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Bioenergy and Greenhouse Gases

Gregg Morris

Green Power Institute

The Renewable Energy Program of the Pacific Institute

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Executive Summary

Bioenergy and Greenhouse Gases (April, 2008)

The greenhouse-gas implications of energy production from biomass are more complex and subtle than the greenhouse-gas implications of energy production from other energy resources. Energy production from fossil fuels removes carbon from geological storage and adds it to the atmosphere. Energy production from non-bioenergy renewables and other non-fossil sources produces energy without significant greenhouse-gas emissions. While biofuels are carbon-based fuels, the carbon in biofuels is already part of the active global carbon cycle, in which carbon exchanges rapidly between the atmosphere and the biosphere. Bioenergy production does not add new carbon to the active carbon cycle, but it can affect global greenhouse-gas levels in some important ways.

Key Findings

Carbon Neutral and Beyond

The greenhouse-gas emissions produced at biomass and biogas generating facilities comes from carbon that is already a part of the linked atmospheric – biospheric carbon cycle. This is in stark contrast to fossil fuel combustion, which removes carbon from permanent geologic storage, and adds it as net new carbon to the carbon already in the atmospheric – biospheric circulation system. Most people focus on this aspect of bioenergy production, and proclaim it to be “Carbon Neutral.”

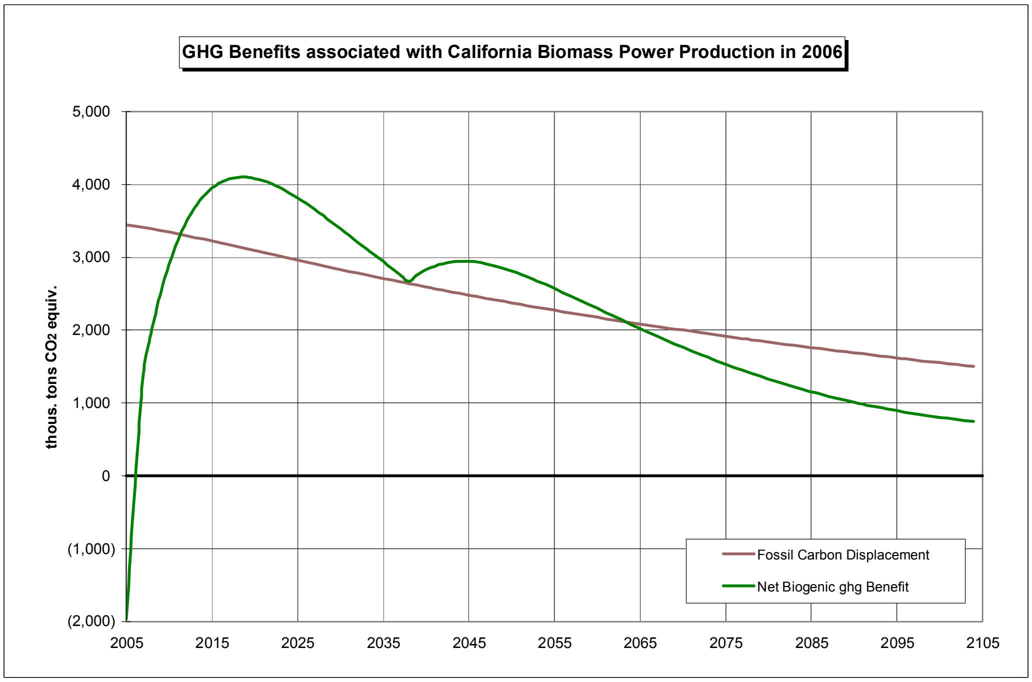
In addition to being carbon neutral, biomass energy production can affect atmospheric greenhouse-gas concentrations in two important ways. First, the total amount of carbon that is sequestered in terrestrial biomass affects the amount of carbon in the atmosphere. Energy production from forest fuels contributes to forest health and fire resiliency, thereby increasing the amount of carbon that is stored on a sustainable basis in the earth’s forests. Second, biomass energy production can change the timing and relative mix (oxidized vs. reduced) of carbon forms emitted into the atmosphere associated with the disposal or disposition of the biomass resources. As a greenhouse-gas, reduced carbon (CH_4) is twenty-five times more potent than oxidized carbon (CO_2) on an instantaneous, per-carbon basis. Therefore the form in which carbon is transferred from the biomass stock to the atmospheric stock is critically important from the standpoint of greenhouse forcing impact.

Alternative Fates

Most of the biomass and biogas resources that are converted to energy would otherwise be open burned, buried, or allowed to accumulate in forests as overgrowth material. Compared to combustion in a controlled boiler, open burning entails poor combustion conditions, and gives rise to significant emissions of carbon in reduced form (methane and hydrocarbons). This elevates the greenhouse-gas potency of the emissions. Biomass burial in a landfill or agricultural field leads to even greater emissions of reduced carbon than open burning. Although the emissions from landfills are delayed, the greenhouse-gas potency of the emissions over the long term is much greater. Overgrown forests tend to be unhealthy, and have heightened sensitivity to fire losses, disease, and pest attacks. Biomass power production can offset some of the costs of forest treatments by paying for the residue removals, in the process promoting better and more extensive forestry management. Although the immediate consequence of forest treatment is to reduce the amount of standing biomass in the treated forest, in the long term the sustainable biomass stocking on the land is enhanced.

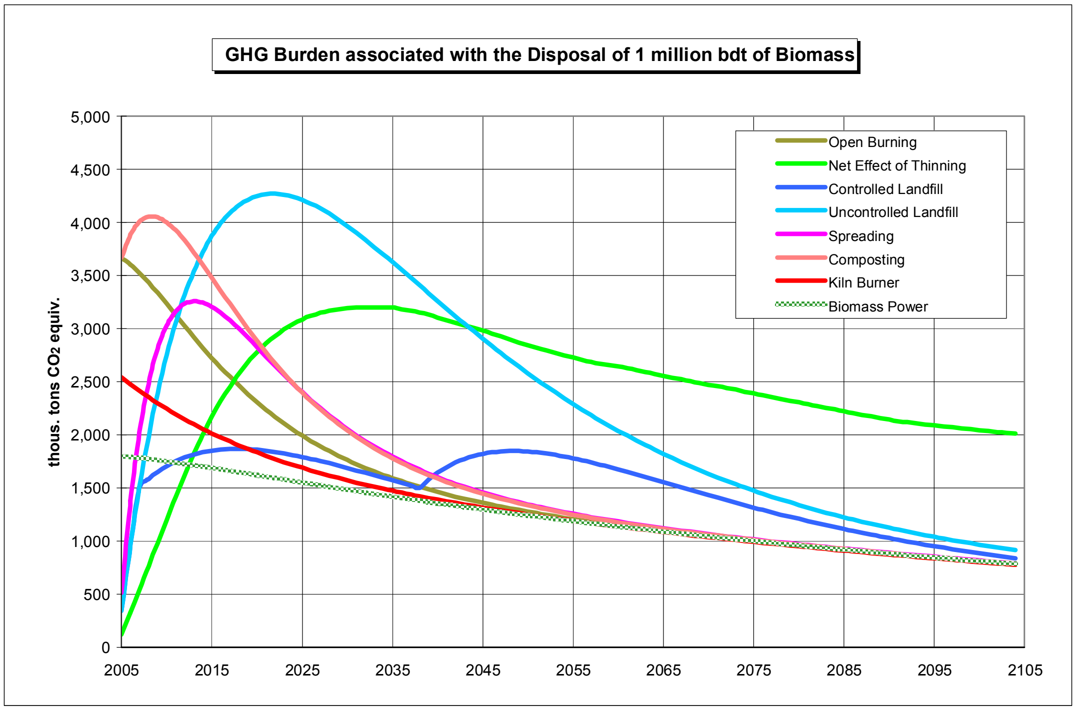
Energy Production from Biomass and Biogas Resources

Bioenergy production provides two kinds of greenhouse-gas benefits. Like all renewable energy generation, bioenergy production avoids the production of an equivalent amount of energy from fossil fuels. In addition, bioenergy production avoids the biogenic greenhouse-gas emissions of the various alternative disposal fates for the residue and waste biomass, replacing them with the lower potency greenhouse-gas emissions of energy production. The figure below shows the long-term atmospheric greenhouse-gas benefits with respect to both the avoided fossil and reduced biogenic greenhouse-gas emissions provided by the operations of the California biomass energy industry during calendar-year 2006. The figure shows the benefits, in terms of long-term atmospheric greenhouse-gas burdens resulting from the industry's 2006 operations. The avoided fossil-carbon emissions, about 3.5 million tons, all occur during 2006. The atmospheric burden of this carbon gradually diminishes over time. All of the emissions of biomass



energy production, and some of the avoided emissions of the avoided alternative disposal of the biomass, also occur during 2006, but some of the emissions of alternative disposal are delayed. Although the shapes of the curves are different, the reduction of the concentration of atmospheric greenhouse-gases due to avoided fossil fuel use and reduced biogenic emissions is approximately the same over the long term. It should be noted that the curves do not account for the qualitative difference between fossil and biogenic emissions, which is that fossil carbon emissions increase the amount of carbon in the active carbon cycle, while biogenic carbon emissions are already part of the cycle.

The figure below shows the profiles over time of the greenhouse-gas burdens associated with biomass energy production, and the various alternative disposal options for the biomass fuels that are included in the analysis, with all curves scaled to the disposal of one million bdt of biomass residues in 2005. As illustrated by the figure, the atmospheric greenhouse-gas profile over time is very different for the energy production alternative, and for the alternative disposal activities.



The curve for stack emissions from the biomass energy alternative is based on the immediate release of virtually all of the fuel-bound carbon as CO_2, followed by its gradual clearance from the atmosphere. The conversion of one million bdt of biomass leads to emissions of 1.75 million tons of biogenic CO_2 equivalents. Open burning and low-efficiency combustors (kiln boilers and fireplaces) also produce their emissions immediately, but their greenhouse-gas emissions are higher, in terms of tons of biogenic CO_2 equivalents, than those of the power alternative.

Biomass that is landfilled, spread, or composted has both immediate and delayed emissions of carbon gases. Biomass left in the forest as over-growth material has a longer lag time in emissions than any of the other alternative fates, but in the long term the greenhouse-gas potency of the emissions stabilizes at a higher level than that for any other alternative. All of the alternative disposal options for the biomass residues produce higher levels of biogenic greenhouse-gas levels than use of the biomass for electricity production.

Bioenergy and Greenhouse-gas Reduction Programs

Existing greenhouse-gas reduction programs are geared toward reducing fossil carbon emissions to the atmosphere. Continuing to add new (fossil) carbon to the carbon that is already in circulation between the atmosphere and the biosphere is the fundamental driver of human-caused global climate change. Bioenergy production can reduce net greenhouse-gas emissions by contributing to healthier and more resilient forests, and by eliminating the reduced-carbon emissions that are associated with the alternative fates for biomass resources that are not converted into useful energy. In order to allow these benefits to be expressed in a way that will allow them to be a part of future greenhouse-gas reduction programs, the net reductions in biogenic greenhouse gases can be denominated as carbon offsets that can be used in whatever cap-and-trade programs are eventually instituted. Theoretically, offsets should be available for the reduction in greenhouse-gas burden associated with the avoided alternative disposal of biomass fuels, net of the biogenic greenhouse gases emitted by the power plant, and for the long-term increase in forest sequestration due to the performance of forest treatments, again net of the power-plant emissions, from using the treatment removals for energy production.

Conclusion

Bioenergy production reduces atmospheric greenhouse-gas levels by enhancing long-term forest-carbon sequestration, and by reducing the greenhouse-gas potency of the carbon gases associated with the return of biomass carbon to the atmosphere that is an intrinsic part of the global carbon cycle. These greenhouse-gas benefits are provided in addition to the benefit common to all renewable energy production of avoiding the use of fossil fuels. The value of the greenhouse-gas offsets that are expected to become available in the next several years should improve the competitiveness of energy production from biomass and biogas resources in the marketplace of the future.

Introduction

The greenhouse-gas implications of energy production from biomass are far more complex and subtle than the greenhouse-gas implications of energy production from other energy resources. Energy production from fossil fuels removes carbon from geological storage and adds it to the atmosphere. Lower-grade fossil fuels like coal produce more CO_2 emissions per unit of useful energy than higher-grade fossil fuels like natural gas. Energy production from non-bioenergy renewables and other non-fossil sources produces energy without any significant greenhouse-gas emissions.

Biofuels, including various forms of solid biomass and biogas, are low-grade, carbon-based fuels, but the carbon in biofuels is already part of the active global carbon cycle, in which carbon exchanges rapidly between the atmosphere and the biosphere. Carbon that is already part of the active cycle is referred to as biogenic carbon, while the carbon in fossil fuels is referred to as fossil carbon. Bioenergy production does not add new carbon to the active carbon cycle, but it can affect global greenhouse-gas levels in two important ways.

It is well known that electricity generation from coal produces twice as much carbon dioxide (CO_2) per kWh generated as electricity production from natural gas. Less well known is that electricity production from biomass, as measured at the stack of a biomass power plant, produces more CO_2 than coal. However, bioenergy facilities emit carbon that is already part of the active carbon cycle, and convert wastes and residues that, when conventionally disposed of, produce even greater amounts of greenhouse-gas emissions than when used for power generation. When the net emissions are properly accounted for, biomass and biogas generators actually reduce the net greenhouse-gas emissions associated with the disposal of some of society's waste and residue materials. This is in addition to the greenhouse-gas benefit common to all renewables that fossil carbon emissions from fossil-fuel generation are replaced with carbon-free renewable energy production and use.

The white paper uses the California biomass and biogas industries, which are the largest in the world, as an analytical foil with which to examine the greenhouse-gas implications of biomass energy production. The results and conclusions are applicable to the greenhouse-gas implications for biomass and biogas energy production across the country and beyond. The white paper begins with a discussion of the global carbon cycle, and the different roles played by carbon from fossil fuels and from biomass and biogas resources in the global carbon cycle. This is followed by a discussion of the biomass and biogas resources that are used for energy production, and the alternative fates for these resources if they are not used for energy production. The greenhouse-gas model is then described and the base-case dataset is introduced, followed by an analysis and description of the greenhouse-gas implications of energy production from biomass and biogas resources. The white paper concludes with a consideration of how the greenhouse-gas implications of biomass energy fit into the developing regulatory frameworks for reducing society's greenhouse-gas emissions.

The Global Carbon Cycle

Carbon is the essential element for life on earth. The earth contains well over one million qmoles of carbon,[1] most of which is locked away in geological storage, inaccessible to the atmosphere. Only a small fraction of the earth's carbon is in the atmosphere, where it is found mainly in the form of the two principal greenhouse gases, carbon dioxide (CO_2), and methane (CH_4). CO_2 is currently found in the atmosphere at a concentration of ~ 380 ppm. Carbon dioxide has an atmospheric residence time that is estimated at between 100 and 200 years, and contributes approximately one-half of the greenhouse-gas forcing effect of all atmospheric gases. Carbon dioxide is removed from the atmosphere via multiple pathways, including uptake by biomasss, and dissolution into the oceans. Methane is found in the atmosphere at a concentration of ~ 1.7 ppm, but has a greenhouse forcing effect that is twenty-five times greater than that of CO_2 on a per-carbon basis.[2] CH_4 has a 12-year residence time in the atmosphere, and its mode of clearance from the atmosphere is by conversion (oxidation) to atmospheric CO_2.

Carbon gases in the atmosphere (~ 60 qmoles of C) are in rapid exchange with carbon in the earth's biomass (~ 150 qmoles of C in terrestrial biomass, mostly forests, divided almost equally between living and dead organic matter), as illustrated in Figure 1. Approximately 8 qmoles of C are exchanged between the earth's biomass and atmosphere annually, with flows roughly in balance. Carbon is taken up by biomass through photosynthesis, and returned to the atmosphere by a combination of respiration, decomposition, and fire. The stock of carbon that is part of the active carbon cycle is thus about 210 qmoles, of which approximately 30 percent is in the air, and 70 percent is in the biomass (living and dead organic matter), at any given time.

Figure 1: Global Carbon Cycle

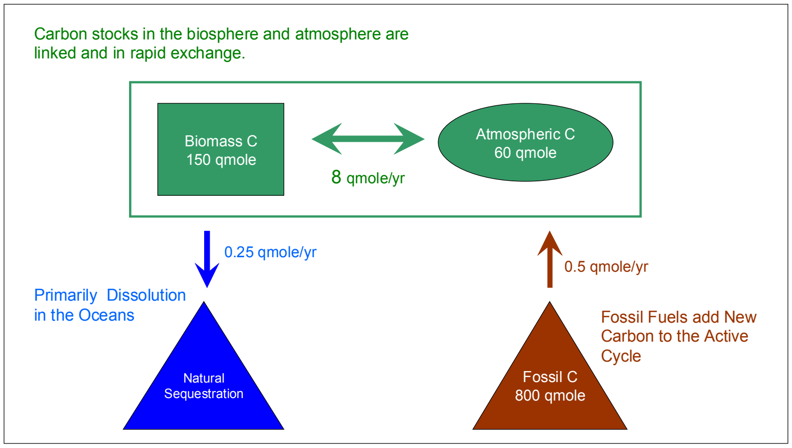


Figure 1 shows the global carbon cycle graphically as it relates to atmospheric carbon. The active circulation part of the global carbon cycle is enclosed by the green rectangle. The carbon circulating within the green rectangle is called biogenic carbon. Note that one qmole = 10^{15} mole, all stocks and flows are approximate.

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[1] 1 qmole = 1 x 10^{15} moles of carbon, weighing approximately 13.25 billion tons.

[2] J.T. Houghton, ed., *Climate Change 1995: the Science of Climate Change*, published for the Intergovernmental Panel on Climate Change by Cambridge University Press, 1996.

Approximately 800 qmoles of carbon are deposited inside the earth in the form of fossil fuels, including natural gas, petroleum, coal, oil shales, and peat. Fossil fuels are the world's principal commercial energy sources. However, the downside of fossil energy use from a greenhouse-gas perspective is that it entails removing carbon from geologic storage, where it is unavailable to the atmosphere, and injecting it directly into the atmosphere, adding it as new carbon to the carbon that is already in the active carbon cycle. Because the stock of carbon in fossil fuels is approximately four times greater than that of the atmosphere, continued fossil fuel use has the potential to seriously unhinge the active carbon cycle (inside the green rectangle in Figure 1) that regulates the Earth's climate, as well as life on Earth.

Carbon Neutral

The greenhouse-gas emissions produced at biomass and biogas generating facilities comes from carbon that is already a part of the stock of the linked atmospheric – biospheric carbon cycle. This is in stark contrast to fossil fuel combustion, which removes carbon from permanent geologic storage, and adds it as new carbon to the carbon already in the atmospheric – biospheric circulation system. Most people focus on this aspect of bioenergy production, and proclaim it to be "carbon neutral."

Existing greenhouse-gas tracking and trading systems, such as those of the Regional Greenhouse Gas Initiative (RGGI) in the Northeast U.S., and the system used by the EU, consider biomass energy to be a zero-greenhouse-gas-emitting technology. These tracking systems, which are the world leaders in greenhouse-gas tracking and trading, are concerned only with accounting for greenhouse-gas emissions from fossil-fuel use. Emissions of CO_2 from biomass are considered carbon neutral, and are not counted towards a facility's or a retail seller's greenhouse-gas emissions in either of these pioneering tracking systems. California's tracking system, which is still in development, will be different. According to current plans, California's tracking system will track emissions of biogenic carbon as well as fossil carbon, but it will consider biogenic carbon to be a separate category of emissions than fossil carbon, and will not require the retirement of biogenic greenhouse-gas emissions against AB 32[3] emissions allowances.

Beyond Carbon Neutral

Carbon neutrality, while an important intrinsic characteristic of bioenergy production, is only part of the story of the greenhouse-gas implications of biomass. In addition to being carbon neutral by virtue of using biogenic carbon, biomass energy production can affect atmospheric greenhouse-gas concentrations in two important ways. First, the total amount of carbon that is sequestered in terrestrial biomass affects the amount of carbon in the atmosphere. In the long term energy production from forest fuels can increase the amount of carbon that is stored on a sustainable basis in the earth's forests by contributing to forest health and fire resiliency in currently at-risk, overstocked forests,, making a positive contribution to efforts to control atmospheric greenhouse-gas levels. Second, biomass energy production can change the timing and relative mix of carbon

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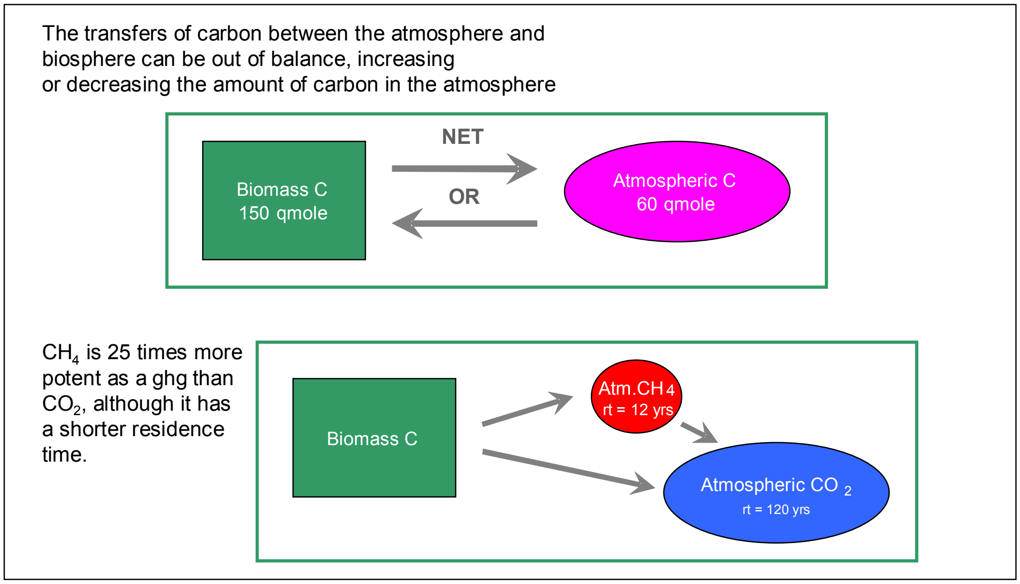
[3] AB 32 is the California Global Warming Solutions Act of 2006.

forms (oxidized vs. reduced) emitted to the atmosphere associated with the disposal or disposition of the biomass resources. Because reduced carbon (CH_4) is twenty-five times more potent than oxidized carbon (CO_2) on an instantaneous, per-carbon basis, the form in which carbon is transferred from the biomass stock to the atmospheric stock is critically important from the standpoint of greenhouse forcing impact.

In current carbon tracking and trading systems, which are primarily focused on fossil CO_2, the potential greenhouse-gas benefits of biomass energy production related to the disposal of biomass resources, including healthier and more fire- and disease-resilient forests, and the replacement of natural CH_4 emissions with CO_2 emissions, are categorized as Greenhouse-gas Offsets. These concepts are illustrated graphically in Figure 2. The accounting rules for greenhouse-gas offsets are in the early stage of development, and will be extremely important for the future of biomass energy production and use, and indeed for forestry in general.

Figure 2: Offsets for Biomass GHG Abatement



Biomass and Biogas Energy Resources

Biomass resources suitable for conversion to energy products come in a wide variety of forms and conditions. The two principal modes of electricity production from biomass in California are combustion of solid fuels in conventional steam-turbine power plants, and biological conversion of the biomass to biogas, coupled to combustion of the biogas in a conventional engine-generator. All of the biomass and biogas resources used for electricity production in the U.S. today are waste and residue materials. A great deal of research effort has been devoted to the development of energy crops, but commercial applications of energy crops for electricity production are not on the horizon, and energy crops are not included in the analysis in this study.

The bioenergy industry is a dual product industry. In addition to producing renewable energy, the bioenergy industry provides a productive use, environmentally preferred waste disposal service for a variety of residue and waste materials. Biomass energy generation in California, the leading biomass energy producing state in the U.S., provides for the disposal of 7.6 million tons per year of the state's solid wastes, and contributes to the disposal of 120 thousand bdt per year of manure and 26.5 billion cu.ft. per year of landfill gas.

The biomass residues used as fuel come from a variety of sources, and would be subject to a variety of alternative fates, such as open burning, decomposition in place, or landfill burial, if the biomass industry was not an available disposal option. The major categories of biomass fuels used in California include:

- Wood processing residues
- In-forest residues
- Agricultural residues
- Urban wood residues
- Landfill gas
- Animal wastes (manures)

Most of the solid-fuel biomass generating facilities in California were designed to use either wood-processing residues or agriculture residues as their primary fuel source. The facilities designed to burn primarily agricultural residues are concentrated in the state's Central Valley. The facilities designed to burn primarily residues from the forest-products industry are concentrated in the northern and eastern-mountain regions of the state. Figure 3 shows the location of the solid-fuel biomass power generating facilities in California today.

Three of the state's biomass facilities were designed to burn primarily urban wood wastes. These facilities were located close to the Los Angeles and San Francisco Bay Areas. Urban wood waste fuels, which were largely overlooked during the industry's early development in the 1980s, have turned out to be far more important than anyone originally anticipated. In fact, with the decade-long shrinkage of the wood-products industry in California, which began in the late 1990s, and the attendant decrease in the generation of wood-processing residues, urban wood residues have become the dominant source of solid biomass fuel used for electricity production in the state. Figure 4 shows the consumption over time of the various categories of solid-fuel biomass in California.

Figure 3

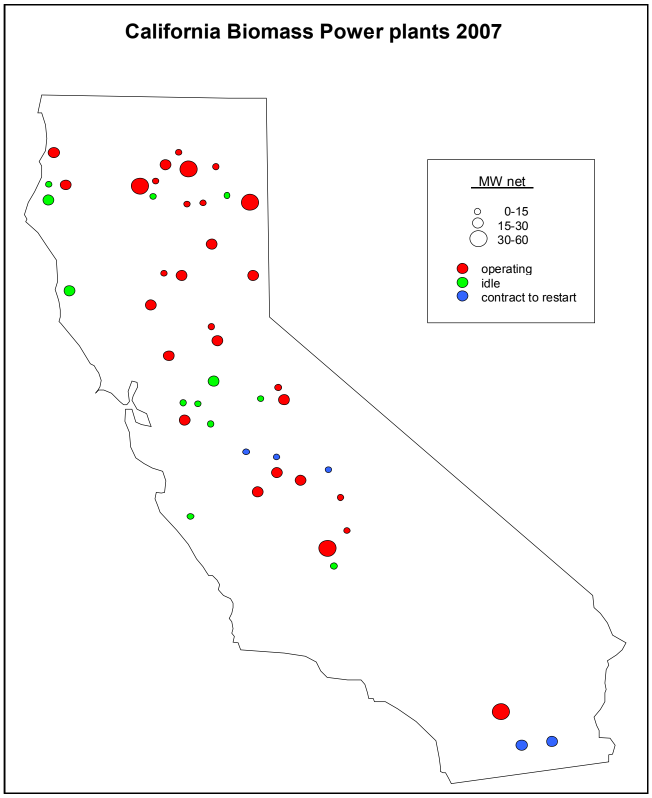
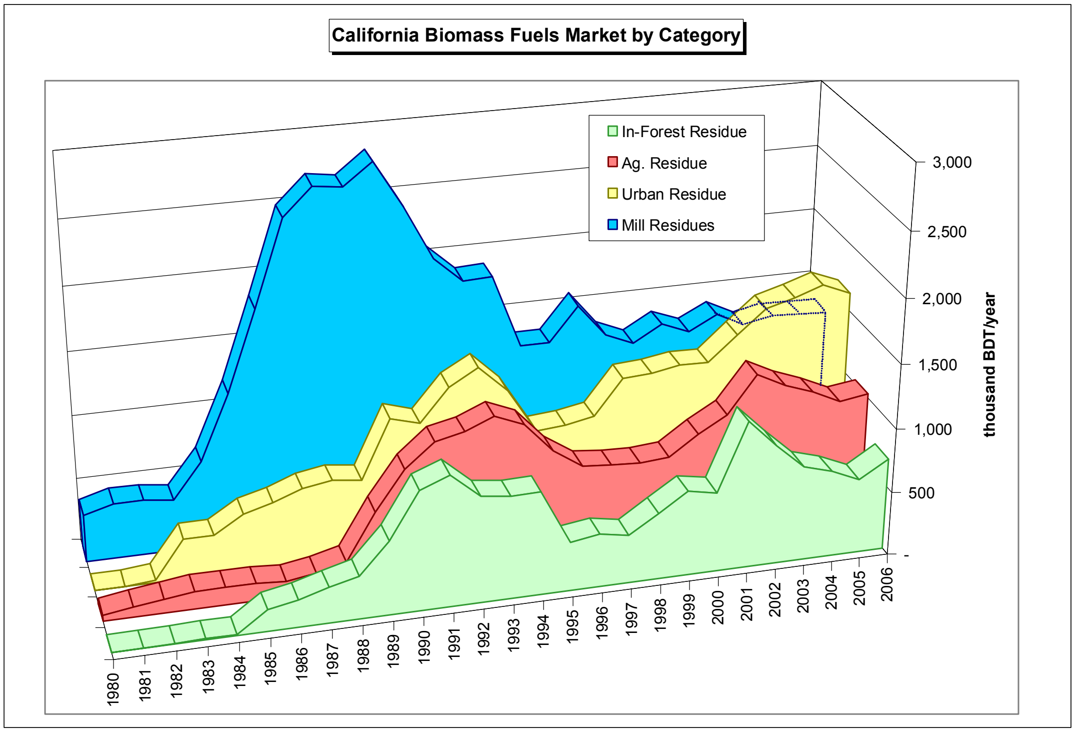


Figure 4



Wood Processing Residues

Wood-processing residues are the waste materials produced during the processing and conversion of lumber into wood products. Until the early 1990s, wood-processing residues were the most important solid-fuel biomass resource in California, consistently accounting for more than a third of the total biomass fuel supply used in the state. In recent years the supply of wood-processing residues has declined in concert with the decline of the state's sawmilling industry. Nationwide wood-processing residues remain the dominant solid biomass fuel source used in the United States.

Almost half of the total biomass content of a typical sawlog becomes residue at a primary sawmill. A variety of secondary forest products industries have been developed to use a portion of this material. Active markets for wood processing residues include pulp chips, wood fiber for fiberboard and composites, animal bedding, and garden products such as decorative bark. Sawmills segregate their residues into the highest-value markets available, but a substantial quantity of the residues, typically 15-20 percent of the total biomass in a sawlog, has no useful product application, and must be disposed. Wood-processing residues are produced in a variety of forms, including:

- bark
- round-offs
- end cuts
- trimmings
- sawdust
- shavings
- reject lumber

The traditional method for the disposal of sawmill residues that lacked secondary-product applications was incineration in teepee burners, a technology that produces large quantities of smoke and air pollution. Beginning in the early 1970s, air pollution control efforts in California applied increasing pressure on sawmills to close down their teepee burners, forcing them to look for new, cleaner disposal alternatives. This was one of the key factors that led to the early development of the biomass energy industry in the state.

Teepee burners have been eliminated as a disposal option for wood-processing residues in California, and in much of the rest of the country as well. The only readily available option for the disposal of these materials, if fuel use were not a possibility, would be landfill burial. However, landfill disposal of wood-processing residues is highly undesirable. Waste wood has a slower decay rate than other forms of biomass in the landfill environment, and thus is slower to stabilize. Moreover, California state solid waste policy is strongly oriented to reducing the amount of material being buried in the state's landfills, and the introduction of a sizable new waste stream would make compliance with state recycling regulations almost impossible for the counties that would be affected.

At the present time, virtually all of the readily available wood processing residues generated in California that have no higher-valued application are used as power-plant fuel. If the biomass energy industry did not exist in California today, some of the sawmill residues currently used for fuel would be used for energy production to provide steam or direct heat to sawmill dry kilns, and as residential firewood. Based on our survey work, we estimate that these applications would probably use about one-quarter of the sawmill residues currently used for power production. A small quantity of the sawmill residues would be composted and/or spread, with the remaining residues destined for landfill disposal.

Wood-processing residues are the cheapest of the four categories of biomass fuels to produce and deliver to biomass power plants. They form the backbone of the state's biomass fuel supply, and would likely be the last type of fuel to exit the system if the demand for biomass fuels in the state declines. The major factor that determines the quantity of mill residues used as fuel in California is the level of activity in the primary forest-products industry. Economic factors along with environmental and other policy-related restrictions on timber supplies have forced many of the state's sawmills to cease operations. This has led to a decline in the amount of wood-processing residues used as power plant fuels in the state that began in the early 1990s.

In-Forest Residues

In-forest biomass residues include two major categories of materials: residues that are generated in the forest when timber is harvested for wood products, which is often called slash, and material naturally occurring in forests in the form of overgrowth material whose removal would provide health and environmental benefits to the remaining forest. Harvesting residues include the tops and limbs of harvested trees, bark (especially when debarking takes place in the forest), and cull logs[4] that are cut and removed during harvesting operations. The cheapest form of management for this material is to leave it in the forest as it is generated, but that is also the worst management practice from a forestry perspective, as leaving harvesting residues in the field retards forest regrowth, and represents a substantial fire hazard. Virtually all timber harvesting contracts in California require loggers to remove the slash they generate. Slash that is generated close enough to an operating biomass energy plant can be collected and used as fuel. The alternative is to collect the slash and burn it in piles.

The other major category of in-forest residue is overstocked material that exists in vast areas of California's forests. Due to aggressive fire-fighting efforts and poor forestry practices during much of the past century, vast areas of the state's forests are overstocked with biomass. Overstocked forests have an enhanced risk of experiencing destructive wildfires, and elevated vulnerabilities to disease and pest attacks. Overstocking generally degrades the healthy functioning of forest ecosystems in the state. Healthy, mature California forest ecosystems are characterized by open canopies and relatively wide spacings among large trees. Overstocked forests typically have high densities of

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[4] Cull logs are trees that are diseased, damaged, misshapen, or otherwise unsuitable for use in the production of commercial wood products.

relatively slender stems, and fairly closed canopies. The overstocked forests are stressed by competition for scarce resources, including light and moisture, resulting in an overall poor level of ecosystem health. Stressed forests are less able to resist pest and disease outbreaks than healthy forests, and when fires strike overstocked forests they tend to burn hotter and higher, with a greater extent and degree of mortality than fires in healthy forests.

Overstocked forests benefit greatly from thinning treatments. The quantity of in-forest biomass whose removal would benefit California's forests is far greater than the total amount of biomass fuel demand in the state. However, this fuel source is generally more expensive to produce than other types of biomass fuels, so the quantity used is limited (forest-residue fuels are the marginal biomass fuel source in California). Moreover, the U.S. Forest Service still has not demonstrated that they have either the will or the capability to perform the needed treatments on the roughly fifty percent of California's forest land that is under their control, and is generally in poorer condition than private forestry holdings in the state.

Forestry officials would like to see large areas of California's forests thinned over the next several years and decades. An official of the U.S. Forest Service once asserted that at least 250,000 acres per year of the land under their jurisdiction needs to be thinned in order to fully realize the desired fire suppression, forest health, and watershed improvement benefits (Morris 1998a). During the peak of the California biomass fuels market in the early 1990s only about 60,000 acres per year were being thinned statewide for fuel production. With the decline in statewide biomass fuels demand that began in the middle of the 1990s the level of thinning for biomass fuels production has declined as well, although it peaked again during the California energy crisis of 2000 – 2001 (see Figure 4).

There are two basic techniques that can be used to reduce the biomass overloading in standing forests: prescribed burning, and mechanical thinning. These operations can be performed separately or in tandem. The primary goal of reducing fire risks and the risks of pest and disease outbreaks in standing forests is the protection of the mature trees. Most of the tonnage of forest overgrowth biomass is material on and near the forest floor, usually called ground fuel. Periodic fires in what is currently understood to be the condition of undisturbed (pre-extensive exploitation) California forests tended to be primarily ground-fuel fires. These natural ground fires control the build-up of excess forest fuels. When ground fuels are left to accumulate for prolonged periods, some of the undergrowth grows into taller poles, called ladder fuels. Ladder fuels provide a mechanism to transfer ground fires to the crowns of mature trees in the forest, thus greatly increasing the damage caused by the fires, turning benign ground fires into out-of-control, destructive wildfires (crown fires). Traditional commercial harvesting operations can exacerbate the fuel-overloading problem in the forest, because neither ground nor ladder fuels are systematically removed. In fact, if slash is left untreated, the fire risk is significantly increased. Both mechanical thinning and prescribed burning can remove ladder and ground-based fuels.

The alternative to mechanical thinning operations for reducing forest overstocking is prescribed burning. The amount of prescribed burning that will be allowed in California in the future, however, may be limited due to environmental and safety concerns. Prescription burning produces more pollution per ton of material consumed than open burning of biomass in piles.[5] In addition, prescribed burning in densely overstocked forest stands entails a significant risk of residual stand damage and initiation of offsite, uncontrolled wildfires. Northern California has experienced this phenomenon several times during the past decade. Mechanical thinning and residue removal prior to prescription burning reduces the pollution and risk factors associated with the treatment, and in some cases can eliminate the need to do any prescription burning at all. Mechanical thinning, however, is expensive, and rarely performed without some of the thinned material being used for fuel and/or higher-valued applications.

Agricultural Residues

Agriculture is a multibillion-dollar enterprise in California, producing large quantities of biomass residues in the process. Approximately one-third of California's biomass energy plants were built in the state's agricultural regions in order to use these residues as fuel. Agricultural fuels currently provide about 20 percent of the state's biomass fuel supply. Many of the state's biomass facilities receive emissions offsets for pollutants that are avoided when biomass residues that would otherwise be open burned are used for energy production. Agricultural residues come in a wide variety of forms, not all of which are suitable for use as power plant fuel. For example, agricultural residues that are too wet for use as power plant fuels are usually best suited for the production of biogas or liquid fuels. Agricultural residues suitable for fuel use in solid-fuel biomass energy plants include materials:

- Food processing residues, such as pits, shells, and hulls
- Orchard and vineyard removals
- Orchard and vineyard prunings
- Field straws and stalks

Food processing residues are generated in concentrated quantities and require some form of disposal. Like wood-products manufacturers, food processors have worked diligently to develop high-valued applications for these materials, such as in feed products. Nevertheless, a surplus of food processing residues in the state remains that is available for use as solid fuel or as biogas feedstock. In the absence of fuel or feedstock markets, these materials would otherwise be open burned or buried in a landfill.

California's agricultural enterprise includes extensive plantings of orchards and vineyards. Orchards and vineyards are permanent woody crops that require annual pruning operations, which produce large quantities of residues. Conventional agricultural practice for the disposal of these prunings is to pull them to the ends of the rows, where they are piled and burned. During the early development of the biomass energy industry

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[5] USEPA, *Compilation of Air Pollutant Emissions Factors, Fifth Edition, Volume I: Stationary Point and Areas Sources*, EPA Report No. AP-42, Washington, D.C., 1995, plus updated supplements.

in California there was a great deal of interest in using orchard and vineyard prunings as fuels. Combustion of this material in a power plant greatly reduces the resulting emissions of smoke and air pollutants compared with open burning, and it has long been recognized that agricultural burning is a major contributor to the air pollution problems in California's major agricultural regions. In 2003, SB 705 was enacted in an attempt to eliminate agricultural burning in the state's San Joaquin Valley. SB 705 has out clauses that delay its implementation if various conditions are not met, and so far the early compliance dates have all been pushed back. Nevertheless, California authorities are continuing their efforts to eliminate open agricultural burning in the state's Central Valley.

In addition to the environmental benefits anticipated during the development of the biomass energy industry in the late 1980s, many farmers were under the impression that fuel sales would offset the cost of pruning, and even create a new profit center for their operations. However, orchard and vineyard prunings have proven to be more expensive and difficult to use as fuels than was originally anticipated. This is a consequence of two factors. First, the density of the resource (tons per acre) is less than originally projected. The result of this miscalculation is that a greater area needs to be harvested in order to produce a given amount of fuel, with a concomitant increase in the cost of fuel-production. Second, prunings are stick-like in nature, often on the order of 20 feet long with a diameter of an inch, making them more difficult to process into fuel form, and creating a special hazard for fuel handling and delivery equipment at the power plant. These considerations have limited the amount of fuel produced from orchard prunings in California. It is estimated that less than five percent of the state's agricultural prunings are being converted to fuel in the current market environment. The remainder continue to be open burned.

In contrast to the experience with prunings, orchard removals and, to a lesser extent vineyard removals,[6] have proven to be a desirable source of biomass fuel. Orchards and vineyards are cleared periodically for purposes of replanting, and in response to changing land use patterns. Orchard clearing, in particular, provides a high density of material (approximately 35 tons per acre) that can be processed into conventional whole tree chips. In addition, this material is generally felled in mid-to-late summer on plantations that have not been irrigated for several months, with the result that the wood is often very dry compared to other sources of recently cut biomass fuels. Fuels derived from orchard clearings are the major agricultural-residue fuels used by California's biomass power industry.

California agriculture also produces large quantities of field residues in the forms of straws and stalks that are disposed of either by open burning, or plowing under in the fields. These residues can be collected and processed into power plant fuels. However, straw and stalk-based fuels tend to be expensive to produce, and their low bulk density (lb per ft^3) presents materials handling problems. In addition, the alkali and chloride content of many straws leads to boiler slagging, which results in decreased boiler

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[6] The use of vineyard removals has been limited by the presence of metal staples, which are difficult to remove from the fuel.

efficiency, and increased maintenance costs. As a result, very little of this material is contributing to the fuel supply at the present time, even though these materials do qualify as agricultural offset fuels.

Most of the agricultural residues used as fuels in California are woody residues derived from the state's extensive orchard crops. Whole-tree chips produced from orchard removals have proven to be a particularly successful source of biomass fuel. Even with the present level of agricultural biomass fuel use in California, and the statutory authority to eliminate agricultural burning in major regions of the state, an enormous amount of agricultural residues suitable for use as power plant fuels continues to be open-burned. The state's short-lived experience with providing an incentive for the use of agricultural prunings demonstrated that these plentiful residues can be successfully used as fuels with only a modest financial boost. The alternative fate for most of the agricultural residues that are used for fuel is open burning, although it is likely that most of these materials would be landfilled or plowed under in the absence of fuel applications if the proposed open-burning ban in the state's Central Valley goes into full effect.

Urban Wood Residues

Fifteen-to-twenty percent by weight of the material that traditionally is disposed of in California's municipal landfills is clean, separable waste wood. This material comes from a variety of sources, including:

- Waste wood from construction contractors
- Old and damaged pallets.
- Drayage and dunnage
- Waste wood from land clearing
- Waste wood from public and private tree trimmers and landscapers
- Waste wood from industrial manufacturers, including packing materials and trimmings, furniture, crates, trusses, spools, etc.

Urban wood residues are brought to landfills in a variety of forms, including loads of chipped wood and brush from public and private tree trimmers and land clearers, debris boxes from manufacturers of wood products and construction contractors, and mixed loads of yard debris. Some amount of demolition wood waste is also used as a biomass fuel in California, although many of the state's facilities have permit restrictions that prohibit the use of painted and/or treated wood. Transfer station and landfill operators can segregate loads containing fuel-useable materials as they enter the gate, and process the material to produce a high-quality fuel product.

Solid waste managers are under pressure to develop diversion applications of all kinds. The alternatives, however, are limited, and most of the obvious markets that can accept urban waste wood, such as spreading as mulch or composting, are already being flooded with material. It can be assumed that most of the urban biomass fuels would otherwise be landfilled in the absence of energy production. At the present time a loophole in current California solid waste regulations allows landfill operators to use wood chips as alternative daily cover (ADC) for their operations, while not counting the biomass as material that was disposed of in the landfill. This loophole in the law may be depressing the amount of fuel that is being produced from urban waste wood in the state. Efforts are underway in the Legislature to eliminate the ADC loophole for waste wood.

Landfill Gas

As discussed above, a fraction of the biomass that enters landfills can be diverted at the gate, processed, and shipped as solid biomass fuel. However, there is a large amount of biomass that has already been buried in landfills, and even with enhanced diversion initiatives some fraction of society's biomass wastes will continue to be disposed of in landfills. Landfills produce landfill gas, which is 50 – 60 percent CH_4, and 40 – 50 percent CO_2. While landfill gas is biogenic carbon, the fact that when left uncontrolled at least half of the biogenic carbon in landfill gas is generated in the form of the more potent carbonaceous greenhouse gas, CH_4, is of substantial concern from a climatological perspective.

In addition to containing large amounts of CH_4, landfill gas also contains noxious volatile organic compounds (VOCs), which in addition to being greenhouse gases with the same approximate per-carbon potency as CH_4, present serious odor issues and contribute to the formation of ground-level ozone. For all of these reasons, larger landfills have been subject to EPA gas-control regulations for some time. As greenhouse gases become subject to regulation over the next several years, the threshold for landfills that are subject to control is expected to be extended to smaller landfills. This already appears to be the case with the Early Actions to reduce greenhouse gases currently under consideration at the California Air Resources Board under AB 32,[7] the state's landmark greenhouse-gas legislation.

The three alternative fates for landfill gas are:

- No control
- Control to meet regulations
- Control beyond regulation to maximize energy production

Landfill gas control involves installing a gas-collection system in landfill cells to collect the landfill gas that is produced as biomass wastes degrade. The collected gas can either be flared, or burned in engines for energy production. Either way, combustion converts the reduced carbon in the landfill gas (CH_4, VOCs) to CO_2, which has a much lower greenhouse-gas potency. The energy production alternative reduces greenhouse-gas emissions by displacing fossil fuel generation. It also has the potential to further reduce greenhouse-gas emissions by motivating a landfill operator to install a more extensive gas collection system than required by regulation, and by motivating a landfill that is not subject to regulation to install a gas-collection system voluntarily.

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[7] One of the provisions of AB 32 requires CARB to adopt and enact a set of "Early Actions" as a way to jump-start the implementation of the state's greenhouse-gas emissions reduction program.

Manures

California has approximately 1.7 million dairy cows that collectively produce about 3.6 million bone-dry ton equivalents (bdt) of dairy manure annually. Most of this material is treated by flushing into open lagoons, where it is allowed to stabilize, and the remaining solids are subsequently applied to the land. Stabilization in a lagoon involves mainly anaerobic digestion, and produces a biogas composed of approximately 60 percent CH_4, and 40 percent CO_2. The energy alternative for manure is similar to conventional disposal practice, except that an enclosed lagoon is substituted for the open lagoon, and the biogas is collected and combusted in an engine or processed into pipeline quality and injectged into a gas transmission line. Stabilized solids that remain after biogas production has occurred are land-applied, just as in current practice with open lagoons. From the greenhouse-gas perspective, all of the carbon emissions that are associated with dairy farming are biogenic. However, a covered lagoon with gas collection and energy production, instead of the conventional open-lagoon alternative, achieves a significant reduction in greenhouse-gas emissions. This is accomplished by converting the reduced carbon in the biogas into CO_2.

In addition to its dairy cows, California has an additional 3.5 million other cattle, and some 230 million broiler chickens. Collectively, these animals produce close to 12 million tons of manure per year.[8] However, under current animal management practices, only manures from the dairy cows is readily amenable to conversion to energy, and this is the only part of the manure-resource base that is covered in this white paper.

Analytical Approach

A detailed dynamic atmospheric concentration model has been developed for analyzing the time-dependent greenhouse-gas concentrations associated with biomass energy production. Atmospheric concentrations over time of the greenhouse gases associated with the biomass energy production pathway can be compared with the atmospheric greenhouse-gas levels associated with alternative means of disposal of the same biomass residues or biogas resources, combined with the atmospheric greenhouse-gas levels associated with the production of the same amount of energy using fossil fuels. The model computes the time-dependent atmospheric stocks of CO_2 and CH_4 that are associated with the biomass residues used for energy production, or subjected to alternative disposal pathways. Included in the calculations are the diesel emissions associated with the production and delivery of the biomass fuels to the power plants. Atmospheric concentrations of the carbon-containing greenhouse gases are followed over a 100-year time horizon. The model tracks the long-term atmospheric greenhouse-gas concentrations resulting from a single year's worth of biomass residue use, or the concentrations associated with sustained use of biomass for energy production at current or changing levels of use.

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[8] California Biomass Collaborative, *Biomass in California: Challenges, Opportunities, and Potentials for Sustainable Management and Development*, CEC Contract 500-01-016, June 2005.

Alternative Fates for Biomass Residues

The first step in analyzing the greenhouse-gas emissions of biomass energy use is to determine what the alternative fates for the biomass would have been if the biomass power option were not utilized. Most of the solid-fuel biomass that is converted to energy in California would otherwise be open burned or buried if the energy-production alternative were not utilized. In the biomass energy production trajectories, virtually all of the carbon in the biomass is converted promptly to CO_2 and emitted to the atmosphere. If, in the absence of energy production, the material is open burned, most of the carbon is also converted promptly to CO_2. However, open burning is less efficient than combustion in a boiler, and a fraction of the biomass carbon is emitted in the form of methane or higher hydrocarbons. This occurs, for example, from smoldering that occurs around the edges of the fire where pyrolysis gases escape combustion. Even though slightly less of the total biomass carbon is promptly added to the atmosphere due to open burning compared to power production (open burning leaves more unburned carbon than combustion in a power plant boiler), it takes only a small amount of the emissions to be in reduced–carbon form to elevate the effective prompt greenhouse-gas emissions to a level that is well above those from a boiler. In addition, with open burning the small amount of carbon that is left in solid form decays over time, leading to delayed emissions of additional quantities of CO_2 and CH_4.

Emissions of carbon gases to the atmosphere from fuel-recoverable biomass disposed of in a landfill occur gradually over a period of many years, which is different than the case of power production, in which the emissions occur promptly. However, the emissions of gaseous carbon from landfills is more than fifty percent in reduced form (CH_4), giving it a much greater greenhouse potency than the larger quantities of CO_2 emitted promptly by the power-production alternative. This is true even for landfills that collect and burn a portion of the biogas in engines or flares, although gas collection and conversion significantly reduces greenhouse-gas emissions compared with uncontrolled landfills. Modern landfills are being designed to collect an increasing percentage of their landfill gas, but some of the gas simply cannot be captured because landfills and their caps are porous, and fugitive gases inevitably escapes.

For biomass that is already buried in landfills, and for biomass that will continue to be disposed of in landfills, gas collection and conversion to energy greatly reduces total greenhouse-gas emissions by converting the roughly 55 percent of the carbon in the collected gas that is in reduced form (CH_4 and VOCs) to CO_2, greatly reducing the greenhouse forcing effect of the emissions. Federal and state regulations already require larger landfills to collect and combust their gases regardless of whether the gas is used for energy production, or simply flared. One of the early action items being adopted by the CARB under AB 32 will increase the range of landfills subject to regulation. In cases where gas collection is already mandated, conversion to energy has the potential to reduce total landfill greenhouse-gas emissions compared to flares, and provides an economic incentive to motivate the landfill operators to collect a greater proportion of the landfill gas than the amount required by regulation, and to do so for a longer period of time after landfill cell closure. However, biogas engines produce higher levels of NOx emissions than flare, making it difficult to permit new landfill-gas energy systems in California today.

If the biomass energy industry were actually to collapse in California, and the state had to deal with a return to the state's solid-waste stream of the nearly eight million tons per year of solid biomass currently used for energy production, it is difficult to predict what would be done with these materials. Renewed efforts presumably would be made to develop new beneficial uses for some of this material. However, known beneficial applications for surplus biomass residues, such as composting, are already flooded with material, even with the existing biomass-energy industry in operation, so the capacity for absorbing additional large quantities of residues into already identified beneficial applications is probably small.

The probable alternative fates for the various types of biomass residues used for energy production in California were discussed qualitatively in the previous section. In order to estimate quantitatively the partitioning of solid biomass fuels into their probable alternative fates (absent their use as fuel), a survey was conducted in May, 2007, among the operating California biomass power plants. Twenty-three facilities participated in the survey, representing 85 percent of the capacity currently operating in the state. Each participating facility provided its best estimation of the probable alternative fates for the biomass fuels used at their facility, in the event that fuel use was not a possibility.

Table 1 shows a quantitative breakdown of the probable alternative fates for the solid-fuel biomass currently used in California, were the energy pathway not available, based on the survey results. More than half of the biomass fuels used in the state in 2005 otherwise would have been buried in landfills in the absence of energy production. Most of the agricultural residues used for energy production would otherwise be open burned. Despite the fact that state policy is oriented to reducing the amount of material disposed of in sanitary landfills, it is prudent to assume that the probable alternative fate for most of the state's urban waste wood that is currently used for energy production would be landfill disposal. A small amount of these residues would be composted or land-spread as mulch. In the case of sawmill residues, some of the residues would be used for kiln-energy production or as fireplace fuel if the electricity generation alternative were not available, with most of the remaining residues destined for landfill disposal.

In the current market for biomass fuels, the amount of in-forest residues being used for fuel has declined from its peak in the early 1990s. The quantity of fuel produced from slash residues has shrunk as a result of the overall decline in commercial forest harvesting in the state. However, most of the decline in the use of in-forest residues in California has been the result of cutbacks in thinning operations that are not connected to commercial harvesting operations. The primary alternative disposal option for fuels derived from slash is open burning, while the alternative for thinning residues is continued in-forest accumulation (i.e., no thinning performed). For purposes of analysis it is assumed that twenty five percent of the in-forest residues currently used for energy production would otherwise be open burned, while most of the remainder would be

Table 1: Alternative Fates for Biomass Residues (CA 2005)

	Mill	Forest	Ag	Urban	Total
Annual Fuel Use (th.bdt/yr)	1,316	583	999	1,726	4,624
If No Fuel Use, % that Would Be Disposed of by					th.bdt/yr
Open Burning	0.0%	25.0%	60.0%	2.0%	780
Forest Accumulation	0.0%	70.0%	0.0%	0.0%	408
Controlled Landfill	63.0%	0.0%	2.0%	55.0%	1,798
Uncontrolled Landfill	10.0%	0.0%	18.0%	20.0%	657
Spreading	1.0%	5.0%	0.0%	10.0%	215
Composting	1.0%	0.0%	10.0%	13.0%	337
kiln boiler / firewood	25.0%	0.0%	10.0%	0.0%	429

allowed to continue to accumulate as overstocked material in the state's forests. If the overall demand for biomass fuels in California were to increase, for example to early 1990s levels, the proportion of in-forest residues whose alternative disposal would be in-forest accumulation would probably increase as well.

Based on the alternative disposal options identified in Table 1, more than half of the biomass fuel used for power production in California in 2005 would have otherwise ended up in the state's landfills, a total of approximately 2.5 million bdt per year of material. In addition, 780,000 tons per year of residues would be added to the amount of biomass that is opened burned in the state, 335,000 tons per year would be composted or spread as mulch, 410,000 tons per year of residues would be added to the quantity of material currently accumulating in California's forests, and 430,000 tons per year of residues would be burned in sawmill boilers used to produce steam for kilns, or home fireplaces.

The possible alternate disposal fates for landfill gas in the absence of energy production are either direct ventilation to the atmosphere, or collection and flaring in compliance with regulatory requirements. Most of the dairy manure that is generated in California is flushed into open lagoons, stabilized, and then the remaining solids are spread on agricultural lands. The energy production pathway is essentially identical, except that the lagoon is covered, and the resulting biogas is collected and combusted in an engine for electricity production. Cattle manure in California is usually left on the ground and scraped up at intervals of 3 – 6 months. As a result of open exposure for extended periods of time, much of the volatiles, and therefore much of the readily digestible energy is lost before the material is collected. Unless basic management practices are changed at cattle production operations, manure conversion to energy is not a viable option.

The Greenhouse-gas Model

The biomass greenhouse-gas model is a stock-and-flow model that incorporates the exponential decay function for carbon loss from various stocks of carbon. The carbon stocks analyzed in the model include the atmospheric stocks of CO_2 and CH_4, and various stocks of fixed biomass carbon in storage, including carbon fixed in forest biomass, carbon buried in landfills, carbon that is land-spread, etc. For each alternative disposal option, the biomass carbon is initially partitioned among three stocks: atmospheric CO_2, atmospheric CH_4, and carbon in the appropriate storage reservoir. The carbon in storage then is subjected to long-term decay into CO_2, CH_4, and permanently stored carbon. The CO_2 and CH_4 emitted by the carbon-in-storage are added to the atmospheric stocks over time, in accordance with the characteristic half-life of the carbon in the storage reservoir. The atmospheric CO_2 and CH_4 stocks are themselves subjected to exponential-decay-removal processes. The removal pathway for atmospheric CH_4 is conversion via oxidation to atmospheric CO_2. Carbon dioxide is removed from the atmosphere via multiple pathways, including conversion to biomass, and dissolution in the oceans.

The model begins with an inventory of the types of biomass fuels used for energy production in California. Factors for partitioning each type of biomass into alternative fates (open burning, landfilling, etc.) are then entered, and the amounts of biomass that would be subject to each category of alternative fate is determined. A summary of the alternative fates of biomass residues used for energy production in California was presented previously in Table 1. The model follows the carbon flows for each alternative fate over a one-hundred year time period, and the atmospheric concentrations of the greenhouse gases CO_2 and CH_4 are compared for the energy production alternative, and for the alternative fates for the biomass residues, should energy production not be performed. The greenhouse-gas emissions of avoided fossil fuel use for electricity production are also determined. Fossil carbon greenhouse gases and biogenic carbon greenhouse gases are tracked in separate accounts. Figure 5 shows the logic flow of the model. Biomass resources under consideration are either used for energy production or meet some alternative fate, typically a conventional disposal option.

Figure 6 shows the stock and flows in the Biomass Greenhouse-gas Model's harvested fuel module. This is the model's basic module, and is used for all of the alternative fates considered in the model with the exception of fuels left in the forest as overstocked material. The emissions of CO_2 and CH_4 from alternative disposal include both immediate and delayed emissions. Virtually all of the emissions from biomass energy production are immediate.

Figure 5: Logic Flow in Greenhouse-gas Model

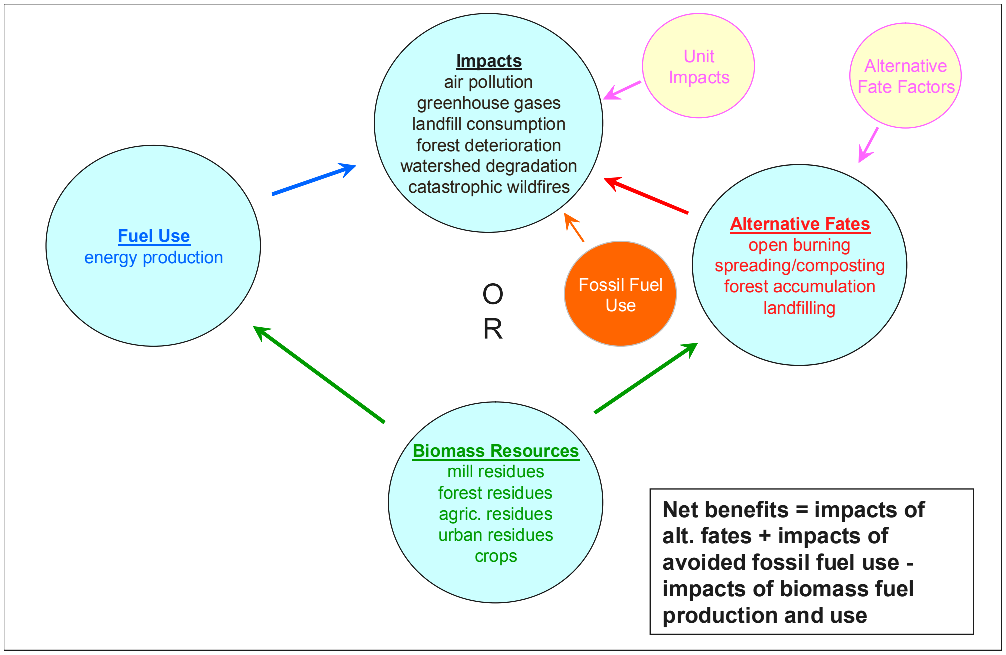
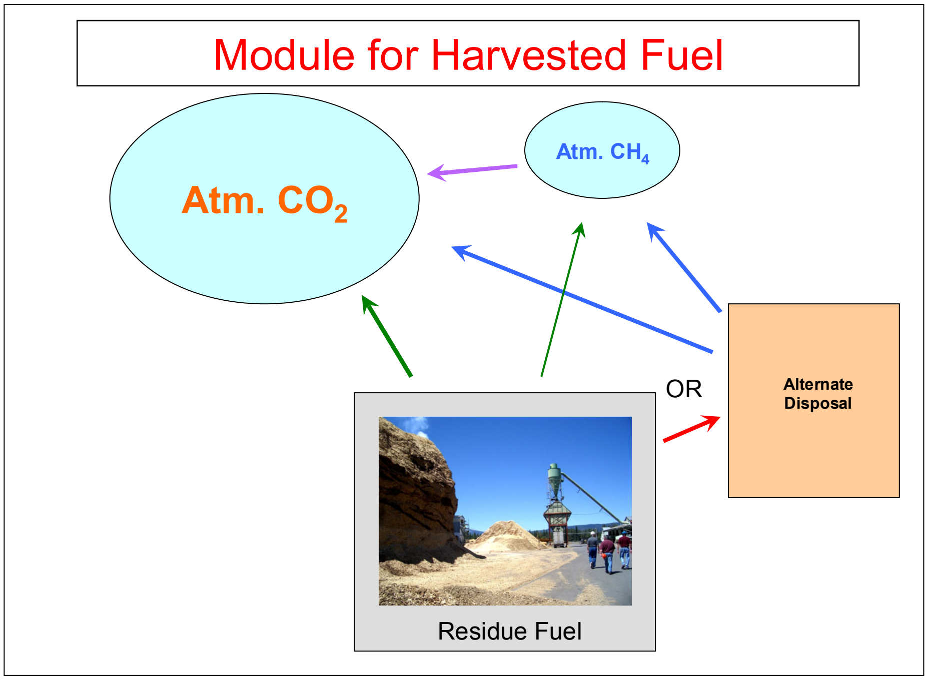


Figure 6: Harvested Fuel Module



Two different types of landfills are included in the model: landfills that already have gas collection systems due to existing regulatory requirements (controlled landfills), and landfills that do not have gas-collection systems (uncontrolled landfills). The difference between the two, as far as greenhouse gases are concerned, is the mixture of the gases that are emitted to the atmosphere. It is assumed that fifty percent of the biomass carbon that is converted to gas in a landfill is converted to CO_2, and fifty percent is converted to CH_4. Gas-collection systems intercept most of the gases that are generated in the landfill (72 percent in the base case), and convert virtually all of the carbon in the collected gas to CO_2. Thus, with the base-case gas collection system the mixture of gases emitted to the atmosphere from a controlled landfill is 14 percent CH_4, and 86 percent CO_2. An uncontrolled landfill emits carbon gases in a mixture of approximately 50 percent CH_4 and 50 percent CO_2.

Modern controlled landfills begin gas collection anywhere from two-to-five years after waste is buried in the ground, and, under current regulations, continue gas collection for thirty years after cell closure.[9] Based on the alternative fate survey described earlier, it is estimated that in the absence of energy production approximately 75 percent of the biomass power-plant fuel in California that would otherwise be landfilled would go to controlled landfills, and 25 percent would go to uncontrolled landfills. It is likely that the proportion of waste going to controlled landfills will increase in the future, as new regulations go into effect. The controlled landfills in California either flare the landfill gas they collect, or burn the gas in engines for energy production, displacing the use of fossil fuels and their resulting greenhouse-gas emissions in the process. For each run of the model the user may specify the proportion of controlled landfills that have landfill-gas energy-production systems.

Analyzing the greenhouse-gas fate of biomass left in the forest as overstocked material is more complicated than that of already harvested biomass, because living biomass sequesters CO_2 from the atmosphere, as well as being a source of carbon emissions during wildfires and insect or disease events.[10] Left in the forest, overstocked biomass initially is treated as being part of a long-term storage reservoir, which is the overstocked forest itself. The overstocked forest has a higher probability of destructive wildfires than a thinned forest, and has a net annual growth rate (bdt/acre) that is lower than that of a thinned forest. When a wildfire does occur, it consumes not only some or all of the overstocked material that would have been removed in a thinning, but also a portion of the growing stock that would have remained in the forest after a thinning. For modeling purposes, the greenhouse-gas impact of leaving biomass in the forest as overstocked material is determined as the difference between the emissions of greenhouse gases from overstocked forests, and the emissions associated with thinned forests. Biomass carbon in a thinned forest has a longer residence time than in the overstocked situation (lower annual probability of fire), thinned forests have greater net annual growth than overstocked forests, and fires in thinned forests cause less extensive damage to the

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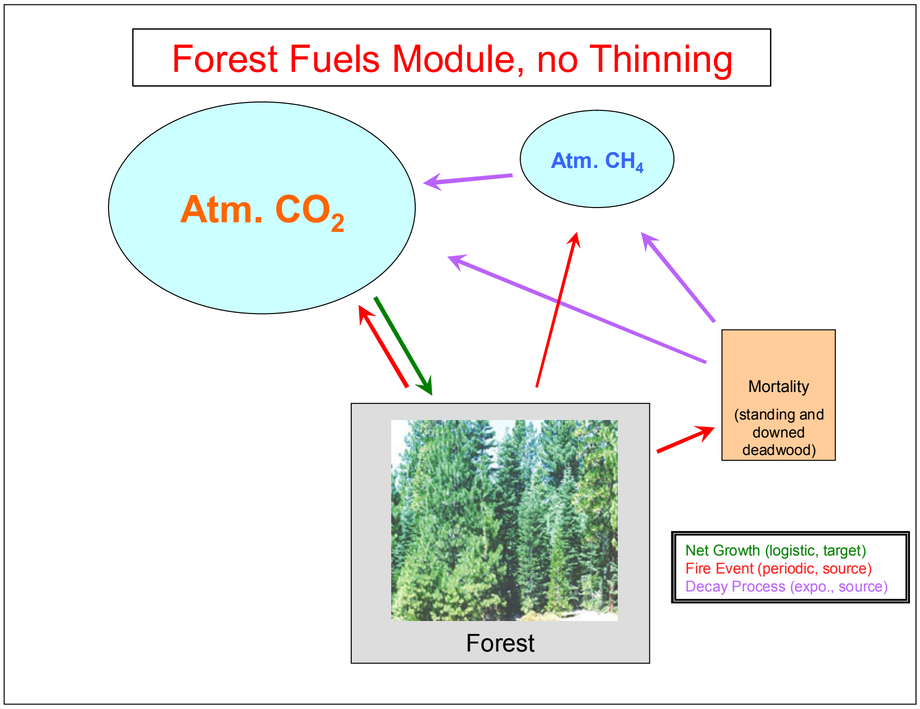
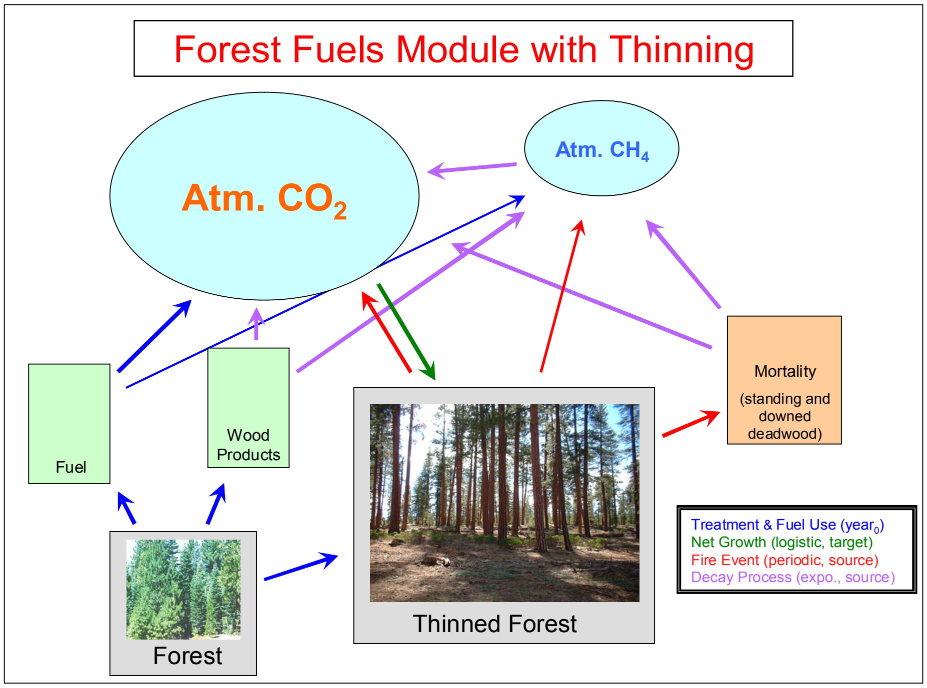
[9] A landfill cell is a subsection of a landfill that is operated as an independent unit, and closed when full while other, newer cells in the landfill are being operated.

[10] Fire is used in this white paper as a proxy for a variety of vectors that hit overstocked and stressed forests harder than healthy forests, including insect infestations and disease outbreaks that kill the trees.

growing stock than fires in overstocked forests. Figure 7 shows the model's forest-fuels modules.

Figure 7





Model Inputs and Base Case Assumptions

Table 2 shows the *Model Inputs Module* for the biomass greenhouse-gas model. All of the input data to the model are entered on this page, in the outlined cells, in blue. The data set shown in the Input Module in the table is the base-case data set. Annual biomass use in the base-case data set is based on 2005 biomass energy production in California, which has an installed generating capacity of 600 MW for solid-fuel biomass, 250 MW for landfill gas, and less than 10 MW for manure biogas generators.

The second data block in the Input Module is a matrix of factors for diesel fuel use in biomass fuel production and delivery. The data shown in the Table are the result of a survey of the California biomass energy industry performed in June, 2007. Thirteen of the state's 28 operating biomass facilities participated in the survey, providing data on diesel fuel use in biomass fuel procurement for their operations. Significant increases in the price of diesel fuel over the past several years have contributed to increased costs for harvesting, processing, and transporting solid biomass fuels to the power plants. In response, the biomass power industry has performed extensive analyses of the amount of diesel fuel use that goes into procuring their fuel, in support of their efforts to increase the level of support credits they receive through the existing renewables program at the California Energy Commission. Due to the fact that the biomass operators have independently analyzed the diesel fuel use that goes into producing and delivering their fuel, the diesel fuel-use data in the base case dataset are robust and representative. For the mix of biomass fuels used in California in 2005, average diesel fuel use in fuel procurement was 3.2 gallons per delivered bdt. Of the total greenhouse-gas emissions associated with the biomass energy production pathway, 2.0 percent are diesel (fossil) carbon, and 98 percent are biogenic carbon from the plant's exhaust stack.

Fuel procurement from sawmill residues requires the least amount of diesel fuel, averaging 1.3 gal/bdt, while fuel production from forest residues requires the most diesel fuel, averaging 4.5 gal/bdt, which represents 2.8 percent of the total greenhouse-gas emissions of the energy production pathway. It is interesting to note that diesel fuel consumption for the transportation of urban biomass fuels in California is higher than for any other category of biomass fuel. This is an indication that this relatively low cost-at-the-source form of biomass fuel is transported further than other types of biomass fuels, a consequence of the geography of the state and the location of the existing generating infrastructure. Diesel fuel emissions in biomass fuels production are accounted for in the model as fossil carbon. The net avoided fossil carbon emissions attributable to biomass energy production are the avoided emissions of electricity production less the diesel emissions in producing the biomass fuels.

The third data block in the Input Module contains the alternative-fates matrix that was discussed earlier and presented in Table 1.

Table 2: Model Inputs Module

	Biomass					**Biogas**			
	Mill	Forest	Ag	Urban	Total	Landfill Gas (bcf/yr)	Manure	% Total	Ann. Growth
Annual Fuel Use (th.bdt/yr)	1,316	583	999	1,726	4,624	26.5	120		0.0%
Diesel Fuel Consumption (gal / bdt)					3.2				
Fuel Production	0.1	2.5	1.8	1.6					
Fuel Transportation	0.7	1.5	1.2	2.0					
On-Site Fuel Handling	0.5	0.5	0.5	0.5					
Alternative Disposal	0.5	2.5	3.0	-					
If No Fuel Use, % that Would Be Disposed of by								dCO_2	dCH_4
Open Burning	0.0%	25.0%	60.0%	2.0%	780	17%	0.0%	23.8	0.0054
Forest Accumulation	0.0%	70.0%	0.0%	0.0%	408	9%	0.0%	-	-
Controlled Landfill	63.0%	0.0%	2.0%	55.0%	1,798	39%	0.0%	5.2	0.0012
Uncontrolled Landfill	10.0%	0.0%	18.0%	20.0%	657	14%	0.0%	6.7	0.0015
Spreading	1.0%	5.0%	0.0%	10.0%	215	5%	0.0%	0.9	0.0002
Composting	1.0%	0.0%	10.0%	13.0%	338	7%	0.0%	3.4	0.0008
kiln boiler / firewood	25.0%	0.0%	10.0%	0.0%	429	9%	0.0%	5.1	0.0012

	Initial Fate			In Storage (yr)		Loss from Storage		Accum. in
Fate of C if use	CO_2	CH_4	Storage	½ Life	Res.Time	CO_2	CH_4	Storage
Open Burning	90.3%	4.8%	5.0%	3.5	5.0	63.0%	27.0%	10.0%
Overstocked Forest			100.0%	35.6	51.3	92.5%	7.5%	0.0%
Thinned Forest			100.0%	49.9	72.1	92.5%	7.5%	0.0%
product			100.0%	55.5	80.0	51.4%	8.6%	40.0%
Controlled Landfill			100.0%	15.0	21.6	71.0%	11.6%	17.5%
lignin fraction				45.0	64.9	32.3%	5.3%	62.5%
Uncontrolled Landfill			100.0%	15.0	21.6	41.3%	41.3%	17.5%
lignin fraction				45.0	64.9	18.8%	18.8%	62.5%
Spreading			100.0%	3.5	5.0	83.1%	11.9%	5.0%
lignin fraction				25.0	36.1	65.6%	9.4%	25.0%
Composting	43.8%	6.3%	50.0%	3.5	5.0	83.1%	11.9%	5.0%
lignin fraction				25.0	36.1	65.6%	9.4%	25.0%
Kiln boiler	96.5%	2.0%	1.5%	10.0	14.4	63.3%	31.7%	5.0%
Lagoon	25.0%	30.0%	45.0%	3.5	5.0	46.7%	23.3%	30.0%
Biomass Energy	99.0%	0.1%	1.0%	10.0	14.4	63.3%	31.7%	5.0%

			ton / mmkWh			% avoided
Avoided Fossil Fuel C	% avoided	mmkWh/y	CO_2	CH_4	Storage	LF gas En.
Coal	50%	2,312	1,100	0.15	3.0	50%
N. Gas / ST & GT	0%	-	570	0.04		0%
N. Gas / Comb. Cycle	50%	2,312	450	0.10		50%
Diesel			22.0	0.005	lb/gal	

Carbon in Atmosphere	½ Life	Res. Time	Rad.Eff.
CO_2	83.2	120.0	1
CH_4	8.3	12.0	25

Electric Generation Efficiency	1.00	bdt/MWh
Biomass Electricity Produced	4,624	mmkWh/yr
% of dry Biomass that is Carbon		48%
% of Biomass Carbon that is lignin		25%
% of dry Manure that is Carbon		40%

First Year of Projection (1, or actual date)	2005		Generation Efficiency, Manure	3.00	bdt/MWh
One-Year Model or Continuous Input (1 = 1-yr, 0 = cont.)?	1		Electricity from Manure	40	mmkWh/yr
No. of Years @ Growth Rate	5				
Ave. Forest Density at Maturity (Stasis)	140	bdt / ac			
Ground Fuels Volatilized During Fire	15	bdt / ac			
Ave. Forest Density Before Thinning	120	bdt / ac			
Ave. Amount of Biomass Removed by Thinning	20	bdt / ac			
% Thinnings used as Small Sawlogs	30%				
% Sawlogs embodied in Product	60%				
Forest Growth Curve (years from 10% - 90%)	90	years			
Lag after Fire to Resume Normal Growth Curve	8	years			
Time Required to Fill a Landfill Cell	4	years			
Lag Before Collection Begins from a New Cell	3	years			
Years Collection Maintained After Cell Closure	30	years			
Proportion of Gas Collected with Controls @ Regulation	72%		Flare Combust. eff.	95%	
Proportion of Gas Collected with Controls Enhanced	77%		Engine Combust. eff.	98%	
Proportion of Controlled LFs w/ Energy Production	35%				
LF Gas Engine Heat Rate	12,000	btu/kWh	Electricity from LFG	1,151	mmkWh/yr

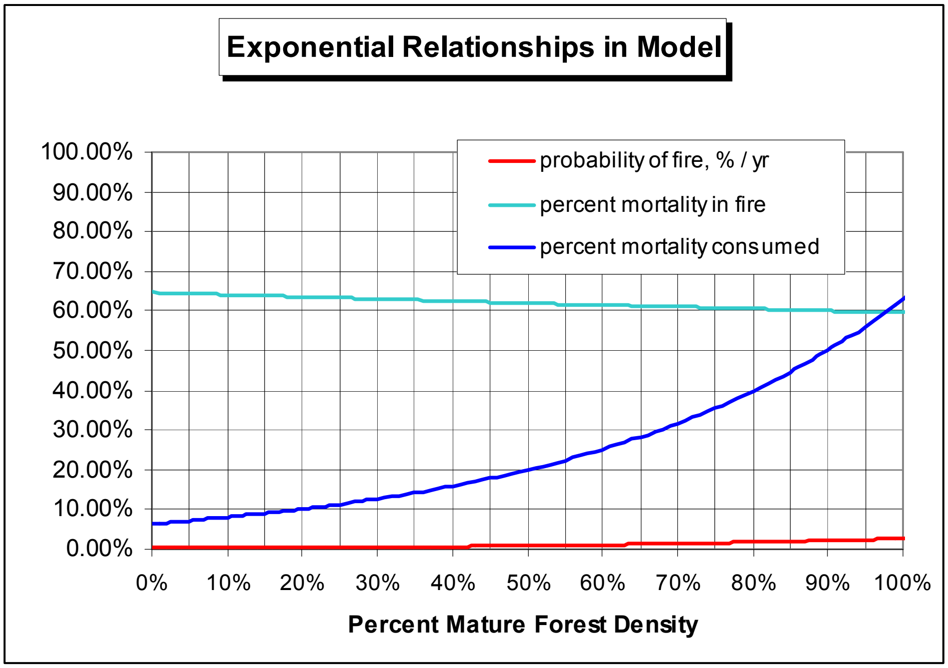
The fourth data block in the Input Module contains information on the partitioning of carbon among various carbon reservoirs considered in the model, and the storage characteristics (half-lives and residence times) of carbon in the various storage reservoirs. In order to illustrate how the information in this block works, take the example of *Open Burning* as the alternative to fuel use for biomass residues, which is the first row in the data block. In the base-case dataset, the initial fate of the biomass carbon subjected to open burning is that 95 percent of the carbon is combusted, and five percent remains as unburned biomass and char. Of the biomass that is combusted, 95 percent is converted to CO_2, and 5 percent is converted to CH_4. The unburned carbon has a 3.5 year half-life in solid form, which is equivalent to a 5.0 year residence time. Ten percent of the unburned carbon is assumed to be permanently sequestered during the 100-year timeframe examined in the model. The carbon that is volatilized from the initially unburned carbon is assumed to be partitioned between CO_2 and CH_4 at a ratio of 70:30.

The next several data blocks in the Input Module provide data on fossil-fuel use avoided by the production of energy from biomass, and data on the storage characteristics of carbon in biomass, and in the atmosphere. Biomass generation provides primarily base-load power. California's marginal base-load power comes from a mixture of in-state natural-gas fired combined-cycle generators, and out-of-state coal generators. The base-case dataset assumes that biomass power production in California displaces a fifty-fifty mixture of coal-fired power, and natural-gas fired combined-cycle power.

The final data block in the Input Module contains a variety of miscellaneous information on carbon storage and flow characteristics, as well as several model setup functions. It also contains a set of parameters describing forest thinning operations that produce in-forest fuels, and a set of parameters describing materials handling and operations in landfills. The base-case data on forest thinning operations were developed as part of the Biomass-to-Energy (B2E) research project, a life-cycle analysis of forest treatment operations performed by the U.S. Forest Service subject to a PIER (Public Interest Energy Research) grant from the CEC. The base-case assumptions on landfill disposal are based on literature sources.

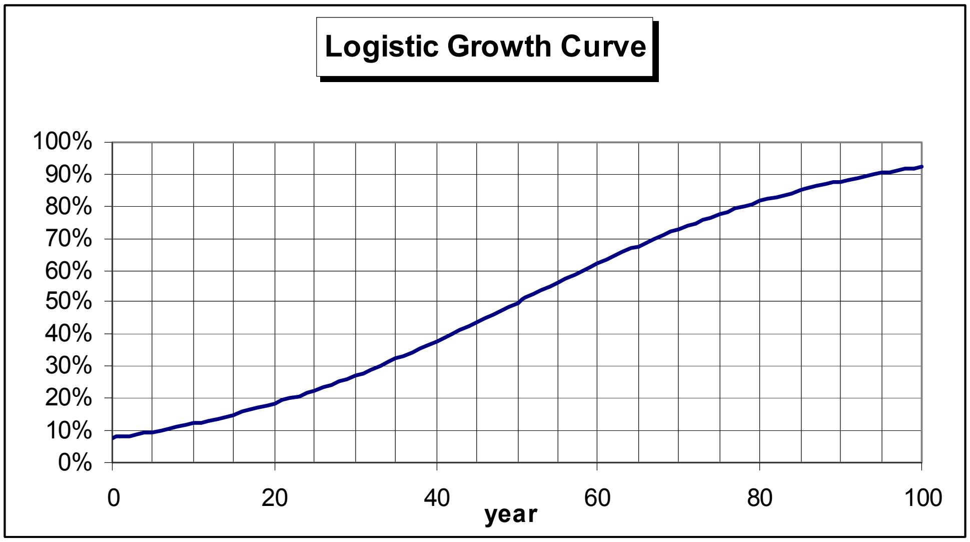
The model incorporates exponential decay mechanics for the loss of carbon from biomass stocks in the model, such as losses of carbon stored in forest biomass due to periodic events, such as fires. The B2E project, of which this study is a part, developed a series of detailed, 40-year fire scenarios for a 2.7 million acre landscape in northern California that is representative of many regions in the state that have extensive potential for forest thinning operations. The relationship between forest density and fire probability, fire mortality, and percent of total mortality that is consumed are derived from the B2E project modeling data. Figure 8 shows the exponential relationships that are used by the greenhouse-gas model.

Figure 8



Net annual forest growth in the model is based on logistic growth mechanics, in which net growth is expressed as a function of standing forest density. Logistic growth is defined by two parameters, the length of time for growth to proceed from a level of ten percent of maximum forest density (density of forest at zero net annual growth) to ninety percent of maximum density, and the magnitude of the maximum density. As in the case of the fire data, the dynamics of the growth curve used in the model are derived from the B2E data. Figure 9 shows the logistic growth curve.

Figure 9

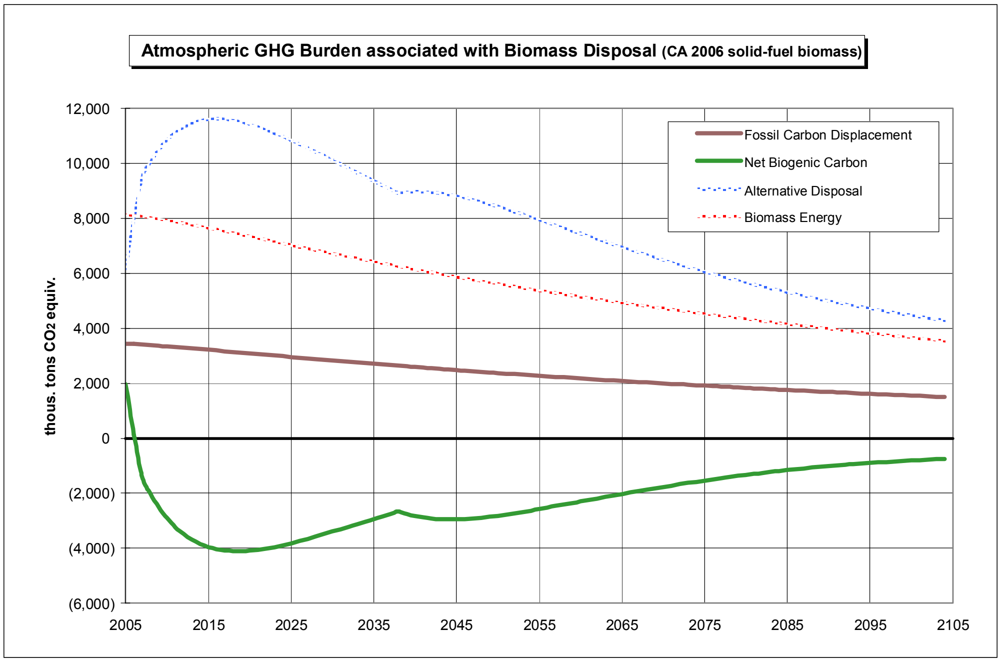


The Greenhouse-gas Implications of Bioenergy Production

Solid-Fuel Biomass

Biomass energy production in California during 2005 converted 7.8 million tons (4.6 million bdt) of biomass wastes and residues into electricity, which avoided the production of approximately 4,600 million kWh of electricity from fossil-fuel sources. This translates into an avoidance of nearly four million tons of CO_2 equivalents from fossil fuel combustion during 2005, as indicated by the brown curve labeled *Fossil Carbon Displacement* in Figure 10. In addition, conversion of the biomass to energy avoided alternative disposal of the residues, and their associated greenhouse-gas emissions. Alternative disposal would have resulted in the immediate emission of more than six million tons of CO_2 equivalents during 2005, mostly from the fraction of the biomass that otherwise would have been open burned. Subsequent emissions of additional greenhouse gases over time from the burial of some of the residues in landfills, and the accumulation of some of the residues as overgrowth in forests, where it increases the risks of catastrophic wildfires, would then ensue. The greenhouse-gas levels associated with alternative disposal of the residues peaks at almost twelve million tons of CO_2 equivalents in 2017, then begins to dissipate, as indicated by the blue line in Figure 10. A small hitch occurs in the curve in the year 2036, when controlled landfills terminate the gas collection process. The upper (blue) curve in the figure shows the biogenic greenhouse-gas profile that was avoided due to biomass energy production in California during 2005. The red curve shows the greenhouse-gas profile for the biomass power plant emissions. The net biogenic greenhouse-gas effect of the California biomass power industry in 2005 is shown by the green curve (red - blue).

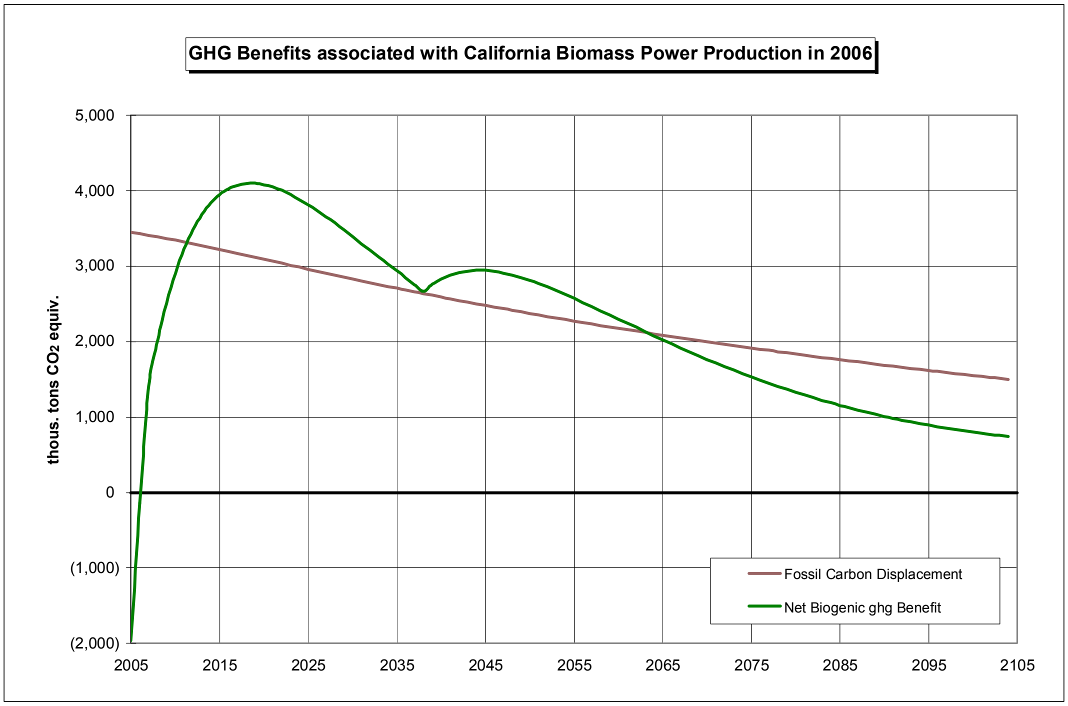
Figure 10



Biogenic greenhouse-gas levels (green curve in the figure) were initially elevated as a result of the operations of the biomass industry in 2005, by about two million tons of CO_2 equivalents. Due to avoided delayed emissions of alternative biomass disposal, net biogenic greenhouse-gas levels due to biomass energy production become negative (a net benefit) within a couple of years of the use of the fuel. After ten years, biogenic greenhouse-gas levels are depressed by almost four million tons of CO_2 equivalents, an atmospheric benefit that is approximately equal to, and in addition to the benefit that was derived from the displacement of fossil energy production. Biogenic emissions remain depressed throughout the remainder of the 100-year timeframe, as illustrated in the figure.

Figure 11 shows the same data, but with the biogenic greenhouse-gas curve flipped in order to overlay the biogenic greenhouse-gas benefit of biomass energy production with the fossil-carbon greenhouse-gas benefit. Although the profiles differ, visual inspection of the figure suggests that the biogenic greenhouse-gas benefits of biomass energy production in California in 2005, when considered over the long term, are approximately equal in magnitude of climate change potential, to the fossil greenhouse-gas emissions that were avoided, and this does not take into account the fundamental difference between fossil carbon emissions, which add new carbon to the system, and biogenic carbon emissions, which involve carbon already in the system.

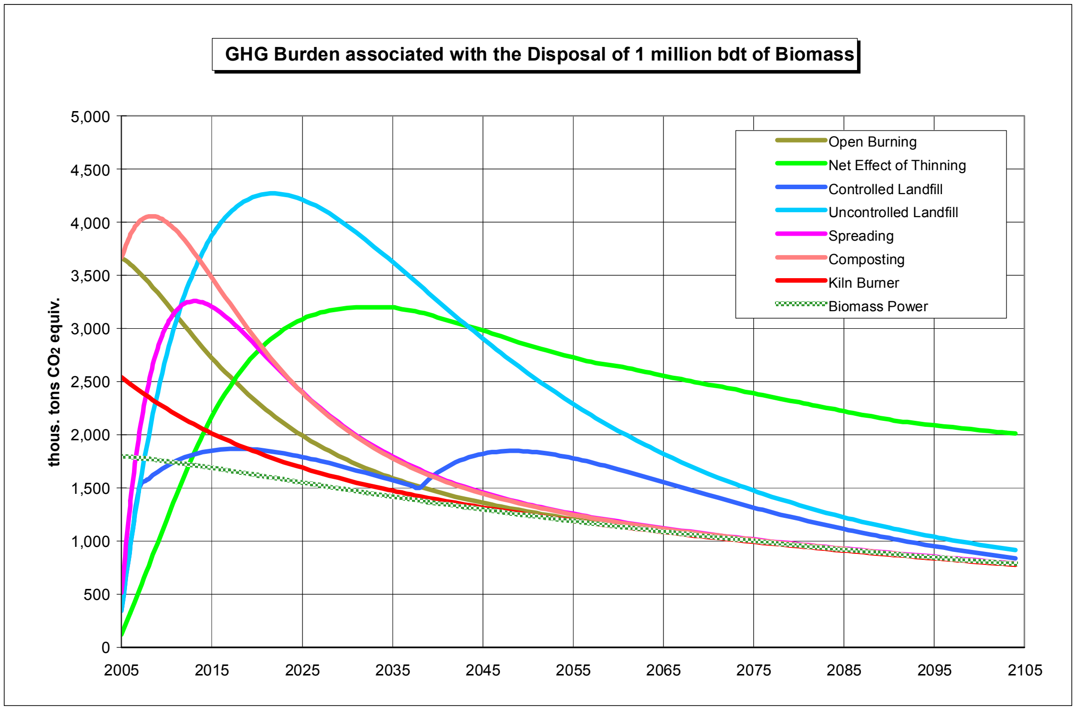
Figure 11



The results show that the use of the 7.6 million tons (4.6 million bdt) of biomass fuel in California during 2005 resulted in a reduction in the atmospheric greenhouse-gas burden of approximately 6.3 million tons of CO_2 equivalents 25 years later. The reduction is due about equally to fossil and biogenic carbon levels, based on the base-case assumptions used in the analysis. In 2012, when the Kyoto protocols require participating jurisdictions to reduce their greenhouse-gas emissions to seven percent below 1990 baseline levels, the use of biomass fuels during the year 2005 in California will have reduced 2012 greenhouse-gas emissions by more than 6.8 million tons of CO_2 equivalents, including both the avoided fossil emissions (3.4 million tons), and the biogenic greenhouse-gas reduction (3.4 million tons).

One of the purposes of conducting this analysis is to determine greenhouse-gas emissions factors for the various activities relevant to biomass energy production, including biomass power plant emissions, avoided fossil fuel emissions, and emissions for the various alternative disposal options for biomass residues. Figure 12 shows the profiles over time of the greenhouse-gas burdens associated with biomass energy production, and the various alternative disposal options for the biomass fuels that are included in the analysis, with all curves scaled to the disposal of one million bdt of biomass residues in 2005. As illustrated by the figure, the atmospheric greenhouse-gas profile over time is very different for the energy production alternative, and for the alternative disposal activities.

Figure 12



The curve for stack emissions from the biomass energy alternative is based on the immediate release of virtually all of the fuel-bound carbon as CO_2, followed by its gradual clearance from the atmosphere, with the assumed residence time of 120 years. The conversion of one million bdt of biomass leads to emissions of 1.75 million tons of biogenic CO_2. Over the long term, all of the alternative disposal options for the biomass residues produce higher levels of biogenic greenhouse-gas levels than use of the biomass for electricity production.

More than half of the biomass residues used for energy production in California today would be landfilled in the absence of energy production. The immediate impact of landfilling biomass, from a greenhouse-gas perspective, is to place the biomass carbon in a fixed-carbon storage reservoir (the landfill), thus keeping it out of the atmosphere. The biomass carbon in the landfill, however, begins to degrade slowly into a fifty-fifty mixture of CH_4 and CO_2, which is emitted to the atmosphere over an extended period of time. Due to the great imbalance in radiative effectiveness between the two forms of carbon, the greenhouse-gas burden of landfill burial exceeds that of energy production within three-to-six years of the disposal of the material in the landfill, even though much less total carbon is released into the atmosphere over the 100-year timeframe of the analysis.

For uncontrolled landfills, the greenhouse-gas burden of burying one million bdt of biomass in the year 2005 increases rapidly for fifteen years after burial of the waste, peaking at more than 4.25 million tons of atmospheric CO_2 equivalents in 2022, using the base-case assumptions. After that time the rate of atmospheric clearance of the accumulated CH_4 exceeds the rate of emissions from the landfill, and the total greenhouse-gas burden associated with the previously buried waste gradually decreases over time.

The greenhouse-gas burden associated with biomass buried in controlled landfills departs from that of uncontrolled landfills as soon as the gas collection system is placed into service, which in the base-case dataset is three years after the burial of the waste (the assumed average period of time until cell closure). The rate of out-gassing of carbon from the landfill is the same for both types of landfills, but the ratio of CH_4 to CO_2 that is emitted to the atmosphere is very different for a controlled landfill. During the 30-year gas collection period the greenhouse-gas burden for one-million bdt of residue in a controlled landfill remains relatively constant, at slightly less than two-million tons of CO_2 equivalents per million bdt of biomass. Following the end of gas collection the greenhouse-gas burden bumps up for a couple of decades, before gradually decreasing. By the end of the one-hundred-year time period, the greenhouse-gas burden from the controlled landfills and uncontrolled landfills is virtually the same, as almost all of the methane emitted to the air by both kinds of landfills has been oxidized to CO_2.

Biomass degradation in the landfill environment is a highly variable process that is dependent on, among other things, evolving landfill-management technology. Borings into old landfills show that the rate of biomass degradation can be radically different in different landfills, and even in different locations within the same landfill. For modeling purposes, biomass disposed of in landfills is assumed to be partitioned into two functionally distinct fractions: relatively degradable carbon (cellulose and hemicellulose), and lignin. The lignin fraction is more resistant to decomposition than the degradable fraction. Each carbon fraction (degradable, lignin) is assigned its own characteristic half-life and percent long-term non-degradable component in the model. The base-case data set used in this analysis assumes a half-life of 15 years for readily degradable carbon, and 45 years for lignin. Furthermore, it is assumed that 17.5 percent of the degradable carbon, and 62.5 percent of the lignin, does not decompose at all during the 100-year timeframe considered by the model. Using the base-case dataset, 56 percent of the original biomass carbon remains entombed in the landfill 25 years after burial. Forty percent of the total biomass carbon remains entombed 50 years after burial. Waste Management Inc. estimates that approximately fifty percent of the carbon buried in a landfill degrades during the thirty-year regulatory control period.

Some researchers report even slower rates of degradation of biomass in the landfill environment.[11] As a sensitivity check, we have constructed a reduced-degradation case for biomass carbon in a landfill. In this case, we assume a half-life of 20 years for readily degradable carbon, and 75 years for lignin. We also assume that 35 percent of the degradable carbon, and 90 percent of the lignin, does not decompose at all during the 100-year timeframe analyzed by the model. In the reduced-degradation case, 72 percent of the original biomass carbon remains entombed in the landfill 25 years after burial, and sixty percent of the total biomass carbon remains entombed 50 years after burial.

Figure 13 shows the biogenic greenhouse-gas profiles for energy production at both controlled and uncontrolled landfills, using the degradation-rate assumptions in both the base-case dataset, and the reduced-degradation-case dataset. Diversion of fuel-usable waste wood from an uncontrolled landfill continues to provide significant greenhouse-gas benefits in the reduced-degradation case, although the magnitude of the benefit is reduced by approximately one-half compared with the base case data. In the case of diverting waste wood from a controlled landfill, the biogenic greenhouse-gas effect does not turn beneficial until forty years after the fuel was diverted for the reduced-degradation case. In this case, the only significant greenhouse-gas benefit of the energy option is the avoidance of fossil fuel use.

Composting and spreading have greenhouse-gas profiles that are similar to the profile for uncontrolled landfills, except that the lag times for degradation are reduced, and the degradation tends to be partially aerobic, as opposed to being entirely anaerobic as it is in a landfill. This results in a higher proportion of emissions in the form of CO_2, and a smaller proportion are the form of CH_4. In the case of composting, the composting process itself encourages rapid, mostly aerobic degradation in the compost pile before it is spread, whereas spreading has no such pretreatment. It should be noted that solid wood residues are generally not desirable material for a composting operation, as wood degrades and stabilizes much more slowly than other forms of green waste in the composting process.

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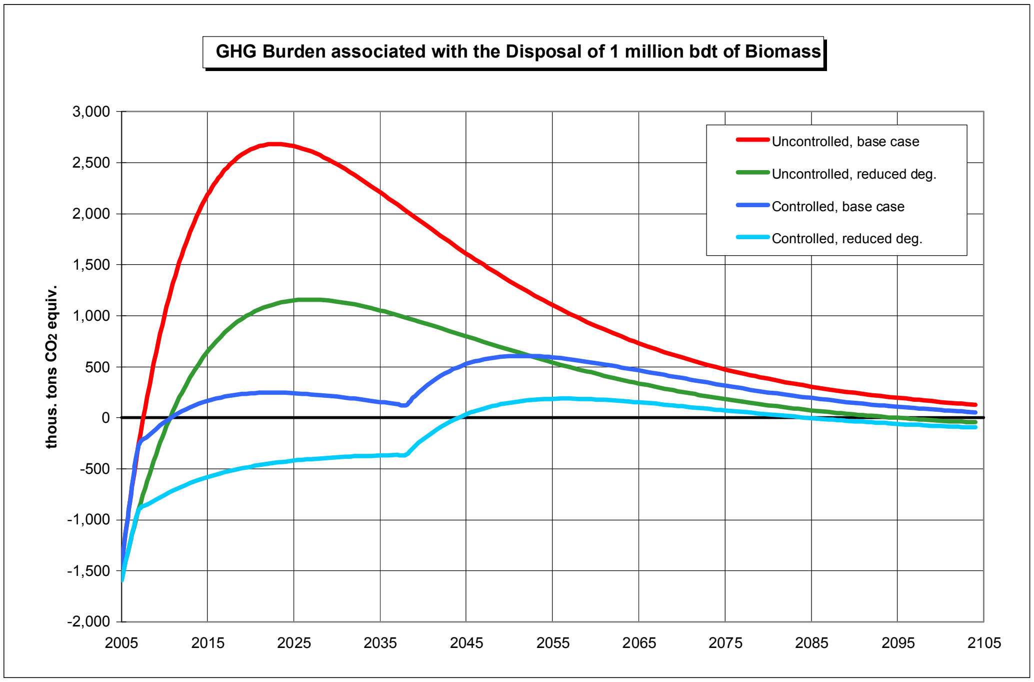
[11] See, for example, Micales & Skog, *The Decomposition of Forest Products in Landfills*, **International Biodeterioration & Biodegradation**, vol. 39, 1997, Barlaz, *Forest Products Decomposition in Municipal Solid Waste Landfills*, **Waste Management**, vol. 26, 2006.

Figure 13



The delay in the onset of greenhouse-gas benefits from using forest residues that would otherwise accumulate in the forest is even more pronounced than that for using landfill-diverted wood wastes. The greenhouse-gas benefits associated with the use of forest thinnings,[12] which result from both enhanced net biomass growth in the treated forest, and reduced risk of destructive forest fires and insect and disease infestations, doesn't peak until approximately thirty years after the forest treatment is performed. Assuming that the treated forest continues to receive periodic treatments over time, a practice that is not reflected in the model, the use of this type of biomass for energy production has a large positive impact on biogenic greenhouse-gas emissions much further into the future than is the case for the other categories of biomass fuels. This is mainly because thinning the forest protects the bulk of the remaining growing stock from fire and disease risks and enhances net annual forest growth. In the absence of thinning an overgrown forest, when a wildfire or disease outbreak does occur, it tends to consume far more total biomass, and thus release far more carbon, than would have been removed by thinning and protecting the bulk of the forest biomass.

California's forests are highly diverse. Overgrown forests that are candidates for thinning operations exist in all of the state's major forest regions, although the types and extent of treatments that are needed vary greatly. We have attempted to construct a base-case dataset that is representative of the types of treatment operations in which unmerchantable residuals are used as biomass fuel. The base-case dataset for forest

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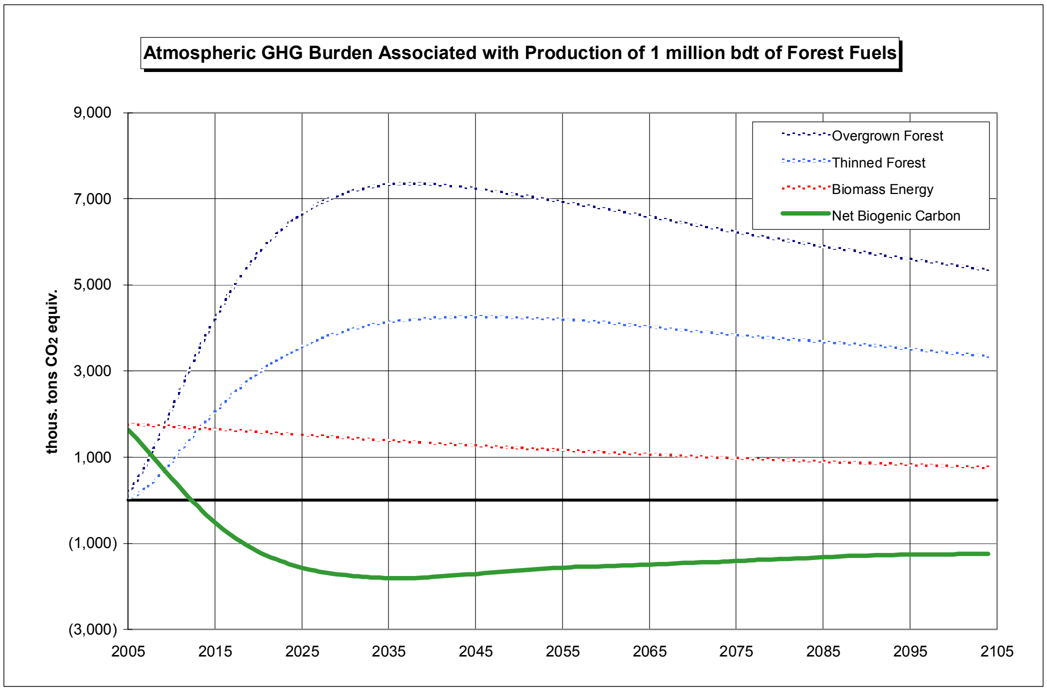
[12] In the context of in-forest residues, net benefit is used in the sense of expected net benefits, with a probability distribution of wildfire assigned to the in-forest residue fuel that is left as overgrowth material in the forest.

thinning operations assumes that twenty bdt per acre of biomass are removed during thinning operations, of which thirty percent of the removals are used as small sawlogs, and the remainder are used as power plant fuel. The forest has a growing stock that averages 120 bdt per acre before treatment, which is a density that is 86 percent of the density (140 bdt per ac.) found in a mature, net-zero-growth forest (forest in stasis). Figure 14 shows the base-case greenhouse-gas profiles for the use of one million bdt of forest treatment fuels in 2005, versus failing to perform the treatments that would produce this fuel. The production of one million bdt of forest fuel using base-case assumptions is associated with the treatment of 61,000 acres of overgrown forest. Treatment of these 61,000 acres of California forest in 2005, presumably scattered around the state, would lead to a reduction in biogenic greenhouse-gas levels of nearly two million tons of CO_2 equivalents 25-years later, as well as avoiding approximately 0.9 million tons of fossil CO_2 emissions in 2005, which would leave a residual level of approximately 0.75 million tons 25 years later.

Figure 14



The net benefit of reduced biogenic carbon due to energy production from forest treatment fuels is not very sensitive to the percent of the removals that are recovered as small sawlogs, which is assumed to be 30 percent in the base case. Eliminating the small-sawlog option entirely and using all of the treatment removals from 61,000 acres as fuel reduces the biogenic emissions benefit by only about 12 percent as compared with the base case benefit. When treatments are performed on stands that have a lower initial stand density than assumed in the base case (86 percent of stasis), the benefits are also reduced. For example, if the treatments are performed on land that is, on average, 64 percent of mature stand density, or 90 bdt per ac, then the biogenic emissions benefits are reduced by about 31 percent when compared with the base case.

Increasing the amount of material that is removed during treatment has the potential to greatly increase the resulting net biogenic greenhouse-gas benefit. The base-case dataset assumes that the treatments remove a total of 20 bdt of biomass per acre. The majority of treatments currently performed in the state are on private forestlands, which are generally in better condition than public forestland in the state. Assuming that in the future the managers of the needier public lands in the state become more amenable to performing treatment operations, it is likely that the average amounts of removals (bdt per acre) will also increase. The base case assumes 20 bdt per ac are removed. If removals are increased to an average of 35 bdt per ac, the biogenic emissions benefits are increased by about fifty percent as compared with the base case benefit.

One of the other primary alternative disposal activities employed for biomass residues in California is open burning. Open burning is similar to energy production in the sense that virtually all of the residue material is converted immediately into greenhouse gases. Open burning, however, is less efficient than controlled combustion in a boiler in terms of converting carbon into CO_2. The result is that, in addition to CO_2, open burning produces significant amounts of methane and other hydrocarbons. The presence of these reduced-carbon gases in the emissions from open burning leads to an initial greenhouse-gas burden of 3.65 million tons of CO_2 equiv. from the disposal of one million bdt of residues. The hydrocarbons convert to CO_2 with a half-life of 8.3 years, causing the greenhouse-gas burden to become indistinguishable from the burden associated with energy production from the same residues by the end of forty years (see Figure 13).

Kiln boilers and fireplaces are also alternative disposal options for biomass residues. These combustion devices tend to burn fuel more efficiently than open burning in piles, but less efficiently than in sophisticated power plant boilers. As a result, the greenhouse-gas profile for kilns and fireplaces is intermediate between the profile for biomass power production, and the profile for open burning. The initial consequence of biomass use for kilns and fireplaces is a greenhouse-gas burden of approximately 2.5 million tons of CO_2 equivalents from the disposal of one million bdt of residues. As in the case of open burning, after about forty years the profile for biomass use in kilns and fireplaces becomes indistinguishable from the profile for power plants.

The greenhouse-gas burden resulting from the open burning of one million bdt of biomass, which initially is more than twice as great as that of energy production using the same amount of biomass, is virtually the same by 40 to 50 years later. The question then becomes: Is the greenhouse-gas emission factor for open burning two times greater than that for energy production, the same, or somewhere in-between? Climate change is clearly a long-term, cumulative problem. Thus, judging the magnitude of the greenhouse-gas implications associated with our current activities requires taking the resulting long-term atmospheric loadings into account. Disposal options that delay the release of the carbon associated with biomass, only to eventually cause higher atmospheric burdens later on, should be valued based on the long-term profile of the resultant atmospheric greenhouse-gas burden.

As illustrated in Figure 12, most of the difference in biogenic greenhouse-gas burden between the energy production and alternative disposal pathways occurs during the first 30 to 50 years after the biomass is converted into fuel or subjected to an alternative fate. Table 3 shows net biogenic greenhouse-gas reduction factors (greenhouse gas due to alternative disposal less greenhouse gas due to energy production) for energy produced from biomass diverted from the indicated alternative disposal categories. The data are the average level of greenhouse-gas burden in the atmosphere associated with the use of the residue during the period indicated following the use or disposal of the biomass. For example, for biomass fuel diverted from open burning, during the first 25 years after the fuel is used the average net reduction in biogenic greenhouse gas in the atmosphere compared to open burning is 0.95 ton CO_2 equiv. per bdt. Beyond about 30 years there is very little residual net advantage in terms of biogenic greenhouse-gas burden for having diverted biomass from open burning to energy production (average net reduction of 0.05 ton CO_2 equiv. per bdt between 25 and 50 years after fuel use). For fuels derived from forest treatment operations (diverted from forest accumulation), the picture is very different. The net reduction in biogenic greenhouse gas averages only 0.55 ton CO_2 equiv. per bdt during the first 25 years after fuel use. However, the average net reduction increases to 2.28 ton CO_2 equiv. per bdt during the following 25 years (years 25 – 50), when the increase in net forest growth, and the decrease in fire, pest, and disease losses, has greatest impact. The table also shows the composite net greenhouse-gas reduction on a CO_2 per bdt basis for the 2005 California biomass fuel mix, and the avoided fossil greenhouse-gas burden during the various time periods following biomass energy production or disposal.

Table 3

Greenhouse Gas Burden

(data are in tons CO_2 equiv. per bdt of biomass, averaged over period)

Net Reduction in Biogenic C	0-25 yrs	25-50 yrs	50-75 yrs	75-100 yrs
Open Burning	0.95	0.05	0.00	0.00
Forest Accumulation	0.55	2.28	1.45	1.25
Uncontrolled Landfill	1.80	1.78	0.70	0.30
Controlled Landfill	0.05	0.38	0.45	0.15
Spreading	0.95	0.18	0.00	0.00
Composting	1.45	0.18	0.00	0.00
Kiln Boiler / Fireplace	0.30	0.05	0.00	0.00
California Biomass Mix 2005	0.68	0.60	0.40	0.20
Avoided Fossil C, CA basis	0.70	0.55	0.45	0.38

For analytical purposes, it is desirable to define a single figure of merit that can be used for comparing the greenhouse-gas emissions and resulting atmospheric-burden profiles for biomass energy production, avoided alternative disposal, and avoided fossil-fuel energy production. A fifty-year time horizon is adopted for comparing the greenhouse-gas profiles of the various avoided net alternative disposal options and avoided fossil-fuel use that are considered in the model. As can be seen in Figure 12, 50 years after fuel use or disposal all of the alternative disposal options except landfill disposal and forest thinning are indistinguishable from biomass energy production in so far as the resulting burden of biogenic greenhouse gases is concerned. Therefore, on a preliminary basis, the greenhouse-gas emissions factors for each activity (energy production or alternative fate) are based on the average atmospheric burden over the fifty-year period following fuel use (this is equivalent to the average of the first two columns in Table 3).

Table 4 shows the calculated values for the net greenhouse-gas reductions for the various biomass disposal options, as well as for the avoided fossil greenhouse gases, based on the base-case dataset developed for this study. The fifty-year average net burden of greenhouse gases, expressed in terms of tons of CO_2 equiv. per bdt of biomass, is shown in the first column in the table. For the categories of forest accumulation residues and residues buried in landfills, a residual emissions factor is added to reflect their enduring positive effect on biogenic greenhouse gases beyond the fifty-year time horizon. The third column in the table shows the sum of the first two columns, which is the fifty-year average plus residual. The last step is to translate the 50-year average emissions burden into an equivalent first year emissions factor based on CO_2. The final column in the table shows the equivalent year-one avoided emissions of CO_2 that produce the same 50-year average greenhouse-gas burden as the amount shown in the column labeled **ton/bdt**$_{tot}$. For example, the use of forest fuels avoids fossil greenhouse-gas emissions of 0.8 ton CO_2 equiv per bdt, and reduces net biogenic greenhouse gases by the equivalent of avoiding an additional 1.87 ton per bdt of CO_2 emissions.

Table 4

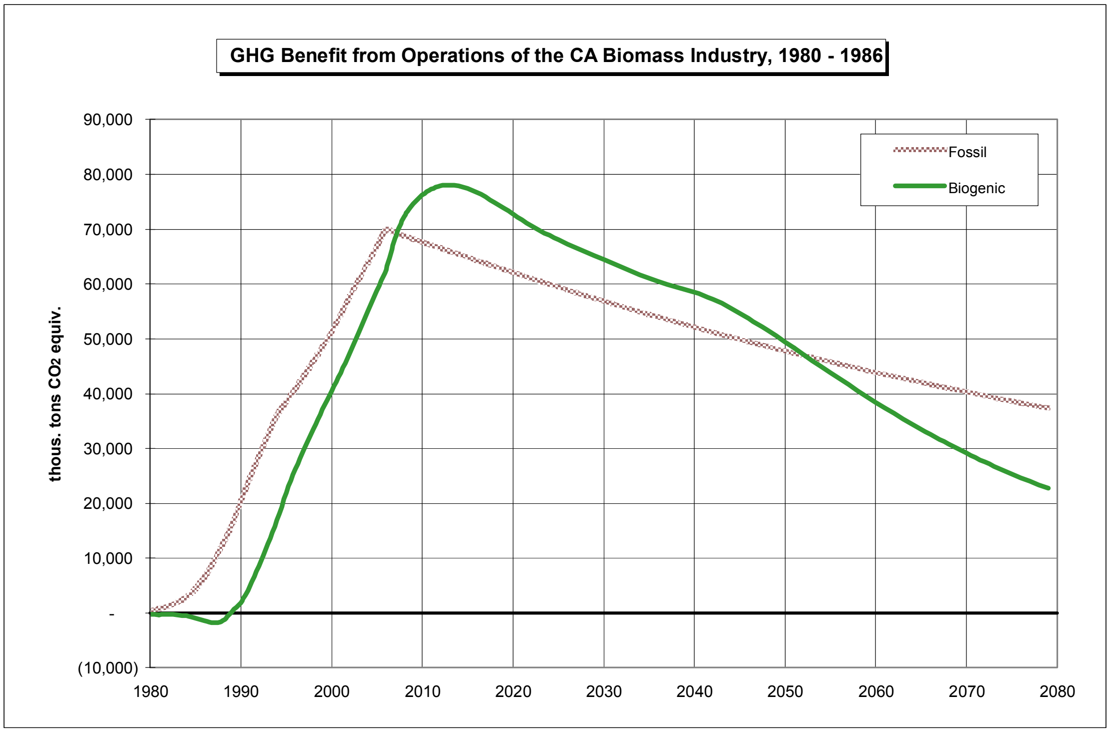
Greenhouse Gas Emissions Factors

(data are in tons CO_2 equiv. per bdt of biomass)

	ton/bdt $_{50yr}$	**residual**	**ton/bdt** $_{tot}$	**ton/bdt** $_{yr\ 1}$
Net Reduction in Biogenic C				
Open Burning	0.50		0.50	0.62
Forest Accumulation	1.41	0.10	1.51	1.87
Uncontrolled Landfill	1.79	0.05	1.84	2.28
Controlled Landfill	0.21	0.01	0.22	0.27
Spreading	0.56		0.56	0.69
Composting	0.81		0.81	1.00
Kiln Boiler / Fireplaces	0.18		0.18	0.22
California Biomass Mix 2005	0.64	0.02	0.66	0.81
Avoided Fossil Fuel Use	0.63	0.02	0.65	0.80
(based on Calif. mix)				

The modern California biomass energy industry has been operating for more than 25 years, growing from an outgrowth of the sawmilling industry into a crucial component of the state's solid waste disposal infrastructure. To date approximately 100 million bdts of biomass have been diverted from the state's landfills or from open burning, and approximately one-million acres of forest land have been treated for wildfire risk reduction because of the operations of the industry from 1980 through 2006. Figure 15 shows the long-term atmospheric greenhouse-gas benefits that have already been achieved by the use of biomass for energy production in California since 1980. The concentrations of biogenic greenhouse gases in the atmosphere at the present time are lower by more than 65 million tons of CO_2 equivalents than would have been the case had the California biomass energy industry not been developed, and they will continue to drop for several years into the future as a result of activities that have already occurred. In addition, approximately 75 million tons of CO_2 equivalents of fossil carbon emissions have been avoided over the past 25 years due to the operations of the state's biomass energy industry, with the result that fossil greenhouse-gas levels in the atmosphere are lower by 70-million tons of CO_2 equiv. than would be the case if the biomass industry had not developed in the state (approximately 5 million tons of the fossil CO_2 avoided since 1980 would have already cleared from the atmosphere – see Figure 15).

Figure 15



Landfill Gas

The section above considered the greenhouse-gas implications of diverting fuel-usable solid wood wastes from landfill disposal to energy production in a biomass power plant. However, regardless of the level of recycling and diversion incentives that are employed for keeping materials out of landfills, a certain amount of biodegradable waste will continue to be landfilled, and will continue to produce landfill gases. In addition, a great deal of material has already been disposed of in the state's landfills, where it is and will continue to undergo natural degradation and produce landfill gas.

For biodegradable material already buried in landfills, and for material that will continue to be disposed of in landfills, collection of the ensuing landfill gas, combined with either energy production or a flare, has a large beneficial effect on greenhouse-gas emissions by the simple and direct conversion of CH_4 to CO_2 from the collected biogas. Converting CH_4 to CO_2 reduces the immediate greenhouse warming potential of the converted gas by a factor of 25. Over time, the greenhouse-gas advantage of having collected and combusted the landfill gas in 2005 dissipates to zero, as the biogenic CH_4 emitted under all scenarios is converted to biogenic CO_2. In addition to reducing biogenic greenhouse gases, using landfill gas for energy production displaces the fossil carbon emissions associated with the production of the displaced energy.

California's 300 largest landfills produce an estimated 118 to 156 billion cubic feet (bcf) of landfill gas.[13] At the present time only about 26.5 bcf of landfill gas are converted to energy in California annually, and an additional 55 bcf of landfill gas is collected and flared. Collection with a flare and collection with conversion to energy are very similar with respect to their effects on biogenic greenhouse gases. Small differences can result from differences in combustion efficiency between a flare and an engine, and from the possibility that a more extensive gas collection system will be installed for an energy system than is required to meet the regulatory requirements for the landfill. New landfill-energy systems are currently facing a regulatory roadblock in California due to NOx emissions levels from the engines.

Figure 16 shows the greenhouse-gas profiles for the approximately 26.5 bcf of landfill gas that was converted to electricity in California in 2006. The figure shows three cases: uncontrolled landfills, landfills controlled with flares, and landfills with gas collection and energy production systems. California's landfill-gas energy systems avoided 900 thousand tons of CO_2 equivalents of fossil carbon emissions in 2005. In addition, for energy systems that are installed at landfills that would otherwise not collect landfill gas at all, the energy systems avoid the emissions represented by the difference between the red curve and the green curve in the figure. For energy systems installed at landfills already subject to control, the energy systems avoid the emissions represented by the difference between the blue curve and the green curve in the figure.

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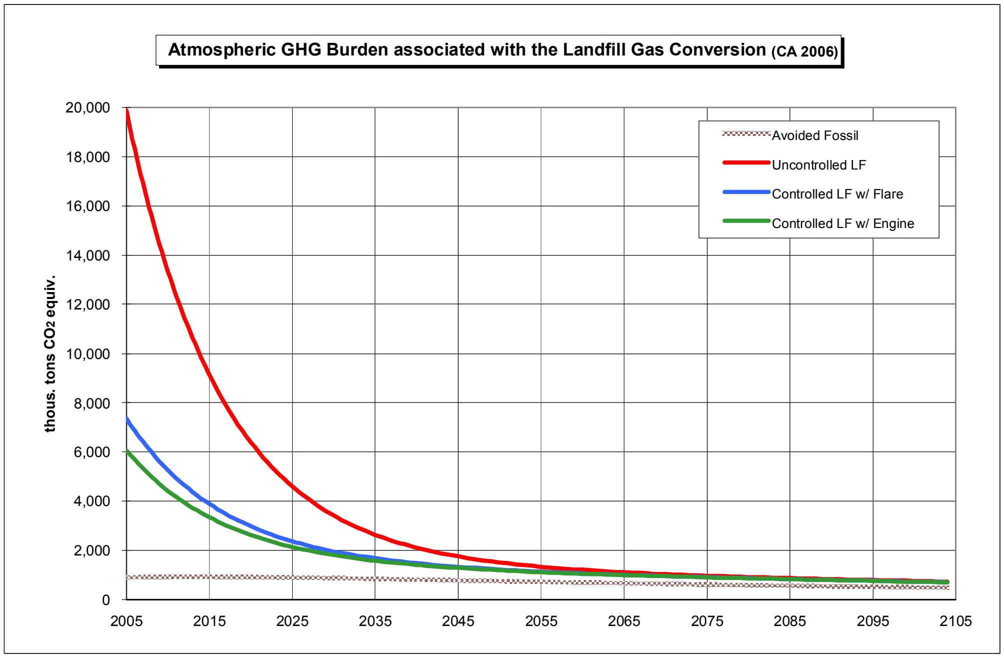
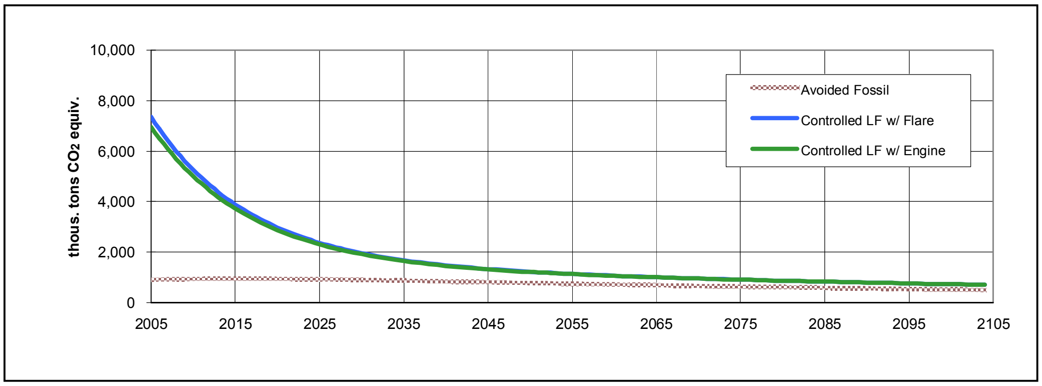
[13] California Biomass Collaborative, *Biomass in California: Challenges, Opportunities, and Potentials for Sustainable Management and Development*, Report to the CEC PIER program, contract no. 500-01-016, June 2005.

Figure 16



The base-case dataset assumes that 72 percent of the total landfill gas is collected at landfills that are controlled to meet EPA gas-collection regulatory requirements. It further assumes that 77 percent of the landfill gas is collected at landfills that employ energy production systems. In many cases landfill energy systems are designed simply to meet the regulatory requirements imposed on the landfill, or 72 percent collection as assumed in the base case. In this case, the green curve in Figure 16 begins at a level of 6,950 thousand tons of CO_2 equivalents, rather than the 6,000 shown in the figure, and is only slightly below the blue curve, as illustrated in Figure 17 below. In other words, for landfill gas energy systems that are sized to meet regulatory requirements, the only greenhouse-gas benefits compared to flare systems are those of fossil fuel displacement. The difference in biogenic greenhouse-gas emissions is minimal, relating to the slight improvement in combustion efficiency in an engine versus a flare (98 percent vs. 95 percent in the base-case dataset).

Figure 17



Biogas from Manures

California dairies produce 3.6 million bdt of manure annually. Cattle feedlots in the state produce an additional 4.4 million bdt. Manure disposal at dairies is a major environmental concern, and has been the subject of a great deal of regulatory activity over the past couple of decades. At the present time the dominant form of manure management at dairies in California is to employ flush systems combined with open lagoon treatment, followed by land spreading of the residual solids. The lagoons support active anaerobic degradation of the digestible fraction of the manure, producing a biogas that is 55 to 60 percent CH_4, and 40 to 45 percent CO_2. In conventional dairy practice the biogas is vented directly into the atmosphere.

Energy production from dairy operations involves a fairly simple retrofit to the conventional manure management system. Collection of biogas is accomplished by constructing a covered lagoon, with a gas collection system that feeds a conventional engine. The engine converts virtually all of the CH_4 in the biogas to CO_2. In addition, energy production from manure displaces the fossil fuel greenhouse-gas emissions associated with the production of the same amount of energy. Dairy-energy systems face the same regulatory challenges as landfill-gas energy systems relating to the NOx emissions from internal-combustion engines run on biogas.

Figure 18 shows the greenhouse-gas benefits of converting one million bdt of manure annually into energy (currently only about 120,000 bdt per year of dairy manure are being converted to energy in California). The biogenic emissions from the energy production alternative (red curve in the figure) do not peak until about eight years after treatment, due to delayed emissions from the land-spread residues. It is interesting to compare Figure 18 to Figure 12, which shows the greenhouse-gas profiles for converting one million bdt of solid biomass into energy versus various alternative fates. On the one hand, the displacement of fossil greenhouse-gas emissions by one million bdt of manure is much less than the amount of fossil displacement by one million bdt of solid biomass, due to differences in energy generation efficiency (e.g. as measured by bdt/MWh: 1.0 bdt/MWh for solid biomass, 3.0 bdt/MWh for manure, see Table 2). On the other hand, the immediate biogenic greenhouse-gas benefit of energy production from manure, 10 million tons CO_2 equivalents per million bdt of manure, is much larger than the immediate or delayed benefit associated with any of the solid biomass profiles, none of which ever exceeds 4.5 million tons CO_2 equivalents per million bdt of biomass. The reason for this is obvious: from the greenhouse-gas perspective, energy production from dairy manure, like energy production from landfill gas, involves the simple and direct conversion of CH_4 to CO_2. By the end of fifty years, the initially very large benefit of energy production from manures is eliminated, as the CH_4 emitted to the atmosphere by conventional open lagoon operations converts naturally to CO_2. Using the same method to calculate emissions factors as was employed for solid biomass yields greenhouse-gas emissions factors of 1.87 ton CO_2 equiv/bdt for energy production from manures, 4.27 ton/bdt for conventional management, and 0.22 ton/bdt for displaced fossil greenhouse-gas emissions.

Figure 18

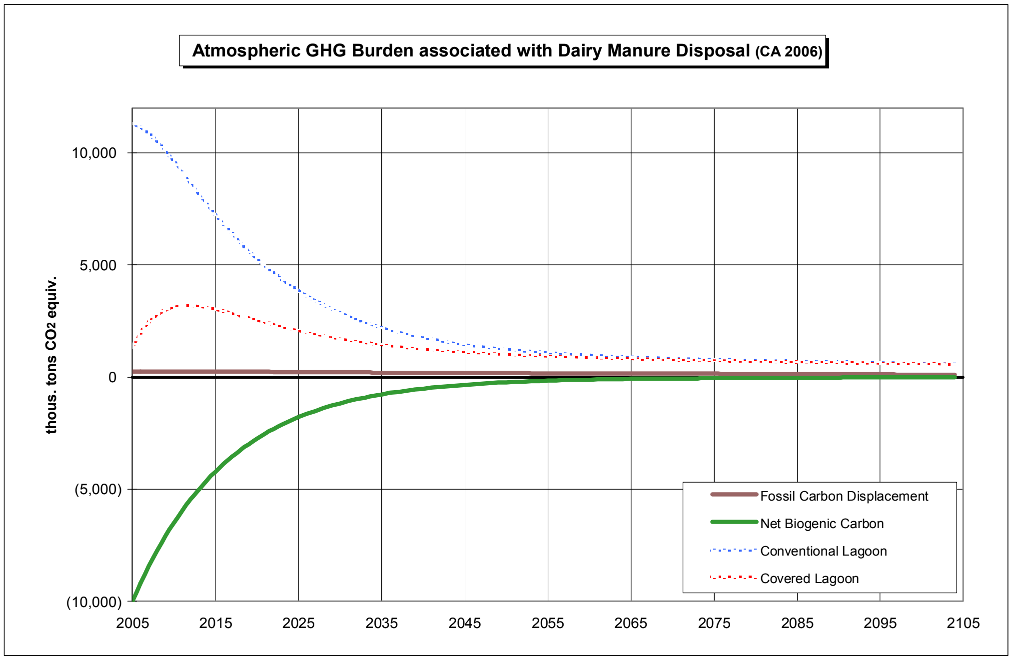


Table 5 shows the greenhouse-gas emissions factors for energy production from landfill gas and dairy manure, using the same methodology used for the calculation of greenhouse-gas emissions factors from solid-fuel biomass energy systems. The emissions factors for landfill-gas systems are expressed in terms of tons CO_2 equiv. per billion btu. The emissions factors are based on the base-case dataset.

Table 5

Greenhouse Gas Emissions Factors for Biogas

(data are in tons CO_2 equiv. per bil. btu for LFG, or per bdt of manure)

	ton/bil. btu $_{\text{50yr ave.}}$	**ton/bil. btu $_{\text{yr 1}}$**
Landfill Gas (LFG)		
Net Reduction in Biogenic C		
Uncontrolled Landfill	230	241
Controlled Landfill	21	22
Avoided Fossil Fuel Use	62	65
	ton/bdt $_{\text{50yr ave.}}$	**ton/bdt $_{\text{yr 1}}$**
Dairy Manure		
Net Reduction in Biogenic C	2.30	2.88
Avoided Fossil Fuel Use	0.21	0.26

Table 6 summarizes the greenhouse-gas emissions factors for biomass and biogas energy systems, all expressed in terms of equivalent tons of CO_2 equiv. emitted contemporaneously with energy production. The emissions factors are expressed in terms of tons per bdt for energy systems based on solid fuels and manures, and tons per billion btu of biomass or biogas resource for all of the bioenergy systems included in the white paper. In addition, the emissions factors are shown in the third column of the table expressed in terms of tons per MWh of electricity produced.

Table 6

Greenhouse Gas Emissions Factors for Biomass and Biogas
(all factors expressed as equivalent year-1 emissions of CO_2 equivalents)

	ton/bdt	ton/bil.btu	ton/MWh
Biomass			
Net Reduction in Biogenic C			
Open Burning	0.62	36	0.62
Forest Accumulation	1.87	110	1.87
Uncontrolled Landfill	2.28	134	2.28
Controlled Landfill	0.27	16	0.27
Spreading	0.69	41	0.69
Composting	1.00	59	1.00
Kiln Boiler / Fireplaces	0.22	13	0.22
California Biomass Mix 2005	0.81	48	0.81
Avoided Fossil Fuel Use	0.80	47	0.80
Landfill Gas (LFG)			
Net Reduction in Biogenic C			
Uncontrolled Landfill		241	2.89
Controlled Landfill		22	0.26
Avoided Fossil Fuel Use		65	0.78
Dairy Manure			
Net Reduction in Biogenic C	2.88	180	8.64
Avoided Fossil Fuel Use	0.26	16	0.78

Treatment of Bioenergy in Greenhouse-gas Reduction Programs

Existing greenhouse-gas reduction programs are geared toward reducing emissions of fossil-carbon gases to the atmosphere. Continuing to add new (fossil) carbon to the carbon that is already in circulation between the atmosphere and the biosphere is the fundamental driver of anthropogenic global climate change. Although the regulatory framework for enacting California's AB 32 system for reducing greenhouse-gas emissions is still being developed, several fundamental principles appear to have been established with respect to the treatment of biogenic emissions within the grand scheme of fossil-carbon greenhouse-gas controls.

The pioneering greenhouse-gas tracking systems developed by the European Union (EU) and the Regional Greenhouse Gas Initiative (RGGI) in the U.S. Northeast track only fossil-carbon greenhouse gases. Bioenergy production is considered carbon neutral in these tracking systems, and biogenic greenhouse gases are not tracked. California is choosing a different approach to the treatment of biogenic carbon. In California, biogenic carbon will be reported and tracked as a separate category of greenhouse gases than fossil carbon greenhouse gases. In the emerging AB 32 compliance system, fossil carbon emissions will need to be matched with emissions allowances, which will be denominated in units (e.g. tons) of CO_2 equivalent emissions. Biogenic carbon emissions will not have to be retired against emissions allowances.

As discussed in this white paper, in addition to being carbon neutral, bioenergy production can reduce net greenhouse-gas emissions by contributing to healthier and more resilient forests, and by eliminating the reduced-carbon emissions that are associated with the alternative fates for biomass resources that are not converted into useful energy. In order to allow these benefits to be expressed in the tracking systems in a way that is usable in a compliance program, the net reductions in biogenic greenhouse gases can be denominated as fossil carbon offsets. The offsets can then be used in whatever cap-and-trade programs are eventually instituted for reducing fossil carbon emissions. California's tracking of biogenic carbon emissions is an important component of this endeavor, as it will facilitate the demonstration of the net reductions in biogenic greenhouse gases that will be needed in order for offsets to be created and certified. Theoretically, offsets should be creatable for the avoided greenhouse-gas burdens associated with alternative disposal of fuels net of the biogenic greenhouse gases emitted by the power plant, and for the long-term increase in forest sequestration due to treatments net of the power-plant emissions from using the fuel for energy production.

Conclusion

Biomass and biogas energy systems are generally recognized to be carbon neutral, because the carbon in the fuel is already part of the global stock of carbon that circulates between the atmosphere and the biosphere. As carbon-neutral energy sources, bioenergy generators will not have to acquire greenhouse-gas emissions allowances to offset their stack emissions of CO_2.

Like all renewable and carbon-neutral energy sources, biomass and biogas energy production displaces the emissions of fossil greenhouse-gas emissions associated with energy production from fossil fuels. In addition, bioenergy production reduces net biogenic greenhouse-gas emissions by avoiding the alternative disposal of the energy resources. The reduction of net biogenic emissions associated with biomass energy production in California has a long-term global warming benefit that is comparable in magnitude to the benefit of avoiding fossil fuel use. In the California RPS program, renewable energy certificates (REC) include the environmental attributes of avoiding the emissions of an equivalent amount of fossil fuel use. The benefits of reducing the warming potential of net biogenic greenhouse-gas emissions associated with biomass and biogas energy generation are not a part of the REC, and should be convertible into greenhouse-gas offsets that bioenergy generators can market in addition to their electricity and REC products (energy and RECs currently are sold as bundled products for projects that participate in RPS-sanctioned utility renewables solicitations). The value of the greenhouse-gas offsets should improve the competitiveness of energy production from biomass and biogas resources in the marketplace of the future.