Chemical Engineering Science: X 10 (2021) 100090

Contents lists available at ScienceDirect

Chemical Engineering Science: X

journal homepage: www.elsevier.com/locate/cesx

Liquid biofuels from food crops in transportation – A balance sheet of outcomes

Meredith R. Barr[a], Roberto Volpe[a,*], Rafael Kandiyoti[b]

[a] School of Engineering and Materials Science, Queen Mary University of London, Mile End Road, London E1 4NS, UK
[b] Department of Chemical Engineering, Imperial College London, London SW7 2AZ, UK

ARTICLE INFO

Article history:
Received 29 August 2020
Received in revised form 20 November 2020
Accepted 25 January 2021

Keywords:
Biofuels
Food crops
Policies
Environment

ABSTRACT

The production and utilization of biofuels from food crops have been reviewed. Developments in Brazil, the United States, the European Union and China have been assessed in relation to the aims of biofuels policies, their costs and outcomes. The energy input for making biofuels has been compared with energy released during their combustion. The effect of using crops for fuel on the cost of grain for food and of arable land have been examined. There is evidence that current international policies have caused environmental degradation greater than the fossil fuels they were purported to replace. However, policy choices are difficult to reverse. Despite vast effort and expense, the actual scale of biofuels production is small compared to the resources that have been mobilized. As these processes have evolved, new groups of commercial interests have coalesced internationally, to take advantage of the subsidies with little recognizable benefit to the environment.

1. Introduction

One key outcome of price hikes and fuel shortages set off by the oil embargoes of 1973–4 was the scramble to produce liquid fuels from raw materials other than crude oil. For nearly a decade, much R&D activity focused on thermochemical routes for converting *coals* to liquid fuels and chemical feedstocks. It also stimulated allied work on sourcing renewable fuels from *plant*-derived materials (biomass).

In the early 1980s, making fuels from biomass was given a public face by American biochemist Melvin Calvin, the Nobel Laureate (1961) credited with discovering the chemical mechanisms of photosynthesis. Calvin publicized the idea of extracting diesel precursors from wild rubber plants, such as *Euphorbia tirucalli* (aveloz), which normally grow on semi-arid "marginal lands" (Duke 1983). In the event, the pathways he proposed for making synthetic fuels proved problematic. However, towards the end of the same decade, concerns about anthropogenic greenhouse gas emissions brought making liquid fuels from "biomass" back into focus as a topic of investigation.

The argument for burning biomass-derived materials as fuel to combat rising CO_2 concentrations in the atmosphere is well known: using plant-derived material as fuel releases carbon dioxide that had been captured from the atmosphere during recent plant growth – and can be recaptured by present day plant regrowth. Therefore, goes the argument, burning plant-derived fuels makes no *"net"* contribution to atmospheric greenhouse gas concentrations.

In this paper, aspects of the production and utilisation of synthetic biofuels, mostly made from food crops, will be examined and discussed. Of the two main types of biofuels considered, "bioethanol" is usually made by fermenting the sugars in crops like wheat, corn (maize), sugar cane mash or molasses, and in some more recent applications, is made from switchgrass or wood-derived biomass. Once the fermentation is completed, the product ethanol is recovered by distillation. "Biodiesels" on the other hand, are made by the esterification of long chain fatty acids present in plant-derived oils with a simple alcohol such as methanol. This reaction produces "fatty acid methyl esters" (FAME), the more common of the biodiesels. In this formulation, the oils are mostly sourced from crops like soy beans, rapeseed, sunflower seeds or palm nuts. Other formulations of biodiesels will be mentioned below.

Below, we examine costs and outcomes associated with the expanding use of biofuels, as they relate to environmental concerns and officially stated aims, viz. the improvement of energy security, stimulating rural development and reducing ('net') greenhouse gas emissions (Franco et al. 2010). An attempt will be made to match the environmental and other outcomes of expanding biofuels pro-

---

* Corresponding author.
E-mail address: r.volpe@qmul.ac.uk (R. Volpe).

https://doi.org/10.1016/j.cesx.2021.100090
2590-1400/

duction against the stated objectives. The effects of what has now become a pattern of pivotal agricultural transformations in several regional contexts (South America, European Union, South East Asia) will be explored. The paper will also examine more recent developments in China concerning biofuel production and utilisation, as well as survey the implications of expanding biofuels production in relation to demand for arable land and the cost of food crops.

2. The evolution of biofuels production & utilisation

Currently, some sixty countries have either declared biofuel blending targets or mandated minimum levels of bioethanol and/or biodiesel blending in petroleum-derived fuels (Lane 2019). The geographic spread of these activities covers many parts of Africa, of the Indian Ocean, of South East and East Asia, and many parts of the Americas and Europe. The evolution of biofuels production and its patterns of utilisation show characteristic differences in these distinct regional contexts (Lane 2019). At the time of writing, Brazil, the U.S.A., the European Union and China provided the greater part of global activity focused on biofuels production and utilisation.

In Brazil, making low-level bioethanol blending mandatory first started in 1931 (Nogueira and Capaz 2013). However, it was the oil price increases during the 1973–4 embargoes that provided the critical stimulus for expanding the use of bioethanol, with the stated aim of reducing the country's oil import bill. At the time, "national self-sufficiency" was the commonly followed model of development and a level of protectionism was considered as normal. Brazil duly invested in increasing sugar cane production; distilleries were modernised and expanded. At that stage, the domestic price of ethanol was about three times that of automobile gasoline. Subsidies were introduced and tax breaks for ethanol producers were put in place to improve the economics of using more ethanol in cars, with the ultimate aim of reducing the expenditure of foreign currency. From 0.6 billion litres in 1975, ethanol reached 11 billion litres (nearly 3 billion U.S. gallons) in 1990 (Ngee Ann Polytechnic Singapore, 2011). [A U.S. gallon ≅ 3.785 L.] By 2008, the production of bioethanol had risen to 28 billion litres. Biodiesel blending (5%) was introduced in 2005 and made mandatory in 2010. By that date, 8.8 million hectares, nearly 12% of the total cultivated area of Brazil, was given over to planting for biofuels production (Nogueira and Capaz 2013). The biodiesel mandate was raised from 8% to 10% (B-10) from March 2018 (Licht 2019).

The expansion of bioethanol production in Brazil had originally been designed as a response to economic security needs as perceived in the context of an import substitution economy, before the move to liberalization in 1990. Since that time (1990), Brazil's oil deficit has somewhat narrowed from 6 to 700,000 barrels pd (about 35 million tons pa) in the 1980s to less than 400,000 barrels pd in more recent times (BP 2020). Until the early-1990s, the country's current account balances had oscillated narrowly on either side of "balanced". After the liberalization of trade policies in 1990, current account balances were allowed to oscillate fairly widely, while the total volume of foreign trade expanded rapidly (Trading Economics 2020), reducing the relative magnitude and significance of the oil import bill.

Meanwhile, the Brazilian state's sustained commitment to the agri-business sector had brought a powerful industry into existence, capable of producing large amounts of bioethanol. At this transition (1990), producing ethanol for the purpose of mitigating greenhouse gas (GHG) emissions could readily be adopted as a convenient new vehicle for maintaining continuity in the ethanol industry, albeit in pursuit of a relatively novel nominal objective. It justified the use of what was already in place, with evident potential for future expansion, backed by decades of accumulated operating experience and knowhow (Filoso et al. 2015).

In Europe, the Commission in Brussels issued its first whitepaper on the use of "renewable" fuels for motor transport in 1997. Three related aims were articulated to explain the intended move towards biofuels. The first was energy security, the perennial concern of a continent that imports a large proportion of the energy it consumes. The second aim was to achieve savings in GHG emissions, and the third was to stimulate rural development (European Commission 1997).

The first EU mandate for blending biofuels in motor fuels was issued in 2003, initially aiming at relatively modest levels: 2% by end-2005 and 5.75% by end-2010 (Directive 2003/30/EC). The "Renewable Energy Directive" passed by the EU Commission in 2009, "repealing Directives 2001/77/EC and 2003/30/EC" raised the biofuel threshold "from renewable sources" to 10% of "all energy in road transport fuels" by the year 2020 (ICCT and DieselNet, 2018; European Commission 2009).

Table 1 shows the stagewise increase in biofuels production capacities in European Union countries between 2000 and 2018. According to the EU Renewable Energy Progress Report 2017, the share of biodiesels in all biofuels used in 2015 was just above 80% (10.9 Mtoe), and that of bioethanol just under 20% (2.6 Mtoe) (Buffet 2017). The EU produces most but not all of its ethanol; imports average about 10% of consumption (Voegele 2019).

Initially, it was intended to source the oils for biodiesel production from European producers, to reduce dependence on imports and maintain security of supply. Some rapeseed could readily be diverted from edible oil use (canola oil) to processing for biodiesel (Schutter, 2013). However, it was clear early on in this process that the available arable land within the EU was not sufficient to produce rapeseed oil in the quantities necessary to fulfil the 10 percent biofuels mandate of the European Commission. Currently, within the European Union, farmers devote nearly 6 million hectares of arable land to rapeseed cultivation (Trompiz et al. 2020), providing about 60% of the vegetable oils used in biodiesel production (Trompiz and Croft, 2017).

Already, between 2000 and 2006, EU imports of palm oil had doubled to fill the gap in supply left by the diversion of rapeseed oil to biodiesel production. By 2013, it was estimated that "...10 m hectares of additional land could be needed by 2020,

Table 1
Total biofuels production capacities in the European Union between 2000 and 2018, in thousand tons per year. Adapted from EUROSTAT "Liquid biofuels production capacities" (last updated 9 April 2020) (Eurostat 2020).

Year	Production capacity (1000 tons per annum)
2000	479
2001	693
2002	810
2003	1,747
2004	2,030
2005	3,173
2006	5,370
2007	11,622
2008	16,130
2009	19,842
2010	21,365
2011	21,750
2012	21,479
2013	22,066
2014	22,117
2015	22,304
2016	21,272
2017	21,982
2018	22,917

including 5 m hectares of additional land outside the EU" (Schutter, 2013). In the event, several million tons (MT) of palm oil required for biodiesel production, as well as 100 thousand tonnes of biodiesel itself, is being supplied by Malaysia and Indonesia (Licht 2019). The irony of importing palm oil from half-way around the world in the name of "security of supply" appears to have escaped the attentions of the European Commission since that time. By the year 2017, more than half of EU biodiesel was being made from imported crops, mostly from South East Asia (White 2017).

Table 2 presents current palm oil export figures given by the U. S. Department of Agriculture. At the time of writing, the EU was one of the world's three largest importers of crude palm oil (6.4 MT pa), nearly joint second with China, behind India importing 9 MT pa. Other importers of significant palm oil quantities include Pakistan, Bangladesh, the United States, the Philippines and Egypt, in decreasing order (IndexMundi 2020). Palm oil is used in preparing a wide spectrum of products, from food to detergents (Tan 2018). In the EU, however, nearly half the palm oil imported is used for biodiesel production (Bannon 2020).

In the United States, the low-level use of ethanol as a fuel additive has a history that goes back to the Ford Model T (1908), designed "to run on a mixture of gasoline and alcohol" (US EIA 2020a). Severely restricted during the prohibition years (1920–1933), the fortunes of ethanol were revived following the repeal of the 18th amendment to the U.S. Constitution (1933), banning the "manufacture, sale, and transportation of alcoholic beverages" (Constitution of the United States, Amend XVIII). Its use as a motor fuel was liberalized, and increased during shortages of petroleum-derived fuels during wartime. However, it was yet again the oil embargoes of the 1973–4 that revived ethanol's fortunes as an alternative fuel. By 1980, the production of ethanol had reached 175 million U.S. gallons, and was steadily rising (RFA 2020).

The large-scale production of bioethanol in the new century served yet another purpose. During the Cold War years, the Soviet Union had provided a ready market for the large post-WW II U.S. grain surplus (Brada 1983). After the break-up of the Soviet Union in 1991, massive improvements took place in agricultural production, with Russian grain harvests increasing rapidly to satisfy domestic demand and then begin to produce surpluses. By 2018–19, Russia was exporting 44 million tons of grain (Donley 2019).

In the face of overproduction, successive U.S. administrations have looked for ways to stabilize U.S. grain prices (Nichols et al. 2006) at levels that would satisfy powerful farm lobbies. By the time the U.S. Congress enacted the Renewable Fuel Standards (RFS) in 2005, setting minimum limits for the use of "renewable fuels, including ethanol" (US EIA 2020a), fuel ethanol production had reached nearly 4 billion U.S. gallons (RFA 2020). The next Renewable Fuel Standard (RFS2), published in the context of enacting the "Energy Independence and Security Act (2007)", required that 36 billion U.S. gallons per annum (pa) of transport biofuels be used by 2022 (RFA 2020).

Table 2
Palm oil exports by country, in metric tons (IndexMundi 2020).

Rank	Country	Exports in 2019(metric tons)
1	Indonesia	28,750,000
2	Malaysia	16,725,000
3	Guatemala	810,000
4	Colombia	775,000
5	Papua New Guinea	570,000
6	Honduras	400,000
7	Thailand	325,000
8	Ecuador	265,000
9	Côte D'ivoire	230,000
10	Costa Rica	210,000

The two successive RFSs provided the impetus to increase ethanol production rapidly. In 2019, the *production* of ethanol had reached about 16 billion U.S. gallons, which was close to the target in RFS2 (RFA 2020). A little over 13 billion U.S. gallons of bioethanol were used as fuel additives in the second half of 2019 and the first half of 2020 (Clemente 2015). At present, the majority of petrol sold in the U.S. contains 10% v/v bioethanol (US EIA 2020a). Corn (maize) makes up a large proportion (approx. 80–85%) of grain processed into ethanol; about 40% of the corn grown in the U.S. ends up as fuel ethanol. Diverting this food crop to the biofuels industry has become of vital importance for grain-growing states, affecting social and political developments at the national level (Clemente 2015). In the United States, creating demand for grain is an overtly political issue.

It is also a sensitive issue. During the autumn of 2019, the U.S. Federal Government increased the number of federally-mandated biofuel *exemptions*, granted to help the economies of relatively small oil refineries. This produced an adverse reaction among grain farmers, worried that the waivers would undermine ethanol and biodiesel demand. In response, the U.S. Environmental Protection Agency promised to enforce the RFS statute requiring that at least 15 billion U.S. gallons of corn ethanol be blended into the fuel supply in 2020 (Meyer 2019). Both primary stakeholders in this arrangement, the oil sector and the corn lobby, consider this to be a "key battleground" (Licht 2019).

In China, meanwhile, crude oil production is expected to remain near 200 MT pa after 2020, while imports are projected to rise steadily to near 650 ± 50 MT pa, by the year 2030. The development of biofuels was initially seen as a means of improving energy security, by helping to narrow the growing gap between stagnating domestic crude oil production and steadily increasing imports (Chang et al. 2012).

During the initial "trial period" between 2002 and 2007, making bioethanol from corn (maize) and wheat reached modest production levels nearing 1.25 MT pa, the bioethanol being used in 10 percent ethanol blends (E10). However, the year 2006 saw a significant increase in the International Food Price Index, from over 101.1 in January to just under 115 by year's end. Small but telling parallel increases in domestic Chinese food grain prices appears to have prompted a course correction in biofuel policies in order to mitigate damage to food security and to the environment (Chang et al. 2012).

The "Medium and Long-Term Development Plan for Renewable Energy" published in 2007 set targets for the years 2010 and 2020 (Chang et al. 2012). However, a new *non-grain fuel ethanol* requirement was added to the production mandate. China aimed to reach 2 MT pa by 2010 and 10 MT pa by 2020. Biodiesels, on the other hand, were to be sourced from waste vegetable oils. Relatively modest biodiesel production targets were set at 0.2 MT pa for 2010 and 2 MT pa for 2020, respectively. Since that regulation was put in place, however, the expansion of biofuels production in China has slowed significantly; production increases have come mainly from capacity expansion within designated existing projects. In 2012, the World Bank estimated that unless additional "fiscal incentives" were provided, China would likely fall short of its target due to the higher production costs of biofuels produced from non-grain feedstocks (Chang et al. 2012).

The indications are that Chinese authorities have been reticent to invest in biofuels in a major way. China's ethanol policy as of 2019 remained highly fragmented, composed of a variety of provincial- and municipal-level policies, as opposed to a central strategy (FAS Office of Agricultural Affairs Beijing 2019). Moreover, the "non-grain" fuel ethanol producers appear to have been cut adrift in that subsidies previously implemented for fuel ethanol production have not been renewed at either a provincial or federal level. The E10 goal, set all those years ago, does not now seem achievable; rather, a blend rate of 3–3.5% by 2020 has been predicted (FAS Office of Agricultural Affairs Beijing 2019). Furthermore, while China is among the world's three largest importers of palm oil (IndexMundi 2020), biodiesel production has not been expanded beyond a limited program in Shanghai (FAS Office of Agricultural Affairs Beijing 2019).

Given its large population, the limited amount of arable land and acute sensitivity to domestic food prices, it would have been surprising for China to incentivise the wider cultivation, on its own soil, of food crops destined for making biofuels. One alternative would have involved *importing* raw materials, or indeed the processed biofuels. However, given the stated concerns about fuel security and the deliberate drive for domestic production, looking for arable land elsewhere would have defeated the original purpose. Meanwhile, in autumn 2017, the government announced a new policy targeting E10 usage in the country, to be implemented by 2020. The immediate motivation appears to have been the large excess of (now rapidly-ageing) national corn stocks (Mason et al. 2017), which had accumulated after crop prices (and consumption) were battered by the precipitous drop in the corn market, following the depredations of African swine fever (Yu 2019). However, the enthusiasm appears to have been short lived. Two years later, uptake seemed to have been limited due to a lack of demand, and to pushback by the powerful state-owned oil companies; as such, the program was unable to effectively increase crop prices as intended (Yu 2019).

It is also possible that China has, in the meantime, absorbed some of the lessons from accumulated experience in the EU, the U.S. and Brazil, regarding the cost implications, as well as the energy and environmental ramifications of making biofuels from "energy crops". Before turning to those aspects of biofuels ventures, however, it will be useful to briefly review some of the literature on the physical chemistry of making and using biofuels.

Within the context of this paper, it is only possible to give an abbreviated answer to questions regarding the role and positioning of the oil industry. Clearly, mandating the addition of synthetic fuels of whatever origin into motor fuels cuts across the sale of petroleum-derived products by the oil industry. When crude oil prices are high and concomitant sale prices at the pump relatively firm, we might surmise that loss of income through biofuels blending would probably be perceived as less damaging. However, a brief look at historical charts of crude oil prices (Macrotrends "Crude Oil Prices") during the last two decades tells a complicated story, with crude oil prices fluctuating over wide ranges. Without requiring insider knowledge, it might be speculated that the 10% biofuels mandate would loom large during periods when global crude oil supplies outstrip demand and crude oil prices decline. At the time of writing, crude oil prices have been hovering near the $40 per barrel mark, after having suffered a severe dip during the early part of 2020, with particularly damaging consequences for the US shale oil industry. At a time when news items state that "Oil bankruptcies could shift clean-up bill to US taxpayers. Insurance covers just a fraction of the estimated $280bn cost of plugging wells" (McCormick 2020), ringfencing 10% of total motor fuel sales for biofuels probably exacerbates the difficulties faced by sectors of the oil industry. Conversely, petroleum-derived fuel producers do benefit from "green washing" of their product by the addition of biofuels, making blended fossil fuels more attractive to consumers and perhaps culling consumer demand for truly sustainable transport fuels.

3. Biofuels in cars and trucks: How do they run?

Bioethanol: In the U.S., during the late 1980s, ethanol was used mostly in large cities as an "oxygenate," blended in motor fuels at 7.5% by volume, to reduce emissions by promoting more complete combustion. At the time, ethanol was gradually replacing the *then* oxygenate of choice, methyl tertiary butyl ether (MTBE), a highly toxic material which was found to contaminate groundwaters and was eventually phased out. By the 1990s, grain (or sugar cane) derived ethanol was being relaunched as a "renewable" fuel (Minteer 2006), (cf. p. 126) blended with conventional gasoline, in concentrations between 10% and 85%, denoted as E10 and E85, respectively (Minteer 2006) (cf. p. 3)

There were, however, several caveats. Due to their higher oxygen content, biofuels have lower energy densities than analogous petroleum-derived fuels. About 1.5 times more bioethanol is required to replace a unit amount of conventional motor fuel (Bryce 2015). As a result, "fuel economy," defined in terms of the distance travelled per unit volume of fuel, decreases with increasing ethanol concentration in the fuel mix. It was estimated that between the years 2007 and 2014, U.S. consumers have paid approximately $10 billion more pa in fuel costs due to biofuel blending (Bryce 2015).

Corrosion of metallic fuel systems no longer appears to be a severe issue with E10 or E20 blends in modern cars (Minteer 2006). In older models not adjusted to the use of biofuel blends, corrosion and metal degradation could have been observed. Ethanol is known to corrode steel car components, leading to stress cracking. Impurities, water and excess oxygen in fuel-grade ethanol blends have been shown to cause this corrosion and cracking. The elastomers and plastic components of most engines of recent manufacture appear to have been adapted to E10 (Goodman and Singh 2014).

Car makers are more wary of higher ethanol levels in motor fuels (Clemente 2015), although, regarding the E85 (85 percent ethanol, 15 percent gasoline) blend, there are some positives. E85 can create more torque and greater horsepower as well as having a cooling effect on the engine. There are reports suggesting, on the other hand, that high-ethanol blends corrode fuel-system components made of magnesium, aluminium and rubber. Potential pitfalls include the hygroscopic nature of E85 with attendant absorption of water into the fuel during storage in the fuel tank, which may lead to preignition problems and possible engine damage. Component lifespan reductions and cold weather start-up problems are also mentioned, except in the case of purpose-built "fuel-flex" vehicles (Guy 2020).

Biodiesels: Common biodiesels are made by the *trans*-esterification of oils or fats (triglycerides), usually with methanol; the reaction produces a fatty acid methyl ester (FAME), releasing glycerine as by-product. FAME biodiesels have properties similar to conventional diesel fuel, making it suitable for blending. Several other formulations, including longer chain alcohols and hydrogenated vegetable oils, suitable for use as biodiesels have been reviewed (Unglert et al. 2020).

Emission properties of biodiesels have been measured using different engine test cycles. Averaging results between tests, biodiesels appear to cause lower levels of carbon monoxide emissions, and lower levels of un-combusted hydrocarbon and particulate matter releases, compared to conventional diesel fuel. The higher NO_x emissions appear due to higher combustion temperatures. Variations in emission levels have also been observed to change with the composition of the original oils/fats used in the *trans*-esterification process. For example, biodiesels made from oils with shorter molecular chains were observed to produce lower levels of emissions, compared to oils with longer chains and greater frequency of double bonds (Unglert et al. 2020; Hoekman and Robbins 2012).

At the level of day-to-day usage, shortened oil change intervals have been reported as one of the consequences of using biodiesels. Lubricating oil dilution due to fuel ingress is common in diesel engines and is known to occur with both conventional diesel and biodiesel. However, the higher boiling point distributions of biodiesels compared to conventional diesels have been observed to lead to greater proportions of *permanent* dilution of the lubricating oil pool. This results in decreased oil viscosity and thus in accelerated component wear (Unglert et al. 2020).

Some biodiesels are reported to attack engine components. “Material compatibility” issues are likely to arise when new synthetic biobased fuels, such as oxymethylene dimethyl ether (OME), are used in new cars as well as existing models (Unglert et al. 2020). In addition, the polarity of biodiesels has been reported to affect deposit formation, peaking at between 15 and 20% biodiesel blends (Fang and McCormick 2006; Eskiner et al. 2017). Deposit formation has been experimentally associated with mutagenicity of combustion emissions (Krahl et al. 2008).

To recapitulate, unintended consequences of biodiesel blending include added wear and tear in engines and ancillary engine parts. More frequent lube-oil changes are necessary to counter oil dilution by fuel ingress, and to correct for lube-oil dilution. Finally, in the admirable phraseology of Unglert et al.: “Measured in terms of global significance, biodiesel in particular, as a polar component in different admixture proportions, poses particular challenges to fuel quality development and guarantee” (Unglert et al. 2020).

4. On the energy value of biofuels

A careful calculation of the energy expended in *making* biofuels, compared with the energy content of the biofuels themselves was presented as long ago as 2005 by Pimentel and Patzek (2005). In a closely argued paper, the authors showed that, when all “recognized” inputs were included, the total fossil-fuel-derived energy that went into preparing the biofuels was greater than the energy released when the biofuels were combusted.

In the case of corn ethanol, the inputs in the calculation included direct costs in terms of energy and money expended for producing the corn feedstock, including the costs of farm machinery and their maintenance, as well as the costs of the subsequent processing (fermentation) and distillation stages. In money terms (USD of the year 2005), the authors calculated that to produce a quantity of corn ethanol with an equivalent energy value to a litre of gasoline would cost $1.88, compared to the *then* current cost of producing gasoline as $0.33 per litre. As already indicated, their higher oxygen content makes biofuels less effective as a fuel: about 1.5 times more bioethanol is required to replace a unit amount of conventional motor fuel (Bryce 2015).

Other costs in the calculation by Pimentel and Patzek included federal and state subsidies, as well as environmental externalities associated with pollution and environmental degradation caused by the production system (Pimentel and Patzek 2005). The latter included the high rates of soil erosion caused by corn cultivation, as well as the high rates of herbicides and insecticides required for this (the highest rates of any crop in the U.S. at that time) (Pimentel and Patzek 2005). Pimentel and Patzek explained that the runoffs from the high rates of nitrogen fertilizers required in corn cultivation caused widespread groundwater and river water pollution. Taken together with the high rates of depletion of aquifers (15% of corn cultivation is irrigated), the authors pointed to widespread environmental degradation due to corn (maize) cultivation, 40% of which is destined for bioethanol production.

Returning to overall energy balances, Pimentel and Patzek showed that ethanol from corn (maize) required 29% more fossil energy than produced by the ethanol fuel. The fuels we would today label as 2nd generation biofuels fared even worse. Ethanol from switchgrass required 50% more fossil fuel energy and that from wood biomass 57% more fossil energy than the ethanol fuel produced. In the same vein, biodiesel from soybean required 27% more fossil energy than it produced, whilst the deficit using sunflower was calculated as 118%.

These findings have not gone unchallenged. Calculations showing net energy *gains* over fossil fuel expenditure in manufacturing ethanol have been claimed in work by the U.S. Department of Agriculture, charged with stabilizing corn markets, and others involved in processing food crops into biofuels (Nichols et al. 2006; Shapouri et al. 2004; Shapouri, Duffield, and Wang 2002). The debates have centred on which inputs to include in the calculations and which might be left out; the work of Pimentel and Patzek appears to have presented a more complete picture of all inputs involved. A detailed comparison of the various calculations is beyond the remit of this paper. The reader is encouraged to examine the relevant publications and compare the conflicting positions.

5. Cultivating energy crops or planting for food & feed

In the United States: It seems clear that planting crops for energy production competes with the use of grain for food and (animal) feed production. This is not a novel finding. One of the stated policy aims of the U.S. Department of Agriculture in promoting programmes for making bioethanol from corn (maize) and wheat was/is to “stabilize” grain prices, presumably by means of stimulating demand.

In 2007–8, sharp rises in corn prices gave rise to popular disturbances in Mexico and elsewhere in Latin America. Within the United States itself, however, the extra expense appears to have been viewed as one that could be readily absorbed by most family budgets. Indeed, in 2009, the United States Congressional Budget Office estimated that this bioethanol-driven rise in the price of corn comprised between 0.5 and 0.8 percentage points of the 5.1% total increase in food prices between April 2007 and April 2008, but that increased energy costs over this period contributed more to this increase than did the use of bioethanol (US Congressional Budget Office 2009).

In 2012, with a severe drought in prospect in North America, the United Nations called for government-mandated U.S. ethanol production to be suspended immediately. In part, the decisions in Washington involved balancing the benefits of high grain prices to grain-growing farmers in states like Iowa, versus the interests of livestock-raising states like Texas – who would look to low prices for grain used to feed cattle. At the time, pork and turkey producers in the U.S. were also suffering from high feed prices (Meyer 2012). The UN intervention was welcomed by politicians and industrialists alike in livestock-raising states, who seized upon this and other foreign concern over U.S. ethanol policy (which had already been expressed by France, India, and China) to lobby against government-mandated ethanol production (Blas and Meyer, 2012).

As an aside, stability is not a known attribute of either the wheat or corn markets in the United States, as may be observed from tabulated commodity prices (“Wheat Prices” 2020; “Corn Prices” 2020). Between the volatility of grain prices and the ups-and-downs of the ethanol market (“Ethanol Prices” 2020), the demand created by the biofuel mandates and federal subsidies appear to play a significant role in keeping prices from occasionally collapsing. In the U.S., as far back as 2006, there were several additional sets of Federal tax incentives for ethanol sold as fuel, including an excise tax exemption, a blender’s tax credit, income tax credit for producing and selling bioethanol as fuel and a “small producer’s tax credit” (Minteer 2006). (cf. p. 128).

The aforementioned Congressional Budget Office paper (US Congressional Budget Office 2009) defines the “break-even ratio” as the ratio between the price of petrol per U.S. gallon and the price of corn (maize) per bushel at which it becomes profitable to expand production of bioethanol in the absence of state support. The paper states the break-even ratio was approximately 0.9 in 2009. According to data provided by the same source, this figure was reached only once, for a period of several months, between 1970 and 2007 (US Congressional Budget Office 2009) (cf. p. 15) Clearly, subsidies will be needed so long as it proves difficult to compete with primary (i.e. fossil) fuels.

Meanwhile, a United Nations Food and Agricultural Organization (FAO) report published in 2008 entitled "The Right to Food and the Impact of Liquid Biofuels" (Eide 2008), summarised concerns about the impact of growing crops for biofuels. After restating the globally-acknowledged duty of states to ensure the basic human right to freedom from hunger for all, the report presented its conclusions in terms of:

> "...liquid biofuel production has indeed contributed and is in the near future likely to continue to weaken the access to adequate food or to the resources by which vulnerable people can feed themselves, in at least three ways: Firstly, by contributing significantly to the increase in food prices. Secondly, by causing land concentration for plantation type production, due to considerations of economy of scale, which have led and are likely to continue to cause evictions or marginalisation of vulnerable groups and individuals. Third, biofuel production causes a number of environmental problems, reduces biodiversity, and lead to competition for water."(Eide 2008)

The document went on to emphasize that the majority of biofuel production, distribution, and use leads to as much, if not more, GHG emissions than does that of fossil fuels when accounting for indirect emissions such as those involved in shifting land use for energy crop agriculture. Furthermore, the report claims that biofuel production cannot increase energy security in advanced economies due to the necessary allocation of land currently in higher-value use. Although increased use of biofuels would reduce pollution in population centres, the report goes on to say, the need for blending to protect car components renders this effect minimal in the short run (Eide 2008).

State intervention in economic matters invariably results in a reallocation of resources between different sectors of an economy, sometimes giving rise to a cascade of outcomes, some of them possibly unintended. Thus, measures taken by the U.S. government to "stabilize" (i.e. support) domestic grain prices, while benefiting grain growers, would tend to increase costs for food processing industries. Cattle and pig farmers end up paying more for "feed" grain, adding to the cost of meat. In the same vein, due to their lower energy content, federal biodiesel and ethanol mandates tend to raise the cost to the consumer of motor fuel per mile travelled, as well as the cost of transport for all the commodities carried by road, including food. Estimates of cross-sector transfers of resources may vary, but we may surmise, the sums involved are not small.

Meanwhile, direct links between the domestic U.S. and world grain markets tend to cascade price fluctuations into the economies of faraway lands where disposable incomes are but a fraction of that of the U.S. consumer.

In the European Union: An early challenge faced in attempting to satisfy the European Commission's "Renewable Energy Directive" mandate of 10% renewable biofuels in all motor fuels by 2020, was the provision of sufficient energy crops to make enough biodiesel. The solution found was to increase imports of palm oil, to supplement the quantities of rape seed oil (canola) contracted from within the EU. We will see that the EU's decision to import supplies from abroad has given rise to a complex set of outcomes and costs, not all of them readily foreseen, desired, or indeed desirable.

The EU currently imports crude palm oil mostly from Malaysia and Indonesia, where European prices for palm oil were evidently found sufficiently attractive for new land to be opened, including by massive deforestation to establish new oil palm plantations (Schutter, 2013). Since then, other lands (cf. Table 2) have competed to get into this economically attractive market, courtesy of EU biofuel subsidies. Meanwhile, how ferrying palm oil from faraway lands is meant to contribute to European energy security has never been properly explained.

In 2010, Franco and co-workers published their findings from an analytical study, partly funded by the European Commission, to examine the "Assumptions in the European Union biofuels policy" (Franco et al. 2010). They pointed out that outsourcing large amounts of food crops to third countries in South East Asia, Africa and Latin America would have profound impacts in these areas. However, EU policy assumes these impacts would be mainly beneficial, and any harmful impacts could be managed by self-regulation or mitigated by technological developments (Franco et al. 2010). The basis for this assumption is unclear, and the authors found it to be "optimistic." They also described "tensions" between agencies of the European Commission: a 2009 report by the Directorate-General for Development of the EU Commission found that EU policy does not sufficiently address the impact of biofuel production and associated large-scale land acquisition on food security (Franco et al. 2010).

In 2013, Jean Ziegler, the UN special rapporteur (2000–2008) on "the right to food," returned to the same points, that nearly all biofuels were made from crops that are "essential food sources for a rapidly expanding global population": wheat, soy, palm oil, rapeseed, sunflower seeds and maize. He pointed out that the EU alone burns enough food-grade biomass each year to feed 100 million people, and that "...prices of vital foodstuffs such as oilseeds are expected to rise by up to 20%, vegetable oil by up to 36%, and maize by as much as 22% by 2020 because of EU biofuels targets" (Ziegler 2013).

Secondly, Ziegler warned of a substantial increase in demand for land, which would doubtless displace smallholder farms and natural habitats. This phenomenon concentrates wealth in the hands of "Land speculators, hedge funds, and agro-energy companies...", while forcing out smallholder farmers. Ziegler points out that on top of taking their land, water, and livelihoods, smallholder farmers and their families are all too often victims of violence associated with the "...monopolisation of land by large biofuel corporations..." (Ziegler 2013).

Third, Ziegler underlined the extents of environmental devastation involved in these processes. "The demand for additional land to accommodate EU biofuels plans means expanding cropland, which will result in felled forests, plundered peatlands and ploughed prairies" (Ziegler 2013). He claims that the environmental harm caused by the use of fertiliser, land clearance, deforestation, and reduction of crop diversity outweigh the "negligible or nil" climate change benefits of biofuels. Similar to the previously-mentioned UN FAO report (Eide 2008), Zeigler points out EU biofuel production, distribution, and use is in fact leading to millions of tonnes of additional carbon dioxide emissions each year. In the big picture, these initiatives took place within a context described by a Financial Times news item, back in 2012, as: "Food is a problem and biofuels is not making it any easier" (Lucas 2012).

In Europe, the vision of burning food-crop-derived fuels in internal combustion engines, and the accompanying ecological devastation both domestically and in tropical belt plantations elicited a measure of public reaction. The response by the European Commission came in October 2012, in the form of a proposal to *limit* (*but not eliminate*) the use of food crops for making biofuels.

COM (2012) 595 (European Commission 2012), published by the European Commission in 2012, limited the use of food-crop-derived biofuels to 5% of motor fuels out of the total 10% renewable biofuels by 2020 target set out by the EU renewable energy directive. It also mandated the inclusion of indirect land use change (ILUC) emissions in assessments of biofuel-associated GHG emissions (Bourguignon 2015). In this context, ILUC refers to the unintended additional greenhouse gas emissions due to *land use change* in the process of expanding the cultivation of crops intended for biofuels.

In the event, the European Commission did not hold the line at 5%. Whatever the parameters of internal negotiations, a compromise value of 7% food crops in biofuels was arrived at and has been maintained throughout the decade ending in 2020. The 2015 review of the Renewable Energy Directive confirmed this 7% limit (IIASA, 2016).

Transport & Environment, an NGO whose major funders include the European Commission (Transport & Environment 2020), forecasted that biodiesels will comprise 57% of EU biofuels in 2020, under the headline: "Biodiesel: Cure worse than the disease" (IIASA, 2016). They explained that some of the consequences of adopting biofuels ranged from necessary material adjustments in engine manufacture and maintenance in response to the use of oxygenated fuels, to fairly abrupt changes in land tenure and crop cultivation patterns abroad. They argued that lucrative EU subsidies were leading to the destruction of rainforests, to be replaced by palm oil plantations, giving rise to familiar patterns of loss of biodiversity and environmental degradation associated with intense oil crop cultivation (IIASA, 2016).

In Brazil: Filoso and co-workers have reviewed the environmental consequences of sugarcane cultivation for bioethanol production in the country (Filoso et al. 2015). *Air pollution* due to the practice of setting fire to sugarcane fields, prior to manual harvesting was cited as one immediate element of environmental degradation relating to sugarcane cultivation. Some of the challenges to be faced were grouped under the deterioration of soil quality, due to erosion, soil compaction and soil acidification, as well as the loss of key soil quality indicators such as carbon, nitrogen and phosphorus levels. High levels of water usage during both the plantation and industrial (i.e. ethanol production) phases were cited alongside the effects of fertilizer and pesticide runoffs into aquifers, lakes and rivers as affecting water quality in the general environment. The damage to water and soil during over half a century of ethanol production was reported to have been extensive (Filoso et al. 2015).

Furthermore, the authors point out that the expansion of sugarcane agriculture presents a threat to areas of natural vegetation, particularly those in endangered biomes, and recommend implementation of "…ecosystem restoration projects to help reverse biodiversity and eco- systems service losses associated with sugarcane expansion in Brazil" (Filoso et al. 2015). It was suggested that more research was needed to better understand how "landscape fragmentation" affects biodiversity of different ecosystems, without which such restoration-aimed policies may be ineffective. The authors seemed merely able to hint that "presently available scientific information" might assist in ending "unsustainable farming" and implement desirable conservation strategies (Filoso et al. 2015).

Looking across the spectrum of countries involved in cultivating and/or processing crops for biofuels and/or using biofuels as parts of their motor fuel inventory, the emerging patterns seem to indicate that environmental concerns do not appear to be in the forefront of the decision-making process – certainly not in every case. Instead, critical decisions appear contingent on the conditions and demands of the countries' respective domestic economies, the vagaries of fluctuating commodity and land prices and the strength of economic and political interests that coalesce around the use of food crops as fuel.

6. How do developments since 2006–7 compare with original aims?

In parts of the World where biofuels blending has been mandated, authorities have generally explained the effort and expense in terms of energy security, reduction of ('net') greenhouse gas emissions and assisting farming communities, sometimes phrased as "rural development". In the case of the EU, these three were the officially stated aims (Franco et al. 2010). At this stage, it seems relevant to ask how the U.S. and the EU, the largest of these blocks, would fare when judged against their own stated aims for producing and mandating the use of biofuels.

Have biofuels brought energy security? Clearly, there is no *quantitative* benchmark for deciding what volume of biofuels production may be judged as providing a measure of "energy security." Given the magnitude of resources committed to develop the use of biofuels, however, it seems useful to compare overall liquid fuel consumption with the scale of biofuels production and use.

The current rate of bioethanol consumption in the United States is about 13 billion U.S. gallons, corresponding to about 40 MT of fuel pa. The total liquid fuels consumption during 2019 was 20,100,000 barrels per day, which works out as a little over *1 billion tons* per annum (US EIA 2020b). Thus, the bioethanol operation in the U.S. comes to a little less than 4 percent of the total. Calculated on the basis of gasoline plus diesel and gas oil (rather than crude oil), which totalled 775 million tons in 2019 (BP 2020), (cf. p. 24) bioethanol production represented a little over 5% of the total. If the approximately 6 MT biodiesel produced in the U.S (Sönnichsen 2020; AVCalc 2020) is added to the volume of ethanol, the percentages reported above would move upwards only marginally.

With regard to Europe, during 2005, total imports of crude oil was recorded as about 4,700,000,000 barrels, a little less than 633 million tons (European Commission 2019). EU imports of crude oil have tended to drift *downwards* between the years 2005–2020. In 2019, they imported some 4,105,000,000 barrels of crude oil (European Commission 2019), about 557 million tons of oil pa, reckoning on seven barrels per ton. This total does not include German imports by pipeline or the Czech Republic, "due to confidentiality". Meanwhile, total crude oil *production* in the EU, amounted to about 150 MT pa in the year 2018 (Eurostat 2019). For the year 2018, the nearly 23 million tons of biofuels production (cf. Table 1) corresponds approximately to 3.3 percent of total liquid fuels consumption.

Taken together, our evidence shows that large amounts of money and effort have gone into subsidising and cultivating (and importing) energy crops for the production of bioethanol and biodiesels, in both the U.S, and the E.U. Compared to the magnitude of the costs and compared to the total volume of petroleum-derived liquids currently utilized, the scale of biofuels production and use arrived at seems relatively minor.

In the EU, furthermore, the importation of a small amount of conventional crude oil, appears to have been replaced by growing more rapeseed, by importing ethanol (much of it from Brazil) (Tsanova 2019), and importing palm oil for making biodiesel, from as far away as Malaysia and Indonesia. How trading over particularly long supply lines is meant to contribute to the "energy security" of the Continent has not been explained.

Rural development & GHG: As already signalled, large tracts of arable land within the EU have been converted to rapeseed cultivation for eventual biodiesel production. The vegetable oil deficit for making sufficient biodiesels to fulfil the mandate has been closed through palm oil imports, mostly from South East Asia, where production has increased sharply during the past decade. Currently, 85–90% of the world's palm oil supply is produced by Malaysia and Indonesia (cf. Table 2). In these two countries, oil palm plantations have expanded into tracts of agricultural land formerly used for conventional agriculture. Oil palm plantations have also expanded to replace vast tracts of pristine forest, with attendant excess CO_2 emissions (''ILUC''), coupled to the destruction of delicate ecosystems and wildlife habitat, with predictable adverse consequences for biodiversity (Hood 2016; Illsley 2018). During the implementation of such massive changes across agricultural and forestry landscapes, the ILUC impacts are large. The ''World Atlas'' calculation suggests that 174 tons of CO_2 is emitted per hectare of rainforest destroyed to make way for palm oil plantations (Illsley 2018). With the magnitude of land use changes involving millions of hectares, it seems difficult, once again, to conclude that GHG emissions are being reduced by the EU providing an expanding ready market for palm oil.

European Union policies on biofuels thus appear to have led to a range of unintended and largely undesirable consequences both within the EU and elsewhere, not excluding the displacement of myriad small farmers to make way for large plantations. As long ago as 2010, *in a study funded by the European Union*, Franco and co-workers had summarised the position in which the EU finds itself: ''There are fundamental contradictions between EU policy assumptions and practices in the real world, involving frictional encounters among biofuel promoters as well as with people adversely affected. Such contradictions may intensify with the future rise of biofuels and so warrant systematic attention'' (Franco et al. 2010).

The vast cost to the taxpayer in Brazil, the U.S. and the EU for subsidizing energy crops stands in stark contrast to the cultivation of *desired* crops planted in response to intrinsic demand. The contrast with crops that are wanted for food or for value-added products, ranging from sugar cane and beets for making sugar, coffee, cocoa, opium for making pharmaceuticals, and even everyday fruits and vegetables could not be greater. None of these latter classes of produce have *ever* been subsidised.

Moreover, there is mounting incontrovertible evidence, and in the case of the European Union, tacit acceptance, that biofuels have caused environmental degradation and GHG emissions greater than the fossil fuels they were purported to replace. As these processes have evolved, however, new groups of commercial interests appear to have formed to take advantage of the subsidies, with little recognizable benefit to the environment.

7. Reticence & pushback

We have seen that state policies relating to biofuels in the United States and in Brazil are straightforwardly designed to underpin incomes of farming sectors raising crops for biofuels, and of industrial organisations set up to process these crops for making biofuels. By contrast, we have observed indications of official reticence in China, where subsidies are being withdrawn and the 2020 biofuels targets of 10% biofuels in diesel and gasoline are unlikely to be met. It appears, the lack of consumer enthusiasm coupled to a level of resistance by SINOPEC and CNPC, the large state-owned oil corporations, have tilted the scales against further large-scale support for biofuels. We may also ask, but cannot answer, the question whether the apparent lack of official enthusiasm may have had something to do with the poor returns and adverse public reaction experienced in the European Union.

In Europe, neither the distorting effect on food prices of diverting food crops to biofuels, nor the rapid concentration in land ownership, nor indeed the environmental degradation resulting from the intensive cultivation of crops for biofuels seems to have ignited the public imagination. However, the deforestation that took place in Malaysia and Indonesia has drawn a measure of public attention. In this connection, we recall that the EU is only one of three largest global importers of palm oil, after India and China, although by far the largest of these three in converting what is basically a comestible commodity into a fuel. Nearly half the palm oil imported into the EU goes to make biodiesel (Buffet 2017).

EU Debates: In October 2012, the European Commission proposed to *limit* rather than eliminate the use of food crops to 5% of the energy content in motor fuels blends [COM (2012) 595] (European Commission 2012). As explained above, before the proposal was finalised, that limit was adjusted up to 7%, where it remained for the rest of the decade to 2020.

The proposal, intended to initiate discussions on the course to be followed in the 2020–2030 decade was published in November 2016: Renewable Energy Directive for 2021–2030 (RED II) (European Commission 2018a). It called for a stepwise reduction of the cap on first generation biofuels, made from food crops, from 7% in 2020 to 3.8% in 2030 (European Commission 2017) (cf. p. 99) Debate was fierce. The partly EU funded NGO ''Transport & Environment'' suggested the cap on the use of food crops to be reduced to zero and indicated the need for greater activity in the area of second generation biofuels – i.e. biofuels made from non-food biomass (White 2017). However, within the EU, the reaction was sharp. Farmers were wary this measure would eliminate an important source of revenue, as there is no alternative market sufficient to absorb the millions of tonnes of rapeseed oil produced in the EU each year (White 2017).

Pressures from all sides were also evident on the ethanol front. The suspension of EU negotiations with the Mercosur countries (Argentina, Brazil, Uruguay, Paraguay, and Venezuela), after dragging on for nearly twenty years, seemed to hinge on, among others, amounts of ethanol to be imported from Brazil at low tariffs. Meanwhile ethanol crop producers in Central and Eastern Europe have pushed back against concessions to Brazil, with their representatives complaining that the industry was ''caught in a pincer movement between EU regulations that could reduce the size of its markets and a succession of trade deals that has led to increased foreign competition'' (Brunsden and Beattie 2017). The deal pursued by the EU was also stuck on beef quotas, thrown into the bargaining. A Mercosur diplomat was reported to have said: ''...the block was waiting to see the EU offer, especially for beef, sugar and ethanol'' (Beesley 2017).

Meanwhile, in the UK, a new ethanol works was being mothballed on account of the UK government delaying a move from the 4.75% biofuel mandate (fixed in 2012) to the expected 9.75%. The facility, which was built at the cost of £350 m to meet the expected demand for biofuels as a result of this move, was now costing investors greatly (Bounds and Tighe 2017).

Inescapably, the resulting ''directive'' covering the mandates for the years 2020–2030 was a compromise, finally agreed upon in June 2018 (European Commission 2018a), when it entered into force as the revised renewable energy directive 2018/2001/EU (European Commission 2018b). It allowed a maximum of 7% food-crop-derived biofuels as a percentage of total transport fuels. In a concession to the critics of EU biofuels policies, article 26(2) stated:

''... the share of high indirect land- use change-risk biofuels, bioliquids or biomass fuels produced from food and feed crops for which a significant expansion of the production area into land with high-carbon stock is observed shall not exceed the level of consumption of such fuels in that Member State in 2019, unless they are certified to be low indirect land-use change- risk biofuels, bioliquids or biomass fuels pursuant to this paragraph.

From 31 december 2023 until 31 december 2030 at the latest, that limit shall gradually decrease to 0%.''

This passage ignited acrimony between palm oil exporters and the European Union. It has been interpreted to mean that the importation of food crops cultivated for biofuel use, grown on newly opened lands will be phased out over the coming decade, "unless evidence is provided that the land was not in use for agriculture or any other activity in January 2008" (European Commission 2017) (cf. p. 21).

The Commission is thus proposing to differentiate between high and low ILUC-risk crop-based biofuels. With the "high ILUC-risk" classification targeting palm oil plantations that would be phased out by 2030, agricultural companies and biodiesel suppliers in both Malaysia and Indonesia will need to convince regulators that palm oil has a low ILUC risk in order to maintain access to the EU market and avoid severe economic consequences of their investment into palm oil production (Licht 2019). Meanwhile, the text of Article 26 (2) has postponed the decision-making process until September 2023, perhaps allowing time for further negotiations.

In another acknowledgement of criticism of EU biofuel policies Article 25 (1) stated that "advanced" biofuels and biogas, meaning those not produced from food crops, should comprise at least 0.2% of transport energy by 2022, 1% by 2025, and 3.5% by 2030 (European Commission 2018b).

Section 8 (below) will briefly review the state of preparedness of "advanced" biofuels and biogas for commercial-scale development.

The pushback - in brief: The revised Renewable Energy Directive 2018/2001/EU (European Commission 2018b) was not well received in countries as wide apart as Brazil, Indonesia and Malaysia. In 2018 the (then) Malaysian Primary Industries Minister T. Kok attacked the proposals as going "...against the very principles of free and fair trade... alarming and deserves the strongest condemnation" (Tan 2018). The Nikkei Asian Review reported the Indonesian trade minister suggesting that "the EU is asking for a 'trade war' with its palm oil curbs" (Tan 2018). The Financial Times in London asked whether these policies were "...protecting the planet or European industry?" Indeed, the revised Directive had been quiet about limits on rapeseed processing to biofuels (Beattie 2019).

The new measures were being pushed back by figures no less prominent than Bolsonaro of Brazil and his Indonesian colleague Joko Widodo. Indonesia had recently raised its biodiesel mandate of 15% dating from 2015 to 20%, although they currently produce only 40% of the necessary volume of fuel (Lane 2019). Malaysia's (then) prime minister Mahathir Mohamad also reacted adversely, accusing the EU of projecting its environmental agendas abroad through trade, as a form of latter day colonialism (Beattie 2019). Meanwhile, the forecast for rapeseed production in the EU for the year 2020 stands at 17.1 million tons, a little above the "disappointing" 2019 harvest of 16.7 million tons (Byrne 2020), and presumably there is enough time until 2023 to reach some sort of common ground with palm oil exporters. There we must leave it for now.

These events show, at the very least, that once a policy course is set, reversing some of these decisions is far from straightforward. During the course of their implementation, policy choices tend to establish new facts on the ground and create a momentum of their own. Developments initiated by EU policy decisions to support and subsidize the cultivation of oil-bearing crops and the establishment of a whole swathe of industry for processing these crops into biofuels, could only be slowed down, let alone reversed, at immense cost. At this point, it is also important to distinguish between the more manageable effects at home, within the EU, and those abroad, in countries that became over-reliant on exporting these commodities, and therefore vulnerable to changes in price structures or indeed demand fluctuations. How to write off investments, forego incomes and reallocate so many monoculture plantations, much of it converted from once functioning rainforests, to some environmentally friendly purpose?

8. The long wait for next generation biofuels

Clearly, there is a need for biofuels produced from feedstocks that do not compete with food production, and, ideally, those that do not compete with any agriculture. So-called "second generation" biofuels address the former issue. They are made from non-edible and/or waste biomass feedstocks. The former category includes non-edible "energy crops" like switchgrass, sorghum and short-rotation coppice. The latter includes post-consumer waste (e.g. municipal waste, animal dung and waste oil) and pre-consumer waste, i.e. agricultural and forestry waste products such as nut shells, corn stover and wood trimmings. Unlike the feedstocks we have heretofore discussed, these are not particularly rich in lipids or simple carbohydrates. Instead, excluding post-consumer waste, they are largely lignocellulosic, meaning they are composed mainly of complex carbohydrates (cellulose and hemicelluloses) and lignin, a complex phenolic polymer. As such, lignocellulosic biomass is unsuitable for either esterification or fermentation.

To produce bioethanol from cellulosic biomass, it is first necessary to break down the cellulose and hemicelluloses into simpler carbohydrates using either chemical, enzymatic or microbial digestion techniques. This additional process, of course, adds energy and capital costs to the balance sheet, so it is unsurprising that Pimentel and Patzek calculated energy recoveries for switchgrass and wood ethanol even lower than that calculated for corn (maize) ethanol (Pimentel and Patzek 2005). A more recent assessment of the energy economy of ethanol production from grasses warns that biomass yield is key to obtaining a positive net energy balance (Illukpitiya et al. 2017). This highlights the way in which non-edible energy crops continue to compete with food crops: through competition for fertile farmland.

When considering waste products, energy used in recovery of the waste product from the desired product must also be accounted for. Melamu and von Blottnitz studied the use of sugarcane bagasse for production of ethanol, and observed that without energy improvements to the sugar mill from which the bagasse was obtained, it was impossible to achieve a negative GHG balance (Melamu and von Blottnitz 2011). The GHG balance, the difference between GHGs emitted during production, distribution and use of biofuels and those removed from the atmosphere during biomass growth, is often forgone in favour of the energy balance in lifecycle assessments of biofuels, but in fact GHG balances of these processes tend to be far less favourable (van Beilen 2010).

An alternative route to ethanol production from lignocellulosic biomass is thermochemical decomposition (e.g. torrefaction, pyrolysis or gasification), in which biomass is heated in absence or with a limited supply of an oxidising agent (e.g. air, carbon dioxide or hydrogen) to produce a light hydrocarbon gas known as "syngas", a heavy hydrocarbon liquid called "bio-oil", and a carbonaceous solid known as "biochar" or simply "charcoal". The most commonly pursued of these substances is syngas, which is produced by gasification (using a limited supply of oxidising agent) as an alternative to natural gas. Flash pyrolysis (using very fast heating rates) tends to produce the highest yields of bio-oil, the most likely candidate for a motor fuel, but this process is extremely energy intensive. Furthermore, bio-oil reduces fuel efficiency due to its low energy density and must be blended for use in a diesel engine due to its high viscosity (Prakash, Singh, and Murugan 2013). Biochar, while a promising candidate for a variety of value-added products reliant on high surface area (e.g. water remediation, energy storage or catalysis), is only of value as a solid biofuel as a replacement for lower-energy–density, higher-emission biofuels such as raw biomass and animal dung, commonly used for cooking and heating in communities without grid access. None of these are particularly exciting prospects for motor transport fuels.

Dimethyl ether (DME) is another potentially viable fuel in the quest for the next generation of green biofuels. It is made by dehydrating methyl alcohol. Industrially, methanol synthesis from synthesis gas, and its dehydration to DME are achieved in a single-step catalytic reactor. Methods for the preparation of synthesis gas from biomass have been summarized, among others, by Hamelinck and Faaij (Hamelinck and Faaij 2006). DME is a clean fuel alternative to petroleum-derived diesel fuel, combining high performance in diesel engines with low emission levels of pollutants, crucially producing low particulates and NOx emissions (Azizi et al. 2014). European Union reports have cited DME as a candidate for large volume production after 2030 (European Commission 2006).

Third generation biofuels, which generally refer to algae-derived biodiesels, are produced from feedstocks which do not require the use of arable land. Algae can be grown in wastewater and in saltwater, the major limitation being surface area exposed to sufficient sunlight. The use of closed-culture systems such as tubular and flat plate photobioreactors, as opposed to open pond cultivation, to maximise lighted surface area with respect to land area of such operations offers greatly increased yields and predictability at the cost of energy, capital, and scalability. These systems tend to require agitation to ensure adequate carbon dioxide content of the growth medium and advanced lighting techniques such as optical fibres or even powered lighting to ensure even and sufficient exposure to light. Ensuring adequate light exposure becomes exponentially more difficult as such systems are scaled up. Furthermore, while it does not require *arable* land, algae cultivation is inarguably land intensive (Xu et al. 2009). For these reasons, algae cultivation for biofuels production is nearly *two orders of magnitude* more costly than that of other biomass feedstocks (van Beilen 2010).

Though current limitations of next generation biofuels are clear, considering the environmental and societal damage caused by conventional biofuels and fossil fuels, the drive towards their use is understandable. Below we examine the success of these efforts:

While the U.S. Environmental Protection Agency raised the advanced biofuels mandate (specifically, the cellulosic biofuel category) slightly in the 2019 RFS, the conventional biofuels mandate, which will be fulfilled primarily by corn (maize) ethanol, has remained unchanged. The RFS goal of 36 billion U.S. gallons pa of biofuels by 2022 is unlikely to be met due to a shortfall in production capacity for advanced biofuels, in particular cellulosic biofuels (Licht 2019).

Brazil's new RenovaBio program, to be enacted in 2020, both increases mandates for general biofuel production (mainly ethanol), as well as those for "alternative" biofuel blending. Biodiesel (currently blended at 10%) is to rise to 15% by 2022 and 30% by 2030. Biomethane is to be blended into natural gas at 5% by 2022 and biokerosene into aviation fuel at 10% by 2030. However, these transitions will not be state-subsidised. While Brazil's ethanol production has been historically dominated by sugarcane, production of corn (maize) ethanol is also expected to rise sharply (Moss 2018).

In the EU, the previously discussed advanced biofuels target of 3.5% of transport fuel by 2030 refers to fuels produced from wastes and residues, while a further 3.5% will be open to low ILUC-risk food-crop-derived biofuels, and the remaining 7% of the 14% renewables for transport energy target will be open to food-crop-derived fuels and renewable electricity (Licht 2019).

Clearly, next generation biofuels are struggling to displace conventional biofuels despite their apparent environmental advantages. Whether this is a result of technological limitations or policy shortcomings is difficult to resolve, but there is no doubt a need for market-ready technical solutions if these processes are to ultimately become competitive.

9. Summary & conclusions

The production and utilization of biofuels have been reviewed with special attention to their costs and the diverse sets of outcomes of biofuels policies. Recent developments in Brazil, the United States, the European Union and China have been assessed and the effects of biofuels production on food crops prices and demand for arable land have been explored. The aims of biofuels policies have been discussed in relation to their stated objectives.

Calculations of the energy expended in *making* biofuels have been compared with the energy content of the biofuels themselves. The estimates appear to vary according to which of the relevant parameters are taken into account. When all recognized inputs are considered, the fossil-fuel-derived energy that enters into the preparation of biofuels has been found to be greater than the energy released when the same biofuels are combusted.

U.S. government policies aiming to stimulate demand in the domestic grain markets by promoting bioethanol blending in conventional gasoline appears to have resulted in periodically raising costs for the food processing industries, and for farmers raising stock for meat. State intervention usually results in reallocating resources between sectors of the economy, with at times unintended consequences. Estimates of cross-sector transfers of resources may vary, but we may surmise, the sums involved in the case of biofuels are not small. Moreover, the direct link between the domestic U.S. and world grain markets has tended to cascade price fluctuations into the economies of faraway lands where disposable incomes are but a fraction of that of the U.S. consumer.

Meanwhile, European imports of crude palm oil from Malaysia and Indonesia have stimulated expansion of oil palm cultivation into tracts of land formerly used for conventional agriculture, as well as into pristine rainforest, with attendant excess CO_2 emissions ("ILUC"), coupled to the destruction of delicate ecosystems and wildlife habitat, with predictable adverse consequences for biodiversity. On the other hand, how ferrying ethanol from Brazil and palm oil from South East Asia is meant to contribute to European energy security has never been properly explained.

The EU's initial assumptions that the impacts of their biofuels policies would be largely beneficial have not addressed the impacts on food availability and large-scale land acquisitions. Fertiliser use, land clearance, deforestation and displacing other crops has led to millions of tonnes of additional carbon dioxide emissions, causing loss of biodiversity and environmental degradation associated with intense oil crop cultivation.

The principal aims of EU decisions for supporting the production and use of biofuels were stated as increased energy security, reduction of GHG emissions and the stimulation of rural development. The patterns emerging from this work suggest that environmental concerns are not at the forefront of current decision-making processes. Instead, critical decisions appear contingent on the conditions and demands of host country economies, the vagaries of commodity and land prices and the strength of economic and political interests that coalesce around the utilisation of food crops as fuel.

Taken together, our evidence suggests that large amounts of money and effort have gone into subsidising and cultivating energy crops for the production of bioethanol and biodiesels. However, the actual scale of biofuels production seems small, compared to the magnitude of the costs and relative to the total volumes of conventional fuels production.

The costs of subsidising energy crops stands in stark contrast to the economics of cultivating *desired* crops, such as coffee, cocoa, opium for pharmaceuticals and even everyday fruits and vegetables. None of these latter classes of produce have needed subsidies.

Moreover, there is mounting evidence, and in the case of the European Union, tacit acceptance, that biofuels have caused environmental degradation and greenhouse gas emissions greater than the fossil fuels they were purported to replace. Calculations suggest that 174 tons of CO_2 is emitted per hectare of rainforest destroyed to make way for palm oil plantations. With the magnitude of land use changes involving millions of hectares, it seems difficult, once again, to conclude that greenhouse gas emissions have been reduced through the use of biodiesels from palm oil. European Union policies on biofuels thus appear to have led to a range of unintended and largely undesirable consequences both within the EU and internationally, not excluding the displacement of myriad small farmers to make way for large plantations.

The EU has faced intense pressures to tone down their biofuels policies, even minor course corrections have been a decade or more in the making. During the course of their implementation, policy choices tend to establish new facts on the ground. Developments associated with subsidising the cultivation of oil-bearing crops and the creation of numerous chemical plants for processing biofuels are difficult to slow down, let alone reverse, except at massive cost. There are differences, furthermore, between the possibly more manageable effects at home, and those abroad, in countries that have become over-reliant on exporting these commodities and are therefore vulnerable to changes in price structures and demand fluctuations. As these processes have evolved, meanwhile, new groups of commercial interests have coalesced, both domestically and internationally, to take advantage of the subsidies on offer, with little recognizable benefit to the environment.

CRediT authorship contribution statement

Meredith R. Barr: Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Roberto Volpe:** Validation, Writing - review & editing, Supervision. **Rafael Kandiyoti:** Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

AVCalc, 2020. "Biodiesel." Aqua-Calc. https://www.aqua-calc.com/page/density-table/substance/biodiesel

Azizi, Z., Rezaimanesh, M., Tohidian, T., Rahimpour, M.R., 2014. Dimethyl ether: A review of technologies and production challenges. Chem. Eng. Process. Process Intensif. 82, 150–172. https://doi.org/10.1016/j.cep.2014.06.007.

Bannon, Eoin, 2020. Biofuels Policies to Massively Increase Deforestation by 2030 - Study. Trans. Environ. https://www.transportenvironment.org/news/biofuels-policies-massively-increase-deforestation-2030-study

Beattie, A., 2019. Is the EU's Green Policy Protecting the Planet of European Industry? Financial Times. https://wwwft.com/content/0432eb26-15f2-11ea-9ee4-11f260415385.

Beesley, A., 2017. Brussels Warns Mercosur on Beef as Trade Talks Revived. Financial Times. https://wwwft.com/content/8cc8f47e-7510-11e7-a3e8-60495fe6ca71.

Blas, Javier, Meyer, Gregory, 2012. UN Urges US to Cut Ethanol Production. Financial Times. https://www.ft.com/content/8808b144-e240-11e1-8e9d-00144feab49a

Bounds, A., Tighe, C., 2017. Investors Lose Hundreds of Millions as UK Biofuels Industry Stalls. Financial Times. https://wwwft.com/content/31b0e84a-d9e1-11e7-a039-c64b1c09b482.

Bourguignon, Didier, 2015. EU biofuels policy: Dealing with indirect land use change. European Parliamentary Research Service. http://www.europarl.europa.eu/RegData/etudes/BRIE/2015/548993/EPRS_BRI(2015)548993_REV1_EN.pdf

BP. 2020. "BP Statistical Review of World Energy 2020." https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf

Brada, J.C., 1983. The Soviet-American grain agreement and the national interest. Am. J. Agric. Econ. 65, 651–656.

Brunsden, J., Beattie, A., 2017. EU Farmers Sow Seeds of Doubt as Brussels Moves to Seal Mercosur Pact. Financial Times. https://www.ft.com/content/d9addf96-baef-11e7-9bfb-4a9c83ffa852

Bryce, R., 2015. End the Ethanol Rip-Off. New York Times. https://www.nytimes.com/2015/03/10/opinion/end-the-ethanol-rip-off.html

Buffet, L., 2017. Reality check - 10 things you didn't know about EU biofuels policy. Trans. Environ. https://www.transportenvironment.org/publications/reality-check-10-things-you-didn%E2%80%99t-know-about-eu-biofuels-policy

Byrne, Jane, 2020. Anticipated decline in EU and UK wheat output, rapeseed crop set to be marginally higher. Feed Navigator. 2020. https://www.feednavigator.com/Article/2020/02/20/Anticipated-decline-in-EU-and-UK-grains-output

Chang, S., Zhao, L., Timilsina, G.R., Zhang, X., 2012. Development of Biofuels in China. World Bank Development Research Group Environment and Energy Team. https://openknowledge.worldbank.org/bitstream/handle/10986/12076/wps6243.pdf?sequence=1&isAllowed=y

Clemente, J., 2015. Why Biofuels Can't Replace Oil. Forbes. https://www.forbes.com/sites/judeclemente/2015/06/17/why-biofuels-cant-replace-oil

Constitution of the United States, Amend XVIII. 18th Amendment to the United States Constitution. Cornell Law School. https://www.law.cornell.edu/constitution/amendmentxviii

Corn Prices, 2020. Business Insider. https://markets.businessinsider.com/commodities/corn-price/usd

Donley, Arvin, 2019. Russian grain exports forecast to rise. World-Grain.Com. https://www.world-grain.com/articles/12106-russian-grain-exports-forecast-to-rise

Duke, James A., 1983. "Handbook of Energy Crops." Purdue. Edu Unpublished. https://hort.purdue.edu/newcrop/duke_energy/Euphorbia_tirucalli.html

Eide, A., 2008. The right to food and the impact of liquid biofuels (Agrofuels). UN FAO (Food and Agriculture Organisation). http://www.fao.org/3/a-ap550e.pdf

Eskiner, M., Ammer, F., Then, D., Staufenbiel, J., Rossner, M., Schröder, O., Krahl, J., 2017. Novel concepts for onboard determination of fuel quality in plug-in hybrid cars. Fuel 209, 224–231. https://doi.org/10.1016/j.fuel.2017.07.102.

Ethanol Prices, 2020. Business Insider. https://markets.businessinsider.com/commodities/ethanol-price

European Commission. 1997. "Energy for the Future: Renewable Sources of Energy. White Paper for a Community Strategy and Action Plan (COM(97)599 Final)." Brussels. https://europa.eu/documents/comm/white_papers/pdf/com97_599_en.pdf

European Commission, 2006. Biofuels in the European Union A Vision for 2030 and Beyond. Final Report of the Biofuels Research Advisory Council. http://ec.europa.eu/research/energy/pdf/draft_vision_report_en.pdf

European Commission. 2009. "Directive 2009/28/EC of the European parliament and of the council." https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32009L0028&from=EN

European Commission, 2012. Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources. https://www.eumonitor.eu/9353000/1/j4nvke1fm2yd1u0_j9vvik7m1c3gyxp/vkcwedyptizi/v%3ds7z/f%3d/com(2012)595_en.pdf

European Commission, 2017. "COM(2016) 767 Final/2; ANNEXES to the Proposal." European Union. https://eur-lex.europa.eu/resource.html?uri=cellar:3eb9ae57-faa6-11e6-8a35-01aa75ed71a1.0007.02/DOC_2&format=PDF

European Commission, 2018a. Renewable Energy – Recast to 2030 (RED II). EU Science Hub. 2018. https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii

European Commission, 2018b. DIRECTIVE (EU) 2018/2001 of the European parliament and of the council. European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN

European Commission, 2019. "Crude Oil Imports by EU Country Including Cost, Insurance, and Freight (2005-2019)." European Union. https://ec.europa.eu/energy/data-analysis/eu-crude-oil-imports_en

Eurostat, 2020. Liquid biofuels production capacities. https://ec.europa.eu/eurostat/web/products-datasets/-/nrg_inf_lbpc

Eurostat, 2019. "Primary Production of Crude Oil, 1990-2017 (Million Tonnes of Oil Equivalent)." https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Primary_production_of_crude_oil,_1990-2017_(million_tonnes_of_oil_equivalent).png

Fang, H.L., McCormick, R.L., 2006. Spectroscopic study of biodiesel degradation pathways. SAE Technical Paper 2006-01-3300. https://doi.org/10.4271/2006-01-3300

FAS Office of Agricultural Affairs Beijing, 2019. China: Biofuels Annual. US Department of Agriculture. https://www.fas.usda.gov/data/china-biofuels-annual-5

Filoso, Solange, Janaina Braga do Carmo, Sílvia Fernanda Mardegan, Silvia Rafaela Machado Lins, Taciana Figueiredo Gomes, and Luiz Antonio Martinelli. 2015. "Reassessing the Environmental Impacts of Sugarcane Ethanol Production in Brazil to Help Meet Sustainability Goals." Renewable and Sustainable Energy Reviews 52 (December): 1847–1856. http://dx.doi.org/10.1016/j.rser.2015.08.012.

Franco, Jennifer, Les Levidow, David Fig, Lucia Goldfarb, Mireille Hönicke, and Maria Luisa Mendonça. 2010. "Assumptions in the European Union Biofuels Policy: Frictions with Experiences in Germany, Brazil and Mozambique." The Journal of

Peasant Studies 37 (4): 661–698. http://dx.doi.org/10.1080/03066150.2010.512454

Goodman, Lindsey R., Singh, Preet M., 2014. Chapter 10: corrosion issues in biofuels. In: Ragauskas, J. (Ed.), Materials for Biofuels, 267–293. https://doi.org/10.1142/9789814513289_0010

Guy, T., 2020. E85 Don't Do It! Unless You Know…." Fuel & Friction. https://fuelandfriction.com/weekend-warrior/e85-dont-do-it-unless-you-know/

Hamelinck, C.N., Faaij, A.P.C., 2006. Production of methanol from biomass. In: Minteer, S. (Ed.), Alcoholic Fuels. CRC Press, 7–49. https://doi.org/10.1201/9781420020700

Hoekman, S. Kent, Robbins, Curtis, 2012. Review of the effects of biodiesel on NOx emissions. Fuel Process. Technol. 96 (April), 237–249. https://doi.org/10.1016/j.fuproc.2011.12.036.

Hood, M., 2016. "Forest-Destroying Palm Oil Powers Cars in EU." Phys.Org. http://phys.org/news/2016-05-forest-destroying-palm-oil-powers-cars.html

ICCT, and DieselNet. 2018. "EU: Fuels: Biofuel Policy." TransportPolicy.Net. https://www.transportpolicy.net/standard/eu-fuels-biofuel-policy/

International Institute for Applied Systems Analysis (IIASA). 2016. New Basis for EU Biofuel Policy. 2016. https://www.transportenvironment.org/sites/te/files/publications/2016%2004%20Globiom%20webinar.pdf

Illsley, C.L., 2018. "Where Are Indonesia's Palm Oil Plantations Located?" World Atlas. https://www.worldatlas.com/articles/where-are-indonesia-s-palm-oil-plantations-located.html

Illukpitiya, Prabodh, Reddy, K.C., Bansal, Ankit, 2017. Modeling net energy balance of ethanol production from native warm season grasses. Energy Econ. 64 (May), 346–352. https://doi.org/10.1016/j.eneco.2017.04.008.

IndexMundi, 2020. Palm Oil Imports by Country in 1000 MT. https://www.indexmundi.com/agriculture/?commodity=palm-oil&graph=imports

Krahl, J., Munack, A., Ruschel, Y., Schröder, O., Bünger, J., 2008. Exhaust gas emissions and mutagenic effects of diesel fuel. SAE Technical Papers 2008-01-2508. SAE Paper 2008-01-2508

Lane, Jim. 2019. "Biofuels Mandates around the World 2020. Biofuels Digest." https://www.biofuelsdigest.com/bdigest/2019/12/31/the-digests-biofuels-mandates-around-the-world-2020/

Licht, F.O., 2019. F.O. Licht's World of Biofuels 2019. Informaconnect.Com. https://informaconnect.com/f-o-lichts-world-of-biofuels-2019/

Lucas, Louise, 2012. Enough to go round but millions still starve. Financial Times. https://www.ft.com/content/dd2683d6-22af-11e2-8edf-00144feabdc0

Macrotrends. Crude Oil Prices - 70 Year Historical Chart. https://www.macrotrends.net/1369/crude-oil-price-history-chart

Mason, Josephine, Aizhu, Chen, Gu, Hallie, Pullin, Richard, 2017. China Sets 2020 Target for Nationwide Ethanol Use to Cut Corn Stocks. Reuters. https://www.reuters.com/article/us-china-biofuels/china-sets-2020-target-for-nationwide-ethanol-use-to-cut-corn-stocks-idUSKCN1BO03R

McCormick, Miles, 2020. Oil Bankruptcies Could Shift Clean-up Bill to US Taxpayers Insurance Covers Just a Fraction of the Estimated $280bn Cost of Plugging Wells. Financial Times. https://www.ft.com/content/93b2c112-95f5-4d4b-8f48-761b698b7df5

Melamu, Rethabile, von Blottnitz, Harro, 2011. 2nd generation biofuels a sure bet? A life cycle assessment of how things could go wrong. J. Cleaner Prod. 19 (2–3), 138–144. https://doi.org/10.1016/j.jclepro.2010.08.021.

Meyer, Gregory, 2012. US Farmers Reel from Soaring Feed Prices. Financial Times. https://www.ft.com/content/80fbb25c-1e7c-11e2-be82-00144feabdc0

Meyer, Gregory, 2019. Trump Administration Biofuels Policy Angers US Farmers. Financial Times. https://www.ft.com/content/97e4aa48-ef8d-11e9-ad1e-4367d8281195

Minteer, Shelley, 2006. Ethanol Blends: E10 and E-Diesel. In: Minteer, Shelley (Ed.), Alcoholic Fuels, CRC/Taylor, 126. CRC Press. https://doi.org/10.1201/9781420020700

Moss, Jacques, 2018. What to Expect from Brazil's RenovaBio Programme. Informaconnect.Com. https://informaconnect.com/what-to-expect-from-brazils-renovabio-programme/

Ngee Ann Polytechnic Singapore. 2011. "Case Study in Brazil." Bioethanol. https://bioethanol-np.blogspot.com/p/case-study-in-brazil.html

Nichols, N.N., Dien, B.S., Bothast, R.J., Cotta, M.A., 2006. The corn ethanol industry. In: Minteer, S. (Ed.), Alcoholic Fuels, 1st Ed. CRC/Taylor & Francis, 59–78.

Nogueira, L.A.H., Capaz, R.S., 2013. Biofuels in Brazil: evolution, achievements and perspectives on food security. Global Food Security 2 (2), 117–125. https://doi.org/10.1016/j.gfs.2013.04.001.

Pimentel, David, Patzek, Tad W., 2005. Ethanol production using corn, switchgrass, and wood; biodiesel production using soybean and sunflower. Nat. Resour. Res. 14 (1), 65–76. https://doi.org/10.1007/s11053-005-4679-8.

Prakash, R., Singh, R.K., Murugan, S., 2013. Use of biodiesel and bio-oil emulsions as an alternative fuel for direct injection diesel engine. Waste Biomass Valorization 4 (3), 475–484. https://doi.org/10.1007/s12649-012-9182-y.

RFA, 2020. Total Fuel Ethanol Production in the United States 1980-2019. Statista. https://www.statista.com/statistics/281494/us-fuel-ethanol-production/

Schutter, Olivier De, 2013. Biofuels: Animal Feed a Minor Factor. Financial Times. https://www.ft.com/content/324b9a06-d807-11e2-9495-00144feab7de

Shapouri, H., Duffield, J.A., Wang, M., 2002. The Energy Balance of Corn Ethanol - An Update; US Dept. of Agriculture. Report. No. 814. https://doi.org/10.22004/ag.econ.34075

Shapouri, H., Duffield, J., Mcaloon, A.J., 2004. The 2001 net energy balance of corn-ethanol. In: Proceedings of the Conference on Agriculture as a Producer and Consumer of Energy, Arlington, VA., June 24-25.

Sönnichsen, N., 2020. Biodiesel Production in the U.S. from 2001 to 2019. Statista. https://www.statista.com/statistics/509875/production-volume-of-biodiesel-in-the-us/

Tan, Huilen, 2018. The EU's Palm Oil Policy Is Triggering Condemnation from the Other Side of the Globe. CNBC. https://www.cnbc.com/2018/12/11/an-important-food-ingredient-faces-demand-headwinds-as-concerns-over-environment-destruction-bites.html

Trading Economics. 2020. "Brazil Balance of Trade." https://tradingeconomics.com/brazil/balance-of-trade

Transport & Environment, 2020. Funders. https://www.transportenvironment.org/funders

Trompiz, G., Croft, A., 2017. Rapeseed to decline in EU as biofuel wanes, exports to boost wheat: report. Reuters https://www.reuters.com/article/us-eu-oilseeds-outlook-idUSKBN1EC1E0

Trompiz, G., Goodman, D., Lewis, B., 2020. Update 1-EU, UK Rapeseed Crop Area Seen Down Slightly - Strategie Grains. Successful Farming/Reuters https://www.agriculture.com/markets/newswire/update-1-eu-uk-rapeseed-crop-area-seen-down-slightly-strategie-grains

Tsanova, T., 2019. "Brazil Expects Huge Rise in Sugar, Ethanol Exports to EU." Renewables Now. https://www.renewablesnow.com/news/brazil-expects-huge-rise-in-sugar-ethanol-exports-to-eu-660445/

Unglert, Martin, Bockey, Dieter, Bofinger, Christine, Buchholz, Bert, Fisch, Georg, Luther, Rolf, Müller, Martin, et al., 2020. Action areas and the need for research in biofuels. Fuel 268, (May). https://doi.org/10.1016/j.fuel.2020.117227 117227.

US Congressional Budget Office, 2009. The Impact of Ethanol Use on Food Prices and Greenhouse-Gas Emissions. 2009. https://www.cbo.gov/sites/default/files/cbofiles/ftpdocs/100xx/doc10057/04-08-ethanol.pdf

US Energy Information Administration (EIA), 2020a. Biofuels Explained: Ethanol. https://www.eia.gov/energyexplained/biofuels/ethanol.php

US Energy Information Administration (EIA), 2020b. US Liquid Fuels. https://www.eia.gov/outlooks/steo/report/us_oil.php

van Beilen, Jan B., 2010. Why microalgal biofuels won't save the internal combustion machine. Biofuels, Bioprod. Biorefin. 4 (1), 41–52. https://doi.org/10.1002/bbb.193.

Voegele, Erin, 2019. Report: EU Ethanol Consumption to Increase in 2019. Ethanol Producer Magazine. http://ethanolproducer.com/articles/16422/report-eu-ethanol-consumption-to-increase-in-2019

Wheat prices, 2020. Business Insider. https://markets.businessinsider.com/commodities/wheat-price

White, S., 2017. More than Half of EU Biodiesel Made from Imported Crops, Study Finds. Euractiv.Com. https://www.euractiv.com/section/agriculture-food/news/more-than-half-of-eu-biodiesel-made-from-imported-crops-study-finds/

Xu, Ling, Weathers, Pamela J., Xiong, Xue-Rong, Liu, Chun-Zhao, 2009. Microalgal bioreactors: challenges and opportunities. Eng. Life Sci. 9 (3), 178–189. https://doi.org/10.1002/elsc.200800111.

Yu, Sun, 2019. China Pulls Back on Setting Tough Ethanol Fuel Content Standards. Financial Times. https://www.ft.com/content/c0b4b550-f526-11e9-a79c-bc9acae3b654

Ziegler, Jean, 2013. Burning Food Crops to Produce Biofuels Is a Crime against Humanity. The Guardian UK Edition. https://www.theguardian.com/global-development/poverty-matters/2013/nov/26/burning-food-crops-biofuels-crime-humanity