Life Cycle Assessment of Second Generation Bioethanols Produced From Scandinavian Boreal Forest Resources

A Regional Analysis for Middle Norway

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Summary

The boreal forests of Scandinavia offer a considerable resource base, and use of the resource for the production of less carbon-intensive alternative transport fuel is one strategy being considered in Norway. Here, we quantify the resource potential and investigate the environmental implications of wood-based transportation relative to a fossil reference system for a specific region in Norway. We apply a well-to-wheel life cycle assessment to evaluate four E85 production system designs based on two distinct wood-to-ethanol conversion technologies. We form best and worst case scenarios to assess the sensitivity of impact results through the adjustment of key parameters, such as biomass-to-ethanol conversion efficiency and upstream biomass transport distance. Depending on the system design, global warming emission reductions of 46% to 68% per-MJ-gasoline avoided can be realized in the region, along with reductions in most of the other environmental impact categories considered. We find that the region's surplus forest-bioenergy resources are vast; use for the production of bioethanol today would have resulted in the displacement of 55% to 68% of the region's gasoline-based global warming emission—or 6% to 8% of Norway's total global warming emissions associated with road transportation.

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Introduction

Background

Emissions stemming from within the Norwegian road transport sector constitute approximately 18% of Norway's total greenhouse gas (GHG) emissions. In Norway (Statistics Norway 2008a) and in many other regions (Ribeiro et al. 2007), road transport is one of the fastest growing GHG-emitting sectors. The need to find zero-carbon or low-carbon substitutes for fossil fuels to obtain reductions in global warming emissions from within this sector is therefore an important element in the climate mitigation policy of Norway (Norwegian Ministry of the Environment 2007) as well as for the European Union (European Commission 2008a). Biofuels are expected to play a significant role in mitigating climate change from land-based transport in the short and medium terms (Ribeiro et al. 2007; IEA 2008). So-called second-generation biofuels—in particular, those produced from woody, or lignocellulosic, biomass—have an attractive fossil energy and life cycle GHG footprint and are appealing in the sense that they generally offer greater land-use and environmental benefits than the first-generation biofuels, which often compete with food crops (Gnansounou and Dauriat 2005; Tilman et al. 2006; Wu et al. 2006a; Koh and Ghazoul 2008; Hill et al. 2009). As with many other European countries, introducing biofuels is among the policies being suggested in Norway to reduce emissions from road transport (OECD 2008).

Wood-Based Biofuels

The idea of locally produced biofuels from woody biomass is gaining increasing attention in Nordic countries due to a vast supply of wood resources combined with recent technological advancements and process developments for converting woody biomass into biofuels such as ethanol, among others. In Norway, the boreal forest offers a considerable and expanding resource base, with annual incremental additions to stock increasing at an average rate of 1.3% per year since 1960 (Statistics Norway 2007). Unlike neighboring Sweden and Finland, whose current utilization of forest resources comprises 9% and 20% of net primary energy demand, respectively, the forest resource base in Norway is relatively underutilized as bioenergy—it contributed less than 1% of Norwegian net primary energy demand in 2007 (Econ Pöyry 2008). Use of the forest resource for the production of liquid biofuel is thus one option being considered, as emerging technologies may soon make it a realistic possibility to convert these resources into low-carbon biofuels on a commercial scale and as Norway seeks to adopt ambitious biofuel infusion targets (Norwegian Ministry of the Environment 2007).

The transition to a biofuel-based transport economy may require an expanded use of biomass resource endowments unique to a specific locale or region. Specific regional efforts are needed to deploy biomass production and supply systems adopted for local conditions (Faaij 2006). Characteristics of an environmentally effective biofuel system design and policy for one region may not be optimal for another. Thus, before sound biofuel and environmental policy decisions can be made at the national level, it is important for local and regional communities to assess the feasibility and performance of their own resource endowments in the systems that make effective use of them for maximizing regional environmental (and socioeconomic) benefits. Thus, for Norway, there is a need to quantify regional wood-resource bases and to evaluate the environmental performance of advanced biofuel systems that use those resources for the production of more sustainable liquid transport fuels.

Life Cycle Assessment

Life cycle assessment (LCA) is the prevailing framework for the systematic quantification and evaluation of the environmental performance of alternative transport technologies (Ribeiro et al. 2007), particularly biofuels (Kammen et al. 2008), and we apply it in this study to evaluate the impacts of an alternative regional transport system based on the bioethanol blend E85, made from local forest resources. Of more than 60 reports on the environmental profile of biofuels worldwide that have been recently reviewed by the OECD (2008), fewer than 20 studies had investigated second-generation technologies. Furthermore, the recently adopted European

Renewable Energy Directive promoting sustainable renewable transport fuels includes minimum life cycle GHG reduction standards (European Commission 2008b), and the application of LCA for use in evaluating GHG emission profiles of biofuels is becoming increasingly more important as researchers seek to promote environmentally effective technologies and comply with new regulatory frameworks. LCA of biofuels can help ensure that sound investments are directed toward those technologies and system designs that are expedient in terms of mitigating global warming and fostering sustainable development in general.

Goal and Scope

In this study, our intent is to evaluate the potential for one particular region in Norway to reduce fossil gasoline use in road transport by substitution with bioethanol produced from local forest resources as a global warming mitigation strategy. We start by quantifying the local resource base, then apply process-LCA to assess the environmental impacts associated with the regional production and use of E85 produced from wood. We consider two wood-to-ethanol conversion pathways to represent ethanol production—one biochemical, and one thermochemically based. We develop four distinct wood-E85 system designs, with permutations we created to observe changes in environmental performance brought about by adjustments to transport logistics and choice of biomass conversion technology within the biofuel system. In the design of our regional wood-biofuel systems, we drew on literature central to the topic of wood-bioenergy systems in Scandinavia (Forsberg 2000; Mälkki and Virtanen 2003; Berg and Lindholm 2005; Wihersaari 2005; Eriksson 2008; Michelsen et al. 2008). LCA results of the four regional E85 systems are compared to results of a reference gasoline system. Table 1 includes a list of abbreviations of terminology commonly used throughout the remainder of the article.

Table 1 List of abbreviations

Abbreviation	*Full term*
PR	Primary industry residual volume
SR	Secondary industry residual volume
F	Surplus gross annual increment volume
B	Regional annual biomass potential volume
GAI	Gross annual increment volume
E100	Unblended ethanol
E85	85 v.% ethanol + 15 v.% gasoline
GWP	Global warming potential
AP	Acidification potential
EP	Eutrophication potential
HTP	Human toxicity potential
WTW	Well to wheel
WTT	Well to tank
TTW	Tank to wheel
FFV	Flex-fuel vehicle
BCBCh	Best case biochemical system
BCTCh	Best case thermochemical system
WCBCh	Worst case biochemical system
WCTCh	Worst case thermochemical system
SI-ICE	Spark-ignited internal combustion engine

Methodology

Resource Assessment

The focal region in our study is hereafter defined as Middle Norway, which comprises the four counties Møre and Romsdal, Sør-Trøndelag, Nord-Trøndelag, and Nordland, located in central Norway with an average latitude of 64° N. Our method for estimating the regional forest-derived resource potential available for use in E85 production considers the supply coming from regional forests in surplus of that currently being utilized by traditional wood industries, plus residuals generated by wood products and processing industries and all logging activities. We use this method to avoid complicated rebound effects that could occur when forest resources are drawn away from other uses. For example, competition for the forest resource may lead to the substitution of commercial roundwood products for fossil fuels, which could offset the reduction of carbon dioxide (CO_2) emissions from the replacement of fossil fuels by biofuels; thus, the use of forest wood by the current industry was given priority over its use to produce biofuel.

Only wood originating from productive natural forests is considered in the assessment.[1]

A combination of national statistical registries and institutional reports was used to derive figures for the economic surplus annual forest growth (F) volume, primary forestry residuals (PR) volume, and secondary industry residuals (SR) volume for 2005 (Norwegian Forest and Landscape Institute 1999a, 1999b, 1999c, 1999d; Bjørnstad and Storø 2006; Statistics Norway 2007). The estimated total biomass potential (B) of the region for 2005 is thus the sum of these volumes, represented by the variables shown on the righthand side of equation (1):

$$\begin{aligned} & B = F + PR + SR, \\ \text{where} \quad & F = GAI - (IRW + WF), \end{aligned} \tag{1}$$

where surplus forest growth (F) is the economically harvestable gross annual increment (GAI) volume in 2005 less the sum of industrial roundwood (IRW) and wood fuel (WF) demanded by the regional commercial wood industry in 2005.

Well-to-Wheel LCA

In this study, we apply a process-based LCA in which we consider two wood-to-ethanol conversion technologies (one biochemical and one thermochemical) to represent ethanol production as part of a regional wood-based biofuel production system. The biochemical process involves a high-temperature dilute acid hydrolysis pretreatment of wood chips, followed by simultaneous saccharification and cofermentation (SSCF) of sugar monomers into ethanol. We adapt material and energy balance along with yield data from Wooley and colleagues (1999) to develop a life cycle inventory built from process flow diagrams of a process designed to convert yellow poplar chips into ethanol. The thermochemical process involves the allothermal gasification of wood chips into synthesis gas, followed by catalytic synthesis into ethanol and other higher weight mixed alcohols. Similarly, we use process flow diagrams for adapting material and energy balance data from Phillips and colleagues (2007) into a process inventory suitable for LCA for a process based on hardwood chips, applying physical allocation procedures to the fraction of ethanol product produced in the process. Both processes are self-sufficient in terms of process energy requirements.

A key assumption we made when modeling the two conversion processes—particularly the biochemical process—lay in our choice to adopt yields based on conversion of hardwood chips to ethanol, because in Norway the dominant feedstock is a mixture of softwood chips. Unlike biofuels from thermochemical conversion processes, for biochemical processes the biochemical biomass composition plays a very important role in process performance, because the feedstock influences the ethanol yield via its holocellulose (hemicellulose and cellulose) sugar composition (Hamelinck et al. 2005). Huang and colleagues (2009) recently examined the effects of biochemical composition of various lignocellulosic biomasses on ethanol production via SSCF and concluded that ethanol production increases linearly with the increase in holocellulose composition. Holocellulose compositions for yellow poplar (Wooley et al. 1999) and Norway spruce (Bertaud and Holmbom 2004)—the dominant feedstock type of the Middle Norway region—are quite similar, and thus we find that the transference of biochemical yields assumption in our model is justified for purposes of LCA. For thermochemical processes, feedstock properties that affect thermodynamic efficiencies are heating value, moisture content, and the chemical composition, particularly the elemental ratios of hydrogen, carbon, oxygen, nitrogen, and sulfur as well as ash content (Prins 2005)—which vary little for yellow poplar and Norway spruce (Energy Research Centre of the Netherlands 2004). Thus, our yield transference assumption in the thermochemical case is also justified for use in LCA modeling.

Goal and Scope Definition

In our well-to-wheel (WTW) LCA study, our goal is to assess the environmental burdens associated with the regional production and use of lignocellulosic-based bioethanols in a fuel-efficient, spark-ignited internal combustion engine (SI-ICE) vehicle converted for flex-fuel use and driven in Middle Norway. The scope covers all life cycle activities associated with the extraction, handling, and processing of the woody biomass resources of the region into the high-ethanol blend E85, along with its use in a flex-fuel vehicle (FFV) manufactured in mainland

Europe. Special emphasis is given to 100-year global warming impact, and benefits of biofuels are benchmarked to a generic gasoline reference system with fuel use in the same vehicle type (uncoverted for flex-fuel use). We adapt life cycle data from Jungbluth (2004) for the processes that make up the reference system, such as oil extraction, transport, and refining, to fit circumstances for Norway. Both E85 and gasoline production in our study are part of our "well-to-tank" (WTT) systems, shown in figure 1. Both gasoline and E85 share identical downstream distribution and handling systems that begin from a refinery gate in Norway, adapted from Spielmann and colleagues (2007).

Included in the LCA are the activities associated with the construction and maintenance of both the gasoline reference vehicle and the FFV, or the activities that compose the car's value chain, known as the "tank-to-wheel" (TTW) system. The problem-oriented (midpoint) CML 2 Baseline 2000 impact assessment method (Leiden University 2001) is used to assess, in addition to global warming potential (GWP; 100-year CO_2-equivalents), other important life cycle impacts, including acidification potential (AP; sulfur dioxide equivalents [SO_2-equivalents]), eutrophication potential (EP; phosphate-equivalents), and human toxicity potential (HTP; 1.4-Dichlorobenzene-equivalents). Emissions from all processes associated with the construction and maintenance of all transport infrastructures as well as the ethanol production facility are included in the impact assessment. We used the LCA software tool SimaPro Version 7.0 to perform impact and contribution analyses (Goedkoop et al. 2004).

WTT System

The fuel ethanol's value chain originates when F and PR biomass are extracted from a forest and SR is purchased from a regional sawmill. Forestry operations are partitioned and allocated to PR on the basis of its economic output share relative to F biomass, and, similarly, sawmill activity is partitioned and allocated to SR biomass according to its economic output share relative to the main sawmill products. The WTT chain terminates when E85 is pumped into the FFV's fuel tank. All processes associated with biomass transporting, biomass handling and processing, wood chip storage, fuel production, fuel blending, and fuel distribution are included in the WTT system, shown in figure 1. Please refer to the Supplementary Material on the Web for a detailed description of the WTT system and life cycle inventories of the foreground processes.

TTW System

The TTW system includes the manufacturing of all car parts, assembly processes, vehicle maintenance, and various transport processes. Essentially, all material and energy inputs, wastes, and emissions associated with manufacturing and maintaining both the gasoline reference and the FFV over its lifetime of 150,000 km[2] are part of the TTW system. The type of car analyzed is a fuel-efficient compact four-seater sized comparable to a Renault Twingo. Life cycle inventory data are adopted from work by Röder (2001). Although these data are not representative of the current average light-duty vehicle type in Middle Norway, we chose the data for our study because we feel that more highly efficient, low-weight vehicles will be increasingly adopted over the medium-term horizon. Adjustments made to the TTW inventory include the replacement of the vehicle's plastic (high-density polyethelyene [HDPE]) fuel tank with one of a noncorrosive thermoset composite (NREL 2002). Data for the production of the substitute fuel tank are adopted from a report by Hischier (2007). The TTW system also includes the direct tailpipe emissions associated with operating the vehicle, scaled to the distance defined as the functional unit (e.g., kg-emissions 1,000/km; g-emissions/km). The FFV's fuel consumption is adjusted to accommodate the optimized engine efficiency associated with E85 use.

Case Descriptions

We created a set of four WTT cases for use when performing life cycle impact assessment—two best cases and two worst cases involving both conversion pathways. We developed two worst case systems to evaluate the effects of additional road transport distance between forest sites and sawmills to the biorefinery. For these two cases,

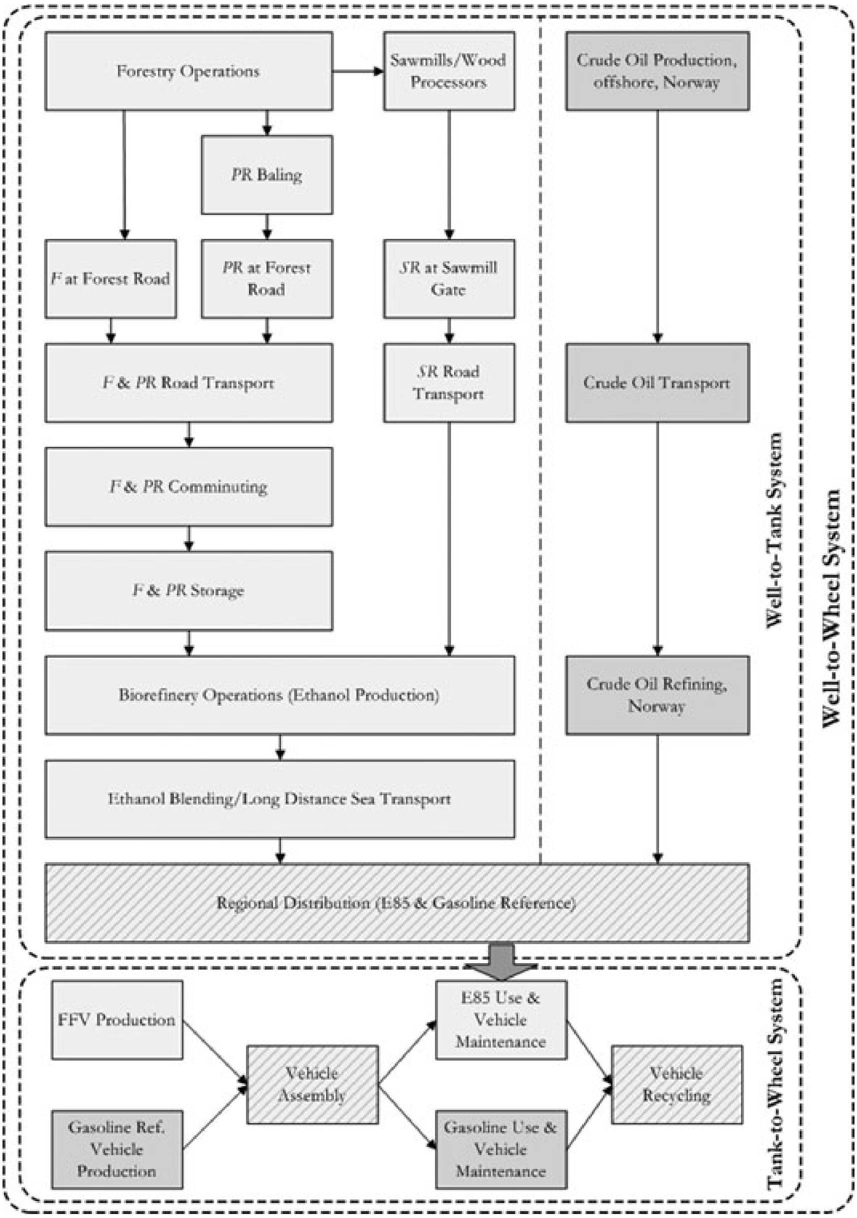

Figure 1 Well-to-wheel system, shown with well-to-tank (WTT) and tank-to-wheel (TTW) system boundaries. Dark gray processes indicate processes unique to the fossil fuel reference system. Light gray processes indicate processes unique to regional wood-E85 production. Light gray with shaded charcoal lines indicate processes that are shared. F = surplus forest growth; PR = primary forestry residuals; SR = secondary industry residuals; FFV = flex-fuel vehicle; Ref. = reference.

we added an extra 50 km of road transport to the 120 km average radius of the two best case transport scenarios for the transport of F and PR biomass from forest roads to the biorefinery. Additionally, we assume no colocation of the biorefinery with a regional sawmill in the two worst cases; thus, the road transport distance required to transport the SR biomass is increased to 50 km.

Both our wood-ethanol literature references provide information about futuristic cases

Table 2 Well-to-tank (WTT) system characteristics

Characteristic	*Best case biochemical*	*Best case thermochemical*	*Worst case biochemical*	*Worst case thermochemical*
Notation	BCBCh	BCTCh	WCBCh	WCTCh
Conversion process	SSCF "best of industry"	Allotherm. gas.-mixed alc. syn.	SSCF base case	allotherm. gas.-mixed alc. syn.
Yield (liters/tonne feed)	261	276	235	276
Conversion efficiency (%)	43	46	38	46
F, PR biomass transport	120 km	120 km	170 km	170 km
SR biomass transport	2 km	2 km	50 km	50 km

Note: Biomass-to-ethanol thermal conversion efficiency is based on a lower heating value (LHV) of 21.5 megajoules per kilogram dry matter (MJ/kg DM) biomass. Allotherm. gas.-mixed alc. syn. = allothermal gasification of wood chips into synthesis gas followed by catalytic synthesis into ethanol and other higher weight mixed alcohols; SSCF = simultaneous saccharification and cofermentation; F = surplus forest growth; PR = primary forestry residual; SR = secondary industry residual.

involving yield improvements (Wooley et al. 1999; Phillips et al. 2007). For the system involving the biochemical (BCh) conversion process, improved conversion efficiencies are based on improved ethanol yields (enhanced enzymatic conversion of hemicellulosic sugars), referred to in the report by Wooley and colleagues (1999) as the futuristic case labeled "near-term best-of-industry yields." In this best case biochemical (BCBCh) system, inputs and emissions are scaled to reflect the improved efficiency. Similarly, Philips and colleagues (2007) also provide data for a futuristic thermochemical (TCh) case exhibiting increased ethanol yield; however, we opted not to develop a case incorporating this yield because to do so would negate the autonomy of the process by requiring an auxiliary process heat and power source based on natural gas. Thus, in both the worst and the best cases that use the thermochemical route, the conversion efficiency and yields are the same. Therefore, the only difference in the worst case thermochemical (WCTCh) system stems from the increased biomass transport distances. Table 2 shows the main system properties and notations of the four E85 cases.

Results

Resource Assessment Results

We found that the surplus growth volume of the region (F) represents a significant and growing resource potential, illustrated in figure 2. In 2005, the economic F volume represented about 73% of the total biomass potential, of which 58% was spruce, 13% was pine, and 29% was broadleaved. On the basis of trend analysis of GAI and commercial roundwood demands of the region over the past decade, we expect this volume to increase at a rate faster than the growth in traditional commercial roundwood demand. The second largest resource available for biofuel production in the region was the volume of PR (about 19%), followed by regional sawmill industry residues (SR; about 8%). Cumulatively, we estimated the regional biomass potential for 2005 to be a figure of around 2.8 million cubic meters (m^3), or around 24.5 petajoules (PJ).[3] This represents a significant underutilized bioenergy potential originating from regional boreal forests. This is consistent with findings reported in a recent Nordic bioenergy market study for all of Norway as well as for both Finland and Sweden (Econ Pöyry 2008).

LCA Results

Together with the four WTT cases, four complete WTW systems are joined, analyzed, and compared to the gasoline reference WTW system.

WTT Impact Analysis

Figure 3 presents the WTT impacts of the cases utilizing the thermochemical ethanol production process, split by worst case and best case scenarios.

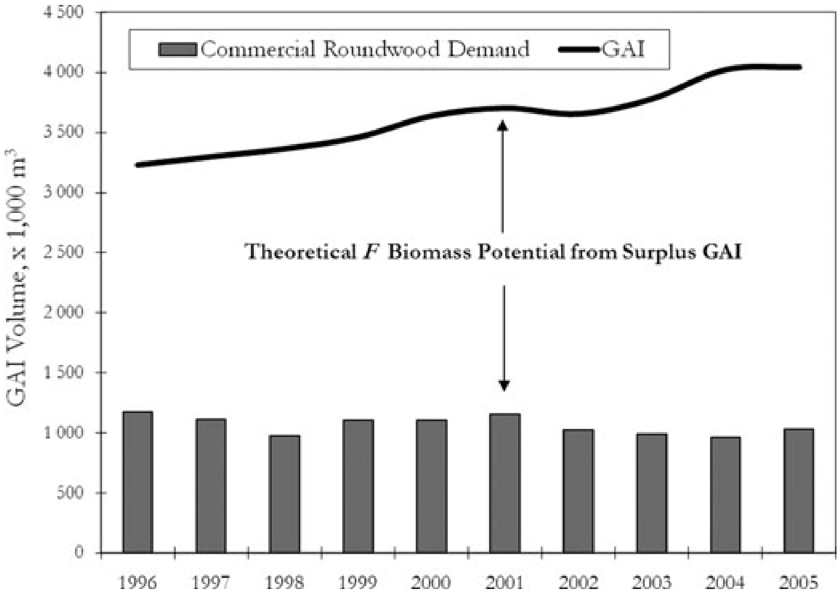

Figure 2 The theoretical volume of surplus gross annual increment (GAI; surplus forest growth [F]) classified as the theoretical GAI volume less the sum of industry demand.

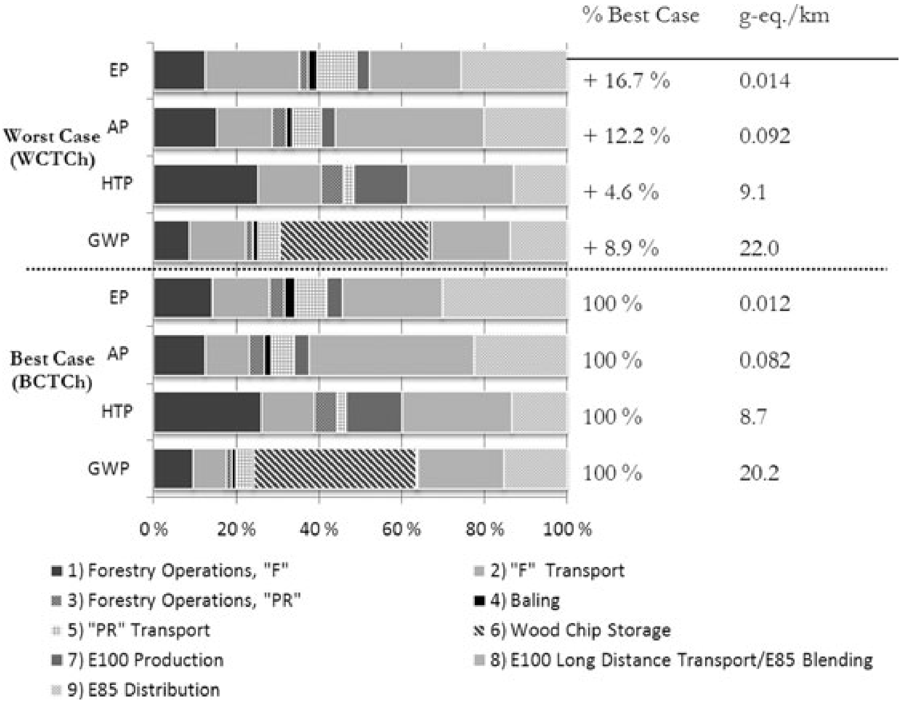

Figure 3 Well-to-tank (WTT) relative and absolute impacts, thermochemical cases. Impact scores are scaled to the operation of a flex-fuel vehicle (FFV) over a distance of 1 km. Only processes contributing at least 1% to any impact category are presented. WCTCh = worst case thermochemical; BCTCh = best case thermochemical; EP = eutrophication potential; AP = acidification potential; HTP = human toxicity potential; GWP = global warming potential; F = surplus forest growth; PR = primary forestry residuals.

For obvious reasons, the best case scenario generated lower impact scores across all impact categories due to the fact that upstream biomass transport distances were shorter. Contribution analysis revealed that the process that contributed the most to GWP in all WTT systems was the wood chip storage process. Anywhere from about 33% to 39% of the total WTT GHG emissions occurred in this process. Downstream E85 distribution and blending processes together generated significant impact across all impact categories due to numerous transport activities involving the combustion of fossil fuels, primarily diesel in road transport and high-sulfur distillates in shipping processes. The E85 blending process, which involved shipping the neat ethanol from the biorefinery in Namsos 530 km to a refinery in southern Norway, generated about 18% to 22% of the total GWP impact of the WTT system. The E85 distribution process contributed 14% to 16% to the total WTT GWP impact, of which direct tanker truck and ship GHG emissions contributed 55% and 24%, respectively. The direct GHG emissions from all transport activity within the thermochemical WTT system contributed 23% to the total WTT GWP. When the upstream biomass road transport distance was increased, as was the case for the WCTCh system, this share grew to 31.5%—an increase of about 9%. The increase in non-GHG emissions of the WCTCh system over the BCTCh system, shown in the top half of figure 3, can be attributed solely to the additional upstream biomass transport activity.

Ethanol production (biorefinery[4] operations) via the thermochemical route generated only trace amounts of GHG emissions, which stemmed directly from the combustion of diesel needed to operate a bulldozer in the stockyard and contributed about 1% to 2% of the total. Although it outperformed the biochemical ethanol production process in all impact categories, the thermochemical production process did generate more HTP relative to the other impact categories, about 91% of which could be attributed indirectly to the production of amines used during an acid gas (CO_2, hydrogen sulfide [H_2S]) removal process. More than 50% of total WTT HTP impacts for all cases, however, were associated with air emissions generated by combustion processes occurring in both forestry operations and E85 blending.

Figure 4 presents the impacts of the cases utilizing the biochemical ethanol production process—again split by worst and best case scenarios. Biochemical production of ethanol, as opposed to the thermochemical process based on gasification, did contribute significantly to global warming impact relative to the other processes. This can be explained by two reasons. First, contribution analysis revealed that the largest contributor to GWP impact was indirect emissions associated with ammonia production. Ammonia is produced in an upstream background process by the steam reforming of natural gas, which generates about 40% to 42% of the total GWP stressors produced by both best and worst case biochemical ethanol production processes (Althaus et al. 2007). Second, direct emissions of methane are produced onsite during a wastewater treatment process. Choice of allocation method concerning small amounts of two coproducts of the process—electricity and gypsum—are irrelevant here, as their shares are insignificant with respect to the volume and value of the main ethanol product, and electricity production in Norway is based on hydropower.

The direct GHG emissions from all transport processes within the biochemical WTT system were found to contribute 17% to the total. When the upstream biomass transport distance was increased, as was also the case for the WCBCh system, this share increased about 10%. Compared with a roughly 3% contribution by the fossil reference WTT, the contribution of direct GHG emissions associated with transport processes in all four E85 systems highlights the significance that transport activity would play in contributing to total GWP impact generated throughout any future regional energy system based on woody biomass.

In general, impacts across all impact categories of the WCBCh system were higher than for the BCBCh system. In particular, we found that the WCBCh system generates about 39% more GWP impact than the BCBCh system. When we subtract the roughly 10% direct share attributed to the increased biomass transport distance, we deduce that the remaining 29% or so (of the 39.1% WTT GWP increase

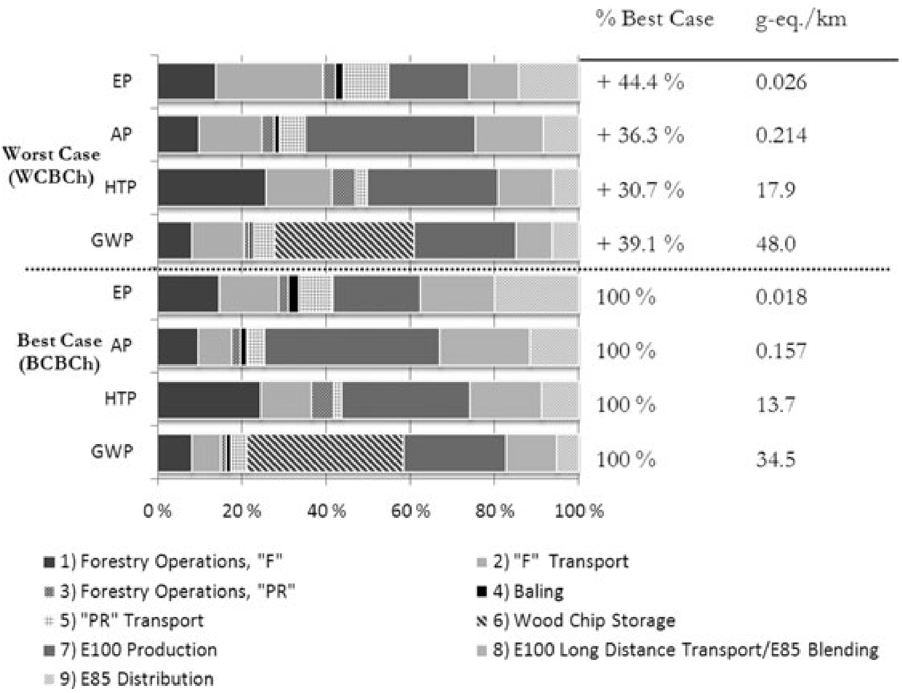

Figure 4 Well-to-tank (WTT) relative and absolute impacts, biochemical cases. Impact scores are scaled to the operation of a flex-fuel vehicle (FFV) over a distance of 1 km. Only processes contributing at least 1% to any impact category are presented. WCBCh = worst case biochemical; BCBCh = best case biochemical; EP = eutrophication potential; AP = acidification potential; HTP = human toxicity potential; GWP = global warming potential; F = surplus forest growth; PR = primary forestry residuals.

shown in figure 4) can be attributed to the lower ethanol conversion efficiency, which, in turn, induces greater total upstream activity. In other words, the lower conversion efficiency results in the need for greater quantities of feedstock inputs and thus the need for more upstream activity associated with biomass production (forestry operations, baling) and biomass transport.

WTW Impact Analysis

Turning our attention to total WTW impacts associated with the E85 systems, we find that environmental benefits mostly come in the way of GWP reductions. In particular, significant reductions in life cycle GHG emissions of 44% to 62% per kilometer driven relative to the fossil system can be observed, shown in figure 5. For all four WTW E85 systems, the majority of the GHG benefits were achieved from reductions in direct tailpipe CO_2 emissions during FFV operation due to the fact that carbon had previously been assimilated by the formerly living biomass through photosynthetic processes occurring during growth.

Referring again to figure 5, we find that the environmental comparative advantages and disadvantages of one biofuel over another stem mainly from fuel production processes, or the WTT system (black bars in figure 5). In the cases utilizing the biochemical conversion technology, impact contributions from the complete WTT system were substantial, relative to the cases utilizing the thermochemical pathway. For impact categories, such as acidification potential and eutrophication potential, the biochemical WTT systems' contributions led to negative WTW benefits relative to the fossil reference. Thus, increasing the total WTW life cycle environmental performance greatly depends on improving the performance of specific processes resting within the biofuel's production system.

Emissions stemming from the production and maintenance of the vehicle itself (TTW system) were found to contribute significantly to all

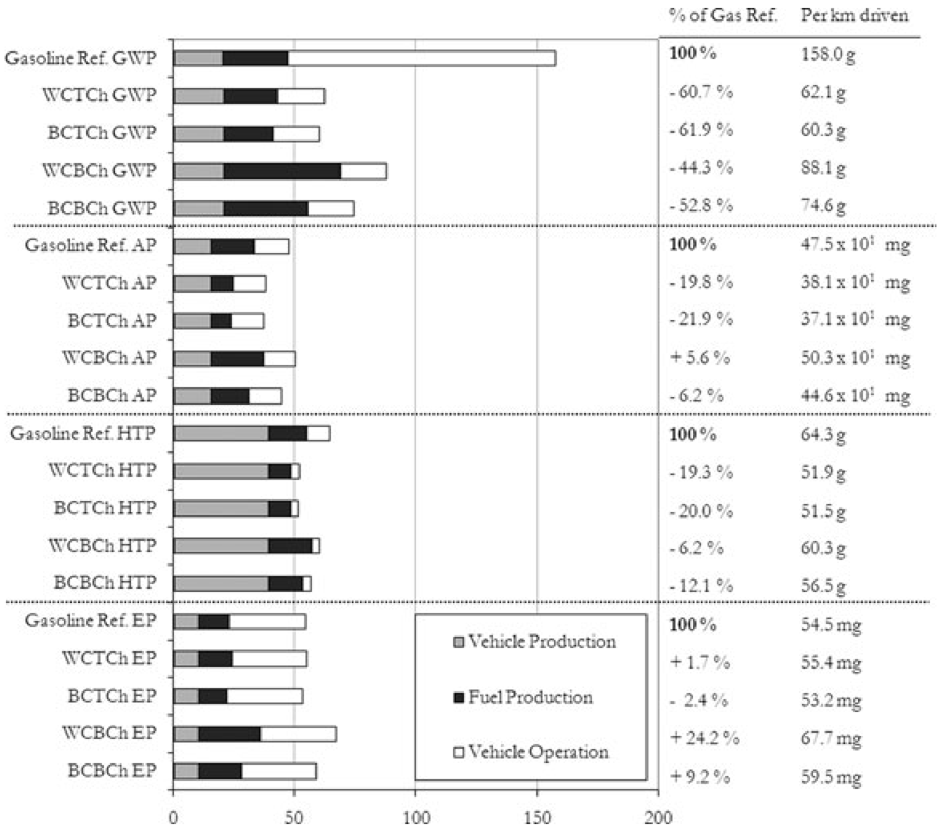

Figure 5 Well-to-wheel (WTW) absolute impacts compared to fossil fuel reference, all cases. Gas Ref. = gasoline reference; GWP = global warming potential; WCTCh = worst case thermochemical; BCTCh = best case thermochemical; WCBCh = worst case biochemical; BCBCh = best case biochemical; AP = acidification potential; HTP = human toxicity potential; EP = eutrophication potential.

impact categories. This is attributed to large quantities of indirect emissions generated in the background system associated with the production of the vehicle's various material components and maintenance infrastructure. In absolute terms, additional TTW impacts associated with the construction of the FFV chosen for assessment in this study are negligible compared to the fossil reference vehicle. We were surprised to find that carcinogenic emissions (HTP) generated during the vehicle production phase contributed significantly more than both the production of E85 and the use of the vehicle combined, on a WTW basis. Contribution analysis revealed that about 75% of the total HTP impact of the TTW system stemmed from production of the car's body component. Direct material inputs of steel and copper in body construction contributed roughly 38% and 56% to the total impact of this process, respectively, as their production is fairly energy-intensive, requiring large amounts of fossil fuel use upstream in their own manufacturing processes, which, in turn, generates atmospheric emissions of particulate matter and other toxic airborne carcinogens in high quantities.

Combined Analysis

If the 2005 biomass potential volume were utilized in ethanol production in processes demonstrating conversion efficiencies similar to those modeled in this study, a significant share of the region's gasoline demand could have been completely displaced (Statistics Norway 2008b), shown as the lefthand *y*-axis in figure 6, broken up by biomass feedstock type.

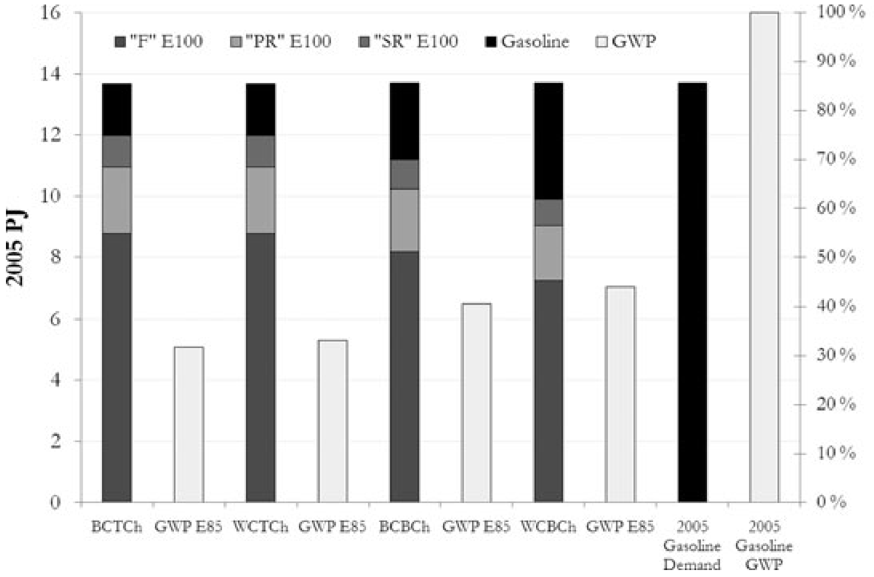

Figure 6 Ethanol production potential by feedstock type of the Middle Norway region shown together with regional gasoline consumption for 2005 (lefthand *y*-axis). The righthand *y*-axis shows the relative well-to-wheel (WTW) global warming potential (GWP) mitigation potentials of the E85 systems (excluding vehicle production) with maximum utilization of the regional resource base in 2005 to produce ethanol (E100). F = surplus forest growth; PR = primary forestry residuals; SR = secondary industry residuals; GWP = global warming potential; PJ = petajoules; BCTCh = best case thermochemical; WCTCh = worst case thermochemical; BCBCh = best case biochemical; WCBCh = worst case biochemical.

Production and use of gasoline in the region generates 92.5 g-CO_2-eq./MJ, which translates to regional life cycle gasoline-based GWP emissions of 1.27 Mt-CO_2-eq. Total use of the resource base in E85 production for displacing regional gasoline consumption in 2005 would have resulted in reductions from anywhere between 700,000 and 864,000 tonnes-CO_2-equivalents, depending on the system. This equates to about 55% to 68% of the region's total gasoline-based transport GWP emissions (see the righthand *y*-axis in figure 6), or about 6% to 8% of Norway's total road transport GHG emissions. Figure 6 illustrates that as the capacity to displace gasoline consumption with E85 wanes due to wood-resource constraints, so does the region's global warming mitigation potential.

Discussion

We set out to evaluate both the resource potential and the environmental performance of a regional transportation system based on E85 made from wood resources. We illustrated that Middle Norway has a growing pool of boreal forest resources that could be exploited for use in bioethanol production without competing with current uses of commercial roundwood. We showed that the region's woody biomass potential is large enough to produce bioethanol in quantities that would nearly displace the region's gasoline consumption on an energy basis. With respect to the E85 production system, we showed that upstream forestry activity and biomass transport played a significant role in the generation of environmental impact across all impact categories. LCA results were sensitive to the amount of these activities that occurred and were influenced by the downstream performance with which wood was converted into ethanol. On a WTW basis, our results showed that E85 transport reduced GHG emissions 44% to 62% relative to the gasoline reference system, depending on the case, with the thermochemical cases outperforming the biochemical in all impact categories. Because impacts varied little between the reference vehicle and the FFV, the potential to improve environmental performance of the complete system resided within the WTT systems. Furthermore, as the performance of the WTT system improved, the relative impact associated with the life of the vehicle became of greater significance, particularly for HTP impacts.

Limitations of our study stem from the exclusion of other important environmental issues, including the time span of forestry activity, the nutrient economy of the forests (including the various options of nutrient generation), recycling and fertilizer compensation, soil emissions, carbon cycle, albedo effects, and effects on biodiversity. Some of these are important issues that are difficult to address with LCA and should be researched before sound policy decisions can be made, particularly the effects on forest biodiversity and natural biogeochemical cycles, as Michelsen (2008) and Changsheng and colleagues (2005) have indicated. For the environmental impacts that were included, uncertainty rests primarily in data quality choices and assumptions. For example, our impact assessment method is based on average European conditions, and for impact categories such as acidification and eutrophication, for example, fate and transport of airborne pollutants contributing to these categories may vary by region, because the buffering conditions in specific regions may be different. Region-specific impact assessments for the non-GWP categories are warranted to obtain a more complete picture of the environmental implications of wood-based E85 production and use in Middle Norway.

Another source of data uncertainty in our study is our choice to include a process of wood chip storage that was found to contribute 33% to 39% to WTT GWP. Although this process contributed significantly to GWP, many variables and assumptions factor into the rates, types, and quantities of GHGs emitted from decomposition processes (Wihersaari 2005). To our knowledge, however, literature on this topic is limited. The choice to include this process in our WTT systems stems from the assumption that a commercial-scaled biorefinery would likely operate with a surplus of biomass feedstock and would require on-site storage to minimize risks in supply interruption that could adversely affect operations. It is important to note the large uncertainty enveloping the size of such piles, however, as well as the duration of storage that would be required and any dry material losses and resulting emissions that might be incurred or avoided. Other LCA studies (Kadam et al. 1999; Kemppainen and Shonnard 2005; Chandel et al. 2007; Edwards et al. 2007; Jungbluth et al. 2007) examining second-generation ethanol produced from wood make no mention of the inclusion of a separate wood chip storage process; nevertheless, we found the process important to include because it has implications regarding the global warming benefits of wood-based biofuels. Further studies are needed that examine in greater detail the interactions of the emission variables of the wood chip storage process and to explore how decomposition processes and subsequent emissions can be more accurately quantified, controlled, and minimized.

We conclude, on the basis of the results of this study, that environmental benefits, notably global warming benefits, can be realized when regional gasoline consumption is displaced with bioethanol blends, such as E85, made from regional forest resources. With the exclusion of impacts from vehicle production and depending on the production system, life cycle GHG reductions of 51% to 71% per kilometer of gasoline-based transport avoided can be realized with wood-based E85 use in the region.

To allow for fair comparison with results of other LCA studies of wood-based ethanols, we recalculated the GWP impact of our study and others and scaled it to E100 at plant gate. For the best case biochemical and thermochemical systems, GWP impacts of 21.7 g-CO_2-eq./MJ and 14.2 g-CO_2-eq./MJ E100, respectively, can be realized—results that fall within the range of values reported in the literature. Zah and colleagues (2007) report 18 g-CO_2-eq./MJ E100 (biochemical) at plant gate in Switzerland and 21 g-CO_2-eq./MJ E100 (biochemical) when woody biomass is imported. Kemppainen and Shonnard (2005) report a value of 9.3 g-CO_2-eq./MJ E100 (biochemical) for the process based on Upper Michigan forest residues. Jungbluth and colleagues (2007) report a value of 19.5 g-CO_2-eq./MJ E100 (biochemical). Wu and colleagues (2006b) report an 85% WTW reduction below the gasoline reference (14.6 g-CO_2-eq./MJ E100 at plant gate[5]) for ethanol made from forest residues, and Fleming and colleagues (2006) report an average WTW reduction of 86% across five studies for "lignocellulosic ethanol."

Although ethanol was the focus of this study, other wood-biofuel systems producing fuels such as Fischer-Tropsch diesel (FTD), methanol, or dimethyl ether (DME), with biomass conversion efficiencies similar to those of this study (Baitz et al. 2004; Delucchi 2006; Wu et al. 2006a; Edwards et al. 2007; Kalnes et al. 2007; Ragettli 2007; RENEW 2008), may yield similar results, as we showed that the conversion efficiency was a key variable in total system environmental performance. A benchmarking literature review shows that the WTW GWP impacts of the other alternative forest wood-biofuel pathways mentioned above offer WTW GHG savings similar to (FTD, methanol; Jungbluth 2008; Zah et al. 2007) and better than (DME; Edwards et al. 2007) the ethanol pathways considered in this study. Furthermore, the regional approach to combining a resource assessment with environmental systems analysis rooted in LCA can be an effective way of quantifying the eco-utility of the region's resource base. We find that a regional alternative transport system based on high-ethanol blended biofuels such as E85 can be an effective regional climate policy strategy *if* the policy emphasis specifically targets the transport sector. If a regional climate policy is simply to maximize global warming mitigation potential and is neither sector-specific nor focused on developing alternatives to liquid fossil fuels used in transport for reasons that extend beyond climate change, the eco-utility of the wood resource base could be more environmentally effective as a substitute for fossil fuel used in stationary heating or other fossil-intensive applications. If, however, sustainability policies specifically targeting land-based transport are made a priority in the region, use of the region's boreal forest resource base for the production of advanced biofuels can prove effective from both an environmental and energy security standpoint. Needed next, in addition to analyses of other advanced biofuel types, are more detailed analyses investigating infrastructure requirements and transport logistics in greater detail, along with technoeconomic analyses, socioeconomic analyses, and policy analyses to ensure that a bioethanol-fueled transport system in Middle Norway can be sustainable on all levels, not just the environmental level.

Notes

1. In 2005, there were no short-rotation forestry operations in the region. "Productive natural forests" exludes forests on protected areas.
2. Although it is not representative of the current average lifetime of light-duty vehicles in Norway, we include the lifetime of 150,000 km to be consistent with numerous other WTW LCA studies that adopt this value (Röder 2001; Schmidt et al. 2004; Chanaraon 2007; Schmidt 2007; Volkswagen AG 2007a, 2007b). This makes for easier benchmarking of results across studies.
3. We used the effective heating value (EHV) of Norway spruce (*Picea abies*) as a proxy for all biomass types with bark and needles, at 21.5 megajoules per kilogram dry matter (MJ/kg DM).
4. The term *biorefinery*, as defined by the American National Renewable Energy Laboratory (NREL), refers to a facility that integrates biomass conversion processes and equipment to produce fuels, power, and chemicals from biomass. In this study, we adopt a loose definition of the term to refer to a facility where only fuel and power are produced by one conversion platform.
5. This value is based on our own WTT calculations for the mixed biochemical—thermochemical biorefinery case in 2030.

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Supplementary Material

Additional Supplementary Material may be found in the online version of this article:

Supplement S1: This supplement contains a description of the resource assessment methodology used in the study, a description of the well-to-tank (WTT) system, and tables of foreground life cycle inventories.