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Liquid biofuels: not a long-term transport solution

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Abstract

Because of concerns about global climate change, possible global oil depletion, and because of potential benefits for both urban air pollution and rural employment and industry, many countries both in and out of the Organization for Economic Cooperation and Development (OECD), are promoting liquid biofuels as a replacement for oil-based transport fuels, and global output is rising steadily. In fact, bioenergy use in general is promoted, and is expected by many to play a major role in climate change mitigation. But bioenergy use in general faces competition for resources such as land, water and fertiliser from the two other general biomass uses, food production and biomaterials. Ethically, food production should take precedence over the other two uses (and at present all bioliquids are made from foodstuffs), and using biomass for biomaterials will in many situations reduce greenhouse gas emissions more than using the same amount of biomass for energy. Where a given amount of biomass is available for transport energy use, it will usually produce more greenhouse gas reductions per vehicle-km if used to produce electricity rather than liquid biofuels. Finally, there are signs that internal combustion engine vehicles could be phased out in the coming decades. If so, liquid biofuels will be phased out along with existing oil-based transport fuels. In conclusion, except for specialist uses, liquid biofuels do not appear to have a long-term future.

Keywords: air pollution; BECCS; biomaterials; climate change; cellulosic ethanol; liquid biofuels; oil depletion

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1. Introduction

Replacing oil-based transport fuels by biofuels has several benefits. It increases energy security by enabling oil imports to be reduced. Use of bioliquids for transport may also reduce greenhouse gases (GHGs) produced per km of vehicle travel, although the exact savings are the subject of much debate, as they are very context-dependent [1-4]. Ethanol as a partial or full replacement for petrol reduces urban air pollution; such pollution reduction is behind the

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US mandate for use of oxygenated fuels. Growing crops for bioliquids, and their conversion to bioethanol or biodiesel also provides support for rural economies.

Finally, liquid biofuels are at least a partial answer to the threat of global oil depletion. Most researchers today feel that annual global oil consumption is more likely to be cut by restraints on oil *consumption* because of the urgent need to cut GHG emissions. But others [eg 5,6] feel that *production* constraints—from either geological or economic considerations—will lead to production cuts in the near future. Wang et al [5] have argued that even if reserves of non-conventional oil (and gas) are large, their production will only 'delay the appearance of the supply constraints of all fossil fuel resources, and to reduce the decline rate of total production after peak; but not to avoid such a peak completely'.

In 2016, 82.31 megatonnes of oil equivalent (Mtoe) of liquid biofuels were produced globally, up from 8.57 Mtoe in 1990, with a 3-fold growth over the past decade. The US and Brazil together accounted for two-thirds of total 2016 production [7]. Nearly all was bioethanol (EOH), with smaller amounts of biodiesel. In the US, ethanol is mainly produced from corn, in Brazil, from sugar cane. Biodiesel is produced from edible oil seeds. For comparison, 2016 global consumption of all liquid fuels (including biofuels and oil from coal) was 4418 Mtoe [7].

This paper is a review of the recent literature on bioliquids, including an analysis of the system effects of greatly increased bioliquids production. It concludes that bioliquids will never be of more than marginal importance globally, and if internal combustion engine vehicles are phased out worldwide, will—along with other liquid transport fuels—cease to be produced.

Nomenclature

BECCS	bioenergy carbon capture and sequestration
CCS	carbon capture and sequestration
CO_2	carbon dioxide
EJ	exajoule = 10^{18} joule
EROEI	energy return on energy invested
FAO	Food and Agriculture Organization
GHG	greenhouse gas
GJ	gigajoule = 109 joule
Gt	gigatonne = 10^9 tonne
HANPP	human appropriation of Net Primary Production
IPCC	Intergovernmental Panel on Climate Change
MJ	megajoule = 10^6 joule
Mtoe	million tonnes of oil equivalent
NPP	Net Primary Production
OECD	Organization for Economic Cooperation and Development

2. Global biomass production and use

Each year, all plants on land fix some 53.6 gigatonne (Gt) of carbon, net of self-respiration, with an energy content of about 2000 EJ [8]. This figure is termed the Net Primary Production (NPP). This NPP provides the energy to fuel all heterotrophic species, including not only humans, other mammals, birds etc, but also microbes that cause decay in plant litter. A significant proportion of NPP is used by humans—the human appropriation of Net Primary Production (HANPP). Estimates for HANPP, which include not only biomass directly consumed by humans, such as for food, fuel and fibre, but also the fodder of domestic animals, and in some studies, items such as the NPP foregone by paving or building over formerly vegetated land, range from 15% of NPP to over 50% [1].

HANPP can be divided into three main general uses: food, energy and biomaterials. Food includes all agriculture except that for producing fibres like wool or cotton. Globally, energy from biomass is mainly fuelwood and dried dung burnt in developing countries, and amounts to roughly 50 EJ per year [9]. Modern bioenergy includes liquid transport fuels and biomass used for power stations or district heating schemes, and totals about 5 EJ annually [7, 10]. Timber for construction is the main biomaterials product, but other products include packaging materials, as well as cotton, flax and wool from the agricultural sector.

It is generally recognised that production of food should have priority, and that increasing the production of bioliquids from foodstuffs—grain, sugar cane and edible seeds—is difficult to justify ethically. But the situation is somewhat complicated by the 'water-energy-food nexus' [11]. Although producing biomass energy takes water, land and other inputs away from food production, at the same time modern agriculture, especially land-saving high-yield agriculture, is heavily reliant on energy inputs. But this nexus still cannot justify the use of *food* crops for energy. Also, neither global food demand nor its inputs for a given population level are fixed; moving to a diet with less animal products would significantly reduce the resources needed to produce food [12] and thus, *ceteris paribus*, increase the potential for the other two biomass uses. Nevertheless, the Food and Agriculture Organization [13] expect animal-based foodstuffs consumed to continue to rise globally. In the past, agricultural intensification increased yields per hectare, and thus reduced land needs for food production. However, any further climate change will decrease yields of important cereal crops [14]. Overall, Pugh et al [15] see 'limited potential for intensification of production on current croplands'. Phosphorus, vital for food production, is of limited global availability [16]; it could be a limiting factor for overall human biomass production.

The so-called second-generation biofuels produced from *cellulosic* biomass are expected to bring significant GHG reductions, though they presently remain uncommercial. For this reason there has been a long-term interest in the production of bioliquids from materials such as grasses and fast-growing woody plants such as willow. In 2007, the US Environmental Protection Agency predicted that annual US cellulosic ethanol production in 2020 would reach 2.21 Mtoe [17]. But despite decades of research, both US and global production of cellulosic bioliquids is still negligible: in 2017, US production totalled only 0.015 Mtoe. Even if cellulosic ethanol production did become globally significant as a transport fuel, its net climate mitigation potential might still be small [18], although this is contested [19]. Substantial uncertainties still exist in GHG emission intensity estimates due to unresolved scientific questions regarding land use emissions, nitrous oxide emissions from nitrogen fertilisers and potential effects of biofuels on vehicle engine efficiency [2,20,21]. Algae is considered as a potential feedstock though algal biofuels have often been found to have much higher GHG intensities than conventional petroleum-based fuels because of their energy intensive life cycle [22]. Further research is needed to evaluate promising feedstocks such as agave that can limit competition for land and water with food production [23].

Although global use of timber as a construction material is growing, it is losing share of the growing construction materials market to competitors such as steel, concrete, bricks and plastics [1,24]. Yet from a climate change mitigation viewpoint, biomaterials are often superior to its competitors. For two similar four-storey buildings in Sweden, Gustavsson and Joelsson [25] found that the timber-framed one had lower construction energy costs per m^2 of floor space compared with the steel-framed building. In general, such energy savings translate into GHG savings as well. Further, construction advances mean that timber frames need no longer be restricted to low-storey buildings [26].

Quite apart from the water-energy-food nexus, some bioenergy use does not conflict with the other two biomass uses. Methane, for example, can be recovered from sewage purification plants and also from municipal garbage dumps. In both cases, combusting the methane for energy has a double benefit, as it not only saves on fossil fuel use but also prevents the release of methane, a potent GHG, to the atmosphere [27]. The organic component of municipal garbage can also be combusted to provide energy, although with more recycling of this waste, this energy source could decrease. A further non-competitive source of bioenergy would be that derived from burning biomaterials for energy, mainly construction timber, at the end of their useful life [1].

3. How should bioenergy be used?

We have shown that the two competing uses for biomass will greatly restrict the amount of sustainable bioenergy that will be available. Even so, many have argued that bioenergy will have a key role to play in climate change mitigation. The IPCC [28] in particular have seen a major role for bioenergy carbon capture and sequestration (BECCS), which if implemented on a large scale, would enable negative emissions of CO_2. Slade and colleagues [29] have shown in a review paper the vast range of estimates for annual global biomass potential in the published literature, ranging from about 100 EJ to close to the entire terrestrial NPP, which is clearly unsustainable.

3.1 Power station fuel or liquid fuel?

For the foreseeable future, much biomass will continue to be used as fuel wood for heating and cooking in low income households in industrialising countries, as is the case today, even if much of this use is not ecologically sustainable. The question is: how should modern bioenergy be used? Bioenergy is unique among renewable energy sources in that it is a physical substance like fossil fuels, and so can be used or converted into solid, liquid or gaseous fuels. Should it be used to make liquid transport fuels, where it most countries it can enhance national energy security, or should it be directly combusted as a power station fuel, perhaps used as a partial coal replacement?

Campbell et al [30] have shown that when bioenergy is used directly in power stations to produce electricity which in turn is used to power battery EVs, significantly greater GHG reductions per vehicle-km are obtained compared with converting the primary bioenergy source into liquid fuels. Its advantage (in terms of reductions in CO_2 per passenger-km) would be even greater if the electricity was used to power electric trains or trams. It also needs to be stressed that collecting CO_2 from vehicle exhausts for burial, as in carbon capture and sequestration (CCS), although possible [31], would be far more costly and energy intensive compared with collection of CO_2 from biomass-fired power station exhaust gases. For one thing, vehicular energy efficiency would be reduced: with on-board CO_2 capture, progressive fuel use would *increase* total vehicle weight, rather than decreasing it as at present.

There is also controversy, referred to earlier, as to whether bioethanol always produces net carbon emission reduction benefits compared with conventional petroleum-based liquid fuels, particularly if full system effects are taken into account [2]. The GHG emission intensity (emissions over the entire life cycle of a fuel per unit energy available) of different liquid biofuels produced from a range of feedstocks can vary significantly [27]. In general, the current generation of biofuels produced from food crops such as ethanol from corn and wheat and biodiesel from soybean tend to offer limited GHG reduction potential. For example, sugar cane ethanol is usually calculated as having large CO_2 savings compared with petrol [19], but these may vanish if the carbon loss from forest soils converted into sugar cane plantations are factored in, or if the use of food crops for liquid biofuels results in forest clearing to grow additional food to replace that used as a feedstock. Fargione et al [32] in particular have discussed the ‘biofuel carbon debt’ that can arise when ‘rainforests, peatlands, savannas, or grasslands’ are converted to produce food-based ethanol or diesel fuels. They claimed that the total debt can be 17-420 times the annual savings from use of the biofuels to replace hydrocarbon liquid fuels. Even cellulosic liquid fuels (see Section 2) could still incur a substantial debt [18].

3.2 An uncertain future for all liquid fuels?

Earlier it was mentioned that oxygenated fuels like ethanol can reduce air pollution. The introduction of such measures as unleaded petrol, three-way catalytic converters have greatly reduced air pollution in Organization for Economic Cooperation and Development (OECD) countries, and are increasingly being introduced in other countries. Nevertheless all high temperature combustion, such as occurs in internal combustion engines, produces various oxides of nitrogen, which are harmful to human health, and are still a major problem in OECD countries. Globally, outdoor air pollution from all causes, including vehicle pollution, is believed to be responsible for somewhere between 1.6 and 4.8 million deaths globally, with most of the deaths in Asia [33]. Besides its effects on human health, air pollution also damages crops and building materials. Hence for both air pollution and climate change mitigation reasons, a number of countries have made the decision to phase out the sale of internal combustion vehicles [34]. China, France and the UK all plan to end sales of both petrol and diesel cars by around year 2040, and Swedish vehicle manufacturer has pledged to produce only electric powered vehicles in the near future [34].

These plans evidently will affect the future of liquid biofuels, regardless of what they are produced from. It could be that the internal combustion engine will be effectively phased out globally in a few decades, and go the way of the steam car a century ago, and with it, all liquid fuels, no matter how ‘green’. Electric-powered vehicles, using either battery packs or (later) hydrogen fuel cells, would then become the default vehicle type, although their climate change benefits are far from assured [35].

4. Discussion and conclusions

Bioliquid fuels are being promoted in many countries for a variety of reasons, including energy security and the risk of possible global oil depletion, climate change and air pollution benefits, and promoting rural economies. But in this paper, we have argued that it will at best be a minor replacement fuel for conventional oil-based transport fuels for several reasons, summarised in the following paragraphs.

Total human use of biomass (HANPP) itself is restricted because it must be shared with all other heterotrophic species on Earth. These provide vital ecosystem services for humankind. Further, bioenergy production in general must compete for scarce resources with the other two general biomass uses: food production and biomaterials. Although it is widely acknowledged that providing food for all is a priority, the inputs needed for this vary with type of diet and agricultural technology. Using biomaterials will usually give carbon emission savings compared with more conventional building materials such as steel or concrete. Even so, at the end of its useful life, which could be decades long, biomaterials could be burnt for fuel.

When a full GHG analysis, including indirect effects, is done for liquid biofuels, its GHG advantages over oil-based fuels often disappear. In any case, bioenergy used for electricity production to power electric vehicles will have lower GHG emissions per vehicle-km than bioenergy converted to ethanol. However, the real problem facing liquid biofuels for transport is that the internal combustion itself may have no future, mainy for air pollution reasons. If so, liquid biofuels production, never more than a few percent of total transport fuel, will gradually taper off.

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