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Alternative Fuels: An Evaluation of Corn Ethanol, Cellulosic Ethanol, and Gasoline

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Editors' Summary: Alternative fuels such as ethanol are taking center stage as the United States searches for environmentally friendly sources of energy that will reduce dependence on foreign oil. Both the Energy Policy Act of 2005 and President Bush's "Twenty in Ten" plan express a commitment to ethanol. In this Article, Jocelyn D'Ambrosio compares ethanol fuels with gasoline. She evaluates each fuel's ability to reduce greenhouse gas emissions, its net energy balance, and its potential effect on future innovation. She concludes that corn ethanol will provide a moderate reduction in emissions, but its production is not as efficient as ethanol from woody plants (cellulosics). She therefore recommends that policymakers encourage cellulosic production, while seeking flexible policies that will not thwart more effective future innovations in alternative sources of energy.

I. Introduction

The United States has become increasingly concerned with climate change in the past year. Articles flood the newspapers with stories of rising temperatures. Prominent reports, such as the United Nation's Intergovernmental Panel on Climate Change, conclude not only that human activity has contributed to rising levels of greenhouse gases (GHGs), but also that global warming is unequivocal.[1] As a result of this all-encompassing concern, regulators are seeking greener alternatives to stall the onset of climate change and reduce oil dependence. One of the solutions favored by both the president and the U.S. Congress is to increase the nation's use of ethanol fuels. The Energy Policy Act of 2005 requires 7.5 billion gallons of ethanol be used as a transportation fuel by 2012.[2] President George W. Bush's "Twenty in Ten" plan, announced in his State of the Union address, seeks to reduce gasoline consumption by 20% in 2017, a goal he hopes to attain with the aid of alternative fuels such as ethanol.[3] More recently, the president issued an executive order directing regulatory agencies whose actions might affect GHG emissions to work together to ensure that the Administration effectively regulates and reduces these emissions.[4] The same day he issued this order, the president publicly announced his plan to increase cooperation and information-sharing to establish higher fuel efficiency standards for new cars and increase the use of alternative fuels.[5] The proposed Cellulosic Ethanol Development and Implementation Act of 2007 also encourages the use of ethanol as a means of reducing oil dependence.[6]

While concerns about global warming, coupled with rising oil prices and unease about foreign oil dependence, has ethanol at the tip of many tongues, its status as a potential savior is not new. Ethanol and other biofuels have been proposed as petroleum alternatives since the inception of Henry Ford's Model T.[7] Yet ethanol fuels have faced many impedi-

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[1] INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE, WORKING GROUP 1, CLIMATE CHANGE 2007: THE PHYSICAL SCIENCE BASIS 2 (2007), *available at* http://www.ipcc.ch/SPM2feb07.pdf (last visited Mar. 13, 2007).

[2] Energy Policy Act of 2005, §1501, 42 U.S.C. §7545(o)(2)(B)(i) (amending the Clean Air Act to establish a renewable fuel program consisting of cellulosic biomass and waste-derived ethanol, and biodiesel).

[3] Twenty in Ten: Strengthening America's Energy Security, http://www.whitehouse.gov/stateoftheunion/2007/initiatives/energy.html [hereinafter Twenty in Ten]. The president also announced his intent to increase alternative fuel usage to 35 billion gallons by 2017 in his State of the Union address. *See* President George W. Bush, State of the Union Address (Jan. 23, 2007) (transcript available at http://www.whitehouse.gov/news/releases/2007/01/20070123-2.html) [hereinafter State of the Union] (stating his goal of reducing gasoline consumption by 20% by 2017, a goal that requires a move toward alternative fuels such as ethanol).

[4] Exec. Order No. 13432, 72 Fed. Reg. 27717 (May 14, 2007).

[5] Jim Rutenberg & Edmund L. Andrews, *Bush Calls for Work Toward Higher Car Fuel Efficiency*, N.Y. TIMES, May 15, 2007, at A17. For a transcript of President Bush's announcement, see President Bush Discusses CAFE and Alternative Fuel Standards, http://www.whitehouse.gov/news/releases/2007/05/20070514-4.html.

[6] S. 167, 110th Cong. (2007), H.R. 395, 110th Cong. (2007).

[7] *See* DOUGLAS BRINKLEY, WHEELS FOR THE WORLD: HENRY FORD, HIS COMPANY, AND A CENTURY OF PROGRESS 1903-2003, at

ments, including an excise tax on alcohol designed to help finance the Civil War,[8] Prohibition in 1919,[9] and Standard Trust's anti-alcohol fuel campaign in the 1930s.[10] While the fuels did enjoy brief successes, for instance during World War I when there was an increased need for fuels[11] and during the 1950s when the federal government investigated potential solutions to the problem of grain surpluses,[12] ethanol has never achieved widespread acceptance. The nation has remained dependent on petroleum notwithstanding conservationist efforts by those like Ford, who feared harmful gasoline emissions, continual farm lobby efforts to find a market for their surpluses, and political fears about foreign oil dependence sparked mainly by the Organization of Petroleum Exporting Countries (OPEC) price increase and the Arab OPEC oil embargo in 1973.[13] Although these past efforts have failed, it was partly because conservation, farming, and political instability alone were not enough. Conservationist concerns were met with disbelief, while the national oil crisis in the 1970s appeared to be over once prices dropped. These concerns were met with visible, though not permanent, solutions ranging from farmer subsidies to implementing Corporate Average Fuel Economy (CAFE) standards to reduce fuel consumption. The nation thus was able to believe that its problems were solved.[14]

Today, as America faces a new set of challenges on the energy front, ethanol is back. Politicians, scientists, lay people, and farmers are simultaneously searching for alternative transportation fuels. With all of these interests converging, the case for ethanol is strong. And because ethanol distilleries currently produce and supply fuel to a number of service stations throughout the Midwest, ethanol is a natural choice for an alternative—a choice that has found its way into both the Energy Policy Act of 2005 and the president's "Twenty in Ten" plan.

Yet before America fully transitions to ethanol, there are questions that must be answered. Is ethanol's energy balance as a fuel favorable? Can ethanol fuels reduce GHG emissions below the status quo? Will implementing an ethanol policy hinder implementing other, possibly more energy-efficient, alternatives? In this Article, I address these questions by comparing ethanol fuels, both from current corn-based production and cellulosic production, with gasoline. Before adopting an alternative, policymakers must consider the costs as well as each fuel's ability to reduce GHGs, its impact on future innovation, and its political feasibility. Only by making such an assessment can decisionmakers be confident that the nation should move to ethanol as a widespread transportation fuel.

Based on the analysis presented here, I conclude that ethanol fuels should be considered only a step toward solving the energy crisis, not the definitive solution. Because cellulosic ethanol not only provides greater emissions reductions than corn-based ethanol, but also will have a more positive net energy balance (NEB) as more efficient conversion enzymes are discovered, cellulosics should be favored. Yet policymakers should be careful not to be swept away in the prevailing winds that favor ethanol. Ethanol-based fuels are only marginally better than gasoline. And because of the agricultural and oil interests that a move to ethanol blended fuels could cement, policymakers should be wary of locking the United States into ethanol. When even more efficient alternative fuels do eventually emerge, the nation will need to be prepared to implement further changes in transportation fuel markets. Policymakers should enact flexible regulations, rather than merely prescribing the use or production of ethanol fuels. Hopefully, adopting a flexible approach will preclude a path dependence that could prevent the public from mobilizing to support a more efficient technology in the future.

II. The Alternatives and the Status Quo: Players in a Potential Shift From Petroleum Fuels

A. Current Corn-Based Ethanol

In the United States, ethanol (C_2H_5OH) production typically begins with corn. The corn is fermented via a three-step process to the potential fuel. In the first step, the carbohydrates are formed into fermentable sugars. Once the carbohydrates are converted to sugars, the sugars are then fermented into a solution, or "beer," that contains diluted ethanol. Finally, ethanol is recovered from the beer through a distillation process.[15] Converting the starches to sugars is an important step, especially when the starting material does not naturally contain glucose. When ethanol is fermented from corn, the carbohydrates have to be cracked by hydrolysis to a fermentable sugar.[16]

The overall synthesis of ethanol takes place using one of two grain processing technologies, either dry or wet grain milling.[17] The primary difference between the two processes is whether the components are separated before

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219-20 (2003) (recounting that throughout World War I, Ford sought to find and use alternative fuels, such as denatured alcohol, for use in his Model Ts and Fordson tractors. Ford worried about the exhaust from gasoline, and even took trips to Cuba in 1917 to investigate purchasing a sugar cane plantation and constructing a distillery to manufacture ethanol because manufacturing ethanol in the United States was illegal at the time).

[8] *See* Hal Bernton et al., The Forbidden Fuel: Power Alcohol in the Twentieth Century 8 (1982) (describing how the growing use of ethanol for power, particularly for use as a lamp oil, "went from boom to bust" when Congress imposed a sales tax on alcohol).

[9] *See id.* at 12 ("The fact that ethanol was the active ingredient in any 'intoxicating liquors' threw a large shadow over any merits it may have had as a fuel.").

[10] *See id.* at 17-19 (detailing the oil industry's backlash that lasted throughout the 1930s. The oil industry circulated pamphlets, aired radio commercials, and otherwise spread the message that alcohol fuels were expensive and illogical remedies proposed, ironically enough, by self-interested parties.).

[11] *See id.* at 11 (expressing that the large demand for fuels needed to run military equipment or produce gunpowder meant that fuels, regardless of how they were produced, were needed to support the war effort).

[12] *See id.* at 34 (stating that in 1958, President Dwight D. Eisenhower commissioned a group of scientists to find new uses for farm crops, yet the commission found that the current economic conditions did not warrant a move to increased use of industrial alcohol for motor fuels).

[13] Bernton et al., *supra* note 8, at 35; Peter Tertzakian, A Thousand Barrels a Second: The Coming Oil Break Point and the Challenges Facing an Energy-Dependent World 74 (2006).

[14] Tertzakian, *supra* note 13, at 89-90.

[15] Michelle Heath, Alternative Transportation Fuels: Natural Gas, Propane, Methanol, and Ethanol Compared With Gasoline and Diesel 169 (Canadian Research Inst. 1991).

[16] International Energy Agency, Automotive Fuels for the Future: The Search for Alternatives 26 (1999).

[17] Heath, *supra* note 15, at 170.

mashing.[18] For example, in dry milling the components are not separated prior to the mashing phase. Each process produces ethanol in addition to valuable byproducts. Dry grain milling yields a protein animal feed, distiller's dried grains with solubles (DDGS).[19] Wet milling produces corn gluten feed and meal—byproducts that tend to have a higher market value than DDGS—yet because these plants require separation of all the components before mashing, the wet milling plants tend to be more complex, and therefore, more capital intensive.[20] Both dry and wet milling produce carbon dioxide (CO_2), which can be harvested and used in beverages, dry ice production, or enhanced oil recovery.[21] Knowing the value of the byproducts is important because the byproducts factor into energy calculations used to determine if ethanol production has a positive NEB.

Corn-based ethanol fuels are currently used throughout the Midwest, where service stations offer gasoline as well as E85, a gasoline-ethanol blend that contains 85% ethanol and 15% gasoline. Many cars produced today are flexible fuel vehicles (FFVs) capable of running on either E85 or gasoline[22]; therefore, a transition to ethanol fuels could be relatively straightforward. Because the transition to corn-based ethanol is already underway, it is important to understand the implications in terms of effect on GHGs or ability to reduce petroleum dependence, both of which are reasons for a move toward current corn ethanol.

B. Cellulosic Ethanol

While ethanol is most commonly produced from corn, ethanol can also be made from fermenting other forms of biomass. Cellulosic ethanol currently makes up a small percentage of ethanol production, but many suggest the United States should concentrate on refining cellulosic production and expanding its use. Cellulosics, including switchgrass (*Panicum virgatum*), mixtures of prairie grasses and forbs, and woody plants are increasingly popular starting material for ethanol production.[23] Because cellulosics tend to be woodier and have stronger cell walls than corn, the first step of ethanol fermentation, converting the carbohydrates into fermentable sugars, requires different enzymes. Acid hydrolysis or enzymatic hydrolysis is often used to break the complex carbohydrates into simple fermentable sugar. New technologies have produced efficient enzymes, some of which are derived from genetically modified bacteria that are 10 times cheaper than products used two years earlier.[24] These enzymes digest the cellulose into sugar (glucose) for fermenting and can double yields while reducing energy inputs.[25]

In addition to requiring different enzymes or catalysts to convert the cellulosic crops to a fermentable product, these woods and grasses, which are not mass produced for use as foodstuffs, require specific cultivation and harvesting methods. For wood to be a viable raw material to produce fuel, the woods must be fast growing and easily harvested. Willow, poplar, and eucalyptus each grow quickly and can be harvested every few years in a process known as short rotation coppicing (SRC).[26] In this method, the plants are trimmed or coppiced after a year of growth so that they will form multiple shoots. The saplings are then left to grow and are harvested two to four years after they have been trimmed. When harvesting, their stalks are cut close to the ground level so that they can continue to grow and the cycle can be repeated. The current yield of wooden saplings is about 10-15 dry tones per hectare per year.[27] Once harvested, these plants can be distilled into ethanol via the same three-step process described above: sugar formation; fermentation; and distillation.

Perennial grasses such as miscanthus, elephant grass, switchgrass, and blue stem are also important ethanol feedstocks. Miscanthus is a bamboo-like cane that multiplies rapidly with very little pesticide or fertilizer input because of its rapid growth and resistance to weeds or other pests. Because miscanthus grows rapidly and can be harvested once a year yielding approximately 15-30 dry tones per hectare—an amount higher than the SRC schemes—miscanthus has the potential to be a very important cellulosic feedstock. An additional benefit beyond their rapid growth is that the roots of miscanthus and other perennial grasses tend to prevent soil erosion.[28]

C. Petroleum Fuels

Petroleum is the current transportation fuel of choice in the United States. Because this Article will compare ethanol—both corn-based and cellulosic—to petroleum fuels, it is important to understand how current fuels are produced.

Petrol is largely made up of saturated hydrocarbons, varying in structure from pentane (C_5H_{12}) to octane (C_8H_{18}).[29] These structural differences, which affect density, chemical composition, and boiling point, vary depending on the area in which the petroleum is discovered. North Sea oil tends to be high in alkanes, or hydrocarbon chains, whereas oil from the Persian Gulf is rich in aromatics, or semi-saturated hydrocarbons rings. Each oil source requires a different refining process to produce a uniform fuel that has decreased volatility, high octane rating to prevent knocking, and good fuel economy.[30] Volatility has a direct effect on vehicle performance. Greater volatility is needed in cold weather, while in hot climates fuels often contain less C_5H_{12} to decrease volatility and prevent vapor locks.[31] Octane rating is important because the higher octane the fuel, the less the engine knocks, a phenomenon that

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[18] *Id.*

[19] *Id.*

[20] *Id.* at 170-73.

[21] *Id.* at 170.

[22] *Id.* at 173.

[23] Jason Hill et al., *Environmental, Economic, and Energetic Costs and Benefits of Biodiesel and Ethanol Biofuels*, 103 PROC. NAT'L ACAD. SCI., July 25, 2006, at 11208.

[24] AMORY B. LOVINS ET AL., WINNING THE OIL ENDGAME: INNOVATION FOR PROFITS, JOBS, AND SECURITY 104 (Rocky Mountain Inst. 2006).

[25] *Id.*

[26] RONALD M. DELL & DAVID A.J. RAND, CLEAN ENERGY 98 (J.H. Clark ed., 2004).

[27] *Id.* at 98-99.

[28] *Id.* at 100.

[29] *Id.* at 39-40.

[30] H.L. MacLean & L.B. Lave, *Evaluating Automobile Fuel/Propulsion System Technologies*, 29 PROGRESS ENERGY & COMBUSTION SCI. 1, 25 (2003).

[31] DELL & RAND, *supra* note 26, at 40.

occurs when the last part of the fuel-air charge self-ignites, causing a vibration in the combustion chamber.[32] Octane rating is inversely related to hydrocarbon chain length, such that increasing chain length decreases the octane number. The octane rating also decreases as the number of aromatic compounds in the structure decreases.[33] The fuel octane number is defined relative to pure iso-octane (iso-C_8H_{18}), which has an octane rating of 100. Refining is therefore an energy-intensive process that produces drivable fuels.

III. Evaluating Each Fuel Source

The previous section described two variants of ethanol—ethanol derived from corn and cellulosics—and petroleum gasoline. As mentioned, ethanol is gaining increased support, not only from the public, but also from stakeholders such as farmers, politicians, and conservationists. Before ethanol is widely implemented, it should be evaluated to ensure that it can solve the problems it is proposed to solve, namely reducing GHG emissions and petroleum dependence. In making this assessment, each method of producing ethanol will be compared to gasoline on a number of metrics, including NEB, petroleum dependence, effect on GHG emissions, other environmental impacts, cost, safety, and impact on future innovation. If ethanol is a viable alternative, it should have a net energy gain, provide environmental benefits, and be economically competitive. The following sections will attempt to evaluate each alternative against these criteria.

A. NEB

One of the primary questions in determining if ethanol is a viable alternative is whether the life-cycle energy needs (often called the well-to-wheels assessment) of ethanol production has a positive NEB. A fuel with a positive NEB requires less nonrenewable energy in production than the equivalent energy content the fuel itself provides.[34] Thus, an analysis of corn-to-ethanol or cellulose-to-ethanol conversion needs to take into account the work done and energy consumed in planting, growing, fertilizing, harvesting, processing, and fermenting the ethanol feedstock. A recent report in *Science*, conducted by Alexander Farrell and some of his colleagues (Farrell et al.), compared six published studies that analyzed corn-based ethanol fuels to determine if ethanol could help achieve environmental goals.[35] Because each of the studies the report analyzed used its own set of assumptions, Farrell et al. developed the Energy and Resource Group Biofuel Analysis Meta Model (EBAMM) to normalize the data and facilitate comparisons. The Farrell et al. analysis made an interesting finding: the two studies that found ethanol was not energy efficient incorrectly did not include ethanol coproducts like DDGS, animal feed, corn gluten, corn meal, and corn oil in allocating their energy input. Because these two studies assumed all energy input went toward the fuel, and not the fuel plus its useful coproducts, their estimates of NEB were incorrect. Producing these coproducts through ethanol fermentation can reduce the need for using other petroleum-dependent pathways.[36] The four studies that accounted for this displacement effect (the coproducts replacing alternative, petroleum-intensive production methods of creating the same products) determined that "ethanol and coproducts manufactured from corn yielded a positive net energy of about 4 [megajoules per liter (MJ)/l] to 9MJ/l."[37] Another study, conducted by Lee Lynd, estimated that the ratios of energy output relative to energy input for cellulosic ethanol range from 4.4 to 10.4.[38] As a means of comparison, Lynd found that the energy output relative to energy input ratio for gasoline production is about 5.[39]

Jason Hill and a few of his colleagues (Hill et al.), in another study, also estimated that the NEB for corn grain ethanol is small. Hill et al. found that corn ethanol provides approximately 25% more energy than is required for its production. Hill et al. also attributed the positive NEB to the energy credit of its coproduct, namely DDGS, rather than to the energy content of ethanol alone. The study found that the estimate of corn grain ethanol's NEB is low because of the high energy input required to produce corn (through the use of fertilizers) and to convert it into ethanol.[40] Therefore, any means of increasing the energy efficiency of corn processing would have a positive effect on the NEB. While the Farrell et al. report did not specifically state the NEB of cellulosic ethanol, it does indicate that cellulosic ethanol production requires low amounts of petroleum and natural gas, and even estimates that the coal inputs might be negative from electricity sales that might displace coal.[41] It also shows that the gasoline requires 1.1 MJ petroleum/MJ of

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[32] *Id.*

[33] MacLean & Lave, *supra* note 30, at 25.

[34] Alexander E. Farrell et al., *Ethanol Can Contribute to Energy and Environmental Goals*, SCIENCE, Jan. 27, 2006, at 506.

[35] *See id.* (comparing six studies of ethanol, including Tad W. Patzek, *Thermodynamics of the Corn-Ethanol Biofuel Cycle*, 23 CRITICAL REVS. PLANT SCI. 519 (2004); David Pimentel & Tad W. Patzek, *Ethanol Production Using Corn, Switchgrass, and Wood; Biodiesel Production Using Soybean and Sunflower*, NAT. RESOURCES RES., Mar. 2005, at 65; Marcelo E. Dias de Oliveira et al., *Ethanol as Fuel: Energy, Carbon Dioxide Balances, and Ecological Footprint*, 55 BIOSCIENCE 593 (2005); H. SHAPOURI & A. MCALOON, THE 2001 NET ENERGY BALANCE OF CORN ETHANOL (U.S. Department of Agriculture 2004), *available at* www.usda.gov/oce/oepnu; M. GRABOSKI, POSSIBLE ENERGY USE IN THE MANUFACTURE OF CORN ETHANOL (National Corn Growers Ass'n 2002), *available at* www.ncga.com/ethanol.main; M. WANG, DEVELOPMENT AND USE OF GREET 1.6 FUEL-CYCLE MODEL FOR TRANSPORTATION FUELS AND VEHICLE TECHNOLOGIES (2004), *available at* www.transportation.anl.gov/pdfs/TA/153.pdf).

[36] Farrell et al., *supra* note 34, at 506.

[37] *Id.*

[38] Lee R. Lynd, *Overview and Evaluation of Fuel Ethanol From Cellulosic Biomass: Technology, Economics, the Environment, and Policy*, 21 ANN. REV. ENERGY & ENVT. 403, 440 (1996).

[39] *Id.* (citing a personal conversation with M.A. DeLuchi). *See also* M.A. DeLuchi, 2 EMISSIONS OF GREENHOUSE GASES FROM THE USE OF TRANSPORTATION FUELS AND ELECTRICITY H-19 (Argonne National Lab, Center for Transportation Research 1993) (finding that the the amount of energy required in refining a barrel of gasoline is about 12.8% of the energy in the barrel, which he notes results in an energy requirement of 19.5% for gasoline. These estimates would result in energy output to energy input ratios of about 7 to about 4, which are consistent with Lynd's estimate. Note this energy output to input ratio accounts for energy used in producing the fuel and the maximum possible energy content of the produced fuel itself, which is a preconsumption maximal energy content.).

[40] Hill et al., *supra* note 23, at 11206.

[41] Farrell et al., *supra* note 34, at 507, fig. 2. *See also* Lynd, *supra* note 38, at 440 (stating that "electricity is expected to be a significant co-product of ethanol manufacture from woody materials" because it is thought that biomass gasification/combined-cycle gas coproduction (BGCCGT) will produce electricity along with ethanol).

fuel, .03 MJ natural gas/MJ of fuel, and .05 MJ coal/MJ of fuel in production.[42]

Closely related to the issue of NEB is the issue of petroleum dependence. Because a positive NEB indicates that less energy, which today is primarily petroleum and other nonrenewable energy, is needed to produce an equivalent amount of energy, fuels with a high NEB are likely to help reduce petroleum dependence. The Farrell et al. report estimated that corn ethanol reduced petroleum use by 95% on an energetic basis.[43] In addition to modeling and repeating existing studies, the Farrell et al. report also used the data from the existing studies to analyze three possible ethanol scenarios: *Ethanol Today*, which assumes conditions used in current corn ethanol production; *CO_2 Intensive*, which estimates levels based on plans to ship Nebraska corn to an ethanol plant in North Dakota, thereby releasing extra CO_2 in petroleum combustion; and *Cellulosic*, which assumes ethanol will be fermented from cellulosics such as switchgrass.[44] Farrell et al. found that producing one MJ of ethanol requires less petroleum than producing one MJ of gasoline for all three cases.[45] When comparing the *Ethanol Today* case to that of *Cellulosic*, Farrell et al. found that *Ethanol Today* is slightly preferred over *Cellulosic*, requiring a petroleum input ratio (MJ input compared to MJ fuel produced) of .06 as opposed to .08.[46] Petroleum input ratio is closely related to the NEB, but not exactly the same—NEB takes into account *all sources* of nonrenewable energy needed to produce the fuel including coal and natural gas, not only petroleum. Because of the relationship of petroleum dependence to NEB, the fact that corn ethanol has less dependence on petroleum than cellulosic ethanol does not necessarily mean that corn ethanol is preferable to cellulosic ethanol. For example, the Farrell et al. report indicated that cellulosic ethanol production required less natural gas, coal, and undefined "other" energy, which represents nuclear and hydrological electricity, in production than both gasoline and *Ethanol Today* (corn ethanol).[47]

Although one oft-cited concern about using ethanol fuels is that they purportedly require more energy in production than they provide as a fuel, the same might be true of petroleum. Just as ethanol fuels require energy at the growth, harvest, and fermentation stages, petroleum fuels also require energy inputs. Each stage of petroleum production, from mining the oil to refining it into a useable fuel, requires energy. Before ethanol is dismissed because of its petroleum-intensive production, we should analyze the petroleum intensity of gasoline production as well. The Farrell et al. report estimates that 1.1 MJ petroleum is required for every MJ of gasoline produced. This number is higher than both the .08 ratio for cellulosic ethanol and the .06 ratio for ethanol today (corn ethanol).[48]

B. GHG Emissions

Automotive exhaust from burning petroleum gasoline consists primarily of CO_2 and water. Automotive exhaust also contains unburnt hydrocarbons, partially combusted products like carbon monoxide (CO), aldehydes, and nitrogen oxides (NO_x). These combustion byproducts readily undergo photochemical reactions (reactions that occur in the presence of light) to produce ozone (O_3) and other harmful products such as peroxyacetyl nitrate (PAN).[49] Additional emissions of volatile organic compounds (VOCs) can result when refueling because of the potential for fuel evaporation. While these evaporative emissions can be reduced by using canisters containing activated carbon that absorbs VOCs from the fuel tank when the vehicle is not running,[50] these methods are imperfect, and evaporative emissions are a primary source of VOCs.[51]

Evaporative emissions are directly related to fuel vapor pressure.[52] Because neat ethanol (100% ethanol) has a lower vapor pressure than gasoline, high-level ethanol blends such as E85 also have lower vapor pressures than gasoline.[53] Ethanol blended fuels are likely to cause fewer environmental problems as a result of evaporative emissions. Furthermore, scientists such as Lynd have predicted that ethanol's lower flame temperature will result in lower NO_x emissions.[54] Because, as mentioned above, O_3 and PAN are not emitted, but rather form as a result of reactions between evaporative and exhaust emissions such as NO_x, VOCs, and CO, reducing NO_x emissions could have a positive impact on reducing O_3 and the other harmful side products of fuel emissions. Additionally, the presence of an oxygen atom in ethanol aids in complete combustion, which in turn reduces the CO and VOCs emitted.[55] Although ethanol fuels and ethanol fuel blends are expected to increase emissions of acetaldehydes, they are expected to reduce formaldehyde, benzene, and 1,3-butadiene emissions that are common to gasoline exhaust.[56] Ethanol fuels are generally expected to decrease toxic air pollutants.[57]

The Hill et al. study found that the production and use of corn grain ethanol releases 88% of the net GHG emissions of production and combustion of an energetically equivalent amount of gasoline.[58] This is described as a measure of net GHG emissions during production and combustion of ethanol compared to net GHG emissions of gasoline, relative to the energy released during combustion, or the GHG per NEB.[59] While the overall percentage reduction is not overly high, it is directly related to the low NEB of corn grain ethanol. As discussed above, producing and fermenting corn to ethanol requires fossil fuel energy input per unit energy output. Because of this energy input, which results in

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[42] Farrell et al., *supra* note 34, at 507, fig. 2.

[43] *Id.* at 506.

[44] *See id.* at 507 (describing its methodology in comparing published data to the three test cases, *Ethanol Today*, which uses typical values from current ethanol production from corn, *CO_2 Intensive* which is based on the idea of shipping corn from Nebraska to an ethanol plan in North Dakota, and *Cellulosic*, which makes assumptions for producing ethanol from cellulosic material, such as switchgrass).

[45] *Id.*

[46] *Id.*

[47] *Id.*

[48] *Id.*

[49] Dell & Rand, *supra* note 26, at 40.

[50] *Id.*

[51] International Energy Agency, Cars and Climate Change 58 (1993).

[52] Lynd, *supra* note 38, at 443.

[53] *Id.*

[54] *Id.*

[55] Cars and Climate Change, *supra* note 51, at 87.

[56] Lynd, *supra* note 38, at 444.

[57] *Id.*

[58] Hill et al., *supra* note 23, at 11207.

[59] *Id.* at 11208.

GHG emissions, the reduction in GHGs for the life cycle of corn ethanol is better than gasoline, but only marginally.[60]

The Farrell et al. report compared ethanol production to gasoline to determine the effect on GHG emissions. It found that the impact of a switch from gasoline to corn ethanol has "an ambiguous effect on GHG emissions."[61] The best estimate the report found was that corn ethanol reduced GHG by about 18%, which is close to the 12% reduction reported in the Hill et al. study above.[62] Modeling based on a corn versus cellulose metric, Farrell et al. found that cellulosic production fared much better than Ethanol Today when analyzing the GHG output associated with production and use.[63] Cellulosic production released about 11 kilograms (kg) of CO_2 equivalent per MJ of fuel produced compared to corn ethanol's 81-83 kg CO_2 equivalent per MJ fuel produced. These numbers should be compared to gasoline, which emits 94 kg CO_2 equivalents per MJ fuel produced. Because deriving ethanol from cellulosics is a relatively new development, cellulosic production has the potential to improve in efficiency and reduce GHG emissions even further.

However, if CO_2 from fossil fuel combustion was the only GHG that ethanol fuels were intended to reduce, a biofuel with NEB greater than 1 (requiring less energy in production than the corresponding energy output) should reduce GHG emissions because the CO_2 released upon combustion of ethanol fuels is mitigated by the CO_2 the plant feedstocks remove from the atmosphere.[64] Furthermore, the amount of CO_2 released upon combustion combined with the amount released in the ethanol production phase tends to be less than the amount of CO_2 that the plants will require for photosynthesis.[65] Thus the net amount of CO_2 released has the potential to be negative. Noting this effect, some suggest that "properly grown feedstocks can even reverse CO_2 emissions by taking carbon out of the air and sequestering it in enriched topsoil whose improved tilth can boost agronomic yields."[66] Petroleum production and combustion, on the other hand, do not have the inherent ability to reduce CO_2.

But CO_2 is not the only GHG of concern. Ethanol made from plant feedstocks that require nitrogen fertilization can result in releases of nitrous oxide (N_2O). Incorporation of nitrogen into the soil can result in microbially mediated production and release of N_2O, a potent GHG.[67] Because growing corn requires larger amounts of fertilizer than growing cellulosic feedstocks like miscanthus, this effect will be felt to a greater extent with corn ethanol.

C. Other Environmental Effects

While ethanol fuels reduce GHG emissions, with cellulosic production providing the greatest decreases, other potential environmental effects must also be considered. As with any agricultural production, corn manufacture uses pesticides and fertilizers, especially nitrogen and phosphorus.[68] These chemicals are not confined to the land on which the crops are grown; runoff from the farms moves the chemicals to other habitats and aquifers, resulting in loss of biodiversity or contamination of drinking water.[69] Using perennial grasses like miscanthus reduces the negative impact of fertilizer or pesticides most commonly associated with corn-based ethanol. Miscanthus grows quickly, is environmentally benign, and requires little to no pesticide or fertilizer because it is highly resistant to weeds and other pests.[70]

Despite their potential to add to the problem of runoff, using biofuels as a vehicle for better farm, range, and forest practices can also help achieve other goals such as reduced soil erosion and improved water quality.[71] Perennial grasses, like many cellulosics, offer environmental advantages because their extensive systems of roots, which can extend up to 10 feet, hold erodible soil.[72]

One possible means of reducing negative environmental effects, both in terms of GHG emissions and pollution associated with fertilizers, is to increase the efficiency of the refinery itself. E3, an ethanol manufacturer in Mead, Nebraska, is an example of an efficient plant. The E3 biorefinery's innovative closed-loop system enables it to produce 25 million gallons of ethanol per year with little impact on the environment.[73] The loop works in the following way. Corn is grown on fields adjacent to the refinery. This corn is fermented to ethanol, while its kernels, which are not used in fermentation, are given to cattle for feed. The cattle themselves provide another source of energy. Methane produced from the manure is used to power the plant, and the leftover waste is used as fertilizer. Using the waste, as opposed to traditional fertilizers, prevents nitrogen and phosphate runoff.[74] This loop not only increases efficiency and the NEB, it also decreases GHG emissions from petroleum inputs in manufacturing, runoff, and the N_2O from fertilizer. While not all biorefineries are this efficient, E3's example demonstrates that technological improvements not only can increase efficiency but also can reduce the potentially adverse environmental effects of most biorefineries.

D. Cost

In 2005, ethanol net production cost was \$0.46 per energy equivalent liter (EEL) of gasoline, while wholesale gasoline prices averaged \$0.44 per liter.[75] Corn-based ethanol production tends to be more costly than cellulosic ethanol because it requires more total energy input from fertilizer and in harvesting efforts. Both cellulosic and corn-based ethanol benefit from ethanol subsidies of \$0.29 per EEL of gasoline. The subsidies are designed to increase ethanol's cost com-

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[60] *Id.* at 11207.

[61] Farrell et al., *supra* note 34, at 506.

[62] *Id.* The erratum, posted June 23, 2006, refined the estimate that Ethanol Today yields a 13% reduction in GHGs cited on page 506, finding that the net GHGs emitted from corn ethanol is 18% below conventional gasoline.

[63] *Id.* at 507

[64] Hill et al., *supra* note 23, at 11207.

[65] *Id.*

[66] LOVINS ET AL., *supra* note 24, at 108.

[67] Hill et al., *supra* note 23, at 11207.

[68] *Id.*

[69] *Id.*

[70] DELL & RAND, *supra* note 26, at 100.

[71] LOVINS ET AL., *supra* note 24, at 108.

[72] DELL & RAND, *supra* note 26, at 100. *See also* LOVINS ET AL., *supra* note 24, at 107 (stating that perennials can have 10-foot-deep roots that curb soil erosion).

[73] Vinod Khosla, *My Big Biofuels Bet*, WIRED, October 2006, at 139.

[74] *Id.* at 140.

[75] Hill et al., *supra* note 23, at 11208.

petitiveness with gasoline.[76] Corn ethanol also benefits from federal crop subsidies that lower corn prices, and thereby lower the cost of obtaining the corn to produce the fuel.[77] With increased demand, these subsidies might disappear, increasing the market price of corn and potentially the price of ethanol to consumers.

In 2005, 14.3% of the U.S. corn harvest was processed to produce 1.48 x 1,010 liters of ethanol, the energetic equivalent of 1.72% of U.S. gasoline usage.[78] The Hill et al. study estimated that devoting all 2005 U.S. corn production to ethanol would have offset only 12% of U.S. gasoline demand. Reaching these maximal rates of biofuel supply from corn is unlikely because these crops are major contributors to human food supplies both because corn is used in livestock feed and because many corn products, like high fructose corn syrup, are directly consumed.[79] The increasing global demand for food, which is expected to double within the next 50 years,[80] will only reduce corn ethanol's ability to be the only substitute for gasoline. Ethanol feedstocks that do not compete with foodstuffs, such as cellulosics that can survive on agriculturally marginal lands and are not themselves food,[81] will likely have fewer opportunity costs.

Although cellulosics can be less costly to produce than corn ethanol both in terms of opportunity costs because they can be grown on agriculturally marginal lands and in terms of actual cost because they require little fertilizer, pesticides, and other significant energy inputs,[82] they require more complex processing plants whose cost might offset the advantages of their lower opportunity and production costs.[83] As with any burgeoning production technique, though, cellulosic ethanol has the potential to become cost competitive with corn grain ethanol through improved efficiency. Advances, such as improved enzymes that more efficiently convert the carbohydrates to sugars, have already resulted in greater energy yields of cellulosic material, further reducing costs.[84]

One potential efficiency cost of using pure ethanol as opposed to gasoline is that a liter of ethanol contains only about 2/3 of the British thermal unit (Btu) content of equal volume gasoline.[85] Because ethanol fuels provide a fraction of the energy output as the current transportation fuels, cars with the same engine efficiency will have to refuel more frequently when using ethanol fuels. This cost might not be very important because it is merely a trade off between decreased emissions for slightly decreased convenience.

A final cost related to implementing ethanol is what has been described as the "chicken and egg problem."[86] Car manufacturers will presumably resist the large capital investments required to make their vehicles ethanol-ready without the certainty of a ready market. Without the automobiles that can use the fuels, filling stations are less likely to offer the fuels for sale. Thus the question arises: which will come first, the ability to sell the fuels or the cars that can run on them?[87] While this potential problem of implementation was a large concern in the early 1990s, today's market for ethanol fuel and compatible cars is different. The National Ethanol Vehicle Coalition (NEVC) lists 1,215 gas stations that provide ethanol to drivers in all but 10 states.[88] Many major automotive manufacturers currently produce FFVs that are capable of running on gasoline, E85, or any combination in between. Both Ford Motor Company's (Ford's) and General Motors Corporation's (GM's) websites have links to their ethanol innovation pages, with Ford offering the F-150, Crown Victoria, Lincoln Towncar, and Mercury Grand Marquis as FFVs.[89] GM touts that it offers more E85 vehicles than any other manufacturer and promises to produce over 400,000 more beginning this year so that by 2012 over one-half of its annual vehicle production will be compatible with E85 or biodiesel.[90] Consumer demand, therefore, is the last link in the chicken and egg puzzle. If consumers decide to purchase FFVs and demand ethanol instead of gasoline at fueling stations, then automakers and fueling stations have a template to respond.

E. Safety

One added advantage of ethanol fuels is their safety in the event of a car accident. Because ethanol has a low vapor pressure, it will evaporate quickly instead of pooling, thereby creating a lesser chance of explosion than gasoline. Gasoline is highly flammable and its vapor pressure is higher than ethanol's; therefore, car accidents involving gasoline-fueled vehicles carry the extra hazard of potential explosions.[91] Furthermore gasoline is toxic and spills can contaminate groundwater and surface water.[92] Water systems might also be adversely affected through ethanol spills, but because ethanol is soluble in water, any spill will disperse throughout the surrounding water rather than pooling in toxic pockets.[93] As gasoline is more toxic than ethanol and is not soluble in water, gasoline pools pose higher toxicity risks than ethanol.[94]

F. Impact on Innovation

While impact on future innovation is not often a metric by which current innovations are measured, it is interesting to note the potential effects of legislation, such as the Energy Policy Act of 2005,[95] that creates incentives for ethanol and

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[76] *Id.*

[77] *Id.*

[78] *Id.*

[79] *Id. See generally* HEATH, *supra* note 15, at 173 (noting that ethanol has two-thirds of the energy content of an equivalent amount of gasoline).

[80] Hill et al., *supra* note 23, at 11209.

[81] *Id.*

[82] *Id.* at 11208.

[83] *Id.*

[84] *Id.* at 11208-09.

[85] HEATH, *supra* note 15, at 176.

[86] *Id.* at 179.

[87] *Id.*

[88] National Ethanol Vehicle Coalition, *E85 Refueling Location Search*, http://www.e85refueling.com (last visited May 26, 2007).

[89] Ford, *Leading the Way With Ethanol-Capable Vehicles*, http://www.Ford.com/en/innovation/technology/ethanolCapableVehicles/default.htm (last visited Feb. 28, 2007).

[90] GM, *Live Green, Go Yellow*, http://www.gm.com/company/onlygm/livegreengoyellow/index.html?directEntry=e85vehicles (last visited Feb. 28, 2007).

[91] MacLean & Lave, *supra* note 30, at 61.

[92] *Id.* at 61.

[93] HEATH, *supra* note 15, at 186.

[94] *Id.*

[95] 42 U.S.C. §15801 (2006).

seeks to implement it as the primary gasoline alternative. For example, the Act establishes a renewable fuels standard (RFS) that requires 7.5 billion gallons of ethanol be used as a transportation fuel by 2012.[96] In enacting this legislation, Congress undoubtedly intended to reduce dependence on petroleum with reliable and clean energy, yet it is unclear whether a legislative prescription is the best means of achieving this end. President Bush, hoping to end his second term on a positive note, has also taken an interest in alternative fuels, including ethanol. In his State of the Union address, he announced his goal of reducing gasoline consumption—and thus gasoline dependence—by 20% over the next 10 years.[97] To reach this goal, the president concluded that the United States "must increase the supply of alternative fuels by setting a mandatory fuels standard to require 35 billion gallons of renewable and alternative fuels in 2017," which he noted was nearly five times the current target.[98] This proposal, the "Twenty in Ten" plan, aims to increase the scope of the current RFS enacted in the Energy Policy Act, expanding it to an alternative fuel standard that will include sources such as corn ethanol, cellulosic ethanol, biodiesel, methanol, butanol, hydrogen, and other alternative fuels.[99] The president's newfound interest in cellulosic ethanol is echoed in bills proposed in Congress, such as the Cellulosic Ethanol Development and Implementation Act of 2007.[100] Although the president has expressed an interest in cellulosic ethanol, some have noted that this interest in climate change and alternative fuels might be distorted by his concerns over energy security.[101] Finally, on May 14, 2007, President Bush issued an executive order and accompanying public statement in which he pushed for more renewable fuels and a cooperative effort between the U.S. Environmental Protection Agency and the U.S. Departments of Agriculture, Energy, and Transportation to increase fuel efficiency.[102]

While ethanol fuels have the potential to decrease emissions and reduce petroleum dependence, other technologies, such as solar or hydrogen power cells, may be even more efficient. Mandating a move toward one fuel alternative could stifle innovation that could lead to even better alternatives. Legislative mandates are likely to succeed because the correct combination of efforts—farm industry, conservation, and political willpower—all exist. Yet as history has demonstrated, "successful social movements can be co-opted by their own success. Once institutions are created to address a social problem, it can become harder to mobilize the public."[103] When the government responds to high-profile concerns, as it seems to be doing in the transportation fuel arena, the public might believe the problem has been solved, i.e., that concerns over GHGs and global warming were cured with a quick and easy switch to a new "green" fuel.[104] This has the potential to make it more difficult to implement future innovations. Thus, if a solar cell did become available, the public might not respond with the same vigor, and a more efficient technology could be thwarted. While this is a very pessimistic view, it is likely that if politicians and the public think the problem has been solved, even if the scientific community finds other more efficient means, regenerating the support and capital necessary to shift to another fuel will prove difficult.

One final concern with a move towards ethanol, and especially ethanol and gasoline blended fuels like E85, is that if ethanol achieves widespread use, another strong interest will have a say in the transportation market. Not only will attempts to move from gasoline and ethanol blends be met with resistance from big oil, but agribusiness will be resistant to change. As both oil companies and agriculture have large lobbying power, their interests combined would be a very formidable opponent. Legislative ethanol mandates and incentives might provide incremental benefits in the short term, but these mandates and incentives could also prevent greener energy plans from developing and succeeding in the future.

IV. Discussion

Before ethanol is unilaterally accepted as a solution to the problems of global warming, GHG emissions, and foreign oil dependence, we should analyze its effectiveness as a remedy. Comparing this information will help in deciding which alternative, if any, the United States should adopt. Because I have not weighted one criterion over another, policymakers are encouraged to look at what ends they want the fuel to serve, i.e., eliminating petroleum dependence or reducing GHG emissions, while noting any negative impacts or trade offs associated with the fuel.

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[96] Energy Policy Act of 2005, §1501, 42 U.S.C. §7545(o)(2)(B)(i) (2005) (amending the CAA to establish a renewable fuel program consisting of cellulosic biomass and waste-derived ethanol, and biodiesel).

[97] State of the Union, *supra* note 3.

[98] *Id.*

[99] Twenty in Ten, *supra* note 3.

[100] S. 167, 110 Cong. (2007), H.R. 395, 110th Cong. (2007). These bills would

> amend the Clean Air Act to require the Secretary of Energy to provide grants to eligible entities to carry out research, development, and demonstration projects of cellulosic ethanol and construct infrastructure that enables retail gas stations to dispense cellulosic ethanol for vehicle fuel to reduce the consumption of petroleum-based fuel.

Id.

[101] *See The Greening of America*, ECONOMIST, Jan. 27, 2007, at 9 ("Unfortunately, Mr. Bush's new-found interest in climate change is coupled with, and distorted by, his focus on energy security."); *see also* Edmund L. Andrews, *Bush Makes a Pitch for Amber Waves of Homegrown Fuel*, N.Y. TIMES, Feb 23, 2007, at A16 (describing President Bush's trip to a laboratory in North Carolina where he learned about enzymes used to make cellulosic ethanol. The article also noted that ethanol's potential to reduce U.S. dependence on foreign oil sparked the president's excitement about cellulosics.).

[102] *See generally* Exec. Order No. 13432, 72 Fed. Reg. 27717 (May 14, 2007).

[103] Cary Coglianese, *Social Movements, Law, and Society: The Institutionalization of the Environmental Movement*, 150 U. PA. L. REV. 85, 113 (2001).

[104] *See id.* at 114 ("the fact that government institutions exist to respond to [crisis] tends to reassure the public and allay its concerns").

Table 1

	Corn Ethanol	**Cellulosic Ethanol**	**Petroleum (Status Quo)**
NEB	positive net energy of about 4MJ/l to 9MJ/l*	4.4-10.4 (energy output relative to energy input ratio)+	5 (energy output relative to energy input ratio)+
Petroleum Dependence	.06 MJ input of petroleum compared to MJ fuel produced* Could reduce petroleum use by 95% on an energetic basis*	.08 MJ input of petroleum compared to MJ fuel produced*	1.1 MJ input of petroleum compared to MJ fuel produced*
Ability to Reduce GHGs	81-83 kg CO_2 equivalent per MJ fuel produced* 88% of the net GHG emissions of production and combustion of an energetically equivalent amount of gasoline (GHG per NEB)** results in N_2O emissions from the fertilizer** has the potential to release a negative amount of CO_2**	11 kg of CO_2 equivalent per MJ of fuel produced* N_2O emissions are realized to a lesser extent than corn ethanol because cellulosics requires less fertilizer** has the potential to release a negative amount of CO_2**	94 kg CO_2 equivalent per MJ fuel produced*
Other Environmental Effects	Requires fertilizer in production, N and P contribute to runoff**	Requires less fertilizer, can grow on marginally valuable land, will not compete with food, has the ability to prevent soil erosion**	
Cost	2005 pricing: $0.46 per EEL of gasoline** Also benefits from crop subsidies	Not widely commercially available so no cost estimates, but does not benefit from crop subsidies	2005 pricing: wholesale gasoline prices averaged $0.44 per liter**
Safety	Low vapor pressure results in less of a chance of explosion upon crash++ Miscible in water, so will disperse, not pool, upon spilling into water+++	Low vapor pressure results in less of a chance of explosion upon crash++ Miscible in water, so will disperse, not pool, upon spilling into water+++	Higher vapor pressure, so pooling upon crash. Also highly flammable++ Immiscible in water, so can contaminate and form pockets+++

* Farrell et al.
** Hill et al.
+ Lynd
++ MacLean & Lave
+++ Heath

Ethanol is currently produced from corn. Yet, as can be seen from the scientific literature, corn ethanol is not as good as cellulosic ethanol on a number of metrics, including achieving reductions in GHG emissions. Because ethanol from corn or cellulose is structurally the same, the emissions released upon combustion are exactly the same. The difference, therefore, arises in the production phases. Producing ethanol from cellulose reduces GHG emissions from the 94 kg CO_2 equivalent per MJ of fuel associated with gasoline to 11 kg CO_2 equivalent per MJ of fuel. The vast reduction is seen because cellulosics require less energy input at the production phase; they grow quickly without energy input from fertilizer and are easily harvested. While corn ethanol also reduces GHG emissions to 81-83 CO_2 equivalent per MJ of fuel, which is still below the 94 kg CO_2 equivalent per MJ of fuel of gasoline, this reduction is not as great as that of cellulose. When considering the effect on GHG, it is interesting to note that both corn ethanol and cellulosic ethanol could reverse CO_2 emissions because the plants remove CO_2 from the atmosphere. Additionally, as the processing plants become more efficient, an even greater potential to reduce GHG emissions below the emissions from producing and combusting gasoline exists. Petroleum, on the other hand, does not have the potential to reverse or decrease its CO_2 emissions.

Critics of ethanol contend that it requires more energy input than the energy derived upon combustion. This criticism has been proven wrong. Both corn ethanol and cellulosic ethanol have a positive NEB. In fact, the NEB of gasoline, which has an energy output relative to energy input ratio of 5, can be achieved by both cellulosic ethanol, whose energy output to input ratio is estimated at 4.4-10.4, and corn ethanol, which releases 4MJ/l to 9MJ/l of energy per liter. Because both cellulose and corn ethanol provide valuable coproducts, fermentation of these fuels not only produces a useful transportation fuel, but also displaces the need for other petroleum-intensive manufacturing processes to produce DDGS, one such coproduct of ethanol fermentation.

In addition to their ability to reduce GHGs, cellulosics also might be a more viable alternative because their multi-yearly harvests provide more raw materials to produce ethanol. Perennial grasses, which can be harvested many times a year, have the potential to provide more fuel than corn, which is harvested yearly. Additionally, because cellulosics can be grown on agriculturally marginal lands, they do not raise the same concerns about potential effect on the food supply. Diverting corn to ethanol production has an obvious effect on food supply. Increasing the amount of land used to produce corn might also affect food supply; because corn requires more fertile land than cellulosics, planting more corn can displace land that could otherwise be used for food production. As demands for food are expected to increase, it is important to have a feedstock that does not compete with foodstuffs either for the fuel feedstock itself or for fertile lands.

Other advantages of cellulosic over corn ethanol include cellulosic's small fertilizer demand, which not only lowers its NEB and reduces GHG, but also has the potential to reduce N_2O emissions from nitrogen fertilizers. Using less fertilizer also reduces the impacts of runoff, a problem associated with traditional agricultural practices employed in growing corn. Finally, cellulosics can also help remedy the problem of soil erosion because their large roots tend to prevent soil from washing away.

Despite the advantages of cellulosic feedstocks over corn ethanol and gasoline on an environmental impact and GHG metric, corn ethanol requires fewer petroleum inputs than cellulosics to produce ethanol. The Farrell et al. report found that corn ethanol has a petroleum input ratio of 0.06 compared to the cellulosic ratio of 0.08 MJ of petroleum in production/MJ of fuel produced. As technology advances and the enzymes and chemicals employed to break cellulosics' tougher cell walls become more efficient, a greater conversion to fermentable sugars can be achieved, which will likely decrease the energy used at the fermentation stages. Both cellulosic and corn ethanol, however, require fewer petroleum inputs than gasoline production, which requires 1.1 MJ petroleum per MJ fuel produced.

Ethanol from both corn and cellulose fares well on environmental metrics. Both reduce net GHG below petroleum GHG levels with cellulose reducing these emissions by the greatest amount. Both have a positive NEB and require less petroleum per MJ that is required to produce one MJ of gasoline. On a petroleum input metric, corn ethanol is slightly favored. Yet, because cellulose is favored on a GHG metric, requires less fertilizer, can be grown on agriculturally marginal lands, and does not compete directly with food sources, cellulosic ethanol should be the favored feedstock for ethanol production.

The above assessment assumes that ethanol should be used as a transportation fuel, but there are some costs associated with ethanol. One study estimated that in 2005, ethanol net production cost was $0.46 per EEL of gasoline, while wholesale gasoline was $0.44 per liter. Ethanol receives subsidies from the federal government, which help it achieve cost competitiveness. Costs are associated with transporting the fuels and refurbishing the fueling stations. While FFVs are currently in production and many are on the roads, unless every new car that is purchased has ethanol capability, a complete conversion will be impossible. The gains in GHG reduction from using ethanol might not be enough to offset the emissions from older automobiles currently in use.

Political and social willpower for ethanol exists. The federal government, under the Energy Policy Act of 2005, mandates using 7.5 billion gallons of ethanol by 2012. President Bush's "Twenty in Ten" plan increases the Act's mandate, requiring 35 billion gallons of alternative fuels by 2017. These initiatives demonstrate that fears about global warming and foreign oil have motivated a move to ethanol. But although cellulosic ethanol looks like a promising fuel source now, potentially more environmentally sound options, such as solar or hydrogen technologies, are also on the horizon. Implementing ethanol legislation that mandates ethanol's use as an alternative alone might prevent future innovation. Also, because social interest is often fleeting, if politicians continue to tout ethanol, the public is likely to accept it as a solution and think that its problems, from GHG to foreign oil, are solved. On this metric, a move to ethanol could limit future, more efficient, innovations. If Congress decides that this is a risk worth taking, it should stipulate in its mandates that most of the ethanol should come from cellulose. This, however, will likely be opposed, as the agricultural lobby is one of the primary supporters and proponents of ethanol regulations.

Although cellulosic ethanol appears to be a better alternative fuel choice than corn ethanol because it can be produced with low agricultural input on lands with low agricultural value while reducing GHG emissions and runoff, the current tenor indicates that corn will be the ethanol of choice. While corn ethanol is currently a somewhat greener step than continuing to use gasoline—though its 81-83 kg CO_2 equivalent per MJ fuel produced is not that great a reduction from gasoline's 94 kg CO_2 equivalents per MJ fuel produced—it is not as efficient at reducing GHG emissions as cellulosic ethanol, which requires only 11 kg of CO_2 equivalent per MJ of fuel produced. Policymakers should consider that corn ethanol's GHG reduction of 10kg CO_2 equivalents per MJ fuel produced will probably have a negligible impact on global warming and climate change. Therefore corn ethanol's use should be limited—not welcomed—as the solution to the U.S. energy woes. Instead, cellulose, which already has been shown to reduce GHG emissions well below corn ethanol and gasoline levels, should be favored. Because cellulosics are the most promising ethanol alternative, policymakers should encourage cellulosic production.

V. Conclusion

When deciding whether to require the use of an alternative fuel, policymakers should consider the regulation's goal and the means selected to achieve it. If ethanol fuels are intended to reduce GHG emissions and help stop global warming, regulators should consider whether corn ethanol's slight reduction in GHGs—emitting approximately 10kg CO_2 equivalents per MJ fuel less than burning gasoline—will have a measurable impact on global warming and climate change. Cellulosic ethanol appears to be a better alternative fuel choice than corn ethanol because it can be produced with low agricultural input on lands with low agricultural value while achieving greater reductions in GHG emissions than corn ethanol. Thus, while the current ethanol production is primarily corn-based, regulators should consider encouraging cellulosics, not only because of their current advantages, but also because of the possibility that enzymes used in producing cellulosic ethanol will continue to increase its efficiency, resulting in a greater NEB. Furthermore, the corn industry might not be able to meet the goals President Bush set in his State of the Union address of requiring 35 billion gallons of renewable fuels by 2017 through ethanol production from corn alone. The vice president of the National Corn Growers Association, Ron Litterer, estimated that cornstarch-based ethanol will only be able to provide 15 billion gallons by 2015 without disrupting corn feed supplies or other corn exports.[105]

Policymakers should also be careful to examine the impact of promoting ethanol as an alternative fuel. After touting ethanol as at least a partial solution to U.S. oil dependence and climate change woes, it might be difficult to rally support for another, potentially more efficient, alternative in the future. Additionally, a fuel such as E85, which still requires gasoline, will be backed by both the agricultural and oil lobbies. It is important, therefore, to consider the long-term effects of mandating a change, such as a path dependence, that might hinder innovation in the future. Although ethanol fuels are a step in a greener direction, regardless of how they are produced, ethanol might not be the best step in the long run. If ethanol is accepted as the next transportation fuel, policymakers should be careful to encourage production from cellulosics while looking toward flexible policies that will not tie the United States to another fuel that might limit potentially more efficient future innovations.

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[105] *On Point: Ethanol, Corn Growers' Ron Litterer Talks High Corn Prices, Bush Admin's Farm Bill Proposal* (E&E TV broadcast Feb. 21, 2007) (transcript available at http://www.eande.tv/transcript/572).