biomass materials. For example, the mulch market consumes large amounts of waste biomass material. Different qualities of mulch are available at different prices. How much mulch and other biomass-derived materials can be diverted from their current markets into electricity generation and the prices at which such reallocations might take place are not well understood,

- In agricultural waste, the significant uncertainty is in the impact of biomass removal on soil quality. A general consensus in the farming community that more agricultural residues need to be left on the soil to maintain soil quality could result in significant losses of biomass for electric power generation purposes,

- In forestry residues, the unknown factor is the impact of changes in forest fire prevention policies on biomass availability. A policy whereby the vegetation in forests is reduced to minimize the potential for forest fires could significantly increase the quantity of forestry residues available, and

- While the amount of material that is recycled from municipal solid waste streams has steadily grown, it is generally recognized that a significant portion of the municipal solid waste stream is still landfilled. An aggressive attempt to recycle more of the municipal solid waste stream might translate into less available biomass for electricity generation.

Biomass Feedstocks

Feedstock for fuel is compromised of four main categories: agricultural residues, energy crops, forestry residues, and urban wood waste/mill residues. A brief description of each type of biomass is provided below:

- *Agricultural residues* are generated after each harvesting cycle of commodity crops. A portion of the remaining stalks and biomass material left on the ground can be collected and used for energy generation purposes. Wheat straw and corn stover make up the majority of crop residues.

- *Energy crops* are produced solely or primarily for use as feedstocks in energy generation processes. Energy crops include hybrid poplar, hybrid willow, and switchgrass, grown on cropland acres currently cropped, idled, or in pasture.

- *Forestry residues* are the biomass material remaining in forests that have been harvested for timber. Timber harvesting operations do not extract all biomass material, because only timber of certain quality is usable in processing facilities. Therefore, the residual material after a timber harvest is potentially available for energy generation purposes. Forestry residues are composed of logging residues, rough rotten salvageable dead wood, and excess small pole trees.

- *Urban wood waste* is waste woods from manufacturing operations that would otherwise be landfilled. The urban wood waste/mill residue category includes primary mill residues and urban wood such as pallets, construction waste, and demolition debris, which are not otherwise used.

As you can see in Figure 3, agricultural residue is the largest component of the biomass market, with forestry residue as a close second.

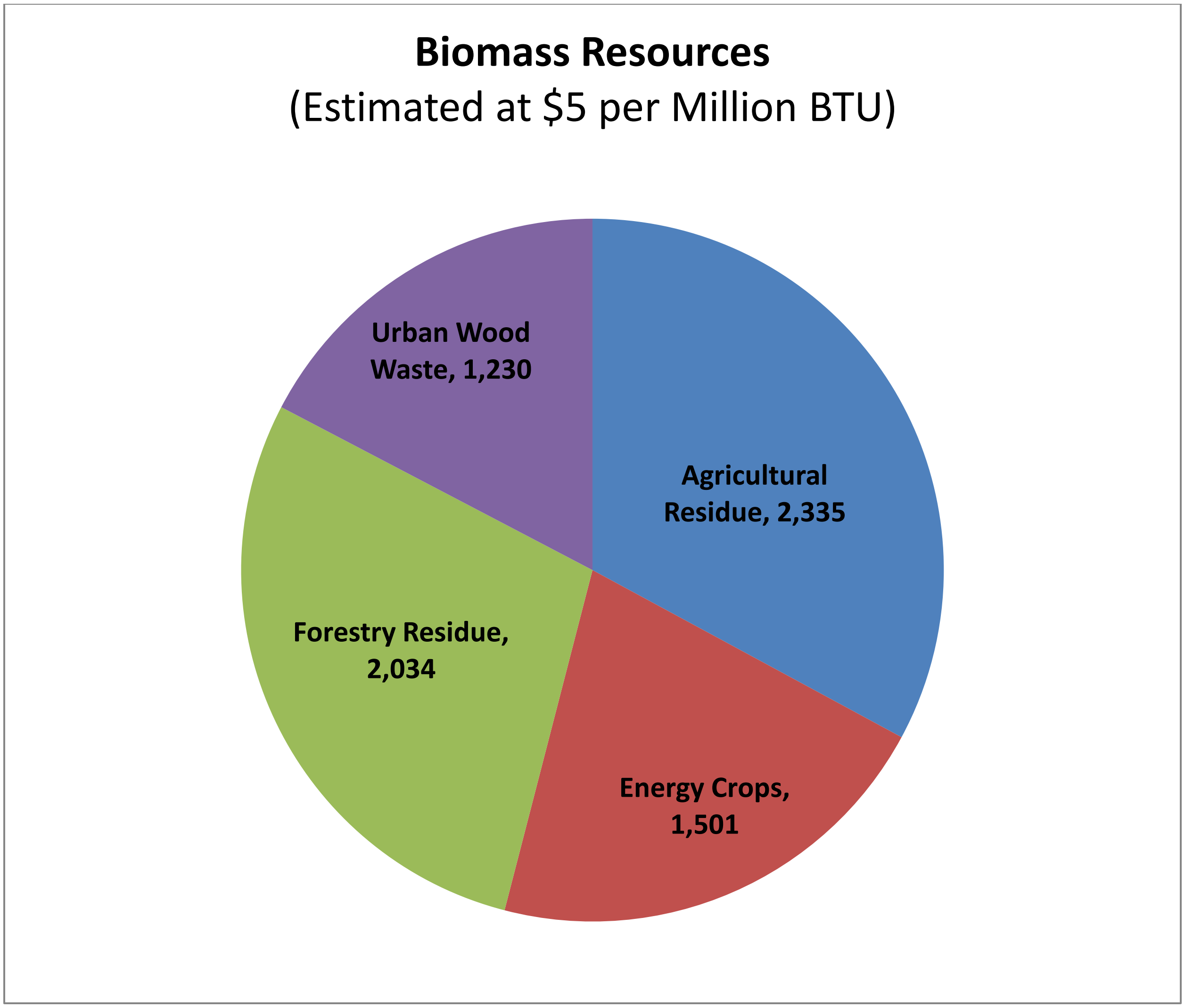


Figure 3

Figure 4 shows the variation in the resource as a function of price. A relatively small portion of the supply is available at $1 per million BTU or less and the supply peaks at around $3-5 per million BTU.

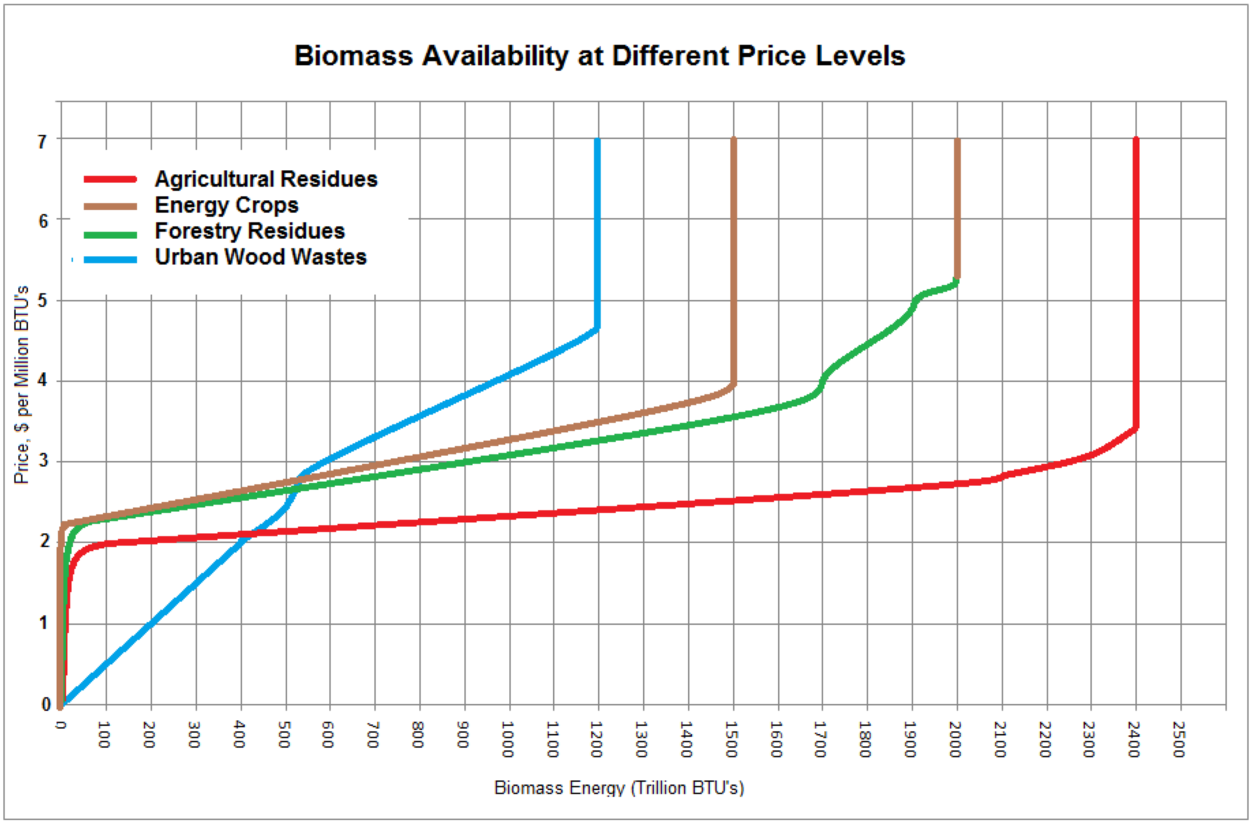


Figure 4

Feedstock cost is a contributing factor that keeps the growth of biomass-based electricity generation at low levels. The available low-cost feedstock (<$1 per million BTU) is almost exclusively urban wood waste. This category of biomass continues to be the only significant resource available at prices up to about $2 per million BTU. At that price level, agricultural residues become viable as a second source of biomass. Energy crops and forestry residues begin to make significant contributions at prices around $2.30 per million BTU or higher.

Table 1 shows the potential electricity production from biomass in both electricity capacity (MW) and energy (MWH). From Table 1 we see that biomass has the potential to generate 1,720,000,000 MWH's of electricity and provide 255,000 MW's of capacity. These figures are based on high load factors that are representative of continuous run plants such as coal-fired power plants.

Table 1
Resource Potential for Biomass For Electricity

Crop	Capacity (MW)	Energy (MWH)
Energy Crops	93,000	584,000,000
Agricultural Residues	114,000	801,000,000
Forest Residues	33,000	231,000,000
Urban Waste	15,000	104,000,000
Total	255,000	1,720,000,000

Agricultural Residue

The underlying assumption behind the agricultural residue is that after each harvesting cycle of agricultural crops, a portion of the stalks can be collected and used for energy production. Agricultural residues cannot be completely extracted, because some of them have to remain in the soil to maintain soil quality. It is assumed that up to 40 percent of the residues could be removed from the soil. In terms of acreage, the most important agricultural commodity crops being planted in the United States are listed in Table 2. Corn, wheat, soybeans, and hay represent the largest share of agricultural crops.

Table 2
Agricultural Crops

Crop	Acres (Millions)
Corn	79.54
Wheat	62.53
Soybeans	74.50
Hay	59.85
Hops	36.12
Cotton	15.54
Grain Sorghum	9.19

Barley	5.84
Oats	4.48
Rice	3.06
Canola	1.51
Rye	1.34

The agricultural residue basically only includes the residues available from corn stover and wheat straws. While this may appear to understate the agricultural residues that are potentially available for energy production, there are compelling reasons for excluding other types of commodity crops. In the case of hay, the whole crop is harvested and fed to livestock; therefore, it is assumed that there would be no useful amount of residue available. In the case of tobacco the whole plant is used, leaving little or no residue. Residue from soybeans is relatively small and tends to deteriorate rapidly in the field, making it unsuitable for collection and energy extraction. Barley, oats, rice, and rye are produced in relatively small geographical areas and thus are not likely to have an impact on the national biomass supply.

Energy Crops

In addition to residue fuels, biomass can be grown specifically for energy purposes. Such fuel will generally be more costly than residues, but much greater quantities can be generated from a given land area, and lands not well suited for crop production (marginal or degraded lands) might be suitable for growing energy crops. Woody crops, which can be harvested as needed and stored more easily after harvesting than herbaceous crops, might supplement seasonal residue fuels, or replace them entirely in the longer term.

Energy crops include hybrid poplar, hybrid willow, and switchgrass. Energy crops are not currently being commercially grown in the United States.

Yields will vary across the country due to differences in weather and soil conditions. The lowest yields are assumed to be in the Northern Plains and the highest in the heart of the Corn Belt, as is the pattern observed with traditional crops. In addition, different varieties of switchgrass, hybrid poplar, and willow are produced in different parts of the country, with different yields.

Switchgrass stands are assumed to remain in production for 10 years before replanting, to be harvested annually, and to be delivered as large round bales. The plants can regenerate, and the same plant can continue to produce switchgrass for up to 10 years. The biomass industry assumes that new switchgrass varieties will be developed and that it will be financially beneficial to plow under the existing switchgrass stand and replant with a new variety. Once established, a switchgrass field could be maintained in perpetuity, but the advantages of new, higher yield varieties would warrant periodic replanting.

Hybrid poplars are planted at a rate of 545 trees per acre and can be harvested after 6, 8, and 10 years of growth in the Pacific Northwest, southern United States, and northern United States, respectively. The product is delivered as whole tree chips.

Willow production is assumed only in the northern United States. Willows are produced in a coppice system with a replant every 22 years. They are planted at a rate of 6,200 trees per acre with first harvest in year 4 and subsequent harvests every 3 years for a total of 7 harvests. Willow is delivered as whole tree chips.

Table 3 shows energy crop yield assumptions.

Table 3
Energy Crop Yield Assumptions

Crop	Dry Tons/Acre
Switchgrass	4.2
Hybrid Poplar	4.4
Willow	4.3

In terms of product quality, hybrid poplar and willow contain about 50 percent moisture when harvested. The trees would typically be fed into a wood chipper. Switchgrass is harvested at about 15 percent moisture, baled, and generally ground in a tub grinder before use.

Switchgrass dominates the biomass supply due to higher average yields and lower average production costs than hybrid poplar or willow.

Forestry Residue

In-forest residues constitute a major source of biomass fuels in the United States. Timber harvesting operations produce forest residues in the forms of slash (tops, limbs, bark, broken pieces) and cull trees.

If left in place these residues are unsightly, impede forest regeneration, and increase the risk of forest fire. Increasingly, harvesting plans on public and private lands require some form of residue management, which usually means either piling and burning, or removal and use as fuel. Logging slash is an important source of biomass fuel.

In addition to logging residues, forest treatment residues (thinnings) comprise an important source of fuel for the biomass energy industry. Vast areas of American forests are overstocked with biomass material, which represents an increased risk of destructive wildfires and a generally degraded functioning of the forest ecosystems. These forests benefit greatly from mechanical thinning operations. The amount of in-forest biomass residues that could be converted to energy is far greater than the total amount of biomass fuel demand in most regions of the country.

However, this fuel source is generally more expensive to produce than other biomass fuels, so the quantity used is less.

The *recoverability factor* is a resource reduction factor that takes into account three site-specific considerations: retrieval efficiency due to technology or equipment, site accessibility or existence of roads, and steepness of slopes.

The distribution of agricultural residues, energy crops, and forestry residues varies considerably. Transportation costs are dependent on distribution and on the quantity needed by a facility. Therefore, the estimation of transportation costs is highly problematic for these resources. For example, the estimated transportation cost for supplying switchgrass to hypothetical facilities varies by 50 percent among facilities of the same size and increases on average by 30 percent when the facility demand changes from 100,000 dry tons per year to 630,000 dry tons per year. Similar or even larger variations can be expected with agricultural residues, because less is removed per acre at harvest, and thus the hauling distances would have to be greater to supply a given quantity of feedstock. There are also regional differences that result from differences in road regulations and labor costs.

Estimating transportation costs for forestry residues is especially difficult, because they vary significantly depending on whether the chips are hauled on primary or secondary roads. There are no national studies that have examined the variations in transportation costs for different feedstocks, different regions, and different facility demands.

Urban Wood Waste

Most of the urban wood waste residues are waste wood from manufacturing operations and wood that would otherwise be landfilled. Urban wood waste is further broken down into wood yard trimmings, construction residues, demolition residues, and other waste wood, including

discarded consumer wood products. The mill residues are further broken down into bark residues and wood residues, both from primary mills.

As much as 20 percent of the solid waste traditionally disposed of in U.S. landfills is clean wood waste that can be segregated and converted into power plant fuel. This material comes from a variety of sources, including:

- Construction and demolition wood waste
- Wood and brush from land clearing
- Wood and brush from public and private tree trimmers and landscapers
- Wood waste from the manufacturing of cabinets, furniture, and other wood products
- Discarded pallets

An important assumption is that urban wood waste will be available only if it is not currently being used for other productive purposes. In other words, it is assumed that if urban wood waste is currently being used for any purpose, it is not be economically attractive to divert it to electricity generation at any price.

Table 4 shows representative characteristics for different subcategories of urban wood waste.

Table 4
Heating Value of Urban Wood Wastes

Urban Wood Wastes	BTU (per Dry Pound)
Bark Residue	8,629
Wood Residue	8,568
Yard Trimmings	8,600
Construction Residues	8,568
Demolition Residues	8,568

The traditional disposal option for urban wood waste is burial in landfills. However, the alternatives that might be used for this material in the future, should the fuels market disappear, are more complicated to project.

Solid waste managers are under pressure to develop diversion applications of all kinds, and at least some of the material currently used as fuel would presumably be diverted into some other outlet, were it not used as fuel. It is assumed that most of the waste wood currently diverted from landfills and converted into biomass fuel would otherwise be buried in the landfills.

Transportation & Handling

Most utilities receive their coal by unit train or by barge; in either case in large quantities. Biomass fuel is much more likely to arrive in smaller quantities from a larger number of suppliers. This will require greater coordination and management at the power plant to efficiently receive the biomass fuel. Railcar blocks will likely be smaller and arrive more frequently. River terminals may have to serve as consolidation points from multiple biomass suppliers. Fuel then would be loaded onto barges and delivered to the utility. Modal options are likely to change as well. Trucks could play a more significant role in biomass fuel transportation than they do with coal, a result of the smaller quantities produced at each location.

Biomass also could require different equipment and unloading infrastructure than most utilities currently use for their coal. Traditional non-torrefied wood pellets, for example, must remain dry, requiring enclosed transport equipment and covered storage. Railcars may have to be covered hoppers instead of the open-top gondolas or hoppers used for coal. Cars will likely be bottom dump with gates instead of doors (as rapid discharge coal cars have today). Trucks will also have to be covered and will either have dumping capability or require a tilt dumping deck at the generating station. Barges will likely have to be covered. So, too, may unloading infrastructure, which also may need to be available for receiving by multiple modes.

Once on-site, many types of biomass, such as traditional wood pellets, will require inside storage. A 100 MW plant could burn an estimated 400,000 tons of biomass pellets annually. A three months' supply will require a 200,000 square foot storage warehouse or ten 10,000-ton silos. If a generating station had units burning both biomass and coal, storage space and infrastructure for each fuel would be required. Other handling equipment, such as conveyors and stacker/re-claimers, may have to be modified or replaced altogether with equipment better suited to the type of biomass fuel selected.

Storage and handling infrastructure also must take into account biomass's high combustibility. This is true for both pelletized and raw biomass. Wood pellets are not as durable as coal and produce more combustible dust. Dust control systems, temperature sensors and fire suppression systems may be required to support safe operations. In storage and handling design, the distances that pellets are dropped either into storage or through the conveying process should be managed to limit pellet damage and dust creation.

Biomass power plant size is often driven by biomass availability in close proximity as transport costs of the (bulky) fuel play a key factor in the plant's economics. It has to be noted, however, that rail and especially shipping on waterways can reduce transport costs significantly, which has led to a global biomass market. To make small plants (less than 1,000 kW) economically profitable the power plants have need to be equipped with technology that is able to convert biomass to useful electricity with high efficiency.

Alternate Fates of Biomass

To account for the nonmarket societal costs and benefits of using biomass residues to produce energy, the impacts associated with energy production have to be compared with the consequences of the alternative fates the residues would experience in the absence of energy production. Thus, these fates must be characterized for the various residues and their associated impacts, as well as for the impacts of energy production, to determine the net environmental implications of biomass energy use.

In many regions of the United States the biomass energy industry has become an integral part of the solid waste disposal infrastructure. If the biomass industry were to fail, finding new disposal outlets for all the biomass residue material currently being used for fuel would be difficult. Identifying the probable alternative fates for these residues is also difficult. The major categories of alternative disposal options for biomass residues include:

- Open burning of agricultural and forestry residues,
- Landfill disposal of waste wood,
- Composting and land application of waste wood,
- Land spreading of wood chips and bark as mulch and cover, and
- In-forest accumulation of residues as downed and over-growth material.

The alternative fates of biomass resources will be discussed in more detail in Chapter 3. But first, let’s look at the technologies to convert Biomass to useful energy.

Chapter 2
Conversion Technologies

There are a number of technology options available to make use of biomass as a renewable energy source. Conversion technologies may release the energy directly, in the form of heat or electricity, or may convert it to another form, such as liquid bio-fuel or combustible biogas.

Torrefaction is a thermo-chemical process that alters the properties of biomass and converts it into a char product with increased energy density, uniformity, and durability.

Heat is the dominant mechanism to convert the biomass into another chemical form. The basic alternatives of combustion, torrefaction, pyrolysis, and gasification are separated principally by the extent to which the chemical reactions involved are allowed to proceed (mainly controlled by the availability of oxygen and conversion temperature). A range of chemical processes may be used to convert biomass into other forms, such as to produce a fuel that is more conveniently used, transported or stored, or to exploit some property of the process itself.

Biochemical conversion makes use of the enzymes of bacteria and other micro-organisms to break down biomass. In most cases micro-organisms are used to perform the conversion process: anaerobic digestion, fermentation and composting.

Biomass combustion is sometimes referred to as a carbon-free process because the resulting CO_2 was previously captured by the plants being combusted. At present, biomass co-firing in modern coal power plants with efficiencies up to 45% is the most cost-effective biomass use for power generation. Due to feedstock availability issues, dedicated biomass plants for combined heat & power (CHP), are typically of smaller size and lower electrical efficiency compared to coal plants (30% using dry biomass, and around 22% for municipal solid waste). Biomass integrated gasification in gas-turbine plants (BIG/GT) is not yet commercial, but integrated gasification combined cycles (IGCC) using black-liquor (a by-product from the pulp & paper industry) are already in use. Anaerobic digestion to produce biogas is expanding in small, off-grid applications.

Because of the variety of feedstocks and processes, costs of bio-power vary widely. Co-firing in existing coal power plants requires limited incremental investment and the electricity cost may be competitive ($20/MWh) if local feedstock is available at low cost. Due to their small size, dedicated biomass power plants are more expensive than coal plants. Electricity costs in cogeneration mode range from $40 to $90/MWh. Electricity cost from new gasification plants is currently around $100-$130/MWh.

There are several ways to produce heat and electricity from biomass:

- **Direct-fired**: Most biomass-based power plants produce combined heat and power in direct-fired systems that burn feedstocks to produce steam, which feeds a turbine that turns a generator. Steam heat is often reclaimed for process or facility uses.

- **Co-firing**: The burning of coal together with biomass feed stocks can supplement energy in high-efficiency boilers while reducing emissions such as sulfur dioxide.

- **Gasification**: These systems convert biomass into a gas using high temperatures in an oxygen-deprived environment. The fuel gas is then burned in a gas turbine combined-cycle system to generate electricity.

- **Pyrolysis**: This destructive distillation process heats dry biomass in an oxygen-deprived environment and rapidly cools it to condense gases into liquid pyrolytic oil, an oxygen-rich, non-petroleum tar that can be burned as a liquid fuel to generate electricity.

- **Anaerobic digestion**: Micro-organisms in an oxygen starved environment break down biomass to release methane, which can be burned to produce steam in boilers or specially designed turbines.

Energy conversion challenges include the variability of biomass fuels, which is very different from that of fossil fuels. For example, paper mill waste may include an uneven mix of bark and wood that may burn unevenly; municipal waste can contain glass and other undesirable materials; and plant-based fuels can be fibrous and difficult to feed.

In general, biomass fuels are less uniform in size, texture, moisture, and BTU content than their fossil fuel counterparts. This variability places heavier demands on operators and requires that processing assets be optimized with a new breed of innovative, application-specific control solutions.

Direct-fired power plants

Most biomass power plants today use direct-fired systems. In dedicated direct-fired biomass operations, the boiler's fuel is 100% biomass which is burned in a conventional steam boiler. The steam is then captured by a turbine and converted to electricity by a generator. The materials used are generally milling and logging residues and energy crops such as fast-growing trees and shrubs. Dedicated biomass plants tend to have lower efficiencies as compared to co-fired coal plants. Biomass plants have heat rates that range from about 12,000 BTU/kWh to over 20,000 BTU/kWh.

Biomass can also be burned to produce electricity in combined heat and power (CHP) plants. The typical size of these plants is ten times smaller (less than 100 MW) than coal-fired plants. The small size roughly doubles the investment cost per kilowatt and results in lower electrical efficiency compared to coal plants. Plant efficiency is around 30% depending on plant size. This technology is used to dispose of large amounts of residues and wastes. Using high-quality wood chips in modern CHP plants with maximum steam temperature of 540C, electrical efficiency can reach 33% (LHV), and up to 40% if operated in electricity-only mode. Fossil energy consumed for bio-power production using forestry and agriculture products can be as low as 2% of the final energy produced.

Net carbon emissions per unit of electricity in CHP systems are below 10% of the emissions from fossil fuel-based electricity. When using MSW, corrosion problems limit the steam temperature and reduce electrical efficiency to around 22%. New CHP plant designs using municipal solid waste (MSW) are expected to reach 30% electrical efficiency, and above 90% overall efficiency in CHP mode if good matching is achieved between heat production and demand.

Incineration of MSW is a mature technology. Emissions of pollutants and dioxin can be effectively controlled, but in many countries, incinerators face public acceptance issues and are seen as competing with waste recycling. Municipal solid waste (MSW) also offers net reduction of CO_2 emissions.

Co-firing

Co-firing substitutes biomass for a portion of coal in an existing power plant furnace, thereby significantly reducing emissions, especially sulfur dioxide emissions. Wood and agricultural residues are burned as a fuel for cogeneration of steam and electricity, mainly in the industrial sector. Because much of the existing power plant equipment can be used without major modifications, co-firing is far less expensive than building a new biomass power plant. For this reason co-firing is the most economic option for introducing new biomass power generation. Biomass is the only renewable energy technology that can directly displace coal use.

Biomass co-firing in modern, large-scale coal power plants is efficient, cost-effective and requires only a moderate additional investment. Even though combustion efficiency of biomass is around 10% less than for coal at the same installation, the co-firing efficiency in large-scale coal plants is higher than the efficiency of direct-fired biomass plants. Co-combustion of up to 10% biomass requires only minor changes in the handling equipment are needed and the boiler is not noticeably de-rated. For biomass exceeding 10% or if biomass and coal are burned separately, then changes in mills, burners and dryers are needed.

Using low-cost local biomass, the incremental investment may have a short payback period (2 years), but low-quality biomass such as wet wood may produce tar and cause slagging and fouling that affects plant reliability and raises costs.

Figure 5, shown below, is a typical coal plant with the addition of a biomass feed line. The biomass section is shown in the lower portion of the drawing. From the biomass storage bin, the biomass is conveyed into a shredder/cutter to reduce the material to the optimum size particles for injection into the furnace. Next the material is dried using waste heat from the turbine. The biomass material then enters silos until being injected into the furnace along with the regular coal supply. The purpose of co-firing is to reduce a portion of the coal supply required to generate electricity.

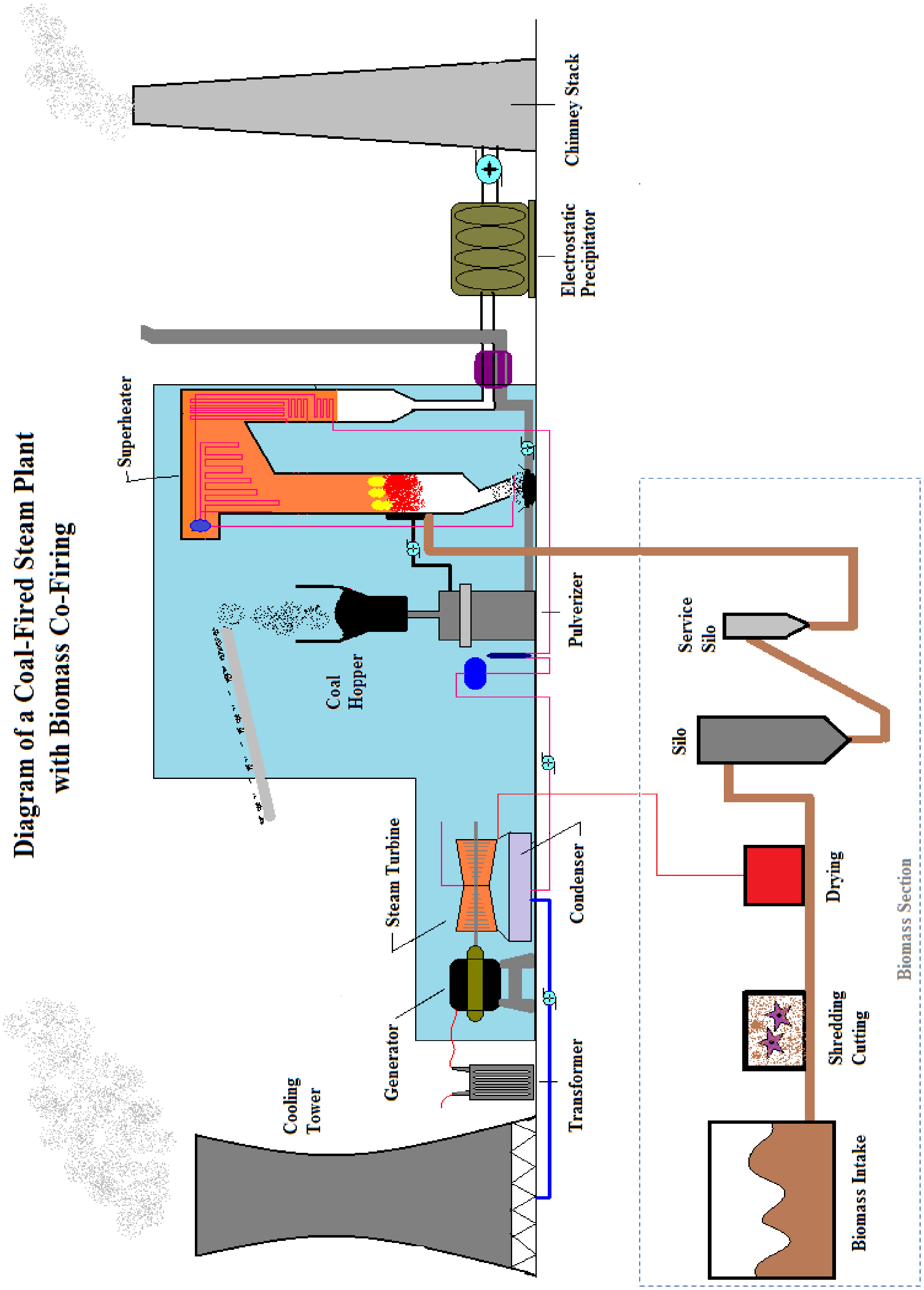


Diagram of a Coal-Fired Steam Plant with Biomass Co-Firing
Cooling Tower
Generator
Steam Turbine
Coal Hopper
Superheater
Transformer
Condenser
Pulverizer
Electrostatic Precipitator
Chimney Stack
Biomass Intake
Shredding Cutting
Drying
Silo
Service Silo
Biomass Section

Figure 5

In the short term, co-firing is expected to remain the most efficient use of biomass for power generation. As electricity from coal represents 40% of worldwide electricity, each percentage point replaced by biomass results in some 8 GW of installed biomass capacity, which reduces CO_2 contributions. This is more than the feasible reduction using small-size, biomass-dedicated power plants with lower efficiency. Co-firing in coal plants can also reduce ash, dust, NOx and SO_2 emissions.

Gasification

Rather than burning biomass directly, gasification, which is a thermo-chemical process, breaks down the feedstock - into its basic chemical constituents. In a modern gasifier, biomass is typically exposed to steam and carefully controlled amounts of air or oxygen under high temperatures and pressures. Under these conditions, molecules break apart, initiating chemical reactions that typically produce a mixture of carbon monoxide, hydrogen and other gaseous compounds.

In the electric power industry, gasification will be combined with a gas turbine. These plants – called Biomass integrated Gasification Gas Turbines (BiG/GT) - are not yet in commercial use, but their economics is expected to improve.

Gasifying biomass to produce a combustible gas provides the possibility for much more efficient overall conversion of a given biomass resource into electric power than is possible with traditional combustion-based technologies. In particular, gasified biomass can be used to power internal combustion engines, gas turbines, and fuel cells, all of which are able to produce electricity at considerably higher efficiency than boiler/steam-turbine systems of comparable size.

Biomass conversion into biogas can be either from fast thermo-chemical processes – called pyrolysis - which can produce biogas and other fuels, with only 2% of ash, or from slow anaerobic fermentation - which converts only a fraction of feedstock but produces soil conditioners as a byproduct. The biogas can be used in small combustion engines with efficiency of 30% to 35%; in gas turbines at higher efficiencies or in highly-efficient combined cycles.

Gasifier Designs

The simplest gasifier design is the *updraft reactor*, named according to the direction of airflow through a packed-bed of reacting biomass. Air is injected at the bottom and biomass enters at the top, from which point it successively undergoes drying, pyrolysis, char gasification and char combustion. The combustion releases heat and carbon dioxide that drive gasification and pyrolysis as the combustion products travel up through the bed. Updraft gasifiers have high energy conversion efficiencies due to the efficient counter-current heat exchange between the rising gases and descending solids. Condensing of pyrolysis tars from updraft gasifiers is problematic in applications where the producer gas must be cooled before it can be used, e.g. in internal combustion engines. Successfully removing tars from the gas before use can significantly penalize overall efficiency, since tars constitute an important fraction of the energy output of the gasifier. Thus, in practical operations, the use of updraft gasifiers has been limited to direct heating applications where no gas cooling is required, such as for producing a fuel that is burned in a "close-coupled" boiler or kiln.

Downdraft gasifiers produce an order of magnitude less tar. In this design, the combustion zone is fixed at the point of air injection, and product gas is drawn out from below. Pyrolysis occurs above and continues within the combustion zone. All pyrolysis products are forced to pass through the hot char gasification zone, where a significant fraction of tar is cracked. In actual field experience it has proved extremely difficult to reduce tar to acceptable levels efficiently and cost-effectively, particularly at small scales. Fairly elaborate and costly gas cleaning systems were recommended for applications where a cool, tar-free gas was needed.

Modified downdraft gasifier designs and gas cleaning systems enable acceptable tar levels to be achieved under commercial operating conditions. One such design is the *open-top reactor*. The most obvious differences between this design and the traditional downdraft gasifier are the open top and the lack of a flow restriction at the "throat," but many differences in details that were identified through theoretical and experimental research, including an understanding of required fuel physical and chemical characteristics, have contributed to the development of this design.

For larger-scale applications, various fluidized bed designs derived from coal gasifiers and combustors are used. The *circulating fluidized-bed* (CFB) is an increasingly popular commercial variant. In a fluidized bed, an inert material, like sand, constitutes the bed into which biomass fuel is continuously fed. Air, oxygen and/or steam are injected from below to keep the bed fluidized. Turbulence leads to excellent heat and mass transfer, producing relatively uniform temperatures throughout and overall faster reactions than in updraft or downdraft reactors. The higher reaction rates lead to higher throughput capabilities per unit volume, and hence lower capital costs per unit of capacity. Fluidized-beds are generally more expensive than fixed-beds at smaller scales due to the high costs for blowers, continuous feed systems, control systems and other instrumentation.

Indirectly-heated gasifiers, designed specifically to take advantage of the higher reactivity of biomass compared to coal, are also being developed. In these designs, biomass is heated by an inert heat-carrying material such as sand or through a heat exchanger. The indirect designs rely on the high reactivity of biomass feedstocks to compensate for the generally lower operating temperatures that can be achieved using indirect heating. A primary attraction of the indirect design is that it produces a much higher energy content product gas than air-blown gasifiers, since there is no nitrogen dilution.

Biomass Gasification Power Plant

A typical BiG/GT power generating system includes three basic elements: a gasifier, gas cooling/cleaning, and the gas turbine. See Figure 6 for the layout of a typical gasification plant. The plant shown in Figure 6 is a biomass integrated gasification plant in conjunction with a combined cycle power plant.

The thermo-chemical processes of gasification include pyrolysis and char conversion. During pyrolysis, the volatile components of the feedstock vaporize at temperatures between about 300C and 600C, leaving behind fixed carbon (char) and ash.

Biomass is high in volatile matter in contrast to coal, so pyrolysis plays a large role in biomass gasification. Products of pyrolysis include carbon dioxide, carbon monoxide, hydrogen, methane, water vapor and complex organic compounds (tars and oils) that condense at high temperatures and can be difficult to decompose ("crack") into lighter permanent gases. In some gasifiers, the tars and oils constitute an important energy component of the product gas. A relatively small amount of char remains after pyrolysis, some of which burns to provide heat for pyrolysis of additional biomass and gasification of the un-combusted char. Since biomass chars react up to 30 times more rapidly than coal chars, biomass gasifiers can typically operate at lower temperatures than coal gasifiers while achieving the same char conversion.

The intended use of the gas, and the particular feedstock to be gasified, influence the design and operation of the gasifier and auxiliary equipment. Cost economies of scale usually permit large-scale systems to be more technologically sophisticated.

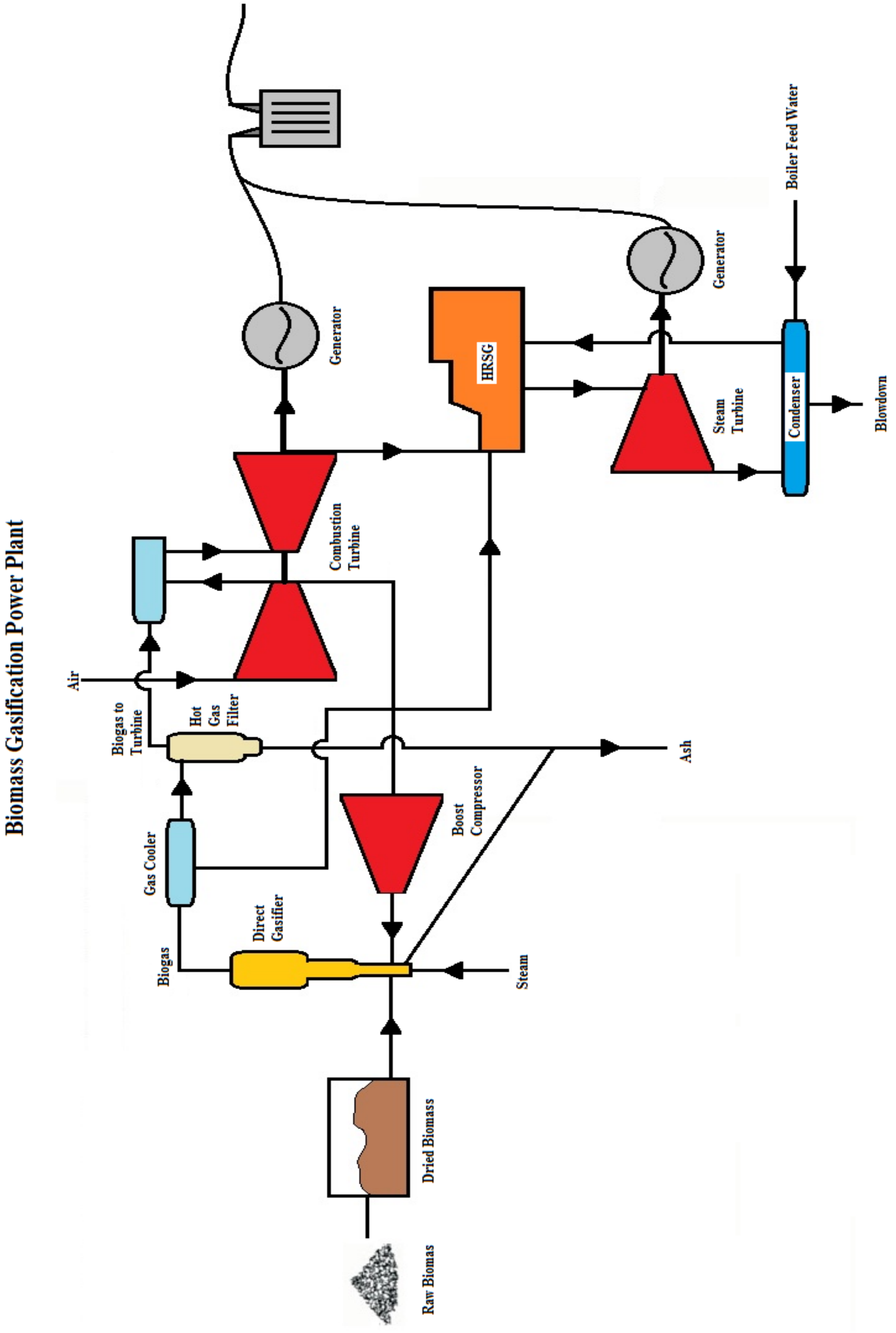

Biomass Gasification Power Plant
Raw Biomas
Dried Biomass
Steam
Direct Gasifier
Biogas
Gas Cooler
Boost Compressor
Hot Gas Filter
Biogas to Turbine
Ash
Air
Combustion Turbine
Generator
HRSG
Steam Turbine
Generator
Condenser
Boiler Feed Water
Blowdown

Figure 6

Gas from the gasifier must be cleaned to avoid contaminant deposition and erosion or corrosion damage to the engine. The gas must also be cooled to increase its density for injection into the engine cylinders. Properly designed and operated, the best commercial gasifiers available today minimize tar production, such that a direct-contact water quench followed by a filtration system for particulate removal can be used. Careful design of the scrubber and filter are critical to ensuring adequate gas cooling and cleaning, as well as ease of maintenance and operation of the cooling/filter system.

Gasified biomass can fuel either diesel or gasoline engines. Diesel engines are favored because of their higher efficiency, greater durability and reliability, simpler maintenance. Commercial diesel engines require only minor modifications to the air intake system so that engine suction draws both air and fuel gas simultaneously. Decreasing air flow with a control valve permits the fuel-air ratio to be adjusted.

A wide variety of biomass feedstocks can be used to fuel BiG/GT systems, but the physical and chemical characteristics (size, texture, moisture content, fixed carbon content, etc.) of the feedstock are important in determining performance. In general, a BiG/GT technology supplier sets feedstock specifications that must be met to insure successful operation, since a gasifier's design and operation varies with the feedstock being used. Commercial BiG/GT systems are available today that will operate on wood chips, maize cobs, cotton stalks, rice hulls, soy husks, coconut shells, palm nut shells, sawdust, and other fuels. Residue fuels, which are available today in most regions of the world, are an attractive fuel source for BiG/GT systems because of their generally low cost.

Anaerobic digestion

The complex process by which organic matter is decomposed by anaerobic bacteria is called *anaerobic digestion*. The decomposition process produces a gaseous byproduct often called biogas, which consists primarily of methane, carbon dioxide, and hydrogen sulfide. It occurs in nature and can be used to produce biogas from biomass in an anaerobic digester.

In the absence of air, organic matter such as animal manures, organic wastes and green energy crops (e.g. grass) can be converted by bacteria-induced fermentation into biogas. This Biogas is a 75% methane-rich gas with CO_2 and a small amount of hydrogen sulphide and ammonia.

Methane (CH_4) is a gas and is the major component of natural gas. It is odorless, colorless, and yields about 1,000 BTU of heat energy per cubic foot when burned. Natural gas is a fossil fuel that was created eons ago by the anaerobic decomposition of organic materials. It is often found in association with oil and coal.

The same types of anaerobic bacteria that produce natural gas also produce methane today. Anaerobic bacteria are some of the oldest forms of life on earth. They evolved before the photosynthesis of green plants released large quantities of oxygen into the atmosphere. Anaerobic bacteria break down or digest organic material in the absence of oxygen and produce "biogas" as a waste product. Aerobic decomposition, or composting, requires large amounts of oxygen and produces heat.

Anaerobic decomposition occurs naturally in swamps, water-logged soils and rice fields, deep bodies of water, and in the digestive systems of termites and large animals. Anaerobic processes can be managed in a digester. The primary benefits of anaerobic digestion are nutrient recycling, waste treatment, and odor control.

Anaerobic digestion is the basic process for landfill gas production from municipal green waste. It has significant potential, but it is characterized by relatively small plant size. Anaerobic digestion is increasingly used in small-size, rural and off-grid applications at the domestic and farm-scale. The rising cost of waste disposal may improve its economic attractiveness.

After purification and upgrading, the resulting biogas can be used in heat plants, stationary engines, fed into the natural gas grid, or used as a transport fuel such as compressed natural gas. Large-size plants using MSW, agricultural wastes and industrial organic wastes need some 8,000 tons of MSW per year per mega-watt of installed capacity.

Biogas produced in anaerobic digesters consists of approximately 80% methane and 20% carbon dioxide, and trace levels of other gases such as hydrogen, carbon monoxide, nitrogen, oxygen, and hydrogen sulfide. The relative percentage of these gases in biogas depends on the feed material and management of the process.

Anaerobic decomposition is a complex process. It occurs in three basic stages as the result of the activity of a variety of microorganisms. Initially, a group of micro-organisms converts organic material to a form that a second group of organisms utilizes to form organic acids. Methane-producing anaerobic bacteria utilize these acids and complete the decomposition process.

See Figure 7 for an overview of an anaerobic digestion plant.

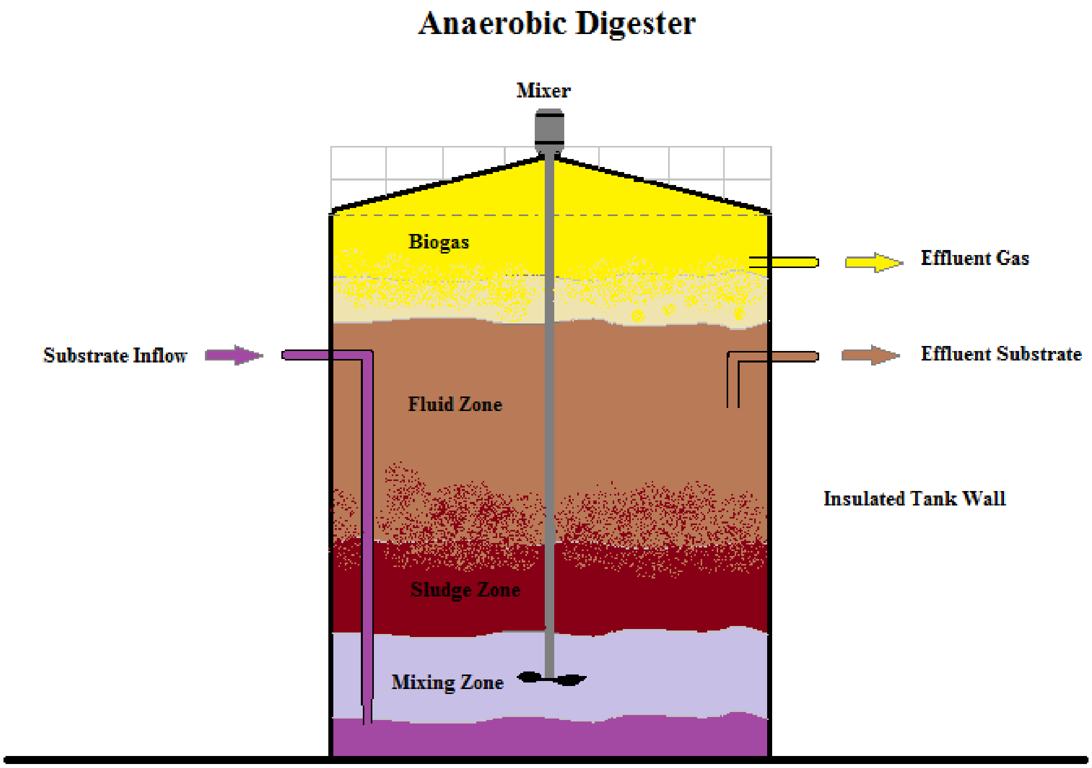


Figure 7

A variety of factors affect the rate of digestion and biogas production. The most important is temperature. Anaerobic bacteria communities can endure temperatures ranging from below freezing to 57C, but they thrive best in the temperature range of about 37C and 54C.

Decomposition and biogas production occur more rapidly in the higher temperature ranges than the lower end of the spectrum. However, the process is highly sensitive to disturbances, such as changes in feed materials or temperature. While all anaerobic digesters reduce weed seeds and disease-producing organisms, the higher temperatures of digestion result in more complete destruction. Although digesters operated in the lower temperature range must be larger (to accommodate a longer period of decomposition within the tank), the process is less sensitive to upset or change in operating regimen.

To optimize the digestion process, the digester must be kept at a consistent temperature, as rapid changes will upset bacterial activity. In most areas of the United States, digestion vessels require some level of insulation and/or heating. Some installations circulate the coolant from their biogas-powered engines in or around the digester to keep it warm, while others burn part of the biogas to heat the digester. In a properly designed system, heating generally results in an increase in biogas production during colder periods. The trade-offs in maintaining optimum digester temperatures to maximize gas production while minimizing expenses are somewhat complex.

Occasional mixing or agitation of the digesting material aids the digestion process. Antibiotics in livestock feed have been known to kill the anaerobic bacteria in digesters. Complete digestion and retention times depend on all of the above factors.

The material drawn from the anaerobic digester is called sludge, or effluent. It is rich in nutrients (ammonia, phosphorus, potassium, and more than a dozen trace elements) and is an excellent soil conditioner. It can also be used as a livestock feed additive when dried. Any toxic compounds (pesticides, etc.) that are in the digester feedstock material may become concentrated in the effluent. Therefore, it is important to test the effluent before using it on a large scale.

Pyrolysis

Pyrolysis is a process similar to gasification. It involves heating the hydrocarbons in a zero oxygen condition. Condensation of the vapors results in bio-oil. The bio-oil can be transported easily. Bio-oil can be combusted in a boiler to produce steam for electricity generation.

Pyrolysis is high temperature (300-700C) material decomposition. Products are solid (charcoal), liquid (oil) or gaseous. Slow pyrolysis produces solid products. Modern fast (flash) pyrolysis at moderate temperature provides up to 80% bio-oil. High temperature is required for gas production.

Pyrolysis offers a way to convert solid biomass into an easily stored and transported liquid which can be used to produce chemicals and fuels. In pyrolysis, the feedstock is subjected to high temperatures in the absence of oxygen and degrades to a mixture of mostly liquid with some gas and solids (char). The liquid, or bio-oil, is rich in carbon and can be upgraded to yield chemical and fuel products.

The process is used heavily in the chemical industry, for example, to produce charcoal, activated carbon, methanol, and to convert biomass into syngas to turn waste into safely disposable substances, and for transforming medium-weight hydrocarbons from oil into lighter ones like gasoline. These specialized uses of pyrolysis may be called various names, such as dry distillation, destructive distillation, or cracking.

Pyrolysis differs from other high-temperature processes like combustion and hydrolysis in that it does not involve reactions with oxygen, water, or any other reagents. In practice, it is not possible to achieve a completely oxygen-free atmosphere. Because some oxygen is present in any pyrolysis system, a small amount of oxidation occurs.

Pyrolyzers are a subset of gasification systems that use either direct or indirect heat generally at a lower temperature range to drive off volatile gases or liquids from the biomass feedstock.

There are physical differences between a gasification and pyrolysis. In general though, processes that operate between 300C and 600C are considered pyrolysis. Processes over 600C are considered gasification. The temperature and time determined the percentage of char, liquid, and gas that is produced.

Figure 8 is an overview of the pyrolysis process. Using this diagram, let’s look briefly at how a pyrolysis system works.

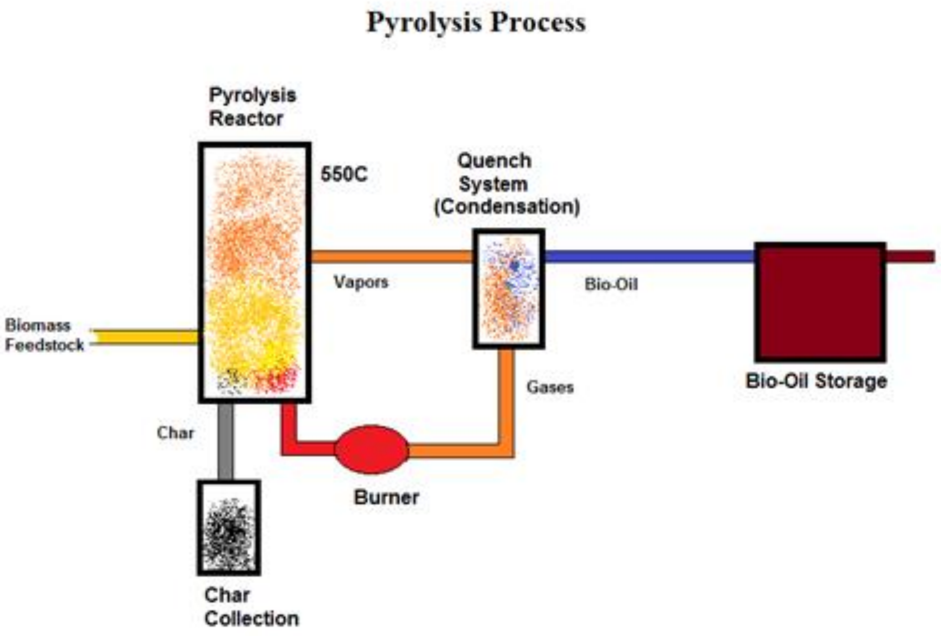


Figure 8

First the biomass feedstock is prepared and feed into a pyrolysis reactor. A burner heats the biomass in the reactor in the absence of oxygen. A by-product of the pyrolysis system is char, which is dropped out of the pyrolysis reactor into a char collection system for disposal. Vapors from the reaction leave the reactor and enter the quench system. Here, through the process of condensation, the vapors are condensed into a bio-oil. Any remaining vapors are fed back to the burner to heat the reactor. The bio-oil that condenses out of the quench system is fed into a bio-oil storage system for later use.

The product of pyrolysis can be a product referred to as bio-oil. Bio-oil can be burned directly in some industrial or commercial boilers or used as a chemical feedstock for higher value products.

It is potentially a competitor to rural biomass power plants in that a high value product can be processed local to a waste wood source and transported in a denser form to other markets.

Processes for biomass pyrolysis

Since pyrolysis is endothermic, various methods to provide heat to the reacting biomass particles can be used:

- One is the partial combustion of the biomass products through air injection. This results in poor-quality products.
- Direct heat transfer with a hot gas, the ideal one being product gas that is reheated and recycled. The problem is to provide enough heat with reasonable gas flow-rates.
- Indirect heat transfer with exchange surfaces (wall, tubes). It is difficult to achieve good heat transfer on both sides of the heat exchange surface.
- Direct heat transfer with circulating solids: Solids transfer heat between a burner and a pyrolysis reactor. This is an effective but complex technology.

There are four types of pyrolytic reactions, which are differentiated by temperature and the processing of residence time of the biomass/waste.

- Conventional or *slow pyrolysis* is characterized by slow biomass heating rates, low temperatures and lengthy gas and solids residence times. Depending on the system, heating rates are about 0.1 to 2C per second and prevailing temperatures are around 500C. Gas residence time may be greater than five seconds. During conventional Pyrolysis, the biomass is slowly devolatillized; hence tar and char are the main by products.
- *Flash pyrolysis* is characterized by moderate temperatures of 400-600C and rapid heating rates greater than 2C per second. Vapor residence times are usually less than two seconds. For flash pyrolysis, the biomass must be ground into fine particles and the insulating char layer that forms at the surface of the reacting particles must be continuously removed.
- The only difference between flash and *fast pyrolysis* - more accurately defined as thermolysis - is heating rates and hence residence times and products derived. Heating rates are 10C per second and the prevailing temperatures are usually higher than 550C. Due to the short vapor residence time, products are high quality, ethylene rich gases that could subsequently be used to produce alcohols or gasoline. The production of char and tar is considerable less during this process. Several reactor configurations have been

shown to assure this condition and to achieve yields of liquid product as high as 75% based on the starting dry biomass weight. Fast pyrolysis of biomass produces a liquid product, pyrolysis oil or bio-oil that can be readily stored and transported. Pyrolysis oil is a renewable liquid fuel and can also be used for production of chemicals.

- *Catalytic pyrolysis* oil consists of a complex mixture of aliphatic and aromatic oxygenates and particulates. It is very viscous, acidic and unstable liquid with relatively low-energy density compared to conventional fossil oil. Such poor quality of the bio-oil requires costly post treatment and makes complete process economically less attractive. Presence of proper catalysts during the pyrolysis process can affect the network of reactions and upgrade the bio-oil. Providing good contact between the solid catalyst and solid biomass/waste is essential to improve the efficiency of pyrolysis process. Lower pyrolysis temperature is crucial maximizing bio-oil yield and quality.

Pyrolysis has the following main advantages over conventional combustion technologies:
The combined heat and power generation via biomass gasification techniques connected to gas-fired engines or gas turbines can achieve significantly higher electrical efficiencies (22% to 37%) compared to biomass combustion technologies with steam generation and standard turbine technology (15% to 18%). Using the produced gas in fuel cells for power generation can achieve an even higher overall electrical efficiency in the range of 25% to 50%, even in small scale biomass pyrolysis plants and during partial load operation.

The improved electrical efficiency of the energy conversion via pyrolysis naturally means that the potential reduction in CO_2 is greater than with combustion. The formation of NO_x compounds can also be greatly reduced and the removal of pollutants is generally in most cases. The NO_x advantages, however, may be partly lost if the gas is consumed in gas-fired engines or gas turbines. Significantly lower emissions of NO_x, CO and hydrocarbons can be expected when the gas is used in fuel cells instead of using it in gas-fired engines or gas turbines.

Chapter 3
Environmental issues with Biomass Power

Bio-energy is considered truly renewable because its source - biomass - is a replenishable resource. Vegetation will continue to grow as long as it is planted. Additionally, biomass energy recycles carbon dioxide during the plant photosynthesis process and uses it to make its own food. In comparison to fossil fuels such as natural gas and coal, which take millions of years to be produced, biomass is easy to grow, collect, utilize and replace quickly without depleting natural resources. Bio-energy is not only renewable, but is also sustainable.

There are both environmental benefits and hazards associated with biomass power. There are also issues with doing nothing because much of the biomass is waste that must be dealt with. In this chapter we discuss the benefits, risks, and alternatives for biomass.

Environmental Benefits of Biomass Power

The production of electricity in biomass power plants helps reduce air pollution by displacing the production of power using conventional sources. The marginal generating source displaced by biomass generation in most cases in the United States is either natural gas-fired power generation or coal-fired power generation. The full net emissions reductions associated with biomass power generation can be calculated as the difference between the net emissions associated with the biomass power cycle alone, and those that would be produced by fossil fuel-based generation, which would be used if the biomass-generated power were not available.

Compared with coal, biomass feedstocks have lower levels of sulfur or sulfur compounds. Therefore, substitution of biomass for coal in power plants has the effect of reducing sulfur dioxide (SO_2) emissions. Biomass co-firing with coal can also lead to lower nitrogen oxide (NO_x) emissions. Perhaps the most significant environmental benefit of biomass, however, is a potential reduction in carbon dioxide (CO_2) emissions.

Although biomass-based generation is assumed to yield no net emissions of CO_2 because of the sequestration of biomass during the planting cycle, there are environmental impacts. Wood contains sulfur and nitrogen, which produce SO_2 and NO_x in the combustion process. However, the rate of emissions is significantly lower than that of coal-based generation. For example, per kilowatt-hour generated, biomass integrated gasification combined-cycle (BiG/CC) generating plants can significantly reduce particulate emissions (by a factor of 4.5) in comparison with coal-based electricity generation processes. NO_x emissions can be reduced by a factor of about six for dedicated BiG/CC plants compared with average pulverized coal-fired plants.

Despite harvesting, biomass crops may sequester carbon. For example, soil organic carbon has been observed to be greater in switchgrass stands than in cultivated cropland soil, especially at depths below 12 inches. The grass sequesters the carbon in its increased root biomass. Typically, perennial crops sequester much more carbon than annual crops due to much greater non-harvested living biomass, both living and dead, built up over years, and much less soil disruption in cultivation.

Greenhouse gas (GHG) emissions will decrease dramatically as bio-fuels of the future are increasingly made from cellulosic feedstocks and as the associated farming, harvesting, transport, and production processes use progressively cleaner, renewable energy sources. Cellulosic ethanol has the potential to reduce GHG emissions by up to 86%.

Environmental Concerns with Biomass Power

If biomass is utilized in a closed-loop process, the entire process (planting, harvesting, transportation, and conversion to electricity) can be considered to be a small but positive net emitter of CO_2. It is not precisely a net zero emission process in a life-cycle sense, because there are CO_2 emissions associated with the harvesting, transportation, and feed preparation operations (such as moisture reduction, size reduction, and removal of impurities). However, those emissions are not the result of combustion of biomass but result instead from fuel consumption (mostly petroleum and natural gas) for harvesting, transportation, and feed preparation operations.

A ***closed-loop process*** is defined as a process in which power is generated using feedstocks that are grown specifically for the purpose of energy production.

Combustion of biomass fuels in modern power plants leads to many of the same kinds of emissions as the combustion of fossil fuels; including criteria air pollutants, greenhouse gases, and solid wastes (ash).

Fuel processing, which in most cases involves some type of grinding operation, produces emissions of dust and particulates. Air emissions and water consumption are usually the principal sources of environmental concern related to biomass facilities.

NOx, hydrocarbons, and CO are usually controlled by using advanced combustion technologies, often including fluidized-bed combustors, staged-combustion, and flue-gas recirculation. Some of the newest biomass power facilities are required to use ammonia injection to further control NOx emissions. SOx emissions generally are not a concern with biomass combustion because biomass, especially woody forms of biomass, has very low sulfur content. Some facilities that have fluidized-bed combustors inject limestone to capture sulfur, but no biomass facilities are required to have flue-gas scrubbers to control SOx emissions.

Particulates are controlled using a variety of technologies. Virtually all biomass power plants use cyclones to remove most large particulates from the flue gas. Most biomass facilities are equipped with electrostatic precipitators for final particulate removal; some facilities use baghouses. Most modern biomass power plants are required to achieve zero visible emissions to meet environmental permit conditions. Their emissions of total and sub-micron particulates are also regulated and controlled to stringent levels, comparable to or better than the emissions levels achieved by the large fossil fuel power plants operated by the electric utility companies.

The type of combustor plays a large part in the overall impact of biomass power. The fluidized-bed combustors achieve lower emissions levels of all criteria pollutants of concern for biomass power plants, compared to the grate burners. The most dramatic difference is in CO emissions, for which the fluidized-bed combustors are more than an order of magnitude better than the grate-burners. The fluidized-bed combustors achieve emissions factors of half or less than the grate-burners for all pollutants for which data are available.

Black carbon - a pollutant created by incomplete combustion of fossil fuels, bio-fuels, and biomass - is possibly the second largest contributor to global warming. Carbon monoxide in the atmosphere has a greenhouse gas warming potential roughly equal to that of CO_2, and in fact the ultimate fate of atmospheric CO is oxidation to CO_2. Thus, at a minimum, the value of CO emissions is equivalent, on a per-carbon basis, to the value assumed for CO_2 emissions.

On combustion, the carbon from biomass is released into the atmosphere as carbon dioxide (CO_2). The amount of carbon stored in dry wood is approximately 50% by weight. When from agricultural sources, plant matter used as a fuel can be replaced by planting for new growth. When the biomass is from forests, the time to recapture the carbon stored is generally longer, and the carbon storage capacity of the forest may be reduced overall if destructive forestry techniques are employed.

Intact forests sequester carbon more effectively than cut-over areas. When a tree’s carbon is released into the atmosphere in a single pulse, it contributes to climate change much more than woodland timber rotting slowly over decades. Current studies indicate that "even after 50 years the forest has not recovered to its initial carbon storage" and "the optimal strategy is likely to be protection of the standing forest".

Environmental Impacts of Disposal Alternatives

All alternatives for the disposal of biomass wastes and residues, including leaving forest residues in place, entail environmental impacts. Energy production from biomass residues produces air pollutants and solid waste (ash), and consumes water resources. These impacts must be balanced against those impacts that would occur if the energy alternative were not available, including the impacts of alternate disposal of the material used as fuel, and the impacts of alternative production of the electricity that must be supplied to the market.

Open burning of forestry and agricultural biomass residues is a major source of air pollution. Open burning produces massive amounts of visible smoke and particulates, and significant quantities of emissions of nitrogen oxides (NOx), carbon monoxide (CO), and hydrocarbons that contribute to the formation of atmospheric ozone. Nevertheless, use of these residues as power plant fuel vastly reduces the smoke and particulate emissions associated with their disposal, and significantly reduces the amounts of CO, NOx, and hydrocarbons released to the atmosphere.

The biomass power industry helps eliminate open burning of agricultural residues. To give the biomass power producers credit for the air quality benefits they provide, some regulators have developed a set of agricultural offset protocols, through which facilities that burn agricultural residues that would otherwise be open burned earn an offset for their emissions of pollutants at the power plant. For most facilities that were permitted on the basis of the agricultural offset protocols, the permits require that one-half to two-thirds of their fuel be obtained from agricultural residue sources.

Burial, spreading and composting, and in-forest accumulation are the principal fates of biomass products if they are not used as an energy source.

Environmental Impacts of Burial

Recoverable wood waste represents approximately 15% (by weight) of the material that typically enters landfills. All these materials enter the landfill gate separate from mixed household garbage.

Separable wood residues enter the landfill in debris boxes, roll-off bins, vans, and pickup trucks. In the absence of a fuel-use option, they are buried along with other wastes entering the landfill gate. Some landfills segregate and shred inbound waste wood to use as daily landfill cover or for other applications, but this represents a small fraction of the total recoverable resource, and these applications would be unlikely to expand significantly if the fuel market collapsed. Indeed, there is reason to believe that nonfuel applications would actually decline if the fuel market collapsed, because the production of these products in most cases depends on the coproduction of fuel, and loss of the fuel market would render production of the other products less viable.

Landfill burial of the wood residues that can be recovered and converted into power plant fuel entails the same kinds of environmental impacts associated with the disposal of all kinds of organic wastes in landfills. Compared to other types of organic wastes, woody materials are slow to degrade, which means that landfill stabilization is delayed. Like all organic material in the landfill, waste wood can be a source of water-polluting leachates, and as the material degrades, it produces emissions of CH_4 and CO_2 in roughly equal quantities. Methane and CO_2 are both greenhouse gases, but CH_4 is much more reactive, by a factor of some 25 times per unit of carbon, so emissions of the residue-bound carbon in the form of a 50:50 mix of CH_4 and CO_2, rather than as pure CO_2, are far more damaging from the perspective of greenhouse gas buildup in the atmosphere.

Large landfills are now required by to collect a portion of the landfill gas and flare it. In general, gas collection systems capture about 80% of the CH_4 released by the landfill, which means that final emissions of the waste carbon to the atmosphere are approximately 90% CO_2 and 10% CH_4. Emitting the carbon in the 90:10 mixture of CO_2 and CH_4 results in an effective greenhouse gas emission 3.4 times more potent than emissions of the same amount of carbon in the form of 100% CO_2. For uncontrolled landfills, the 50:50 mixture of the gases emitted leads to an effective greenhouse gas emission 13 times more potent than emissions of the same amount of carbon in the form of 100% CO_2. The only effective means of eliminating CH_4 emissions from the disposal of wood residues that would otherwise be buried in a landfill is to use the material as fuel.

Use of waste wood as a fuel results in immediate emissions of CO_2; burial of the material in a landfill results in delayed emissions of CO_2 and CH_4. Wood waste decays slowly in the landfill environment, so emissions of most ultimate landfill gases are significantly delayed. The immediate result of diverting landfill-bound waste wood to a power plant is that virtually all the carbon content is added to the atmospheric stock of CO_2, rather than being stored underground as buried waste. This means that the atmospheric greenhouse gas burden associated with the biomass residue used as fuel is greater in the immediate aftermath of its combustion than if the material were landfilled. Over time, however, the landfill out-gases a mixture of CH_4 and CO_2, and the much greater radiative effectiveness of CH_4 rapidly leads to a greater greenhouse gas burden, which eventually becomes a major liability for the landfill option, even with the use of gas-control systems on landfills.

Environmental Impacts of Spreading and Composting

An alternative disposal option to landfilling biomass wastes is surface spreading, which can be done with or without prior composting of the material. Bark and wood chips can be used directly for mulch, which usually consists of open spreading of the untreated material. Biomass can also be composted before spreading, although woody material is not ideal for composting, because it breaks down more slowly than other types of biomass residues, such as residential green waste.

Composting of biomass residues accelerates the natural decomposition process. Decomposition occurs through aerobic and anaerobic pathways, producing a mixture of CO_2 and CH_4 emissions. In a well-managed compost operation the emissions are primarily CO_2, because of frequent aeration of the material. The compost product, which contains approximately 50% of the original biomass carbon, is then spread, where it continues to decompose, although no longer at an accelerated pace.

Environmental Impacts of In-Forest Accumulation

All forests are prone to periodic fires. However, the natural fire cycle has been altered in the United States by past forestry practices, by vigorous fire suppression efforts, and by increasing populations in wooded areas. These phenomena have increased the amount of fuel loading and degraded forest health and productivity.

The fuel building up in the nation's forests includes standing dead and diseased wood, downed woody material of all varieties, and an overall increase in the density of the forest growing stock. The accumulation of dead and diseased wood, both standing and downed, is particularly problematic from a forest fire risk perspective because it usually has a lower moisture content than growing stock, making it easier to ignite, hotter burning, and more prone to spreading of fire. As the fuel loading continues to increase, fires that burn out of control tend to be much more severe and destructive than the naturally occurring periodic fires that were a component of the pre-industrial ecosystem. They burn much hotter than the traditional fires, and consume much larger areas with more extensive destruction.

Fuel overloading also contributes to the degradation of the health and ecosystem functioning of forests and watersheds. For example, healthy, relatively undisturbed forest ecosystems have approximately a 40% level of canopy closure, whereas other forests have an approximately 65% or more canopy closure level. This elevated level means that the amount of available rainfall that enters the evapo-transpiration cycle is higher than in the native ecosystem, and less of the rainfall moves through the watershed as runoff and groundwater. Reduced flows of runoff and groundwater mean that less water is transferred to the meadows and lowlands, where water is stored during the rainy season and released gradually during the dry season. The net result of this chain of events is that useful water production from many watersheds is lower than if the forests were in a more natural condition.

Summary

Biomass is a renewable resource that allows us to generate electricity from both waste products and purpose grown crops. If forecasted levels of biomass potential are going to be achieved, a variety of wood and agricultural biomass sources will be required to meet anticipated demand. And a supply of purpose-grown biomass sources will be needed as residuals alone will not be sufficient.

Because biomass technologies use combustion processes to produce electricity, they can generate electricity at any time, unlike wind and most solar technologies, which only produce when the wind is blowing or sun is shining. Biomass power plants are the second largest amount of renewable energy in the nation.

Energy production from biomass entails emissions during a variety of energy conversion processes, while avoiding the emissions associated with the production of a like amount of energy from fossil fuels. At the same time, disposal in biomass energy facilities avoids the environmental impacts associated with alternative disposal fates for the residues used as fuel, such as landfill burial or open burning.

One major problem with the biomass industry is that the supply chain just doesn't exist. There is not a coherent market to collect, transport, and consume biomass material. The current biomass market is localized - and may always be - because of the cost of transporting biomass to a power plant. Storage is also an issue. Another issue is the quality of the biomass fuel itself varies widely.

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