GCEP

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Technical Assessment Report

An Assessment of Biomass Feedstock and Conversion Research Opportunities

GCEP Energy Assessment Analysis
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Abstract

Biomass is a solar energy resource with the potential to be a significant contributor to an energy portfolio with low greenhouse gas emissions. One quarter of the global land biomass production of approximately 65 TW is already appropriated by humans, but much of this total is left to decay naturally. Agricultural and forest product residues can provide a biomass energy conversion feedstock without increasing land requirements. Including crops grown specifically for energy conversion, the biomass resource is estimated to be about 10-15 TW, though serious land and freshwater use considerations exist. These feedstocks can be combusted, gasified, biologically digested, or fermented depending on the composition of the fuel and the desired energy carrier product. Research opportunities include improvements in the photosynthetic efficiency and nutrient requirements of energy crops, biomass-tailored thermochemical conversion systems, and genetic engineering of microorganisms for more efficient biological conversion and the efficient production of hydrogen directly from sunlight.

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Foreword

This report is one of a series of assessments on various areas of the energy landscape prepared by GCEP staff. The assessments are intended to provide an introduction to the energy area as well as context for future fundamental research activity towards reducing greenhouse gas emissions. By examining the goals and potential of the energy transformations in question as well as the current progress and research towards these ends, the assessments take a step toward elucidating the most promising areas for future research. This report, produced by GCEP Energy Analysis staff, was written by Wes Hermann with contributions from Paolo Bosshard, Emilie Hung, Rebecca Hunt, and AJ Simon. Please address all correspondence to gcep@stanford.edu.

Introduction

Until this past century, human civilization historically depended almost solely on biologically derived energy to supply its needs for food, heat and work. Biomass is still used in significant quantities for heating and cooking in rural villages in some developing countries. Today, fossil fuels make up the majority of energy consumption, on a scale over an order of magnitude larger than historical biomass consumption. Concerns about the increasing concentration of carbon dioxide in the atmosphere prompt consideration of biological systems as a significant energy resource. Though both fossil fuels and biomass are ultimately products of the solar resource, the ability to re-grow harvested biomass and recapture the carbon emitted to the atmosphere through photosynthesis allows the possibility of carbon neutrality. Due to the increased demand for energy and pressures on land use caused by the agricultural needs of a growing population, large scale implementation of biomass may require new technologies for production and conversion. This report provides an overview of the terrestrial biomass system and current human appropriation, discusses technical barriers to large scale utilization, and identifies opportunities for fundamental research that might overcome these barriers and enable a pathway for biomass to play a significant role in a low greenhouse gas emissions energy portfolio.

Other solar energy conversion technologies, such as photovoltaics, currently exist with efficiencies an order of magnitude larger than typical biological solar energy conversion. The attractiveness of biomass energy lies in its simplicity, familiarity and low cost. Nature has designed a sophisticated, although relatively inefficient, solar conversion system embedded in the cells of every photosynthetic autotroph. These organisms self-assemble out of water and nutrients in soil and carbon in the air with energy input only from the sun. Use of the products of these mechanisms is only a matter of harvest and conversion. Several current technologies improve the production efficiency of biological systems but have their own energy considerations. Fertilizers serve to replace nutrients removed with the harvest. These fertilizers and other chemical inputs such as pesticides that enable the use of high density monoculture crops each carry an energy penalty against the overall efficiency, but may significantly increase the yield. Each of these inputs as well as infrastructure energy costs such as harvest and transport should be included in any evaluation of overall conversion efficiency and efficacy as a greenhouse gas reduction option.

There exists a diverse array of conversion mechanisms for biomass feedstock including combustion, gasification, anaerobic digestion, and alcohol fermentation. However, low efficiency conversion of solar energy to these feedstocks may lead to unacceptable land requirements if the biomass energy is to make a significant contribution to the current energy system. There are also several direct biological methods for converting sunlight to an energy carrier that may someday rival or exceed the efficiency of other conversion methods, though many technical and economic barriers remain. Future bioenergy technologies have the opportunity to increase the attractiveness of large scale biomass energy by increasing the solar conversion efficiency as well as improving the conversion to viable fuels and energy carriers.

This report breaks down the subject of energy from biomass into three parts: the biomass resource, feedstock cultivation, and the conversion of feedstock into other energy carriers. The first section gives a natural context to present and future biomass energy systems, examining the factors determining the ultimate size of the biomass resource. The remaining two sections emphasize energy conversions and the role of technology in their performance and large scale feasibility.

Part I: The Biomass Resource

The Biomass System

The biosphere processes large amounts of energy of varying types and quality. A useful way to analyze this system is to trace the work potential, or exergy, of the various energy flows from the sources, such as the sun, to its eventual destruction in natural decay or human utilization. Energy is not destroyed though these processes, but the exergy of these streams can be destroyed when the quality of the energy degrades. It is useful to examine the large natural destructions of exergy and consider the potential to divert this exergy for human utilization. Of the 86 PW solar radiation exergy incident on the surface of the earth [1,2,3], 90 TW remains in chemical exergy contained in the products of terrestrial photosynthesis, or the net primary production (NPP) [4]. As illustrated in Figure 1, humans appropriate a considerable portion of the 65 TW land NPP, using 15 TW of this exergy flow [5] in addition to approximately 1 TW destruction of the 30 ZJ terrestrial biomass reservoir through land use change [6]. The accumulated reservoirs of land and marine terrestrial biomass, or standing biomass, are indicated by ovals in Figure 1. About 5 TW of human usage are associated with traditional burning of wood, with an ultimate utilization as heat of less than half this value due to incomplete harvest leaving much of the tree to decay. Another 5 TW biomass exergy destruction can be attributed to agricultural activity, with about 0.8 TW remaining in food product [7]. This difference between agricultural biomass production and useful products immediately suggests an abundance of crop residues, though they have utility in recycling nutrients back into the soil. Lesser amounts of biomass exergy flow provide the feedstock for forest products and fiber.

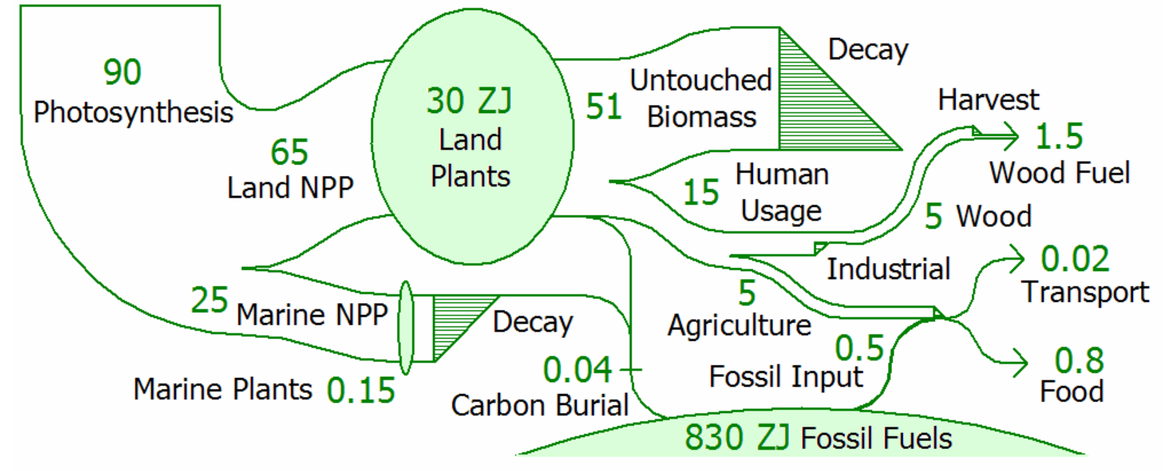

Figure 1: Exergy flow in TW through the natural and human appropriated terrestrial biomass system [4-9]

The human appropriation of photosynthesis for energy services is dominated by traditional combustion of wood. This occurs predominantly in countries that have yet to implement widespread commercial energy. Forest product residues are often burned for process heat to run mill equipment or to generate electricity. A relatively small but rapidly increasing amount of biologically produced energy is used for transportation fuel. Starchy crops such as corn are converted into approximately 30 billion liters of ethanol annually [10]. Biodiesel is produced on a smaller scale from bean and seed oil crops such as soy, sunflower or rapeseed.

Most of the world's biomass is in the form of woody forest materials [9]. These forest species store biomass energy for relatively large amounts of time. Marine biomass has a large overall productivity, or rate of converting sunlight to biomass, but a small standing reservoir due to the short lifetime of the organisms. The surface area, productivity and reservoir size of different biomass types are listed in Table A.

Biomass Metric	Forests	Savanna and Grasslands	Swamp and Marsh	Other Terrestrial	Marine
Net productivity [TW]	42	10	3	9	25
Biomass Reservoir [ZJ]	29	1	0.5	1	0.15
Surface Area [10^6 km^2]	48.5	24.0	2.0	74.5	361
Productivity per Area [W/m^2]	0.86	0.42	1.5	0.1	0.07
Biomass per Area [MJ/m^2]	600	40	250	10	0.4

Table A: Distribution of biomass by biome, production, and accumulation [9]

Biomass Feedstock Characteristics

In order to improve or develop energy conversion processes for biomass, it is important to understand its composition. Most land biomass is composed primarily of cellulose, hemicellulose, lignin and proteins [9]. Celluloses are composed of long chains of saccharides. Proteins are found in most biomass, but are particularly abundant in herbaceous species. Lignins are phenolic polymers that contribute to structural rigidity of plant tissues. Table B provides the compositions of representative types of biomass fuel and the carbon content and higher heating value (HHV) of the components. The moisture content of biomass varies widely. Due to the ability to dry biomass naturally without energy input, the dry-basis energy content is the most appropriate metric.

Biomass Component	**Bermuda Grass (herbaceous) [% mass]**	**Poplar (woody) [% mass]**	**Pine (woody) [% mass]**	**Refuse Fuel (waste) [% mass]**	**Carbon Content [% mass]**	**HHV [MJ/kg]**
Cellulose	32	41	40	66	40-44	17
Hemicellulose	40	33	25	25	40-44	17
Lignin	4	26	35	3	63	25
Protein	12	2	1	4	53	24
Ash	5	1	1	17	0	0

Table B: Biomass composition and chemical properties [9]

Several types of biomass are used as energy conversion feedstocks, including wood, agricultural and forest product residues, municipal solid waste, and industrial waste. Except for the production of corn-derived ethanol as a transportation fuel, there few large scale efforts to grow crops intensively for conversion to energy carriers. It has been proposed that fast growing species such as switchgrass or sugar cane would be an economical option for energy-dedicated crops [11]. High quality woody feedstocks such as hybrid poplar and pine have also been considered [12]. These feedstocks could be combusted, gasified, or biologically digested, depending on the composition of the fuel and the desired energy carrier product. Many plant species are potentially viable energy feedstocks and can be selected based on cost, net greenhouse gas emissions, and appropriateness to the intended energy conversion process and growing environment.

Biomass has some advantageous chemical properties for use in current energy conversion systems. Compared to other carbon-based fuels, it has low ash content and high reactivity. However, high moisture, a tendency to form tars, and an ash chemistry that leads to the formation of low melting point solids when heated presents challenges to some conversion methods [13]. Some biomass feedstocks may be high in nitrogen and chlorine. The combination of both alkalis and chlorine can corrode metals that form the structure of conversion devices. Under some conversion conditions, higher N content may lead to the formation of nitrogen oxides. Sulfur concentrations are much lower than in many coals, decreasing the potential for sulfur oxide creation during conversion.

While the elemental composition is important to combustion conversion systems, biomass also has the property that it can be biologically converted though anaerobic digestion or fermentation. The chemical structure of the feedstock determines the fraction that can be utilized. Various types of carbon-based compounds in biomass feedstock are more or less available for this type of conversion. For example, lignin is resistant to chemical breakdown by the microorganisms and enzymes that are currently used to digest solid biomass. Though they are hampered by incomplete utilization, biological conversion processes may be simpler, much more efficient, and less capital intensive than thermochemical pathways to make gaseous and liquid fuels.

Biomass and Greenhouse Gases

Photosynthesis is a natural mechanism for capturing and concentrating carbon dioxide (CO_2) directly from the air. Combustion of fossil fuels introduces new carbon to the air that had been stored in stable geologic reservoirs. The zero net emissions of CO_2 to the atmosphere by the photosynthesis process make biomass energy attractive. Since CO_2 exists at such low concentrations in the atmosphere, the energy requirement to bring CO_2 to the concentration present in the products of biomass combustion (320 kJ/kg CO_2) is about three times the energy requirement for processes that capture CO_2 from the more concentrated effluent streams of electric power plants (110 kJ/kg)[1]. This can serve as a measure of the service plants perform by assembling carbon-based fuels from the environment, bringing atmospheric carbon dioxide to higher concentrations.

Standing biomass can serve as a finite sink for carbon. Changing land cover to vegetation that contains more carbon in the plants and soil captures carbon from the atmosphere. The difference in carbon content between forests and agricultural land or pasture is approximately 12 kg C/m^2 in the plants [9,14] and about 1 to 5 kg C/m^2 in the first meter of soil [15]. Off-setting the current rate of carbon emissions from fossil fuel conversion (6.5 PgC/yr) over the next 50 years would require the conversion of about 25 million km^2 of land to forest. Conversely, the clearing of forests and other net CO_2 emission land use practices currently contributes an additional 1.6 PgC/yr to the atmosphere [6]. Any reduction in this rate would have the same utility as intentionally cultivating higher carbon content vegetation.

Biomass also plays a significant role in the transfer of methane to the atmosphere. Methane is the second most influential gas to the anthropogenic radiative forcing of our climate [16]. Anaerobic decay of biological matter in places such as rice paddies and land fills produces methane. Various methods of land management or methane capture could reduce human emissions of methane.

Resource Potential

Bioenergy potential is linked to agricultural intensity, biomaterials production and population through land and water use. Energy crops compete directly for arable land

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[1] Ideal gas mixing exergy for a concentration of 380 ppm CO_2 to 10% concentration by mol and 14% by mol to 95% by mol.

with agriculture and biomaterials crops except for in cases where energy crops can grow on otherwise unsuitable land. The types of future food demand also play an important role in bioenergy potential, as production of meat and animal products requires significantly more land than crops per energy unit of food product. Several authors have developed models taking into account population and land competition to produce an estimate for the global bioenergy potential from dedicated energy crops and process residues. Most of these model results are highly sensitive to generally imprecise predictions of food demand and agricultural intensity. The portion of the results the authors labeled "technically achievable" or "high scenario" is presented in Table C. These figures provide an estimate of the bioenergy resource potential barring many economic considerations.

Study	**Timeframe**	**Energy Crops [TW]**	**Residues [TW]**	**Total [TW]**
IPCC Third Assessment Report (2001)	2100	10	n/a	n/a
Fischer and Schrattenholzer (IIASA, 2001)	2050	10	4	14
Yamamoto *et al.* (1999)	2100	5	9	14
Lightfoot and Greene (2002)	2100	9	n/a	n/a
Hoogwijk *et al.* (2003)	2050	33	3	36

Table C: High-end estimates of global biomass potential [17-21]

The biomass resource can be increased along several dimensions, most of which can be visualized by examining Figure 1. Increasing the efficiency of the photosynthesis process or the delivery of water and nutrients to plants can increase the overall primary production. A larger portion of global primary production can be appropriated by humans instead of naturally decaying, though ecosystem impact would have to be considered. Larger portions of the residues and waste streams generated by agriculture or forest products could be utilized. Finally, the efficiency of biomass conversion to energy carriers could be improved. Several of these opportunities can be directly pursued by technology and would benefit from fundamental research.

The impact of bioenergy on greenhouse gas emissions depends on the scale of deployment and life cycle emissions from artificial inputs, transportation, and energy conversion. Due to the present low conversion efficiency of plants in addition to the already low energy density of insolation, large amounts of land area would be required to implement a bioenergy system that would make a significant contribution to global primary energy. Technological improvements on the biological energy capture mechanisms of plants and the subsequent conversion of the carbohydrate products to energy carriers could influence future adoption significantly.

Part II: Cultivation of Biomass Feedstock

Yield of a crop grown for energy conversion is directly related to photosynthetic efficiency, land area, water requirement, and energy inputs such as fertilizers and transportation. The current yields of crops proposed for large-scale energy conversion per energy input are too small to compete effectively with other energy sources. The track record of past success with food crops and the expectation that recent molecular biological, genetic and other bio-technical methods can be applied to accelerate progress on energy crops suggests yields can be significantly increased. These methods could increase photosynthetic efficiency, reduce water and nutrient requirements, or develop plants that produce photosynthate more amenable to energy conversion.

Photosynthesis

Photosynthesis is the fundamental process in biomass energy whereby energy in sunlight is captured and stored in the chemical bonds of the tissues of living plants. Table D lists observed overall conversion efficiencies from solar energy to chemical energy contained in the resulting biomass of several plants considered for biomass energy conversion. Natural annualized efficiencies range from 0.2 to 3% [9]. Any increases in this overall efficiency would have a large effect on the land and water required.

	Switchgrass	**Corn**	**Willow and Poplar**	**Tropical Sugarcane**	**Tropical Napier Grass**	**Tropical Tree Plot**
Conversion Efficiency (%)	0.22 - 0.56	0.79	0.30 – 0.41	2.24 - 2.59	2.8	0.95

Table D: Overall conversion efficiency from insolation energy to biomass of various crops [9]

Photon energy incident on a plant is used or dissipated in a number of different ways. The various fates this energy meets are illustrated in Figure 2 for an aquatic plant species with sufficient nitrogen [22]. Only a small fraction of the energy is converted into plant matter.

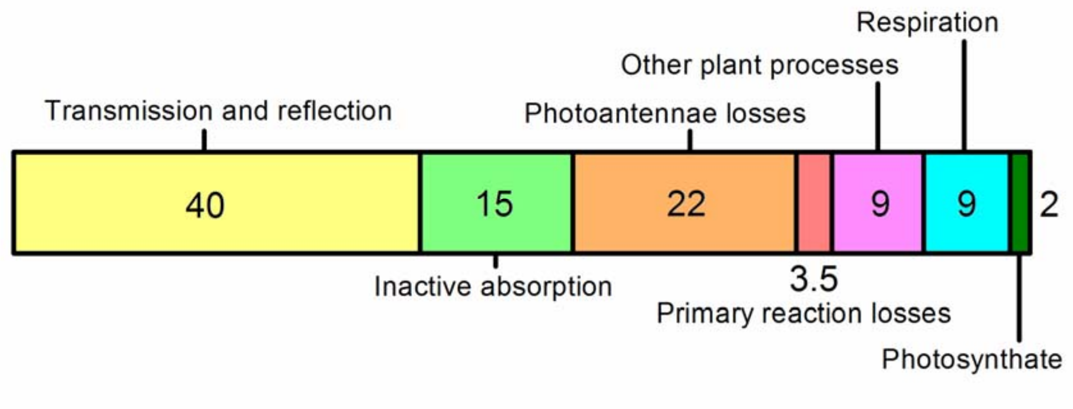

Figure 2: The fate of incident photon energy on an aquatic plant, percent of total [22]

An examination of the much larger portion of incident photon energy that does not become stored in plant matter may point to opportunities for improvement. Much of the light incident on plants passes right through or reflects away. Inactive absorption losses occur when light is absorbed by a part of the plant other than the photosynthetic pigments. Increasing the photo-active area of plants could improve their efficiency. Once a photon strikes an active pigment, a set of chemical reactions on the molecular level carry the energy of a photon through a set of electron transfers that eventually produce a molecule that is stable and stores energy. While this process is taking place, the chlorophyll “antennae” in which this electron and energy transfer occurs is unable to receive another photon. Any photons that arrive during this time are not captured, incurring a loss called light saturation or photo-inhibition. The degree of loss from light saturation is due to the size of the antenna—if it is large then it takes a longer time and more photons to perform the electro-chemistry. Shorter or alternately designed antennae could reduce this loss [23]. The primary reaction directs the photon energy to the photosynthesis reaction chain or other plant processes [24]. More of this photon energy could be routed to producing photosynthate or be more efficiently utilized. Respiration losses refer to the processes in which the plant consumes some of the produced photosynthate to build tissue and cell structures. The primary difference between C_3 and the relatively recently evolved and more efficient C_4 plants such as corn and sugarcane is a reduction in photorespiration [24].

Biomass Water and Nutrient Requirements

The productivity of biomass depends on the presence of the required amounts of sunlight, water, and various nutrients, as well as proper environmental conditions including temperature and humidity. The harvestable biomass in a given area depends on the natural and artificial concentration and replenishment of these requirements. Plant engineering may be able to reduce the need for water and nutrients, allowing higher yields and lower cost.

Plants dominate the global freshwater cycle, consuming a large mass of water relative to their productivity. Most of the water consumed by plants is cycled though transpiration, the evaporation of water from the leaves of plants. This process not only helps cool the plant, but sets up a pressure gradient from the roots to the leaves, facilitating the transport of water and nutrients [25]. As illustrated in Figure 3, plants utilize about 58% of the freshwater cycle and humans appropriate the biomass processing one third of this transpiration. Paths ending in vertical arrows represent water that evaporates back into the atmosphere and paths ending in horizontal arrows represent water that reaches the ocean as liquid. It is clear that humans already appropriate a large fraction of the freshwater cycle. Any increase in this fraction may put various ecosystems and the natural services they provide at risk [26]. Therefore, increases in the water use efficiency (WUE) of plants may be a good option for increasing global productivity in applications such as energy crops.

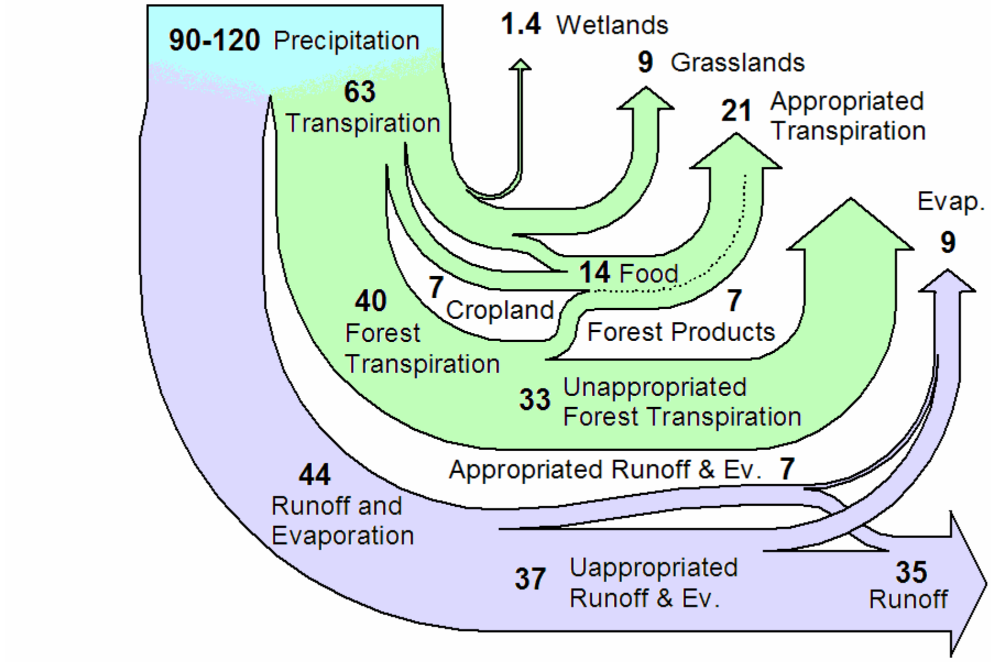

Figure 3: Global flow of freshwater [1000 km^3/yr] [27]

The water use efficiency (WUE) of a plant is the ratio of total water input to biomass productivity. Corn, poplar, sugar cane, miscanthus and wheat, all considered for energy conversion, have WUE ranging from 100 to 800 kg H_2O per kg biomass using various irrigation styles and fertilizer inputs with C_4 plants at the bottom of the range [28-32]. Much of this water evaporates or drains without cycling through the plants. Any increases in WUE from better farming and management practices or engineered plant species offset a proportional amount of water that would otherwise be diverted from natural ecosystems.

Most plants have growth rates limited by a particular nutrient. However, each nutrient has a maximum uptake requirement after which it will no longer contribute to plant growth. It has been shown that most autotrophs require similar ratios of major nutrients, with carbon, nitrogen, potassium and phosphorous present in the ratio 2000-20000:100:30:8 [33]. The accumulation of nutrients in dry plant matter accounts for 5-10% of the mass. Considering undisturbed biomass recycles almost all of its nutrients back into the ground upon death and decay, such a large removal rate has implications for the required replenishment of these nutrients. A relatively long amount of time must elapse for these nutrients to be replaced naturally.

Nutrient availability	**Nutrient**					
	C	N	K	P	Ca	Mg
Free nutrient access	2-20*10^3	100	64.6	14.6	7.0	9.4
Growth limiting	--	100	30	8	2	4

Table E: Ratios of nutrient uptake for deciduous plants (N=100) [32]

Several strategies exist for increasing the productivity of biomass growth by artificially supplying requirements that may not be present naturally. Replacing lost nutrients or increasing the nutrient input to a nutrient limited system through the use of artificial fertilizer is one of these methods. The current production processes of these fertilizers often utilize fossil fuel feedstock and require energy for chemical conversion. Current nutrient use efficiencies, or the amount of nutrient uptake divided by the nutrient application, are at most 40% for N, 10% for P, and 40% for K [34]. Plants with higher nutrient use efficiency or that require less nutrients altogether could decrease cultivation energy inputs. Pumping water to a region that is too dry to sustain the preferred species or growth rates could also increase yields. The ultimate resource potential is limited by the availability of all of these inputs, as well as the energy implications of methods used to supplement them artificially.

Cultivation GHG Emissions and Energy Inputs

An assessment of the potential impact biomass energy conversion pathways would have on global greenhouse gas emissions must include consideration of the energy inputs and emissions associated with the entire conversion process from raw materials to energy carriers. The lifecycle energy inputs dictate how much final energy is needed to both satisfy the load and make up for the inputs, while the lifecycle greenhouse gas emissions determine the effectiveness of the pathway as a mitigation option.

Lifecycle considerations for the production of biomass feedstock may include the energy and emissions associated with tilling, seeding, fertilizers, pesticides, harvest, transport, and land use change. Those aspects that involve farm equipment or chemicals are easy to quantify. Trucks and machinery are almost exclusively petroleum fueled. Pesticides and fertilizer use fossil fuel feedstock and have an energy cost associated with production.

Land use change has transient effects and is more difficult to quantify. Methane emissions from soil bacteria and nitrous oxide emissions from fertilizers change with the crop become constant relatively quickly. Changes in soil carbon from cultivating a new crop bring an exchange of carbon with the atmosphere over a period of several years until a new equilibrium is reached. After this point, soil carbon has no net effect on emissions. For example, the soil carbon emissions associated with switching to corn from pasture land fall to less than half of the initial value in 10 years [35].

Once the biomass feedstock is produced, energy inputs and emissions associated with conversion to an energy carrier must also be counted in a consideration of the overall lifecycle from solar energy to energy carrier. These include process heat and any pumping or machinery assisting mass transfer. The overall efficiency is then calculated by dividing the remaining exergy in the produced carrier by the original feedstock exergy plus the work potential of any energy inputs. Fair comparisons between bioenergy and other conversion pathways can only be performed by considering all lifecycle inputs and emissions.

Part III: Biomass Energy Conversion

Once a feedstock is obtained, there are many methods available to convert its energy into an energy carrier for use in energy services. While thermochemical conversion processes such as combustion and gasification are more familiar, advanced biological methods have the potential to be less expensive and more efficient.

Biomass feedstock contains energy in the chemical bonds of its constituent varieties of carbohydrates. With higher oxygen content than fossil fuels, biomass feedstocks have fundamentally lower energy content. The maximum useful energy that can be theoretically extracted from biomass feedstock is its chemical exergy. For a complex fuel with varied, interconnected structures such as biomass, the exergy can be modeled as a function of its elemental composition [36,37]. The chemical exergies of several proposed energy crops are listed in Table G. These values are slightly larger than the experimental heating values, in part because they include the diffusive exergy of the conversion products.

Biomass Conversion Feedstock	**Elemental Mass Fraction [%]**						**Specific Exergy (Dry) [MJ/kg]**
	C	**H**	**O**	**N**	**S**	**Ash**	
Poplar	49	6	43	0	0	1	19.2
Corn Stover	44	6	43	1	0	6	18.2
Bagasse	45	5	40	0	0	10	17.8
Water Hyacinth	40	5	34	2	0	20	15.2
Brown Kelp	28	4	24	5	1	42	10.9

Table G: Specific exergy on a dry basis of representative biomass samples [36,37,38]

The efficiency of a biomass conversion process can be calculated by dividing the energy carrier output by the exergy of the feedstock input.

Combustion

Biomass combustion is currently the most common energy conversion method. Because biomass-fired plants are usually smaller, and therefore less well-insulated, than coal-fired Rankine plants, current efficiencies remain at approximately 25% [39]. Transportation of low-density biomass feedstock is a barrier to building larger plants. Other challenges to expanded biomass conversion through combustion include low energy content, particle size, and alkali metal slagging.

While biomass inherently has a low energy density due to its high oxygen content, water further lowers the energy content of biomass feedstock if it has not been dried. Though exposure to the atmosphere would eventually dry the biomass to ambient moisture concentrations without energy input, this could take considerable time depending on ventilation and particle size.

Biomass combustion also suffers from geometric difficulties unique to biomass as a fuel. Standing biomass is often in the form of stalks, logs, or leaves. Biomass fuel particles must be made small enough for adequate combustion. Optimum particle size is determined by comparing the gain in efficiency from smaller particles with the added energy and cost of reducing the particle size of the fuel.

Alkali and alkali earth elements such as Na, K, Ca, and Mg compose much of the ash content of biomass fuels and cause slagging problems in combustion systems. These elements form minerals with low melting points that can condense into deposits on the heat transfer surfaces of boiler power systems and cause fuel and ash particles to agglomerate. The slag especially disrupts the flow of fuel and ash in fluidized bed combustion systems [40,41]. New plants designed to accommodate the composition of biomass feedstock or plants engineered to retain less of these elements could help advance biomass combustion.

Co-firing or co-combustion of biomass, with coal and/or natural gas, is another path to improved efficiency and lower cost. Coal/biomass cofiring uses the environment and equipment of a large coal-fired power plant to enable biomass fuel to be combusted with higher efficiency and lower capital cost compared to biomass combustion in stand-alone biomass combustion power plants. However, current systems burning fuel mixtures with biomass content over about 10% encounter particle size constraints and other difficulties mentioned above.

Gasification

Thermochemical gasification involves the partial oxidation of solid biomass fuel, with the products being mostly CO with some H_2. These products can then under go a shift reaction to produce a stream composed of primarily H_2 and CO_2 or other industrial products. Biomass gasification faces similar challenges to biomass combustion and due to the solids-handling requirements of the feedstock and the chemical properties of its ash. None of the industrial or small-scale plants yet built have exceeded 33% efficiency [39].

Anaerobic Digestion

Anaerobic digestion refers to the process whereby microorganisms convert chemical energy in solid biomass material into an energy carrier, often with high efficiency relative to thermochemical conversion. The products are usually a mixture of methane and CO_2 in almost equal proportions. These microorganisms have the flexibility to process waste streams as well as biomass feedstock from residues and energy crops. A comparison of present digestion conversion efficiencies by feedstock is listed in Table H.

Feedstock	Methane Yield (MJ/kg feedstock)	Feedstock Exergy (MJ/kg feedstock)	Conversion Efficiency (%)
Poplar	12.26	19.2	64
Sugarcane	11.49	17.8	65
MSW	8.43	15.1	56
Cellulose	14.17	17.4	81

Table H: Biomass digestion efficiencies by feedstock [42-46]

Research opportunities in anaerobic digestion involve understanding, control and breeding of microorganisms well-suited for the digestion environment. Cost is a major barrier to increased utilization. As illustrated in the table above, conversion efficiency for the cellulose portion of biomass feedstock is higher than the overall efficiency for feedstocks containing lignin or hemicellulose. Development of organisms that can better utilize non-cellulose portions or plant species with a higher portion of cellulose could also benefit anaerobic digestion.

Alcohol Fermentation

Fermentation involves conversion of feedstock by microorganisms in a process similar to digestion, but the products are alcohols or organic acids instead of methane. Feedstock energy conversion by fermentation is in wide-scale use, with a global production of about 20 GW ethanol [47].

While present fermentation converts mostly starches and sugars, fermentation processes that include cellulosic materials would be better candidates to become a large scale energy conversion pathway. Current systems use acid hydrolysis to convert cellulosic biomass to easily fermentable sugars. Acid hydrolysis involves the breaking up of linocellulose to cellulose and hemicellulose, then finally into glucose and pentoses (mainly xylose). Table J shows a comparison of starchy corn kernel conversion with current efforts at cellulosic conversion. The two conversion methods have similar efficiency, but the corn stover fermentation uses a low-cost agricultural residue. The large process energy input for corn stover fermentation suggests an opportunity for improvement.

Feedstock	Feedstock Exergy [MJ/kg feed]	Ethanol yield [MJ EtOH/kg feed]	Process Energy [MJ/kg feed]	Conversion Efficiency (%)
Corn kernels	19.4	11.9	6.43	46
Corn stover	18.2	13.4	13.3	43

Table J: Current fermentation conversion efficiencies for corn feedstocks [34,38,48,49]

Enzymatic hydrolysis is a new approach to fermentation using enzymes that catalyze the breakup of cellulose and hemicellulose. Different enzymes, called cellulases, cut the cellulose or hemicellulose at discrete points within the molecule. The goal is to find organism strains that will have high productivity while making cellulases that are stable at extreme temperatures. The organism *T. reesei* has been found to withstand these temperatures and is commonly used to make the enzyme cellulase. However, industrial microorganisms are presently unable to ferment sugars such as pentose and hexose resulting from the cleavage of hemicellulose. Research is needed to develop new strains of microorganisms capable of fermenting a wide range of sugars and develop methods of enzyme production at large scale and low cost [50,51].

Hydrogen

In addition to thermochemical hydrogen production by gasification, hydrogen can be produced biologically. There are currently two proposed pathways to use organisms for hydrogen production. Direct production through "photo-biohydrogen" utilizes microorganisms capable of using solar photons to separate oxygen from water. Appropriate enzymes then perform an electrochemical process that unites two electrons from the oxygen producing step with two H^+ ions to make hydrogen as the other product. Indirect hydrogen production through photosynthesis in microalgae uses a dark fermentation step where the carbohydrate produced by photosynthesis is converted to hydrogen gas.

Direct hydrogen conversion from sunlight may offer higher theoretical efficiencies [52] compared to the 0.2% to 2.6% photosynthetic efficiencies in energy crops today [9]. However, the scientific and technical feasibility of the process has to develop and costs of a photo-bio-reactor will be a challenge.

Indirect biohydrogen involves oxygen inhibition of the electron transfer step and hydrogenase production of hydrogen from carbohydrate [53]. The oxygen and hydrogen must be separated at the cellular scale. Hydrogen fermentation research objectives include finding or engineering optimal strains of microorganisms and enzymes.

Conclusions

Expanding biomass energy to a scale capable of impacting the global emissions of greenhouse gases will require improvements in the growth of feedstock as well as the efficiency of conversion pathways. The majority of the losses in current biomass energy systems are due to the relatively inefficient photosynthesis process, the high energy requirements of plant processes that support the growth and development of plants, and industrial energy inputs during cultivation and processing. Engineering plants to more efficiently produce photosynthate or microorganisms to directly produce other energy carriers such as hydrogen could relax many of the barriers associated with land, water, and nutrient requirements. Biological conversion processes promise efficiencies higher than thermochemical conversion, but require research to improve microorganisms and molecular level biological processes. Advances in understanding of genetics and biological conversion processes at the molecular level will allow more control over the efficiencies and economics of these pathways. Biomass energy has the potential to make a significant contribution to a carbon constrained energy future, but technological advances will be required to overcome the low energy densities and conversion efficiencies characterizing present and historical utilization.

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