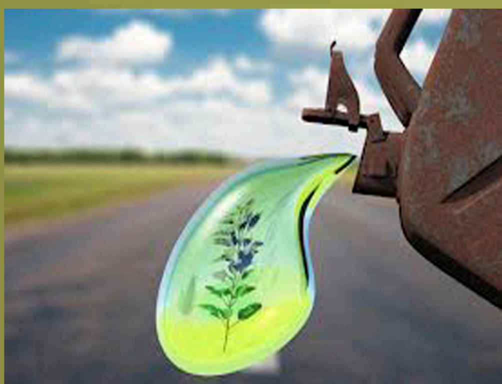

California's Energy Future - The Potential for Biofuels

California Council on Science and Technology
May 2013

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Message from CCST

The California Council on Science and Technology (CCST) is pleased to present the following report on biofuels, an assessment of the potential for biomass-based fuels to contribute to the energy needs of California. This document is the final report in a series of documents produced as part of the California's Energy Future (CEF) project, which was undertaken to help inform California state and local governments how to reach the state's goals of significantly reducing total greenhouse gas (GHG) emissions by 2050.

These goals were mandated by the California's Global Warming Solutions Act of 2006 (AB32) and Executive Order S-3-05. In order to comply, California needs to reduce its GHG emissions to 80% below 1990 levels by 2050 while accommodating projected growth in its economy and population. This will likely require maximizing efficiency in all economic sectors, electrification of much of the transportation sector and many stationary uses of heat, a doubling of electricity production with nearly zero emissions, and development of low-carbon fuels. In addition, as the summary CEF report indicated, substantial amounts of low-carbon biofuels will likely be required along with optimistic efficiency, electrification, and implementation of other renewable energy sources. The current report analyzes the potential of next-generation biofuels to facilitate meeting California's GHG reduction goals.

We believe that the biofuels report presents valuable insights into the possibilities and realities of meeting California's future energy needs and GHG emissions targets by 2050, and hope that you will find it useful.

Jane C.S. Long
California's Energy Future Committee
Co-chair

Miriam John
California's Energy Future Committee
Co-chair

I. Executive Summary

California has a policy goal of reducing greenhouse gas emissions (GHG's) to levels 80% below 1990 emissions (90% below 2005 emissions) by 2050[1]. Transportation emissions currently account for 40% of California's GHG emissions. The focus of this report is an assessment of the potential for biomass-based fuels to contribute to the energy needs of California, particularly for transportation, in 2050 while attaining the current policy goals for GHG emissions.

This report is a supplement to the Summary Report, "California's Energy Future – The View to 2050", which provided an overview of scenarios by which California might achieve substantial GHG reductions. Thus, this analysis is to be placed in context of a hypothetical future energy system with reduced and shifted demands for liquid and gaseous fuels. As described in the Summary Report[2], demand for fuels was adjusted for population growth and widespread implementation of efficiency and electrification measures in transportation[2], residential and commercial buildings, and industry. According to the analysis, low-carbon liquid and gaseous fuels will be required to meet these goals, even if energy efficiency and other low-carbon electricity are widely implemented.

Key Finding of the California's Energy Future Summary Report for Biofuels

One of the key findings in the California's Energy Future Summary Report is that implementation of key efficiency efforts could reduce fuel demand in 2050 to roughly 2005 levels (half of the business-as-usual scenario). Electrification of industry and transportation, to the extent reasonable by 2050, could further reduce demand to roughly 75% of 2005 levels for gaseous fuels and 66% for liquid fuels. While most of the light-duty fleet and rail transportation could be electrified, liquid fuels would still be required for aviation, marine, and heavy duty transportation. Gaseous fuel would be required for some heavy industry and load-following in electricity generation from intermittent renewable sources such as wind and solar. Thus, substantial amounts of low-carbon biofuels would be required even with optimistic efficiency, electrification, and implementation of other renewable energy sources.

To determine the role of biomass-based fuels in California's Energy Future for this report, six scenarios were examined involving two demand cases and three supply cases (Table 1). The first analysis set was a "stress test" case, in which biofuels were used to meet a business-as-usual (BAU) demand case of 44 billion gallons of gasoline equivalent (bgge), nearly double the 2005 demand. Three supply cases were then examined to meet this demand.

The first supply case consisted of a business-as-usual fossil fuel mix, which starts with a projection of the current distribution of fossil gasoline and diesel usage, with 10% blending of corn ethanol in fossil gasoline and 20% blending of soy biodiesel in fossil diesel (Table 1). This was compared with two future next-generation biofuel scenarios requiring deployment of near and far-term technologies. These scenarios assumed *no limitation in infrastructure and no limitation of biomass feedstock to supply the demanded hypothetical fuel mixtures*.

1 Assembly Bill 32; Executive Order S-01-07
2 Yang C, Ogden J, Sperling D, and Hwang R (2011) Transportation energy use in California (December) A California's Energy Future Report. California Council on Science and Technology.

In the near-term biofuel scenario, cellulosic ethanol is blended at 85% with fossil gasoline (E85) to meet the gasoline demand. Similarly, conventional biodiesel from soy and waste oils is blended at 85% with fossil diesel (B85) to meet the diesel demand. In the far-term biofuel scenario, advanced biomass-derived hydrocarbons (drop-in renewable gasoline and diesel) replace conventional fuels with 10% blending of cellulosic ethanol and conventional soy biodiesel (Table 1).

Next, the greenhouse gas emissions were calculated and the ability of the various cases to meet the emission reduction goals of Executive Order S-01-07 and Assembly Bill 32 (AB32) was assessed (Table 1). In the business-as-usual (BAU) demand case, only deployment of advanced bio-derived hydrocarbons (drop-in biofuels from biomass that can directly substitute for fossil gasoline and diesel) have the potential to meet the GHG reduction goals for liquid fuels[3].

	Supply Cases		
	BAU* Fossil Fuel Mix	**Near-Term Scenario (Cellulosic E85/Biodiesel)**	**Far-Term Scenario (Advanced Bio-derived Hydrocarbons)**
Stress Test (BAU Demand) Case *2050 Liquid Fuel Demand = 44 bgge/year*			
2050 GHG Emissions ($MtCO_2eq$/yr)	460	116 to 187	-20 to 123
Percent Change from 2005 Emissions	+209%	-15% to -53%	-55% to -109%
Meets AB32/S-01-07 Target**?	**No**	**No**	**Maybe**
"Realistic" (Efficiency and Electrification) Demand Case *2050 Liquid Fuel Demand = 16 bgge/yr*			
2050 GHG Emissions ($MtCO_2eq$/yr)	167	33 to 110	-44 to 33
Percent Change from 2005 Emissions	-24%	-50 to -85%	-85% to -120%
Meets AB32/S-01-07 Target?	**No**	**Maybe**	**Yes**

Table 1. GHG intensities for different fuel mixtures and demand cases for California in 2050.

*BAU = business-as-usual, assumes current practice is continued unaltered into the future. Supply cases are technology driven and are not limited by biomass supply or infrastructure.
**Target for statewide emissions <85 $MtCO_2eq$/yr, a 90% decrease from 2005 emissions.

3 There is a wide range in the final emission numbers due to uncertainties in the lifecycle analysis of the various fuel types and the possible mixtures of technologies used to produce them.

The California's Energy Future study group then evaluated the changes in demand of fuels that would result from implementation of efficiency measures in building and transportation and widespread electrification of light industrial activities, residential heating, light-duty vehicles, bus and rail[4]. In this second "realistic" case, demand was adjusted to account for other low-carbon technologies including efficiency and electrification. Under the scenario conditions, the amended liquid fuels demand for all uses was reduced from 44 billion gallons in gasoline equivalents (bgge) in the business-as-usual case to 16 bgge, 14.8 bgge of which is used in transportation[5] (Table 1). The three supply cases were then examined to meet the modified demand case. Both cellulosic E85 and biodiesel in the near-term scenario and advanced hydrocarbons (next-generation drop-in fuels) have the potential to reach emission goals with the reduced demand.

	Baseline Scenario		**Optimistic Scenario**	
	Biomass (million tons/yr)	**Fuel (bgge)**	**Biomass (million tons/yr)**	**Fuel (bgge)**
Energy Crops	4.5	0.4	43	3.4
Residual Biomass*	36	2.9	80	6.4
Total	41	3.3	123	9.8
Percent BAU Liquid Fuel Demand		7.5%		22%
Meets S-06-06 goal?		**No**		**No**
Percent of HEE** Liquid Fuel Demand		21%		61%
Meets S-06-06 goal?		**No**		**No**

Table 2. California in-state biomass availability and associated fuel production potential in 2050.

*Residual biomass includes crop and forest residues, as well as municipal, processing, and animal wastes
**High-Efficiency and Electrification Case

4 Demand calculations were provided by the spreadsheet model, developed by J. Greenblatt (October 2011) available through the California Council on Science and Technology http://www.ccst.us/publications/2011/2011energy.php. Estimates have been updated with publication of subsequent reports associated with the study. See also Greenblatt J and Long J (2012) California's Energy Future: Portraits of Energy Systems for Meeting Greenhouse Gas Reduction Targets http://www.ccst.us/publication/2012/2012ghg.pdf and Greenblatt J, Wei M, McMahon J (2012) California's Energy Future: Buildings and Industrial Efficiency. CCST. Changes were not deemed sufficient to impact the conclusions of this report.

5 The CEF study also examined demand for gaseous fuels (e.g. methane and propane), mainly in buildings, industry, and electricity production. Allocation of biomass for gaseous fuels is not examined in detail in this report.

Finally, California has a policy goal of producing 75% of biofuels from in-state resources[6]. Two additional scenarios were constructed to determine the potential of in-state biomass to meet the 2050 demand cases (Table 2). The first scenario assumed modest recovery (40% on average) of residual[7] biomass from agricultural and forestry activities with no growth in municipal waste and very little production of purpose-grown biomass for energy.

The second, highly optimistic scenario assumed higher recovery of residues (66% on average). This scenario assumed growth in municipal wastes based on continued population growth and extensive demolition and construction residues under an aggressive building efficiency program. An increase in forest residues was projected to account for more extensive fire management and a reinvigorated forest products industry. This scenario also projected growth of both dedicated herbaceous and woody biomass crops for bioenergy production. Growth of bioenergy crops was restricted to half the acreage that had been cultivated previously for either crop or timber production but which is no longer used for such purposes. Using these projections, in-state biomass could meet 7-21% of the BAU demand and 22-61% of the amended demand under the high efficiency and electrification scenario (Table 2). Neither scenario was sufficient to meet the policy goal of 75% in-state production transportation fuel from in-state biomass supplies. While import of biomass could supply in-state biorefineries to meet this goal, this solution would be more costly than import of biofuels themselves to meet the GHG reduction goals. Biofuels could reasonably be imported from other states and/or other countries such as Brazil to meet some of the BAU demand or all of the amended demand in 2050. Decisions regarding biomass use and biofuel import will greatly affect the ability of the State to meet its policy goals.

Conclusions

Next-generation biofuels can reduce greenhouse gas emissions of transportation to meet the target GHG reduction goal but deep replacement of fossil fuels through implementation of low-carbon lignocellulosic ethanol and advanced biomass derived hydrocarbons (drop-in biofuels) and reduction in demand is required.

- If liquid fuel demand doubles (business-as-usual), replacement of gasoline with cellulosic ethanol (E85) and conventional biodiesel reduces greenhouse gases 15-53%, falling short of the 90% reduction goal. The footprints of the residual fossil fuel and soy biodiesel appear to outweigh the lower carbon benefits of cellulosic ethanol. The case is less clear if the business-as-usual 2050 demand is met with a combination of lignocellulosic ethanol and drop-in biofuels resulting in a 55-109% reduction in greenhouse gases for liquid fuels, which could either fall short of or exceed the GHG goal.
- Under a reduced future demand scenario with high efficiency and electrification, both the Cellulosic E85 and Cellulosic/Drop-In Scenarios could meet the GHG reduction goals for liquid fuels. The E85 portfolio reduces liquid fuel emissions 50-85% while the Drop-In Fuel portfolio reduces liquid fuel emissions 85-120%.

Although still in development and scale-up, it is expected that technologies can be deployed to produce a new generation of low carbon biofuels (e.g. cellulosic ethanol and drop-in biofuels) to

6 Executive Order S-06-06. Targets 40% of biofuels consumed in California to be produced in California by 2020, increasing to 75% by 2050.

7 The terms “residues” and “residual biomass” refer to material that is currently unused or discarded. Examples include leaves and stalks following corn harvest, end-of-season vineyard trimmings, unrecyclable demolition wood and other organic materials that are currently burned or landfilled.

meet demand by 2050. Whether this deployment occurs in California depends on many factors including the biomass supply and economic considerations.

The ability to meet the low-carbon biofuel demand from in-state biomass supplies is limited by a number of economic, social, and sustainability barriers. Conversion of all the estimated recoverable residues (36-79 million dry tons per year) would yield approximately 2.9-6.3 bgge per year. Energy crops could provide an additional 5-43 million dry tons of biomass (0.4-3.4 bgge per year) for a total of 3.2-9.8 bgge gasoline equivalents.

- If demand doubles as in the business-as-usual case, in-state biomass would meet approximately 7-22% of the projected business-as-usual demand in 2050.
- If demand is curbed as in the high efficiency and electrification test case, in-state biomass could supply 21-61% of the amended demand in 2050.
- For the purpose of this study, the California's Energy Future Committee made a consensus decision that for the median case, in-state biomass resources could supply 7.5 bgge per year. If used entirely for transportation, this amount of biomass could produce fuel to meet 18% of the transportation BAU demand or just under 50% of the high efficiency and electrification transportation demand.

The availability of biomass for fuel production will be impacted by other demands for renewable energy including biomass for direct combustion to produce electricity to meet policy goals such as the Renewable Portfolio Standard, or demand for biomethane (biogas) to be used directly or in renewable electricity production.

- In recognition of the competing demand for biomass-derived energy, the final version of the Summary Report allocated 2 bbge per year to electricity production and 5.5 bgge per year to biofuels, meeting 13% of BAU liquid fuel demand or 34% of the amended liquid fuel demand in 2050.

The concerns regarding large-scale use of biomass for energy in California are largely a matter of sustainable resource management. The possible impacts of bioenergy production are similar to those for modern agriculture, forestry and light industrial processing. Possible benefits from large-scale biomass production in California are both economic and environmental, hinging on sustainable practice and small- to medium-scale deployment.

The concerns about and benefits of biofuels in California can be appropriately managed through proper choice of species and production criteria for feedstocks and fuel conversion technologies in any given region. Examples include: the use of arid-tolerant feedstocks and water-minimal conversion technologies for lands with limited water supplies; the use of grasses that sequester soil carbon and recycle nutrients combined with nutrient recovery from processing; and the use of plants that can tolerate and ameliorate poor or damaged soils, allowing use of land not suitable for food or feed production.

Possible Benefits of Bioenergy in California include:

- Job creation and associated economic benefits, especially in rural communities
- Domestic energy security
- Diversification of energy sources and local energy supplies
- Remediation of toxic, saline, or damaged soils

- Improved land management
- Improved water quality

Possible Concerns Regarding Bioenergy in California include:

- Negative interactions with food/feed lands and markets (indirect land use change)
- Negative changes to ecosystem services
- Decreased water availability and water quality (eutrophication)
- Soil depletion
- Invasive species management

It is likely that any demand unmet by in-state biomass would be supplied by imported biofuels for final in-state blending, rather than through import of biomass feedstocks.

- In-state biomass is not sufficient to fulfill both liquid fuel and gaseous fuel demand in 2050.
- The CEF Committee assumed that other regions would be engaged in similar activities to reduce greenhouse gases, thus biofuels available for import might be limited. California's "fair share" was set to equal the amount of in-state biomass production – 7.5 bgge in 2050.
- With this restriction, the total amount of biofuel available assuming no biomass to electricity would meet 34% of the BAU demand in 2050 and 93% liquid fuel demand in the high-efficiency and electrification case. If some biomass were diverted to electricity, these numbers are lowered to 26% and 73%.
- Import of ethanol from Brazil is cheaper than ethanol from the Midwest[8], even with taxes and tariffs in place. Brazil has the potential to produce 100 billion gallons of conventional ethanol (67 bgge) from sugar by 2030 and another 70 billion gallons cellulosic ethanol (45 bgge)[9]. While this could meet both the demand cases, the amount available to the California market is uncertain.

8 Myers Jaffe A, Medlock K, Soligo R (2010) The logistics, economics and policy of ethanol markets in the US and potential for imports from Latin America. 33rd Annual Conference, IAEE, June 7.

9 Somerville C, Youngs H, Taylor C, Davis SC, Long S (2010) Feedstocks for lignocellulosic biofuels. Science 329:790-792.

II. Biofuel Technologies

Introduction to the Technologies

Biomass may be converted to a variety of liquid and gaseous fuels by different biochemical, catalytic, and thermochemical routes (Figure 1). It is likely that biorefineries will make multiple products. For example, lignocellulosic ethanol plants could produce ethanol from fermentation of depolymerized structural sugars, biomethane from anaerobically digested stillage, fertilizer from the anaerobic digester sludge, and lignin co-products such as aromatic molecules for commodity chemicals or pellets for electricity generation.

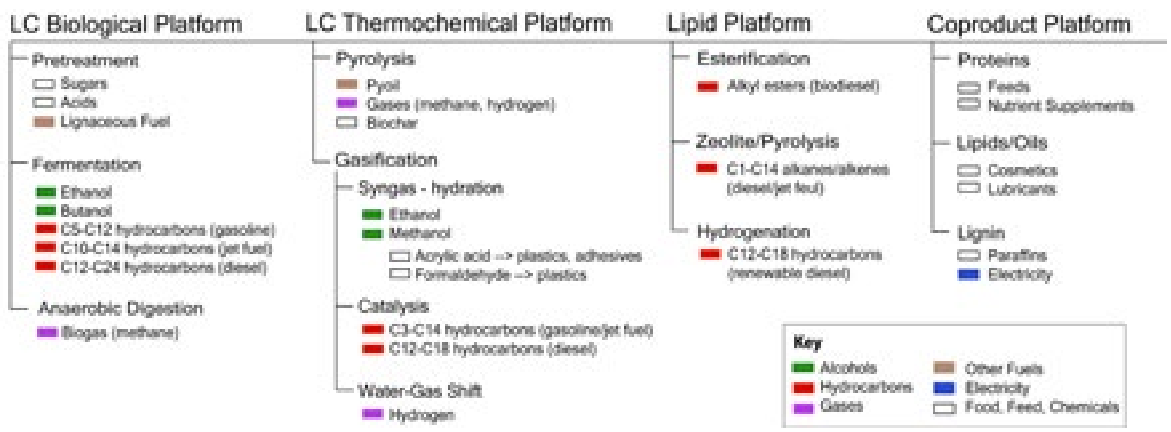

Figure 1. Platforms for production of fuels and associated co-products.

The technologies are classified into bins according to readiness for deployment (Table 3). Bin 1 is already at commercial scale. Bin 2 is at demonstration scale – moving to commercial scale in the next 5 years. Bin 3 is at pilot scale – moving to demonstration scale. These technologies could be 5-10 years from commercial deployment. Bin 4 is experimental or benchtop scale and is possibly 20 or more years away from commercialization[10].

Bin 1 (commercial scale)	**Bin 2 (demonstration scale)**
Sugar to ethanol (fermentation)	Lignocellulose to ethanol (fermentation)
Starch to ethanol (fermentation)	Algal oil to biodiesel (esterification)
Fatty acids to biodiesel (esterification)	Lignocellulose to diesel (thermocatalytic)
	Fatty acids to alkanes (hydrogenation)
Bin 3 (pilot scale)	**Bin 4 (bench scale)**
Sugar to hydrocarbons (fermentation)	Sugar to hydrocarbons (catalysis)
	Artificial photosynthesis

Table 3. Technology bins based on current scale of deployment for biofuel production.

10 Throughout this report anecdotes of company activities will be described. These serve solely as illustrative examples and do not represent an exhaustive representation of commercial activities.

Ethanol From Sugar- and Starch-producing Crops such as Corn and Sugarcane

Production of ethanol from sugar is a centuries-old biological fermentation process that has long been used at the industrial scale. The process requires a simple chamber, the sugar feedstock, usually derived from sugarcane juice or concentrated molasses or from another sucrose or glucose-rich feedstock such as sweet sorghum, sugarbeet, or fruit juice, and a fermenting organism such as yeast or bacteria. The organisms metabolize the sugar for hours to days under controlled conditions, excreting ethanol as a waste product. The reaction ends when the concentration of ethanol becomes lethal to the organism. For most bacteria and yeast, this is 5-7% alcohol by weight but some industrial yeast strains can tolerate as much as 10-14%. The cells and other particulates are removed and the broth undergoes distillation or membrane separation and pervaporation to isolate the ethanol to ~95%. The ethanol can be dried further and is treated with a small amount of hydrocarbon (denaturant) when used as a fuel.

Starchy crops such as corn are also widely used for ethanol production. Starch is a large, branched polymer of glucose that is easily degraded by chemical or enzymatic treatment. Once the glucose is liberated from the polymer, it can undergo standard microbial fermentation.

While small-scale production of biofuels from food or feed crops provides economic stability to farmers and rural communities, questions regarding the long-term sustainability of large-scale use of such feedstocks arise from possible competition with food and feed markets, as well as high requirements for nutrients such as nitrogen. Stillage residues can be used as animal feeds, commonly known as distiller's grains, reducing competition with feed markets. Similarly, nutrients can be recovered from ashes and stillage residues and used for fertilizers, reducing the inputs for biomass production. Generally, fermentation methods use more water than catalysis; however, additional treatment of wastewater by anaerobic fermentation allows water recycling and generation of biomethane. Treated water can then be applied to fields in some areas to offset water use for crop growth.

Alcohol Production from Cellulosic Biomass via Fermentation

Unlike the sugars in sucrose and starch, which are relatively easy to degrade, the sugars in lignocellulosic biomass, such as leaves and stems, are relatively inaccessible. Whereas starch is a storage polymer that is relatively easy to hydrolyze with acids or enzymes, lignocellulose is a dense composite matrix of extremely recalcitrant structural polymers. Release of the sugars from lignocellulose requires several steps. Pretreatments, typically exposure to high-temperature acids or bases, partially degrade the material and open the matrix for subsequent hydrolysis by bacterial or fungal enzymes or other catalysts. More efficient single step depolymerization remains a long-term research goal.

Ethanol can be produced from lignocellulosic biomass by several different routes, three are considered here: standard hydrolysis and sugar fermentation, gasification and CO fermentation, and gasification with chemical catalysis. Yields of lignocellulosic ethanol are predicted to be lower per ton of feedstock than those from sugar or starch due to the complexity of the polymer matrix and depend on the feedstock density, composition, and conversion efficiency (Table 4).

Roughly one-third of lignocellulosic biomass is the polyphenolic polymer, lignin, which cannot be fermented. Lignin can be converted directly to fuels through thermochemical catalysis but remains as a solid by-product in the fermentation routes; however, residual lignin can be combusted separately to produce heat and electricity. Based on National Renewable Energy Laboratory (NREL) estimates, the process is assumed to generate more than 8,000 Btu of excess electricity per gallon of ethanol produced.

Feedstock	Theoretical yield of ethanol gallons per dry ton
Corn grain	124.4
Corn stover	113.0
Rice straw	109.9
Cotton gin trash	56.8
Forest thinnings	81.5
Hardwood sawdust	100.8
Sugarcane bagasse	111.5
Mixed paper	116.2

Table 4. Ethanol yield from various biomass feedstocks[11].

Technical yields for production of ethanol from the carbohydrate portion of chipped wood were estimated at 51 gallons per ton for hydrolysis and fermentation, 88 gallons per ton using gasification and fermentation, and 63 gallons per ton for gasification and catalysis[12]. The National Academy uses conversion factors of 82 gallons ethanol or 55 gallons gasoline equivalent per ton of biomass[13].

A dozen or so companies are moving forward from pilot or demonstration scale operations to full commercial scale, tackling diverse technical challenges. The efficiency of saccharification (conversion of lignocellulosic biomass to fermentable sugars) continues to be a costly barrier to biochemical conversion. Several pretreatment regimes that facilitate conversion of the cellulose fibers are being investigated but all are relatively energy intensive and some produce compounds that can inhibit fermenting organisms. Enzyme production for saccharification remains the most expensive component of biological conversion routes. In many plant species, up to a third of the biomass may be hemicellulose, a polymer containing five-carbon sugars such as xylose which require different metabolic pathways than six-carbon sugars such as glucose. Several companies have devised methods to utilize the five-carbon sugars generated from the hemicellulose component, however, efficient use of both sugar types remains problematic. Finally, there are several opportunities for optimization of the overall process including particle size reduction, recycling of water, heat, and steam within the process, and generation of co-products including electricity, animal feed, methane, or other chemicals as is now common in corn refineries.

Microbial production of longer chain alcohols such as butanol occurs in a manner similar to ethanol. Yields are projected at 50-100 gallons per ton, depending on the metabolic route used. Butanol has more desirable fuel properties than ethanol but is much more toxic to microorganisms than ethanol, thus lower percentages are achieved at the end of the fermentation[14] resulting in less efficient yields and higher distillation costs. Commercialization of butanol from sugars and starch is currently underway. Gevo has retrofitted a corn ethanol plant in St. Joseph, Missouri as

11 US Department of Energy, Energy Efficiency and Renewable Energy Biomass Program (http://www1.eere.energy.gov/biomass/ethanol_yield_calculator.html)

12 Wei L, Pordesimo LO, Igathinathane C and Batchelor WD (2009) Process engineering evaluation of ethanol production from wood through bioprocessing and chemical catalysis. Biomass and Bioenergy 33: 255-66.

13 Committee on America's Energy Future (2009) Alternative liquid transportation fuels. In America's Energy Future: Technology and transformation.National Research Council of the National Academies, National Academies Press, Washington, D.C.

14 A final concentration of <2% butanol after fermentation is tolerated vs. 5-7% for ethanol.

a butanol demonstration-scale facility[15]. Butamax has partnered with Fagan, Inc. to retrofit corn ethanol plants to butanol production and has begun signing "early adopters" to commercialize their butanol technology[16]. Conversion of lignocellulosic biomass to butanol is still in development.

Thermochemical Conversion of Cellulosic Biomass to Alcohols and Advanced Hydrocarbons

Pyrolysis and gasification are thermochemical conversion routes. The biomass is heated and transformed into a mixture of organic solids, liquids, and gases. The phase distribution and chemical composition is determined by the rate and extent of heating.

Anaerobic fast pyrolysis typically yields 60 to 70% bio-oil, 10-20% combustible gases and 15-25% char. The char can act as a carbon sequestration mode if buried and has been reported to improve soil quality[17]. The bio-oils can be directly combusted in gas turbines, boilers, and diesel generators for power or steam generation; however they are corrosive and must be stabilized to prevent engine damage. Alternatively, they can undergo steam re-forming to generate hydrogen or syn-gas. Kior has been actively pursuing wood to bio-oils in Mississippi and plans to retrofit a paper mill to the process. Pyrolysis is one of the technologies that could enable small-scale distributed pre-processing of biomass, reducing transportation costs by converting the biomass into a more energy-dense intermediate.

Biomass, bio-gas and bio-oil can be gasified to a syn-gas mixture of CO and H_2, which can then be catalyzed by a number of different routes to produce substitutes for gasoline or diesel. Yields are approximately 28 to 50 gallons diesel equivalent per ton biomass[18]. Problems with economic commercialization of gasification technologies persist. Range Fuels had revised production estimates at their commercial-scale gasification and catalysis facility in Soperton, Georgia from 100 million gallons ethanol per year (EISA 2007) down to 1 million gallons methanol per year in 2009. The company then went out of business altogether[19]. In contrast, Coskata has achieved some success with microbial fermentation of the CO produced from waste biomass gasification at semi-commercial scale in Madison, Pennsylvania[20].

Methane Production from Anaerobic Digestion

Bio-gas is a mixture of gases (mainly methane and carbon dioxide) produced during anaerobic fermentation of biomass. Two main sources for biogas production are organic wastes, such as manure or landfill organics, and harvested biomass, such as dried or ensiled grasses. Yield ranges from 150 to 650 liters methane per kg dry material for grasses[21] and up to 280 liters per kg dry refuse, although some field tests show a more modest range of 3-100 liter per kg[22]. Projects to convert dairy waste (mostly manure) to biogas for electricity generation have been supported by the state of California in

15 http://www.gevo.com/news_Retrofit-Demo-Plant-pr_100509.php
16 Butamax (2012) Press release (www.butamax.com/latest-updates.ashx) accessed 5-May-2012
17 Steiner C, Teixera WG, Lehmann J, Nehls T, Vasconcelos de Macedo JL, Blum WEH, Zech W (2007) Long-term effects of manure, charcoal and mineral fertilization on crop productivity and fertility on a highly weathered Central Amazonian upland soil. Plant Soil 291:275-90.
18 Huber GW, Iborra S and Corma A (2006) Synthesis of transportation fuels from biomass: Chemistry, catalysts, and engineering. Chemical Reviews, online 10.1021/cr068360d CCC.
19 http://www.rangefuels.com/range-fuels-produces-cellulosic-methanol-from-first-commercial-cellulosic-biof uels-plant.html accessed November-2010; "The Range Fuel Failure" Biofuels Digest, 5-December-2011
20 http://www.coskata.com/facilities/
21 Prochnow A, Heiermann M, Plchl M, Linke B, Idler C, Amon T and Hobbs PJ (2009) Bioenergy from permanent grassland - A review: 1. Biogas. Bioresource Technology 100:4931-4944.
22 El-Fadel M, Findikakis AN and Leckie JO (1997) Environmental impacts of solid waste landfilling. Journal of Environmental Management 50:1-25.

the past, but many of those projects are currently idle due to increased restrictions on NOx emissions from older, more affordable combustion engines. Replacement with newer reciprocating engines could alleviate this constraint.

California landfills currently generate 59-78 billion cubic feet of methane from landfill gas[23]. Typically, the raw mixture contains 50-75% methane, 25-50% carbon dioxide, 0-10% nitrogen and 0-3% each hydrogen, hydrogen sulfide, and oxygen. Because of the costs of compression and storage, most landfill gas is flared off or burned to generate electricity. There are 63 landfill gas-to-electricity facilities in California, displacing some conventional methane or coal-based electricity.

Biogas can be upgraded to >95% methane at a cost of $5-$15 per GJ[24], which could be fed into the natural gas infrastructure or compressed for use in modified vehicles. Upgrading technology to achieve pipeline quality is a mature technology and acceptance of biogas in natural gas pipelines is routine in countries such as Germany, where feed-in tariffs and robust quality assurance standards exist. Pipeline owners in the U.S. have been more reticent, largely due to a lack of sufficient quality monitoring mechanisms. The costs to transport upgraded methane are estimated at $0.30-$1.20 per mmBtu per 1,000 km of pipeline. In contrast, the costs to liquefy, store, transport and regasify methane range from $3.00-$4.70 per mmBtu[25]. Extensive pipeline expansion would be needed to allow economical injection of biomethane into the grid by smaller supply sites. In Germany, this cost is absorbed by pipeline owners, who are obligated to build out to any biogas installation within 5 kilometers of an existing pipeline.

At retail gas/fueling stations, a modified fuel delivery infrastructure, similar to that needed for a hydrogen-based transportation system would be required. Fuel tank filling for a gaseous energy carrier is significantly more involved than for liquid fuels. Compressed natural gas is under a pressure of about 240 atmospheres, but the gas is drawn from the local grid at pressures much lower. Commercial facilities, with fill times commensurate with that of other petrol fuels, employ a high-pressure storage tank into which the gas is first transferred and pressurized using a large capacity compressor ("fast-fill"). Alternatively, for some applications smaller compressors can be used to direct fill the tank at a rate of about 2 hours per gallon – generally run overnight ("time-fill")[26]. IEA estimates costs for delivery at $200,000 to $500,00 per filling station[27].

Widespread use of biogas for transportation could have substantial benefits for air emissions but will likely require expanded use of natural gas in vehicles[28]. All the major car manufacturers now have natural gas vehicles. In 2010, the global fleet contained nearly 12 million natural gas vehicles (roughly 1%) growing to 18 million in 2011. In the U.S. a small market for compressed natural gas vehicles is developing, to which biogas could contribute. This has been especially successful for small fleet vehicles such as buses and short-distance trucks, which can rely on in-house gas fueling stations. Limited access at retail stations is still problematic. According to the IEA, "Consumers view availability of stations as an obstacle if the number of CNG fuelling stations is less than 10%-20% of conventional stations. The challenge is attaining an optimum ratio of vehicles to refueling stations"[29].

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23 California Integrated Waste Management Board (2007) Potential for creating bioenergy and biofuels from landfill-bound residuals and landfill gas. 10 pp.

24 International Energy Agency (2008) From 1st to 2nd generation biofuel technologies: An overview of current industry and RD&D activities.

25 International Energy Agency (2009) World Energy Outlook 2009. Paris.

26 Natural Gas Vehicles for America (2009) Natural Gas Vehicles Technology (http://www.ngvc.org/tech_data/index.html) Accessed March 2, 2010.

27 Nijboer M (2010) The contribution of natural gas vehicles to sustainable transport. IEA Working Paper, 84 pp.

28 Kolodziej R (2010) Biomethane in vehicles: An introduction. Presentation 2nd Annual Biogas USA Conference (October).

California leads the nation in natural gas vehicle adoption yet the state has only 153 NG fueling stations out of 8,300 retail fuel centers (1.8%)[29]. With these considerations, and the recent change in availability and price of fossil natural gas, it is difficult to predict how biomethane as a transport fuel will develop.

Biodiesel and Renewable Diesel

Oils and lipids from biological sources can be easily transformed to biodiesel and, if processed with hydrogen, to alkane mixtures. Transesterification of plant seed oils and animal fats to fatty acid methyl esters is the most common route to biodiesel production. Hydrothermal processing biomolecules (reaction with water at high pressure and temperature) and hydrotreating (reaction with hydrogen at high temperature and pressure) results in "renewable diesel" and "green diesel", respectively. The greenhouse gas footprints of renewable and green diesel are highly dependent on biomass feedstock and the source of hydrogen used.

Microalgae have been extensively studied for potential biofuel production. Similar to the lipids of higher plants, algal lipids can be esterified to make biodiesel and have compositional properties that are amenable to cosmetic, lubricant, and nutraceutical use. Like oilseeds, algae produce significant amounts of lipids for intracellular storage and as part of their photosynthetic membrane. Because of the physical properties of the cells, separation of these fuel precursors from algal biomass can be difficult and resource intensive[30]. Following extraction of the oils for fuel production, the residual algal biomass can be used as fish or poultry feed or as a nutrient supplement for humans. The hydrothermal conversion of total algal biomass has been proposed to obviate the need for expensive drying and organic solvents associated with traditional algal lipid extraction[31]. In this case, the products would be a nitrogen-rich bio-oil, which would require further treatment for fuel use, and biochar, rather than a feed product[32].

Other Routes to Alcohols and Advanced Hydrocarbons (Drop-in Biofuels)

Several routes for the direct conversion of sugars to molecules that could substitute for gasoline or diesel in existing infrastructure are being explored. LS9, Inc. has achieved engineered microbial conversion of sugars to fatty acid methylesters (often term microbial biodiesel or microdiesel) for under $3 a gallon[33] at their demonstration plant in Florida and is planning commercial-scale production in Brazil. Amyris Fuels, LLC has synthesized fuel molecules via isoprenoids synthesis in a DOE-funded pilot plant in Emeryville, California and is building a demonstration-scale facility in Campinas, Brazil.[34]

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29 California Natural Gas Vehicle Alliance (http://www.cngvc.org/why-ngvs/fueling-options.php) Accessed March 2, 2013; California Energy Almanac (http://energyalmanac.ca.gov/gasoline/piira_retail_survey.html) Accessed March 2, 2013.

30 Singh A, Singh Nigam P and Murphy JD (2011) Mechanism and challenges in commercialization of algal biofuels. Bioresource Technology 102: 26-34.

31 Roberts GW, Fortier MOP, Sturm BSM, and Stagg-Williams SM (2013) Promising pathway for algal biofuels through wastewater cultivation and hydrothermal conversion. Energy Fuels 27:857-867.

32 Garcia Alba L, Torri C, Samorì C, van der Spek J, Fabbri D, Kersten SRA and Brilman DWFW (2012) Hydrothermal treatment (HTT) of microalgae: Evaluation of the process as conversion method in an algae biorefinery concept. Energy & Fuels 26:642–657; Heilmann, SM, Jader LR, Harned LA, Sadowsky MJ, Schendel FJ, Lefebvre PA, et al. (2011) Hydrothermal carbonization of microalgae II. Fatty acid, char, and algal nutrient products. Applied Energy 88:3286–3290; Vardon DR, Sharma BK, Scott J, Yu G, Wang Z, Schideman L, et al. (2011) Chemical properties of biocrude oil from the hydrothermal liquefaction of Spirulina algae, swine manure, and digested anaerobic sludge. Bioresource Technology, 102:8295–8303.

33 Bill Haywood, Advanced Biofuels Markets, San Francisco November 2010.

34 http://www.amyrisbiotech.com/about-amyris/business-strategy/commercialization

III. Biomass Feedstocks

California produces a wide variety of plant material each year that could be used to supply biorefineries. California leads the nation in crop production, is second only to Texas in terms of livestock production, and has the third-highest forest acreage in the contiguous U.S. By 2050, the state could produce 40-100 million tons of dry biomass. This section will describe the types of biomass feedstocks which are being produced now in California or could reasonably be produced in the future. How this supply might match demand for fuels in 2050 is addressed in Section IV of this report.

Feedstocks for Conventional Biofuels

With regards to conventional biofuel production, California produces only ten percent of the corn consumed in the state, mainly by livestock (beef and poultry). Current corn ethanol plants operating in the state import grain from the Midwest. Given the high cost of land, additional cost of irrigation, and relative value of other crops (fruits and vegetables) that can be grown on land with available water, it is unlikely that California corn would be used for biofuels (see section VI of this report). Similarly, the state produces negligible amounts of soybean. Oil seeds produced in the state, including sunflower and safflower, are sold exclusively for human consumption. It is unlikely that production of biodiesel will be economically competitive on a large scale with other human uses (see section VI of this report). Most California biodiesel plants use waste grease. However, this resource is limited.

Several alternative crops have been proposed for production of conventional biofuels in California. Camelina and Jatropha are alternative oil seed-producing plants that could be used to produce biodiesel through conventional routes on marginal land or as second-season crops. Although still in development, such crops could fit some agricultural niches by 2050.

Lignocellulosic Feedstocks

California has significant lignocellulosic biomass potential. Forest residues are nearly half the available residual biomass. Municipal or land-filled waste is approximately 20% and agricultural wastes are nearly a third of the available residual biomass (Figure 2).

Agricultural Residues

Agricultural residues are the parts of plants leftover from crop production. California produces over 200 different crops and each has different residues. The top biomass producers are shown in Figure 2. Nearly 5 million tons of field and seed residue are produced each year in California, along with 5 million tons of orchard and vineyard prunings and 3 million tons of vegetable and food processing waste.

Agricultural productivity, which affects residue production, in California is projected to increase despite climate change, water challenges, and continued population growth. Urbanization is projected to result in loss of ~8% of agricultural land to development from 2005-2050, with 5% of the change occurring in 2020-2050[35]. Changes in water availability are predicted to force crop redistribution, with increasing acreage of high-value crops and decreased irrigation. These projections are not without controversy. While some models predict crop yields per acre will increase 25-40%, others predict yield decreases of 3-30%[36] and/or mixed effects[37], and still others predict that regardless of crop choice or distribution, gross production of agricultural residues is likely to remain steady while technical yields have the potential to increase due to more efficient residue management.

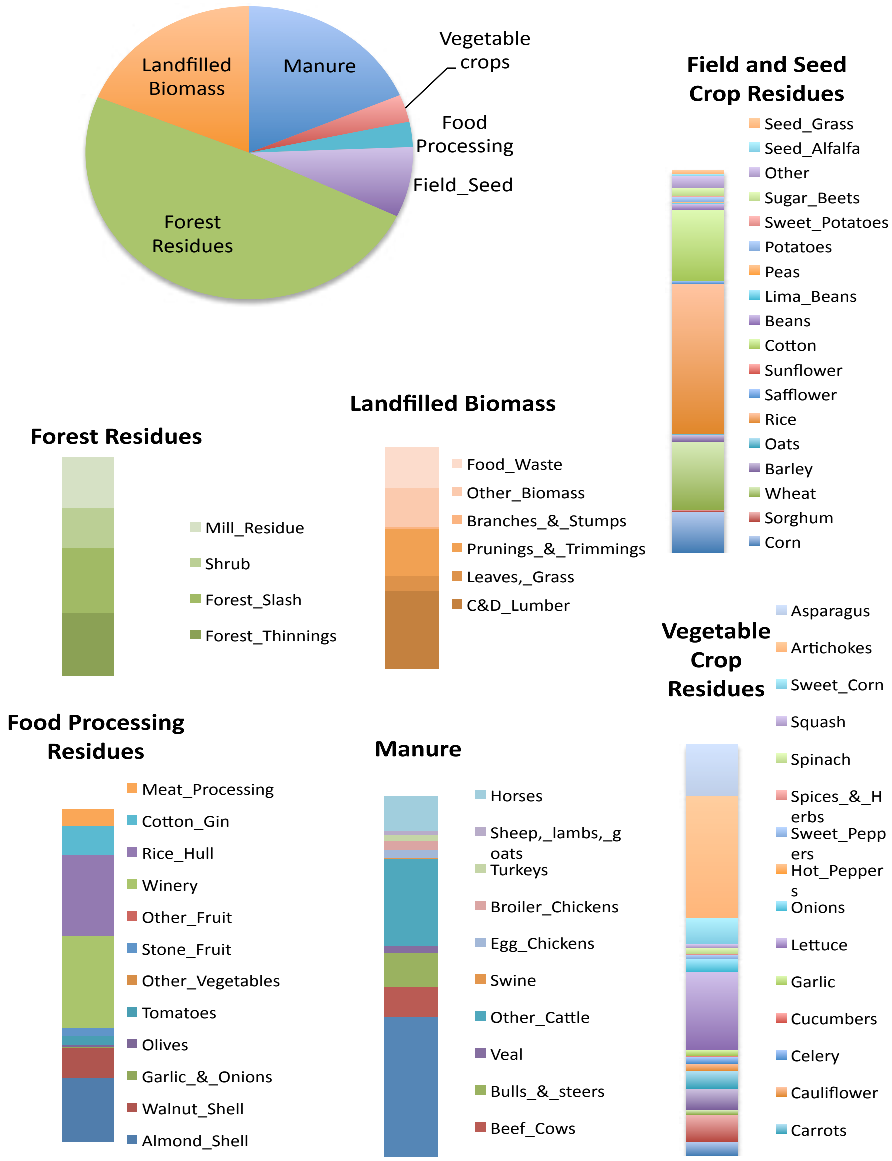

Figure 2. Distribution of California residual biomass by type.

35 Howitt R, Medellin-Azuara J and MacEwan D (2009) Estimating the economic impacts of agricultural yield related changes for California. California Climate Change Center, California Energy Commission and California Environmental Protection Agency.

36 Lee J, De Gryze S and Six J (2009) Effect of climate change on field crop production in the central valley of California. California Energy Commisssion and California Environmental Protection Agency.

37 Lobell DB, Torney A and Field CB (2009) Climate extremes in California agriculture. California Energy Commisssion and California Environmental Protection Agency.

Forest Residues

California has roughly 33 million acres of forest (approximately one-third of the state). 19.5 million acres is considered productive timberland, of which only half undergoes regular harvest or has managed vegetation to reduce fire risk. Harvest of public forests has decreased 90 percent in the last 25 years[38]. Of the approximately 67 billion cubic feet of growing stock, only 0.5 billion cubic feet is removed annually[39]. Currently, 27 million tons of forest and mill residues are produced each year in California.

Woody residues can be divided into mill residues (unsalable lumber, sawdust, bark, etc. from sawmills and pulp mills), forest thinnings and logging residues or harvest slash (unsalable trees, small trees, limbs and leaves, usually left at the roadside), and municipal trimmings (dead trees, limbs, shrubs, leaves – such as those from power line tending or yard waste). For the purposes of this report, municipal trimmings will be addressed as municipal solid waste, as are residues from construction and demolition.

Climate change is forecasted to increase pressure to develop privately owned timberlands, decreasing timber production in the state by 5-8% by 2020[40]. The risk of wildfire is projected to increase 2-4 fold by 2050[41]. Both these trends suggest that management efforts are likely to increase resulting in increased forest residue harvest. The effect of climate on overall forest productivity is difficult to predict. Higher temperatures and CO_2 levels should increase woody plant growth rates; however, changes in pest and pathogen distributions are likely to be detrimental in the near term.

Sustainable practice requires reasonable nutrient recycling from the energy processing facility back to forest soils. Wood ash (generated during gasification or combustion) and stillage (generated during fermentation) have many of the major nutrients (potassium, calcium, phosphorous, and magnesium) needed for woody biomass production. Both forms of recycled nutrients must be supplemented with nitrogen. Wood contains very little nitrogen; leaves and needles retain the majority of organic nitrogen, most of which is volatized during gasification or combustion, thus, the addition of 100-300 kg nitrogen per hectare per rotation (10-50 years for most species, as low as 6 years for short-rotation and coppice) is recommended following removal of logging residue. Returning leaf and needle litter would also benefit nutrient recycling.

Finally, the ability of forests to capture and store carbon is related to soil characteristics, forest population dynamics, and stand age and growth cycles. Steady-state, old-grown forests may act as standing carbon reserves but they fix very little carbon annually. Fire and natural mortality can cause large releases of biogenic carbon from such systems. In contrast, short rotation and actively growing forests have high annual carbon fixation rates. Recent models indicate that correctly timed harvesting of forest biomass can have positive impacts on long-term carbon fluxes[42].

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38 Stewart W (2010) Forestry's underground benefits deserve mainstream consideration: Low-carbon energy adds to forest's climate benefits. California Forests 14(1):8-9.

39 USDA Forest Service Pacific Northwest Research Station (2008) California Inventory Results. In Pacific Northwest Forest Inventory and Analysis http://www.fs.fed.us/pnw/fia/statewide_results/ca.shtml, August 2009, Portland, OR.

40 Hannah L, Costello C, Guo C, Ries L, Kolstad C and Snider N (2009) The impact of climate change on California timberlands. California Climate Change Center, California Energy Commission and California Environmental Protection Agency.

41 Bryant B and Westerling A (2009) Potential effects of climate change on residential wildfire risk in California. California Climate Change Center, California Energy Commission and California Environmental Protection Agency.

42 Davis S, Dietze M, DeLucia E, Field C, Hamburg S, Loarie S, Parton W, Potts M, Ramage B, Wang D, Youngs H, Long S (2012) Harvesting carbon from eastern US forests: Opportunities and impacts of an expanding bioenergy industry. Forests 3:370-397

Municipal Solid Waste

Californians send 1.2 billion tons of waste to landfills yearly, of which roughly 56% is biomass excluding plastics and textiles. Municipal solid waste represents almost half of the state's total organic residues, while animal wastes contribute almost ten percent. Pressure on landfills is extreme is some parts of the state, prompting renewed interest in energy recovery from waste[43]. Typically, animal and municipal wastes such as yard trimmings and food waste have a high moisture content, which hinders straight gasification, although it can be fermented to ethanol or to methane, as any other lignocellulosic source. Increased pressure to recycle construction materials may decrease the woody biomass in this residue. Because the waste has high moisture, making transportation costly, it is likely that processing facilities will be close to the source (city or farm) generating the waste. The resultant smaller scale will likely necessitate that these facilities may provide local heat and power, reducing greenhouse gas emissions. Alternatively, a small portion of transportation fuels could be offset by upgrading biogas to methane followed by compression, storage, and ultimately and combustion in modified vehicles. Energy recovery from municipal organic material should be coordinated with waste reduction and recycling efforts.

Dedicated Energy Crops

Currently, crops originally cultivated for food and animal feed including corn, sorghum, sugarcane, sunflower, safflower, and palm are used to produce biofuels such ethanol and biodiesel. Great uncertainty regarding the long-term sustainability of such production, pressure on food markets, and indirect land-use change necessitate the development of next-generation biomass feedstocks that do not compete for resources or land with food and feed crops.

Annual crops must be harvested and replanted each growing season. In much of the state, California's mild weather allows year-round agriculture, depending on the water regime, thus several annual crop cycles could be completed on a single plot. In contrast, perennial crops die back and become dormant at the end of the growing cycle, producing new biomass in the next season without the need for tilling and planting. Biomass harvest cycles for perennials are variable depending on the crop. For example, perennial grasses may be harvested each season; whereas coppiced trees or agaves may be harvested every 3 to 5 years. Although perennial crops can be more difficult and costly to establish and may limit the farmer's flexibility to change crops, they offer many advantages. The retention of living root material throughout the year can decrease erosion, contribute to the accumulation of soil carbon, and help to retain soil moisture. In addition, perennials with long growing cycles may have increased biodiversity over annual crops. Additional planning is required to stagger harvest schedules for long-cycle perennial systems but the lack of tilling and reseeding may reduce greenhouse gas footprints for bioenergy from perennial versus annual biomass sources.

Resilient, perennial energy crops can be grown on land that is not suitable for conventional agricultural production. This can include abandoned agricultural cropland, rangeland, or reclaimed developed land. EPA calculates that California has some 8.9 million acres in abandoned agricultural land not enrolled in the conservation reserve program[44]. If this land were used to grow a perennial

43 Youngs HL (2011) Waste-to-Energy in California: Technology, Issues, and Context. Do waste-to-energy technologies have a role to play in California's path to a cleaner environment. http://www.ccst.us/news/2011/20111208wte.php

44 Environmental Protection Agency (2009) Draft regulatory impact analysis changes to renewable fuel standard program. Washington, D.C. Table 1.1-20 p48. This is roughly equal to the amount of land in agricultural production in 1997.

energy grass such as switchgrass at 5-15 dry tons per acre annually, it would yield roughly 45 to 133 million tons of biomass or 2.5 to 10.6 billion gallons of gasoline equivalents[45] per year.

In California, roughly 8 million acres of unreserved forested land is considered unproductive for timber[46] but could be used to farm woody biomass for energy use. Poplar and pine can be sustainably farmed to produce conservatively 10-20 tons harvested feedstock per acre using nutrient recovery, with a potential yield of 8-16 billion gallons of cellulosic ethanol per year.

Agroforestry offers tremendous opportunities to optimize land use for both food and energy production. For example, woody biomass production can be combined with sheep and cattle grazing[47]. Approximately 9 million acres (~10% of the state) falls in this category of low-rent land. Increasing economic pressures are driving the conversion of this land to other agricultural usage (e.g. vineyard) or other development, which can result in increased soil degradation, greenhouse gas production, and loss of habitat. Additionally, establishment of tree farms offers increased carbon sequestration potential. At only 50% recovery, this could represent 4-5 billion gallons cellulosic ethanol per year or 3 billon gallons gasoline equivalents per year.

Drought-resilient plants such as fibrous agave or henequen (*Agave Americana, A. sisalana, A. fourcroydes,* or *A. angustifolia*) could yield 5-20 dry tons per acre per year (annualized over a five year rotation) in semi-arid lands with no external water or mineral inputs. Jatropha (*Jatropha curcas*) could generate ~200 gallons of biodiesel per acre per year with minimal water. Unlike most conventional agricultural plants, such plants would not compete with higher value and higher input agricultural food crops and could provide some ecosystem service benefits. Since dedicated energy crops would not be used for food or feed, they could also be used to remediate contamination and reclaim salinized or infested soils. In particular, selenium toxification of soils presents a hazard to humans and livestock. Biomass crops can absorb selenium from soils, which can then be safely removed during the refining process.

Animal Waste

In all, California could produce as much as 16 million tons of animal waste in 2050. Sales from livestock and livestock products account for roughly 27% of total agricultural income in California. The state is home to 5.3 million dairy cows, cattle and calves, 20 million egg-laying hens, 15 million turkeys, 500,000 goats, sheep and lambs, and 150,000 pigs. While manures are relatively energy poor compared to many other biomass feedstocks, they represent a substantial opportunity to reclaim energy from a waste product that requires remediation in any case to prevent eutrophication of surface waters, as well as human health risks.

Animal waste can be processed on-site using small-scale anaerobic digestion units or dried and transported for use in other conversion processes. Nutrients can be recovered in most cases and used as fertilizers. The California Energy Commission has had numerous incentive programs to encourage the use of anaerobic digestion on dairy farms; however, to date only 15 of the state's 1600 dairies

45 Assuming a conversion of 55 to 80 gallons gasoline equivalents or 80 to 120 gallons ethanol per ton biomass, which varies according to the biomass composition, conversion method and associated selectivity of conversion with regards to various biomass components, and conversion efficiency.

46 Battles J, Robards T, Das A and Stewart W (2009) Projecting climate change impacts on forest growth and yield for California's Sierran mixed conifer forests. California Climate Change Center, California Energy Commission and California Environmental Protection Agency.

47 McCreary D (2001) Agroforestry is promising for previously cleared hardwood rangelands. California Agriculture, 55:37-41.

are using the technology. Economics are only partially to blame for the lack of implementation. For example, a planned biogas facility in Pixley, CA would have treated 36 million gallons of manure from 3 nearby dairies to produce biogas for to Calgren Renewables, a nearby ethanol biorefinery. The project had the potential to reduce greenhouse gas emissions by 31,000 $MtCO_2$ per year and had a 4.7 million dollar grant from the CEC, yet there was public resistance which ultimately delayed the project permanently.

Wastewater

Californians produce roughly 4 billion gallons of wastewater per day, with 268 facilities processing more than 1 million gallons per day. Although the organic material in wastewater (sewage) is relatively energy-poor, only one-tenth of the energy content is used in current processing, leaving a substantial resource for energy recovery for other uses. Wastewater treatment plants naturally release methane, a greenhouse gas, which is often flared (unproductively burned) for safety. As of 2005, only 23 facilities in California were using the biomethane to generate heat and electricity.

Algae

California has the potential to grow algae in a variety of formats including large ponds, in off-shore enclosures, or in contained photobioreactors. The state is home to one of the nation's few commercial algal culture facilities, Earthrise Nutritionals, located in the Sonoran desert in southern California. The company has been growing *Spirulina* for human consumption in raceway ponds since 1976. Algae has been studied as a feedstock for biofuels for nearly 30 years because some strains store large amounts of lipids or oil, up to 40% of the cell volume, under nutrient limiting conditions. Recent estimates of theoretical productivity for open ponds indicate 350 tons of biomass per hectare per year is achievable, with that amount of algae producing approximately 41 thousand gallons per hectare per year[48]. The organisms can be grown photosynthetically in large mixed ponds or in artificial photobioreactors. Photosynthetic cultures typically require a carbon dioxide input and can be paired with carbon capture efforts, a strategy being pursued by Southern California Gas Company in collaboration with Scripps Institute of Oceanography. Alternatively, they can be grown heterotrophically in fermenters. Heterotrophic cultures require a sugar substrate, similar to bacteria or yeast, a strategy being pursued by Solazyme. Both growth methods require substantial nutrient inputs. Following extraction of the oils for fuel production, the residual algal biomass can be used as fish or poultry feed or as a nutrient supplement for humans. Cultivation in raceway ponds, the most economical method, is possible in the flat regions of southern and central California, although temperature fluctuations will limit production of some strains to 7 months of the year[49]. An alternative strategy, using floating bioreactors and nutrients supplied by wastewater, is being evaluated by NASA at a wastewater treatment facility in Santa Cruz[50], however productivity of the system has not been disclosed.

There is an enthusiastic community of scientists and entepreneurs working on development of photosynthetic algal culture systems, largely at small scale with interesting prospects to treat wastewater and industrial CO_2. However, the feasibility of widespread commercial scale algal biofuel production in California by 2050 is uncertain. The largest source of uncertainty is the estimated cost

48 Stephens E, Ross IL, King Z, Mussgnug JH, Kruse O, Posten C, et al. (2010) An economic and technical evaluation of microalgal biofuels. Nature Biotechnology 28:126–128.

49 Belay A (2007) Spirulina (Arthrospira) production at Earthrise. presentation at the Algal Biotechnology Seminar Series, University of California, San Diego, October 2.

50 http://www.nasa.gov/centers/ames/news/features/2012/omega_algae_feature.html

of production which varies widely in the academic literature and in public statements by start-up companies. Scaling up to production has a number of technical issues, as well as issues related to siting and land use change. Current pond designs require extremely level surfaces, adding to the cost of construction. Although some present day nutraceutical algae farms use unlined ponds for cultivation, it is uncertain whether this will be tolerated for future biofuel installations. Some companies envision using genetically modified algal strains but it is unclear whether such GMOs will find public acceptance. Siting issues increase with phycofarm size, counter to the economy of scale. It is uncertain how this will evolve in California. The most suitable sites would be either in desert or salinized agricultural land, reasonably close to population centers that could supply wastewater and/or CO_2. The possibility that there will be substantial resistance to large-scale land use change at these sites needs to be carefully considered and addressed in order for projects to be successful. The long delays in California in finding suitable sites for solar thermal energy facilities suggests public resistance to conversion of desert lands to new uses. While none of these obstacles are insurmountable, they introduce a level of uncertainty that makes projection of the probable scale of commercial algal biofuel production in California by 2050 extremely difficult. This uncertainty has prompted us to exclude photosynthetic algae from the biomass potential scenarios. We believe that the issues surrounding the future potential of algal fuels are complex enough that a separate study is warranted. We do include heterotrophic algae using sugar feedstocks as a viable conversion pathway, as part of the possible advanced hydrocarbon pathway. This path is treated as similar to other biological conversion pathways relying on carbohydrates from non-algal biomass sources and is thus restricted by the biomass estimates in the two scenarios in section IV.

IV. Matching Biofuel Supply and Demand in 2050

Baseline Demand in 2005

In 2006 Californians drove an estimated 28 million vehicles using approximately 16 billion gallons of gasoline and 3 billion gallons of diesel fuel[51]. Demand for ethanol to meet a 10% gasoline blend was 950 million gallons per year in 2005. In 2009, California imported 95% of the ethanol and 61% of the petroleum used to produce transportation fuels within the state. Although ethanol production capacity in California was approximately 242 million gallons per year (mgy) in 2007, the state produced only 50 million gallons[52]. The remaining 900 million gallons was imported, with ~85% from domestic suppliers, largely in the Midwest, and 15% from foreign suppliers such as Brazil. Biodiesel capacity in the state totals around 80 million gallons per year, less than 3% of the total demand in 2005.

Projected Demand

Diesel usage is expected to increase 2-3% per year reaching 6-8 billion gallons per year by 2030. Total clean fuel demand is estimated to rise to 25-32 billion gallons gasoline equivalents (bgge) by 2030[53]. These projections are similar to the conditions for this stress test, which considers a doubling of 2005 demand by 2050 to 44 bgge (Figure 3). Gaseous fuel demand rises to 24 bgge by 2050 under the business-as-usual scenario.

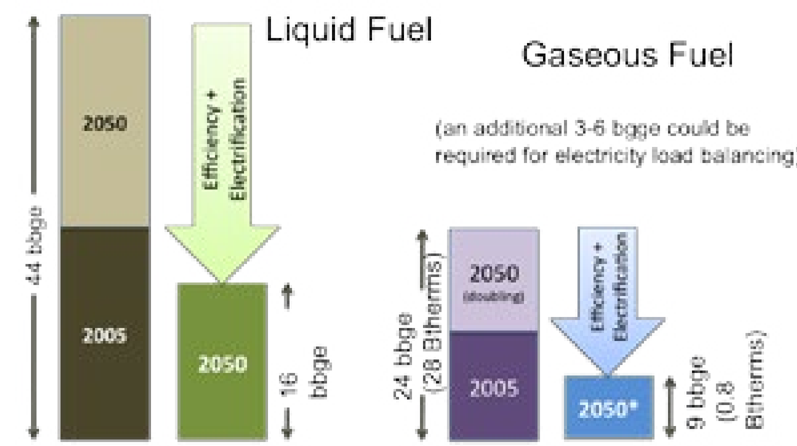


Figure 3. California 2050 fuel demand cases[54].

51 Schremp G, Page J and Weng-Gutierrez M (2007) Transportation energy forecasts for the 2007 integrated energy policy report. California Energy Commission.
52 Schremp G (2007) Ethanol in California: Security and supply. In Platts 2007 Gasoline Blendstocks ConferenceHouston, TX.
53 Williams RB, Jenkins BM and Kaffka S (2008) An assessment of biomass resources in California, 2007. A PIER Collaborative Report, California Biomass Collaborative, California Energy Commission.
54 From Table 3, Long J, et al. (2011) California's Energy Future – The View to 2050 Summary Report. California Council on Science and Technology.

Note on Gaseous Fuel Demand

As indicated in Figure 3, efficiency and electrification also reduce gaseous fuel demand. Gaseous fuels, mainly methane and propane, are important for many industrial processes that could not be electrified. Methane also plays an important role in firming electricity by allowing fast-ramping capacity required to respond to changes in electricity demand. This need is especially important in scenarios with high intermittent power sources such as wind and solar. Thus, gaseous fuel demand may change, depending on the portfolio used to decarbonize the power sector. Although this report mainly deals with liquid fuel from biomass for transportation, biomass could also contribute to low-carbon gaseous fuels in the form of biomethane from anaerobic digestion or other gases formed through thermochemical routes. Although some forms of biomass are a better fit to the technologies for gas production, decisions on how to best allocate biomass resources may be required to fit the low-carbon electricity mix employed. In some cases, maximum energy recovery can involve production of both liquid and gaseous fuels from the same biomass in a single facility. In other cases, decisions to use biomass for gaseous fuels will divert production from liquid fuels, which must be considered when estimating biofuel potentials.

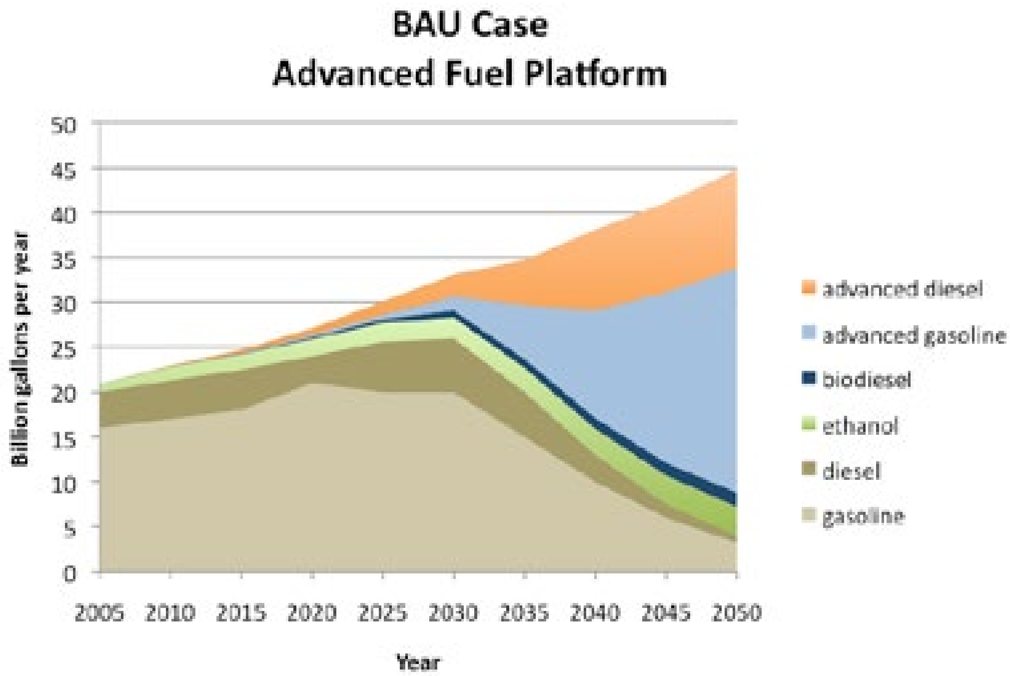
Fuel Mixture Scenarios

Three supply cases were then postulated to meet the fuel demand for each test case, resulting in six scenarios (Table 1). The base case business-as-usual fossil fuel mixture reflects the current trend toward 10% ethanol in gasoline and 10% biodiesel in conventional diesel[55]. This fuel mixture was applied to the two demand cases to determine the business-as-usual greenhouse gas emissions in Section V of this report.

Two alternative biofuel supply scenarios were then constructed for each demand case. The near-term scenario projects displacement of conventional gasoline by an 85% blend of cellulosic ethanol with fossil gasoline and introduction of a 85% blend of biodiesel with fossil diesel (Figure 4, top and Figure 5, top). In the far-term scenario, advanced biomass-derived hydrocarbons (drop-in fuels) replace gasoline and diesel with 10% cellulosic ethanol and 10% residual fossil gasoline and 2% fossil diesel (Figure 4, bottom and Figure 5, bottom).

In all scenarios, demand increases until roughly 2018 when efficiency and electrification measure ramp-up, curbing the need for liquid fuel. Gasoline demand is reduced to a greater extent than diesel through a combination of higher miles per gallon in combustion engines and the adoption of hybrids and fully electric vehicles. Diesel demand is reduced through electrification of buses and rail transportation. Replacement of fossil fuels with biofuels occurs over time with a projected building and implementation rate. The combined changes in fuel demand and biofuel use result in the first noticeable replacement of fossil fuel volume with biofuels in 2025, with increasing substitution to 2050. This build-in rate is reflected in delayed greenhouse gas emissions in Section V of this report.

55 Pending requests to EPA for an increase in the blending ratio to 15% ethanol will change these projections only slightly.



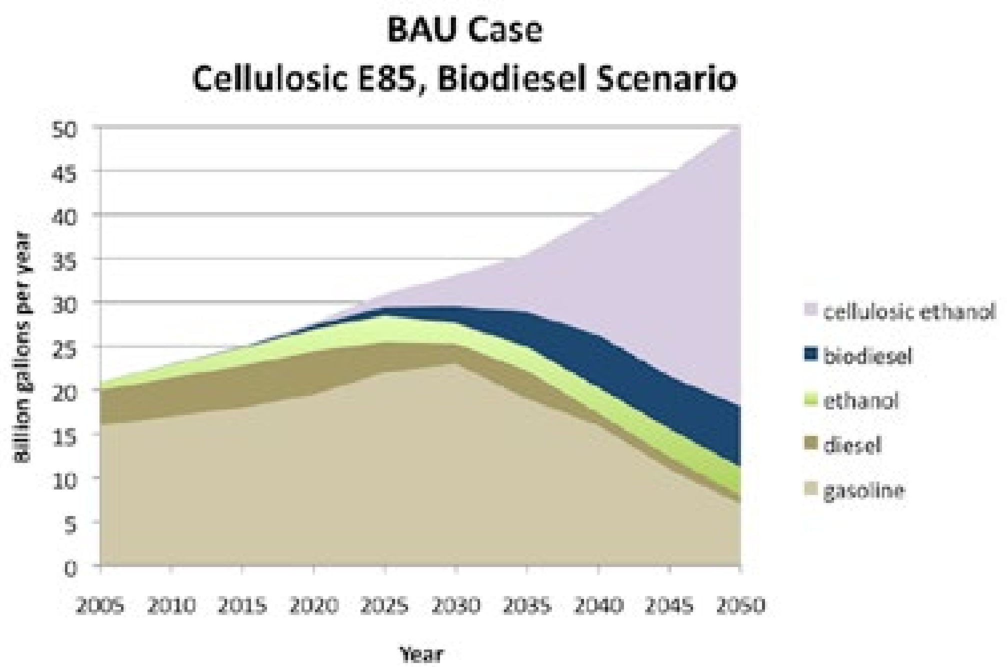


Figure 4. California liquid fuel business-as-usual demand in 2050 met by cellulosic ethanol and biodiesel (top) or advanced hydrocarbons/drop-in biofuels (bottom).

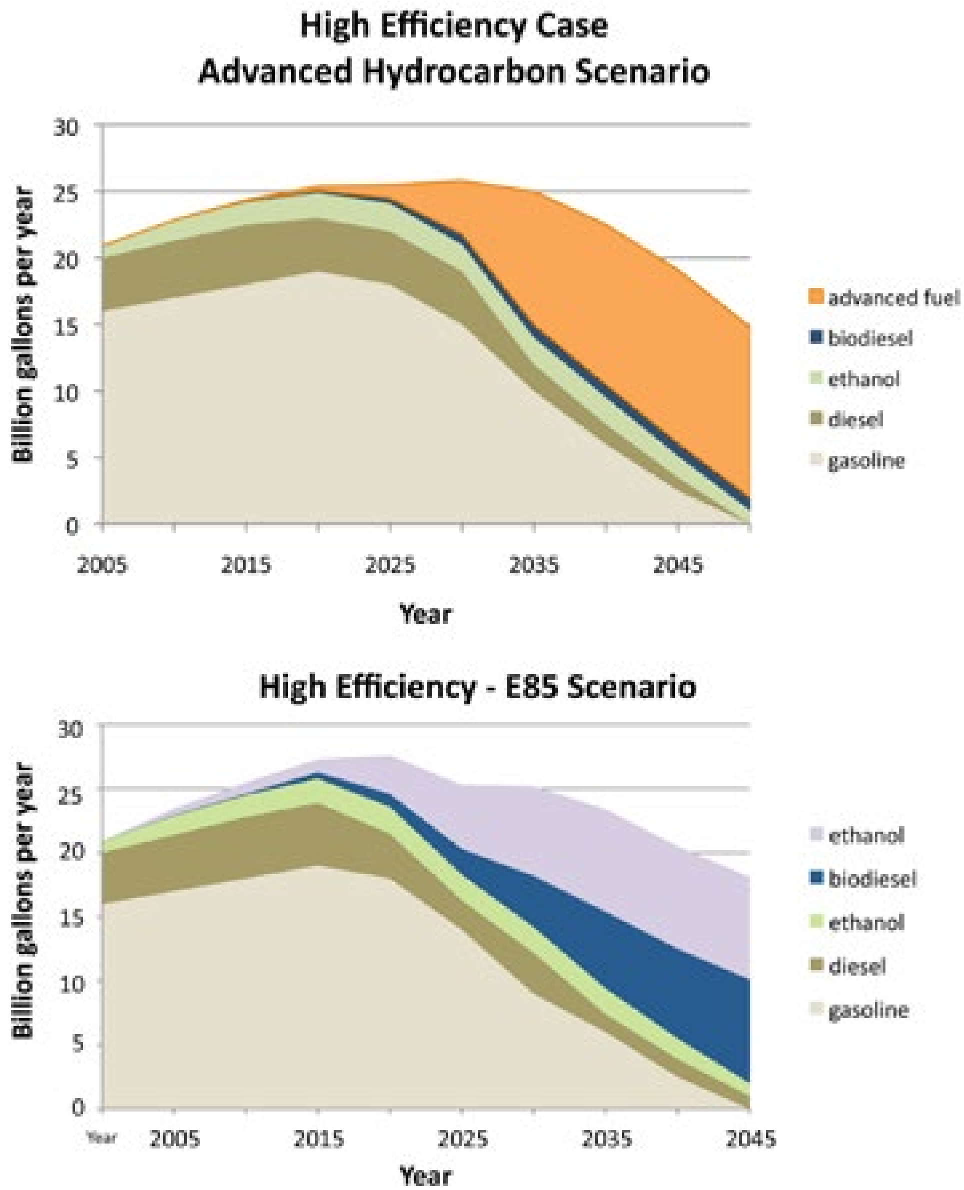


Figure 5. Fuel supply profiles for the high-efficiency demand test case* met with cellulosic ethanol and biodiesel (top) or advanced hydrocarbon/drop-in biofuels (bottom).

*The near-term E85 cellulosic ethanol/conventional biodiesel scenario (top) reflects the large decrease in gasoline demand suitable for ethanol substitution due to electrification. The advanced hydrocarbon or drop-in fuel scenario (bottom) does not distinguish between gasoline or diesel substitution for the purposes of GHG reduction calculations.

Feedstock Requirements

Corn Ethanol

The production capacity of most corn ethanol facilities ranges from 20 to 200 million gallons per year. A 100 million gallon per year corn ethanol facility requires roughly 35 million bushels of corn at 2.8 gallons of ethanol per bushel. In the Midwest, this can be supplied from within a 50-mile radius of the plant. Ethanol plants in California typically import almost all feedstock from Midwest farms. California cultivates only 500,000 acres of corn for local feed, compared to roughly 11.5 million acres of corn cultivated annually in the state of Iowa.

Next-generation Biofuels

The capacity of next-generation biofuel plants will be determined by the availability of feedstocks. Most proposed facilities range from 5 to 100 million gallons per year. A 50 million gallon per year facility requires a little over 1,200 tons of biomass per day, or roughly 12,000 acres of forest pulp, 22,000 acres of Miscanthus, 160,000 acres of switchgrass, or 270,000 acres of corn stover based on average productivity estimates. The resource requirements for a biomass to hydrocarbon facility will be similar to that for the biomass processing and fermentation portions of producing cellulosic ethanol; however the fuel refinement process will differ greatly.

Algal Biofuels

The feedstock requirements for algal facilities depend largely on the culture technique and the organism and the separation technique. Most research has focused on large open raceway ponds, which face problems with contamination and are difficult to site[56]. Photosynthetic production requires a light source and supplemental CO_2; whereas heterotrophic growth requires a sugar source. Sugars could be generated from cellulosic sources as technology improves. All cultures require substantial nutrient inputs which could be derived from waste sources. Because the input requirements can be substantial, scenarios to pair algal culture with other industrial processes have generated broad interest. For example, tempered flue gases or gases from carbon capture projects could provide nutritional CO_2 to algal cultures. Sewage, manures, or other wastewaters may provide some of additional nutrients such as reduced nitrogen.

California Biomass Supply Potential

Despite California's great wealth of resources, the governor's goal of primarily in-state energy production can only be partially met by the current biomass inventory. Some additional growth of energy crops such as high-productivity grasses and trees, could be feasible and import of compliant biofuels is likely to continue to supplement in-state energy production.

In 2005 and 2007, the California Energy Commission, in conjunction with the California Biomass Collaborative, estimated the gross biomass yield along with the technically recoverable portion to 2020[57] For the purposes of this study, projections were extended to 2050 under two scenarios

56 A confluence of temperature, CO_2 source, brackish water source is required. A detailed assessment was conducted by J Sheehan, T Dunahay, J Benemann and P Roessler (1998) A look back at the U.S. Department of Energy's aquatic species program: Biodiesel from algae. Close-out report. National Renewable Energy Laboratory, NREL/TP-580-24190, 328 pp.

57 Jenkins BM (2005) Biomass in California: Challenges, opportunities, and potentials for sustainable development. In PIER Collaborative Report California Biomass Collaborative, California Energy Commission.; Jenkins BM (2006) A preliminary roadmap for the development of biomass in California." In PIER Collaborative Report CEC-500-2006-095-D: California

described below[58]. In accordance with the work of Jenkins *et al.*, the baseline biomass scenario (Table 5; Figure 6, top) presumes very little introduction of energy crops (5 million dry tons), no increase in herbaceous crop residues or forest residues after 2010, 1% per year growth in processing and municipal waste and a 2% per year increase in processing waste. Also in this scenario, technical advances only increase the recoverable yield by 3%. If all the technically available biomass, 41 million dry tons, were converted to fuel in this scenario up to 3.3 billion gallons gasoline equivalent could be produced annually.

	Baseline Scenario			**High-Biomass Scenario**		
Biomass Source	**Productivity (Gross Biomass)**	**Technically Recoverable Yield**	**Percent Recovery**	**Productivity (Gross Biomass)**	**Technically Recoverable Yield**	**Percent Recovery**
Primary						
Herb. Energy Crop	5	4.5	90	30	25.5	85
Woody Energy Crop	0	0	0	25	17.5	85
Shrub/ chaparral*	0	0	0	4.9	2.7	55
Secondary						
Herb. crop residue	6.5	2.1	33	8.6	4.3	50
Woody crop residue	3.5	2.4	70	5.4	4.0	75
Forest residue	26.8	14.3	53	30.1	19.6	65
Tertiary						
Processing waste	1.8	1.4	80	3.3	2.6	80
Animal waste	15.8	5.5	35	15.0	9.0	60
Municipal waste	41.7	10.4	25	53.7	37.6	70
Total	**101.1**	**40.6**	**40**	**185.1**	**122.8**	**66**

Table 5. Projected California biomass yield in 2050 (million dry tons per year).

*Previous estimates for shrub and chaparral in 2007 was 4.9 million dry tons per year with a 55% recovery[1,4].

A second "high-yield" scenario was forecasted (Table 5; Figure 6, bottom). In this scenario, herbaceous and forest residues were predicted to increase 1% per year[59] and a substantial investment in energy crops, both herbaceous and woody, is projected. All other productivities are unchanged but a

Biomass Collaborative, California Energy Commission.

58 Potential supply for phototrophic algal biomass was not projected due to uncertainties in production models and siting which require more detailed modeling and scenario building; however, the possible use of lignocellulosic sugars as a biomass source for heterotrophic algal conversion are considered.

59 This assumes increased production of agricultural and forest products from which these residues are derived.

more ambitious learning curve is postulated with improved technical recovery (Table 5). A biomass recovery of roughly 123 million tons could yield up to 9.8 billion gallons gasoline equivalent.

The technical yield of forest residue is predicted to increase from 50% to 65% recovery by 2020 and 70% by 2030 due to a combination of improved technology and infrastructure and changing forest management practices. We assume only 40% possible production from abandoned and non-productive timberlands.

Estimates for total biomass potential in California range from 100-185 million dry tons per year by 2050 with the major differences in the predicted growth in municipal solid waste and adoption of energy crops. Innovation in harvesting technology continues as new feedstocks are explored and developed. Uncertainty regarding the efficiency and infrastructure requirements of these feedstocks is reflected in the wide-ranging estimates of the percentage of available biomass that can be economically recovered (Table 5). In California, recovery of 40-70% is possible, representing 40-120 million dry tons per year by 2050[60]. Nationwide, 550 million to 1 billion dry tons of biomass are estimated to be available for biofuels production[61].

As external validation of our higher predictions, EPA's FASOM modeling predicts 7.3 million dry tons in agricultural residue from barley, corn, rice, sorghum, and wheat alone in California by 2022[46]. Typically, yields have increased 2% per year, such that an increase to 12 million dry tons could be projected, absent detrimental climate induced effects by 2050. Factors affecting yield are varied and large uncertainties regarding these predictions merit in-depth analysis assisted by improved biomass tracking and modeling.

Potential for Imported Biofuels and Biomass Feedstocks

Transportation of lignocellulosic biomass is costly, typically limiting transportation to within a 50 mile radius of the conversion facility. Thus, it is likely that any demand unmet by in-state biomass would be supplied by imported biofuels for final in-state blending. In 2007, California imported nearly 900 million gallons of biofuel, 95% in state consumption. Nearly 85% was purchased from domestic suppliers, largely in the Midwest, and 15% from foreign suppliers such as Brazil. Import of ethanol from Brazil is cheaper than ethanol from the Midwest, even with taxes and tariffs in place.

Brazil has plans to develop an additional 55 million hectares of sugarcane for ethanol production through cattle intensification, which could enable production of 100 billion gallons of conventional ethanol (67 bgge) from sugar by 2030 and an additional 70 billion gallons of cellulosic ethanol from sugarcane residual biomass (45 bgge). However, the California's Energy Future Committee assumed that other regions outside California would be engaged in similar activities to reduce greenhouse gases, thus biofuels available for import might be limited. California's "fair share" was set to equal the amount of in-state biofuel production – 7.5 bgge in 2050. With this restriction, the total amount of biofuel available would meet only a little over one-third of the BAU demand in 2050 but would be sufficient to meet demand in the high-efficiency and electrification case.

60 Williams RB, Jenkins BM and Kaffka S (2008) An assessment of biomass resources in California, 2007. In PIER Collaborative ReportCalifornia Biomass Collaborative, California Energy Commission.

61 R. D. Perlack and B. J. Stokes (2011)ORNL/TM-2011/223. US Billion-ton Update: Biomass supply for a bioenergy and bioproducts industry. Oak Ridge National Laboratory, Oak Ridge, TN 2011 August pp. 1-229.

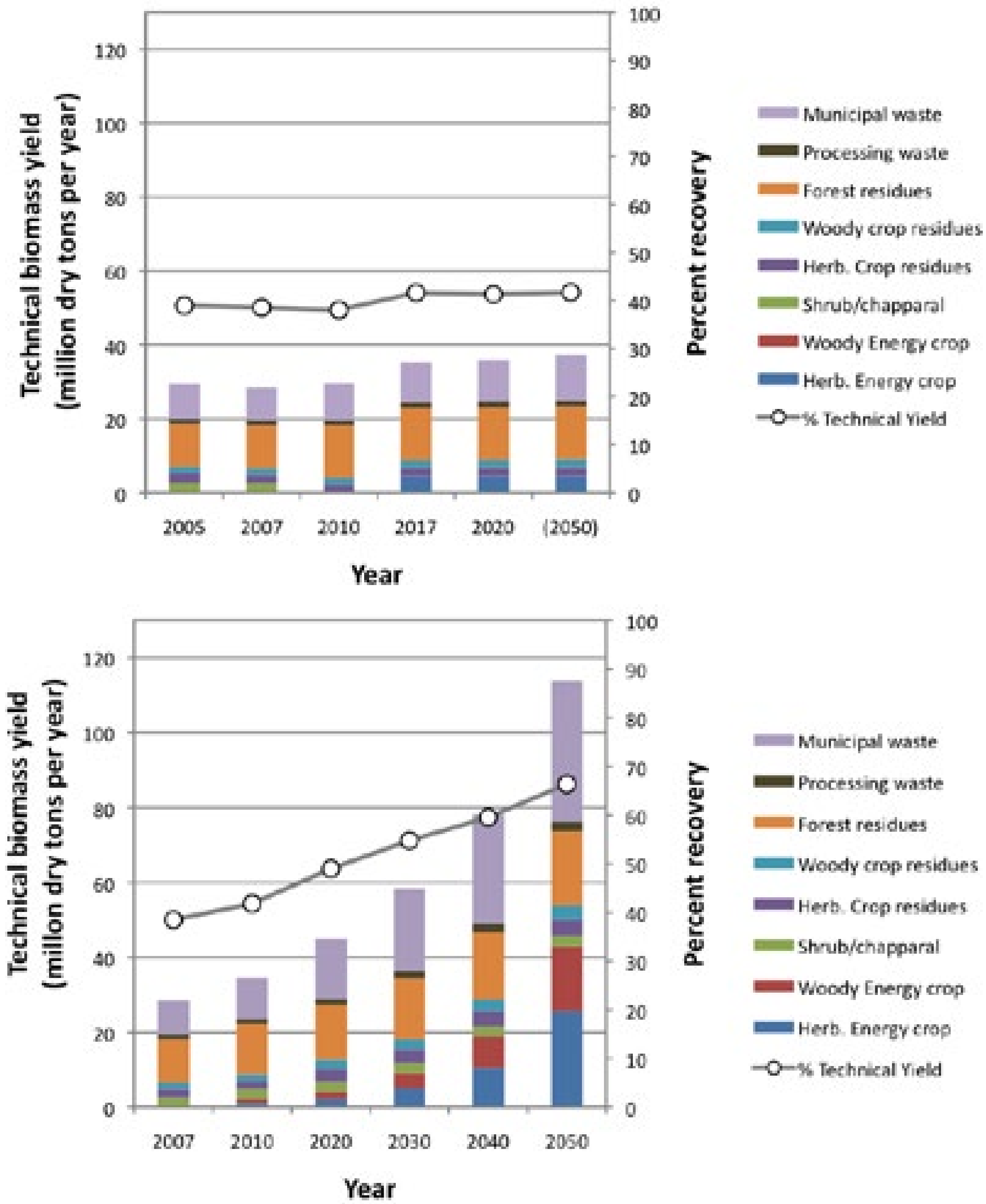


Figure 6. Projections of annual yield of technically recoverable biomass in California. Top panel: Conservative yield, minimal energy crop scenario based Jenkins et al.[19] Bottom Panel: Optimistic yield, substantial energy crop scenario (Animal waste not shown).

Decisions Regarding Biomass Use

Ultimately, matching biomass supply to the demand for bioenergy products such as liquid fuels, gaseous fuels, and electricity or other products such as food, feed, fiber, and chemicals depends on decisions regarding biomass use. Figure 7 shows an example of a decision matrix for producing different energy carriers from biomass. Some biomass is best suited for particular conversion technologies, which will influence the decision process. For example, although it is technically possible to make liquid fuels from animal waste or organic materials in wastewater, conversion to biogas is the most feasible and economical. In contrast, herbaceous crops and their residues could be converted to either biogas or liquid fuels with relatively equal feasibility (in fact both options are being pursued commercially). Since natural gas prices are extremely low in California, a scenario for liquid fuels seems most plausible at the present. Woody crops and their residues are amenable to either electricity generation or liquid fuels. Here the choice may depend on the feasibility of siting of and transport to the two different types of conversion facilities and a scenario in which some portion of the available biomass can go to each end product. Similarly, municipal waste, which is a highly diverse source of biomass, could be divided in such a way that some wastes such as food and wet green waste goes to biogas production while the remaining dry wastes such as paper and woody wasted go to either electricity or liquid fuel production. With opposition of direct use of municipal waste to generate electricity[43], conversion to liquid fuels and biogas could be favored. The uptake of biogas supply is likely to depend on willingness of pipeline owners to accept biogas in the current natural gas infrastructure. Conversion decisions need not be exclusive. For example, conversion of lignocellulosic biomass to liquid fuels by biological conversion technologies results in production of a lignin residue that can be used for electricity production and wastewater from which biogas can be produced. This process is called co-generation.

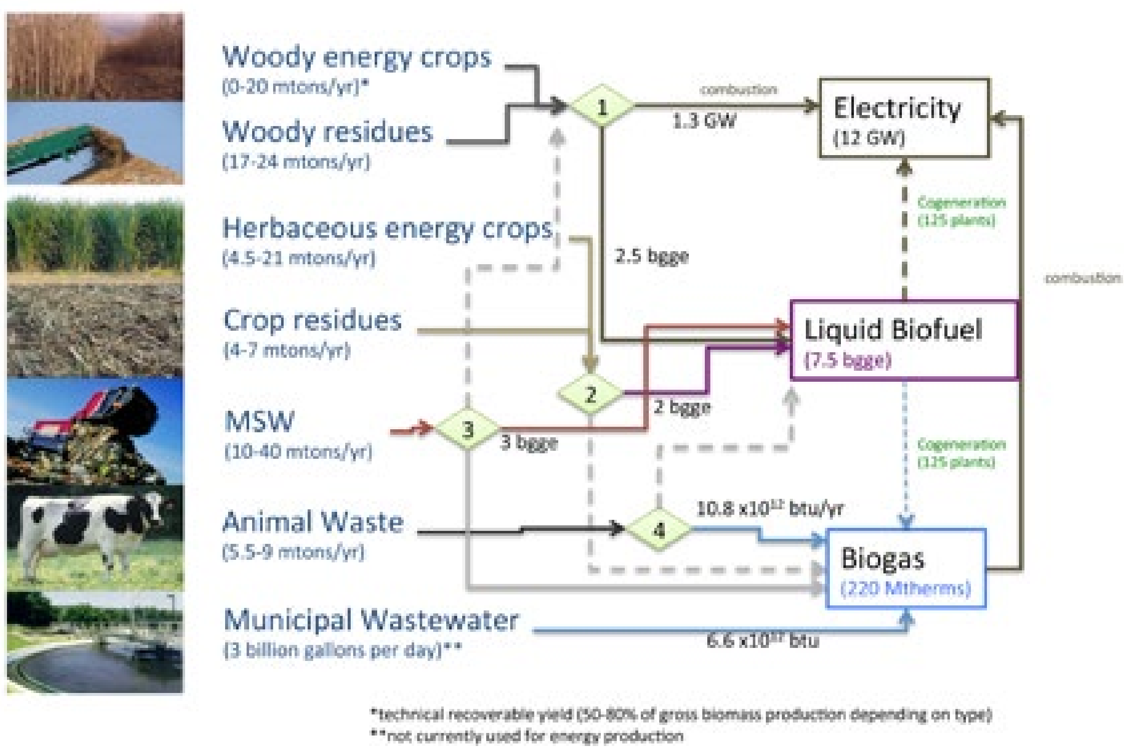


Figure 7. Example decision matrix for conversion of biomass from various sources to bioenergy products.

Other Constraints

Construction and operation of biofuel facilities and growth and use of biomass feedstocks in California face many barriers summarized in Table 6.

Barrier	Category	Example	Possible Mitigation Strategies	Difficulty to Overcome
Risk Aversion (Market Uncertainty)	Social, Economic, Policy	Large capital investment, Difficulties with loan insurance for energy crops	Economic incentives for new feedstock growth and conversion (e.g. BCAP), research and education on sustainable agronomics of new and current feedstocks, stable policies, government insurance	High
Land Availability for Biomass Production	Physical, Social, Ecological, Economic, Policy	Conflicts with current food/feed agriculture needs. Conflicts with ecosystem needs	Intensify land use, repurpose abandoned ag land, preserve current ag land. Forward-looking land-use policy, thorough environmental impact assessment, regional socio-economic impact assessment	High
Water Availability for Biomass Production & Conversion	Physical, Social, Ecological, Economic, Policy	Increased agricultural pressure on water systems already under stress, conflicts with ecosystem needs	Incentivize use of more water efficient feedstocks, require water recovery, recycling and treatment in processing facilities, facilitate equitable water use through local and regional governance	High
Biomass Availability	Economic	Competition with biomass markets for fiber and electricity	Incentives for use of renewable & sustainable feedstocks for fuels (e.g. BCAP), development of new market mechanisms	Medium
Economic Biomass Yield	Technology	Design & implementation of high biomass crops	Development of improved agronomic practices and higher yielding cultivars	Medium
Economic Conversion Efficiency	Technology, Economic	High cost of enzymes and catalysts prohibit scale-up	Investment in research and commercialization, development of more efficient enzymes, microbes, catalysts	Medium
Nutrient Availability	Physical, Ecological, Technological, Economic, Policy	Nitrogen fertilizers have large footprints, possible limits in potassium, ecological effects of leaching and overuse	Use plants with high nutrient efficiencies, incentivize advanced nutrient diagnostics, precision agriculture, and nutrient recycling from processing facilities	Medium
Transportation & Distribution	Economic, Infrastructure	Connecting rural biomass sources to urban consumers	Investment in roads and rail, increased efficiency of transport, support for regional conversion plants (incentives for intelligent siting)	Low
Biomass Recovery	Technological, Ecological	Sustainable and economic removal, transport and storage of biomass	Development of new machinery for efficient one-pass harvest and transport or novel feedstocks, research on sustainable removal levels	Low

Table 6. Barriers to widespread implementation of biofuels in California.

Uncertainties in Land and Biomass Availability

In the last decade, a serious effort has been launched to improve mapping and characterization of various biomass feedstocks in California. Productive lands such as active agricultural and timber lands are better annotated than more marginal lands such as chaparral, pasture, and range lands and an accounting of the agricultural potential of abandoned crop lands is sorely needed. Understanding how generation of residues will change with alterations in food and wood product production in the face of global economic markets and climate change remains a challenge. For example, the high-biomass scenario presented here assumes growth in both agricultural and forest residues through increasing innovation in production capability and demand; however, rising costs of labor in California, climate change and associated restrictions on water availability, combined with the fungibility of food and wood products in the global market could result in loss of production in the state which would negatively impact the availability of residues. Finally, a mapping of conserved agricultural lands (lands enrolled in the federal conservation and reserve program or CRP) with critical habitat is needed to assist responsible return of land to production if required. Coordination of responsible biomass production and management with the state's farmland conservation effort, which is designed to protect farmland from urban development, seems synergistic to both state goals.

Uncertainties of Feedstock Recovery

Economic factors may limit recovery of certain agricultural, processing, or municipal residues. Terrain and ecosystem health constraints may limit recovery of forest residues. Feedstock yields and recoveries may also be affected by climate change, increased soil salinity, or other environmental factors that cannot be controlled.

Sustainable production may require reduced harvest strategies for different crops. Adaptation of feedstocks and practices to changing growth conditions will require ongoing investment in breeding, agronomic, silvicultural, and biotechnical research. Mineral nutrient recovery and recycling must be included in evolving practices to ensure sustainable feedstock recovery and maintenance of soil health.

Conversion Barriers

The efficiency of saccharification (conversion of lignocellulosic biomass to fermentable sugars) continues to be a costly barrier to biochemical conversion. The cost of enzyme production remains the single-largest operating cost. Unprecedented investment in this area of research has contributed to substantial decreases in cost and is likely to reduce costs significantly by 2050; however, it does remain a significant barrier to plant design and optimization and thus investment. Alternatively technologies for depolymerization are being commercialize that may eliminate the need for enzymes. The final issues of cost are uncertain but significant progress is underway.

Biomass Transportation

Biomass is not energy dense compared to other energy feedstocks. For example, gasoline and diesel have roughly 46 MJ per kg, while coal has 24 MJ per kg and wood 17 MJ per kg. This means that transportation of biomass is relatively expensive, ranging from \$2 to \$5 per GJ[62], necessitating careful siting of biomass conversion facilities for favorable economic conditions. Coordination of feedstock availability and storage is vital to ensure continuous processing. Technologies for biomass

62 Searcy E, Flynn P, Ghafoori E and Kumar A (2007) The relative cost of biomass energy transport. *Appl Biochem Biotech* **136–140**:639–652.

densification, transport and storage vary according to feedstock and are generally in the research stages for emerging energy crops. Improper storage can result in significant losses of the feedstock and cost of transport remains the single most important factor in determining feedstock pricing. Methods to cost-effectively densify feedstocks are sorely needed to improve storage and transportation efficiencies and economics. Optimization of distributed pre-processing and other transport enabling technologies could allow long-range movement of biomass which would facilitate biorefinery siting, enable economies of scale in biorefinery design, and result in more sustainable natural resource allocation, minimizing environmental impacts.

Market Uncertainty and Capital Investment

Stability in the price of oil, uncertainties in the investment landscape due to the economic downturn and the slow development of a carbon market have slowed investment in advanced biofuels infrastructure. Continued investment by federal agencies such as the U.S. Department of Agriculture, the U.S. Department of Energy, and state governments allowed a few projects to progress in 2009, despite massive insolvencies at the time, in the corn ethanol industry, which represent the natural investors in biofuels technology. The majority of investments have been for small-scale demonstration and pilot plants; however, several companies continue to move forward with commercial endeavors. In the case for cellulosic ethanol these plants represent only 1-2% of the U.S. mandate. The aggressive schedule for biofuels implementation will not be met without further investment in commercial-scale production facilities.

Social Infrastructure Constraints

Biomass production and harvest will be limited by a lack of trained equipment operators. Labor constraints have limited mechanization efforts in Brazil and farmers in the U.S. often have difficulty procuring trained operators at the height of the harvest season. The necessity to double-pass to remove residues, increased handling and slower harvest rates will exacerbate this shortfall. New energy crops and increased pressure to develop and improve sustainable farming techniques will require investment in agronomy, forestry, plant science, soil science and ecology. In addition, a new slate of biorefineries and feedstock processing will require construction engineers, mechanical engineers, chemical engineers, chemists, microbiologists and biochemists, and operation managers.

Policy Constraints

The lack of consensus of definitions of renewable fuels and renewable biomass complicates the policy landscape for biofuels and affect rates of energy crop adoption by farmers and foresters and investment in capital expenditures for processing. Harmonization of state and federal policy, along with increased interagency collaboration will reduce uncertainties and increase stability of biofuel production costs and long-term investment. This, in turn, will have a positive effect on labor and other economic growth factors.

Limitations on the use of biomass are emerging. For example, many municipalities are incentivizing or requiring composting of some types of biomass such as food and yard waste without energy recovery. Limitations on the recovery and use of forest biomass recovery on public lands at the state and federal level will also affect the energy potential from in-state sources. Concerns regarding environmental impacts of biomass use will likely shape future policy regarding bioenergy deployment. Development of a comparative and tangible measure of ecosystems services seems especially crucial to developing reasonable biomass-related policies in California and elsewhere.

V. Projected 2050 Greenhouse Gas Emissions

Greenhouse gas emissions vary according to the biomass source (feedstock), methodologies used in feedstock growth, harvest, transport and storage, the pathway for conversion of the biomass to fuel, and the boundary condition used in lifecycle analysis. In particular, patterns of land use change have enormous impacts on the lifecycle greenhouse gas emissions of biofuels. Estimates of the total lifecycle (direct and consequential/indirect) emissions are extremely controversial due to the high uncertainties in the calculation methodologies, which require prediction of a number of poorly understood variables in process flows, geophysical phenomena, global economics, and other dynamic large- and small-scale phenomena. This uncertainty is reflected in the widely different values assigned by agencies attempting to build regulatory frameworks for anticipated biofuels expansion.

The California Air Resources Board (CARB) estimates that total lifecycle greenhouse gas emissions from production and use of corn ethanol are 10% less than emissions from conventional gasoline; while EPA estimates these same emissions could increase as much as 30% or decrease up to 50%, depending on the conversion route. Similarly CARB estimates that production and use of ethanol derived from sugarcane could result ~20% lower emissions than gasoline while EPA estimates reductions ranging from 20-40% (Table 7). CARB calculates that production and use of cellulosic ethanol from woody sources (lignocellulosic) could produce 70-80% fewer greenhouse gases; while EPA projects even more substantial reductions for cellulosic ethanol (80-110%), with the possibility of net carbon sequestration using sustainably managed perennial crops over a long time period[63].

Fuel Pathway	Percent Change in GHG 100 year, 2% Discount	Percent Change in GHG 30 year, 0% Discount
Corn Ethanol (Natural Gas Dry Mill)	-16	+5
Corn Ethanol (Best Case Natural Gas Dry Mill)	-39	+18
Corn Ethanol (Coal Dry Mill)	+13	+34
Corn Ethanol (Biomass Dry Mill)	-39	-18
Corn Ethanol (Biomass Dry Mill with Combined Heat and Power)	-47	-26
Soy-Based Biodiesel	-22	+4
Waste Grease Biodiesel	-80	-80
Sugarcane Ethanol	-44	-26
Switchgrass Ethanol	-128	-124
Corn Stover Ethanol	-115	-116

Table 7. Changes in greenhouse gas emissions estimated by EPA[64].

63 Anderson-Teixeira KJ, Davis SC, Masters MD and DeLucia EH (2009) Changes in soil organic carbon under biofuel crops. GCB Bioenergy, 1, 75-96.

64 EPA estimates include direct lifecycle and land-use emissions for CO_2, N_2O and methane. Possible additional emissions caused by indirect or consequential effects (such as international market-induced land-use change when agricultural production is displaced) are also considered. EPA (2009) Draft Regulatory Impact Analysis: Changes to the Renewable Fuel Standard Program EPA-420-D-09-001.

Emissions from conventional soy- and palm-based biodiesel are controversial as well. Conversion of land to palm or soy production results in substantial carbon emissions and ecosystem loss; however, use of pre-existing plantations for palm oil production may offer some carbon savings. Although we do not anticipate palm diesel production in California, it could represent a portion of imported fuel. Depending on the timeline used, EPA calculates greenhouse gas emissions for soy biodiesel to range from -22% to +4% of the gasoline baseline (Table 7). Greenhouse gas emissions for renewable diesel production from jatropha or algae are largely unknown. Both could be grown on marginal land, land deemed non-productive for food or feed crops.

In order to gain approval under the EISA advanced biodiesel will have to meet at least a 50% CO_2 reduction over diesel from fossil sources. Carbon emissions from the production of advanced hydrocarbons from biomass via catalysis or biotechnologically enhanced fermentation are also not known; however we conservatively estimate that these emissions will be similar to those for cellulosic ethanol production.

Using the EPA estimates and the BAU demand curves postulated in section IV[65], adoption of E85 and cellulosic ethanol[66] could reduce emissions by 15-50% below 2005 levels while the adoption of advanced hydrocarbons (drop-in biofuels) derived from lignocellulosic biomass could reduce emissions from 50% to 110%, with the theoretical possibility of net soil carbon sequestration (Figure 8, top panel). Adopting a high-efficiency and electrification demand case allows reduction of emissions by 50% to 85% below 2005 levels with implementation of cellulosic E85 and biodiesel and 85% to 120% below 2005 levels with lignocellulosic advanced hydrocarbons (Figure 8, bottom).

Although the widespread adoption of biofuels to meet future demand in California will reduce greenhouse gas emissions by 2050, the delay required for implementation of new technologies such as low-GHG biofuels will result in short-term GHG increases. Long-term benefits are real and achievable, especially with a concomitant reduction in demand, through efficiency, behavior changes or alternative technologies.

65 In each scenario the fuel mixture (fuel type, source and technology) is varied over time, the range of EPA GHG reduction estimates for each fuel-technology set were used to calculate the range of GHG reductions at each time point, thus the width of the box is proportional to the range of values in the mixture at any given timepoint, and thus represents a qualitative indicator of the uncertainty propagated in the calculation.

66 We have conservatively used the EPA numbers for dedicated energy crops to account for all the lignocellulosic biomass, although the majority of biomass in California is projected to come from residues that would not have indirect land-use change impacts, and many energy crops would have higher productivity per acre than switchgrass.

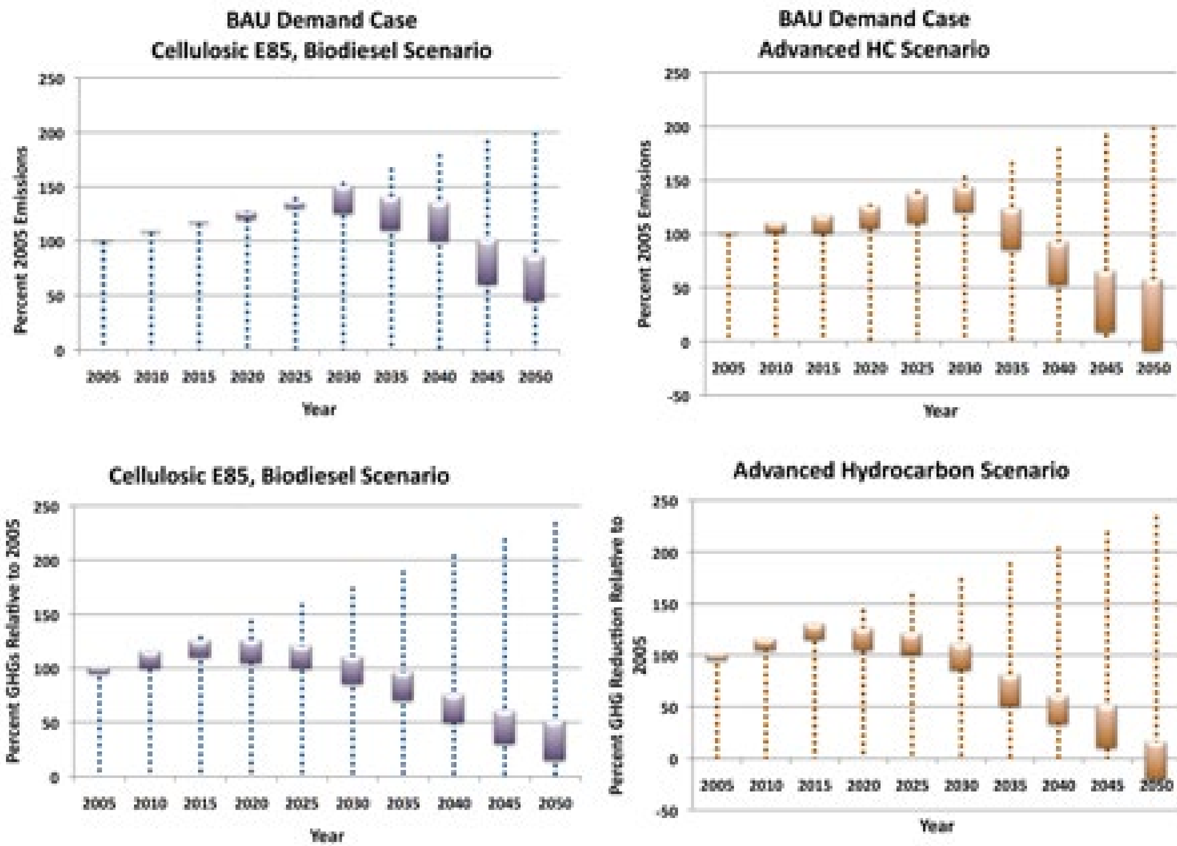


Figure 8. Combined projected greenhouse gas emission reductions in the business-as-usual demand case and the high efficiency and electrification case.

Baseline (dotted lines), E85 (left, blue), advanced hydrocarbon (right, red) scenarios. Boxes represent the range in projected GHG reductions with uncertainty, weighted for each technology embedded in the scenario**.**

VI. Infrastructure, Costs and Jobs

Existing Biofuel Infrastructure: Conventional Ethanol and Biodiesel

The U.S. has a long history of sporadically supporting production of first generation biofuels. There are approximately 185 plants in the U.S., with the capacity to produce almost 12 billion gallons of ethanol and 150 plants with the capacity to produce 2.4 billion gallons of biodiesel.

Commercial production of ethanol in California began with waste streams (beverage waste and cheese whey). The implementation of incentives promoting corn ethanol prompted construction of several facilities in California (Table 8) but limited production of corn in the state (mostly for cattle-feed) necessitates the import corn from the Midwest by rail. Transport costs, volatility in the fuel market, an economic downturn, and uncertainty over climate change policies contributed to the collapse of the corn ethanol market. In 2009, all of the corn ethanol refineries in California (242 mgy capacity) were idled and plans for facilities to provide an additional 66 million gallons per year were placed on hold or abandoned (Table 8). With the recent passage of the revised Renewable Fuel Standard, investments in corn ethanol are beginning to rebound and several plants have resumed operations.

Company	Location	Capacity	Feedstock	Status
Planned Refineries				
California Ethanol + Power, LLC	Brawley	66 mgy	Sugarcane, sweet sorghum	(2014)
Existing Refineries				
AE Biofuels	Keyes	55 mgy	Corn**	
AltraBiofuels (Phoenix BioIndustries LLC)	Goshen	31.5 mgy	Corn	idle
Calgren Renewable Fuels, LLC	Pixley	55 mgy	Corn	
Golden Cheese Company of California	Corona	5 mgy	Cheese whey	
Pacific Ethanol	Madera	40 mgy	Corn	idle
Pacific Ethanol	Stockton	60 mgy	Corn	
Parallel Products	Rancho Cucamonga	4 mgy	Food /beverage waste	

Table 8. California bioethanol refineries*[67].

*Total existing capacity is estimated at 250 million gallons per year (mgy), of which 71 mgy is idle. Another 66 mgy capacity is planned.
**Originally Cilion Ethanol, plant idled in 2009, leased by AE Biofuels and retrofitted to accommodate utilization of up to 25% agricultural residues (stover, straw) from 50-100 mile radius of the plant.

California currently has 83 million gallons per year biodiesel capacity in operation (Table 9). Most are small-scale operations, producing less than 2 million gallons biodiesel per year by esterifying waste oils. Waste biodiesel facilities have been less pressured by the economic downturn; however

67 Ethanol Producer Magazine (Renewable Fuels Association).

current low oil prices coinciding with the end of the biodiesel tax credit have caused uncertainty regarding the future of these facilities and several planned refineries.

Company	Location	Capacity (mgy)	Feedstock	Status
Planned Refineries				
Baker Commodities	Vernon	15	animal by-products (yellow grease)	
Energy Alternative Solutions, Inc.	Watsonville	1	yellow grease, virgin vegetable oils	
BioFriendly Fuel Partners	San Francisco	20	multiple	
Darling International	San Francisco	10	waste vegetable oils, animal fats	approved 2008
Encore BioRenewables	Southern CA	5	used vegetable oils	announced 2008
Operating Refineries				
Bay Biodiesel LLC	San Jose	5	virgin oils, yellow grease	
Biodiesel Industries Ventura LLC	Ventura	0.1	multiple	
Biodiesel Industries	Port Hueneme	1	used cooking oil	
Blue Sky Bio-Fuels Inc.	Oakland	4	multiple	
Crimson Renewable Energy LP	Bakersfield	25	multiple	
Community Fuels	Stockton	13	multiple	
Energy Alternative Solutions Inc.	Gonzales	1	yellow grease	
Extreme Biodiesel	Corona	2	multiple	
Imperial Western Products	Coachella	12	multiple	
New Leaf Biofuels LLC	San Diego	2	yellow grease	
Noil Energy Group Inc.	Commerce	5	multiple	
Promethean Biofuels Co-op	Temecula	2.1	used cooking oil	
REP-LA1 LLC	Santa Fe Springs	10	multiple	
R Power Biofuels LLC	Redwood City	1	multiple	
San Francisco Public Utilities Commission	San Francisco	0.4	recycled brown grease	
Simple Biofuels LLC	Chilcoot	2	yellow grease	
Southern California Biofuel	Anaheim	1	yellow grease	
Yokayo biofuels Inc.	Ukiah	0.5	waste vegetable oil	

Table 9. California Biodiesel Refineries*[68].

*Currently operating capacity totals 87 million gallons per year (mgy) with another 51 mgy planned.

68 Biodiesel Magazine (Renewable Fuels Association).

Next-generation Biofuels

Production of lignocellulosic ethanol at the pilot and demonstration scales has progressed substantially in the last ten years. In 2004 Iogen opened the first demonstration scale facility to produce ethanol (1 million gallons per year) from wheat, oat and barley straw in Ottawa, Canada. Many more have followed suit in the United States and Europe with mixed success. The transition to commercial-scale has not yet happened but a dozen companies have substantial investments in commercial-scale facilities slated to be operational by 2015 in North America, Europe and Asia.

California is home to many of the companies developing next-generation biofuel technology (Table 10). In California, cellulosic ethanol production was first demonstrated by Bluefire Ethanol. The company received financial assistance from the California Energy Commission and the U.S. Department of Energy to build produce ethanol from municipal waste in Lancaster, CA. The commercial-scale facility planned for Corona, CA faltered when the company became frustrated by the slow permitting process and moved the planned facility to Mississippi. Although the technology is being developed in California, many drop-in biofuel companies are developing their demonstration- and commercial-scale facilities overseas. For example, Amyris, a company using bacteria to convert sugar into drop-in gasoline and jet-fuel, is building a biorefinery in Brazil. Solazyme, a company using algae to convert sugar into biodiesel, has plans for a facility in France and Origin Oil, using algae to convert waste carbon dioxide to biodiesel, is building in Australia.

Company	Location	Capacity (mgy)	Feedstock	Fuel Produced
Altair	Bakersfield	2	Camelina	Renewable jet
Amyris Biotechnologies Inc.	Emeryville	0.1	Sucrose	Drop-in biofuel
Bluefire Ethanol	Lancaster	0.1	Green waste, MSW	Cellulosic ethanol
EdenIQ	Visalia	0.8	Corn kernels	Cellulosic ethanol
Kent Bioenergy	Mecca	0.01	CO_2	Algal diesel
LS9	San Francisco	0.1	Sucrose	Microdiesel
Origin Oil	Los Angeles	0.01	CO_2, wastewater	Algal diesel
RenTech	Rialto	8	Wood waste	FT diesel
REII	Sacramento	0.2	Ag and wood waste	FT diesel
Solazyme	South San Francisco	0.1	Sucrose	Algal diesel
Solena SAS	Gilroy	6	MSW	Biojet

Table 10. Pilot-scale Biorefineries in California for Advanced Biofuels Including Cellulosic Ethanol and Drop-In Biofuels.

The first commercial scale cellulosic ethanol biorefinery in California could be a retrofitted corn facility. Aemetis (formerly AE Biofuels) has leased the idled Cilion 55 million gallon per year corn ethanol plant in Keyes[69]. They will resume corn ethanol production and retrofit the facility to handle up to 25% agricultural residues such as corn stover and wheat straw from the surrounding area. The company has partnered with Edeniq to develop the technology, which they plan to market and license as an add-on to corn ethanol. This strategy has also been adopted by Gevo. Working in a

69 Global Bioenergy Industry News (2009) AE Biofuels to reopen Cilion ethanol plant. December 24.

corn-ethanol facility, the company plans to evolve their butanol technology from sugar feedstock to corn starch and eventually to lignocellulosic biomass. This approach provides an interesting bridge for companies to transition to cellulosic conversion technologies with less capital expenditure and risk.

New Infrastructure

If the required feedstocks were available, the E85 BAU demand projections would require approximately 30 conventional ethanol plants operating at 100 million gallons per year, 458 conventional biodiesel plants operating at 15 million gallons per year, and 537 cellulosic ethanol plants operating at 60 million gallons per year to be operational by 2050. To meet the advanced hydrocarbon case, 12 conventional ethanol and 30 cellulosic ethanol plants, 98 conventional biodiesel, 250 advanced gasoline and 110 advanced diesel plants would be required by 2050 assuming 100 million gallons per year for advanced hydrocarbon facilities. Both scenarios require operation of existing facilities to capacity and completion of currently planned builds. With limited biomass available, 150 plants operating at 50 million gallons per year would be sufficient to produce 7.5 bgge of biofuel.

To utilize the majority of biomass, residue harvesting infrastructure and transportation routes will be required. Most likely, road and rail will be used to transport loose or compacted biomass to the processing facility. Storage facilities may also be needed, depending on the residue type. There may be an opportunity for regional pretreatment facilities enabling larger scale fuel production facilities.

Fuel substitutes with physical properties that differ substantially from conventional petroleum, gasoline, and diesel will require additional infrastructure investments for transport, storage, and handling and could require vehicle fuel systems and/or engine modifications. For example, the EPA estimates that a transition to high ethanol blends such as E85 would require $122,000 in infrastructure investments per refueling station.

Biomass and fuel can be transported by road or rail and there are opportunities to transport many fuels by pipeline. Ideally, transportation would be limited, with the processing plant sited close to the feedstock and the fuel market (urban center); however, this is rarely the case. Many sites of maximal biomass production are far from transportation hubs. Additional road and rail lines may be needed to facilitate harvest of remote biomass (forest residues) or fuel transport[70]. This will influence the siting of plants and effect cost curves for available biomass[71]. Economic barriers to biomass transport necessitate siting of the biofuels processing facility near the biomass source yet also near highway or rail infrastructure, limiting viable sites. A water source for processing and cooling may also limit siting and permitting. A map of proposed processing sites, in proximity to feedstock source and infrastructure, has been developed by the team at UC Davis[73]. Additional technologies for biomass densification could enable biomass transport and alleviate some of the pressures on biorefinery siting and design.

70 Jenkins BM, Williams RB, Parker N, Tittman P, Hart Q, Gildart MC, Kaffka S, Hartsough BR, and Dempster P (2009) Sustainable use of California biomass can help meet state and national bioenergy targets. California Agriculture, 63:168-177.

71 Parker N, Tittman P, Hart Q, Nelson R, Skog K, Schmidt A, Gray E, and Jenkins B (2010) Development of a biorefinery optimized biofuel supply curve for the Western States. Biomass and Bioenergy 34:1597-1607.

Costs

Capital costs for a corn ethanol facility are around $200M for a 100 million gallon per year plant. The cost of producing ethanol from corn is currently $1.60-$1.90 per gallon. Sugarcane ethanol operating costs in the U.S. averaged $0.60-0.82 per gallon from 1992 to 1996 average ($0.85-$1.16 in 2010)[72]. The capital costs of developing a 15 million gallon per year biodiesel plant was estimated at approximately $9.6 million in 2002 with operating costs of $0.31 per gallon[73].

Capital investment required for construction of a 50-100 million gallon per year cellulosic ethanol processing facility is estimated at $250-$500 million. Projections for operating costs also vary from $2.35 to over $4 per gallon,[74] falling with technology improvements such as better sugar yield and conversion and improved enzyme costs. An increase in the construction rate is projected to occur between 2030 and 2040, once technology has been through at least one complete cycle of commercial-scale operation and wide-spread industry adoption.

The cost of converting lignocellulosic biomass to hydrocarbons via fermentation will likely be less than that for ethanol, if the organism can be engineered to secrete the fuel. Hydrocarbons will spontaneously separate from the aqueous phase, reducing the refining input required to distill ethanol from water. Eliminating the distillation apparatus alone will reduce capital costs by $28 million[75] and lower operating costs by reducing water, electricity, and heat consumption. For the purpose of estimating build costs in this exercise, advanced fuel plants have the same capital and operating costs as cellulosic plants.

The projected costs for algal production of lipids are quite variable, depending largely on the culture technique. Photoreactors are small, contained growth chambers or bags with artificial light that allow controlled growth conditions and the use of genetically modified organism at high efficiency. The high establishment, maintenance and operation costs limited the application of photoreactors to small-scale efforts[76]. Open ponds have been used successfully with non-modified organisms, although growth conditions within the pond can be quite variable, lowering efficiency. Capital cost estimates range from $39,000 to $599,000 per hectare of pond ($350 million to 20 billion for a facility that would produce 50 million gallons gasoline of biodiesel annually)[77]. Estimates for

72 Shapouri, H. (2005) Comparative advantage in ethanol production: U.S. grains vs. sugar USDA/OCE/OEPNU Energy From Agriculture: New Technologies, Innovative Programs and Success Stories St. Louis, Missouri, Dec. 14-15. Current values estimated using changes in the Consumer Price Index.

73 Radich A (2004) Biodiesel Performance, Costs, and Use. Energy Information Administration (http://www.eia.doe.gov/oiaf/analysispaper/biodiesel/); Hollis P. (2003) Georgia study looks at viability of biodiesel plant Farm Press October.

74 DOE has estimated $2-$4 per gallon for production of ethanol from corn cobs, with steep cost reductions as technology and efficiencies improve.

75 Aden A, Ruth M, Ibsen K, Jechura J, Neeves K, Sheehan J, Wallace B, Montague L, Slayton A and Lukas J (2002) Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover. National Renewable Energy Laboratory, United States, 154 pp.

76 Evidence of the high cost is the bankruptcy of GreenFuel, a company using photoreactors exclusively.

77 Davis R, Aden A and Pienkos PT (2011) Techno-economic analysis of autotrophic microalgae for fuel production. Applied Energy, 88:3524–3531; Demirbas A and Demirbas MF (2011) Importance of algae oil as a source of biodiesel. Energy Conversion and Management,52:163–170; Jonker J GG and Faaij APC (2013) Techno-economic assessment of micro-algae as feedstock for renewable bio-energy production. Applied Energy 102(C):461–475; Lundquist T J, Woertz IC, Quinn NWT, and Benemann JR (2010) A realistic technology and engineering assessment of Algae biofuel production. Energy Biosciences Institute Whitepaper October 2010, 1–178; Nagarajan S, Chou SK, Cao S, Wu C and Zhou Z (2012) An updated comprehensive techno-economic analysis of algae biodiesel. Bioresource Technology, in press; Norsker NH, Barbosa MJ, Vermuë MH and Wijffels RH (2011) Microalgal production — A close look at the economics. Biotechnology Advances, 29:24–27; Pienkos PT (2009) Historical Overview of Algal Biofuel Technoeconomic Analyses. NREL/PR-510-45622 DOE Algal Biofuels Workshop December 9, 2008; Stephens E, Ross IL, King Z, Mussgnug JH, Kruse O, Posten C, et al. (2010). An economic and technical evaluation of microalgal biofuels. Nature Biotechnology 28:126–128.

operating costs also vary widely, ranging from $1.59 to $790 per gallon. NREL has attempted to provide some harmonization to the analysis, suggesting a selling price of roughly $10 to 12 per gallon of biodiesel from algal lipids for production at the scale of of 5 billion gallons per year[78]. The scenario evaluated production at ten hypothetical 405 hectare unit farms scattered along the Gulf Coast (4050 hectares of total pond area and 4850 ha total facility footprint, including all processing operations). Capital costs accounting for 70% of the production cost for open ponds at $584 million ($120,000 per hectare).

Solazyme has a contract to provide algal biodiesel from non-photosynthetic algae to the Navy at roughly $425 per gallon as a test case. However, algal lipids are also used as nutritional supplements and have application as cosmetics and lubricants. These high-value uses are far more profitable than commodity fuel production. For example, Spirulina sells for $60,000 per ton with minimal processing, whereas the extracted algal lipids produced by the Solazyme for cosmetics retail for $2.3 million per ton[79].

Costs are also influenced by the price of feedstocks, which can range from $20-$100 per dry ton for most sugar and lignocellulosic feedstocks. For lignocellulosic feedstocks, it is difficult to accurately predict pricing for a market that is largely unformed. Because biomass is bulky and expensive to transport, feedstock pricing is likely to be a local issue. In the absence of a well-developed biomass market, the first commercial LC plants are securing long-term contracts (15 years or longer) for feedstocks in advance of construction. It should be noted that some forest and agricultural wastes are being converted to value-added byproducts. Examples of competing uses include use of woody waste for composite materials or mulch and use of food wastes for compost or animal feed. The use of biomass for combustion for heat and power can occur as a complement or competitor to biofuel production, affecting local feedstock prices. Oleaceous feedstocks are more expensive, ranging from $530 per ton for soybean to $890 to $63,000 per ton for algae[80].

Jobs and Generated Income

Each 50-100 million gallon per year corn ethanol plant supports nearly 1,100 employees (Table 11). The plant employs 35 to 50 full-time workers during normal operations, 200 temporary construction jobs, 100-140 indirect jobs generated by the purchase of goods and services by the industry, and another 100-140 induced jobs generated by employee expenditures in the community[81,82]. This job profile, including machine operators, engineers, architects, surveyors, and regulatory officials, will be very similar for next-generation biofuel plants.

Jobs supplying the biomass to the refineries are also supported. The average corn ethanol plant supports 240 direct jobs in agriculture and transportation, with an additional 700 indirect and

78 Davis R, Fishman D, Frank ED, Wigmosta MS, Aden A, Coleman AM, Pienkos PT, Skaggs RJ, Venteris ER, and Wang MQ (2010) Renewable Diesel from Algal Lipids: An Integrated Baseline for Cost, Emissions, and Resource Potential from a Harmonized Model. Some companies have made claims for extremely low costs but so far they have not been subjected to peer review.

79 Earthrise Spirulina retails for $30 per 16 ounces. Sephora's Algenist concentrated serum sells for $72 per ounce.

80 These feedstock differ in their embedded energy (41 MJ/kg for algae vs. 17 MJ/kg for LC biomass and 18.66 MJ/kg soybean) thus the cost by energy content is $2.50 to $7.80 per GJ for lignocellulosic biomass at $40-$120 per ton, $31.32 for soybean and $23.93 to $1694 per GJ for algae biomass.

81 United Nations Environment Programme (UNEP), International Labor Organization (ILO) (2008) Green Jobs: Towards decent work in a sustainable, low-carbon world. 376 pp.

82 Urbanchuk J (2012) Contribution of the ethanol industry to the economy of the United States. Report to the Renewable Fuels Association.

induced full-time equivalents. By one estimate, production of 13.9 billion gallons of corn ethanol in the U.S. in 2011 contributed $42 billion to GDP and generated $29.9 billion in household income.

	Direct	Indirect	Induced	Total
Biomass supply (farming, harvest, transport, storage)	240	300	400	940
Biorefinery (50-100 million gallon per year ethanol)	35-50 (full-time) 200 (part-time)	100-140	100-140	235-430
Total	475	400	500	1135

Table 11. Jobs associated with bioethanol production from corn in the Midwest.

In cellulosic plants, jobs generated by biomass harvest will be highly dependent on the feedstock type. For example, harvest of agricultural or forest residues will likely add some additional positions to current activities in these industries but may also provide additional months of seasonal employment for current employees, offering more stable income and the associated economic benefits. Jobs in biomass transportation will likely be higher than corn ethanol, as most biomass feedstocks are less dense, requiring additional infrastructure and handling per ton by comparison. This largely depends on the biomass supply scenario. IMPLAN modeling of bioenergy production from wood in Mississippi estimated the following employment generation (Table 12)[83].

	Direct	Indirect	Induced	Total
Biomass supply (Recovery of 4 million tons logging residues)	585	481	646	1712
Biorefinery (52 million gallon per year bioethanol plant)	908	261	586	1756
Total	1493	742	1232	3468

Table 12. Projected jobs associated with biofuel production from wood in Mississippi.

Jobs in forestry have been particularly impacted by the development of cheap pulp production outside of the United States. California has closed over 125 mills and lost over 9,000 mill jobs in the last 20 years (Figure 9)[84]. This does not include the jobs in harvest and transport to supply these mills. In addition, Californians spend roughly $1 billion annually to fight wildfires[85]. Small trees, which act to fuel forest fires, have increased as California forests have aged without regular maintenance. Density has increased from 70 trees per acre in the early 1900s to 400 trees per acre with high mortality, while harvest has decreased 90 percent in the last 25 years[86].

83 Perez-Verdin G, Grebner DL, Munn IA, Sun C, Grado SC (2008) Economic impacts of woody biomass utilization for bioenergy in Mississippi. Forest Product Journal 58:75-83.
84 The Pulp and Paperworkers' Resource Council http://www.pprc.info/index.htm
85 Powers RF (2010) Carbon opportunity lost in unmanaged forests: Active forest management can reduce greenhouse gas emissions. California Forests 14:12-13.
86 Stewart W (2010) Forestry's underground benefit deserve mainstrain consideration: Low-carbon energy adds to forestry's climate benefits. California Forest 14:8-9.

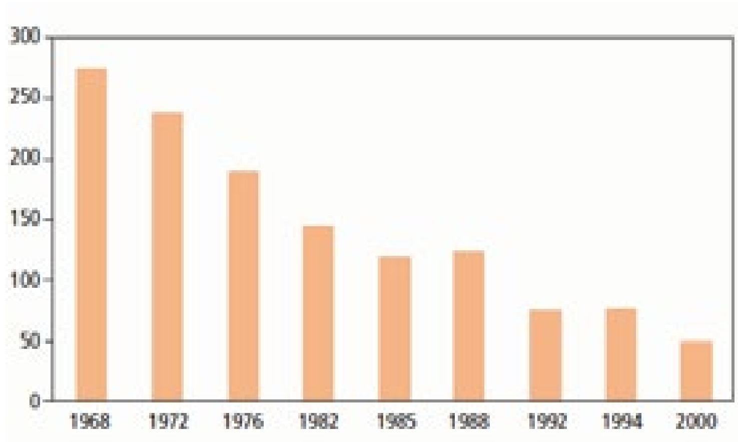


Figure 9. Number of California forest product (timber, pulp and paper) mills[87].

Taking together, each biorefinery could result in 1,000-3,000 jobs. Using the California's Energy Future Committee median estimates of 7.5 bgge in-state biofuel production in the absence of bioelectricity, 150 plants would be needed, employing possibly 150,000-450,000 workers. While the job numbers may be upper estimates, there is an argument to be made regarding investment in in-state fuel production. Because biomass is a local, mostly rural resource that is expensive to transport, jobs and income generated from bioenergy are likely to have positive economic impacts on small communities and are less likely to be outsourced than many of the manufacturing jobs associated with other renewable technologies.

87 Laaksonen-Craig S and McKillop W (2003) Forestry, Forest Industry and Forest Products Consumption in California. University of California Division of Agriculture and Natural Resources Publication 8070. 19pp.

VII. Other Environmental Factors

Food Versus Fuel

California is the top-producing agricultural state in the nation. Because of its mild to warm and varied microclimates, California can produce high-value specialty crops such as fruits and vegetables nearly year-round. As a result, California has the highest agricultural land values in the nation. It is economically unlikely that commodity crops such as purpose-grown bioenergy crops will ever be competitive with high-value specialty crops. For comparison, the average value for cropland in California was $9,230 per acre in 2011, compared with $5,700 per acre in Iowa, $5,800 per acre in Illinois, $4,800 in Indiana, and $2,960 in Nebraska[88]. Acceptable prices for next-generation bioenergy crops range from $20 to $60 per ton, well below other commodities such as hay ($161 to $299 per ton), and feed grains ($242 to $274)[89]. As mentioned previously, California imports 90% of its feed grains, largely due to the difference in land and water pricing. The development of regionally-specific California bioenergy crops specifically selected for non-productive lands, in concert with management guidelines, should allow the bioenergy production with minimal impacts to current agricultural activities.

In fact, one of the biggest threats to prime agricultural land in California is development for non-food human use such as housing, industry, and transportation. Largely driven by early settlement patterns and the historical role of agriculture and urban development, the majority of areas with dense population coincide with prime soils. Population growth drives demand for land to be used for housing, industry and infrastructure which then exerts pressure on the agricultural-urban boundary in the form of increased land pricing. This leads to land fragmentation and weakened agricultural production systems. Recognizing this phenomenon, California passed the Williamson Act[90], which provided some protection to agricultural and open space land combining tax relief and contracts to stave off development. The average enrollment of lands in the program from 1980 to 2008 was 16 million acres[91]. However, even with these protections, California has lost almost a million acres of prime farmland during that same time period. Nearly 30,000 acres per year of were lost from 1982-1997 and 40,000 acres each year from 2002-2006[94]. In the last 22 years, four of five agricultural acres that go out of production are converted to urban use[92]. State budget cuts are dramatically reducing investment in land enrollments under the Willamson Act. A recent survey indicates that 37% of farmers plan to sell land if the Act is eliminated, with 76% of that going to non-agricultural uses[93].

Water Use

Biofuel production has two main water use categories: feedstock production and processing. Water is a critical component of biomass production as it is used to make carbohydrates and drives transport of nutrients through the various plant tissues. Water use in feedstock production can be substantial, several thousand gallons per ton. Water use is generally categorized by withdrawal from "green"

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88 USDA National Agricultural Statistics Service, August 2011.

89 USDA Agricultural Prices, Volume 12, Number 2 (released February 2012).

90 Land Conservation Act of 1965, AB2117, SB1142. Bolstered by Article 28 (now Article 13) of the State Constitution and the creation of Farmland Security Zones in 1998.

91 California Department of Conservation http://www.conservation.ca.gov/dlrp/lca/stats_reports/Pages/index.aspx

92 California Department of Conservation (2008) California Farmland Conversion Report 2004-2006. 105pp.

93 Wetzel WC, Lacher IL, Swezey DS, Moffitt SE, Manning DT (2012) Analysis reveals potential rangeland impacts if Willamson Act eliminated. California Agriculture 66:131-136.

water (natural precipitation and runoff) and "blue" water (groundwater) sources. This can create confusion regarding the water footprint of biofuels since not all analysis agrees on whether natural precipitation and evapotranspiration should be considered as a "use" by the growing biomass since it would occur in the natural ecosystem regardless. This discrepancy can lead to water footprints differing along several orders of magnitude creating apprehension and possibly misconception. While several regions in California experience extreme water stress, other areas receive adequate rainfall to support vigorous biomass production. Accordingly, this issue requires careful thought and watershed-specific analyses to determine whether growing a particular biomass feedstock sufficiently perturbs an ecosystem enough to be of concern.

Biomass Production

The primary concern with water consumption in biomass production is the sustainability of irrigation in agriculture. This is a complicated subject specific to the watershed, crop, and management. While water use for high-value food crops is consistent with the state's economic goals, we do not envision water allocations for commodity energy crop production. While irrigated corn is grown in California, it is used exclusively for food (sweet corn) and feed (silage and grain corn). The currently operating corn ethanol plants in California import corn from the Midwest. Passage of Assembly BiIl 523 in August of 2012, which eliminates any state funding to support corn ethanol has prompted some producers to change feedstocks. For example, California Ethanol has contracted with Chromatin to supply it with sorghum, a drought-tolerant relative of corn[94]. Tests on irrigated sugarcane have been conducted in the Imperial Valley by California Ethanol and Power[95], although it seems unlikely that sugarcane would be viable unless it is treated as a lignocellulosic feedstock and even then, in very limited application. Most biodiesel in the state uses waste grease and oils as feedstock which would not have an additional water use. Oilseed crops with high drought tolerance such *Camelina* are also being explored for rainfed dryland agriculture on acres that had been previously used for irrigated agriculture[96].

It is generally accepted that lignocellulosic feedstocks would not be irrigated. Switchgrass trials at several locations provided ample yield (up to 17 tons per acre) without irrigation[97]. Similar trials are underway with agaves and *Miscanthus*. In the case of agricultural residues, irrigation may be used for production of food with simultaneous biomass production. Since biomass is a byproduct of the production of food production in this case, it would not result in an extra water burden. For example, drip irrigation for grape cultivation is common but the use of residual vineyard trimmings or pomace would not result in an added water burden. Forests and forest residues are not currently irrigated in California.

Processing

Corn ethanol plants typically require about 4-5 gallons of water per gallon of ethanol. Water is used in processing for washing, hydrolysis, and fermentation and also in cooling the distillation towers. The annual requirement for a 100 million gallon per year plant is 400-500 million gallons of water per year. This is roughly equivalent to a municipal water supply to a town of 5,000 people[15]. Advances in water conservation have reduced the water use of corn ethanol production from 5.8 gallons water per gallon ethanol to roughly 3 gallons of water per gallon of ethanol in the last ten

94 Schill SR (2013) Chromatin to contract Sorghum acres for Pacific Ethanol. Ethanol Producer Magazine. February 19.

95 http://www.californiaethanolpower.com/why-sugarcane/sugarcane-in-california/ (Accessed December 2012).

96 Blake C (2011) Wanted: California farmers to grow 25,000 acres of Camelina. Western Farm Press. September 16.

97 Pedroso GM, DeBen C, Hutmacher RB, Orloff S, Putnam D, Six J, vanKessel C, Wright SD and Lindquist BA (2011) Switchgrass is a promising, high-yielding crop for California biofuel. California Agriculture 65(3):168-173.

years[98]. Efforts to recycle wastewater and produce biomethane will likely reduce water use. For example, a new ethanol plant in North Dakota will use wastewater from the city of Fargo. Currently biodiesel plants consume from 1-3 gallons water per gallon of biodiesel. Thus a 15 million gallon per year facility would consume 15-45 million gallons of water per year.

The requirements for cellulosic ethanol are not yet known. Some estimates indicate a range of 5 to 10 gallons water per gallon ethanol for cellulosic ethanol when first implemented and range from 2-6 gallons water per gallon ethanol as efficiencies improve. Thus a 50 million gallon per year plant would use from 100 million to 1 billion gallons per year. Thermochemical conversion requires less water, roughly 2 gallons water per gallon ethanol, mainly for distillation and cooling[100]. There are opportunities to reduce this footprint through continuous processing, in-house water treatment (which can also produce biogas for on-site heat and electricity generation), membrane use, and water recycling. For example, in Brazil, a new method has been pioneered for sugarcane processing which uses water recovered from the biomass to run the process, as well as recycling distillation, fermentation, and cooling water following anaerobic wastewater treatment[99].

The water requirements for algae vary widely according to the culture method used[100]. Evaporative water losses from open ponds are considerable. Lifecycle water use for freshwater open ponds can range from 32 to 3,650 liters of water per liter of algal biofuel while closed photobioreactors could require 30-63 liters freshwater per liter of biodiesel. NREL estimates an annual mean of 195 liters of water per liter of oil in their Gulf Coast scenaro. Different algae strains can be grown in fresh or saline waters. Several test projects have shown that partially treated municipal wastewater can provide some of the nutrient input requirement. Freshwater input is still needed to prevent salts from becoming too concentrated with evaporation. 200-2000 liters of fresh make-up water per liter of diesel could be required. Thus a 50 million gallon per year facility could use 500 million to 50 billion gallons of water per year.

Emissions from Fire

Fires and natural cycles of senescence and degradation result in sporadic and uncontrolled carbon emissions. The accumulation of senesced biomass exacerbates fire risk which not only results in release of carbon, but other greenhouse gases such as N_2O and volatile organic carbons, as well as particulates that represent significant health risks. Wildfires also increase the likelihood of sediment accrual in watersheds 70 times over that generated during mechanical removal and several times over controlled burns[101].

While occasional fire cycles are ecologically necessary, general fire risk management often involves the regular removal of accumulated biomass. Such removal is recommended in 13.4 million acres of California forest and timberlands designated as Fire Regime Condition Class 2 and Class 3. USDA estimates over 100 million bone dry tons of recoverable biomass (out of a total estimated 370 million total bone dry tons) in this category. This is biomass that is likely to be burned by wildfire or in controlled removal.

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98 Wu M, Mintz M, Wang M and Arora S (2009) Consumptive water use in the production of ethanol and petroleum gasoline. (Ed, Center for Transportation Research) Argonne National Laboratory, Agonne, IL.

99 Brian Conroy, BP, personal communication.

100 National Research Council (2012) Sustainable development of algal biofuels in the United States. National Academie Press, Washington, D.C. 275 pp.

101 USDA Forest Service Research and Development (2003) A strategic assessment of forest biomass and fuel reduction treatments in western states.

Nearly 800,000 tons of biomass was burned for various reasons in 2005 in the San Joaquin Valley alone[102]. Drought and pest damage may result in significant loss of living biomass and accumulation of fire-prone deadfall. Management of chaparral by regular mowing may actually increase biomass productivity in addition to reducing fire risk[103]. Efficient collection of this biomass would provide feedstock for biofuel or electricity generation while controlling carbon emissions; however it is likely that biomass harvest will not be feasible in sensitive areas, or areas with steep terrain or poor soils.

102 Pacific Gas and Electric Company (2007) Issues affecting the bioenergy action plan: Barriers and solutions to advancing sustainable bioenergy development in California. Bioenergy Interagency Working Group.

103 Adams TE and Sands PB (1999) Clipping chemise reduces brush fire hazard. California Agriculture, 53: 25-29.

VIII. Conclusions

California can supply a substantial amount of biofuel from in-state resources through the use of residual biomass including agricultural wastes, forest thinnings and harvest residues, municipal wastes, and purpose-grown energy crops such as perennial grasses and short rotation woody crops by 2050. The judicious use of such feedstocks will be required to obviate long-term sustainability concerns and maximize efficient resource management.

Biofuels can reduce greenhouse gas emissions of transportation to meet the target goal but deep replacement of fossil fuels through both low-carbon drop-in biofuels and reduction in demand is required. If demand doubles, as in a business-as-usual case, replacement of gasoline with cellulosic ethanol (E85) and conventional biodiesel reduces greenhouse gases 16-53%, falling short of the 90% reduction goal. Under a reduced future demand scenario with high efficiency and electrification, a Cellulosic E85 and Biodiesel portfolio could reduce emissions by 50% with possible negative carbon emissions while a Drop-In Fuel portfolio could reduce emissions by a minimum of 85% with possible negative carbon emissions.

Although still in development and scale-up, technologies can be deployed to produce low carbon biofuels to meet demand by 2050. Whether this deployment occurs in California depends on many factors including the biomass supply and economic considerations. Regionally specific approaches should minimize inputs such as water and nutrients, avoid competition with current food and feed production and protect precious ecosystems. The concerns regarding large-scale use of biomass for energy in California require sustainable resource management. The possible impacts of bioenergy production are similar to those for modern agriculture and forestry and light industrial processing. Possible benefits from large-scale biomass production in California are both economic and environmental, hinging on sustainable practice and small- to medium-scale deployment.

Decisions regarding conversion of non-productive lands formerly used for agricultural or timber production to bioenergy crops may be required to achieve the maximum potential for in-state fuel production. If handled with forethought, such opportunities can create jobs and have positive effects on rural economies in the state, while maintaining our commitment to environmental goals. Implementation of a highly efficient transportation system is essential to ensuring that the supply of low-carbon fuels is sufficient. Conversion of all the estimated recoverable residues (36 to 79 million dry tons per year) would yield approximately 2.9 to 6.3 billon gallons (gasoline equivalent) per year. Energy crops could provide an additional 5-43 million dry tons of biomass (0.4 to 3.4 billon gallons per year) for a total of 3.2 to 9.8 billion gallons gasoline equivalents. This could meet 7 to 22% of the projected business-as-usual demand in 2050 and 21 to 61% of the amended demand in 2050.

It is likely that any demand unmet by in-state biomass would be supplied by imported biofuels for final in-state blending, rather than through import of biomass feedstocks. Import of ethanol from Brazil is cheaper than ethanol from the Midwest, even with taxes and tariffs in place. Brazil has the potential to produce 100 billion gallons of conventional ethanol (67 bgge) from sugar by 2030 and another 70 billion gallons cellulosic ethanol (45 bgge). While this could meet both the demand cases, the amount of biofuel available to the California market is uncertain. Further economic analysis will be required to determine more realistic potential scenarios for biomass allocation, biofuel production, and biofuel import. The influence by policy frameworks and other social factors beyond the scope of this report should also be examined to refine future bioenergy portraits.

Appendix A: Biofuels Policy

Several pieces of legislation set the stage for this report. In 2006 Executive Order S-06-06 established the first state targets for bioenergy production. Among them, the goal that 40% of the biofuels (bioethanol and biodiesel) consumed in California should be made in the state. Shortly thereafter Assembly Bill 32 (AB32 or the California Global Warming Solutions Act of 2006) was enacted, mandating the reduction of California's greenhouse gas emissions to 1990 levels by 2020. The following year, Executive Order S-01-07, targeted the goal of reducing carbon from transportation fuels by 10 percent in 2020, and the federal Environmental Independence and Security Act (EISA), mandated the expansion of renewable energy production, including biofuels. In April 2009, the California Air Resources Board passed Resolution 09-31 establishing the nation's first Low Carbon Fuel Standard, containing recommendations and analysis regarding the production of biofuels. Soon after, the U.S. Environmental Protection Agency proposed amendments to their Renewable Fuel Standard to meet EISA requirements.

Year	Title	Action
California		
1999	Executive Order D-5-99	Phase-out of MTBE (substitution of ethanol for MTBE)
2000	Assembly Bill 2076	Recommends alternative fuels to displace 20% of petroleum by 2020, 30% by 2030, as well as increased efficiency/reduced VMT
2002	Assembly Bill 1493	Requires lower greenhouse gas emissions for cars, trucks and SUVs by 2016
2005	Assembly Bill 1007	Requires California Energy Commission to propose methods to increase alternative fuel use to 20% by 2020, 30% by 2030
2006	Executive Order S-06-06	Governor's Office sets first state targets for bioenergy 40% biofuels consumed in California to be produced in California by 2020 (75% by 2050)
2006	Assembly Bill 32 California Global Warming Solutions Act	California Legislature mandates reduction of California's greenhouse gas emissions to 1990 levels by 2020
2007	Executive Order S-01-07	Governor's Office sets target for reducing transportation fuel carbon (enables creation of a low-carbon fuel standard)
2007	Assembly Bill 118	Created the California Energy Commission's Alternative and Renewable Fuel and Vehicle Technology Program.
2008	Assembly Bill 109	Authorized the California Energy Commission to develop and deploy renewable fuels and advanced transportation technologies to help attain the state's climate change policies
2009	Low Carbon Fuel Standard	California Air Resources Board sets the LCFS GHG emission limits for acceptability of biofuels

2012	Assembly Bill 523	Eliminates all future state funding for the production of ethanol derived from corn after July 2013
Federal		
1978	Energy Tax Act	Provided tax incentives to stimulate ethanol production
2005	Volumetric Ethanol Excise Tax Credit	Provided tax incentives to stimulate ethanol production
2007	Energy Independence and Security Act 2007	Increased annual biofuel targets, limiting corn ethanol and encouraging production of advanced (cellulosic) biofuels
2008	Food Conservation & Energy Act of 2008 (Farm Bill)	Provided tax incentives to stimulate cellulosic ethanol production
2009	Amended Renewable Fuel Standard (RFS2)	Expanded definitions of allowable renewable fuels and feedstocks
2010	Biomass Crop Assistance Program (BCAP)	Provides incentives for new uses of biomass, defrays establishment costs for perennial crops

Table 13. Relevant policy decisions at the state and federal levels regarding biofuels.

Appendix B: List of Tables and Figures

Appendix C: Acronyms and Terms

Anaerobic Digestion	The process by which bacteria consume biomass in the absence of oxygen
BAU	business-as-usual (assumes steady growth rate and continuation of current practices)
BCAP	Biomass Crop Assistance Program, a federal program through USDA that provides monetary incentives to farmers to encourage development of bioenergy crops.
bgge	billions of gallons of biofuel in gasoline equivalents by energy content
biogas	A mixture of carbon dioxide, methane, and trace gases during anaerobic digestion
CARB	California Air Resources Board
Conversion Technology	A process which uses any combination of heat, chemistry or biochemistry to alter the physical state or chemical composition of a substance – in terms of bioenergy this refers to conversion of sugars, lipids, and plant-derived biopolymers into energy dense liquids, gases, or electric current.
DOE	United States Department of Energy
Drop-in fuel	A fuel with similar properties to another fuel such that it can replace that fuel without any changes in engines or infrastructure
E85	Fuel blend containing 85% ethanol and 15% gasoline
EISA	Energy Independence and Security Act
EPA	Environmental Protection Agency
gge	Gallons of Gasoline Equivalent
GHG	Greenhouse Gas (atmospheric gases with global warming potential such as carbon monoxide and dioxide, nitrous oxide, and methane, typically expressed in equivalents of CO_2
ha	hectare (equivalent of approximately 10,000 m^2 or 2.47 acres)
LC	Lignocellulosic
lignocellulose	A matrix of biopolymers that form the major structural components of plant bodies such as leaves and stems which are not digestible by humans)
LCFS	Low Carbon Fuel Standard
Mha	millions of hectares
mgy	millions of gallons fuel produced per year
RFS	Renewable Fuel Standard
USDA	United States Department of Agriculture
USFS	United States Forest Service

Appendix D: California's Energy Future Full Committee

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