Energies **2014**, *7*, 4430-4445; doi:10.3390/en7074430

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

Promoting Second Generation Biofuels: Does the First Generation Pave the Road?

Hakan Eggert [1,2,]* and Mads Greaker [1,2]

[1] Department of Economics, University of Gothenburg, 40530 Gothenburg, Sweden
[2] Research Department of Statistics Norway, 0033 Oslo, Norway

* Author to whom correspondence should be addressed; E-Mail: hakan.eggert@economics.gu.se;
Tel.: +46-31-786-4175; Fax: +46-31-773-1326.

Received: 6 May 2014; in revised form: 3 July 2014 / Accepted: 7 July 2014 /
Published: 11 July 2014

Abstract: The U.S., Brazil and a number of European and other countries worldwide have introduced various support schemes for bioethanol and biodiesel. The advantage of these biofuels is that they are relatively easily integrated with the current fossil fuel-based transport sector, at least up to a certain point. However, recent studies point to various negative effects of expanding the production of first generation (1G) biofuels further. 1G biofuels' problems can be overcome by a transition to second generation (2G) biofuels. So far, 2G biofuels are much more costly to produce. We therefore ask: to what extent is targeted support to 2G biofuels likely to bring costs down? Additionally, are current support schemes for biofuels well designed in order to promote the development of 2G biofuels? We find that the prospects for cost reduction look better for 2G bioethanol than for 2G biodiesel. Bioethanol made from cellulose is far from a ripe technology, with several cost-reducing opportunities yet to be developed. Hence, targeted support to cellulosic ethanol might induce a switch from 1G to 2G biofuels. However, we find little evidence that production and use of 1G bioethanol will bridge the conversion to 2G bioethanol. Hence, to the extent that private investment in the development of 2G bioethanol is too low, current support schemes for 1G biofuels may block 2G bioethanol instead of promoting it.

Keywords: bioethanol; biofuels; learning; second generation

---

1. Introduction

Approximately 17% of all carbon dioxide (CO_2) emissions come from road transport, according to the International Energy Agency (IEA) [1]. Global demand for transport seems to continue growing; The World Energy Outlook [2] projects that transport fuel demand will grow by nearly 40% by 2035. Hence, in order to limit global CO_2 emissions in accordance with the 2 °C target, policy makers most likely need to implement measures aiming at emission from transport. Biofuels have been promoted as one possible and promising way of reducing CO_2 emissions from the transport sector. Moreover, the technology is available today without reducing consumer utility from cars, which might happen with hydrogen and electric cars. The U.S. and a number of European countries have therefore introduced various support schemes for research and development (R&D) and the deployment of biofuels. Growth of global biofuel production is mostly a result of ambitious government support programs. Clearly, the support has not only been driven by a concern for green house gas (GHG) emissions; both the European Union (EU) and the U.S. have invoked arguments about "energy security" and the need for regional development.

It is common to distinguish between first generation (1G) biofuels made from feedstock also suitable for human food production and second generation (2G) biofuels made from cellulosic material not useable as a food source. Substitution of fossil fuels with 1G biofuels on a global scale would likely have severe effects on food security [3,4]. However, biofuels have the potential to replace a substantial part of petroleum use in the transport sector if technologies using cellulosic biomass (2G biofuels) succeed. IEA [5] predicts that biofuels may provide 27% of total transport fuel in 2050. Biofuels crops must then increase from 2% of total arable land today to around 6% in 2050. Much of this increase, however, could take place on pastures and currently unused land, which is suitable for second generation biofuels.

Recent contributions have also questioned whether 1G biofuels actually lead to any short-term CO_2 reductions when indirect land use changes are taken into account [6–9]. According to the U.S. Environmental Protection Agency (EPA), cellulosic ethanol is by far the most promising biofuel with respect to its potential for reducing GHG emissions. Emissions reductions from converting to cellulosic ethanol can be around 100%, which is far better than most 1G biofuels, except perhaps sugarcane ethanol from Brazil [10]. Still, some scholars hold that, even if cellulosic biofuels become commercially successful, they may still replace only a few percent of the fossil fuels on a global scale [11].

The main problem with 2G biofuels is that they are significantly more expensive than most 1G biofuels [12]. In this article, we therefore ask: to what extent is targeted support to 2G biofuels likely to bring costs down? Additionally, are current support schemes for biofuels well designed with respect to promoting the development of 2G biofuels?

The paper is structured as follows. In the next section, we discuss the opportunities for cost reductions in the production of 2G biofuels. The third section reviews the current public support schemes for biofuels in Brazil, the EU and the U.S. Multiple policy instruments are in use, but the question arises whether they promote the development of 2G biofuels. This is discussed in the fourth section in light of the findings in the earlier sections. The last section concludes.

2. Materials and Methods

In this paper, we draw on economic theory to discuss to what extent and by which measures 2G biofuels should be supported. With respect to the state of the 2G biofuel technology, we rely on a number of reports cited in the text. This is also the case for our survey of current biofuels policies.

2.1. Cost Reduction Potential of 2G Biofuels

2.1.1. Experience Curves

Several studies [13,14] hold that government interventions with subsidies for production, consumption and R&D have been instrumental in the development of the demand and supply of alternative energy. These supporting activities have spurred investments and, together with mandates for renewable fuels that guarantee a market for these fuels, have promoted successful development [4,15].

According to IEA [16], "strong policy signals on the sustainable production and use of biofuels, and efforts to spur the competitiveness of 2G technologies, will need to accompany their large-scale market penetration…". It has been shown in numerous studies that a significant, negative trend can be found between the cost of a new technology and the accumulated supply of it; take, for example, solar panels [17]. This relationship is often referred to as an experience curve. The question is whether such an experience curve is likely to exist for 2G biofuels.

There are several more fundamental mechanisms at work behind an experience curve; see IEA [17]. First, as personnel engaged in the planning and production of the new product gain experience with the new technology, say, a 2G biofuel plant, they are likely to become more efficient and better organized, with respect to both how to build and how to run the plant. Second, experience may also induce R&D, which may lead to further improvements in technology, *i.e.*, so-called process innovations. Third, when the fundamentals of the production process are well known, it is often possible to scale up production in order to reap economies of scale.

With experience curves, the accumulated production of a new technology will have to reach a certain level before the new technology becomes competitive. In the beginning, the unit costs of the technology may be far above the market price for the established technology. However, as accumulated production picks up, the difference between the unit cost of the new technology and the price of the incumbent technology will decrease. The integral over the differences in costs from zero production until the level of accumulated production at which the new technology becomes competitive is coined "the learning investment".

A crucial question is to what extent private firms will undertake the learning investment without government support. This will, among others, depend on the extent to which discoveries made by one firm can be utilized by other firms. If there is a low degree of learning spillovers, it is not obvious that governments should support technologies in their early stages so that firms may gain experience. This is analyzed by [18–20]. The general result is that, if firms are not able to learn easily from other firms' experience, they will likely internalize the experience effect and run with negative profits in the early stages to gain experience. If there is a high degree of spillovers between firms, learning investments will be too low, because all firms have an incentive to free ride on the experience of other firms. Hence, the industry will invest too little in learning, which implies that there is the need for public funding in order to reach a sufficient level of learning investment.

Below, we consider the extent to which there exists an experience curve for the two main 2G biofuel conversion technologies. On the other hand, it is hard to know a priori whether firms can patent or in other ways protect new insights gained through increased experience.

2.1.2. 2G Biofuel Technologies

Two dominant conversion processes are used to produce biofuels from cellulosic feedstock: biochemical and thermo-chemical. While the biochemical process is used to produce ethanol, the thermo-chemical process produces biodiesel. The thermo-chemical process is often referred to as Fischer–Tropsch synthesis. There already exists an extensive worldwide commercial application of Fischer–Tropsch synthesis for producing diesel from coal, and the experience accumulated from these activities seems to be directly relevant for the conversion of biomass to biodiesel. Yet, the production costs for 2G biofuels based on the thermo-chemical pathway are far from competitive with those of 1G biodiesel or fossil diesel. According to Larson [21], the thermo-chemical route is largely based on existing technologies that have been around for many decades. We therefore hold that there are probably limited opportunities for further cost improvements from experience.

Experience with the biochemical pathway is much more limited. To date, most of the production of ligno-cellulosic ethanol has taken place in laboratories or pilot-sized plant settings [21]. Only recently have companies begun to construct and operate commercial-sized demonstration plants. Examples are Beta Renewables, which started up a 40,000 t/year plant in Crescentino, Italy. Abengoa Bioenergy is about to start up a 75,000 t/year plant in Kansas, U.S., and POET-DSM with their Project Liberty—a 60,000 t/year plant in Iowa, U.S.—also scheduled to start production in 2014. Although the technology has been shown to be effective, the efficiency of conversion processes still has a way to go to achieve theoretical maximum conversion efficiencies. Thus, compared to the ripe thermo-chemical pathway to 2G biodiesel, the biochemical pathway to cellulosic bioethanol is more of an infant technology.

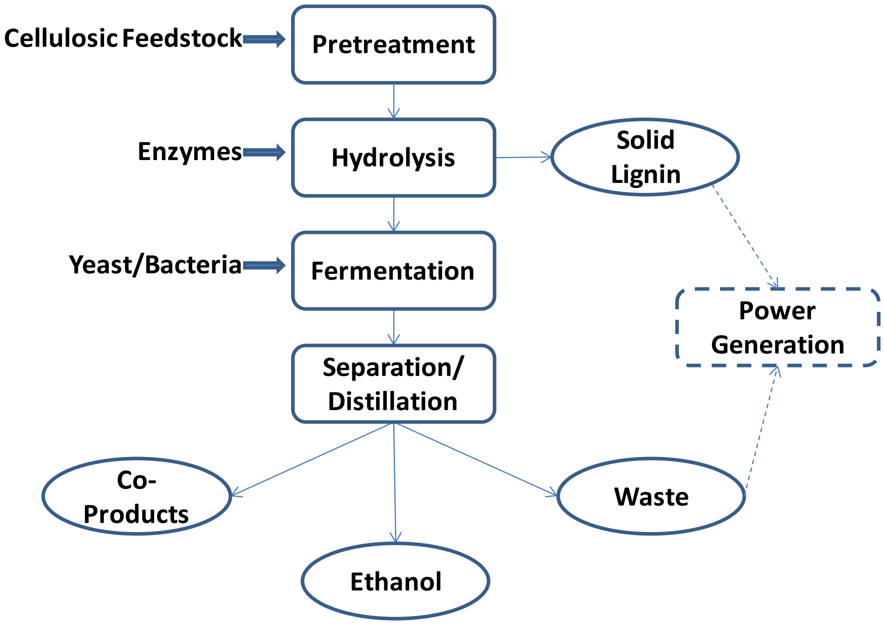
Potential for Cost Reductions in the Biochemical Pathway

It is instructive to look at the different processing steps in turn. The biochemical conversion pathway is presented in Figure 1.

The literature points to opportunities for cost reductions in nearly all production stages. As far as we understand, these opportunities are not related to experience with 1G biofuel production. For instance, while the pretreatment stage in the production of 1G biofuels is relatively straightforward, pretreatment of cellulosic feedstock is generally extensive and costly due to the strong chemical bonds of the cellulose structure. This stage has been identified as requiring learning to improve pretreatment efficiency [22].

Furthermore, the market for cellulosic biomass feedstock is poorly developed. Today, most crop residues have low economic value and, in order to minimize disposal costs, cereal crops have been bred and managed to reduce straw and stover yields. These yields can easily be increased if there is a value for these agricultural residues, *i.e.*, if they are used as feedstock in the production of cellulosic ethanol [16].

Figure 1. Biochemical conversion process to be placed here.



In the hydrolysis stage, enzymes that are able to degrade cellulosic substrates are essential. Note that these enzymes are not in use by 1G biofuel producers. Note also that chemical costs per unit of production represent a significantly higher proportion of the total unit cost of production for cellulosic ethanol than for corn-based ethanol [23].

Further reductions in costs within this stage will be driven by a combination of new enzymes and by gaining experience from large-scale facilities to integrate and optimize the overall conversion process. Enzyme recycling, *i.e.*, treating multiple batches of feedstock with the same enzymes, may reduce enzyme costs dramatically.

In the fermentation stage, micro-organisms (bacteria and yeast) are used to convert the sugars produced in the previous stage into ethanol. In the production of ethanol from 1G feedstocks, the hexose sugar is metabolized by saccharomyces or "baker's yeast", *i.e.*, well-known natural yeast cells. The 2G process produces both hexose and pentose sugars as a result of the hydrolysis process. Cost-effective fermentation relies on the ability of organisms to co-ferment pentose and hexose sugars if the feedstock contains a large amount of pentoses. Significant progress has been made in engineering micro-organisms for co-fermentation, yet their sensitivity to inhibitors and the production of unwanted by-products remain serious problems that have to be overcome for the systems to become commercially viable [24].

In the product separation stage, ethanol is separated from the fermentation broth by distillation and dehydration. There are no significant differences or difficulties in this final product separation phase between 1G and 2G biofuels.

We conclude that significant cost reductions for cellulosic ethanol seem to depend on a series of small and large innovations in all stages of the production process. Further, these innovations are not likely to be induced from increased production of 1G biofuels.

2.2. Current Public Support to Biofuels

2.2.1. Price on Carbon

The external costs from using fossil fuels in the transport sector call for policy intervention to internalize these costs. The standard approach is carbon taxes. In 2013, a global comparison gives the following gasoline prices in United States Dollar (USD) per liter: U.S. 0.9, Russia 1.1, Canada 1.2, Brazil 1.3, China 1.7 and EU-27 1.7–2.4 [25]. EU prices may be too high, but if we assume that EU prices reflect the external costs, global efforts to control GHG emissions would benefit tremendously from an upward adjustment of the prices of gasoline. Policies to ensure correct carbon pricing may, however, be far from feasible in most countries. In fact, global subsidies of oil products are increasing and have amounted to almost USD 200 billion in 2010 [26]. Still, we stress that correct carbon pricing is an essential cornerstone for any long-term sustainable policy to get closer to a carbon-neutral transport system.

2.2.2. Tax Rebates and Other Subsidies to Biofuels

Subsidies to biofuels may be a substitute for correct carbon pricing, if such a policy promotes an alternative to gasoline with presumably lower GHG emissions. On the other hand, it will often lead to excessive use of transport fuels, because the private cost of transport is reduced compared to a situation with no subsidies and the correct level of carbon taxation.

The U.S. federal government has provided various supports to ethanol production and consumption since 1978. The most important one was the excise tax credit for ethanol fuel blenders in the range of 40 to 60 cents per gallon that was initiated under the Energy Tax Act of 1978 [27] and that expired in December, 2011. There is also a cellulosic biofuel producer credit of USD 1.01 per gallon, in effect from 2009 to December, 2013 [28].

Brazil's biofuel industry was initiated in 1975 as a response to the 1973 oil crisis. The country invested heavily in the development of the ethanol industry with a group of policies to promote ethanol use. However, in 1996, the Brazilian government initiated a program to reduce subsidies, and by 1999, it stopped controlling ethanol prices and eliminated direct industry subsidies. Mandated ethanol content in gasoline has varied in the range of 18%–25%, depending on global sugar prices. In addition, flex-fuel vehicles are common, thanks to policies, such as lower taxes on those fuels compared to traditional fuels. Overall, the average replacement of gasoline during 2011–2013 in Brazil is estimated to be 35% [29]. According to Moreia *et al.* [30], ethanol production in Brazil has stagnated since 2009. This is likely partly due the financial crisis, but also potentially due to the large discoveries of pre-salt oil, making Brazil less reliant on sugar cane ethanol to be self-sufficient in the future. So far, Brazilian supportive policies have not been aimed at any second generation biofuel.

Initially, the EU did not use excise tax exemptions for biofuels as extensively as the U.S. (and Canadian) governments, but from 2000 onward, most member states have introduced exemptions at various levels up to 100%. Spain provides subsidies for plant construction and has exempted alcohol used for biofuel from taxation through 2012, amounting to USD 0.57/L [31]. Germany is one of the few countries with excise tax privileges provided to 2G biofuels [32]. Sweden has promoted ethanol with high- and low-blend ethanol, tax benefits and similar policies, relying on Brazilian imports with some domestic production. As a result of various subsidies, during the period 2002–2010, the EU was found to play a major role in determining the world market biodiesel prices, while U.S. and Brazilian ethanol prices were found to play a major role in determining the ethanol prices in other countries [33].

2.2.3. Blending Mandates and Renewable Fuel Standards

The major producers of 1G biofuels, the U.S. and Brazil, are moving away from tax rebate and direct subsidy policies. The provision of biofuels in Brazil is primarily based on the mandatory blending mandate, which is 20% as of 2013. In 2013, some 60 countries use or are about to introduce blending mandates, some with non-binding targets, but many with mandatory ones [34]. A likely contributing factor to the popularity of mandatory blending mandates is that governments can subsidize biofuels without spending; all costs for the subsidy are covered by fuel consumers. However, if there is an existing tax on fossil fuels, a mandate may shrink the tax base [35].

A mandatory blending mandate corresponds to a tax on fossil fuels and a subsidy to biofuels, which means that, for any given price ratio between fossil fuels and biofuels, there exist a tax and subsidy that correspond to any level of mandatory blending mandate [36]. This can be illustrated in a simple example. Assume that market prices of fossil fuels and biofuels are USD 0.5 and USD 1 per L, respectively (when adjusted for the lower energy content in biofuels). If the government introduces a 5% mandatory blending mandate, it would incur no public costs. Fuel suppliers would buy biofuels and sell blended fuel, charging USD 0.525/L, and would make similar profits per L to what they previously made. Consumers would pay an implicit tax of 5% on fossil fuels, and all of that money would go to the suppliers of biofuels as an implicit subsidy. Total fuel consumption would be slightly reduced given a higher fuel price. Thus, a blending mandate partly works as a substitute for correct gasoline taxation. If prices on fossil fuels increase or if production costs of biofuels are reduced, it implies a reduction of the carbon tax and the biofuel subsidy.

In the U.S., the change of biofuel support started with the Renewable Fuel Standard (RFS), originating with the Energy Policy Act of 2005. The RFS program requires the amount of renewable fuel blended into transport fuels to increase annually and finally reach 36 billion gallons in 2022, *i.e.*, 7% of the expected annual gas and diesel consumption in 2022. In 2010, the EPA specified rules for the expanded program (RFS2) that uses four categories of renewable fuels, which are required to emit lower levels of GHG relative to the fossil fuel they replace. Conventional biofuels are required to reduce GHG emissions by 20%, supposedly increasing to 15 billion gallons by 2015 and then held constant at that level. Cellulosic biofuels with at least a 60% GHG lifecycle reduction were planned to increase from zero in 2010 to more than 15 billion gallons in 2022 [37]. The mandates guarantee a market for 2G biofuels, but the EPA may delay or waive the mandate if, e.g., there is a lack of production capacity, as for the cellulosic ethanol volume. In 2012, the target for cellulosic ethanol was 500 million gallons, later revised to 10.5 million gallons, while the actual output was 0.02 million gallons (TransportPolicy.net [28]). However, this is about to change with a number of new 2G plants coming on line, as mentioned above.

The EU has a target of 10% renewable fuel in the transport sector by 2020, and several of the member states have introduced or plan to introduce a blending mandate. The EU's Renewable Energy Directive states ambitions for 2G biofuels, and contributions by biofuels from non-food sources will be considered to be twice that made by 1G biofuels, but there is still no specific quota for 2G biofuels. In 2012, the EU commission proposed that a maximum of half of the 10% renewable fuel target for the transport sector can be fulfilled by 1G biofuels. As of December, 2013, the proposal has not yet been ratified [38].

2.2.4. Tariffs on Imported Biofuels

Initially, biofuel imports had substantial tariffs, but recently, we have seen a major change. In December, 2011, the U.S. abandoned its previous 54 cents tariff, used to offset the domestic subsidy that expired in December, 2011. Brazil temporarily suspended its 20% tariff on imported ethanol in 2010; in 2011, the suspension was prolonged to the end of 2015 [29]. Hence, recent developments indicate continued mutual free trade between the major ethanol producers, Brazil and the U.S. The EU uses tariffs on undenatured and denatured ethanol, € 0.19/L and € 0.10/L, respectively, with an exemption for developing countries [39]. In 2013, the EU imposed an anti-dumping duty of 62.3 euros (USD 81.80) per ton on imports of U.S. bioethanol, which in 2011 provided 20% of EU ethanol consumption [40]. Overall, recent EU measures do not signal trade liberalization, and so far, the EU has not signaled more liberal treatment of imported second generation biofuels.

2.2.5. GHG Emission Standard Coupled with Blending Mandate

The initial enthusiasm, paired with rapid expansion of first generation biofuels in the early 2000s, was halted by 2008. This change was primarily due to the financial crisis, but there were also influential critiques concerning indirect land use changes and the concern that subsidized biofuels may have spurred deforestation, when the search for new land to grow biofuels feedstock has led to even tropical rainforests being cut down [6,7].

As a response, the EU has been working on introducing a GHG standard for biofuels. The proposal is that conversion to biofuels should imply a minimum GHG savings of at least 35% compared to fossil fuels from 2013 onward, rising to 50% and 60% in 2017 and 2018, respectively. These standards could work in favor of cellulosic ethanol, but will also benefit imports of high-performing 1G biofuels, such as Brazilian ethanol.

3. Results: Does Current Support to Biofuels Promote 2G Biofuels?

Our point of departure is that there may be three motives for supporting biofuels. First, current carbon taxes on fossil fuels may be insufficient. That is, in order to reach the ambitious GHG emissions reduction goals many countries have set for themselves, carbon taxes must be higher. As long as increasing carbon taxes for political reasons is difficult, a second best policy may be to introduce blending mandates for biofuels or subsidies to biofuels.

Second, private investments promoting technological development in alternatives to fossil fuels may be too low due to knowledge spillovers in R&D and learning. With substantial knowledge spillovers, an individual firm's R&D investments and/or learning investments are less likely to pay off in the future, and a firm is likely better off abstaining from investment and hoping to free ride on other firms' investment. The collective result would then be too little investment compared to the socially optimal level.

Third, on the demand side, the necessary infrastructure development might not happen, making suppliers reluctant to invest in new production capacity. Although bioethanol can be blended into gasoline, there is a "blend wall", that is, without a transformation of the car fleet to a flexifuel standard, such as in Brazil, biofuel demand is constrained to approximately 10% of the gasoline demand. Below, we evaluate the different support measures surveyed above in light of these concerns.

The third motive seems less of a concern in most countries, as long as the blend wall is still far from being met. This is the case for most of the EU, while for the U.S., where biofuels accounted for roughly 7% of total transport fuel consumption in 2012, the blend wall has been discussed [41]. With respect to the first motive, it is of course crucial that biofuels actually reduce GHG emissions; this depends on the type of biofuel. With respect to the second motive, we doubt that 1G biofuels have a significant potential for further cost reductions. Further, we hold that there is likely an experience curve for cellulosic ethanol, but that more experience with 1G biofuels does not induce a movement down this curve. Thus, the potential for technological development may be a rationale for support to 2G bioethanol in particular. The question is then to what extent current support to biofuels benefits cellulosic ethanol, which, according to economic theory and its potential for GHG reduction, should receive more support than 1G.

3.1. Use of Carbon Taxes

A GHG tax on conventional fuels will increase the price of conventional fuels and make biofuels in general more profitable. Because a GHG tax on conventional fuels is warranted regardless of the existence of biofuels, it should be pursued without considering possible learning effects for 2G biofuels. On the other hand, as long as neither 1G nor 2G biofuels are subject to carbon taxes, they do not provide an extra incentive to undertake learning investments in 2G biofuels if the reason for the lack of private investments is knowledge spillovers. Moreover, if 2G bioethanol has a greater GHG emission reduction potential than other biofuels, but no one pays carbon taxes, the market penetration of 2G bioethanol may be too small relative to other biofuels.

3.2. Blending Mandates and Subsidies

A blending mandate is a combination of a carbon tax and a subsidy to biofuels. To the extent that current carbon taxes on biofuels are too low, one should therefore expect blending mandates to outperform pure subsidies. Greaker *et al.* [42] show that a blending mandate postpones fossil fuel extraction and reduces climate costs, even if biofuels entail significant GHG emissions. Grafton *et al.* [43] on the other hand show that a pure subsidy to biofuels has an ambiguous effect on fossil fuel extraction. Thus, in the absence of correct carbon pricing, a blending mandate may be a better policy.

On the other hand, when it comes to spurring technology learning, an unconditional blending mandate supports all biofuels, implying that the currently least expensive ones will benefit the most. Without any differentiation between the types of biofuels, a blending mandate will likely not spur 2G biofuels, since more production of 1G biofuels probably does not lead to cost reduction in 2G biofuels.

A subsidy to biofuels should be differentiated according to the GHG reduction potential and according to the likelihood of future cost reduction from increased experience. This has not been the case so far, as all types of biofuels have received the same subsidies. Moreover, when a blending mandate is combined with other subsidies to biofuels, it implies an indirect subsidy also to fossil fuels and, therefore, increased consumption [35]. Drabik [44] extends this result to other ethanol and feedstock production subsidies. Greaker *et al.* [42] show that a subsidy to biofuels combined with a blending mandate speeds up fossil fuel extraction. Hence, subsidies should not be used alongside blending mandates. It is then better to reserve a share of the mandate for 2G biofuels.

3.3. Blending Mandate Combined with GHG Standard

A GHG standard is an option for differentiating between the types of biofuels in a blending mandate. The standard determines which biofuels are eligible for the blending mandate. Because many 1G biofuels from the U.S. and EU score badly in terms of GHG-reducing potential, a standard may benefit cellulosic ethanol.

Some imported 1G biofuels also score well in terms of GHG-reducing potential, most notably sugar cane ethanol from Brazil, and these 1G biofuels will also benefit from a GHG standard. Some may use this as an argument for a tariff. That is, they would like to protect the emerging 2G biofuels industry from competition from imported 1G biofuels, even if these biofuels entail low GHG emissions. However, because a blending mandate is also a substitute for correct gasoline taxation, fulfilling the blending mandate with low emission 1G biofuels need not be wrong. One should rather find other ways to increase the support to cellulosic ethanol, for instance, reserving a share of the mandate for new technologies.

3.4. Tariffs on Imported Biofuels

A concern is that countries without restrictions on GHG emissions may develop comparative advantages in emission-intensive biofuels production, such as palm oil from former rainforest areas. Thus, there is a potential problem of carbon leakage with increased biofuels usage. Carbon leakage provides arguments for the use of border carbon adjustment (BCA) policies, *i.e.*, a carbon tariff, and a GHG standard for biofuels. If the foreign producer was subject to an optimal emission tax, it would only increase the production of biofuels until the last unit produced entails the level of CO_2 emissions with a damage cost equal to the optimal emission tax. In the absence of an optimal tax in the producing country, an optimal solution can be achieved by a combination of a BCA and a standard. The standard should be set so that the emission level of CO_2 per unit of biofuel produced equals the emissions for the last unit that would have been produced under an optimal tax. Because the standard would not provide an incentive to reduce emissions below the required level, a BCA should also be used, equal to the marginal environmental damage from the last unit of output exported. This combination has the same effect as if the foreign producer were subject to an optimal emission tax [45].

The combination of a BCA and an import standard yields a welfare improvement compared to the case when only the BCA is used. These results face at least two serious challenges if applied to real-world conditions. First, costs for monitoring and enforcement of a standard may offset the gains. Second, if the exporting country also produces for domestic usage, firms have an incentive to export low emission production and sell high emission biofuels to the domestic market, a problem known as shuffling [46]. Possibly, shuffling can be counteracted by applying the standard to the whole biofuel production in the exporting country. However, BCAs and standards may be challenged within the World Trade Organization (WTO) rules. De Gorter and Just [47] forcefully argue that standards are illegal under WTO law, but Horn and Mavroidis [48] hold that a BCA will be considered domestic policy and not a trade instrument. In fact, using a BCA may pass this scrutiny if it can be proven that it is actually protecting the environment.

To conclude, trade policy, if used at all, should only aim to correct for insufficient internalizing of the costs of GHG emissions from the production of the imported biofuels. Introducing BCAs related to the environment entails the risk that BCAs will be misused in a protectionist fashion and the possibility that their use will be expanded to a variety of social justice purposes. One example of misplaced protectionism could be labor and health. It may be argued that it is unfair that a domestic industry in an importing nation has to provide better workplace safety and health systems than a foreign exporting producer in a less developed country. To correct for such unfairness and to prevent "social dumping" some argue that it is necessary to level the playing field by using border measures. However, such measures would actually punish poor nations for being poor and prevent them from becoming richer, which could lead to better work safety and health for workers in the future. For an insightful discussion on BCA and trade issues, see Fischer and Horn [49].

4. Discussion

Blending mandates and subsidies to biofuels are the second best policies. Thus, governments should not stop striving to get fossil fuel prices right. Two-thirds of the global oil consumption is used for transportation, and a major share of the transport fuel is consumed in the U.S. and Canada. In fact, more than 40% of the global gasoline consumption and about 20% of the diesel consumption takes place in North America. In 2003, the per capita consumption of oil in the U.S. and Canada was 11 L per day, while the corresponding figure in other industrialized countries was 4.9 L per day, and the global per capita consumption was 1.9 L per day [50]. In the EU, prices for a liter of gasoline amounts to USD 1.7–2.4, while the corresponding figure for the U.S. and Canada is USD 0.9 and 1.2, respectively. The high per capita consumption in North America is likely, to some extent, a result of a very low gasoline price. It is of course possible that the gasoline prices in the EU are too high in relation to the external effects caused by fuel consumption, yet if we assume that the current prices in the EU do approximately reflect the external costs, the global efforts to control GHG emissions would benefit tremendously from an adjustment of U.S. prices to the same level as in the EU. Such a development would also facilitate gasoline price increases in countries, like Russia and China, which are currently about USD 1.1 to 1.7 per liter [25].

In Section 2, we argue that there likely is an experience curve for 2G bioethanol made from cellulosic material. This may be a rationale for government support. Obviously, it is difficult to assess what levels of funds are needed. IEA [51] makes an attempt to analyze the gap between current funding levels and what is needed to achieve a 50% reduction in energy-related CO_2 emissions from 2005 levels by 2050, in accordance with the stabilization of the global temperature increase at 2 °C. The report was commissioned by the Major Economies Forum on Energy and Climate (MEF), where

Australia, Brazil, Canada, China, the European Union, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, Russia, South Africa, the United Kingdom and the United States collaborate. Ten categories of low-carbon energy technologies/practices, including bioenergy, are mapped. Overall, assuming that the public sector spending accounts for 50% of total research, development and demonstration spending, the estimated gap is USD 14 billion, or about three-times current levels. In terms of bioenergy, required annual spending by MEF economies is estimated to be USD 800–900 million, compared with the current level of USD 590 [51]. These figures seem modest compared with the IEA's latest estimates that fossil-fuel consumption subsidies worldwide amounted to USD 409 billion in 2010, up from USD 300 billion in 2009, with subsidies to oil products representing almost half of the total [2].

It is also important that 2G support policies are limited in their time span. It is well-known from the infant industry literature [52] that governments, by supporting specific industries, run the risk of creating powerful lobbies that later hamper the withdrawal of support programs when the R&D potential is exhausted. Today, we see signs that the support programs for 1G biofuels may have created such a "political lock-in," making it difficult to scale down support, even though 1G biofuels have proven less promising than originally thought. Hence, governments should strive to keep flexibility when crafting support programs for cellulosic ethanol.

5. Conclusions and Policy Implications

This paper reviews the current status of 2G biofuels, particularly biochemical ethanol made from cellulose, and discusses policies that could facilitate the competitiveness of such fuels. 1G biofuels have been and are still substantially subsidized, and this has contributed to the increasing production and use of such fuels. However, recent studies claim that the future of biofuels lies in 2G biofuels, and we find little support for the often-made argument that 1G will bridge the conversion to 2G biofuels. Our first finding is that the potential for cost reductions seems greater for 2G bioethanol than from 2G biodiesel. While 2G biodiesel is a proven technology with excessively high costs, ethanol made from cellulose is far from a ripe technology. Moreover, expert reports point to several potential technological breakthroughs that may reduce cellulose ethanol costs substantially.

Our second finding is that current support for biofuels may not promote the development of 2G ethanol. Many argue that 1G biofuels are likely to pave the way for 2G biofuels; however, based on our literature survey of 2G biofuels technologies, we do not find any strong support for this argument. First, the challenging parts of the cellulosic ethanol production process are not necessary in the production of 1G biofuels and, hence, not present in 1G production. Second, the current car fleet can absorb large amounts of cellulosic ethanol without any costly adjustments to either cars or filling stations. Clearly, 1G biofuels have facilitated a development of a necessary biofuel "infrastructure" on the demand side of the market (consumer acceptance and storage facilities at gasoline stations). However, until 2G biofuels have proven their true potential, we believe that the demand side of the market does not need further development for 2G biofuels to gain experience and for production costs to come down. This implies that governments should not increase existing levels of support to 1G biofuels.

Third, we consider the argument that the import of "cheap" 1G biofuels from developing countries could halt the market introduction of cellulosic ethanol to an undesirable extent. The infant industry argument would hold that 2G bioethanol should receive protection in order to be able to develop. However, given that targeted measures to promote the deployment of 2G bioethanol are put in place, adding another instrument, which also benefits domestic 1G biofuels, seems superfluous. Trade policy should only aim to correct for insufficient internalizing of GHG emission costs from the production of biofuels in countries without a price on carbon.

There may be a scope for successful public intervention by providing targeted support to R&D and to technology learning in order to achieve the necessary cost reductions for 2G bioethanol, both from innovations and from accumulated industry-wide experience. Ethanol made from cellulose using the biochemical conversion process is far from a ripe technology, but it has the potential to reduce GHG emissions from the transport sector without leading to devastating changes in land use practice, something that recent critiques have held against 1G biofuels. Note, however, that this only holds as long as feed stock for 2G biofuels either comes from unused parts of current agricultural products, such as corn stover, or is grown on marginal land that is unsuitable for food production and other production purposes.

This article questions the use of blending mandates to promote 2G bioethanol. Most blending mandates do not distinguish between 1G and 2G biofuels and, hence, do not provide targeted support to 2G bioethanol. In order to spur investments in 2G bioethanol facilities, blending mandates would need to be combined with a set of standards for biofuels, e.g., types of feed stock and GHG reduction potential.

With targeted support to 2G bioethanol, there is no need to pay attention to the infant industry argument, *i.e.*, that competition from well-performing foreign 1G biofuels should be limited by trade policy. Trade policy, if used at all, should only aim to correct for insufficient internalizing of GHG emission costs from the production of these biofuels [45].

It is by no means certain that 2G bioethanol will play a central role in the decarbonizing of the transport market. Even if a favorable environment for innovations and scale economies is created, necessary cost reductions may not be achieved. The GHG emissions from land use change connected to large-scale growing of cellulosic feedstock may turn out to offset the gains from changing fuel. Finally, other options, such as hydrogen or electric vehicles, may experience major innovations that make them preferable to vehicles running on biofuels. Hence, it is important to avoid a technological lock-in with biofuels. Furthermore, one should also be aware of the risk of the political lock-in created by the increasingly influential lobby groups for biofuels.

Acknowledgments

This work was sponsored by Environment and Trade in a World of Interdependence (Entwined), funded by the Foundation for Strategic Environmental Research (Mistra), Sweden. We also acknowledge financial support from the Norwegian Research Council and Formas through the program, Human Cooperation to Manage Natural Resources (COMMONS).

Author Contributions

The two authors have co-operated for the preparation of this work. All sections were co-written and repeatedly discussed by the two authors.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. *CO_2 Emissions from Fuel Combustion Highlights*; International Energy Agency (IEA): Paris, France, 2013.
2. World Energy Outlook. Available online: http://www.worldenergyoutlook.org/publications/weo-2013/ (accessed on 29 June 2014).
3. Von Lampe, M. Agricultural market impacts of future growth in the production of biofuels. *OECD J. Gen. Papers* **2006**, *6*, 1–57.
4. Rajagopal, D.; Zilberman, D. Environmental, economic and policy aspects of biofuels. *Found. Trends Microecon.* **2008**, *4*, 353–468.
5. *Technology Roadmap—Biofuels for Transport*; Organisation for Economic Co-operation and Development (OECD)/International Energy Agency (IEA): Paris, France, 2011.
6. Fargione, J.; Hill, J.; Tilman, D.; Polasky, S.; Hawthorne, P. Land clearing and the biofuel carbon debt. *Science* **2008**, *319*, 1235–1238.
7. Searchinger, T.D.; Heimlich, R.; Houghton, R.A.; Dong, F.; Elobeid, A.; Fabiosa, J.; Tokgoz, S.; Hayes, D.; Yu, T. Use of US croplands for biofuels increases greenhouse gas through emissions from land-use change. *Science* **2008**, *319*, 1238–1240.
8. Khanna, M.; Hochman, G.; Rajagopal, D.; Sexton, S.; Zilberman, D. Sustainability of food, energy and environment with biofuels. *Perspect. Agric. Vet. Sci. Nutr. Nat. Resour.* **2009**, *4*, 1–8.
9. Lapola, D.M.; Schaldach, R.; Alcamo, J.; Bondeau, A.; Koch, J.; Koelking, C.; Priess, J.A. Indirect Land-Use Changes Can Overcome Carbon Savings from Biofuels in Brazil. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 3388–3393.
10. EPA Lifecycle Analysis of greenhouse gas emissions from renewable fuels. Available online: http://www.epa.gov/otaq/renewablefuels/420f10006.pdf (accessed on 9 May 2014).
11. Field, C.B.; Campbell, J.E.; Lobell, D.B. Biomass Energy: The scale of the potential resource. *Trends Ecol. Evol.* **2008**, *23*, 65–72.
12. Carriquiry, M.A.; Xiaodong, D.; Timilsina, G.R. Second-Generation Biofuels Economics and Policies. *Energy Policy* **2011**, *39*, 4222–4234.
13. Hochman, G.; Sexton, S.; Sexton, D. The economics of biofuel policy and biotechnology. *J. Agric. Food Ind. Organ.* **2008**, *6*, 1–22.
14. Rajagopal, D.; Sexton, S.E.; Roland-Holst, D.W.; Zilberman, D. Recent developments in renewable technologies: R&D investment in advanced biofuels. *Annu. Rev. Resour. Econ.* **2009**, *1*, 309–332.

15. Fischer, C.; Newell, R. Environmental and technology policies for climate mitigation. *J. Environ. Econ. Manag.* **2008**, *55*, 142–162.
16. *Deploying Renewables: Principles for Effective Policies*; Organisation for Economic Co-operation and Development (OECD)/International Energy Agency (IEA): Paris, France, 2008.
17. *Experience Curves for Energy Technology Policy*; Organisation for Economic Co-operation and Development (OECD)/International Energy Agency (IEA): Paris, France, 2000.
18. Spence, M.A. The Learning Curve and Competition. *Bell J. Econ.* **1981**, *12*, 49–70.
19. Fudenberg, D.; Tirole, J. Learning-by-doing and market performance. *Bell J. Econ.* **1983**, *14*, 522–530.
20. Dasgupta, P.; Stiglitz, J. Learning-by-doing, market structure and industrial and trade policies. *Oxf. Econ. Pap.* **1988**, *40*, 246–268.
21. Biofuel Production Technologies: Status, Prospects and Implications for Trade and Development. Available online: http://unctad.org/en/docs/ditcted200710_en.pdf (accessed on 10 July 2014).
22. *Gaps in the Research of Second Generation Transportation Biofuels*; International Energy Agency (IEA): Paris, France, 2008.
23. Coyle, W.T. *Next-Generation Biofuels: Near-Term Challenges and Implications for Agriculture*; Diane Publishing: Washington, DC, USA, 2010.
24. *First- to Second-Generation Biofuel Technologies: An Overview of Current Industry and RD&D Activities*; Organisation for Economic Co-operation and Development (OECD)/International Energy Agency (IEA): Paris, France, 2008.
25. Global Petrol Prices. Available online: http://www.globalpetrolprices.com/gasoline_prices/ (accessed on 9 May 2014).
26. Energy Subsidies. Available online: https://www.iea.org/publications/worldenergyoutlook/resources/energysubsidies/ (accessed on 9 May 2014).
27. Janda, K.; Kristoufek, L.; Zilberman, D. Biofuels: Policies and impacts. *Agric. Econ.* **2012**, *58*, 372–386.
28. TransportPolicy.net. Available online: http://transportpolicy.net/index.php?title=Main_Page (accessed on 9 May 2014).
29. USDA GAIN Biofuels Annual Brazil Report. Available online: http://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_Sao%20Paulo%20ATO_Brazil_8-21-2012.pdf (accessed on 9 May 2014).
30. Moreira, J.R.; Pacca, S.A.; Parente, V. The future of oil and bioethanol in Brazil. *Energy Policy* **2014**, *65*, 7–15.
31. *World Energy Outlook*; International Energy Agency (IEA): Paris, France, 2010.
32. *Renewables in Global Energy Supply: An IEA Factsheet*; Organisation for Economic Co-operation and Development (OECD)/International Energy Agency (IEA): Paris, France, 2010.
33. Rajcaniova, M.; Drabik, D.; Ciaian, P. How Policies Affect International Biofuel Price Linkages. *Energy Policy* **2013**, *59*, 857–865.
34. Global Renewable Fuel Alliance. Available online: http://globalrfa.org/biofuels-map/ (accessed on 9 May 2014).
35. De Gorter, H.; Just, R.D. The economics of a biofuel mandate. *Am. J. Agric. Econ.* **2009**, *91*, 738–750.

36. Eggert, H.; Greaker, M. *On Biofuels and Trade: Tariffs, Standards or Import Subsidies?* Gothenburg University: Gothenburg, Sweden, 2009.
37. Alternative Fuels Data Center. Available online: http://www.afdc.energy.gov/vehicles/flexible_fuel_emissions.html (accessed on 9 May 2014).
38. Europa.eu. Available online: http://europa.eu/rapid/press-release_IP-12-1112_en.htm?locale=en (accessed on 9 May 2014).
39. *Bioenergy Policy, Markets and Trade and Food Security*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2008.
40. Reuters. Available online: http://www.reuters.com/article/2013/04/18/biofuels-eu-idUSL5N0D51EC20130418 (accessed on 9 May 2014).
41. Farmdocdaily. Available online: http://farmdocdaily.illinois.edu/2014/03/implying-the-probability-of-an-epa-reversal.html (accessed on 9 May 2014).
42. Greaker, M.; Hoel, M.; Rosendahl, K.E. *Does a Renewable Fuel Standard for Biofuels Reduce Climate Costs?* Statistics Norway Research Department: Oslo, Norway, 2014.
43. Grafton, R.Q.; Kompas, T.; van Long, N.J. Substitution between biofuels and fossil fuels: Is there a green paradox? *J. Environ. Econ. Manag.* **2012**, *64*, 328–341.
44. Drabik, D. *The Theory of Biofuel Policy and Food Grain Prices*; Cornell University: Ithaca, NY, USA, 2011.
45. Eggert, H.; Greaker, M. Trade policies for biofuels. *J. Environ. Dev.* **2012**, *21*, 281–306.
46. Bushnell, J.E.; Peterman, C.; Wolfram, C.D. Local solutions to global problems: Climate change policies and regulatory jurisdiction. *Rev. Environ. Econ. Policy* **2008**, *2*, 175–193.
47. De Gorter, H.; Just, D.R. The social cost and benefits of biofuels: The intersection of environmental, energy and agricultural policy. *Appl. Econ. Perspect. Policy* **2010**, *32*, 4–32.
48. Horn, H.; Mavroidis, P.C. Burden of proof in environmental disputes in the WTO: Legal aspects. *Eur. Energy Environ. Law Rev.* **2009**, *18*, 112–140.
49. Border Carbon Adjustments from a Trade Policy Perspective. Available online: http://entwined.ivl.se/publications/publications/bordercarbonadjustmentsfromatradepolicyperspective.5.488d9cec137bbdebf94800074.html (accessed on 9 May 2014).
50. EIA. Available online: http://www.eia.doe.gov/steo/contents.html (accessed on 9 May 2014).
51. *Global Gaps in Clean Energy Research, Development, and Demonstration, Prepared in Support of the Major Economies Forum (MEF) Global Partnership by the International Energy Agency*; International Energy Agency (IEA): Paris, France, 2009.
52. Grossman, G.M. Promoting New Industrial Activities: A Survey of Recent Arguments and Evidence. *OECD Econ. Stud.* **1990**, *14*, 87–125.