Various policy instruments along with increasing oil prices have contributed to a sixfold increase in global biofuels production over the last decade (2000–2010). This rapid growth has proved controversial, however, and has raised concerns over potential conflicts with global food security and climate change mitigation. To address these concerns, policy support is now focused on advanced or second-generation biofuels instead of crop-based first-generation biofuels. This policy shift, together with the global financial crisis, has slowed the growth of biofuels production, which has remained stagnant since 2010. Based upon a review of the literature, this paper examines the potential long-run contribution of biofuels to the global energy mix, particularly for transportation. We find that the contribution of biofuels to global transportation fuel demand is likely to be limited to around 5% over the next 10–15 years. However, a number of studies suggest that biofuels could contribute up to a quarter of global transportation fuel demand by 2050, provided technological breakthroughs reduce the costs of sustainably produced advanced biofuels to a level where they can compete with petroleum fuels.

1. Introduction

Biofuels have been considered as an option to supplement fossil fuels for transportation since the oil crises of 1973 and 1979. Brazil’s national ethanol programme (Proálcool) is a good example. This programme was aimed at exploiting Brazil’s huge potential for sugarcane production for ethanol. Brazil also introduced a flex-fuel vehicle programme in 2003 and increased the blending mandate for ethanol to 25% in 2007. Owing to supply constraints, the Brazilian government slightly relaxed this mandate in 2011 by lowering it to 18%. Currently, the blend ranges from 18% to 25% [1].

1 Owing to supply constraints, the Brazilian government slightly relaxed this mandate in 2011 by lowering it to 18%. Currently, the blend ranges from 18% to 25% [1].
and policies led to substantial and sustainable use of ethanol within Brazilian transportation; by 2009, ethanol accounted, on a volumetric basis, for 47% of automobile fuel consumption, although the share decreased to 38% in 2011 because of an ethanol price rise [1]. In the USA, the oil crises and environmental concerns over the use of tetraethyl lead as a gasoline octane booster contributed to the promotion of corn-based fuel ethanol during the 1970s, with production reaching 175 million US gallons per year (or 13.6 PJ)\(^2\) by 1980 [3]. Some sub-Saharan countries also introduced biofuels in the early 1980s. For example, Zimbabwe initiated ethanol production in 1980 in response to economic sanctions and foreign-exchange limitations imposed during colonial rule [4]. Malawi responded to the second oil crisis in 1979 by producing fuel ethanol in the early 1980s. However, these initiatives died as oil prices dropped and key incentives for these programmes disappeared.\(^3\)

Interest in biofuels resurfaced in the early 2000s because of concerns about climate change, long-term oil supply security and oil price volatility, and a political desire to subsidize farmers. More than 40 countries around the world have now introduced policies and programmes to support biofuels. For example, Member States of the European Union (EU) have committed to a target of at least 10% of transport fuel, on an energy basis, coming from biofuels (and other renewables) by 2020. Similarly, India has set a target of meeting 20% of transportation fuel, on a volumetric basis, through biofuels by 2017, and China, Malaysia and Indonesia have enhanced their efforts to increase production, trade and consumption of biofuels [6]. Sub-Saharan countries, such as Senegal, Angola, Mali, Malawi and Mozambique, have also expressed a strong interest in biofuels [7]. Globally, existing policies and increased oil prices have contributed to a threefold increase in fuel ethanol production between 2004 and 2010, and a more than eightfold increase in biodiesel production [6].

The resurgence of biofuels has ignited a fierce debate about whether or not policies and programmes to support biofuels should be continued and/or expanded. At one extreme, biofuels are promoted as a solution to climate change problems and global energy insecurity (e.g. [8–10]), while, at the other extreme, they have been labelled as a threat to food supply and a potential cause of hunger and famine [11–13]. The potential contribution of biofuels to reducing greenhouse gas (GHG) emissions has also been challenged [14–16]. These debates have tempered the earlier enthusiasm about biofuels and led many countries to scale down policies promoting food crop-based biofuels. For example, China has decided against using corn to produce biofuels; Brazil has introduced regulations on the type of land that can be used for new cultivation of sugarcane and palm; and India has reoriented biofuel policies towards by-products such as molasses, as well as non-edible feedstocks such as jatropha\(^4\) [17]. After registering a rapid growth rate of 22% per year, on average, over the 2004–2010 period, global production of biofuels has remained stagnant since 2010 [18(2012)].

Although biofuels are surrounded by controversy, and global production has recently stagnated, they may yet have a role in the future global energy supply mix. While rapid expansion of biofuels could exert pressure on food security, a limited and sustainable production of biofuels could still play a role in meeting clean fuel demand for transportation in future [17]. Countries unconstrained by land supply could continue production of biofuels without creating conflicts with food production. In those sub-Saharan African countries which depend entirely on imports for their petroleum supply and which have relatively abundant land, a small fraction of arable lands could be enough to substantially substitute their petroleum imports. Thus, production of biofuels is expected to continue in future although it is uncertain whether it will regain past growth rates. However, two questions obviously arise: how big a role could biofuels play in the

\(^2\)1 PJ = 10\(^{15}\) joule; we used the US corn ethanol energy content of 77.75 MJ per gallon for technology prior to 1990 [2].

\(^3\)China’s biodiesel programme was abandoned after the drop in oil prices in the mid-1980s [5]; the sugarcane-based ethanol programmes in Kenya and Zimbabwe failed owing to drought, poor infrastructure and inconsistent policies [6].

\(^4\)Jatropha is a non-edible oil crop which grows naturally in many parts of the world. It has been promoted as biodiesel feedstock, particularly in India and sub-Saharan Africa, because it can grow on low-quality lands that are not normally suitable for other crops. However, neither its economics nor its agronomy have been fully understood. The cost of biodiesel varies widely depending on labour costs and yield per hectare [7].
future energy supply mix, and what are the key factors determining this role? This review aims to address these questions.

This paper is organized as follows. We first provide an account of the current status of biofuel markets, economics and policies. This is followed by a comparison and evaluation of several projections of biofuels production over the period up to 2050. Section 4 discusses some of the key economic, social and environmental concerns that will influence future market size and policy design. Finally, §5 provides a number of conclusions.

2. Biofuel market, economics and policy support

Biofuels can be divided into two groups—first- and second-generation biofuels—based on the feedstock used for production and the technologies used to convert that feedstock into fuel. Ethanol produced from the fermentation and distillation of the sugar or starch content of plants, such as sugarcane, cereals and cassava, and biodiesel, or fatty-acid methyl ester (FAME), produced through the transesterification\(^5\) of lipids from oilseed crops such as rapeseed, soya bean and palm oil, are known as first-generation biofuels [19,20]. Biofuels produced using technologies that convert lignocellulosic biomass, such as agricultural and forest residues, are known as second-generation or advanced biofuels, as are biofuels produced from non-traditional feedstock such as jatropha and micro-algae. First-generation biofuels have been in commercial production for many years in various countries, but large-scale commercial production of second-generation biofuels has yet to commence.

(a) Biofuel markets

Global production of fuel ethanol grew from 17 billion litres (349 PJ)\(^6\) in 2000 to 86.5 billion litres (1777 PJ) in 2010, an average annual growth of approximately 18%. In the same time frame, global production of biodiesel grew from 0.8 billion litres (28 PJ) to 18.5 billion litres (648 PJ), an average annual growth of approximately 37% (figure 1). Nevertheless, biofuels accounted for just 2.7% of global road transport fuels, on an energy content basis, in 2010. As indicated in figure 1, the growth in global production of ethanol and biodiesel slowed down significantly after 2008.\(^7\)

Figure 2 displays the distribution of ethanol and biodiesel production by country/region in 2011. The two leading ethanol producers, the USA and Brazil, accounted for almost 90% of total ethanol production. Other producers of ethanol in large quantities include Germany, France, Canada, Australia, Belgium, China, Colombia, India, Spain and Thailand [18(2012)]. Production of biodiesel is more evenly distributed across different countries and regions, with the top 10 countries accounting for less than 75% of total production. Although second-generation biofuels are not yet in commercial production, the EU, USA, and Canada, along with China, Brazil, India and Thailand, are investing in research and pilot production projects.

The share of biofuels in the current global energy supply mix is very small. In 2010, global production of biofuels (i.e. ethanol and biodiesel) was 2424 PJ, compared with 531 724 PJ of all primary energy commodities [18(2012),21].\(^8\) As illustrated in figure 3, oil accounted for the largest share (32.2%) of global primary energy supply in 2010, followed by coal (27.7%) and natural gas (21.7%) with biofuels accounting for only 0.5%.

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\(^{5}\)Transesterification refers to a chemical reaction that yields biodiesel from animal fats and plant oils.

\(^{6}\)The Renewable Energy Network’s Global status report for 2012 [18(2012)] gives production data in litres. The data were converted into energy units using conversion factors of 20.54 MJ l\(^{-1}\) for ethanol and 35 MJ l\(^{-1}\) for biodiesel; 1 MJ = 10\(^6\) joules and 1 PJ = 10\(^{15}\) joules. On an energy equivalent basis, 11 of ethanol is equivalent to 0.67 l of gasoline and 11 of biodiesel is equivalent to 0.86 l of diesel.

\(^{7}\)The annual global production of ethanol first decreased in 2011, mainly because of drought in Brazil and high sugar prices, which caused some Brazilian sugar–ethanol complexes to switch over to production of sugar. Global production of biodiesel, however, continued to increase in 2011.

\(^{8}\)The International Energy Agency (IEA) reports energy use in million tons of oil equivalent (mtoe). This was converted to joules using a conversion factor of 41.868 PJ per mtoe.
Figure 1. World fuel ethanol and biodiesel production (PJ). Source: [18(2012)], citing various sources. (Online version in colour.)

Figure 2. Regional production of ethanol and biodiesel in 2011 as a percentage of global production. Source: [18(2012)], citing various sources. (Online version in colour.)

(b) Economics of biofuel

The economics of biofuels largely depend upon the price of oil and the price of feedstocks. The latter generally account for 60–90% of the total production costs of first-generation biofuels [23, 24]; thus, the costs of biofuels are closely tied to the prices of feedstock commodities, whereas the available price depends on crude oil prices [25]. Hence, a comparison of the market prices of biofuels and petroleum products is helpful to evaluate their economics.

A comparison of the historical price of biofuels and their petroleum counterparts indicates that the competitiveness of biofuels varies between countries and with the feedstocks used. In volumetric terms (US$ per litre) the ‘plant gate’ price of Brazilian ethanol was lower than the ‘refinery gate’ price of gasoline in most years since 2002, but in energy terms ethanol was more expensive than gasoline in all years except 2008. Similarly, neither US ethanol nor European biodiesel could compete, on an equal energy content basis, with US gasoline and diesel, respectively (figure 4a–c).⁹

⁹We have used average fuel prices compiled from various sources, because no single source provides all price data needed. Special care has been taken to make the data comparable.
Figure 3. Share of different sources in global primary energy supply (2010). Data sources [18(2011),22]. (Online version in colour.)

Figure 4a shows that, on a volumetric basis, the wholesale price of corn ethanol in the USA did not fall below the refinery gate prices of gasoline (unleaded 87 RON) until 2010. US ethanol remains more expensive than gasoline on an energy equivalent basis, but the ratio between the two fell from 2.17 in 2000 to 1.18 in 2012. Brazilian ethanol derived from sugarcane is more competitive than US ethanol, but is still usually more expensive than gasoline. Biodiesel has always been more expensive than diesel, even on a volumetric basis, despite the fact that a litre of biodiesel provides around 14% less mileage than diesel (figure 3c). Moreover, unlike ethanol in the USA, the price gap between biodiesel and diesel, on an energy equivalent basis, has not decreased.

Although not discussed here it is worthwhile mentioning that there are several studies which estimate the production costs of biofuels, using the existing literature [30] or analysing cost differences between feedstocks [31], although both of these are now a little dated. Nevertheless, some findings of these studies are still relevant. For example, the costs of Brazilian ethanol are lower than for US corn or European wheat ethanol, partly as a result of using sugarcane residue (or bagasse) to meet on-site heat demand and to generate electricity. The cost of ethanol produced from grains appears lower if the value of by-products such as dry distillers grains is taken into consideration. Similarly, the price of biodiesel could fall if a market can be found for the main byproduct, glycerin, which is used in the food, beverages and pharmaceuticals industries [24,32]. It is cheaper to produce ethanol from molasses, a by-product of sugar production, than from sugarcane as the market for molasses is weaker [7]. Biodiesel from jatropha presents an interesting, albeit relatively untried, alternative if yields can be improved to commercial levels and if sufficient low-cost labour can be assembled for the highly labour-intensive seed collection process [7,33]. Compared with first-generation biofuels, the capital costs of second-generation biofuels account for a higher share of overall costs, while the feedstock costs are significantly lower [33]. The costs of producing biodiesel from micro-algae appear to be prohibitively high at present, but these could fall in the future as technology improves and production expands [34].

(c) Biofuel support policies

Biofuels are supported by governments in multiple ways including blending mandates or targets, subsidies, tax exemptions/credits, reduced import duties, support for research and development and direct involvement in biofuel production, as well as other incentives to encourage the local
production and use of biofuels. Table 1 summarizes the biofuel mandates and targets, either already in place or planned, in various countries around the world.

Some countries define their targets in terms of the total volume of biofuels. For example, the US Renewable Fuel Standard (RFS) requires the annual volume of biofuels blended to rise to 36 billion gallons (2854 PJ)\textsuperscript{10} by 2022 [35]. Similarly, China aims for 13 billion litres (267 PJ) of ethanol and 2.3 billion litres (81 PJ) of biodiesel per year by 2020 [18(2010)].\textsuperscript{11} Other countries specify biofuel obligations in terms of the percentage share of the blend. For example, E10 stands for

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\textsuperscript{10}Based on 35 billion gallons of ethanol with energy content of 77.75 MJ per gallon and 1 billion gallons of biodiesel with energy content of 132.5 MJ per gallon.

\textsuperscript{11}Note that many countries do not clearly specify targets for each individual biofuel (e.g. ethanol and biodiesel), but have targets for biofuels as a whole. Mandates are, however, typically specified for each biofuel. Targets are interpreted as wishes or ambitions and could be voluntary, and governments may not necessarily have a strategy to achieve the targets. Mandates, on the other hand, are obligatory.
Table 1. Ethanol and biodiesel mandates and targets in selected countries.a

<table>
<thead>
<tr>
<th>Country</th>
<th>Ethanol</th>
<th>Biodiesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>E6 (New South Wales); E5 (Queensland)</td>
<td>B2 (New South Wales)</td>
</tr>
<tr>
<td>Argentina</td>
<td>E5</td>
<td>B7</td>
</tr>
<tr>
<td>Belgium</td>
<td>E4</td>
<td>B4</td>
</tr>
<tr>
<td>Bolivia</td>
<td>E10</td>
<td>B2.5 by 2007 and B20 by 2015</td>
</tr>
<tr>
<td>Brazil</td>
<td>E18–E25</td>
<td>B5</td>
</tr>
<tr>
<td>Canada</td>
<td>E5 (national, Alberta, British Columbia, Ontario); E7.5 (Saskatchewan); E8.5 (Manitoba)</td>
<td>B2 (national); B2 (national, Alberta, Manitoba, Saskatchewan); B3–B5 (British Columbia)</td>
</tr>
<tr>
<td>China</td>
<td>E10 in nine provinces</td>
<td></td>
</tr>
<tr>
<td>Colombia</td>
<td>E10</td>
<td>B20</td>
</tr>
<tr>
<td>Costa Rica</td>
<td>E7</td>
<td>B20</td>
</tr>
<tr>
<td>EU</td>
<td>10% renewable in transport (2020)</td>
<td>10% renewable in transport (2020)</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>E10</td>
<td></td>
</tr>
<tr>
<td>Finland</td>
<td>E5.75</td>
<td>B5.75</td>
</tr>
<tr>
<td>Germany</td>
<td>E10</td>
<td></td>
</tr>
<tr>
<td>Indonesia</td>
<td>E3; E5 (2015); E15 (2025)</td>
<td>B2.5; B5 (2015); B20 (2025)</td>
</tr>
<tr>
<td>Italy</td>
<td>E4; E5 (2014)</td>
<td>B4; B5 (2014)</td>
</tr>
<tr>
<td>Jamaica</td>
<td>E10</td>
<td>B5</td>
</tr>
<tr>
<td>Malaysia</td>
<td>B5</td>
<td></td>
</tr>
<tr>
<td>Malawi</td>
<td>E20</td>
<td></td>
</tr>
<tr>
<td>The Netherlands</td>
<td>E4</td>
<td>B4</td>
</tr>
<tr>
<td>Norway</td>
<td>B3.5</td>
<td></td>
</tr>
<tr>
<td>Pakistan</td>
<td>B5 (2015); B10 (2025)</td>
<td></td>
</tr>
<tr>
<td>Panama</td>
<td>E2 (2013); E5 (2014); E7 (2015); E10 (2016)</td>
<td></td>
</tr>
<tr>
<td>Paraguay</td>
<td>E18–E24</td>
<td>B5</td>
</tr>
<tr>
<td>Peru</td>
<td>E7.8</td>
<td>B5</td>
</tr>
<tr>
<td>Philippines</td>
<td>E10</td>
<td>B2</td>
</tr>
<tr>
<td>South Africa</td>
<td>2% of transport energy</td>
<td></td>
</tr>
<tr>
<td>South Korea</td>
<td>B2.5</td>
<td></td>
</tr>
<tr>
<td>Spain</td>
<td>B7</td>
<td></td>
</tr>
<tr>
<td>Thailand</td>
<td>E10</td>
<td>B3</td>
</tr>
<tr>
<td>UK</td>
<td>B4</td>
<td></td>
</tr>
</tbody>
</table>

(Continued)
Table 1. (Continued.)

<table>
<thead>
<tr>
<th>country</th>
<th>ethanol</th>
<th>biodiesel</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA(^a)</td>
<td>E10 (Florida, Iowa, Hawaii, Massachusetts, Minnesota, Missouri, Montana, Oregan); E2 (Louisiana and Washington State)</td>
<td>B10; B20 (2015) (Minnesota); B5 (New Mexico and Oregon); B4 (Massachusetts); B2 (Louisiana and Washington State)</td>
</tr>
<tr>
<td>Uruguay</td>
<td>E5</td>
<td>B5</td>
</tr>
</tbody>
</table>

\(^a\)E and B stand for ethanol and biodiesel, respectively; most mandates are in volumetric units except EU renewable fuel mandates, which are on an energy basis. The numbers associated with E and B represent the percentage of ethanol and biodiesel in the blends. For example, E10 stands for 10% ethanol in an ethanol–gasoline blend. All mandates were in place by the end of 2012 unless specified otherwise.

\(^b\)At the national level, the Renewable Fuels Standard 2 (RFS2) requires 36 billion gallons of renewable fuel to be blended annually with transport fuel by 2022. Source: [18(2012)].

10% ethanol and 90% gasoline, on a volumetric basis, in an ethanol–gasoline blend; similarly B2 stands for 2% biodiesel and 98% diesel, on a volumetric basis, in a biodiesel–diesel blend. The target specified by the EU 2009 Renewable Energy Directive is expressed in energy terms because it also includes other renewable energies and technologies such as biogas and electric vehicles.

Tax exemptions/credits and production subsidies are widely used. The USA used to provide the largest subsidies in the form of a blenders’ tax credit of 45 cents per gallon of ethanol (plus an additional 10 cents per gallon for small producers) and $1 per gallon of biodiesel, but these expired at the end of 2011 [36]. A federal tax credit of $1.01 per gallon for cellulosic ethanol from 2009 through 2012 was introduced by the Farm Bill of 2008 [37]. A number of US states also offer production incentives and sales tax reductions or exemptions. Similarly, Canada subsidizes ethanol production at C$0.10 per litre and biodiesel at C$0.20 per litre for the first 3 years, declining thereafter, while five Canadian provinces provide further producer incentives and/or tax exemptions in the region of C$0.09–0.25 per litre [38]. Ethanol production in Brazil was supported through price guarantees, subsidies, public loans and state-guaranteed private bank loans during the industry’s development, but it no longer receives any direct government subsidies [39]. Tax incentives for biofuel production are available in Argentina, Bolivia, Colombia, Paraguay and Portugal, and fuel tax exemptions exist in at least 10 EU countries, as well as Canada, Australia, Argentina, Bolivia, Colombia and South Africa [18(2010)].

Import tariffs are also used in a number of countries to support domestic biofuels production (table 2). India levies the highest import tariffs on ethanol in Asia as it attempts to scale up domestic production [30], whereas Brazil promotes ethanol with one of the highest import tariffs in the world on gasoline [39]. In other instances, tariffs are employed to protect domestic producers from perceived unfair competition. For example, in 2009 the EU imposed 5 year anti-subsidy (or the so-called ‘countervailing’) and anti-dumping duties on US biodiesel producers [47].

While blending mandates and targets, tax incentives, subsidies and import tariffs tend to be the more common policies to encourage biofuel production and consumption, other policies are also employed. In Brazil, the government requires the use of ethanol in government vehicles, imposes a ban on diesel-powered personal vehicles and promotes the sale of flexible-fuel vehicles that can use pure ethanol, gasoline, or any blend of the two, which represent 95% of all new vehicle sales [48]. Similarly, Colombia has mandated the introduction of E85 flex-fuel technology in 60% of new vehicles with under 21 engine capacity starting from 2012, and for larger capacity vehicles from 2013, with the quota growing to 100% of new vehicle sales by 2016 [45]. Thailand, on the other hand, has banned imports of palm oil entirely in order to spur domestic production [30], and India does not permit the use of imported ethanol to meet its blending mandate for the same reason [45].

Large-scale development of first-generation biofuels raises serious concerns about adverse environmental impacts and potential conflicts with food production. As a result, policy-makers are increasingly interested in second-generation biofuels, based on cellulosic and non-crop...
Table 2. Biofuel import tariffs. Sources: [30,40–46]. An ad valorem tax pertains to the actual market value of the commodity in question. NAFTA, North American Free Trade Agreement.

<table>
<thead>
<tr>
<th>country</th>
<th>import tariff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>5% + AU$0.38 per litre (except for USA, New Zealand)</td>
</tr>
<tr>
<td>Brazil</td>
<td>20% on both undenatured and denatured ethanol from outside Mercosur</td>
</tr>
<tr>
<td>Canada</td>
<td>C$0.05 per litre tariff on ethanol imports from outside NAFTA</td>
</tr>
<tr>
<td>EU</td>
<td>(i) ethanol duty of €0.102 per litre for pure ethanol or ethanol–gasoline blend with 70% or more ethanol content (denatured ethanol); 6.5% ad valorem on biodiesel; punitive tariff on biodiesel from the USA (owing to blenders’ tax credit in USA) (ii) 101 countries developing ethanol and vegetable oil enjoy duty-free access under the generalized system of preferences</td>
</tr>
<tr>
<td>China</td>
<td>30% import duty on ethanol</td>
</tr>
<tr>
<td>Indonesia</td>
<td>$1.078 per litre (200% ad valorem) on ethanol</td>
</tr>
<tr>
<td>India</td>
<td>highest import tariffs on ethanol in Asia: 253–605% (denatured) and 52% (undenatured); 12.5% on biodiesel</td>
</tr>
<tr>
<td>Japan</td>
<td>ad valorem import tariff (23.8%) on ethanol reduced to 10% by 2010</td>
</tr>
<tr>
<td>Malaysia</td>
<td>import tariff of 3% on biodiesel; import tariff of 1% on ethanol</td>
</tr>
<tr>
<td>Switzerland</td>
<td>import tariff on ethanol of CHF35 per 100 kg</td>
</tr>
<tr>
<td>Thailand</td>
<td>ad valorem import tariff of 5% on biodiesel</td>
</tr>
<tr>
<td>USA</td>
<td>(i) ad valorem import tariff of 2.5% (undenatured) or 1.9% (denatured); 19% on biodiesel (ii) imports under the Caribbean Basin Initiative enter the USA tariff free within increasing import quotas</td>
</tr>
</tbody>
</table>

feedstocks. A clear policy shift has been occurring as countries divert policy support to the latter [17]. Examples include: (i) the US cap on corn-based ethanol and enhanced mandates on cellulosic ethanol; (ii) a ban on the use of corn to produce ethanol in China and Angola; (iii) a limitation on expansion of sugarcane and palm cultivation in designated areas in Brazil; and (iv) the EU’s new proposal to meet half of its 2020 biofuel targets through non-crop-based biofuels.

3. Long-run projections of global biofuel production

Several international and national organizations have made long-term projections of the global production of biofuels. Using a simple, engineering model the IEA [49] projects that global production of biofuels will increase from 2424 PJ in 2010, or 3% of global transportation fuel supply, to 31 820 PJ in 2050, or 27% of projected global transport fuel demand. The IEA anticipates that this increase can be met without adverse impacts on global food supply and GHG emissions. The IEA projection is based on several assumptions that are contentious. For example, it assumes that the majority of production will come from second-generation feedstocks grown on ‘marginal’ lands that are not suitable for crop production. Average yields (tonnes per hectare) are assumed to increase by 0.7%, 1.3% and 1% per year for conventional ethanol, cellulosic ethanol and conventional biodiesel, respectively. The IEA also assumes that some novel technologies such as micro-algae-based biodiesel will be commercially available by the year 2030. Despite the long time horizon (40 years), these assumptions look optimistic.

12The study assumes that a 30-fold increase over currently announced advanced biofuel production capacity is needed by 2030; a further quadrupling of the capacity is needed by 2050. The study also assumes that 50% of the feedstock for advanced biofuels will come from wastes and agriculture and forest residues.
Table 3. Long-term projections of biofuels from selected existing studies.

<table>
<thead>
<tr>
<th>study</th>
<th>projection horizon</th>
<th>values in final year of projection horizon</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>biofuel production (PJ)</td>
</tr>
<tr>
<td>IEA [49]</td>
<td>2010–2050</td>
<td>31 820</td>
</tr>
<tr>
<td>BP [51]</td>
<td>2012–2030</td>
<td>6754</td>
</tr>
</tbody>
</table>

The 2012 Organization for Economic Cooperation and Development/Food and Agricultural Organization (OECD-FAO) agricultural outlook [50] projects that annual global production of ethanol will reach 180 billion litres (3697 PJ) by 2021, which is slightly more than twice the 2010 level (86 billion litres or 1777 PJ). This study makes a similar projection for biodiesel, with annual production expected to increase from 18.5 billion litres (647.5 PJ) in 2010 to 44.6 billion litres (1561 PJ) in 2021.

Several private organizations have also developed projections of biofuels supply and demand. For example, BP [51] expects global liquid fuel demand to increase from the current level of 87 million barrels per day (mbd) (184 690 PJ y\(^{-1}\)) to 103 mbd (219 000 PJ y\(^{-1}\)) in 2030, with biofuels contributing 19% of the incremental demand (34 020 PJ y\(^{-1}\)). The study estimates that biofuels would provide up to 7% of global transport fuels by 2030.

Several research institutions have also made long-term projections of biofuel production. For example, the 2011 projection by the Food and Agriculture Policy Research Institute (FAPRI) of Iowa State University (ISU) suggests that global annual production of ethanol and biodiesel could reach 149.2 billion litres (3065 PJ) and 27.2 billion litres (952 PJ), respectively, by 2025 [52]. This projection implies an average annual growth rate (AAGR) for ethanol and biodiesel, over the 2010–2025 period, of 3.7% and 2.6%, respectively. These growth rates are very small compared with those observed in the recent past—AAGRs for ethanol and biodiesel were 20% and 37%, respectively, for the 2004–2010 period [18(2011)]. Table 3 summarizes and compares these different projections. The projections made by OECD-FAO, FAPRI-ISU and BP are comparable despite differences in the time horizons, models and the assumptions and data used. A contribution of 7% to total transportation fuels by 2030 looks reasonable since biofuels already contribute around 3%. However, a technological breakthrough on second-generation or non-crop-based biofuels may be needed to realize these projections without causing notable conflicts with food production.

4. Key concerns regarding biofuels

Important concerns about the impact of biofuels on food security, GHG emissions and biodiversity have already contributed to the dilution of policies to promote biofuels and could potentially constrain their growth in the future.\(^{13}\) Below we summarize the available evidence on these impacts based upon a review of the literature.

(a) Impacts on food prices

Biofuels affect food security by increasing food commodity prices; by diverting food commodities, such as corn and wheat, towards the production of biofuels, thereby reducing food supply; and by feedstock production displacing land previously used for the cultivation of crops.

\(^{13}\)A number of studies (e.g., [8–10]) argue that biofuels could contribute to long-run energy and food security. However, studies in favour of biofuels are limited; most literature addressing issues with biofuels focuses on key concerns of biofuels, such as food and fuel conflict and controversial climate neutrality of biofuels.
A number of studies have estimated the impact of biofuels expansion on food prices. The estimates vary widely, however, owing to differences in methodology, data and underlying assumptions. The studies can be divided into two groups: (i) estimates of the influence of biofuel production on historical food prices, particularly during the 2007–2008 period, and (ii) estimates of the future impact of different levels of biofuels production on global food prices. Studies analysing the first issue typically use ‘partial equilibrium’ models, which model the food and agricultural sector in isolation, ignoring interactions with other sectors; studies analysing the second issue typically use ‘general equilibrium’ models, which account for the interactions between multiple sectors and agents. The former have tended to find that biofuels have a relatively large impact on food prices, while the latter have generally found relatively small impacts. Below, we summarize some of these estimates.

Baier et al. ascribe almost 17% of the rise in corn prices and 14% of the rise in soya bean prices between mid-2006 and mid-2008 to expanded biofuels production. They attribute nearly 14% of the rise in corn prices and 10% of the rise in soya bean prices to US biofuels production, and approximately 2% of the price increase for both crops to EU biofuels production. Rosegrant estimates that biofuels accounted for 30% of the increase in weighted average grain prices during 2000–2007, with impacts of 39%, 21% and 22%, respectively, on corn, rice and wheat prices. Mitchell argues that the diversion of the US corn crop to biofuels provided the strongest influence on food prices during the 2007–2008 period, blaming 70–75% of the increase in food commodities prices on biofuels expansion and the related consequences of low grain stocks, large land-use shifts, speculative activity and export bans. Similarly, Hochman et al. identify biofuel expansion as the major factor behind the price inflation of rapeseed, corn and soya bean. For example, they estimate that corn prices would have been 9% lower in 2007 were it not for the increase in biofuels production, and attribute 19.8% of the increase in corn prices between 2001 and 2007 to biofuels expansion.

The studies mentioned above were all published as technical reports or working papers, not in peer-reviewed journals. Moreover, no similar studies have found biofuels to blame when food prices increased again in 2011, and a number of studies contest the contribution of biofuels to rising food prices. Speculation by financial investors, in particular index fund activity, may have played the more important role in the price spike, and the role of biofuels was perhaps much smaller than initially claimed. Ajanovic also argues that the volatility in food commodity prices is better explained by changes in the oil price, as well as speculation in the oil market, among other factors.

Projections of the long-run impacts of biofuels on food prices generally suggest that these will be smaller than the short-run impacts observed in the recent past. Using a global computable general equilibrium (CGE) model with explicit representation of land-use change and biofuels sectors, Timilsina et al. estimate that the price of sugar will increase by more than 9% as a consequence of existing biofuel targets and mandates, while the impact on other food-based feedstocks will be significantly lower. Similarly, Kretschmer et al. project the price of corn, sugar crops, wheat and other grains increasing by only 0.2–1.7% relative to the reference scenario by 2020 if the EU’s 10% biofuel target is achieved (ignoring the targets of non-EU countries). Using a similar approach, Al-Riffai et al. also estimate a rather small effect of the EU biofuel policies on food prices. Fischer et al. use a global CGE model to estimate that the implementation of existing mandates and targets would increase crop prices by some 30% in 2020 when compared with a reference case that freezes biofuels production at 2008 levels. The price increase would, however, drop to 15% for cereals if commercial application of second-generation biofuels is accelerated. Britz & Hertel show that if 6.25% of liquid fuel in the EU in 2015 were displaced by biodiesel, oilseed prices would rise by 48% compared with that in 2001.

In summary, while some studies claim that biofuels production has played an important role in increasing regional and global food prices, particularly during the 2007–2008 global food crisis,
other studies project rather smaller impacts in the period to 2020. These estimates are sensitive to
the modelling approach and assumptions used, and particularly to the assumed future volume of
biofuels production. Overall, while there is consensus that the expansion of biofuels has increased
global food prices over the past decade, and will continue to do so in the future, there is little
agreement on the magnitude of those impacts.

(b) Impacts on land supply

While small-scale production of biofuels might not cause reallocation of land from food
production, large-scale expansion of biofuels almost certainly would. Land reallocation could
occur on two fronts: (i) diversion of land from crops not used for biofuels (e.g. rice, fruits
and vegetables) towards production of crops used for biofuel production (e.g. corn, sugarcane
and sugarbeet, rapeseed) and (ii) diversion of forest and pasture towards croplands. Biofuel-induced
land-use change occurs not only through the direct conversion of forest or agricultural lands
to biofuel feedstock cultivation, but also takes place indirectly when agricultural areas are
expanded elsewhere to make up for the crops that are displaced by the encroachment of biofuel
feedstock cultivation. This type of impact of biofuels is termed indirect land-use change (ILUC)
[68,69]. For example, when cultivation of sugarcane is expanded onto land previously used
for soya beans, then soya bean cultivation may move to pasture land and, in turn, forest
land may be converted into pasture. A number of studies have attempted to estimate these
complex impacts.

Some studies [44,60,61,70] estimate significant reallocation of lands across cropland and
between cropland, pasture and forests because of biofuel mandates and targets. Timilsina et al.
[61], for example, estimate that a doubling of biofuel targets and mandates could increase
the land needed for sugarcane, oilseeds, barley and wheat production by up to 9% in 2020, at the
expense of rice, fruits and vegetables. Hertel et al. [70] estimate that meeting US and EU biofuel
mandates will substantially increase the harvested area for oilseeds in the EU (48%), Canada
(19%) and Oceania (19%) and for sugarcane in Brazil (23%). Fischer et al. [44] show that the
expansion of biofuels to meet existing targets could increase demand for arable lands by 1–3%
in 2020 depending on the scenario considered. Britz & Hertel [67] find that substituting 6.25% of
liquid transport fuels in the EU by biodiesel in 2015 would lead to a 0.54% expansion of global
cropland, mostly through conversion of pasture to croplands, except in Canada where conversion
of forest dominates.

Some studies downplay the impacts of biofuels on land reallocation. For example, Gauder
et al. [71] do not consider land reallocation a significant constraint on the expansion of
biofuels in Brazil. They estimate that an additional 20 million hectares of land will become
available for agricultural production in Brazil in the period to 2020. As a result, 67% of
Brazil’s 2007 road transport energy could be met by domestically produced ethanol while still
increasing primary food production by 140%. Moreover, productivity gains should enable the
production of 32 million m$^3$ (or 657 PJ) of ethanol in 2020, while maintaining food production
beyond what is necessary to feed the projected population in Brazil, without an expansion of
cropped area.

Some studies argue that, if large areas of previously abandoned arable lands are brought
back into cultivation, the impact of biofuels on land supply could be limited. For example, more
than two-thirds of West Africa’s cultivable lands are currently not farmed, including 9 million
hectares of irrigated lands [72]. As an illustration, only 45% of the estimated 9 million hectares
of cultivable land in Burkina Faso was sown in 2007, leaving considerable land available for new
crops. Similarly, Watson [73] estimates that almost 6 million hectares of suitable land is available
for sugarcane cultivation in Angola, Malawi, Mozambique, Tanzania, Zambia and Zimbabwe,
with over 2.3 million hectares in Mozambique alone. Moreover, in order to avoid competition for

\footnote{15 If co-products of biofuels are accounted for, the land requirements of increased corn ethanol production in the USA to meet
the mandated volume in 2015 would be reduced.}
land with food crops, it has often been recommended that degraded or marginal lands be targeted for biofuel production, although degraded lands, typically lacking water and nutrients, are likely to have a low productivity for biofuel feedstock as well.

In summary, biofuels production has both direct and indirect impacts on land use, but the scale of these impacts depends upon the type, location and scale of biofuels production. If consumption of biofuels is limited to a small fraction of total transportation fuels at the global level, the impacts on land use could be manageable. On the other hand, if larger volumes of transportation fuel were to be derived from biofuels, this would lead to significant regional and global impacts on land use and food supply. Development of second-generation biofuels would help relieve the stress on land and food supply, but commercial production of second-generation biofuels has yet to commence and the use of energy crops, such as switchgrass, to produce second-generation biofuels would still cause land-use change, though to a lesser extent than crop-based first-generation biofuels.

(c) Impacts on greenhouse gas emissions

The substitution of fossil fuels with biofuels has the benefit of avoiding GHG emissions associated with fossil fuel combustion. However, a large-scale expansion of biofuel could trigger substantial GHG emissions through land-use change—particularly if farmers clear ‘virgin’ forests to meet increased demand for food and feedstocks. Biofuels, in general, have lower GHG emissions than their fossil fuel counterparts if the emissions arising from both direct land-use changes and ILUC are ignored. For example, the OECD [42] estimates that sugarcane ethanol reduces GHG emissions by 90% compared with gasoline, while the IEA [24] estimates that second-generation biofuels from cellulosic feedstocks can reduce GHG emissions by 70–90% compared with gasoline and diesel. Ethanol derived from molasses and cassava in Thailand can reduce GHG emissions by 64% and 49%, respectively, compared with conventional gasoline [74], while GHG reductions from wheat-based ethanol vary from as low as 18% to as high as 90% depending upon the country, farming practice, yield and other factors [44]. The GHG benefits of corn-based ethanol are generally acknowledged to be poor, but estimates vary from anywhere between negative emission savings to more than 50% relative to gasoline, depending on the type of fuel used in ethanol-processing plants [75]. Jatropha-based biodiesel has also been estimated to yield substantial life cycle GHG emission savings in the range of 66–68% compared with a reference fossil fuel chain when co-products are used, although this estimate relies on several optimistic assumptions such as high seed yields and minimal nitrogen requirements [76].

However, once the release of carbon stored in forests or grasslands during land conversion to crop production is taken into consideration, the appeal of biofuels as a means of reducing GHG emissions severely diminishes. A number of studies have shown that the emissions related to land-use change caused by biofuel expansion could be so high that it would take many years to offset those emissions through the replacement of fossil fuels. This has been labelled as the ‘carbon payback period’ or ‘carbon debt’ [14–16]. Fargione et al. [14], for example, estimate a carbon payback period of 48 years when Conservation Reserve Program land is converted to corn ethanol production in the USA; over 300 years when Amazonian rainforest is converted to soya bean biodiesel production; and over 400 years when tropical peatland rainforest is converted for palm oil biodiesel production in Indonesia or Malaysia. Similarly, Romijn [77] estimates a carbon payback period of more than 30 years for a large-scale jatropha cultivation on miombo woodland in sub-Saharan Africa.

Since the carbon losses from land-use change are incurred at the time of land conversion, while GHG savings from the substitution of biofuels for fossil fuels accrue gradually over time, the biofuel mandates and targets announced by various countries would not result in GHG savings in the near term. For example, the carbon debt from implementing currently announced...
biofuel targets could be 30–50 years [44]. Timilsina & Mevel [78] find a shorter payback period, varying between 1 and 20 years depending on the source of new land demanded by increased biofuel production. If the entire demand for new cropland is met through pasture lands without causing any deforestation, the biofuels targets would cause net GHG reductions, starting from 1 year after the implementation of the targets. On the other hand, if the new land demand is met through diversion of forests to croplands, net GHG reduction would not occur until 20 years after the implementation of the targets. Havlík et al. [69] report that the cumulative net carbon emissions from land-use change when first-generation biofuel consumption is increased to 7.5% of total transport energy consumption in 2030 would be 70–80% higher than without any additional biofuel production beyond 2005 levels. This equates to a carbon payback period of 22–27 years.

Some countries have introduced policy instruments to control the adverse impacts of biofuels on climate change mitigation. For example, Brazil has initiated a programme (ZAE Cana) to coordinate the allocation of available land to the production of sugarcane (which could be applied to other biofuel feedstocks as well) in order to halt deforestation and ILUC [79]. The new Renewable Fuels Standard (RFS2) in the USA requires that new facilities to produce first-generation biofuels should reduce GHG emissions by 20% in comparison with gasoline; advanced biomass-based diesel and non-cellulosic advanced biofuels should reduce emissions by 50%; and cellulosic biofuels should reduce emissions by 60% [46]. Although existing first-generation ethanol plants are exempted from this requirement, the RFS nonetheless demands that at least half of the biofuels mandated by 2022 should decrease life cycle GHG emissions by 50%. Consequently, the GHG emission savings attributable to the biofuel mandate of RFS2 in 2022 (including second-generation biofuels) are estimated to be around 100 million tonnes of CO₂ (Mt CO₂) per year [80].

In summary, biofuels reduce GHG emissions to varying degrees compared with their fossil fuel counterparts provided their indirect impacts on land-use change (ILUC) are ignored. Once ILUC effects are taken into consideration, the climate change benefits of most biofuels severely diminish. A large-scale expansion of biofuels at the global level would even increase GHG emission, instead of decreasing it, at least over one or two decades.

(d) Impacts on biodiversity and ecosystems

The impact of biofuel production on biodiversity varies according to the type of land considered. Since many current biofuel crops are especially suited for cultivation in tropical areas, biofuel expansion could convert natural ecosystems in tropical countries that are biodiversity hotspots into feedstock plantations [81]. The expansion of oil palm plantations, for example, which do not require much fertilizer or pesticide, can trigger the loss of rainforests and the associated biodiversity, and perhaps half of the oil palm plantations in Malaysia and Indonesia replaced natural forests and the associated biodiversity [82]. The Mata Atlantica region, one of the foremost biodiversity hotspots in the world, is home to more than 60% of the sugarcane cultivation in Brazil, while Brazilian sugarcane and soya bean production is also contributing to the clearance of the world’s most biodiverse savannah, the Cerrado [30]. Although sugarcane cultivation is not suited for the climatic conditions of the Amazon, the expansion of sugarcane plantations elsewhere in Brazil, such as the state of São Paulo, could displace soya bean or corn plantations or livestock breeding operations to the Cerrado or the Amazon [83]. Some of the promising feedstocks for second-generation biofuels are classified as invasive species; for example, South Africa includes jatropha on its list of invasive species [4]. Without appropriate management, the introduction of such species to new lands may have unintended consequences [32].

Since around 70% of global freshwater is already dedicated to agriculture, the potential impact of biofuels on water supply could also be serious. For commercial yields, the water requirement for the major biofuel feedstocks (especially sugarcane, oil palm and corn) is substantial, which means increased demand for irrigation and potential strains on water supply.
In Brazil, for example, where 76% of sugarcane production is rain-fed, some irrigated sugar-producing regions in the northeast are already approaching the hydrological limits of their river basins [32].

5. Conclusion

Global biofuels production grew by approximately 20% per year between 2000 and 2010, owing to a combination of supportive policies and increasing oil prices. By 2010, biofuels were providing around 3% of global transportation energy use. This rapid growth has led to several concerns, however. The production of biofuels has contributed to food price increases, including the 2007–2008 global food crisis, and is increasingly seen as a threat to food security. The potential contribution of biofuels to climate change mitigation has also been challenged. These concerns have caused many countries to reduce their policy support for biofuels, particularly those derived from crops. Many biofuel programmes have been redesigned to avoid negative impacts on food supply, and there has been an increased focus on second-generation or advanced biofuels. Because of these policy shifts and the global financial crisis, biofuel production has remained stagnant since 2010.

On an energy equivalent basis, the plant gate prices of ethanol and biodiesel remain higher than the refinery gate (or import) prices of their petroleum counterparts. Moreover, the scope for reducing the production costs of first-generation biofuels appears limited because feedstock accounts for more than half of the production costs, and a substantial reduction in food prices is unlikely because of increasing global food demand. At the same time, technological breakthroughs with second-generation biofuels have been slow to emerge, and it may be some time before they become competitive against their petroleum counterparts.

Besides the cost disadvantages, concerns about the negative impacts on food production and the environment could further limit the growth of biofuels. Most studies show that biofuel production has increased food prices, although the estimated size of the effect varies widely owing to differences in the modelling approach and underlying assumptions. Studies projecting the long-term impacts of biofuels indicate that, as long as biofuels account for a small fraction of the global transportation fuel demand (up to 10%), impacts of biofuels on land use, food supply and food prices would be small. If a larger volume of transportation fuel were to come from biofuels, it would cause a significant impact. Although the use of second-generation biofuels could help relieve the stress on land and food supply, their large-scale commercial production would not be feasible unless either their prices drop dramatically or heavy subsidies are provided by the governments. Moreover, second-generation biofuels do not necessarily avoid the land and food supply impacts, as energy-rich feedstock such as switchgrass still competes with food crops on land use. The climate change mitigation benefits of biofuels severely diminish if their ILUC effects are taken into consideration.

Existing literature on the projections of global biofuel demand suggests that biofuels will contribute less than 5% of global transport fuel over the next decade. These studies, however, expect second-generation biofuels to make a technological breakthrough within a decade or two, thereby allowing biofuels to make a bigger contribution to global transportation fuels by the middle of the century. The IEA projects that biofuels could meet 27% of global transportation fuels by 2050 without threatening global food security as more and more production will come from advanced biofuels grown in lands which are unsuitable for crops. However, such long-term projections are associated with considerable uncertainty and this estimate looks optimistic. Although the cost disadvantage and conflict with food supply pose tough challenges, biofuels will probably play a small but important role in meeting global transportation fuel demand because other clean energy alternatives for transportation services are highly limited.

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