Bio-Methanol: How Energy Choices in the Western United States can Help Mitigate Global Climate Change

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Abstract

Converting available biomass from municipal, agricultural and forest wastes to bio-methanol can result in significant environmental and economic benefits. Keeping these benefits in mind, one plausible scenario discussed here is the potential to produce energy using bio-methanol in five of the western United States. In this scenario, the bio-methanol produced is from different biomass sources and used as a substitute for fossil fuels in energy production. In the U.S. West, forest materials are the dominant biomass waste source in Idaho, Montana, Oregon and Washington, while in California, the greatest amount of available biomass is from municipal wastes. Using a 100% rate of substitution, bio-methanol produced from these sources can replace an amount equivalent to most or all of the gasoline consumed by motor vehicles in each state. In contrast, when bio-methanol powered fuel cells are used to produce electricity, it is possible to generate 12 to 25% of the total electricity consumed annually in these five states.

As a gasoline substitute, bio-methanol can optimally reduce vehicle C emissions by 2 to 29 Tg of C (23-81% of the total emitted by each state). Alternatively, if bio-methanol supported fuel cells are used to generate electricity, from 2 to 32 Tg of C emissions can be avoided. The emissions avoided, in this case, could equate to 25 to 32% of the total emissions produced by these particular western states when fossil fuels are used to generate electricity. The actual C emissions avoided will be lower than the estimates here because C emissions from the methanol production processes are not included; however, such emissions are expected to be relatively low. In general, there is less carbon emitted when bio-methanol is used to generate electricity with fuel cells than when it is used as a motor vehicle fuel.

In the State of Washington, thinning "high-fire-risk" small stems, namely 5.1-22.9 cm diameter trees, from wildfire-prone forests and using them to produce methanol for electricity generation with fuel cells would avoid C emissions of 3.7 – 7.3 Mg C/ha. Alternatively, when wood-methanol produced from the high fire risk wood is used as a gasoline substitute, 3.3 – 6.6 Mg C/ha of carbon emissions are avoided. If these same "high-fire-risk" woody stems were burned during a wildfire 7.9 Mg C/ha would be emitted in the State of Washington alone. Although detailed economic analyses of producing methanol from biomass is in its infancy, we believe that converting biomass into methanol and substituting it for fossil-fuel-based energy production is a viable option in locations that have high biomass availability.

Keywords: forest fires; biomass; methanol; electricity; gasoline; C emissions

1. Context of biomass energy and greenhouse gas emissions

Considerable attention is being focussed on many global environmental and natural resource problems including climate change, reductions in fossil fuel use and related carbon emissions, human/ecosystem health, waste disposal, and diminishing economic livelihoods for rural communities [1-8]. These problems are often interrelated and solutions need to be implemented on global scales. In many cases, problems are being simultaneously addressed by linking cross-sectoral economic solutions for rural communities with sustainable use of bio-resources to produce energy. Emerging environmentally friendly technologies, which replace fossil fuels consumed during energy production with sustainable options, can provide a critical link and a viable solution to address multiple problems [5,9-11].

Within the last 10 years, the European Union and the United States have implemented policies to increase their use of renewable resources for energy production and to reduce their dependence on fossil fuels [e.g., 1,12,13]. To date, these policies have had difficulties in achieving the two objectives. The Renewable Energy Road Map published by the Commission of the European Communities in 2007 [14] indicates that the European Union will not be able to meet its target of deriving 12 percent of its total energy consumption from renewable sources by 2010. In addition, the EU's goal of having two percent of its transportation fuel market share come from biofuels by 2005 has not been attained [14]. From a global perspective, despite the targets set by these policies, the world's fossil CO_2 emissions are estimated to have increased by more than 20 percent between 1990 and 2004, while the proportion of fossil fuels in the world's energy mix also increased between 2000 and 2004 [15]. Jefferson [15] wrote "prospects for sustainable energy are bleak on current trends" and noted that traditional uses of biomass for energy decreased globally from 11% in 1990 to 8.8% in 2004. A similar pattern is evident in the United States where renewable energy supplied only 6% of the country's total energy needs in 2003 (of that 6% only 4.1% was from biomass) [16]. In the U.S. the primary focus has been on developing cleaner coal technology [17], which can reduce fossil carbon emissions but is ultimately not sustainable since there is a continued reliance on a non-renewable resource.

For biomass to be a viable alternative for fossil fuels, it will need to be available in significant amounts and collected in a sustainable manner. It is also important that biomass sources not compete with the more traditional uses of biomass as fuel or with food crop production [18] such as the production of ethanol from corn. Of the sources discussed here, forests are an ideal biomass source for bio-energy production and typically do not compete with food crop production, either. They are mostly managed without fossil fuel intensive options such as fertilizers or herbicides to enhance growth rates. However, in some locations of the world, wood biomass is scarce [19] or it is difficult to grow because areas are degraded as a result of past land-use legacies [20], but this is not an issue in the United States where biomass availability is high. In the U.S., agricultural, municipal, and forest wastes together are capable of sustainably providing enough residual biomass to generate one billion dry tons of biomass annually. This amount of biomass is sufficient to produce a substitute which can replace up to 30% of the annual U.S. petroleum consumption on a sustainable basis [21].

Once it is clear that sufficient quantities of biomass wastes are available, decisions as to what products to manufacture from each biomass source need to be made. These decisions need to simultaneously factor in the magnitude of economic and environmental costs and benefits associated with the manufacturing process. One promising approach is to convert biomass to liquid fuels and there are several options available to facilitate this conversion [22]. New technologies are rapidly evolving to convert cellulosic wastes to sugar compounds for enzymatic ethanol production [22]; however, commercialization of this process has been forecasted to be more than a decade in the future [23].

Although wood is increasingly being used to produce energy [19,24,25] much of it is still being converted with inefficient processes (e.g., combustion) that are similar to, albeit more refined than, technology used during World War II (e.g., gasification) [26]. In order to ensure sustainable energy production while at the same time achieving a reduction in emissions requires the adoption of new technologies that are currently available to convert biomass to biofuels. Only when this occurs will the full potential of biomass to reduce CO_2 emissions during energy production be realized. The efficiency and economics of conversion are important considerations in carbon emissions reduction estimates. In estimating reductions in emissions, the quantity of C emissions avoided depends not only on the amount of fossil fuel energy needed to manufacture the product but also on the quantity of fossil fuel saved when renewable, environmentally-friendly alternatives are used.

As a heuristic device, we analyze the potential for converting biomass to methanol using mobile conversion systems in five states of the western United States. The biomass materials considered are wastes collected from landfills, agricultural crops, and forests. In addition, thinning the small diameter stems that increase the risk of catastrophic forest fires is also examined since it has its own set of environmental and social benefits. Since most of the western states do have large areas of forests, there is added urgency to reduce the risks associated with catastrophic fires. To address the risk associated with fire, while at the same time reducing emissions and enhancing the carbon sequestration role of forests, high-fire-risk biomass from forests should be one of the key sources considered to meet the energy demands in the western U.S. The existing high-fire-risk conditions in western forests [27], coupled with the need to reduce 'environmental insecurity' resulting from global warming, makes the American West an ideal place to assess the need for biomass energy.

2. Data, assumptions and calculation methods

2.1. Data, assumptions

Initially, in order to establish a unified basis for calculations, we quantified the amount of methanol derived from either 1 Mg of dry landfill wastes, agricultural or wood biomass using a small-scale mobile conversion system. We then estimated the C emissions avoided when the bio-methanol produced is substituted for gasoline or when it replaces an energy-equivalent amount of natural gas-methanol in fuel cells to produce electricity. In estimating C emissions we compared fuel cells powered by bio-methanol versus fuel cells powered using methanol derived from natural gas, the most common source for methanol available today (26). For scenarios using bio-methanol as a substitute for gasoline, we assumed 100% substitution of gasoline in motor vehicles even though a range of methanol/gasoline mixtures are in use. Currently, M85, a fuel mixture consisting of 85% methanol mixed with 15% unleaded gasoline or lower blends, are commonly discussed and are already being used in fleet vehicles; for safety reasons, 100% methanol has also been commonly used by race cars participating in the Indy Racing League since the 1960s [10,26,28-29].

In considering the viability of producing bio-methanol in the western states, annual biomass availability for methanol production in California, Idaho, Montana, Oregon and Washington was estimated. These data were subsequently used to calculate the annual sustainable amount of methanol that could be produced from landfill and agricultural wastes, and forest biomass. The appropriate data were then also used to calculate methanol production on a per hectare basis for forests in Washington State. These data were then used to calculate C emissions reductions based on: (1) using bio-methanol to replace the energy equivalent of all of the gasoline used in the five states and (2) generating all of the electric power needs in the five states using fuel cells powered by bio-methanol instead of natural gas-derived methanol. While this approach does not discuss in detail the issue of technology substitution of M100 compatible vehicle engines and the direct comparison of bio-methanol powered fuel cells versus the current electricity generation mix in each state, the approach does provide a straightforward way to demonstrate the significant potential contributions of using bio-methanol to reduce carbon emissions in the five states.

Presenting a complete energy balance for biomass conversion to biofuels is not the objective of this paper since there is considerable debate on the data used to balance the life-cycle of energy consumed and produced during the conversion of biomass to biofuels [30-32]. Instead, the analysis here focuses on emissions avoided from converting biomass to methanol and using it as a transportation fuel or to produce electricity. Estimates of net C emissions reductions will likely be somewhat higher than the achievable absolutes in actual practice primarily because of not factoring in C emissions that result from the myriad of inefficiencies in any processing operation or what is emitted during the conversion process. This is less of an issue in this study because the mobile integrated biomass to methanol conversion system, as described in Vogt et al. [5], is C neutral because fossil fuels are not used to power any stage of the conversion process other than to initially power the fuel cells. For the scenarios discussed here, bio-methanol produced is used to power fuel cells that generate electricity to power the conversion process as well as to fuel the trucks transporting the mobile biomass conversion system to the site.

2.2. Calculation methods

Even though some current literature reports that the efficiencies of methanol production from wood vary between 45 to 57% [5,9,28,33-36], in this study a conservative extraction efficiency of 25% is used as our lower threshold and 50% for our highest value (Table 1). We used the same extraction efficiencies to calculate the amount of methanol produced from agricultural wastes even though less methanol is produced from these materials [37]. All the results are based on the same units of measurement – either 1 MWh of electrical energy produced or 1 Mg of dry biomass used. The amount of C emissions avoided are estimated by determining the amount of energy produced, or electricity derived, from 1 Mg of biomass that could replace or substitute for an equivalent amount of energy produced from non-renewable resources such as natural gas, gasoline, or other fossil fuel products (Table 1). Estimates of C emissions avoided are conservatively calculated for biomass-derived energy, so potential emissions avoided may be even higher. For example, many parts of the life-cycle of fossil-fuel uses and the resultant C emissions from the procurement, shipping, and processing of gasoline and natural gas, were not considered in the estimates here.

Data used to calculate the information included in this paragraph was obtained from the Perry's Chemical Engineers Handbook [38] and is provided in greater detail in the footnotes included in Table 1. One dry Mg of biomass produces 315 L and 630 L of bio-methanol when the conversion efficiency is 25% and 50%, respectively. Substituting bio-methanol from 1 Mg dry biomass (with extraction efficiencies of 25 and 50%) for natural gas-derived methanol used for electricity production would avoid carbon emissions equivalent to 232 to 462 kg C (Table 1). When gasoline is substituted with an energy equivalent amount of bio-methanol produced from 1 Mg of biomass, 210 to 420 kg C emissions are avoided. These data were then used to determine C emissions that could be avoided when replacing energy produced from fossil fuels with the potential energy that could be produced from biomass-derived methanol at state levels for five western states (California, Idaho, Montana, Oregon, Washington) in the U.S.

In this study, the annual sustainable level of forest biomass included forest thinnings, mill residues and organic debris from land clearing [4,27,39-42]. Further analyses were based on including the entire small diameter, high fire-risk forest material (5.1-22.9 cm in diameter) that could be collected at one time. For our calculations, only 25 percent of the total agricultural biomass reported available was used to produce methanol because removing all agricultural biomass is not sustainable [21,23]. The remaining 75% of the agricultural wastes are not precisely "wastes" since their removal would eventually decrease the soil's organic matter content and nutrient status. On the other hand, since the total biomass annually available from the landfills and forests can be sustainably collected, total biomasses from landfills and forests were used in the calculations.

In the state of Washington, we explored two scenarios at the scale of a hectare of forestland. For Scenario 1, a conservative 4 Mg/ha of dry wood was collected in a *Pseudotsuga menziesii* forest in western Washington. The estimate used here is conservative as this amount of biomass regenerates in one year in these forest types [43].

Scenario 2 is a one time removal of high fire-risk small diameter material (5.1 – 22.9 cm diameter class stems) from a hectare of forestland [27].

To compare the renewable and non-renewable options, state-level data on how much gasoline is consumed and how much electricity is used during a one year period were used to calculate the proportion of demand that could be met using bio-methanol. Carbon emissions avoided by substituting bio-methanol for fossil fuels in the transportation and in electricity production sectors were then calculated as a fraction of the current annual emissions by state (also calculated on a per-hectare for Washington).

3. Results

3.1. Biomass availability from municipal wastes, agriculture and forests

Data show that for four of the states, forests contribute the largest proportion of the total annually available biomass wastes (Table 2). In California, the greatest potential biomass availability was from municipal wastes. In contrast, both Idaho and Montana had more biomass available in agricultural materials than in municipal wastes. Overall, Washington, Oregon, and California had a higher proportion of their total annual biomass available from municipal wastes than from agricultural wastes.

In forests in California, Idaho, Montana, Oregon and Washington, the total amount of high fire-risk aboveground dry biomass is considerably higher than what can be collected from forest wastes annually (Table 2). The total amount of biomass currently available in the high fire risk category; however, is equivalent to collecting forest wastes in California over a four year period, 10 years in Idaho, 20 years in Montana, six years in Oregon and eight years in Washington. Subsequently, the amount removed from each would have to go back to normal levels to be sustainable.

3.2. Bio-methanol production and its substitution for gasoline and electricity

There is a high combined potential for bio-methanol production from all of the biomass sources examined in the five states studied (Table 3). Forest biomass had the potential for producing the highest amount of bio-methanol in Idaho, Montana, Oregon and Washington while the principal source in California was municipal waste. If all the harvestable high fire-risk wood was converted into methanol, from 36,005 to 71,499 ML of bio-methanol could be produced in these five states (Table 4).

When supplementing gasoline with bio-methanol produced from all biomass wastes, a significant percent of the annual gasoline consumed in each state could be replaced by bio-methanol (lowest range = 36.1-102.2%; highest range = 72.3-204.3%) (Table 3). In contrast, a lower proportion of the total electricity consumed annually in each state could be generated using bio-methanol, produced from all biomass supplies, and fuel cells (lowest range = 6.0-12.7%; highest range = 11.9-25.4%) (Table 5).

In this comparison, methanol from forest materials could substitute from a third to all of the gasoline consumed in these states because of the higher available supplies of forest wastes (except for municipal wastes in California) (Table 3). Methanol from forest materials as the H-source for fuel cells could produce enough electricity to replace from 6.9 to 18.7% of the electricity consumed in Idaho, Montana, Oregon, and Washington (Table 5). If all of the high fire risk forest materials were converted to methanol, bio-methanol from this process has the potential to provide for about half to over 700 percent of the gasoline consumed annually in these states as well as from a third to over 300 percent of the electricity generated annually (Table 4).

3.4. C emissions avoided when substituted for gasoline and electricity

As expected, the net C emissions avoided varied by the source of the biomass, the amount of biomass wastes that could be collected in each state and whether bio-methanol was used to supplant gasoline consumption or to generate electricity (Tables 6 and 7). For an equivalent amount of bio-methanol, producing electricity always resulted in less C being emitted compared to using bio-methanol as a gasoline substitute.

In Idaho, Montana, Oregon and Washington, forest wastes-derived bio-methanol reduced greater amounts of annual C emissions when used to produce electricity (lowest range = 6.2-32.4%; highest range = 12.3-64.5%) relative to when it was used as a gasoline substitute. In California, methanol from municipal wastes could reduce annual C emissions by 8.8-17.5% when electricity was generated with fuel cells and by 7.9-15.9% when it was used as a gasoline substitute (Tables 6 and 7).

4. Discussion

4.1. Selecting the Appropriate Biomass Supply and Biofuel

To increase the proportion of energy derived from non-fossil fuel resources, biomass needs to be converted into multiple products suitable for substituting for a variety of energy uses. In contrast to the EU, U.S and state level policies favor the conversion of agricultural crops, and to a lesser extent wastes, into bio-ethanol or biodiesel as substitute fuels for motor vehicles [3,23,44-45]. These policies mention the use of forest materials to produce energy but provide few if any incentives for the production of biofuels from these materials [13,46]. To widen the scope of available options, the U.S. needs to strongly consider other viable options such as biomass conversion to methanol. In the EU, bio-methanol is already being used as a motor vehicle fuel as well as the hydrogen source for fuel cells [5,7,9-10,28,47-49].

It is more efficient to identify the most sustainably available sources of biomass for each individual locale, and then convert that biomass to the appropriate biofuel for that region. It is also clear that no one biomass source will be sufficient to mitigate the environmental impacts of fossil fuel energy use. For example, even if all the corn and soybean crops in the U.S. were diverted from the food supply to produce biofuels (an unsupportable extreme), this would satisfy only about 12% of the gasoline demand and 6% of the diesel demand annually [50]. This is in contrast to Brazil where the conversion of agricultural crops (e.g. sugar cane) to produce ethanol-gasoline mixtures has been the practice for some time [51] and is commercially successful. However, where agricultural crops (e.g.., corn, soybean) require the expenditure of more energy to grow and harvest than the energy which results from their conversion [7,52], and where the C emissions avoided are low [53-54], alternative biomass sources must be considered to produce biofuels.

This study suggests that forest wastes, and municipal wastes in California, should be part of the biomass supplies converted to biofuels in the western U.S. For the five western states included in this study, the benefits of producing biofuels from annual harvests of biomass wastes are evident by the high proportion of each state’s gasoline consumption and electricity generation that bio-methanol could replace. Using optimal conversion efficiencies and a variety of biomass wastes to methanol, from three-fourths to four-fifths of the gasoline currently consumed annually could be substituted by bio-methanol in California and Washington. However, the states of Idaho, Montana and Oregon could annually satisfy 100 percent of their gasoline consumption needs and have additional bio-methanol to export to other states or for use in alternative programs. At the highest conversion efficiency of biomass to methanol, all biomass sources collectively could sustainably provide up to 25.4% of the current electricity generated per state.

4.2. Optimizing the Role of Biofuels in Reducing Carbon Emissions

Increasingly, energy production systems are evaluated based on their contribution to mitigating C emissions. Since virtually all of the methanol consumed throughout the world is produced from natural gas, using methanol from biomass would avoid the emissions of greenhouse gases that occur during natural gas production, transport, and distribution. Since natural gas is 97 percent by volume methane (a gas which is 22 times more potent than CO_2 in global warming [55-56]), there is considerable interest in reducing its emissions into the atmosphere. Even though today's methanol does not constitute even a minor fraction of the transportation fuels market, any process that avoids the use of natural gas for energy production will positively impact the energy and C emissions picture of these states.

Substituting bio-methanol for fossil fuels can significantly reduce the amount of C emitted in the five states whether the end product is used as a transportation fuel or to generate electricity. For example, converting all of the biomass sources to bio-methanol at optimal conversion efficiencies, C emissions could be reduced by 2.0 to 28.9 Tg C when bio-methanol was substituted for gasoline and by 2.2 to 31.9 Tg C when it was used to produce electricity. As a proportion of the C annually emitted by each state, using bio-methanol to replace fossil fuels potentially reduced total state C emissions by 22.8 to 80.7% when bio-methanol was used as a gasoline substitute. When bio-methanol was used in fuel cells to produce electricity, up to 25.0 to 88.8% of the total state emissions were avoided.

4.3. Why Produce Biofuels to Decrease the High Fire Risk of Western U.S. Forests?

A number of approaches are available to mitigate carbon emissions and these have been well covered in several reports [1,2,6,8,12,14]. Much of the reduction in C sequestration in standing forest biomass is due to wildland fires. If wildfires did not occur, estimates indicate that changing current land-use practices to enhance C sequestration in forests globally would offset 10-20% of the emissions from fossil fuel combustion [57]. However, today less C is being sequestered in U.S. forests than was recorded 12 years ago [16,27]. In the U.S. the amount of the total fossil fuel CO_2 emissions offset by forests has decreased from 19 percent in 1990 to 12 percent in 2002 [16]. It will be difficult to reverse the declining trends in forest C sequestration because of the continuing risk and damage from catastrophic fires.

Land areas throughout the western U.S. are especially at risk from severe fires because of overly dense stands that are a result of many years of active fire suppression. The resultant stand structure, overstocked with numerous small diameter trees, contributes to the fuel load and also acts as a ladder fuel to encourage crown fires. In the western U.S., the positive effects of carbon sequestration by afforestation projects (replanting trees in areas where trees have not grown for at least 50 years) could easily be negated and even contribute to the problem through additional emissions if uncontrolled or unintentional burning of over-stocked, high fire-risk forests occurs [16,27]. If the forest is exposed to a severe fire and releases the sequestered carbon, it may take up to three or four decades for the site to approach its original state of C sequestration.

Calculations made for the five western states discussed here suggest that these states are ideal locations to convert biomass into biofuels because of the widespread availability and ease of access to biomass, particularly biomass at risk of being burned during a catastrophic fire. If this high fire risk material were converted to bio-methanol to supplement motor vehicle fuels, it has the potential to replace the gasoline consumed in one year in California, eight years in Idaho, 22 years in Montana, nine years in Oregon, and three years in Washington. If this same amount of high fire-risk forest materials were used to produce methanol to generate electricity with fuel cells, 38,062 to 75,584 GWh of electricity would be available from this source in these five states.

As this comparison illustrates, biofuels produced from biomass can supplement or substitute for a considerable amount of the energy needed in some western U.S. states. In addition to the energy benefits, managing forests for fire is important as a management objective since wildfires can have considerable socio-economic and ecological impacts. The 1997-1998 wildfires in Southeast Asia, caused by drought and extensive land clearing, adversely affected the health of an estimated 20 million people. These fires also produced extensive damage to the region's forests and biodiversity, at a total estimated cost of US$4.4 billion in South Asia [58-59]. Reducing the risk of forests to catastrophic forest fires also offers the added benefit of contributing significantly towards mitigating C emissions by simultaneously reducing the amount of forest area that is high risk and fire prone while reducing the C emissions that result from fossil fuel combustion. For the five states included in this study, converting small diameter wood materials to bio-methanol as a substitute for fossil fuels can reduce C emissions by 24 to 47.7 Tg C when substituted for gasoline and 26.4 to 52.4 Tg C when producing electricity using fuel cells.

4.3. Washington Forests Case Study: Biofuels and C Emission Trade-offs

Our familiarity with forest resources in the state of Washington and the fact that considerable research and data are available makes Washington the ideal choice for this case study. Currently, wood biomass for energy production in Washington holds a very small share of the energy market; data for 2003 indicates that about five percent of the total energy needs were derived from biomass use in 2003 [60]. In Washington, the low use of wood biomass for energy, occurring in a state that has a high amount (48%) of land area in forests [61], allows for robust comparisons. Much of the forest area has a high fire-risk status in Washington that would result in the loss of key ecosystem components during a wildfire [27]. This loss of key ecosystem components due to a catastrophic fire has to be balanced by the need to sustainably collect forest materials so that sufficient amounts of materials are left in the forest to maintain the forest as a healthy ecosystem (e.g., decomposers [62]).

We assessed two scenarios at this scale: Scenario 1 = a one time conservative and sustainable harvest of wood; Scenario 2 = completely removing the small diameter high fire-risk material from a hectare of forestland at one time (15.82 Mg/ha [27]). For Scenario 1, wood-methanol avoided emissions of 0.9 to 1.9 Mg C/ha and 0.8 to 1.7 Mg C/ha when used to generate electricity with fuel cells or as a gasoline supplement, respectively. For Scenario 2, if the total high fire-risk small diameter wood was converted to bio-methanol to either generate electricity with fuel cells or as a substitute for gasoline, a higher level of reduction in C emissions is possible (3.7–7.3 and 3.3–6.6 Mg C/ha, respectively). In areas where the fire-risk is sufficiently high necessitating the removal of a greater proportion of the high fire-risk material for forest health and safety, Scenario 2 would provide the optimal reductions in C emissions. If the amount of C emissions avoided by substituting bio-methanol for fossil fuels were compared to the C sequestration potential (0.6 Mg C/ha/yr) during the first 10-20 years of afforestation on arable land in Europe [63], afforestation would provide a lower level of C emissions avoidance compared to collecting a conservative amount of small diameter wood material to produce bio-energy (Scenario 1).

A range of values have been reported in the literature for how much carbon emissions are avoided (1.7 to 9 Mg C/ha [48,63-65]) when substituting biomass for fossil fuels. These published values are based on harvesting all the wood on a given area of land instead of only collecting the smaller diameter size-class stems as was examined in this study. As would be expected, the magnitude of C emissions avoided in Scenario 1 is at the lower end of the published range while the results from Scenario 2 are at the middle to the upper end of the range. Carbon emissions avoided are higher when using the wood-methanol derived from 1 Mg of dry biomass to produce electricity with fuel cells compared to using it as a gasoline supplement. This is due to the fact that C emissions are avoided at two stages in the production of electricity: when substituting bio-methanol for natural gas-methanol and during the production of electricity with fuel cells.

Washington is fortunate in that most of its electricity is generated using hydro-electric dams which emit little C when producing electricity (66). Replacing all existing hydro-electric dams with bio-methanol/fuel cells to produce electricity is not an option here so Washington will have to consider alternative approaches to reducing total state C emissions. Compared to neighbouring states, total C emissions are high in Washington due to its high population density and the resultant high rates of motor vehicle fuel consumption (66). To further reduce state C emissions, Washington could adopt a strategy of substituting bio-methanol for fossil fuels to produce electricity in the rural parts of the state where electricity supply is less dependable while also producing motor vehicle fuels in those regions where biomass supplies are high.

Conclusions

In this paper, we have attempted to illustrate the large potential for reducing C emissions through the use of bio-methanol in the transport and electric power sectors (e.g., fuel cells). While technological, policy, and market changes make exact predictions of the transportation fuel and/or electric power generation mix difficult, bio-methanol would seem to be a renewable fuel source with great potential for economic and environmental benefits and worthy of strong consideration as the U.S. looks toward a more climate-sensitive future. With the current level of investments in hydroelectric and thermal generation (coal or natural-gas fired plants), it will take considerable time and capital investment to replace these facilities with fuel cells. Even so, with energy demands on the rise, newer generation facilities are considering the use of fuel cells. In such cases, bio-methanol is an ideal alternative to natural gas derived methanol and will generate emissions reductions.

Producing bio-energy from biomass materials is an environmentally friendly solution to meeting energy demands in highly populated areas with considerable urban waste issues, as well as in rural areas where forest fires contribute to increased CO_2 emissions or where forest health needs to be restored. When forest fire-risk is high and in developing countries where most of the energy produced is from fuelwood [24], using bio-methanol to produce electricity is an attractive alternative. Even developing countries could produce and use bio-methanol to reduce their CO_2 emissions. Biomass-derived methanol is a promising solution to pursue because its conversion is almost carbon neutral when forest biomass is used as the raw material. At the same time, new economic opportunities could be created in developing countries that would discourage over harvesting of trees by providing sustainable economic alternatives. In addition, when waste materials that have little value in today's markets are transformed to produce a fuel that provides an added and previously unrealised economic value, much needed income is generated in rural areas.

An added benefit to using biomass-derived methanol is its "multiple-use" characteristic, which allows for its use as a substitute for fossil fuels in several industrial processes. In addition, bio-methanol's versatility allows it to be used as a transportation fuel additive, or to produce electricity with fuel cells which can also be used to replace batteries, or as a precursor for many chemical compounds in the chemical industry [5,28,50]. In addition, since methanol is an important ingredient needed to make bio-diesel, markets for bio-methanol will be strong in areas producing and marketing bio-diesel. Several analyses have also suggested that methanol is the preferred biofuel over cellulosic ethanol because a larger quantity of methanol is produced per metric ton of biomass converted. In addition, methanol is cheaper to produce, and less C is emitted during its manufacture and use [7,10,28,67].

At present, adoption of bioenergy systems is hampered by the costs of transporting biomass to large processing facilities from remote locations. The scale at which biofuels are produced is an optimization challenge that needs to balance the negative costs of transporting biomass long distances with the economics and environmental benefits of the conversion process at different scales [5,47,68-71]. One solution is a compact mobile methanol production system which could be a part of a larger distribution network. A mobile system would allow cost effective transportation of a compact, high energy-density product (methanol) rather than bulky wood chips or cellulosic waste [5]. Interestingly, even large industrial companies are exploring the use of distributed networks for biofuel production. For example, Boeing recently published in their Air Transport Intelligence News that “Instead of a single, huge repository of biofuel feedstock to supply the world’s airlines, Boeing envisions the growth of a distributed network with multiple feedstocks harvested for biofuel” where the selected feedstock would be “the most appropriate for its geography and climate” [72].

If biomass derived biofuels are used to substitute for fossil fuels and reduce C emissions into the atmosphere, biomass should be collected sustainably and transformed using environmentally designed technology. Using recent cutting-edge technological developments and efficient C-neutral technologies to transform biomass into biofuels will provide us will viable solutions to several global problems. While this approach provides for a “climate friendly” forest management option, such an approach need not and should not replace other on-going C sequestration projects (e.g., afforestation), or the management of forests for old growth conditions, longer rotations and ecological sustainability [73-74].

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Table 1
C emissions avoided and products from the transformation of 1 Mg dry wood into methanol used for electricity production in fuel cells or as a gasoline supplement equivalent

Fuel	Amount product / 1 Mg biomass (Mg)	Lower Heating Value[b] (kWh/kg fuel type)	Electrical energy produced per kg of fuel[c] (kWh/kg fuel)	Amount C emissions per MWh equivalent electrical energy production[d,e] (kg C/MWh)	Carbon emissions avoided by substituting bio-methanol[a] for natural gas-methanol or gasoline (kg C)
Firewood (combustion)	1	4.44	1.33	(300)	--
Methane		13.9	4.17	180	
(A) Wood-methanol equivalent to amount substituted for natural gas-methanol	0.25 – 0.50[a]	5.53	1.66	--	75 – 149
(B) Electricity production with wood-methanol in fuel cells			1.83	274	157 – 313
(A) + (B)	-	-	-	-	232 - 462
Gasoline		12.3	3.69	228	210 – 420

[a] Based on wood conversion efficiency to methanol = 25%, 50%

[b] Lower heating values of fuels: biomass (wood) = 4.44 kWh/kg; methanol 5.53 kWh/kg; gasoline (isooctane) 12.3 kWh/kg; methane 13.9 kWh/kg [38].

[c] Electrical energy produced from wood based on combustion, followed by steam generation, followed by steam turbines, at an overall efficiency of 25%. Energy from methanol based on reforming it with steam to produce hydrogen and feeding hydrogen to a PEM fuel cell. Overall efficiency of process is assumed to be 33%. C emissions and electrical energy production with fuel cells includes energy and C emissions resulting from the conversion of methanol produced from 1 Mg of dry wood so that this equalled the amount of methanol displaced when producing methanol from natural gas. Electrical energy produced from methane and gasoline is based on 30% efficiency for turbines or engines. IdaTech fuel cells use 960 mL of methanol per kWh electricity produced [75].

[d] Carbon concentration of 0.84 kg C/kg gasoline; 0.75 kg C/kg methane; (5) 1 MWh is roughly equivalent to 4828 km driven in a “basis” car (at 12.75 km/L). 1 Mg biomass converted to methanol that is used to make hydrogen for a fuel cell is approximately equivalent to about 6758 kilometres driven in the “basis” car.

Table 2
Amount of dry biomass annually available from municipal wastes, agriculture and forests [4,27,40-42]

	Total Biomass in Municipal Wastes[a] (Mg/yr X 1,000)	Total Biomass in Agriculture[b] (Mg/yr X 1,000)	Total Biomass in Forests[c] (Mg/yr X 1,000)	Aboveground Biomass with High Fire-risk in Forestlands[d] (Mg X 1,000)
California	38,000	4,200	26,830	113,490
Idaho	427	1,788	5,873	72,940
Montana	500	1,560	2,641	70,220
Oregon	1,653	1,500	12,700	82,550
Washington	3,472	2,412	8,104	57,150

[a] Municipal wastes includes yard burn, paper, wood residues
[b] Agricultural biomass includes wheat straw, grass seed straw, barley straw, corn stover, other field residues, hops residues, mint slug
[c] Forest biomass includes forest thinnings, mill residues, land clearing debris
[d] High fire risk forest biomass consists of biomass materials with diameters of 5.1 to 22.9 cm and is 28% of the total fuel treatment reduction needed to reduce the high risk of loosing key ecosystems components in a wildfire (the remaining 72% consists of materials 23 cm in diameter and higher) [27]

Table 3
Annual bio-methanol[a] production and percent of annual gasoline consumption substituted by bio-methanol by state[b]

State	Annual methanol production from municipal wastes (litres X 1,000,000/year) [Annual gasoline consumed substituted by bio-methanol by state, %]	Annual methanol production from agricultural wastes (litres X 1,000,000/year) [Annual gasoline consumed substituted by bio-methanol by state, %]	Annual methanol production from forest wastes (litres X 1,000,000/year) [Annual gasoline consumed substituted by bio-methanol by state, %]	Annual % gasoline consumption substituted by methanol from municipal, agriculture, forest wastes
California	11,970 - 23,940 [19.9 – 39.8]	1,323 – 2,646 [2.2 – 4.4]	8,451 – 16,903 [14.0 – 28.1]	36.1 – 72.3
Idaho	135 – 269 [5.4 – 10.8]	563 – 1126 [22.6 – 45.2]	1,850 – 3,700 [74.2 – 148.4]	102.2 – 204.3
Montana	158 – 315 [8.2 – 16.3]	491 – 983 [25.5 – 51.0]	832 – 1664 [43.2 – 86.3]	76.8 – 153.7
Oregon	521 – 1,041 [9.1 – 18.1]	619 – 1,239 [10.8 – 21.6]	4,001 – 8,001 [69.7 – 139.3]	89.5 – 179.0
Washington	1,039- 2,078 [10.2 – 20.4]	757 – 1,513 [7.1 – 14.1]	2,553 – 5,105 [23.8 – 47.7]	41.1 – 82.2

[a] 25% (315 litres methanol/1 Mg biomass) and 50% (630 litres methanol/1 Mg biomass) conversion efficiency of conversion of biomass to methanol was assumed for the different biomass sources; biomass data from Table 2

[b] Litres gasoline consumed by state in 2005: California – 60,185,588,760, Idaho – 2,493,916,155, Montana – 1,927,431,045, Oregon – 5,742,224,676, Washington – 10,712,095,263 [76]

Table 4
Bio-methanol from high fire-risk forest materials and C emissions avoided[a] when substituted for gasoline[b] and used to produce electricity[c] [27]

State	Substituting bio-methanol for gasoline		Substituting bio-methanol for natural gas-methanol and using fuel cells to produce electricity	
	Methanol production (litres X 1,000,000) [Annual gasoline consumed substituted by bio-methanol, %]	Net carbon emissions avoided (Tg C) [Annual C emissions avoided, % of state total]	Electricity production (MWh x 1,000) [Annual electricity consumed provided by bio-methanol-fuel cells, %]	Net carbon emissions avoided (Tg C) [Annual C emissions avoided, % of state total]
California	35,749 – 71,499	23.833 – 47.666	37,792 – 75,584	26.330 – 52.432
	[59.4 – 118.8]	[23.7 – 47.5]	[15.8 – 31.7]	[26.2 – 52.2]
Idaho	22,976 – 45,952	15.317 – 30.635	24,289 – 48,578	16.922 – 33.698
	[921.3 – 1842.6]	[363.9 – 727.8]	[114.5 – 228.9]	[402.0 – 800.6]
Montana	22,119 – 44,239	14.746 – 29.492	23,383 – 46,767	16.291 – 32.442
	[1147.8 – 2295.2]	[170.0 – 340.0]	[182.3 – 364.7]	[187.8 – 373.9]
Oregon	26,003 – 52,007	17.336 – 34.671	27,489 – 54,978	19.152 – 38.138
	[452.8 – 905.7]	[120.4 – 240.8]	[60.8 – 121.6]	[133.0 – 264.9]
Washington	18,002 – 36,005	12.002 – 24.003	19,031 – 38,062	13.259 – 26.403
	[168.1 – 336.1]	[71.3 – 142.5]	[24.4 – 48.7]	[78.7 – 156.8]

[a] C emitted by state in Tg C in 2001: California = 100.4528 Tg C; Idaho = 4.209278 Tg C; Montana = 8.67542 Tg C; Oregon = 14.39892 Tg C; Washington = 16.83851 Tg C [16]

[b] When substituting gasoline with bio-methanol produced at a 25% efficiency of conversion of biomass to bio-methanol, C emissions are reduced by 210 kg C/1 Mg of dry biomass and 420 kg C/1 Mg dry biomass with a 50% efficiency of conversion of biomass to bio-methanol.

[c] When substituting bio-methanol for natural gas-methanol to produce electricity with fuel cells at a 25% efficiency of conversion of biomass to bio-methanol, C emissions are reduced by 232 kg C/1 Mg of dry biomass and 462 kg C/1 Mg dry biomass with a 50% efficiency of conversion of biomass to bio-methanol.

Table 5
Potential annual electricity production using fuel cells[a] and percent substituted by bio-methanol by state

State	Annual electricity production from municipal wastes (MWh x 1,000) [Annual electricity consumed by state provided by bio-methanol-fuel cells, %][b]	Annual electricity production from agricultural wastes (MWh x 1,000) [Annual electricity consumed by state provided by bio-methanol-fuel cells, %][b]	Annual electricity production from forest wastes (MWh x 1,000) [Annual electricity consumed by state provided by bio-methanol-fuel cells, %][b]	Range of annual electricity consumed by state provided by biomass methanol and fuel cells (%)
California	12,654 – 25,308	1,399 – 2,797	8,934 – 17,869	9.6 – 19.3
	[5.3 – 10.6]	[0.6 – 1.2]	[3.7 – 7.5]	
Idaho	50 – 99	595 – 1,191	1,956 – 3,911	12.7 – 25.4
	[0.2 – 0.5]	[2.8 – 5.6]	[9.2 – 18.4]	
Montana	40 – 79	519 – 1,039	879 – 1,759	12.2 – 24.4
	[0.3 – 0.6]	[4.1 – 8.1]	[6.9 – 13.7]	
Oregon	433 – 866	655 – 1,309	4,229 – 8,458	12.0 – 24.0
	[1.0 – 1.9]	[1.4 – 2.9]	[9.4 – 18.7]	
Washington	1,098– 2,196	800 – 1,600	2,698 – 5,397	6.0 – 11.9
	[1.4 – 2.8]	[1.0 – 2.0]	[3.5 – 6.9]	

[a] At 25% conversion efficiency of biomass to methanol produce 315 liters methanol/1 Mg biomass and at 50% conversion efficiency of biomass to methanol produce 630 liters methanol/1 Mg biomass; biomass data from Table 2. Electrical energy produced (kWh/1 Mg Biomass) when biomass-methanol equivalent in amount to natural gas-methanol is used to power fuel cells = 333 kWh/1 Mg dry biomass with 25% conversion efficiency of biomass to methanol and 666 kWh/1 Mg dry biomass with 50% conversion efficiency of biomass to methanol. Ida Tech fuel cell uses 960 mL of methanol/kWh.

[b] Electricity used in 2005 by state (kWh x 1,000,000/year): California = 238,710.0; Idaho = 21,219; Montana = 12,825; Oregon = 45,213; Washington = 78,134 [77-78]

Table 6
C emissions avoided by substituting bio-methanol for gasoline

State	Carbon emissions avoided when substituting bio-methanol for gasoline			
	Municipal waste-methanol (Tg C) [Annual C emissions avoided, % of state total]	Agricultural waste-methanol (Tg C) [Annual C emissions avoided, % of state total]	Forests waste-methanol (Tg C) [Annual C emissions avoided, % of state total]	Methanol from all biomass/waste sources (Tg C) [Annual C emissions avoided, % of state total]
California	7.980 – 15.960 [7.9 – 15.9]	0.882 – 1.764 [0.9 – 1.8]	5.634 – 11.269 [5.6 – 11.2]	14.496 – 28.993 [14.4 – 28.9]
Idaho	0.090 – 0.179 [2.1 – 4.3]	0.375 – 0.751 [8.9 – 17.8]	1.233 – 2.467 [29.3 – 58.6]	1.698 – 3.397 [40.4 – 80.7]
Montana	0.105 – 0.210 [1.2 – 2.4]	0.328 – 0.655 [3.8 – 7.6]	0.555 – 1.109 [6.4 – 12.8]	0.987 – 1.974 [11.4 – 22.8]
Oregon	0.347 – 0.694 [2.4 – 4.8]	0.413 – 0.826 [2.9 – 5.7]	2.667 – 5.334 [18.5 – 37.0]	3.427 – 6.854 [23.8 – 47.6]
Washington	0.729 – 1.458 [4.3 – 8.7]	0.504 – 1.009 [3.0 – 6.0]	1.702 – 3.404 [10.1 – 20.2]	2.935 – 5.871 [17.4 – 34.9]

Table 7
C emissions avoided by substituting bio-methanol in fuel cells

State	Carbon emissions avoided when substituting bio-methanol for natural gas-methanol and using fuel cells to produce electricity			
	Municipal waste-methanol (Tg C) [Annual C emissions avoided, % of state total]	Agricultural waste-methanol (Tg C) [Annual C emissions avoided, % of state total]	Forests waste-methanol (Tg C) [Annual C emissions avoided, % of state total]	Methanol from all biomass/waste sources (Tg C) [Annual C emissions avoided, % of state total]
	8.816 – 17.556	0.974 – 1.940	6.225 – 12.395	16.015 – 31.892
California	[8.8 – 17.5]	[1.0 – 1.9]	[6.2 – 12.3]	[15.9 – 31.7]
	0.099 – 0.197	0.415 – 0.826	1.363 – 2.713	1.876 – 3.737
Idaho	[2.4 – 4.7]	[9.9 – 19.6]	[32.4 – 64.5]	[44.6 – 88.8]
	0.116 – 0.231	0.362 – 0.721	0.613 – 1.220	1.091 – 2.172
Montana	[1.3 – 2.7]	[4.2 – 8.3]	[7.1 – 14.1]	[12.6 – 25.0]
	0.383 – 0.764	0.456 – 0.908	2.946 – 5.867	3.786 – 7.539
Oregon	[2.7 – 5.3]	[3.2 – 6.3]	[20.5 – 40.7]	[26.3 – 52.4]
	0.806 – 1.604	0.557 – 1.110	1.880 – 3.743	3.243 – 6.458
Washington	[4.8 – 9.5]	[3.3 – 6.6]	[11.2 – 22.2]	[19.3 – 38.4]