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Past, Present and Future: A Role for Liquid Biofuels in Transitioning to Net Zero?

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Abstract

Over the last decade, the uptake rate of first-generation biofuels (ethanol and biodiesel) has decelerated as low blend limits have increased only slowly and extreme volatility in oil prices has limited investment in biofuels production infrastructure. Concerns over the environmental impacts of large-scale biofuels production combined with tariff barriers have greatly restricted the global trade in biofuels. First-generation biofuels produced either by fermentation of sugars from maize or sugarcane (ethanol) or transesterification of triglycerides (biodiesel) presently contribute less than 4% of terrestrial transportation fuel demand and techno-economic modelling foresees this only slowly increasing by 2035. With internal combustion and diesel engines widely anticipated as being phased out in favour of electric power for motor vehicles, a much-reduced market demand for biofuels is likely if global demand for all liquid fuels declines by 2050. However, second-generation, thermochemically produced and biomass-derived fuels (renewable diesel, marine oils and sustainable aviation fuel) have much higher blend limits; combined with policies to decarbonise the aviation and marine industries, major new markets for these products in terrestrial, marine and aviation sectors may emerge in the second half of the 21st century.

Keywords

Biofuels, Ethanol, Biodiesel, Renewable Diesel, Sustainable Aviation Fuel, Biomass

1. Introduction

By 2014, liquid biofuels (ethanol and biodiesel) were being produced on a large and industrial scale but only accounted for 2.5% - 2.8 % of total transport fuels usage despite global oil prices having rapidly increased from the 1990s [1]. An analysis offered several distinct but interconnected indicators by which to gauge the emergence of biofuels from niche markets over the subsequent decade [2]. These indicators could be grouped into the headings of technical, biotechnological, national/multinational biofuels and environmental policies and the unpredictable economics of oil prices (**Table 1**).

A decade later, how useful are those diagnostic indicators? In particular, how have national and international policy shifts regarding greenhouse gas emissions, climate change and sustainability shifted the debate towards or away from liquid biofuels use in internal combustion and diesel engines? Policies on climate change were not highlighted (**Table 1**) because biofuels were broadly apprised as capable of reducing CO_2 emissions, although this was not a universally agreed conclusion in the 1990s and the first decade of the twenty-first century [3] [4].

The technical group of indicators in **Table 1** includes a then much-discussed geopolitical aspect of fuel ethanol production, *i.e.* the extrapolation of sugarcane ethanol production to the "18 more Brazils" scenario [5] [6]. Brazil was a paradigm for fuel ethanol production because of its very early acceptance of fuel ethanol for mass transportation, its national policies on blending and its use of Flex Fuel Vehicles (FFVs) which could easily alternate between gasoline and gasoline/alcohol blends [7].

Ethanol can, in many ways, be regarded as the first industrial bio-commodity chemical [8]. The use of ethanol (the exemplary first-generation biofuel) and other second-generation alcohols (for example, butanol) as feedstocks for a wider range of chemicals conventionally derived from petrochemistry were explored as novel routes to evolve a "greener" heavy chemical industry no longer based on fossil fuels [9] [10].

Table 1. Indicators for liquid biofuels use [2].

Indicator Group	Examples	Expected Effect on Biofuels Use
Technical	Higher blending limits with petrofuels	Positive
	Greatly increased "sugar states" ethanol	Positive
	Increased palm oil for biodiesel	Positive
Biotechnological	Advanced biofuels development	Positive
	Bio-commodity products from biofuels	Neutral/negative
	Novel "energy crops"	Positive
	Increased use of waste agro-industry streams	Positive
Policies	Renewable Fuels Standard (USA)	Positive
	Renewable Energy Directive (EU)	Negative
	"Food versus fuel"/"food first" (UN agencies)	Negative
	Higher biofuels imports (EU, Japan)	Positive
Economic	Sustained high oil price	Positive
	Sustained low oil price	Negative

Missing from **Table 1** is the concept of an affordable electric vehicle (EV); Tesla had launched what the company had claimed to be the start of increasingly affordable EVs in 2012 [11]. To many commentators, the recent emergence of a potentially massive EV market already heralds the end of biofuels as significant factors in energy use in an increasingly decarbonised world powered by renewable energy in the forms of photovoltaic cells and wind turbines [12].

This article, therefore, draws conclusions from publicly available datasets on how biofuels production did (or did not) prosper in what was a decade notorious for economic turbulence and disruptions to conventional fossil fuel markets [12] and against the background of increasing environmental awareness as publicised by the United Nations Climate Change Conference of 2021 [13]. A second aim is to go beyond present biofuels production to integrate predictions and forecasts to identify future trends to 2030 and beyond, when environmental concerns may greatly restrict the use of conventional internal combustion and diesel engines for vehicular transport.

2. Methodology

Data has been sourced from national and international agencies and associations [1] [12] [14]-[20]. Cited sources include statements and descriptions of methodologies used in their preparation.

Key non-SI units used: kboe = thousand barrels of oil equivalent, kt = thousand tons, km^3 = thousand cubic metres, kb/d = thousand barrels per day, Mboe per day = million barrels of oil equivalent per day.

3. Results

3.1. Comparisons between the First Two Decades of the 21st Century

Global production of fuel ethanol and biodiesel increased during the decade after 2013, with the US and Brazil remaining the major national producers of maize-derived and sugarcane-derived ethanol, respectively (**Figure 1**).

Average Annual Growth Rate (AAGR) estimates were, however, much lower than in the previous decade of 2004-2013 (**Figure 2** and **Figure 3**).

By 2022, liquid biofuels use had reached 3.67% of total transportation fuel demand (**Figure 4**). As with global biofuels production, the AAGR value of the contribution of liquid biofuels between 2013 and 2022 was much lower than in the previous decade (**Figure 5**).

The Brazilian experience was idiosyncratic with a continued (but erratic) rise in the contribution of liquid biofuels to reach >30% by 2018 (**Figure 5**). Sugar and fuel (anhydrous) ethanol production figures for Brazil have showed unclear relationships in the 21st century with, at best, a weakly positive correlation (**Figure 6**). Inevitably, a third parameter has been significant, *i.e.*, the gasoline to ethanol price ratio, especially when FFVs offer a daily choice based on pump prices alone [21]. Crude oil prices exhibited extreme volatility after 2000 (**Figure 7**). Factoring in these price fluctuations, it possible to identify an important feature of the Brazilian fuel markets: fuel ethanol production increased as oil prices recovered rapidly from the price crash of 2008 (itself caused by the sharp global economic downturn after 2007/8) but ethanol production then stagnated when oil prices collapsed again after 2014 to only recover sufficiently to rival the high prices of 2012-2014 prices by 2022, when military conflict in East Europe then severely disrupted energy markets. Fuel ethanol production was unusually low due to unusually low sugar production in 2018-2019 but this was an isolated combination of events in Brazil in the decade (Figure 6).

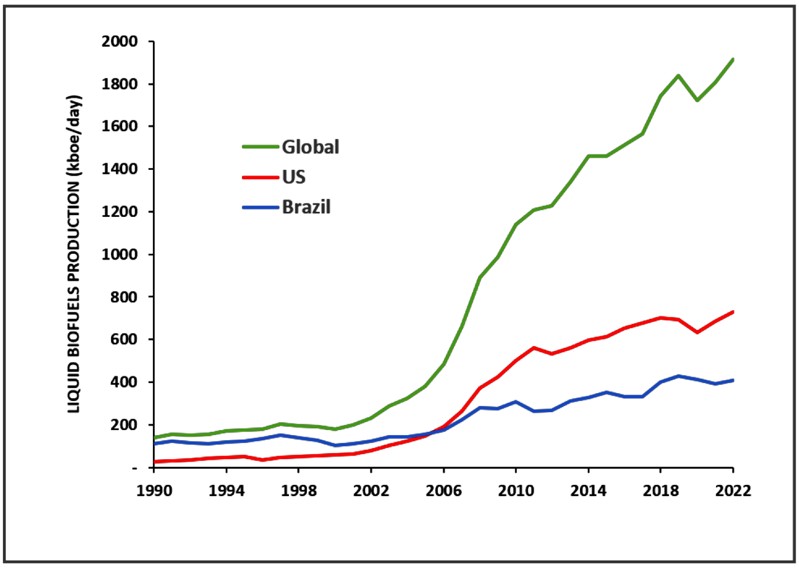

Figure 1. Global, US and Brazilian production of fuel ethanol and biodiesel 1990-2022; data from [1].

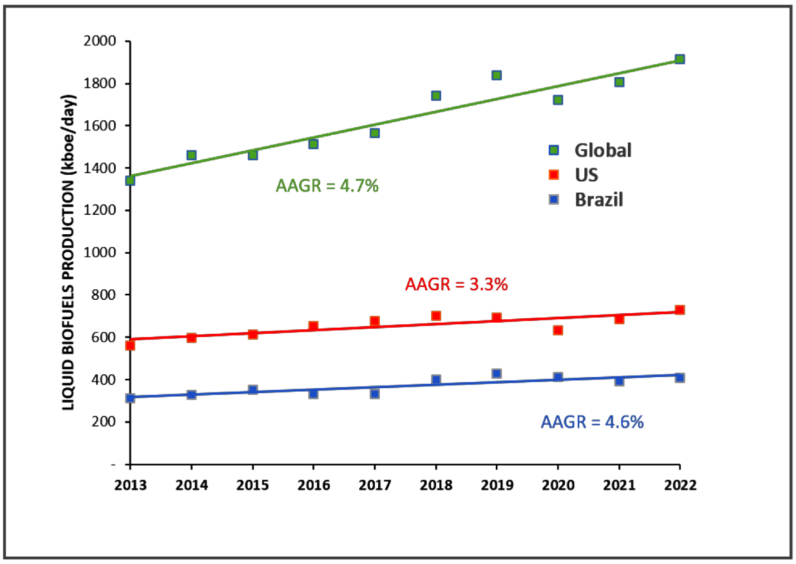

Figure 2. Average Annual Growth Rate (AAGR) 2013-2022 estimates of growth in liquid biofuels production from data in [1].

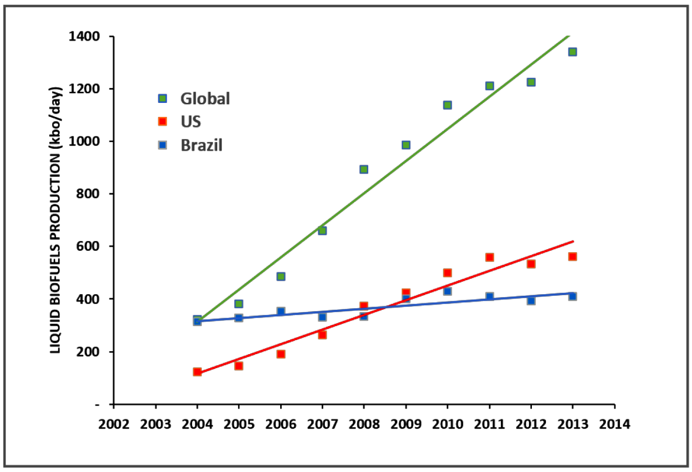

Figure 3. Average Annual Growth Rate (AAGR) 2004-2013 estimates of growth in liquid biofuels production, from data in [1].

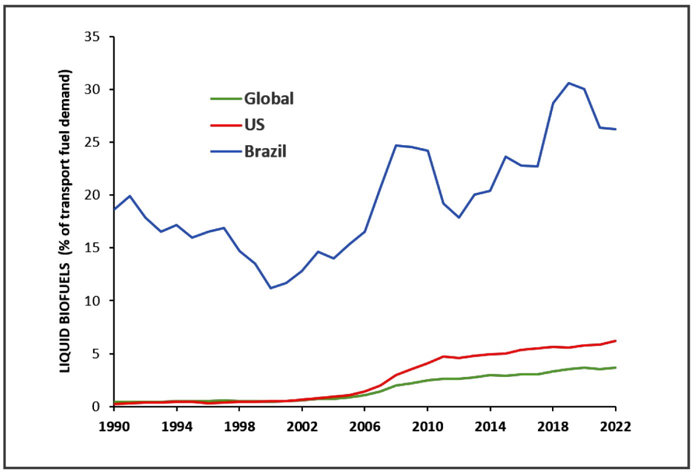

Figure 4. The contribution of liquid biofuels to terrestrial transportation fuel demand 1990-2022; data from [1].

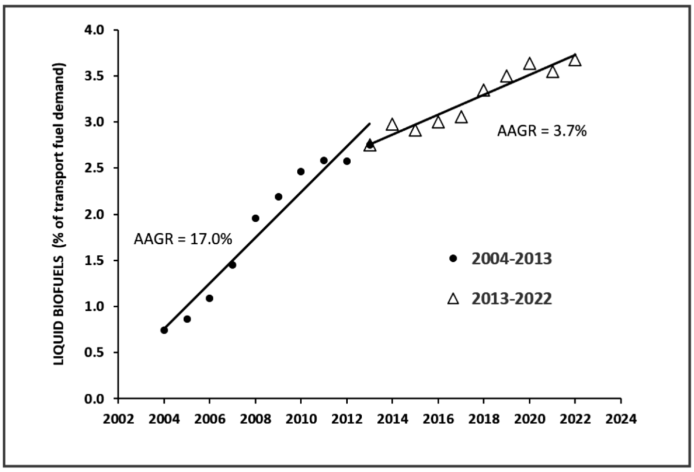

Figure 5. Average Annual Growth Rate (AAGR) 2004-2013 estimates of the contribution of liquid biofuels to total transportation demand, from data in [1].

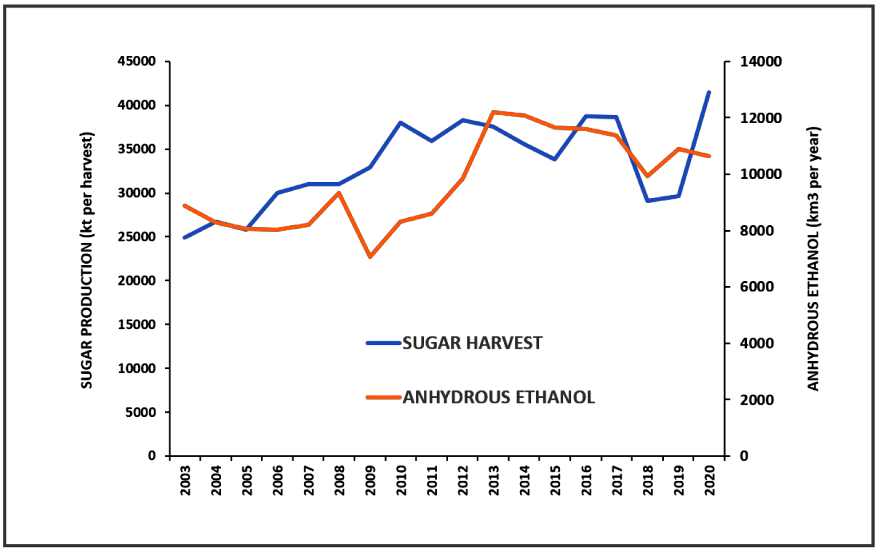

Figure 6. Sugar and fuel (anhydrous) ethanol production in Brazil; data from [14].

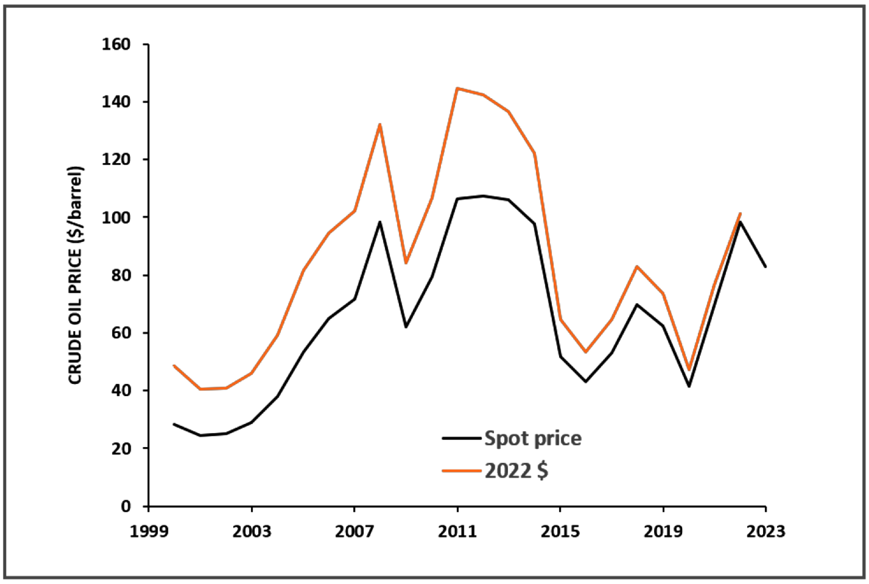

Figure 7. Crude oil prices 2000-2022 as both spot prices and with adjustments for inflation [1] and 2023 spot price mean (https://www.eia.gov/todayinenergy/detail.php?id=61142).

The extensive debate about the oil price crash of 2008 was well summarised in [22]: a strong increase in demand from industrialising nations (especially China) met a restricted supply scenario in which producing less oil for a higher price was seen by oil producers as beneficial to themselves in the short and long terms despite the inevitable risk of triggering a global economic downturn. After 2014, a very different mechanism has been adduced, *i.e.*, the disruptive effect of high production volumes of oil from non-conventional sources in North America by hydraulic fracturing and horizontal drilling from shale reserves ("fracking") [23]. This greatly increased availability of oil challenged monopolistic oil producers but was by itself insufficient to prevent a recovery in oil prices as the world moved beyond the Covid-19 pandemic.

The link between oil prices and biofuels production has been conceptualised as a short-term price limitation, *i.e.*, any period of low oil prices leaves all biofuels vulnerable to being priced out of the market place and a guideline minimum oil price of $70 per barrel required to avoid this is often quoted [24]. Even a few months in which the price of a biofuel is uneconomic risks plant shutdowns and even mothballing because biofuels do not enjoy the option of greatly decreased feedstock prices, unlike petrochemically derived fuels. **Figure 7** demonstrates that crude oil prices were below the accepted critical value for four years or more, which would have greatly restricted any expansion of first-generation biofuels production while inhibiting any moves from demonstration plants to production-scale facilities for second-generation (advanced) biofuels.

The two unusual factors in the decade after 2013, the Covid-19 Pandemic and military conflict in Eastern Europe, are generally considered to have had only transient effects on demand for liquid fuels, the major impact (which will possibly be a long-lasting feature) being a restructuring of the global trade in natural gas [12] [15].

Finally, any move towards the "18 more Brazils" scenario [5] [6] has been very muted in the decade after 2013 with only the Asia-Pacific region achieving biofuels production to rival that of Brazil alone, *i.e.* >400 ktoe per day (**Figure 8**).

The Asia Pacific region is of most interest, however, when forecasts for biofuels beyond the present decade are made. In line with the failure to markedly expand fuel ethanol production in sugar-growing regions, trade in fuel ethanol has remained muted, estimated as being only 9% of production in 2022 and predicted to decrease to 8% by 2030 [16]. A key factor has been, and continues to be, environmental concerns for preserving the Amazonian rainforest, which has prevented the ratification of the EU-Mercosur trade agreement [25].

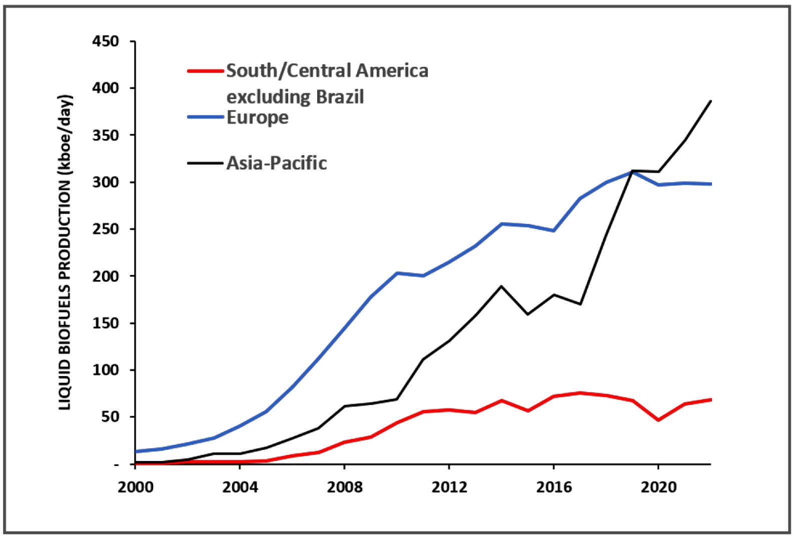

Figure 8. Liquid biofuels production in Europe, Asia-Pacific and South/Central America (excluding Brazil) 2000-2022; data from [1].

3.2. Short-Term Predictions of Biofuels Production and Use to 2030

As an important voice in the "food versus fuel" debate concerning first-generation biofuels, the Food and Agriculture Organization (FAO) predicts a rapid recovery post-Covid but only a slow increase in fuel ethanol consumption until 2030, with the Brazilian and Indian markets contributing most of the increase [16]. Apart from Brazil, where the ethanol blending limit is 27%, much smaller maxima are the rule: 2% in China, 4% but intended to rise to 20% in India, 14% in Thailand while in Europe blend limits have already increased from 5% to 10% but no with clear plans to move any higher [16] [26].

Biodiesel consumption stalled during the Covid-19 pandemic but had recovered to pre-pandemic levels by 2022, although little or no further growth is predicted up to 2030 [16]. One nation's commitment to biodiesel production is, however, notable: Indonesia has a large internal market for biodiesel from palm oil and a national policy of financially subsidising national production. Moreover, Indonesia has a high blend limit of 30% with conventional petro-diesel and this is intended to greatly reduce fossil fuel imports. Indonesia is predicted to become the second largest biodiesel producer (after the European Union) by 2030, although tariffs and environmental concerns for palm oil plantations will stifle any export trade [16].

3.3. Projections up to 2050

Beyond 2030, forecasts for biofuels production and consumption are complicated by announced and potential national policies to end the manufacture and sale of internal combustion- and diesel-engine vehicles in combination with the accelerated deployment of technologies to reduce greenhouse emissions and climate change.

For example, British Petroleum has three forecasting models: 1) "New Momentum", which is the most conservative and is based on current changes in global energy use and predicts 2050 global greenhouse emissions decreasing by 30% relative to a 2019 baseline; 2) "Accelerated", in which 2050 global greenhouse emission fall by 75% relative to a 2019 baseline; 3) "Net Zero", in which 2050 global greenhouse emission fall by 90% relative to a 2019 baseline [12]. The three models predict very different long-term outlooks for liquid biofuels used in terrestrial transportation (**Figure 9**).

All three scenarios predict modest increases in the contributions of liquid biofuels to the total fuel demand of light road vehicles by 2035 from a 2019 estimate of 4.1%; by 2050; however, the "Accelerated" and "Net Zero" scenarios predict marked falls in the use of liquid biofuels as EVs replace internal combustion- and diesel-engine vehicles. Similar trends are predicted for medium- and heavy-duty vehicles (from a lower 2019 estimate of 3.1%) as EVs and hydrogen-and natural gas-powered vehicles increasingly dominate this transportation sector (**Figure 10**).

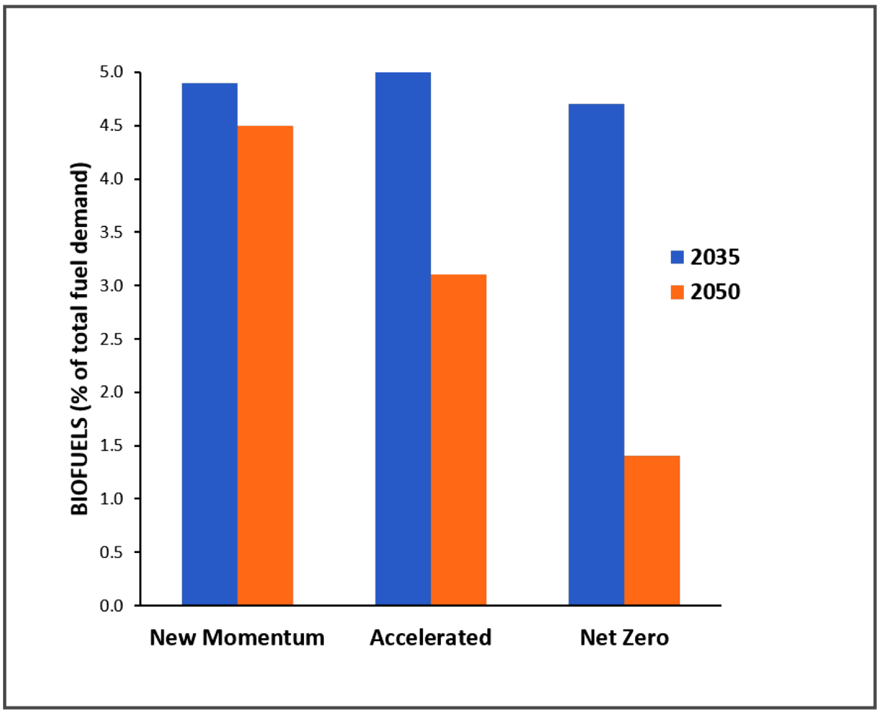

Figure 9. British Petroleum's predicted liquid biofuels use for light vehicles for 2035 and 2050; data from [12].

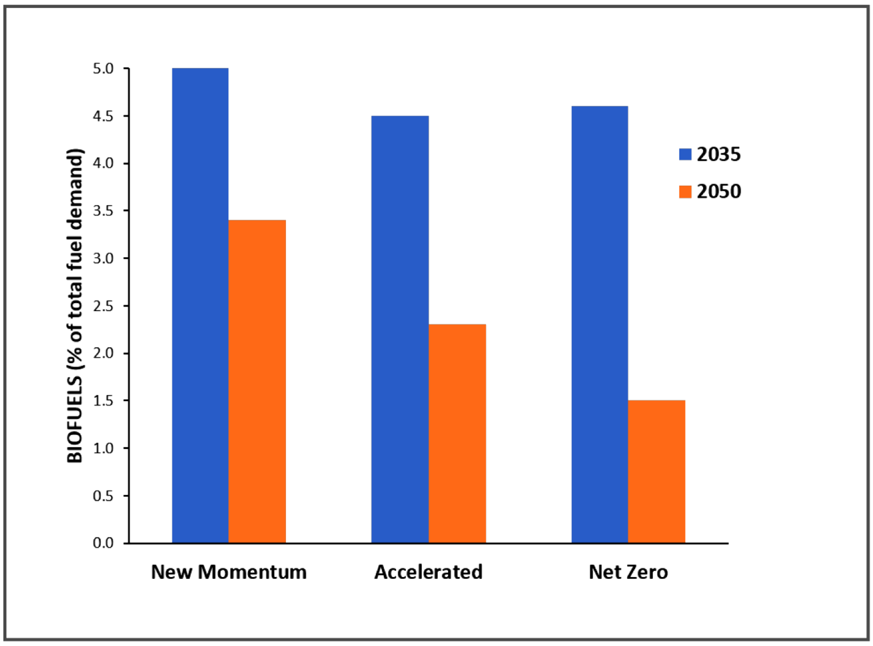

Figure 10. British Petroleum's predicted liquid biofuels demand for medium and heavy vehicles in 2035 and 2050 with three different prediction models; data from [12].

A major uncertainty is the exact timeframe of obsolescence of internal combustion diesel engines as EVs take progressively larger market shares. Recent analyses point to internal combustion engines remaining in 20% of light-duty vehicles by 2070 [27]. This longevity has several factors, most importantly the increasing lifespans of internal combustion engines and the ability of conventionally powered vehicles to rival the life-cycle reduction in CO_2 emissions from EVs if a high-ethanol blend fuel (E85, 85% ethanol) becomes available, even one using first-generation fuel ethanol from corn (maize). Additionally, while electricity generation still has a major fossil fuel contribution, the much-emphasised environmental superiority of EVs will remain incompletely realised. The combination of all these factors could be an extended transition phase between conventional engines and battery-powered vehicles lasting until the end of the present century. In that scenario, continuing demand for liquid biofuels for vehicular transport could outlast and extend beyond current predictions (**Figure 9** and **Figure 10**).

The International Energy Agency (IEA) also has three different forecasting models which are increasingly challenging in their deployment: the STEPS scenario (Stated Policies Scenario) accepts present national and international energy and climate policies; APS (Announced Pledges Scenario) assumes that all national energy and climate targets can be met by 2050; NZE (Net Zero Emissions by 2050) assumes that global warming will be limited to 1.5˚C [15]. While these different scenarios all predict increasing demand for liquid biofuels by 2030 and 2050 compared with a 2020 estimate of 2.2 Mboe/day, the NZE model predicts a collapsing market demand for liquid fuels across terrestrial, marine and aviation sectors by 2050 (**Figure 11**).

In those circumstances, the NZE outcomes imply that a 2.4-fold increase in total liquid biofuels production by 2050 would more than meet the diminished demand for liquid biofuels for all transportation modes.

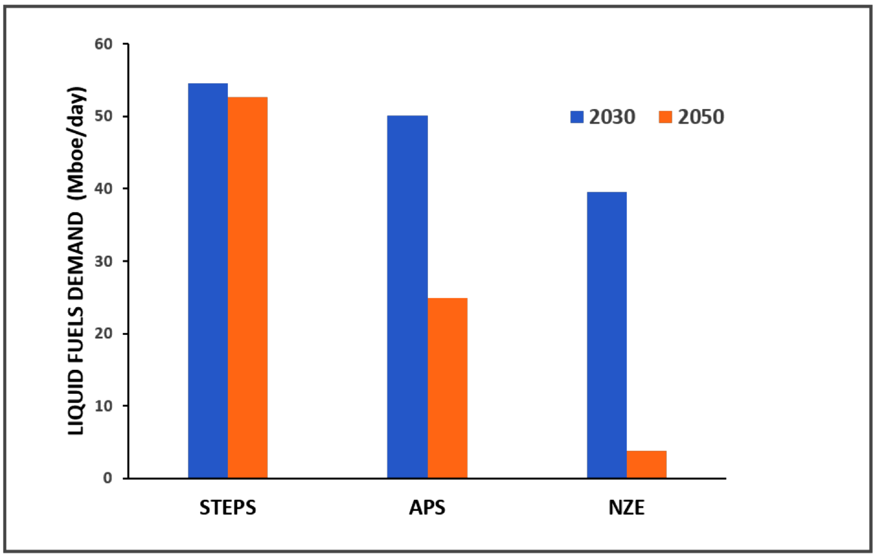

Figure 11. The International Energy Agency's predicted changes in total liquid fuels demand for global transportation by 2030 and 2050 with three different forecasting models: Stated Policies Scenario (STEPS), Announced Pledges Scenario (APS) and Net Zero Emissions by 2050 (NZE); data from [15].

3.4. Renewable Diesel and Sustainable Aviation Fuel

Two second-generation biofuels with the potential to be produced from plant biomass or waste streams rather than from food crop-derived sugars have begun to offer potentially large future markets for liquid fuels: renewable diesel (RD) and sustainable aviation fuel (SAF).

RD (originally termed hydrotreated vegetable oils) is essentially a set of alkane hydrocarbons highly comparable to and compatible with conventional diesel and can be blended with conventional diesel at any ratio up to 100%; moreover, the high energy density, very similar storage stability to diesel and claims of lower pollutant emissions all combine to portray RD as a superior biofuel to ethanol or biodiesel [7] [28] [29]. Novel catalysts are continuing to be developed for highly efficient RD production [30] [31]. Commercial RD production uses hydrotreatment of various lipid feedstocks; other processes under development are mostly chemical, including pyrolysis, gasification and hydrothermal processing of biomass feedstocks [17]. Some biotechnological processes have been considered, such as the biological conversion of sugars to hydrocarbons [32].

By 2022, RD production in the US was estimated as 1.5 billion gallons per year; additional plant capacity of 4.2 billion gallons per year under construction or planned [17]. After 2021, RD production in the US has accelerated markedly while biodiesel production had been declining since 2020; RD overtook biodiesel for the first time in 2023 [17]. RD may reach 5% of total fuel demand by 2035 (**Figure 10**) but then either declines [12] or continues to increase so that all road transport demands could be met [15].

SAF has had a short production lifetime but its consumption in the US (mostly met by domestic production) has been increasing rapidly since 2018 [18]. The top four technologies with the highest permitted blending limits use chemical and thermochemical processes (**Table 2**, data from [19]). The Alcohol-to-Jet product takes alcohols derived by microbial fermentation of cellulosic biomass and converts the alcohols via chemical treatments [33]. Other biotechnological processes, including transforming sugars to hydrocarbons and the conversion of microalgal triglycerides into fuels, are established but have much lower permitted blending levels, 5% - 10% [18].

Table 2. High blending limit technologies for sustainable aviation fuel; data from [19].

Technology	Biomass feedstock	Blending Limit
Fischer-Tropsch Synthetic Paraffinic Kerosene	Woody biomass, agricultural and forest wastes, energy crops, municipal solid waste	50%
Hydroprocessed Esters and Fatty Acids	Triglycerides: plant oil, animal oil, yellow/brown greases	50%
Biomass to syngas and conversion to paraffinic kerosene	Woody biomass, agricultural and forest wastes, energy crops, municipal solid waste	50%
Catalytic Hydrothermolysis Synthesized Kerosene	Fatty acids or fatty acid esters or lipids from fat oil greases	50%
Alcohol-to-Jet Synthetic	Alcohol-to-Jet Synthetic	30%

Because of high possible blend limits, the potential for SAF to become a (and possibly) the major global liquid biofuel is emphasised by International Air Transport Association: SAF only accounts for 0.2% of total aviation fuel use in 2023 but its increased use could reduce total aviation CO_2 emissions by 5% by 2030 [15] [20]. To accomplish this, SAF production by 2030, would need to reach approximately 1.7 x10^7 tonnes from a 2023 baseline of only 5.7×10^5 tonnes. Blend limits by 2030 have been addressed by national governments, for example 10% (UK), 6% (EU) and 2% or 10% in international flights (Japan and India, respectively).

Sufficient feedstock availability to meet even these modest goals is a major concern [34]. A projected 1 billion dry tons of biomass for SAF in the US has been claimed [35] but this is probably based on a 2005 estimate for the whole of US biofuels production [36]. Biomass (lignocellulose) has generally proved its intractability as an industrial-scale biotechnological biofuels feedstock [37].

A radical alternative production route to SAF is the power-to-liquids (PtL) approach in which renewable energy powers hydrogen production from the electrolysis of water and the capture of CO_2 from the atmosphere, combines them to generate CO which, when mixed with more hydrogen, gives the reactants for a Fischer-Tropsch process to generate the required hydrocarbon mix for aviation fuel [38] [39]. This route is highly attractive for nations and regions with little sustainable plant biomass but life cycle analysis casts doubt on the claims for PtL as an effective means of reducing carbon emissions in climate change mitigation because of its complexity and energy intensity [38].

Whatever the production route, British Petroleum's forecasts all include substantial increases in the use of SAF, rising to 45% by 2050 in the Net Zero scenario (**Figure 12**). Such an increase, driven by high blend limits, would make a major contribution to decarbonising the global aviation industry.

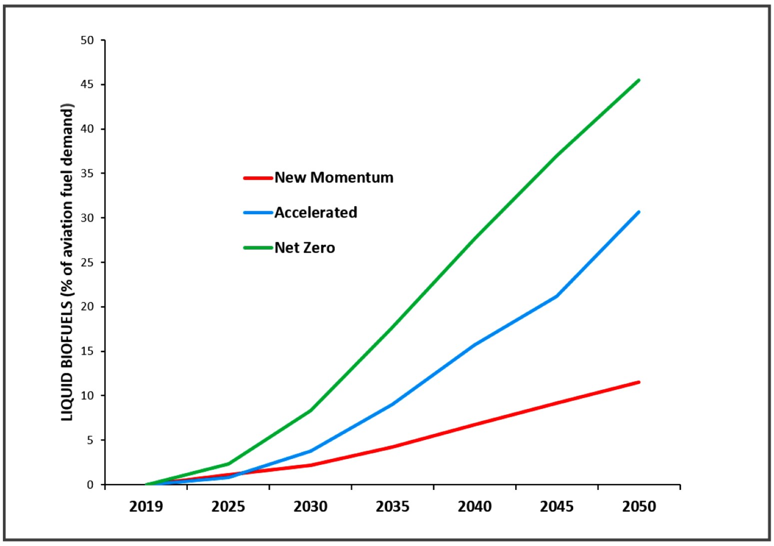

Figure 12. British Petroleum's predicted trends in SAF demand by the aviation industry to 2050 with three different forecasting models; data from [12].

Marine oils for shipping can be manufactured from biomass by variations of thermochemical processes used for RD production to generate varying mixes of longer-chain alkanes with definite greenhouse gas abatement potential as well as reducing atmospheric pollution [40]. In British Petroleum's three forecasting models [12], only the more radical programs to lower CO_2 emissions predict major increases in the use of liquid biofuels in global shipping (**Figure 13**). All models, however, envisage hydrogen-derived liquid fuels ("E-methane" and "E-methanol") contributing to marine fuel demand by 2050; these fuel products share similar production pathways to PtL forms of SAF [41].

A crucial economic factor in considerations of future trends in terrestrial, aviation and shipping sectors is that of crude oil price. The APS and NZE models developed by the IEA [15] forecast oil prices by 2050 that are 40% and 75% down on 2022 prices, respectively (**Figure 14**).

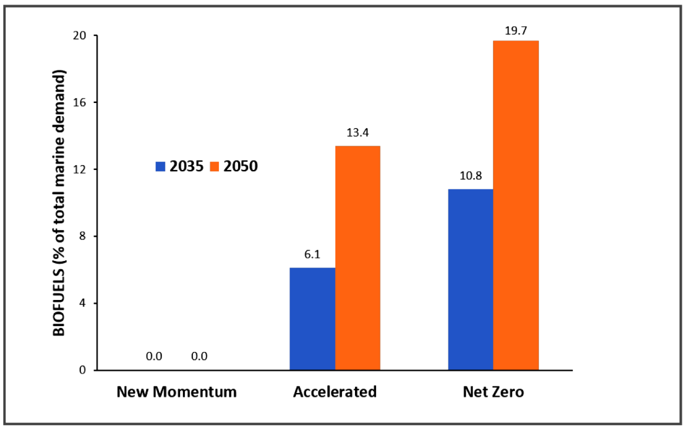

Figure 13. British Petroleum's predicted marine demand for biofuels by 2035 and 2050 with three different forecasting models; data from [12].

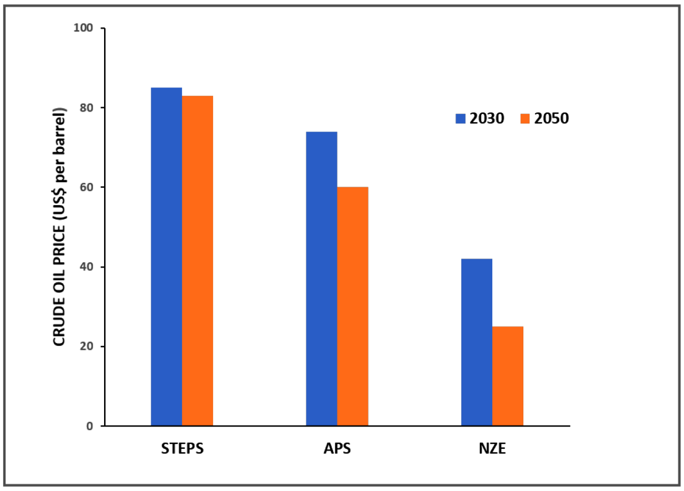

Figure 14. The International Energy Agency's predicted falls in crude oil price (in US$ 2022) by 2030 and 2050 with three different forecasting models: Stated Policies Scenario (STEPS), Announced Pledges Scenario (APS) and Net Zero Emissions by 2050 (NZE); data from [15].

Such low prices could be instrumental in limiting the global extraction of oil because of its much lower market value; this long-term trend could, therefore, contribute to 50% of known conventional oil reserves and most (if not all) unconventional oil reserves being left untapped on purely economic grounds [42].

3.5. Bio-Commodity Chemicals

First-generation liquid biofuels catalysed development of biotechnological utilisation of plant biomass and bioproduction routes for commodity chemicals. The nature of the biofuels industry (*i.e.* high-volume, low-price products) and concerns over the large-scale changes in agricultural land use scenarios [43] [44] [45] persuaded increasing numbers of commentators to argue that using the advances in knowledge gained from biofuels biotechnology would be better utilised in the production of bio-commodity chemicals to reduce global dependence on petrochemical feedstock chemicals.

Biochemical pathways and methodologies are known for all the intermediates of the petrochemical industry but their commercial viability is undefined [10]. This was dramatically illustrated in the last decade by the development but rapid commercial failure of the biotechnological production of succinic acid, a compound with established petrochemical routes from maleic anhydride or 1,4-butanediol [46] [47] [48]. Low crude oil prices after 2014 (**Figure 7**) rendered "bio-succinic acid" effectively unsaleable.

4. Conclusions

Over the last decade, liquid biofuels have struggled to escape being niche contributors to global markets for transportation fuels. Low blending limits and extreme price changes for crude oil have combined to stifle investment, combined with regional policies and import limitations motivated by environmental concerns [2].

In 2024, with the projected sharp decline in the sales of internal combustion and diesel engine-powered vehicles by 2030-2040 as climate change mitigation favours the mass production of EVs, potential demand for liquid biofuels is uncertain as climate change mitigation policies will evolve. In some forecasts, liquid biofuels remain as niche players in global fuel markets; in more radical scenarios driven by greenhouse has mitigation strategies, liquid biofuels could fully meet a much-reduced demand for liquid fuels with comparatively small increases in production rates as conventional engine types (internal combustion, diesel and jet) are restricted or even removed from the market place.

However, thermochemically produced biofuels, in particular, renewable diesel, marine oil and sustainable aviation fuel, remain potentially major markets for high blend limit biofuels if sufficient biomass resources can be accessed. Markets for these biofuels may be driven by fears over energy insecurity coupled with the desire to decarbonise the aviation and marine industries with thermochemical production technologies which can manufacture all the types of contemporary fuels used for transportation (terrestrial, marine and aviation).

The biotechnological "legacy" of ethanol as a first-generation biofuel will lie in the impetus given to biochemical, enzymological and molecular biological work on pathways for micro-organisms to utilise cellulose, hemicelluose and lignocellulose substrates and their contribution to Circular Economy practices with, for example, residues from breweries and paper manufacture [49]. Although the idea that ethanol could be regarded as a major route to solving energy crises and fossil fuel dependency has faded, hopes persist for the industrial use of readily bio-manufactured ethanol as a feedstock for a wide range of bio-commodity chemicals [50] [51].

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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