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Review

Can Bioenergy Once again Become a Major Global Energy Source?

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Abstract: For all of human history except the past two centuries or so, bioenergy provided nearly all the world's primary energy. Then, fossil fuels largely replaced bioenergy, but concern about climate change and fossil fuel depletion will force a move back to renewable energy, including bioenergy. The main method used here to study the future of global bioenergy was a literature surview of relevant published papers, with emphasis both on those published after 2020, and those having a global focus. The key finding is that bioenergy is unlikely to greatly increase its share of global energy consumption, for several reasons. Liquid biofuel production for transport is likely to almost disappear as countries progressively phase out internal combustion engine vehicles. Traditional firewood use is also projected to fall. There are also doubts about the technical potential of bioenergy, not only because it must compete with the other uses for biomass—food, fodder, fibre and timber—but also because in many cases its climate change mitigation impact is less than for other approaches, including alternative renewable energy sources. The overall conclusion is that bioenergy will have a minor but still useful role in the future global energy system, but global energy reductions are likely to be more important for climate stability than bioenergy.

Keywords: bioenergy; corn ethanol; electric vehicles; energy return on investment (EROI); fuelwood; global climate change; liquid biofuels; net primary production (NPP); renewable energy (RE)

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1. Introduction

For hundreds of millennia, bioenergy provided humans with nearly all their energy needs. Over the past two millennia or so, very small amounts of water, wind, solar and geothermal energy were also used [1]. Small quantities of fossil fuels (FFs) were also combusted, until the rapid growth of coal after 1800, followed by oil and gas in the 20th century, saw FFs eclipse bioenergy as the dominant energy source. Even in 1850, wood still accounted for over 90% of all primary energy. Although the share of all forms of bioenergy has fallen to around 10%, total bioenergy production today is probably as high as it has ever been [2]. Further, it is still by far the largest global renewable energy (RE) source.

The 10% figure for bioenergy share of total primary energy is a global average. Its share varies widely from country to country, from 80% or more in some African countries, to near zero in countries like Kuwait, Singapore or the UAE [3]. In tropical Africa, as well as some Asian and Latin American countries, bioenergy is consumed in the form of fuelwood or animal dung, and is combusted at very low energy efficiencies. This traditional use of bioenergy still appears to account for a significant share of bioenergy use today (Table 1). Other forms of bioenergy include conversion into liquid fuels for transport (chiefly bioethanol and biodiesel), as a fuel for electric power production and modern boilers, and as an input into the production of biogas. Table 1 gives the breakdown for bioenergy in year 2020, as reported by the International Energy Agency (IEA) [4]. One problem is that, although statistics for modern bioliquids are fairly accurate, those for traditional fuelwood are not. Since few if any low-income countries measure fuelwood used, the global estimates are at best a guess. It is also possible that biogas use is undercounted [5].

Table 1. IEA estimates of present (2020) global bioenergy (EJ), by type.

Bioenergy Type	2020 EJ
Modern solids	31.8
Modern liquids	3.8
Modern biogas	2.2
Traditional fuelwood	24.1
All biomass	**61.9**

Source IEA [4].

Henry Ford's 1908 T-model was designed to run on ethanol as well as gasoline or kerosene (and Rudolf Diesel designed his engine to run on vegetable oils). However, steadily declining gasoline prices—and the advent of Prohibition in the US—made widespread use of ethanol as a fuel impractical [6]. Although ethanol (EOH) as a vehicle fuel has a long history, in the US, production of liquid biofuels was greatly boosted by the Renewable Fuel Standard (RFS) of the 1970s, which mandated a minimum volume of renewable fuel for transport fuels, mainly for energy security reasons in the wake of the OPEC oil embargo [7].

Since then, the RFS goal has been broadened to respond to the climate change implications of transport fuels. Today, according to Lark et al. [8]: "To comply with the policy's GHG reduction goals, the RFS requires conventional renewable fuels to generate life cycle GHG savings of at least 20% relative to gasoline." At present, more than 98% of US gasoline has EOH added to reduce air pollution [9]. However, as in other countries, EOH production is also seen as promoting energy independence and rural prosperity. Ethyl tertiary-butyl ether (ETBE), derived from bioethanol, is an alternative additive, but there are concerns about groundwater contamination [10].

Figure 1 shows the growth in global liquid biofuels production from the 1990s to present. The two leading countries for production are the US, where corn is the main input feedstock, and Brazil, where cane sugar is the preferred feedstock. In 2020, these two countries accounted for almost 60% of global liquid biofuel production [11]. Most of the rest is produced in Europe, where a variety of feedstocks are employed, including seed oils and grain, and Asia, particularly Indonesia, where biodiesel is produced from palm oil [12]. Global output fell in 2020, which is probably the result of lower global road travel in that year, caused by the COVID-19 pandemic. However, global bioethanol production in 2021 was still well below the 2019 value [11], despite the pick-up in global road transport and transport fuels generally.

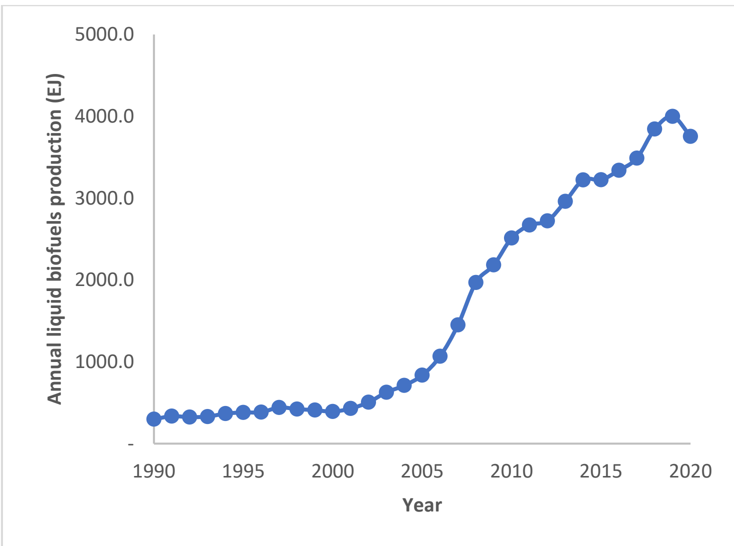

Figure 1. Global liquid biofuels production (in EJ) from 1990 to 2020. Source: BP [11].

As Table 1 shows, bioenergy can be used in solid, liquid or gaseous form, and so it is more versatile than other RE sources. It is also the only RE source which is combusted like FFs—in fact, all FFs have originated from biomass. It can be mixed with FFs as a fuel in thermal power stations. Other RE sources either produce primary electricity (hydro, wind, solar, tidal and wave energy) or heat, which can either be used directly, or fed to a thermal power station (geothermal) [1]. Because bioenergy exists in material form, it is not necessary to convert it into other energy forms for storage, as is the case for most other RE sources [5]. The exception is hydropower, where the energy is stored as gravitational energy. Bioenergy can also be stored as living plant mass, and harvested as needed.

The world population has already passed 7.9 billion, and the UN median forecast for 2050 is over 9.7 billion, and for year 2100, nearly 11 billion [13]. Many hundreds of millions of the present world population have an inadequate calorie intake and otherwise inadequate diets, and this number could rise if progressive climate change decreases yields of important food crops [1]. A key problem is the possible conflict between food crops and bioenergy production. This is especially the case with modern bioliquids, as they use either cereals (mainly corn) or sugar cane for making bio-ethanol, and edible oils for making biodiesel. The European Union proposal was originally for 10% of transport fuels to be from bioenergy by 2020, but more recent policies recognise the negative impacts of bioliquids consumption, especially from palm oil production [14].

As a response, particularly in the US, interest was revived in producing ethanol from cellulosic materials, such as crop or forestry wastes, a technology more than a century old. In 2007, President George W. Bush "announced a proposed mandate for 35 billion US gallons (130×10^9 litres) of ethanol by 2017" [15]. However, the technology is complex, and the resulting EOH is expensive compared to gasoline. The result is that there are still no commercially operating cellulosic ethanol plants: in the US in 2021, less than one million litres were produced [16].

In recent years, a number of countries and cities, mainly in Organization for Economic Cooperation and Development (OECD) countries, have made plans to ban the sale of internal combustion engine vehicles (ICEVs) by year 2030 or 2040, mainly to decrease urban air pollution [17], although climate change mitigation is also seen as important. Even though the introduction of three-way catalytic converters and unleaded petrol has greatly reduced air pollution, oxides of nitrogen, produced by high-temperature combustion, have proved harder to reduce.

Such a ban would affect liquid biofuels—even though, as shown above, EOH was introduced as an additive to reduce air pollution—as well as oil-based fuels and natural gas. The only vehicles allowed would be either electric vehicles (EVs) or hydrogen fuel cell vehicles. EVs have shown extraordinary growth in numbers in recent years, and in 2021, the global vehicle fleet numbered 11.3 million worldwide [18], encouraged by various subsidies, including subsidies for EV purchases, and waiving of fuel taxes. The IEA anticipates this number rising to between 139 and 227 million as early as 2030 [18,19]. Even without ICEV bans, the future of all combusted fuels for ICEVs appears bleak. One sector where liquid biofuels may have a future is aviation. In 2019, global final energy consumption for aviation was 14.4 EJ, compared with 120.9 EJ for all transport. At present, bioliquid use in aircraft is tiny, but the Biden administration has outlined a "Grand Challenge" to meet 100% of aviation fuel demand from bioliquids by 2050 [16].

Despite the probable difficulties liquid biofuels for transport—especially light vehicle passenger transport—will face in the future, research interest in biofuels in general and even in liquid biofuels, is still very high. Figure 2, using the Scopus database of published papers, shows papers published since 1990 containing at least one of the terms "bioenergy", "bioliquids", "bioethanol", "biodiesel", "biomethane", or "fuelwood" in either the title, abstract or keywords. Liquid biofuels are still considered an option for some transport uses, such as air travel [20]. One area of increased interest is in the so-called bioeconomy, which would give an important place for bioenergy [21–23]. According to Ubando et al. [21], a "Biorefinery is a sustainable means of generating multiple bioenergy products from various biomass feedstocks through the incorporation of relevant conversion technologies". Further, biorefineries act "as a strategic mechanism for the realization of a circular bioeconomy". Any move toward a bioeconomy should lead to heightened interest in bioenergy, as costs can be shared among the various products produced.

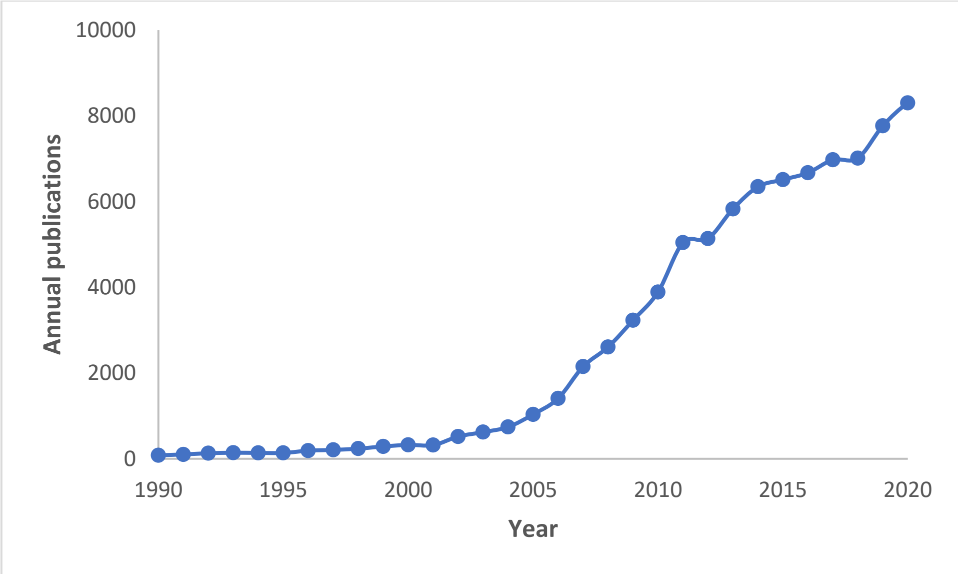

Figure 2. Scopus database for biofuels papers published annually vs. year, 1990–2021.

This Introduction has emphasised the history and current status of liquid biofuels more than the other bioenergy sources because, as mentioned, liquid biofuels, for surface transport at least, do not appear to have much of a long-term future. The research question this review asks is "What is the future for bioenergy?" The rest of this review is accordingly organised as follows. The first problem is how to select the papers to be reviewed from the thousands available. The global technical potential for bioenergy, and likewise its climate change mitigation potential, are key questions for assessing bioenergy future potential as an energy source. The future of bioenergy is next examined, as seen by various international energy organisations and companies. Finally, conclusions are offered, stressing both the uncertainty of all future forecasts, and that bioenergy must compete with other non-carbon sources, as well as with energy reductions and carbon dioxide removal (CDR).

2. Methodology

As can be seen from Figure 2, many thousands of papers on bioenergy topics are published each year, as recorded in the Scopus database. Clearly, only some of these can be included in the review. First, preference was given to papers which discussed bioenergy from a global viewpoint. As discussed above, countries differ greatly in their use of bioenergy, from almost zero to majority shares in some tropical African countries. Second, this review favours papers which take an "Earth Systems Science" approach to bioenergy, and, further, recognise that bioenergy is only one of the human uses for biomass. This is crucial, since the full energy and environmental costs of bioenergy are often only seen when factors such as the effects on land use, biodiversity, or water availability are also considered. These costs can often occur in regions or countries distant from the producing region or country. Third, recent papers—especially on or after 2020—were favoured over earlier ones. Nevertheless, some earlier research papers were included either to show trends in bioenergy research, or because these papers are still regarded as important for the topic.

Historical data on energy and biomass use by country and for the world overall are available from BP [11], the IEA [24] and the International Renewable Energy Agency

(IRENA) [3]. The causes and impacts of climate change were obtained from the recent reports of the Intergovernmental Panel on Climate Change (IPCC) [25,26].

Sections 3 and 4 cover the present situation for biomass, including discussion of its technical potential and impact on climate change mitigation. The *future* of bioenergy is discussed in Section 5. The approach used here is to analyse the numerical forecasts/scenarios from a number of organisations that regularly publish forecasts or scenarios for both total global energy and their component sources (including bioenergy) for year 2050. The publications also give figures for 2019, 2020 and sometimes earlier. The organisations whose most recent forecasts (all made in 2020 or 2021) were included were:

- The International Energy Agency (IEA) [4];
- The Energy Information Agency (EIA) (US) [27];
- ExxonMobil [28];
- Organization of the Petroleum Exporting Countries (OPEC) [29];
- Shell [30];
- BP [31];
- DNV [32].

3. Technical Potential for Bioenergy

The maximum global limit for all human biomass use, whether for food, forage, energy, or materials, is ultimately fixed by the net primary production (NPP) of Earth's terrestrial ecosystems, defined as "the gross annual fixation of living plant matter, minus respiration" [33]. Globally, NPP is today around 3000 exajoule (EJ) annually, with about 1900 EJ produced by terrestrial ecosystems (e.g., tropical forests, grasslands), and the remainder produced by ocean ecosystems. If instead we look at the total biomass in Earth's terrestrial ecosystems, Schramski et al. [34] reported that this value has fallen 45% since the start of the current era, from around 35,000 EJ to 19,000 EJ in year 2000. Presumably, NPP has fallen in a roughly similar manner.

Humans use a significant share of the 1900 EJ terrestrial NPP for producing energy, materials and food. This ratio is called the Human Appropriation of Net Primary Production (HANPP). It can be defined as the "share of global biological productivity that is used, managed, or coopted by human actions" [35]. The exact figure is disputed, with values ranging from 10% all the way up to 55%, depending on which items are included [29]. Higher vales include NPP lost by, for example, urbanisation and roads. Nevertheless, using a consistent basis for measuring HANPP, Krausmann et al. [36] reported a doubling in its value over the 20th century.

An important question is: what is the upper limit for HANPP, given that NPP has to provide for all heterotrophic species, not just humans. If HANPP as a share of NPP rises too high, it is possible that the absolute value of NPP could fall because of ecosystem deterioration: HANPP might be high as a percentage, but in terms of gigatonne of carbon (GtC) or EJ, it might decline [33]. Kleidon [37] gave an upper limit for HANPP of 45%. Running [38] entitled his *Science* artcle "A measurable planetary boundary for the biosphere". He saw that terrestrial NPP seems fixed at about 53.6 GtC per year—its value for the past three decades. Running thus regards this as a limit to place alongside the well-known planetary limits of Rockström et al. [39]. He estimated current HANPP at about 20.4 GtC, and thought that this value could be increased by no more than 5 GtC, which would give an upper limit value of 47%. The Kleidon and Running estimates are close, and correspond to an upper limit of HANPP in energy terms of very roughly 900 EJ [33]. Bishop et al. [40] went even further, and argued that for biosphere integrity, HANPP must be greatly reduced—down to about 9.7 GtC annually.

We need to remember that, today, as in the deep past, there are three important uses for biomass. The first is as an energy source, the theme of this review. However, biomass has also long been used as a construction material, and as a clothing material (such as wool, cotton or flax), and more recently, as a source of paper and cardboard. It is possible in certain cases to replace concrete and steel, both carbon-intensive construction materials with timber, such that net energy use and emissions are lowered, without loss of building function [33]. Even more important, from an ethical point of view, we should make it a priority that all of Earth's people are adequately nourished, which could become increasingly difficult, not only as the world population grows, but also as climate change reduces yields for some important food staples [25,41]. This point is increasingly recognised by bioenergy researchers, and a number of papers examine how the resources of land, water and so on could be lowered if the world moved to a more vegetarian diet, e.g., [42,43]. Such a move would, *ceteris paribus*, allow for a greater share of future biomass to go to energy production. Nevertheless, at present, global consumption of animal-based protein is still growing [33].

Given the discussion above, we cannot even in principle say what the global technical potential for bioenergy is, as we do not know how much biomass should be preferentially allocated to materials and food to both satisfy ethical imperatives and to lower carbon emissions. A further complication is that the three uses are *interconnected*. Construction timber can be burnt as fuel at the end of its life, and food and timber require energy for their production—some of which could well be bioenergy.

One proposed way around the problem of alternative uses for biomass is to use microalgae for energy. This proposal has been around for decades, and microalgae are already grown to produce highvalue products such as cosmetics and food additives. Microalgae can be grown in fresh water, or salt water, or even polluted water [44]. Microalgae can be grown in either open ponds or closed reactors. The algae also grow very fast, so that the harvesting cycle can be as short as 1–10 days. Commercial interest was shown in microalgae harvesting for bioenergy a decade or so ago, but interest and investment faded [45]. However, research interest is still very high, as shown in Figure 3, which plots annual papers published on the Scopus data base with the words "microalgae" AND "energy" in either the title, abstract or keywords from 1990 to 2021.

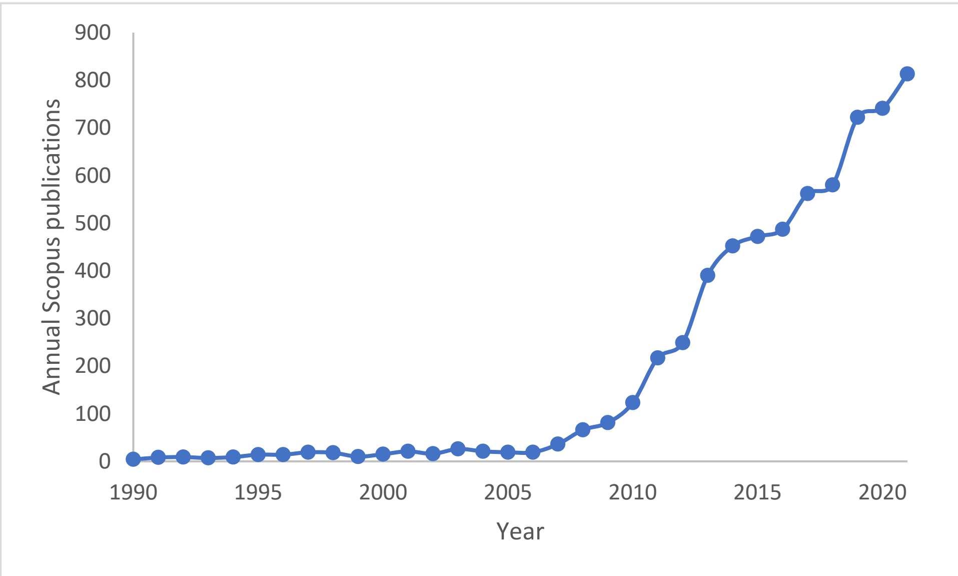

Figure 3. Annual Scopus publications for microalgae AND energy, 1990 to 2021.

As is the case for any energy source, renewable or otherwise, the energy produced must be greater than all the energy inputs needed to produce the output, and some researchers argue that the ratio of output to input energy (EROI) must be much greater, perhaps as high as seven or more [46]. Yet Ketzer et al. [47], in their review paper, found that only four of the 23 studies they analysed had EROI values of greater than 1.0 (with values of 1.01, 2.01, 3.35 and 3.72). All EROI values for the closed reactor studies were less than unity. High production costs are also a problem. Fernández et al. [48] reported costs for dried microalgae only, of USD 5.7/kg for open ponds, and 10 times higher for closed bioreactors.

4. Bioenergy and Climate Change

Although the question may become increasingly irrelevant for road transport, at least, the climate change benefits of biofuels in general are being increasingly questioned. In the US, controversy exists as to whether or not corn ethanol actually reduces CO_2 emissions compared with gasoline. Recent research by Lark et al. [8] and Spawn-Lee et al. [49] examined the environmental outcomes for the Renewable Fuel Standard (RFS) in the US, and concluded that "the RFS caused enough domestic land use change emissions such that the carbon intensity of corn ethanol produced under the RFS is no less than gasoline and likely at least 24% higher." Needless to say, this position is strongly contested, with Scully and colleagues [50] arguing that the best estimate of carbon intensity for corn ethanol is 46% lower than that for neat gasoline in the US. These large differences found for carbon intensity are unlikely to be resolved any time soon, as the debate is already several decades old; nor is climate change the only sustainability consideration. Stenzel et al. [51] entitled their recent article "Irrigation of biomass plantations may globally increase water stress more than climate change." Biodiversity loss is another consideration for large energy plantation monocultures.

In Europe, as well as diesel made from locally grown oil seeds and grain, diesel made from palm oil, imported from plantations in Malaysia and Indonesia, is important. Yes, does this imported biodiesel help reduce global transport-related greenhouse gases when a full accounting is done? Again, there is little agreement among researchers. The paper by Abubakar et al. [52], while acknowledging the environmental costs of palm oil production in Malaysia, argued that these can be managed and compensated for. Meijide et al. [53] studied emissions from Indonesia palm oil plantations and concluded: "Due to the high emissions associated with forest conversion to oil palm, our results indicate that only biodiesel from second rotation-cycle plantations or plantations established on degraded land has the potential for pronounced GHG emission savings." A key problem, as Hooiger et al. [54] have pointed out, is that the tropical peatlands in Southeast Asia contain over 42 Gt of soil carbon. If this land is cleared for oil palm plantations, the soil carbon is released. Such carbon emissions should be included in any assessment of oil palm's climate mitigation potential.

Just as for estimates of HANPP, there is great uncertainty as to what extent the use of bioenergy can ameliorate climate change, or in some cases, whether it does at all. One important question is: in cases where bioenergy does help for climate change mitigation, what is the best way to use it? We have already seen that using timber as a replacement for steel or concrete can help lower emissions. Campbell et al. [55] found that CO_2 emissions reductions for transport were greater if bioenergy was used in power stations rather than used to make liquid fuels for transport. The electricity produced could be used to power EVs, which, in any case, are more efficient than ICEVs. Of course, all this may be largely beside the point if ICEVs are increasingly phased out after 2030, although it is possible that biodiesel could find some use in airplanes and heavy freight transport vehicles [16]. On the other hand, traditional fuelwood is presently combusted at very low efficiency [56], and either needs to be replaced by other energy sources or used as soon as possible in more efficient stoves.

Energy plantations in northern climates can have conflicting effects on climate change mitigation. On the one hand, the resulting bioenergy can replace fossil fuel use. However, on the other hand, compared with snow cover, the albedo of trees is much lower, so more insolation is absorbed, which will tend to raise climate forcing [57]. Energy plantations in warmer climates would not suffer this disadvantage.

Sterman et al. [58] have raised another important point to consider for bioenergy from tree plantations. Unlike the crops grown to produce biodiesel and bioalcohol, trees take many years to mature. Even when the wood is grown to generate electricity, they argued that CO_2 emissions could be greater than for coal-burning power stations, at least for this century. This can occur because:

- Wood has a much lower heating value, and so its CO_2/kWh is higher, which creates an initial carbon debt.
- Regrowth of forest on the land harvested will remove CO_2 from the atmosphere—assuming regrowth is allowed to occur. However, any such regrowth takes many decades.
- Until full regrowth occurs, atmospheric CO_2 levels will be higher than for coal-fired power, so CO_2-induced radiative forcing will be higher. Yet, we need to seriously reduce climate forcing in the next decade or two.

In summary, bioenergy in some uses may have at best marginal climate change mitigation benefits. This situation will, in turn, favour the use of other RE sources such as wind and solar, which have both higher EROI values, and far higher global technical potential; it will also favour overall energy reductions.

5. The Future for Bioenergy

In this section, we look at the global future for bioenergy, in the context of the global future for energy in general. A number of annual forecasts for both global bioenergy and total energy are available up to 2045 or 2050—or even, as with Shell, out to year 2100—and are shown in Table 2. The forecast values are usually the output of integrated assessment models, which attempt to combine economic, climate and energy systems to assess least-cost solutions. OPEC and DNV use single-value forecasts (DNV call theirs the "best estimate"). Other organisations use several scenarios that attempt to cover the gamut of possible futures, so the range from these is given. The EIA forecast for total energy stands out as being appreciably higher than the others. In all cases, most of the growth in total primary energy is seen as occurring in non-OECD countries. All the forecasts shown see year 2045 or 2050 bioenergy as being greater than today (61.9 EJ in 2020, see Table 1), although barely so in the case of ExxonMobil. Except for one IEA scenario, and DNV, future global primary energy is seen as being greater than today's.

Table 2. Estimates of future global bioenergy and total energy (EJ), in 2050.

Organisation	Bioenergy	Total Energy	Bioenergy (%)
IEA [4]	93–107	543–744	12.5–18.7
EIA [27] [1]	NA	780–1140	NA
ExxonMobil [28]	64	695	9.3
OPEC [29] [1]	78	742	10.5
Shell [30]	88–109	704–901	9.8–13.8
BP [31]	NA	653–750	NA
DNV [32]	74	589	12.6

[1] Data for 2045.

Figure 4 shows how total bioenergy use is forecast to vary for each of the four IEA (2021) scenarios: Stated Policies (SPS); Announced Pledges (APS); Sustainable Development (SDS); and Net-Zero Emissions (NZE). In all cases, traditional use of bioenergy is expected to decline, reaching zero by 2050 in both the SDS and NZE scenarios. The lowest value for bioenergy (93.2 EJ) occurs in the SPS scenario, even though traditional biomass is still 17.2 EJ in this scenario, which is close to a "business-as-usual case". The small range for 2050 bioenergy output is remarkable, given that the four scenarios encompass widely different futures, particularly those of the IEA. Further, despite huge variations in the use of other RE sources (especially wind and solar) and FF, the range for bioenergy considering all forecasts in Table 2 is less than twofold. The IPCC [26] does not give any forecasts or scenarios for any given year, but does present two illustrative scenarios for "net zero CO_2 emissions global energy systems". With bioenergy use of 92 and 93 EJ, the values fit in with those in Table 2. An important reason why the forecasts for bioenergy are only about 50% greater than in 2020 is that most growth in RE is expected to come from wind and solar energy.

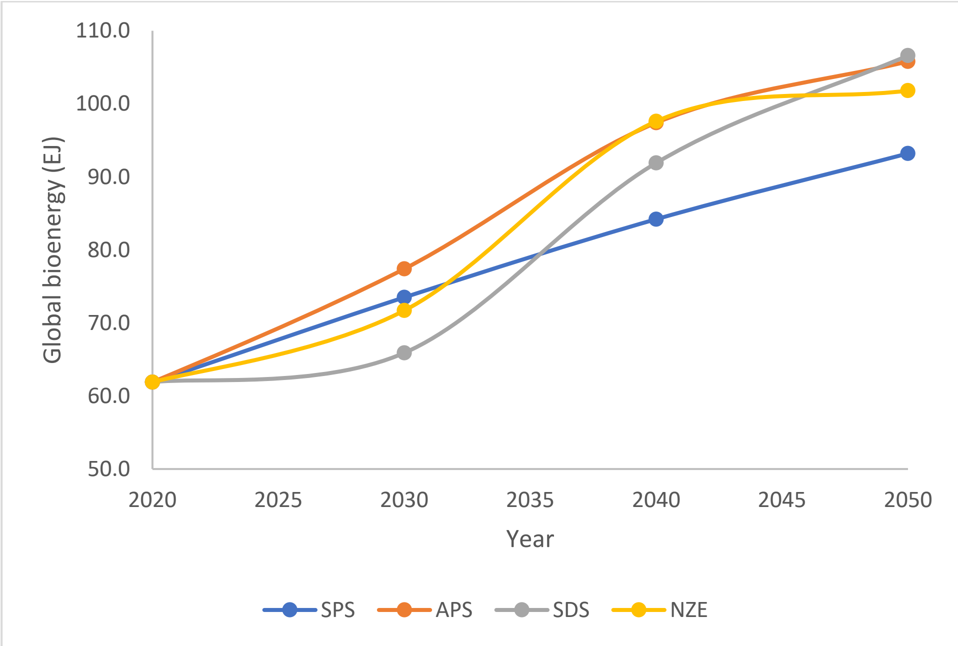

Figure 4. Actual bioenergy use in 2020, and IEA scenarios for bioenergy 2020–2050 (in EJ) [4].

The range from 64–109 EJ is also small compared to some forecasts for the technical potential for bioenergy, with some forecast values well above 500 EJ. Rogelj et al. [59] present various scenarios, including one with 300 EJ annually from bioenergy carbon capture and sequestration (BECCS) in 2050. BP [31] include for 2050 the expected sources of *modern* bioenergy, as follows, for a total of 70.9 EJ:

- Agricultural residues: 38.8 EJ
- Forestry residues: 11.8 EJ
- Municipal solid wastes: 11.8 EJ
- Manure: 7.0 EJ
- Waste oils: 1.5 EJ.

Of course, the narrow range of values for bioenergy use in year 2050 does not guarantee that bioenergy use in 2050 will fall within this range. In 2019, there was wide agreement that global GDP, energy use and plane travel in 2020 would all be higher than their 2019 values. This did not happen, because of the COVID-19 pandemic. The future is inherently uncertain, and is likely becoming more so. One possible cause of this is that Earth is moving toward an increasing number of global limits [60]. Further, synergy occurs, so that approaching one limit increases the probability of another being breached.

Future costs of energy, and the cost differences between competing fuels, are important in assessing the future use of any given energy source. However, such costs add another major uncertainty. If a carbon tax is levied, this will help non-fossil energy sources in general (depending on its level), but as shown, the benefit for bioenergy may be marginal. Further, other RE sources have their own unpaid external costs [61,62]. If these costs were included in assessments, their relative benefits would be much lower, and their costs higher. Also, especially for biofuels, unit costs vary greatly from country, being lowest in countries like Brazil with abundant bioenergy resources, and relatively low labour costs. Finally, research from Sweden [63] has found that investment in bioenergy pilot and demonstration plants is important for technological innovation and presumably cost reductions.

Despite the increasingly urgent warnings from the IPCC [25,26] and others [64–66], fossil fuel use worldwide has rebounded after the pandemic-induced fall in 2020. Indeed, China is building new coal-fired power stations [67]. Any FF growth will slow down the uptake of bioenergy—and RE in general.

6. Conclusions

It is becoming increasingly more difficult to predict the future course of our planet. Very few had forecast the current pandemic, which had profound consequences for the global economy, energy use, transport, global inequality, and of course, human health and suffering. Future use of bioenergy will depend on a number of factors. First, how large will global energy consumption be, in say, year 2050? Given the present global inequality in energy use per capita, some estimates are much higher than at present. Second, will climate change mitigation be tackled by reducing fossil fuel use, or by CDR methods such as negative emissions technology. CDR would allow fossil fuel use to continue, but none of the various approaches have been tried at the vast scale required, and would take decades to implement [1,68]. An even more ambitious initiative is solar geoengineering, such as by use of sulphate aerosols in the upper atmosphere to reflect insolation and raise Earth's albedo [69]. Alternatively, will lip service be paid to climate change mitigation, but high levels of fossil fuel use continue to be used, as at present?

Perhaps to an extent greater than for other energy sources, whether fossil or renewable, this review (see Sections 3 and 4) has shown the large uncertainties, not only in the technical potential for bioenergy, but also to what extent its use instead of fossil fuels can cut GHG emissions. A further big unknown is future use of traditional fuels. As already mentioned, its global consumption is not known with any precision. If global inequality continues unchecked, the future could see rising levels of fuel wood in low-income countries. Unfortunately, much of this use could well be unsustainable, as forests and woodlands are cut at a rate exceeding their regrowth. This situation is already happening in some regions, and can affect biodiversity as well as carbon emissions [70].

Further, bioenergy must compete with other RE sources, especially wind and solar energy. These are burdened to a far lesser extent than bioenergy with competition for fertile land or water. Their theoretical potential is also far higher than for bioenergy [62]. The IEA [4] in all their scenarios expect the combined growth in these two RE sources to increase from its 2020 level by a factor of around seven in its "business-as usual" "Stated Policies Scenario" to a factor of almost 20 in its NZE scenario. However, these two RE sources have their own uncertainties concerning their high use of scarce minerals and their EROI values [46,61].

Some specialised modern forms of bioenergy could grow in importance, as listed in Section 5. Use of landfill and sewage plant gas (biomethane) can not only reduce methane emissions to the atmosphere, but can also help replace FF use—a double benefit for climate change mitigation. Municipal organic wastes can and are being incinerated for power or district heating schemes, thus saving on landfill space as well as generating renewable energy. Biomass materials can first be used for construction, packaging or newsprint, then at the end of their useful life, combusted for energy, and although a significant share of forest and crop wastes need to be left in place to maintain soil fertility and prevent wind and soil erosion, the sustainably used residual can be a useful addition to clean energy. Bioenergy will have a role to play in future energy production, but the exact amount is subject to rising uncertainty.

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Nomenclature

APS	Announced Pledges Scenario
BECCS	bioenergy carbon capture and sequestration
CCS	carbon capture and sequestration
CDR	carbon dioxide removal
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalent
EJ	exajoule = 10^{18} joule
(EIA)	Energy Information Agency
EOH	ethanol
EROEI	energy return on investment
ETBE	Ethyl tertiary-butyl ether
EV	electric vehicle
FAO	Food and Agriculture Organization
FF	fossil fuel
GHG	greenhouse gas
GJ	gigajoule = 10^9 joule
Gt	gigatonne = 10^9 tonne
HANPP	human appropriation of Net Primary Production
ICEV	internal combustion engine vehicle
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MJ	megajoule = 10^6 joule
NPP	Net Primary Production
NZE	Net-Zero Emissions
OECD	Organisation for Economic Co-operation and Development
OPEC	Organization of the Petroleum Exporting Countries
RE	renewable energy
RFS	Renewable Fuel Standard
SDS	Sustainable Development Scenario
SPS	Stated Policies Scenario

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