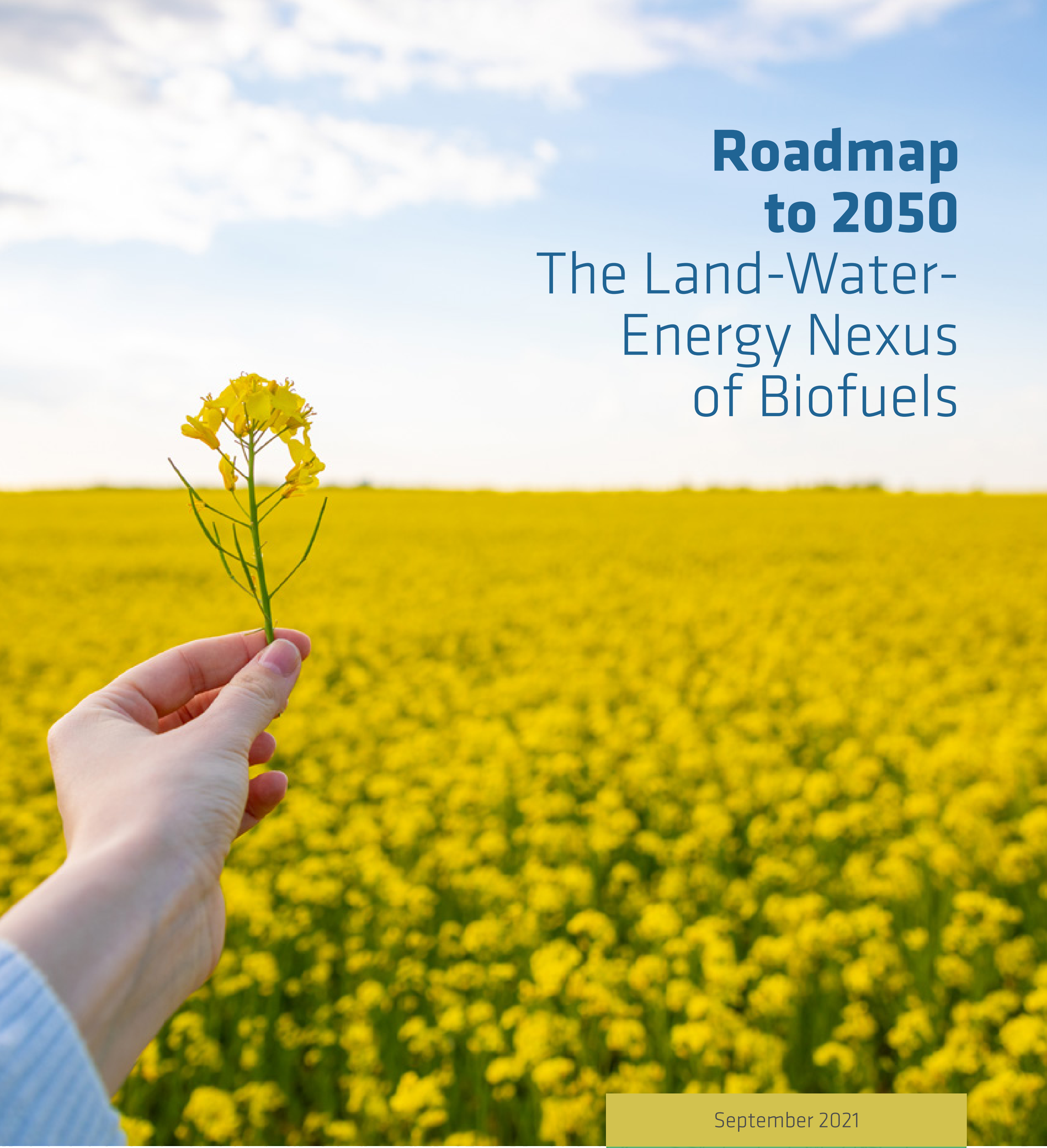
Roadmap to 2050

The Land-Water-Energy Nexus of Biofuels



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Acknowledgements

LEAD AUTHORS

Maurizio Masi, Politecnico di Milano
Emanuele Oddo, Politecnico di Milano
Maria Cristina Rulli, Politecnico di Milano; and
Joaquim E. A. Seabra, Universidade Estadual de Campinas
Chun Sheng Goh, Jeffrey Sachs Center on Sustainable Development, Sunway University

Contributing Authors
Paolo D'Odorico, University of California, Berkeley
Jampel Dell'Angelo, Vrije Universiteit Amsterdam
Nikolas Galli, Politecnico di Milano
Luiz A Horta Nogueira, Universidade Federal de Itajubá
Tom Richard, Pennsylvania State University; and
Monia Santini, Centro Euro-Mediterraneo sui Cambiamenti Climatici

**affiliations for identification purposes only*

Managing Editors
Elena Crete, Sustainable Development Solutions Network and Gianluca Crisci, Fondazione Eni Enrico Mattei

Editors
Fiona Laird, Sustainable Development Solutions Network and Cheyenne Maddox, Sustainable Development Solutions Network

Layout and Figures
Phoenix Design Aid A/S

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Key Contextual Definitions:

Biodiesel a renewable, biodegradable fuel manufactured from vegetable oils, animal fats, or recycled restaurant greases that undergo transesterification

Ethyl-tertiary-butyl ether (ETBE) a fuel ether, or blending component for fuel, that contains oxygen in a chain of carbon and hydrogen atoms, ETBE can be blended with gasoline or biofuels to decrease emissions and improve fuel performance because of its high oxygen and octane content. ETBE can be produced from ethanol and isobutylene (non-renewable), or through renewable ethanol and renewable isobutene (renewable)

Crop-based biofuels biofuels made from agricultural products, including sugarcane, wheat, corn, and soybean

Second generation biofuels biofuels produced from biomass sources such as wood, organic waste, food waste, and specific crops

Third generation biofuels biofuels produced from crops specifically intended for biofuels such as algae

Bioenergy renewable energy produced by living organisms

Pasture a land use type used for livestock grazing; may be cultivated and consists of vegetation such as grasses, legumes, other forbs, or shrubs

Rangeland lands where the indigenous vegetation is primarily managed through ecological versus agronomic processes; vegetation includes grasses, grass-like plants, forbs, and possibly shrubs or dispersed trees and spans grasslands, savannas, shrublands, most deserts, tundra, alpine communities, marshes and meadows

Marginal land land found on the edges of areas that are cultivated and is land that can be economically marginal (hard to make money on), biophysically marginal (hard to grow crops on), and/or socially marginal

Hydrotreated vegetable oil (HVO) straight chain paraffinic hydrocarbons produced through hydroprocessing of oils and fats; HVO is a diesel-type hydrocarbon that can be used as a substitute for diesel

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Executive Summary

2020 marked a watershed year for nations to increase their emission commitments through the submission of updated nationally determined commitments (NDCs) as outlined in the Paris Agreement. As of early 2021, 124 countries accounting for 61% of global GHG emissions, have communicated a net-zero targets[1]. These commitments, the most ambitious the world has ever seen, will only be feasibly met if near term actions align with the long-term pathways needed to collectively halt emissions and balance the planet's carbon budget.

Accompanying many of these NDCs are Low-Emission Development Strategies (LEDs) which articulate the key sectors and technologies on which nations will rely to decarbonize their economies. In addition to these national commitments, companies and key sectors are also taking seriously the goal of net zero emissions for example by joining the *Race to Zero* campaign launched by Champions Gonzalo Muñoz and Nigel Topping. These commitments have been supported by a growing number of sector strategies, coalitions and roadmaps articulating their course to net zero emissions. In the transport industry, the Global Maritime Forum launched the *Getting to Zero Coalition*, Deloitte and Shell released a *roadmap for decarbonising the global road freight industry* and the International Civil Aviation Organisation (ICAO) are working on their *Zero Climate Pact*. While some of these commitments still fall short of the necessary ambition needed to keep warming to 1.5 C, they do indicate a shift in the historic rhetoric. Key to the success of any of these efforts is the successful scaling of the solutions employed to meet these goals. The following report will try to better understand the feasibility of scaling biofuels to replace liquid fossil fuels in emissions reduction efforts, with a focus on the impacts to land, water and local economies.

In these efforts to design pathways toward net zero emissions, the precautionary principle reminds us to carefully assess the sustainability and scalability of our solutions. The Getting to Zero 2030 Coalition has provided a high level description of the energy inputs it considers under the definition of a zero carbon fuels source. These include primarily biomass derived fuels, hydrogen and synthetic non-carbon fuels (ammonia) and synthetic fossil fuels[2]. However they clarify that "Fuels derived from biomass are another option for reducing GHG emissions. In terms of carbon accountancy, this is more commonly described as "net-zero" because biomass derived energy is normally still a hydrocarbon that on combustion releases CO_2. But because the production of biomass takes CO_2 out of the atmosphere in equivalent quantity to that emitted in combustion, it can theoretically be considered as net-zero. GHG emitted in upstream processes (e.g. land-use, harvesting, processing/refining, transport) needs to be accounted for in addition and currently results in a small net positive carbon emission." Some cellulosic biofuel pathways under development, especially those coupled with geologic Carbon Capture and Storage (CCS) have the potential to be a strongly carbon negative fuel and offset positive emissions. With a stagnant growth of the global biofuel supply chain, coupled with their inclusion in many of the transport industries long-term decarbonization strategies, the sector still begs the question: are biofuels sustainable and if so, at what scale and what role do they play in the future global energy mix?

[1] Black, R., Cullen, K., Fay, B., Hale, T., Lang, J., Mahmood, S., Smith, S.M. 2021. Taking Stock: A global assessment of net zero targets, Energy & Climate Intelligence Unit and Oxford Net Zero.

[2] 2021. *Globalmaritimeforum.org*. https://www.globalmaritimeforum.org/content/2019/09/Getting-to-Zero-Coalition_Zero-carbon-energy-sources.pdf.

Given the growing interconnectedness of our world, and the elaborate and complicated supply chains on which many of our goods and services rely, an integrated approach is needed to assess the life cycle performance of the solutions chosen to meet Paris Agreement emissions goals, ensuring that other delicate systems are balanced along the way, including socio-economic wellbeing of local communities and the environmental well being of the planets natural habitats. It is with this realization that this project has been undertaken as a joint research project by the UN Sustainable Development Solutions Network (SDSN) and the Fondazione Eni Enrico Mattei (FFEM). Calling on the expertise of land-use, energy, water, and biofuel technology scientists, engineers and professionals from around the world, these partners convened a world class consortium to discuss, debate, and refine the potential for biofuels to be incorporated into national and sectoral decarbonization strategies. In the chapters ahead, these researchers attempt to better understand the intricacies of the global biofuel market, the evolution of key technologies, and the intersection of biofuel production on the land, water, and the local economies from which they are created.

As commitments from national governments require a progressive phase-out of fossil fuels as a primary source of energy in the next decades, this report intends to explore the potential role that biofuels can play to accelerate that process by analysing main production trends and emerging technologies. In addition, the report attempts to assess crucial controversies connected to their scalability, such as their impact on the environment and the potential competition of biofuel demands on agriculture and food production (in particular for traditional biofuels) in a global context characterized by increasing energy and food demand.

As per consolidated tradition, the approach adopted for such analysis is as holistic and inclusive as possible. The analysis carried out by authors and experts who took part in the drafting process of the *Roadmap* is diversified and offers perspectives according to specific local, national and regional contexts, as well as to specific economic sectors and technologies.

Biofuels' role in the global energy mix is still quite marginal. However, breakthrough technologies and management practices, including responsibly managed first generation biofuels, cellulosic bioethanol, advanced bio-oils, biogas from wastes, thermochemical processes, and synthetic biofuels, combined with the utilization of alternative feedstocks such as forest, wood, and agricultural residues; industrial and municipal wastes; and algae may raise their status as a valuable solution to tackle CO_2 emissions for specific sectors – notably long-haul shipping and aviation – and in specific geographic contexts. Perennial biomass crops sequester carbon in the soil, and most biofuel conversion technologies produce nearly pure streams of waste CO_2 containing 30% to 50% of the carbon in the original biomass; both of these mechanisms may justify a larger role for biofuels in addressing the expected overshoot of fossil emissions beyond the Race to Zero targets. The report's analysis spans from an assessment of biofuels' feedstocks sustainability – ranging from traditional crop-based biofuels to second- and third-generation biofuels.

There exist important considerations in evaluating sustainability of biofuels, as biofuel production has had far reaching impacts for food, water, land use, and social systems. Biofuel production, especially first generation biofuels, can divert crops away from food production if not properly managed, causing decreased availability of and access to food, and decreased resiliency of food supply to shocks. Demand for biofuels may cause pastures to be converted into biofuel crop land, potentially resulting in deforestation to make space for new pastures; further as land cover changes and biofuel crops replace other ecosystems this can reduce natural carbon sinks. Additionally, using water for biofuel crops may put pressure on already-limited water resources. And finally, biofuel production can result in small-scale traditional farming being replaced by large-scale industrialized commercial agriculture, impacting social systems, cultural values, and economic opportunities and risking loss of traditional ecological knowledge, threatening exploitation and dispossession of cooperatively owned land.

Case studies of biofuels in Malaysia and Indonesia, Brazil, the United States, and the European Union put the findings of this report in context. In Malaysia and Indonesia, palm oil is a major export and production generates substantial revenue. Ensuring sustainability of palm oil production, and the potential for palm-oil based biofuels, will require diversifying downstream production possibilities; use of low-carbon land resources for production expansion; and holistic thinking that takes into account land, energy, and food and is creative about how multiple types of land use can co-exist.

In Brazil, all Brazilian vehicles use some type of biofuel, and bioenergy is the most important renewable energy source in the country. Local production of biofuels, mainly from sugarcane crops, has allowed for reduced energy imports, increased energy security, and brought social and environmental benefits. Brazil's success in biofuel use highlights the importance of R&D, which allowed Brazil to balance some of the water and land use challenges of biofuel production, and expanded the potential for biofuel use to be an effective solution for decarbonising transport.

U.S. biofuel use has faced varying public and government support; compounded by commercialization challenges and a "food-versus-fuel" debate, biofuel use in the U.S. has lagged in investment and uptake in comparison to other renewables. However, biofuel use for aviation, renewable natural gas, geologic carbon storage, and the potential of cellulosic biofuel crops to offer carbon mitigation along with biodiversity, water quality, and other ecosystem service benefits presents expanding opportunities for biofuel use in the U.S.

Currently the largest producer of biodiesel worldwide and among the top producers of advanced biodiesel/HVO, the EU's high level of production is supported by a strong policy framework. The EU's experience with biofuels illustrates their high potential connected to the mobilization and conversion of waste and residues, from both an economic and resource standpoint.

The authors of this report were challenged to answer the intricate question of are biofuels sustainable and if so, what criteria needs to be met in order to achieve sustainability on a global scale. Given the diversity of geographic and subject matter expertise included in this project, no single answer was found to address this question. However, building off of work previously conducted and incorporating some of the latest research on the land-energy-water nexus of biofuels, the authors found that:

- Historically, traditional biofuel production has been fraught with challenges related to land use competition with food resources, water scarcity issues, environmental degradation, and adverse impacts on global markets. Learning from these experiences and ensuring all spillover impacts from biofuel cultivation are addressed is key. In this report we highlight new technologies, practices in diversifying crop management, life-cycle analysis, and biofuel certification schemes that offer an opportunity to produce biofuels more sustainability in the future for the purpose of global and local emissions reduction efforts as they are used to replace fossil fuels.

- Biofuels will never and should not be expected to produce 100% of our renewable energy needs, but 10% or even 20% globally is a feasible, realistic, and affordable path toward large scale negative emissions in the coming two decades.[3] This point is further substantiated by the International Energy Agency's Net Zero By 2050 analysis which states that "Low-emissions fuels today account for just 1% of global final energy demand, a share that increases to 20% in 2050 in the NZE. Liquid biofuels meet 14% of global transport energy demand in 2050, up from 4% in 2020; hydrogen-based fuels meet a further 28% of transport energy needs by 2050."

- There are potential applications for biofuels in the pathways to a net-zero future, specifically in aviation, heavy-duty transport, and shipping, as long as a proper life-cycle analysis is completed in the production and supply chain of the fuel.

- There is currently no globally optimal biofuel technology on the market. Optimal biofuel technologies and feedstocks must be assessed based on local contexts taking into consideration local socio-economic and environmental factors.

- There are currently an array of certification schemes in place that can be used to assess the sustainability of biofuels and these should be built upon if the industry is to scale sustainably into the future.

- Many traditional biofuel feedstocks compete with agricultural productivity, especially when land and water resources are constrained. The global biofuel market should be monitored and regulated to minimize these impacts and negate any impacts on food security.

[3] Haberl, Halmut, Karl-Heinz Erb1, Fridolin Krausmann1, Steve Running2, Timothy D Searchinger3 and W Kolby Smith. 2013. *Environ. Res. Lett.* 8 031004.

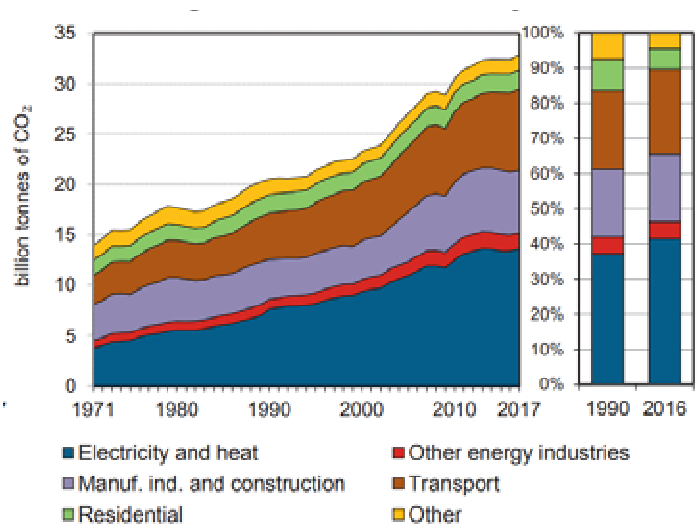
Chapter I

1. BIOFUELS IN THE GLOBAL ENERGY MIX

Lead Author: Joaquim E. A. Seabra, Universidade Estadual de Campinas

Transport accounted for almost 30% of global final energy demand and roughly 25% of global energy-related CO_2 emissions in 2017. Emissions from transport increased by 2% annually at the global level in the period 2000-2017, reaching 8 Gt CO_2 (Figure 1.1).[4] Road transport, mostly for passenger travel, accounted for three quarter of total transport emissions and it is the mode that increased the most in absolute terms (+ 1.7 $GtCO_2$), while international aviation led in terms of rate of growth (3% versus 2% of road transport).[5] Transport is the least diversified energy end-use sector: it consumes about two thirds of global oil final energy demand – with more than 90% of the final energy demand consisting of oil products –, which suggests a significant challenge for deep decarbonization.[6]

FIGURE 1.1 Global CO_2 Emissions by Sector, in Gt CO_2 (IEA, CO_2 emissions from fuel combustion).



Biofuels are the only renewable energy source used directly in the transport sector . They have the potential to leapfrog traditional barriers to enter the market as they are liquid (or gaseous) fuels compatible with current engines and blendable with current fuels. Ethanol, for example, is easily blended up to at least 10% with modern conventional gasoline vehicles, and to much higher levels in vehicles that have been modified to accommodate it. Biodiesel can be blended with petroleum diesel fuel in any ratio up to 100% for operation in conventional

[4] IEA, 2019. CO_2 emissions from fuel combustion 2019, Statistics. International Energy Agency, France.

[5] Ibid.

[6] IEA, 2017. Technology Roadmap - Delivering Sustainable Bioenergy. International Energy Agency, Paris, France.; IPCC, 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty, IPCC Special Report. Intergovernmental Panel on Climate Change.

diesel engines. Further, biofuels share the long-established distribution infrastructure with little modification of equipment.[7]

In most countries embarking on biofuels initiatives, the recognition of non-market benefits is often the driving force behind efforts to increase their use, especially with respect to climate change. Some studies suggest that biofuels can provide significant reductions in greenhouse gas (GHG) emissions when compared to fossil fuels on a life cycle basis (see chapter 3.8 for details). This can be particularly relevant for hard-to-abate sectors, such as aviation, heavy-duty transport, and shipping. Even though a wide range of estimates exists, particularly large reductions are estimated for ethanol from sugarcane and from cellulosic feedstocks, as well as other waste-derived biofuels. Further, bioenergy can be combined with carbon capture and sequestration (BECCS) to help not only with emissions mitigation, but also promote the removal of CO_2 from the atmosphere.

Biofuels can also provide air quality benefits when used either as pure, unblended fuels or, more commonly, when blended with petroleum fuels. The benefits include lower emissions of carbon monoxide (CO), sulphur dioxide (SO2) and particulate matter (particularly when emissions control systems are poor, such as in some developing countries), although biofuels can increase some emissions categories, such as evaporative hydrocarbon emissions and aldehyde emissions from the use of ethanol. Usually, biofuels are also less toxic than conventional petroleum fuels and, in some cases, they can reduce wastes through recycling.[8]

As for vehicle performance, ethanol has a very high octane number and can be used to increase the octane of gasoline, either directly blended with gasoline or previously converted to ethyl-tertiary-butylether (ETBE) before blending. Biodiesel, in turn, can improve diesel lubricity and raise the cetane number, aiding fuel performance.[9]

Furthermore, the production of crop-based biofuels provides an additional product market for farmers and brings economic benefits to rural communities. But the production of biofuels can also draw crops away from other uses (such as food production) and increase their price. For specific circumstances, this may translate into higher prices for consumers and lead to an undesired competition with food supply. However, when well-planned and carefully implemented to avoid environmental and social risks, biofuels can generate benefits and contribute to many policy objectives, as well as to strategic demands from society and the economy.[10]

1.1 Biofuels' Share in Global Energy Mix

In 2018 3.7% of transport fuel demand was by renewables, corresponding to around 4 exajoules (EJ). Biofuels provided 93% of all renewable energy, the remains coming from renewable electricity (IEA, 2019). In the same year, they contributed around 90 Mtoe or almost 2 million barrels of oil equivalent (mboe) per day. In the early 2000s, biofuels were experiencing double-digit growth but after 2010 that growth slowed down due to economic

[7] IEA (Ed.), 2004. Biofuels for transport: an international perspective. International Energy Agency, Paris, France.

[8] Ibid.; Souza, G.M., Victoria, R.L., Joly, C.A., Verdade, L.M., 2015. Bioenergy & sustainability: bridging the gaps. Scientific Committee on Problems of the Environment (SCOPE), Paris Cedex.

[9] IEA, Biofuels for transport.

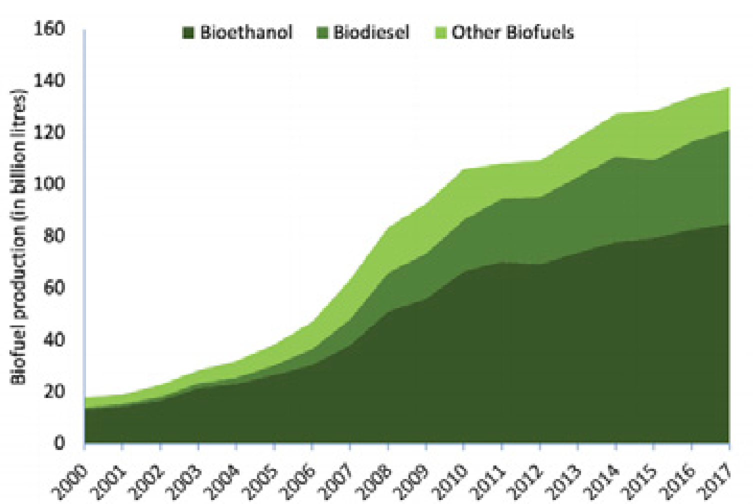
[10] ICAO, 2018. Sustainable aviation fuels guide, Version 2. ed, Transforming Global Aviation Collection. ICAO, UNDP, GEF.

and structural challenges, as well as policy uncertainty in key markets. As a result, production increased at a slower average annual growth rate of 4% over 2010-18.[11]

First generation bioethanol (i.e., produced from food crops) is still the major contributor to the global biofuel supply. The production of second and third generation biofuels from cellulosic plant tissues or algae is overall negligible (but is expected to be substantial in the coming 10-20 years according to the experts). Ethanol contributes to about 70% of the global biofuels production, followed by biodiesel (Figure 1.2).[12] Bioethanol is produced mostly with corn and sugarcane followed by wheat, sugarbeet and sorghum. Biodiesel produced with rapeseed oil accounts for more than half of the global production, followed by palm oil and soybean oil. Most of the global consumption of biodiesel takes place in OECD+EU27 countries. The greatest biodiesel consumers are France and Germany, followed by the United States and Italy. These countries rely mostly on rape-mustard seed oil (and, in smaller amounts, palm oil and soybean oil), as do most of the other OECD+EU27 countries. Different oil consumption patterns are found in Brazil, which strongly relies on soybean oil.

In the last few years progress has been made in biofuels applications for aviation, due to the enhanced policy support in the United States and Europe. Flights using biofuel blends have surpassed 200,000, and continuous biofuel supply is already available at six airports. Nevertheless, the 15 million liters produced in 2018 accounted for less than 0.01% of the aviation fuel demand. In the marine sector, the use of biofuels is under consideration in certain cases, but uptake remains low due to the current higher costs.[13]

FIGURE 1.2. Global Production of Liquid Biofuels (WBA, Global Bioenergy Statistics 2019).



[11] IEA, 2019. World Energy Outlook 2019. OECD/IEA, Paris, France.; IEA, Technology Roadmap.

[12] WBA, 2019. Global Bioenergy Statistics 2019. World Bioenergy Association, Sweden.

[13] IEA, 2020. Transport Biofuels [WWW Document]. URL https://www.iea.org/reports/transport-biofuels.

Transport biofuels play an important role in a limited number of markets. In 2016, just six countries had fuel ethanol production levels over 1 billion liters, in a global market dominated by the United States and Brazil, who jointly represented around 85% of the global production (Table 1.1).[14] Biodiesel production is more evenly distributed, with ten markets having production levels over 1 billion liters, contributing to a total of just under 36 billion liters of global production.[15]

TABLE 1.1. Biofuel Production Ranking and Key Feedstocks (OECD/FAO, Agricultural outlook 2019-2028).

	Production ranking (base period)		Major feedstocks	
	Ethanol	Biodiesel	Ethanol	Biodiesel
United States	1 (50%)	2 (19%)	Maize	Soybean oil / diverse other oils
European Union	4 (5%)	1 (36%)	Maize / wheat / sugar beet	Rapeseed oil / waste oils
Brazil	2 (24%)	3 (12%)	Sugar cane	Soybean oil
China	3 (8%)	8 (3%)	Maize	Waste oils
India	5 (2%)	15 (0.5%)	Molasses	Palm oil
Canada	6 (1.6%)	10 (1.4%)	Maize	Waste oils
Indonesia	23 (0.2%)	4 (10%)	Molasses	Palm oil
Argentina	9 (1%)	5 (7%)	Maize / sugar cane	Soybean oil
Thailand	7 (1.5%)	6 (4%)	Molasses / cassava	Palm oil
Colombia	13 (0.4%)	9 (1.5%)	Sugar cane	Palm oil
Paraguay	15 (0.3%)	19 (0.03%)	Maize / sugar cane	Soybean oils

Note: Percentage numbers refer to the production share of countries in the base period.
Source: OECD/FAO (2019), "OECD-FAO Agricultural Outlook", OECD Agriculture statistics (database), http://dx.doi.org/10.1787/agr-outl-data-en.

1.2 International Trade

The international trade of biofuels is relatively modest and dominated by a few global players (Figure 1.3).[16] In the case of ethanol, global trade represents less than 10% of the production. The United States is a net exporter of corn-based ethanol and a modest importer of sugarcane-based ethanol. The need for sugarcane-based ethanol imports is related to the Low Carbon Fuel Standard in place in California and to the limited filling of the advanced mandate. As for biodiesel, Argentina is the lead biodiesel net exporter, followed by the European Union (mainly exports to the United Kingdom) and Canada.[17]

For the period 2019-2028, biodiesel trade is projected to decrease as most countries with biodiesel mandates or targets will fill these domestically, and imports from developed countries, in particular the United States and the European Union, are expected to decrease. Argentinian exports, however, are expected to increase, while

[14] OECD/FAO. 2019. Agricultural outlook 2019-2028. Special focus: Latin America. OECD Publishing / Food and Agriculture Organization of the United Nations, Paris, France and Rome, Italy.

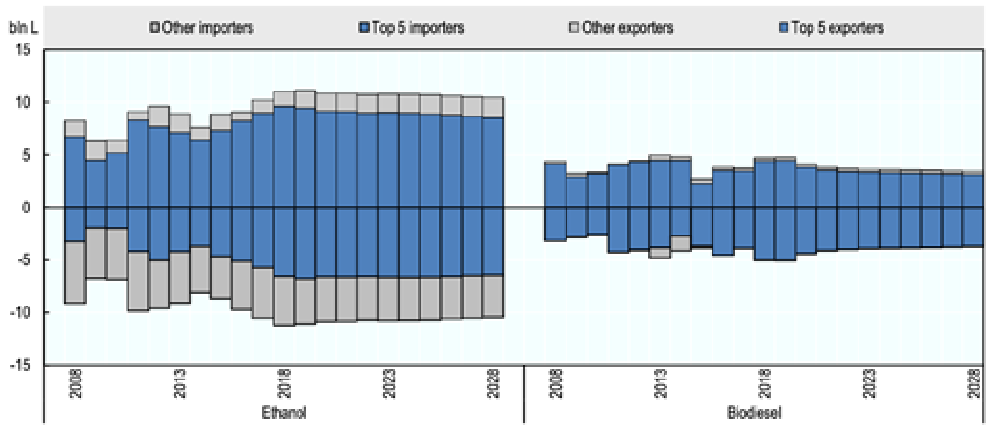
[15] Ibid.

[16] OECD/FAO. 2019. "OECD-FAO Agricultural Outlook". OECD Agriculture statistics (database). http://dx.doi.org/10.1787/agr-outl-data-en.

[17] OECD/FAO, Agricultural outlook 2019-2028.

exports from Indonesia and Malaysia should decline due primarily to diminishing export markets, notably the European Union. US ethanol exports should also decrease because of a combination of strong domestic demand and weak international demand. Brazilian ethanol exports are not expected to expand over this period given that the Brazilian ethanol industry will mostly fill sustained domestic demand and that domestic ethanol prices are expected to remain slightly above international ones.[18]

FIGURE 1.3. Outlook for Global Biofuel Trade (OECD/FAO, OECD/FAO Agricultural Outlook).



Note: Top five ethanol exporters in 2028: United States, Brazil, Pakistan, European Union, United Kingdom. Top five ethanol importers in 2028: Brazil, United States, Japan, Canada, China. Top five biodiesel exporters in 2028: Argentina, European Union, Canada, United States, Indonesia. Top five biodiesel importers in 2028: European Union, United States, United Kingdom, Peru, Canada.
Source: OECD/FAO (2019), "OECD-FAO Agricultural Outlook", OECD Agriculture statistics (database), http://dx.doi.org/10.1787/agr-outl-data-en.
StatLink http://dx.doi.org/10.1787/888933959284

1.3 Potential Growth of Bioenergy by 2050

The amount of biomass for energy technically available in the future depends on the evolution of a multitude of social, political, and economic factors.[19] As there is no standard methodology to estimate the technical bioenergy potential, diverging estimates exist. Most of the recent studies estimating technical bioenergy potentials assume a 'food / fibre first principle' and exclude deforestation, eventually resulting in an estimate of the 'environmentally sustainable bioenergy potential' when a comprehensive range of environmental constraints is considered.[20] Recent estimates of global technical bioenergy potentials in 2050 span within a range of almost

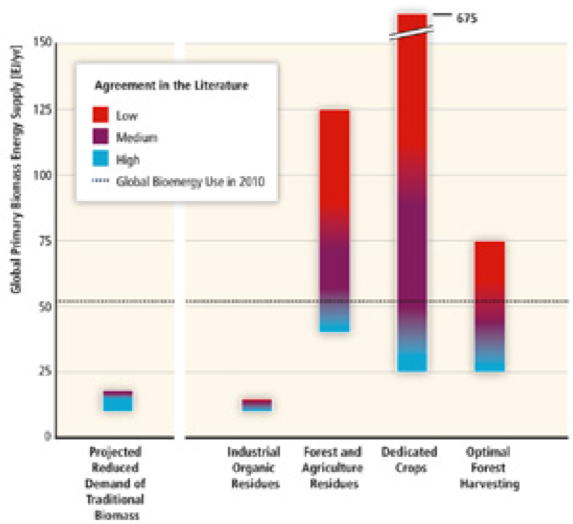
[18] OECD/FAO, Agricultural outlook 2019-2028.

[19] Dornburg, V., van Vuuren, D., van de Ven, G., Langeveld, H., Meeusen, M., Banse, M., van Oorschot, M., Ros, J., Jan van den Born, G., Aiking, H., Londo, M., Mozaffarian, H., Verweij, P., Lysen, E., Faaij, A., 2010. Bioenergy revisited: Key factors in global potentials of bioenergy. Energy Environ. Sci. 3, 258. https://doi.org/10.1039/b922422j.

[20] Batidzirai, B., Smeets, E.M.W., Faaij, A.P.C., 2012. Harmonising bioenergy resource potentials—Methodological lessons from review of state of the art bioenergy potential assessments. Renewable and Sustainable Energy Reviews 16, 6598–6630. https://doi.org/10.1016/j.rser.2012.09.002; IPCC (Ed.), 2014. Climate change 2014: mitigation of climate change: Working Group III contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York, NY.

three orders of magnitude, from less than 50 EJ/yr to more than 1,000 EJ/yr (Figure 1.4). Most studies agree that the technical bioenergy potential in 2050 is at least approximately 100 EJ/yr with some modelling assumptions leading to estimates exceeding 500 EJ/yr.[21]

FIGURE 1.4. Global Technical Bioenergy Potential by Main Resource Category for the Year 2050 (IPCC, Climate change 2014).



Given the often-debated food versus fuel dilemma, the land requirement for food production is central for biofuels potential estimates. Projections from FAO, based on population and dietary trends, indicate a net increase in land used to grow food crops by 2050 of about 70 Mha resulting from an increase in land area under agriculture in developing countries of 130 Mha and a decrease of over 60 Mha in developed countries.[22] In terms of availability, the land available for rainfed agriculture is estimated to be 1.4 Bha of 'prime and good' land and a further 1.5 Bha of marginal land that is 'spare and usable'. Almost 1 Bha of this land is in developing countries in sub-Saharan Africa and Latin America with much of it currently under pasture/rangeland.[23]

When it comes to land demand for biofuels, observations from the 34 largest biofuel producing countries (responsible for over 90% of global production in 2010) indicated that the sharp increase in biofuel production between 2000 and 2010 led to a gross land demand of 25 Mha out of a total of 471 Mha arable land.[24] However, nearly half of the gross biofuel land area was actually associated with commercial co-products (primarily animal feeds, such as distillers dry and wet grains, soy and rape meal) which results in a net direct biofuel land demand

[21] IPCC, Climate change 2014.

[22] Alexandratos, N., Bruinsma, J., 2012. World agriculture towards 2030/2050: the 2012 revision (No. 12– 03), ESA Working Paper. FAO Agricultural Development Economics Division, Rome.

[23] Souza et al., Bioenergy & sustainability: bridging the gaps.

[24] Langeveld, H., Dixon, J., Keulen, H. van (Eds.), 2014. Biofuel cropping systems: carbon, land, and food, First edition. ed. Routledge, Abingdon, Oxon.

of 13.5 Mha (i.e., 2.4% of arable land area). Additionally, it is interesting to note that the agricultural land area in those countries decreased 9 Mha over the same period, enabled by the increasing cropping intensity.[25]

Those figures suggest that, at a global level, competition with agricultural lands would not be a key constraint for the expansion of biofuels. The critical issue is hence how bioenergy production could be gracefully incorporated into human and natural systems, accounting for any negative externalities from agricultural intensification, rather than managing a competition for land between energy and food. Today, sugarcane, corn, rapeseed and soybean are the relevant feedstocks for biofuels, but many other crops and even yet undomesticated plants have the potential to play important roles as well. Lignocellulosic biomass in the form of energy crops, agricultural wastes and forest residues represents the most abundant source of renewable biomass and is widely recognized as the primary future feedstock for the biofuel and bio-based industry. But meeting future energy needs with high productivity feedstocks will require the expansion of agronomic research and breeding trials on marginal land (and possibly unsuited land for food crop production), as well as the development of cost-effective supply chains.[26]

1.5 Perspectives

The IPCC's Special Report shows that without increased and urgent mitigation ambition in the coming years, in order to have a sharp decline in GHG emissions by 2030, global warming will surpass 1.5°C in the following decades, leading to irreversible loss of the most fragile ecosystems, and crisis after crisis for the most vulnerable people and societies.

The potential and strategies to reduce energy consumption and CO_2 emissions in transport differ significantly among the modes. The contribution of various measures for the CO_2 emission reduction from IEA's reference scenario to the Beyond 2°C Scenario (B2DS) in 2050 can be decomposed to efficiency improvement (29%), biofuels (36%), electrification (15%), and avoid/shift (20%).[27] The total amount of biofuels consumed in the transport sector would be 24 EJ in 2060, mainly allocated to the difficult-to-decarbonize modes: HDV (heavy-duty vehicles, 35%), aviation (28%), and shipping (21%).

The projections of IPCC's scenarios are more pessimistic than IEA's, though both clearly project deep cuts in energy consumption and CO_2 emissions by 2050 (Figure 1.5).[28] The share of low-carbon fuels in the total transport fuel mix increases to 10% and 16% by 2030 and to 40% and 58% by 2050 in 1.5°C-overshoot pathways from IPCC and the IEA, respectively.

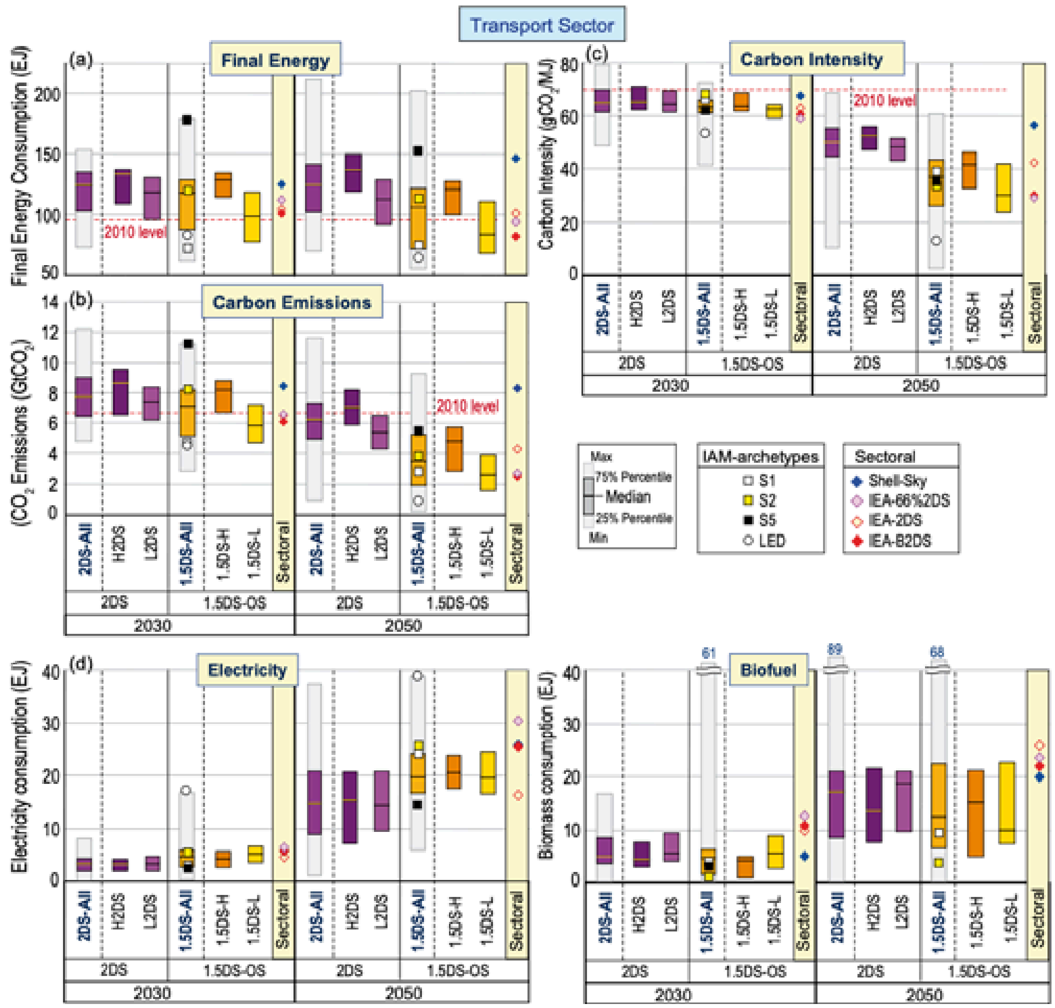
[25] Woods, J., Lynd, L.R., Laser, M., Batistella, M., Victoria, D. de C., Kline, K., Faaij, A., 2015. Land and Bioenergy, in: Bioenergy & Sustainability: Bridging the Gaps. Scientific Committee on Problems of the Environment (SCOPE), Paris Cedex, pp. 258–301.

[26] Souza et al., Bioenergy & sustainability.

[27] The Beyond 2°C Scenario (B2DS) explores the feasibility of accelerating clean energy technology deployment in pursuit of more ambitious climate goals. The B2DS has the potential to approach carbon neutrality by 2060 and limit temperature increases to 1.75°C by 2100.;
IEA, Technology Roadmap.

[28] IPCC, Global Warming of 1.5°C.

FIGURE 1.5. Comparison of (a) Final Energy, (b) Direct CO_2 Emissions, (c) Carbon Intensity, (d) Electricity and Biofuel Consumption in the Transport Sector between IPCC's and IEA's Scenarios (IPCC, Global Warming of 1.5°C.).



More recent IEA's projections estimate global biofuels demand around 10 EJ in 2040 in the Sustainable Development Scenario[29], being more than half from aviation and shipping.[30] The 2021 Net Zero by 2050 IEA report states that ""Low-emissions fuels today account for just 1% of global final energy demand, a share that increases to 20% in 2050 in the NZE. Liquid biofuels meet 14% of global transport energy demand in 2050, up from 4%

[29] The Sustainable Development Scenario maps out a way to meet sustainable energy goals in full, requiring rapid and widespread changes across all parts of the energy system. This scenario charts a path fully aligned with the Paris Agreement by holding the rise in global temperatures to "well below 2°C ... and pursuing efforts to limit [it] to 1.5°C", and meets objectives related to universal energy access and cleaner air (IEA, World Energy Outlook 2019).

[30] IEA, World Energy Outlook 2019.

in 2020; hydrogen-based fuels meet a further 28% of transport energy needs by 2050. Low-carbon gases (biomethane, synthetic methane and hydrogen) meet 35% of global demand for gas supplied through networks in 2050, up from almost zero today." However, the Covid-19 crisis has radically changed the global context for energy use. As a consequence of global lockdown measures, mobility declined at an unprecedented scale in early 2020. Road transport in regions with lockdowns in place dropped between 50% and 75%, with global average road transport activity almost falling to 50% of the 2019 level by the end of March. Global aviation activity had declined to a staggering 60%.[31]

Transport biofuel production is anticipated to contract by 13% in 2020, the first decrease in output in two decades. Due to the expected decreases in gasoline and diesel demand in 2020, IEA anticipates a contraction of 15% in ethanol output, and a 6% reduction in biodiesel and hydrotreated vegetable oil (HVO) production. However, if transport fuel demand rebounds in 2021, biofuel production could also return to 2019 levels. Longer-term implications for growth may arise from the suspension of new policy initiatives in some countries due to low oil prices.[32]

[31] IEA. 2020. Global Energy Review 2020 - The impacts of the Covid-19 crisis on global energy demand and CO_2 emissions. International Energy Agency, Paris.

[32] IEA. 2020. "Renewable Energy Market Update". Fuel Report. Paris: International Energy Agency. https://www.iea.org/reports/renewable-energy-market-update.

Chapter II

2. BIOFUELS TECHNOLOGIES

Lead Author: Emanuele Oddo, Politecnico di Milano and Maurizio Masi, Politecnico di Milano

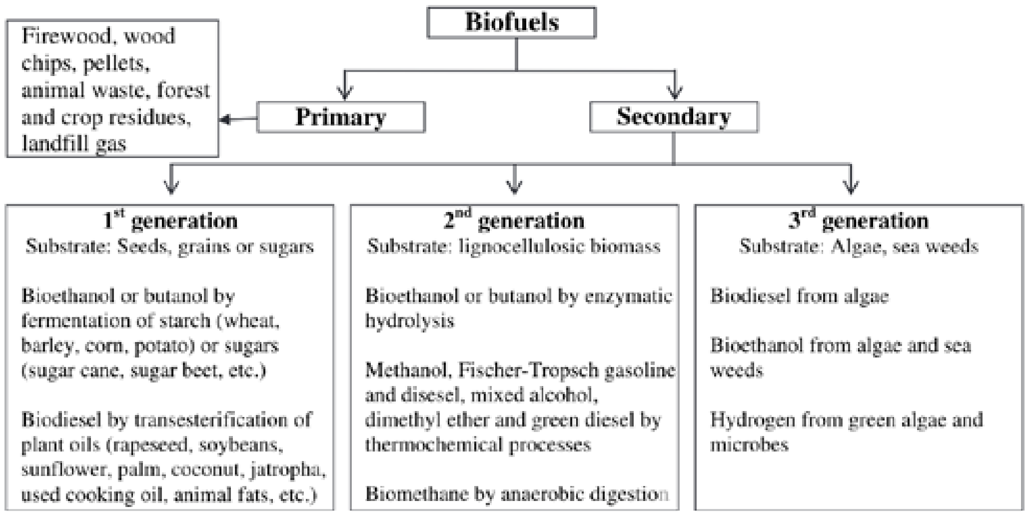
As energy from traditional fossil sources (oil, natural gas and coal) are progressively depleted and/or discouraged due to their impact on the overall GHG emissions, biomasses are more and more becoming a key asset for the production of sustainable fuels in the near future. The term biomass refers generically to the accumulation of a broad spectrum of animal and plant resources and their wastes. Although biomass carbon balance benefits from former plants' utilization of CO_2 for the photosynthetic processes, other factors should be taken into account like the water/nutrients consumption for cultivation, soil depletion and water/energy consumption during conversion. All these aspects will be addressed in the following sections of this chapter as well as in Chapter 3.

Traditionally, biomasses for biofuel production were identified exclusively with direct products from crops cultivation, mainly sugar and starchy crops or oil seeds. Biofuel obtained from these feedstocks are generally referred to as "first generation" (1G) biofuel. Although 1G feedstocks still make up the largest share for biofuel production, the exploitation of other feedstocks, such as agri-food residues and municipal/industrial wastes is gaining importance. This is the result of a significant effort to try to overcome the main issue of 1G biofuel, namely competition with food. Biofuels obtained from these non food-based sources are usually defined as "second generation" (2G) biofuels. Furthermore, algae feedstocks are attracting great attention due to their peculiar characteristics, mainly low land occupation, fast growth rate and availability of biomass. Given algae peculiar features and the relative novelty of their exploitation, biofuels obtained from such feedstock are qualified as "third generation" (3G).

Albeit fairly widespread, this classification is not the only one in the literature. Sometimes, a distinction is made according to the novelty of the process. As a result, bioethanol production from sugarcane (food-based) could be classified as 2G if novel industrial practice is applied. Equally, digestion of wastewaters would be considered 1G, although wastewaters are not food-based, because anaerobic digestion is an old, well-established process. Further criteria have been proposed, including also the properties of the fuel (i.e. profitability as drop-in biofuel). This broad range of definitions makes it even more challenging to make a clear comparison between the approaches to biofuel production.

For the sake of simplicity, we will stick to the former criteria of competition with food. Hence, production routes will be classified into two main groups, namely traditional and advanced technologies. The traditional group encompasses 1G biofuels from food-based feedstocks, that is to say bioethanol from sugar/starchy crops, biodiesel from vegetable oils and possibly biogas from agricultural crops. On the other hand, the advanced group includes 2G and 3G production routes exploiting respectively residues/wastes, such as bioethanol from lignocellulosic crops, thermochemical conversion of agri-food residues or digestion of manure, and algae (biodiesel, jet-fuel, biomethane, etc.). Such a scheme is quite common and it is very similar to the one reported in Figure 2.1. Primary biofuels, included in the figure, refer to untreated (at most pelletized), usually woody biomasses which are directly exploited for energy production. According to the specific focus of the report, only secondary biofuels will be taken into account in the following.

FIGURE 2.1 Classification of biofuels.[33]



As a final introductory remark, it is important to recall that biofuels usually display rather different composition and functional properties (density, viscosity, cloud point, etc.) compared to fossil fuels. This is especially true for 1G biofuels like bioethanol and biodiesel – which still makes up the majority of global biofuel production – but it also applies to many 2G/3G products. In fact, direct use of biofuels as a standalone feed for engines is usually not possible. Such issue can be overcome in two main ways. The first one is to design new engines capable of processing the raw biofuels coming from conversion of biomass. This is challenging from a technological standpoint, especially due to the high variability of feedstocks, but not unattainable. For instance, flex-vehicles are capable of processing different blends of gasoline and bioethanol up to 100% of biofuel. The other solution is upgrading of biofuels through additional treatments. The resulting biofuels, usually indicated as "drop-in", can thus operate with existing engines without major adjustment thanks to their superior properties.

2.1 Policies and targets for biofuels

Biofuel production at the industrial and commercial scale is relatively new compared to well-consolidated petroleum-derived fuels. Indeed, the lack of infrastructure and technological know-how in many developing countries qualify the biofuel production routes as infant and risky technology. Therefore, energy policies in such context are crucial for the fostering of biofuel platforms through the definition/standardization of the different bio-derived products and the unfolding of different supportive actions for their strengthening in the local and global market.

Policies arise according to different needs. Energy security is surely one of the most recurrent. In fact, the dependence on imported sources of energy, combined with price volatility and supply disruptions, make the availability of local energy sources very attractive. Secondly, the chance or need to promote economic and social quality of rural areas, especially in developing countries, can give an impulse to biofuel policies. Such contributions

[33] P.S. Nigam, A. Singh / Progress in Energy and Combustion Science 37 (2011) 52-68

may come in many forms and may affect biofuel technologies at different levels along the supply chain. For instance, subsidies in the agri-food sectors, tariffs and tax incentives as well as subsidies for biofuels or flex-fuel vehicles purchase are pretty common. Moreover, a common policy adopted in OECD states is the definition of mandatory levels of blending of biofuels in conventional liquid fuels, acting as a trigger for biofuel industry growth.

European Union has put in motion a set of supporting actions during the last decades within the member states. Three fundamental Directives (EU) on biofuel legislation were approved in 2003 (2003/30/EC, 2003/96/EC and 2003/17/EC), setting the stage for national initiatives via voluntary targets for biofuel consumption and biofuel share in the energy balance as well as the application of tax incentives for biofuels. At the same time, support to the biofuel market came also from the Common Agricultural Policy and Rural Development Policy. More recently, Directive (EU) 2018/2001 (promotion of the use of energy from renewable sources) was approved by European Parliament in December 2018, defining the new target of 32 % share of energy from renewable sources in gross final consumption of energy by 2030. Additionally, the directive requires each member state to compel fuel suppliers with obligations so that the share of renewable energy within the final consumption of energy in the transport sector is at least 14 % by 2030.

Similarly, the United States deployed a set of tax incentives for biofuel production in 2005 with the Energy Policy Act. The Act also established some quantitative targets in the form of Renewable Fuels Standard (RFS) program. Later, the Energy Independence and Security Act of 2007 defined new, more demanding targets, namely a phased increase of biofuels volume up to 36 billion gallons by 2022, mainly covered by advanced biofuels. In addition, the Biomass Crop Assistance and Biorefinery Assistance Programs are supplementary tools for sustaining biofuels deployment through assistance to landowners and operators involved in biofuel feedstocks production as well as funding of newly constructed and retrofitted plants for advanced biofuel production.

2.2 Traditional biofuels

This section deals with 1G biofuel technologies, namely fermentation of sugar or starchy crops to bioethanol, transesterification of vegetable oils (FAME), hydrogenated vegetable oils (HVO) and anaerobic digestion of agricultural crops to biogas. These technologies easily encompass the vast majority of the current biofuel production (more than 90%). In fact, it was estimated that conventional ethanol and biodiesel/HVO accounted respectively for 71% and 20% of 2018 biofuel production (154.4 billion L).[34] This dominance of traditional technologies is the result of a variety of factors, but one of the most prominent surely is the high risks connected to the deployment of many advanced biofuel technologies.

By contrast, traditional technologies are well-consolidated and the chemistry of the process is typically well-understood, thus lowering installation and operating costs and, in general, the risks of investing in commercial-scale plants. However, such processes essentially rely on food-based feedstocks, such as sugar/starchy crops for bioethanol or vegetable oils for biodiesel/HVO. This brings up a number of issues. The yield of biofuel per area of land occupied is typically low. Still, the main drawback is the reduction of available land for agriculture, arising competition with the food sector. Several approaches can be implemented to overcome this shortcoming. For instance, crop rotation and integration with food cultivation is possible. Also, optimization of farming and harvesting processes can significantly improve the yield per area of land, that is to say to reduce the required land

[34] IEA. (2019). Transport biofuels. In *Renewables 2019: Analysis and forecast to 2024*.

with equal fuel productivity. Finally, selected crops able to grow well on non-arable soils may allow mobilizing new land, although biodiversity, soil balance and pre-existing uses of marginal lands should be safeguarded as well.

2.2.1 Bioethanol from sugar and starchy crops

Bioethanol is obtained from the biochemical conversion of agricultural crops through yeasts fermentation. It is a very old, well-established technology and it currently makes up the largest share of biofuel production. In 2019 bioethanol capacity reached globally 115 billion L. In the United States, ethanol production reached 59.5 billion L in 2019[35], making it the first bioethanol producer globally with 52%. A similar level was expected for 2020, but the pandemic severely affected the ethanol industry and a 12% drop (the lowest output since 2014) is expected for the following year.[36] Brazil was the runner-up in 2019, with a bioethanol production of 36 billion L (31%). Brazil has also suffered strongly in 2020 due to gasoline demand drop, low oil prices and increased profitability of sugar cane on the sweeteners market. All these factors contributed to an expected fall of 16.5%.[37]

Sugar crops are the traditional feedstock for bioethanol production. This includes a sound variety of plants such as sugar cane, sugar beet, sugar millet and sweet sorghum, their main feature being the high content in fermentable sugars (sucrose, glucose and fructose). Preferred feedstocks are generally C_4 plants – they exploit a more efficient carbon fixation process (i.e. conversion of CO_2 into organic compounds) compared to C_3 plants. Sugar cane is a perennial C_4 grass with 12-24% of sugars on a wet weight basis, mainly sucrose (90%) with minor share of other sugars. Sugar cane is currently the largest feedstock for bioethanol production in Brazil, the second ethanol producer globally. In the EU, sugar beet is exploited alongside corn (see below) for 1G ethanol production. It contains 14–21% of fermentable sugars[38]. Sweet sorghum is another common feedstock, with high yield of both lignocellulosic fractions and fermentable sugars[39], making it eligible for both 1G bioethanol and lignocellulosic ethanol (see corresponding section in Advanced Technologies) production. Moreover, sweet sorghum contributes in small measure to the sugar market, contrarily to other crops like sugar cane and sugar beet.

Sugar crops are firstly milled and pressed to extract the sugar juice before fermentation. In the case of sugar cane, the extraction efficiency through pressing is very high (easily above 90%) and the main by-product is sugar cane *bagasse* (solid residues from pressing), which can be valorized again through conversion to lignocellulosic ethanol (see corresponding section in Advanced Technologies). Depending on the process, fermentation may be performed directly on the fresh juice or on a concentrated juice (*thick juice*). Fermentation is also applicable to molasses, the main by-product from sugar-refining, which still contains 45 to 60% sucrose and 5 to 20 % glucose and fructose.[40]

The other common feedstock for 1G ethanol is a vast group of starch-containing crops, including corn, wheat, barley, rye, sorghum, and cassava. corn is by far the most common feedstock for ethanol production in the

[35] International Energy Agency. (2020). Transport biofuels. In *Renewables 2020: Analysis and forecast to 2025*.

[36] Ibid.

[37] Ibid.

[38] Tian, Y., Zhao, L., Meng, H., Sun, L., Yan, J. 2009. Estimation of un-used land potential for biofuels development in (the) People's Republic of China. Applied Energy 86: 77–85. doi: 10.1016/j.apenergy.2009.06.007.

[39] S.C. de Vries, G.W.J. van de Ven, M.K. van Ittersum, K.E. Giller, Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques, Biomass and Bioenergy 34 (2010) 588–601. https://doi.org/10.1016/j.biombioe.2010.01.001.

[40] B.E. Della-Bianca, T.O. Basso, B.U. Stambuk, L.C. Basso, A.K. Gombert, What do we know about the yeast strains from the Brazilian fuel ethanol industry?, Appl. Microbiol. Biotechnol. 97 (2013) 979–991. https://doi.org/10.1007/s00253-012-4631-x.

US, the largest bioethanol producer. The starch content in the corn kernel is very high, easily above 70%, while simple sugars are only present in a few percent. On the other hand, wheat is the main crop used in Europe for ethanol. Given the relevance of these feedstocks, it is common in the literature to refer to them generically as *corn crops* to indicate either corn in the US or wheat in Europe. Barley and sorghum have a starch content of 50-75%, depending on the varieties, and can be exploited as rotation crops for corn. Sweet potatoes have also been considered recently as a possible feedstock due to their high starch content of 75%.

Starch is a polymeric carbohydrate made up by numerous glucose units and it is not a ready fermentable sugar. Thus, additional pre-treatment is required to reduce starch to simpler sugars (mainly glucose). This is achieved through hydrolysis and saccharification of the biomass by addition of proper enzymes (i.e. amylase). Depending on the process, the whole crops may be fed to the fermenter after grounding and hydrolysis (dry milling) or fractionation of the feedstock may be performed before hydrolysis/saccharification (wet milling). In the wet milling scheme, corn oil and gluten are recovered and they can be valorized as side-products, but the additional units result in increased capital costs and occupied area. Thus, the choice of process scheme should take into account the specific regional constraints on market and logistics of side-products.

Sugar or starchy biomass is then subjected to alcoholic fermentation. The biochemical reactions proceed anaerobically in presence of selected yeast strains (i.e. *Saccharomyces cerevisiae*) at controlled temperature of 30-35°C, allowing the conversion of fermentable sugars into ethanol and carbon dioxide. The stoichiometry of the reaction for glucose would suggest a high yield in ethanol. However, ethanol has an inhibitory effect on the yeasts, which progressively hamper the biomass growth. This results in limited conversion of sugars and especially low concentration of ethanol in the outlet solution, which typically accounts for 10% in volume at most. By exploiting alternative/engineered strains, it may be possible to raise the content up to 20% v/v. Thus, the outlet stream requires extensive concentration to reach 99% purity. This is achieved through a combination of evaporation, distillation columns and a final dehydration step to overcome the 95/5 azeotrope of the ethanol/water solution. In the case of corn feedstocks, distiller's dried grains and solubles (DDGS) are obtained as by-products. This is a mix of soluble organic and inorganic compounds which can either be sold as fodder, be used as substrate for anaerobic digestion to biomethane (see corresponding section in this chapter) or for energy integration in the process.

Clearly, production of CO_2 negatively affects the carbon balance of the process. A possible solution is the integration of a carbon capture system, so that CO_2 is directly recovered at the outlet of the fermenter. The recovered CO_2 may be sold to local industries (i.e. beverages and food, enhanced oil recovery) or it may be injected for dedicated geologic carbon storage. The first option would raise the economic profitability of the plant, provided that the logistics is favorable and transportation costs are not too high, but has little impact on the overall carbon balance. Conversely, geologic carbon storage is probably the only option providing carbon negative use of CO_2, but the technology costs are not always lower than the social cost of carbon, which may hinder its deployment. In any case, the highest costs for the process are tied to the purification (i.e. rectification plus dehydration) of ethanol, which is an energy- and water-intensive process. In particular, the dehydration step - required to achieve 99.5% purity of ethanol - is critical and may limit the economic profitability of the plant. Traditionally membrane or entrained distillation were the most common technologies for this stage, but many plants in the US and the EU also apply molecular sieves with pressure swing operation, providing energy savings for the process.[41]

[41] F. Mueller-Langer, S. Majer, A. Perimenis, Biofuels: A Technical, Economic and Environmental Comparison, in: L.Y. Bronicki (Ed.), Renewable energy systems, Springer, New York, 2012, pp. 110–137.

Table 2.1 reports some average figures about three relevant feedstocks (sugarcane, corn and sugar beet). Although corn clearly stands out for ethanol conversion efficiency compared to sugar crops, it is also penalized by low biomass productivity. Sugar cane displays the highest yield thanks to the high biomass productivity. Moreover, it is estimated that the average production cost of bioethanol in the US is 0.51-0.58 USD per liter of gasoline equivalent (lge), with a break-even of 64-76 USD per barrel.[42] Hence, US bioethanol is not competitive with its fossil counterparts in domestic production, although policies support may play a relevant role in this respect. On the other hand, the production cost for Brazil bioethanol is estimated as 0.54-0.62 USD/lge, with a corresponding break-even of 50-60 USD per barrel[43], making the biofuel competitive with domestic gasoline production.

TABLE 2.1. Biomass productivity (as tons of dry solids per hectare), ethanol conversion and ethanol yield for some relevant feedstocks.

FEEDSTOCK	BIOMASS PRODUCTIVITY (TON DS. HA^{-1})	ETHANOL CONVERSION (L TON^{-1})	ETHANOL YIELD (M^3 HA^{-1})	REF.
Sugarcane	16–39	220–275	5.0–10.8	[44]
Corn	7.5–10	360–460	2.0–4.6	[45],[46],[47],[48]
Sugar beet	3–25	430–440	5.0–10	[49],[50],[51]

The obtained ethanol is generally used for blending with gasoline, according to quality standard ASTM D5798. The most common blending is E10 (10% of ethanol), but blending in the range 10.5-15% (E15) is also possible. Blending containing 50-85% of ethanol can be commercialized for use in flexible-fuel vehicles, which are designed to work properly with either gasoline, bioethanol or blending of variable amounts. Alternatively, the alcohol-to-jet process can be exploited to convert ethanol to drop-in jet fuel. In this process, ethanol is dehydrated and oligomerized (i.e. rearranged) into various hydrocarbons suitable for jet-fuel. The process was approved in 2016 according to ASTM D7566.

[42] IEA (2019), How competitive is biofuel production in Brazil and the United States?, IEA, Paris https://www.iea.org/articles/how-competitive-is-biofuel-production-in-brazil-and-the-united-states. Accessed November 2020.

[43] Ibid.

[44] FAO, The state of food and agriculture 2008: Prospects, risks and opportunities, Food and Agriculture Organization of the United Nations, Rome, 2008.

[45] Ibid.

[46] E. Close, A. Gnansounou, A. Dauriat, Ethanol fuel from biomass: a review, J Sci Ind Res, 64 (2005), pp. 809-821

[47] A. Bonomi, O. Cavallet, M.P. Cunha, M.A.P. da, Lima, Virtual biorefinery: an optimization strategy for renewable carbon valorization (1st ed), Springer (2015)

[48] Renewable Fuels Association (RFA). Pocket guide to ethanol. Washington; 2015

[49] FAO, The state of food and agriculture 2008: Prospects, risks and opportunities, Food and Agriculture Organization of the United Nations, Rome, 2008.

[50] M. Balat, H. Balat, C. Öz, Progress in bioethanol processing, Progress in Energy and Combustion Science 34 (2008) 551–573. https://doi.org/10.1016/j.pecs.2007.11.001.

[51] UNICA. Números finais da safra 2014/2015 e iniciais da nova safra 2015/2016. União Da Indústria Cana-de-Açúcar; 2016. Accessed July 2020.

2.2.2 Biodiesel from vegetable oils (FAME)

Biodiesel is the conventional expression to refer to a mixture of fatty acid methyl esters (FAME), using vegetable oils and animal fats as feedstocks. In the last years, its production has constantly increased, as it is currently the only viable alternative for diesel engines for heavy-duty transport. For instance, US biodiesel production increased from 343 million gal in 2010 to 1.278 billion gal in 2014, an increase of 272% during this 5-year period.[52] In 2019, biodiesel and HVO (see following section) production reached 48 billion L and a slight contraction of 5% is expected for 2020 due to pandemic crisis.[53] European Union is still the largest producer with a biodiesel and HVO output of 15.7 billion L in 2019. In second place the United States reported 8.4 billion L for the same year.[54] The production decline in 2020 is expected to be small for both countries as the demand for biodiesel did not drop as much as for gasoline.

Vegetable oils (VO), both edible and non-edible, are the typical feedstock for biodiesel production, while animal fats and recycled frying oils account for a minor share. The most common cultivations include rapeseed, soybean, and oil palm, but feedstock distribution is highly localized. Rapeseed is the most common feedstock in the EU and displays an oil content around 40% of dry weight. Soybean is the typical choice in the US and in Brazil, which are also the largest producer worldwide with capacities of more than 100 million metric tons in 2018/2019.[55] Compared to rapeseed, soybean has a lower content in oil (about 20%), but it provides Nitrogen to the soil and can thus be easily integrated in crop rotation systems with Nitrogen-intensive crops, like corn in the US. Instead, oil palms require tropical or subtropical environments and are very widespread in Malaysia and Indonesia. The oil content usually falls in the range 45-55%.

Vegetable oils are extracted from the crops either through mechanical pressing or solvent extraction, usually using hexane as an extracting agent. Mechanical extraction efficiency varies in the range 60-80% depending on the selected press.[56] Conversely, solvent extraction can easily reach 95-99% efficiency and it yields a purer oil compared to pressing, but regeneration of the solvent through distillation is required, making it an energy-intensive process.[57] The obtained crude oil is then refined to remove phosphorus compounds (*degumming* with citric/phosphoric acid) and free fatty acids (neutralization with KOH/NaOH), the latter precipitating as soap stocks.

In principle, the refined VO could be used directly as fuel for biodiesel engines, thus cutting down the production flow solely to the extraction and refining of the oils. However, the higher viscosity and lower volatility of VO compared to diesel as well as reactivity of fatty acids may result in several issues, including clogging of filters/injectors and build-up of deposits. Thus, conversion to fatty acids methyl esters (FAME) is preferred to the direct use of VO in diesel engines. VO are subjected to a catalyzed transesterification reaction in presence of methanol and a proper catalyst (e.g. methylates/hydroxides). The process is generally operated in the range 50-150°C for 30-180 min and it is exothermic (i.e. it releases energy during conversion). By properly tuning the operating

[52] Agricultural Marketing Resource Center. An Overview of the Biodiesel Market: Production, Imports, Feedstocks and Profitability. https://www.agmrc.org/renewable-energy/renewable-energy-climate-change-report/Renewable-energy-climate-change-report/march-2016-report/an-overview-of-the-biodiesel-market-production-imports-feedstocks-and-profitability. Accessed May 2020.

[53] International Energy Agency. (2020). Transport biofuels. In Renewables 2020: Analysis and forecast to 2025.

[54] Ibid.

[55] FAOSTAT, FAO Statistics Division: http://www.fao.org/faostat/en/#home. Accessed November 2020.

[56] W.M.J. Achten, L. Verchot, Y.J. Franken, E. Mathijs, V.P. Singh, R. Aerts, B. Muys, Jatropha bio-diesel production and use, Biomass and Bioenergy 32 (2008) 1063–1084. https://doi.org/10.1016/j.biombioe.2008.03.003.

[57] A.E. Atabani, A.S. Silitonga, I.A. Badruddin, T.M.I. Mahlia, H.H. Masjuki, S. Mekhilef, A comprehensive review on biodiesel as an alternative energy resource and its characteristics, Renewable and Sustainable Energy Reviews 16 (2012) 2070–2093. https://doi.org/10.1016/j.rser.2012.01.003.

conditions, yield in FAME can easily reach 90-95% and even higher values.[58] The main products are fatty acids methyl esters, which mainly differ from VO for their increased cetane number and reduced corrosivity. Along with FAME, glycerin is obtained as a by-product and is easily separated from the esters through gravity. It can be valorized for use in many industry sectors, such as thickening agents in cosmetics, food and paper. However, high level of purification is required, so that the economic profitability may vary greatly depending on the local market.

Owing to the wide variety of feedstocks, the resulting characteristics can vary substantially. Table 2.2 reports some estimates of oil productivity and biodiesel properties for different feedstocks. Palm oil stands out for oil productivity compared either to rapeseed or soybean. Also, it provides the highest cetane number, bearing in mind that average #2 Diesel display cetane number of around 50. However, the cloud point (i.e. behavior of the fuel at low temperature) is also a key parameter, as it strongly affects biodiesel application in colder climates and especially for aviation. This is particularly relevant considering the great difficulty in implementing electrification in the air transport segment. In this respect, rapeseed oils provide biodiesel with a lower cloud point compared to the other feedstocks, which makes it also viable for colder climates. Still further upgrading for use in aviation sector is needed, considering that winter Diesels provide a cloud point between -30 and -20 °C. On the other hand, palm oil use may be restricted to low fraction in blending due to its high cloud point (i.e. poor behavior at low temperature).

TABLE 2.2. Oil productivity, cetane number and cloud point according to different feedstocks.

VARIABLE	OIL PRODUCTIVITY ($L\ HA^{-1}\ Y^{-1}$)	CETANE NUMBER (-)	CLOUD POINT (°C)
Rapeseed	1190[59]	55[60]	-3.3[61]
Soybean	446[62]	49[63]	1.0[64]
Palm oil	5950[65]	61[66]	13.0[67]

[58] M. Athar, S. Zaidi, A review of the feedstocks, catalysts, and intensification techniques for sustainable biodiesel production, Journal of Environmental Chemical Engineering 8 (2020) 104523. https://doi.org/10.1016/j.jece.2020.104523; S. Dey, N.M. Reang, P.K. Das, M. Deb, A comprehensive study on prospects of economy, environment, and efficiency of palm oil biodiesel as a renewable fuel, Journal of Cleaner Production (2020) 124981. https://doi.org/10.1016/j.jclepro.2020.124981.

[59] A.E. Atabani, A.S. Silitonga, I.A. Badruddin, T.M.I. Mahlia, H.H. Masjuki, S. Mekhilef, A comprehensive review on biodiesel as an alternative energy resource and its characteristics, Renewable and Sustainable Energy Reviews 16 (2012) 2070–2093. https://doi.org/10.1016/j.rser.2012.01.003.

[60] M. Athar, S. Zaidi, A review of the feedstocks, catalysts, and intensification techniques for sustainable biodiesel production, Journal of Environmental Chemical Engineering 8 (2020) 104523. https://doi.org/10.1016/j.jece.2020.104523.

[61] M.J. Ramos, C.M. Fernández, A. Casas, L. Rodríguez, A. Pérez, Influence of fatty acid composition of raw materials on biodiesel properties, Bioresour. Technol. 100 (2009) 261–268. https://doi.org/10.1016/j.biortech.2008.06.039.

[62] A.E. Atabani, A.S. Silitonga, I.A. Badruddin, T.M.I. Mahlia, H.H. Masjuki, S. Mekhilef, A comprehensive review on biodiesel as an alternative energy resource and its characteristics, Renewable and Sustainable Energy Reviews 16 (2012) 2070–2093. https://doi.org/10.1016/j.rser.2012.01.003.

[63] M. Athar, S. Zaidi, A review of the feedstocks, catalysts, and intensification techniques for sustainable biodiesel production, Journal of Environmental Chemical Engineering 8 (2020) 104523. https://doi.org/10.1016/j.jece.2020.104523.

[64] M.J. Ramos, C.M. Fernández, A. Casas, L. Rodríguez, A. Pérez, Influence of fatty acid composition of raw materials on biodiesel properties, Bioresour. Technol. 100 (2009) 261–268. https://doi.org/10.1016/j.biortech.2008.06.039.

[65] A.E. Atabani, et al., A comprehensive review on biodiesel.

[66] M. Athar, S. Zaidi, A review of the feedstocks.

[67] M.J. Ramos, et al., Influence of fatty acid composition.

Table 2.3 reports volume potential and estimations of biodiesel production cost for 10 different countries, as retrieved by Johnston and Holloway (2007). The variation in costs between countries is strongly affected by feedstock price, as the cost of raw oil may account for 60–80% of the total price of biodiesel production.[68] More recently, IEA reported average production cost of biodiesel for US and Brazil of respectively 0.76-0.86 and 0.73-0.98 USD per liter of diesel equivalent (lde), which corresponds to break-even of 104-120 and 81-120 USD per barrel.[69] Thus, the cost of biodiesel was not competitive with fossil counterparts in either country, which was mainly due to soybean oil costs being almost three times higher than average crude oil prices in the same year. Moreover, the cost of biodiesel in both countries was generally higher than for ethanol.[70]

TABLE 2.3. Volume potential and production cost of biodiesel for 10 selected countries.[71]

COUNTRY	VOLUME POTENTIAL (MILLION L)	PRODUCTION COST (USD L^{-1})
Malaysia	14,540	0.53
Indonesia	7,595	0.49
Argentina	5,255	0.62
USA	3,212	0.70
Brazil	2,567	0.62
Netherlands	2,496	0.75
Germany	2,024	0.79
Philippines	1,234	0.53
Belgium	1,213	0.78
Spain	1,073	1.71

Biodiesel can either be used directly as a fuel for diesel engines or it can be blended with fossil fuels before end-use, according to quality standards EN 14214 and ASTM D6751. A blending up to 20% by volume (B20) is generally considered an acceptable compromise for proper functioning of the engine without significant modification and similar performance compared to fossil fuel. Conversely, pure biodiesel usage (B100) should account for the lower energy content per unit volume compared to fossil diesel. Moreover, biodiesel may dissolve residues from fossil fuels deposited inside the engine, which are released causing clogging issues. Biodiesel was also reported to increase NO_x emissions, but other pollutants emissions were decreased instead. In fact, an assessment of North

[68] A.E. Atabani, et al., A comprehensive review on biodiesel.

[69] IEA (2019), How competitive is biofuel production in Brazil and the United States?. https://www.iea.org/articles/how-competitive-is-biofuel-production-in-brazil-and-the-united-states. Accessed November 2020.

[70] Ibid.

[71] M. Johnston, T. Holloway, A global comparison of national biodiesel production potentials, Environ. Sci. Technol. 41 (2007) 7967–7973. https://doi.org/10.1021/es062459k.

American heavy-duty engine emissions from common biodiesel blend (B20) highlighted a reduction of particulate matter, hydrocarbons, and carbon monoxide by 10-20% compared to emissions from fossil diesel.[72]

2.2.3 Hydrotreating of vegetable oils (HVO/HEFA)

Hydrotreating is an alternative process to FAME, exploiting essentially the same feedstocks as transesterification (vegetable oils and/or animal fats). Oils and fats are subjected to catalytic saturation of double bonds and oxygen removal. The hydrotreating output is a mix of linear alkanes, usually referred to as hydroprocessed esters and fatty acids (HEFA). If plant oils are exploited as feedstock, the obtained biofuel is commonly indicated as hydrogenated vegetable oils (HVO). HEFA/HVO display some significant advantages compared to FAME, namely improved stability and low temperature behavior, making it a worthy candidate not only for biodiesel application, but also as a jet-fuel for aviation.

The process is conducted at high pressure (50-150 bar) and temperature in the range 300-450 °C and it is an exothermic process (i.e. energy is released during reaction). VO are converted to straight-chain alkanes and propane, while CO_2 and water are obtained as side-products. The main process of saturation is often coupled with hydrocracking and isomerization (i.e. breaking and rearrangement of hydrocarbons chains), further boosting low temperature behavior of HVO, so that the resulting biofuel is often referred to as "iso-HVO". The yield is generally in the range 60-80%[73], but it can approach or even surpass 90% by proper selection of catalyst and operating conditions.[74] The obtained HEFA/HVO display lower viscosity compared to both diesel and biodiesel, cloud point between -10 and -30°C and high cetane number in the range 85-100 – in fact, HEFA/HVO are also known as "super cetane" for this reason.[75] The main side-product is propane, which is more valuable compared to FAME glycerin.

The layout and operating conditions of biomass hydrotreating do not differ significantly from those employed in the petroleum industry for diesel/jet-fuel cuts. This is a great advantage compared to other biofuel technologies as it significantly lowers the risk connected to the process deployment. Moreover, revamping of decommissioned plants as well as VO hydroprocessing in the same reactor with fossil cuts (*co-feeding*) are possible with minor adjustments, easing integration and transition to bio-based production. Clearly, care must be taken in the possible presence of inhibitors/poisons for the catalyst, as the composition of biomasses is significantly different from the fossil feed to the hydrotreater.

Notable examples of HVO production are already available at the commercial scale, such as Neste in Rotterdam and Singapore (1.28 billion liters per year each), World Energy in California (150 million liters per year) and Diamond Green Diesel in Louisiana (1.04 billion liters per year). ENI plant in Venice (Italy) is the first case of repurposing of a disused refinery plant for the production of HVO. The facility ensures a yearly production of 462

[72] Yanowitz, Janet, and Robert L. McCormick. 2009. Effect of biodiesel blends on North American heavy-duty diesel engine emissions. *European Journal of Lipid Science and Technology* 111 (8): 763–772. doi: 10.1002/ejlt.200800245.

[73] C.J. Chuck (Ed.), Biofuels for aviation: Feedstocks, technology and implementation, Academic Press is an imprint of Elsevier, Amsterdam, 2016.

[74] M.C. Vásquez, E.E. Silva, E.F. Castillo, Hydrotreatment of vegetable oils: A review of the technologies and its developments for jet biofuel production, Biomass and Bioenergy 105 (2017) 197–206.

[75] S.-Y. No, Application of hydrotreated vegetable oil from triglyceride based biomass to CI engines – A review, Fuel 115 (2014) 88–96. https://doi.org/10.1016/j.fuel.2013.07.001.

million liters of HVO from vegetable oils, exploiting a patented hydrotreating technology known as Ecofining™ (ENI/UOP).[76] Other notable cases of reconversion of former refineries to hydro-processing of bio-oils are Total La Mede (France) (Total SA) and Marathon Petroleum Corp.[77]

According to IEA, HVO represents the only route to date that has been able to deliver commercially meaningful amounts of drop-in biofuels and these feedstocks are the main source of the bio-jet fuels that are currently used in aviation.[78] This is especially true considering that electrification of the aviation segment will require significant effort and time. Additionally, HVO can be also blended with diesel in different amounts, usually 30-50% v/v. It is worth noticing that the addition of HVO is not reducing the fuel performances, but the other way around, and that HVO can also be exploited directly as a drop-in biofuel (according to quality standard EN 15940). These superior characteristics of HVO are boosting its market share. In 2018 the overall HVO production was 5.5 billion L, but it is expected to more than double in 2024, reaching almost 13 billion L.[79]

As for FAME, the main cost for HEFA/HVO production is still the feedstock price, which accounts for 60–75% of the final product cost.[80] In addition, hydrogen supply is required for the treatment. This is not an issue when performing *co-feeding*, as hydrogen is available in refineries from catalytic reforming. However, this is not the case for revamped or fully bio-based plants. Different approaches are available in this case for hydrogen supply. It could be produced directly from a minor share of the feedstock, but this is usually not very beneficial considering that the hydrogen amount in biomass is very limited (always less than 10%). Alternatively, green hydrogen from electrochemical split of water is possible, if access to a viable water source is available. The strategy for hydrogen supply will strongly depend on local constraints in terms of hydrogen price and water/feedstock availability. As a consequence, profitability of HVO processes will also be related to regional context. As a general rule, though, HVO may have lower production costs (especially in terms of capital investments) compared to FAME for the same feedstock.[81]

2.2.4 Crops digestion to biogas

When proper conditions are provided, agricultural crops can be broken down by microorganisms and converted to a gaseous mix of methane, CO_2, and minor impurities. Such biochemical conversion, known as digestion, occurs naturally in anaerobic conditions (i.e. without oxygen) and it has long been exploited for the stabilization of organic residues. The output of the process is usually referred to as biogas. In 2018, biogas and biomethane production was around 35 million tonnes of oil equivalent (Mtoe), with the EU as the leading producer with a capacity of nearly 20 Mtoe.[82] Digestion currently accounts for about 90% of the worldwide biomethane production.[83] However, agricultural crops are strongly localized in the EU, where agricultural crops and crop

[76] ENI. Ecofining. https://www.eni.com/it-IT/attivita/biocarburanti-sostenibili-ecofining-tm.html. Accessed 5 July 2020.

[77] Total SA. La Mède: a facility for the energies of tomorrow. https://www.total.com/energy-expertise/projects/bioenergies/la-mede-a-forward-looking-facility. Accessed 5 July 2020.; Marathon Petroleum Corporation. Dickinson Refinery. https://www.marathonpetroleum.com/Operations/Refining/Dickinson-Refinery/. Accessed 5 July 2020.

[78] IEA Bioenergy Task 39, "The potential and challenges of drop-in biofuels: The key role that co-processing will play in its production".

[79] International Energy Agency. (2019). Transport biofuels. In Renewables 2019: Analysis and forecast to 2024.

[80] M.C. Vásquez, E.E. Silva, E.F. Castillo, Hydrotreatment of vegetable oils: A review of the technologies and its developments for jet biofuel production, Biomass and Bioenergy 105 (2017) 197–206.

[81] K. Sunde, A. Brekke, B. Solberg, Environmental Impacts and Costs of Hydrotreated Vegetable Oils, Transesterified Lipids and Woody BTL—A Review, Energies 4 (2011) 845–877. https://doi.org/10.3390/en4060845.

[82] IEA 2020, "Outlook for biogas and biomethane: prospects for organic growth".

[83] Ibid.

residues make up almost half of biogas production. This is not true for the US and China, where most of the biogas production comes respectively from municipal solid wastes and from animal manure.[84]

Many varieties of grass, sugar and oily crops, cereals, and corn (including whole plants) are viable for biogas production. An ideal feedstock for digestion should have dry solids content of 20-40%. The process can be operated on wet, pasty biomasses, thus removing the need for extensive drying and lowering the operating costs, but processing of dry biomasses (e.g. grains from cereals) is also possible. As such, the feedstock can be exploited right after harvesting of the plant. Alternatively, it can be stored in silage clamps or baled, which is quite typical for grass feedstocks, with capacity of 10,000 tons of silage for a medium-size plant.[85] Integration with other biofuel production routes (fermentation/FAME) is also possible to increase flexibility.

Although the process occurs naturally, it is usually conducted in controlled conditions, namely in the so-called digesters, to maximize the biomethane yield. Reactor are operated either in the 20-45°C range (mesophilic) or between 50 and 65°C (thermophilic)[86] Mesophilic conditions provide higher stability against load variations or inhibitors, but they also yield lower biogas (and thus biomethane) compared to the thermophilic region.[87] Hence, thermophilic conditions are preferred to mesophilic ones for large-scale centralized units in order to maximize the biogas yield. Depending on the feedstock, biogas in the output varies in the range 50-70% v/v. The remaining share is almost completely made by carbon dioxide. Table 2.4 reports the crop yields and calculated biogas yield for digestion of different crop feedstocks. corn is the preferred choice in the EU due to its high yields.

TABLE 2.4. Biomass productivity (as tons of dry solids per hectare) and methane yield for some relevant feedstocks.[88]

FEEDSTOCK	CROP YIELD (TON DS. HA^{-1})	METHANE YIELD (M^3 HA^{-1})
Corn (whole crop)	9 – 30	1,660 – 12,150
Wheat (grain)	3.6 – 11.75	1,244 – 4,505
Barley	3.6 – 4.1	1,144 – 2,428
Sorghum	8 – 25	2,124 – 8,370
Grass	10 – 15	2,682 – 6,305
Oilseed rape	2.5 – 7.8	540 – 2,387
Sunflower	6 – 8	832 – 2,880
Sugar beet	9.2 – 18.4	1954 – 6309

[84] Ibid.

[85] IEA 2011, Technology for anaerobic digestion of crops in *Bioenergy Task 37 :Biogas from crop digestion*.

[86] Kothari, Richa, A. K. Pandey, S. Kumar, V. V. Tyagi, and S. K. Tyagi. 2014. Different aspects of dry anaerobic digestion for bio-energy: An overview. *Renewable and Sustainable Energy Reviews* 39:174–195. doi: 10.1016/j.rser.2014.07.011.

[87] Gupta, Priyanka, Raj Shekhar Singh, Ashish Sachan, Ambarish S. Vidyarthi, and Asha Gupta. 2012. A re-appraisal on intensification of biogas production. *Renewable and Sustainable Energy Reviews* 16 (7): 4908–4916. doi: 10.1016/j.rser.2012.05.005.

[88] IEA 2011, Significance and potential of crop digestion in *Bioenergy Task 37: Biogas from crop digestion*.

Carbon dioxide makes a large share of the biogas stream and it must be removed to achieve a sufficient biomethane purity (above 95%) to feed it to the grid. Upgrading technologies exploit the different properties of the biogas components to separate them, with water scrubbing and membrane separation accounting for almost 60% of biomethane production globally today.[89] The captured CO_2 can either be stored or sold to local industries (i.e. beverages and food, enhanced oil recovery), depending on the local market and logistics. Alternatively, carbon dioxide can be converted to methane, thus raising the overall biomethane yield of the plant. This is possible through methanation, which is a catalyzed reaction conducted at high temperature (300-400 °C) in presence of Fe or Ni catalysts. However, great care must be taken in the presence of trace contaminants, which may poison the methanation catalysts. This include ammonia, H_2S, and other Sulfur-derived species, which may be found in the biogas stream depending on the feedstock. As a result, further purification of the biogas is required, thus raising the energy and operating costs of the process.

The obtained biomethane can be fed to the natural gas grid or used as a drop-in biofuel for transport. As the technology for anaerobic digestion has been long exploited, its commercial deployment is less critical compared to other technologies. In 2018 the estimated average costs of biogas production in centralized small- (100 m3 h^{-1}), medium- (250 m3 h^{-1}), and large-scale (750 m3 h^{-1}) digesters were respectively about 57 USD/MWh, 44 USD/MWh and 32 USD/MWh.[90] Clearly, larger capacities result in reduced capital investments and especially reduced operating costs, but the regional context, especially logistics, also plays a relevant role. Indeed, the costs related to handling and transportation of the feedstock may be critical, in particular when the local infrastructure is poor. This will not only result in increased overall costs for the plant, but it will also negatively affect the carbon balance of the process, as trucks or other heavy-duty vehicles will be engaged for the biomass transportation for local retailers to the centralized facility.

2.3 Advanced Biofuels: feedstocks

This section deals with advanced technologies for the conversion of a vast group of 2G and 3G biomass into biofuels. This large ensemble of processes shares the ambition to overcome the main issue of 1G biofuels, that is to say the competition with food. New 2G feedstocks are thus mobilized, based on agri-food residues, lignocellulosic crops and municipal/industrial wastes. Additionally, 3G feedstocks based on algae cultivations have recently attracted attention thanks to their ability to flourish on poor/unsuitable land or water, thus reducing greatly the land usage, and their great flexibility.

2.3.1 Forest and wood-processing residues

This class refers to all raw materials generated from forests management (forestry residues) as well as from the wood-processing industries. Forestry residues are usually left on the ground during management operations. This includes several varieties of grass and fast-growing trees, which are high yield raw materials. The low bulk density of these feedstocks can be a strong constraint for their valorization, as it may raise significantly handling and transportation costs. This can be avoided through the deployment of small facilities next to the collection sites (e.g. skid plant or small digesters), thus cutting transportation costs. Alternatively grinding and palletization is

[89] Cedigaz (2019). Global biomethane market: Green gas goes global (press release, 20 March). https://www.cedigaz.org/global-biomethane-market-green-gas-goes-global/.

[90] IEA 2020, “Outlook for biogas and biomethane: prospects for organic growth”.

possible to ease handling and transportation of the biomass. Clearly the choice will strongly depend on the local context, namely the availability of infrastructure.

A possible application of forestry residues is the biochemical conversion to ethanol, but the high content of lignin requires dedicated mechanical or chemical pre-treatments. These treatments depend on the type of biomass (i.e. the relative content of lignin) but they significantly contribute to the overall costs of operation. Typically, hardwood species like birch or acacia contain more degradable lignin components compared to softwoods like pine or whitewood. Provided this demanding pre-treatment, the thermochemical treatment of the feedstock (see corresponding section) may be preferable for the economic profitability of the process, also due to its higher flexibility.

Wood-processing waste from the lumber industry and paper processing usually do not require pre-treatment for their handling. As for forestry residues, conversion of lumber and paper industry wastes to ethanol is partially hindered by the recalcitrant nature of the substrate. Again, it may be more attractive to pursue the thermochemical route, to convert such feedstocks to either char, bio-oil or syngas. In particular, pulp black liquor from the paper industry can be effectively subjected to hydrothermal liquefaction (see corresponding section) to produce bio-oil for marine and road applications. Alternatively, it can be gasified to produce synthetic fuels or biogas.

2.3.2 Agricultural residues

Agricultural residues include a wide variety of wastes from agricultural crop harvesting, coming in the form of leaves, seed, pods, straw, and stalks. They are often left on the ground and remain unused due to the high costs of recovery and transportation. In rural areas crop residues are used either as animal feed or fuel for cooking or they can be exploited as natural fertilizer for the fields once burned to ashes.[91]

An example of this is India, where commonly rice straw is either burned or exploited as fuel for brick industry or domestic uses. Open-field burning of crop residues is an easy solution for farmers for clearing the fields from uncollected residues, but it contributes to GHG emissions substantially. It has been estimated that in 2016 the US, Brazil, China, and India altogether burned 181.8 MT of crop wastes (including rice, wheat, corn, and sugarcane residues), resulting in 15.8 MT of CO_2 emissions.[92] Moreover, burning of the residues is also negatively affecting the soil health due to destruction of microbes and loss of nutrients. Depending on the type of waste, agricultural residues fit into a wide range of applications. Wet biomasses and many crop residues can be converted to biogas through digestion. Lignocellulosic residues with sufficient sugar and/or starch contents, like corn cobs, may undergo hydrolysis and be subsequently fermented to 2G bioethanol. Oleaginous residues from oil crops can be refined/grounded to obtain vegetable oils, which can be used to produce biodiesel via transesterification and/or HVO through hydrotreating.

[91] Prasad, S., Mahesh K. Malav, S. Kumar, Anoop Singh, Deepak Pant, and S. Radhakrishnan. 2018. Enhancement of bio-ethanol production potential of wheat straw by reducing furfural and 5-hydroxymethylfurfural (HMF). *Bioresource Technology Reports* 4:50–56. doi: 10.1016/j.biteb.2018.09.007.

[92] Deshavath, Narendra Naik, Venkata Dasu Veeranki, and Vaibhav V. Goud. 2019. Lignocellulosic feedstocks for the production of bioethanol: availability, structure, and composition. In *Sustainable bioenergy: Advances and impacts*, ed. Mahendra Rai and Avinash P. Ingle, 1–19. Amsterdam, Netherlands, Cambridge, MA: Elsevier.

The production of crops residues is constantly increasing globally. Cherubin et al. estimated the production of crop residues in four regions (USA, Asia, Africa and Europe) from different crops (cereals, legumes, oilseed, sugar and tubers) in the year 2003 and 2013.[93] Comparing the grand total, world residues increased from 3803 MT in 2003 to 5011 MT in 2013, corresponding to a net increase of 31.7%. Moreover, a study by Hiloidhari et al. estimated that a total dry biomass from 26 different crops in India of 686 MT, of which 34% (234 MT) is not exploited for competing uses (cooking, heating, fertilizer, etc.) and is available as feedstock for bioenergy.[94]

When dealing with agricultural residues, one should always bear in mind that for most processes the raw materials will require pre-treatment before biofuel production. This will in turn affect the biofuel production cost, especially for energy-intensive processes like bioethanol production. Moreover, the generally low bulk density of such feedstocks result in increased handling and transportation costs. This limit is partially overcome through palletization and briquetting, but it may play a crucial role in the profitability of the technology, especially in regions where poor infrastructure is available. Finally, excessive harvesting of the leftovers may negatively affect the soil balance, depending on the considered residues.

2.3.3 Industrial and municipal wastes

A huge variety of wastes can be recovered from industrial processes. Apart from crop residues, the food sector accounts for wastes produced along the entire food processing supply chain. This includes residues from food processing itself, like peel or zests, but also products discarded as they are not meeting quality requirements. Moreover, significant amounts of uneaten food are discarded by restaurants, hotels and private homes without exploitation. It is estimated that roughly one-third of the processed food is lost along the supply chain. This is a huge reservoir of unused biomass, which could be easily exploited for a wide range of applications. For instance, digestion of food residues to produce biogas is possible. Discarded oil seeds, used cooking oil (UCO) and animal fats represents an attractive feedstock for conversion to FAME/HVO. The UCO market for HVO production is expanding rapidly, especially in European countries and in the US, due to the fuel's superior characteristics.

Wastewaters are also generated during vegetables, fruit, and meat washing. These effluents are rich in solid and dispersed organic matter and could be sent directly to digestion to produce biogas. At the same, washing wastewaters might be also mobilized for fermentation to bioethanol if the sugar or starch content is sufficiently high, although high processing costs are expected for the concentration of the product. Moreover, the oil fraction commonly separated during wastewater pre-treatments could again be valorized through transesterification to FAME or hydrotreating to HVO/HEVA.

Municipal wastes come in two main forms. Municipal solid waste (MSW) are generally disposed of in open landfill, where biogas is naturally generated due to decomposition of the wastes. Such gas can be recovered and purified to be fed in the natural gas grid. MSW could be treated in a digester to increase the yield of biomethane during

[93] Cherubin, Maurício Roberto, Dener Márcio da Silva Oliveira, Brigitte Josefine Feigl, Laisa Gouveia Pimentel, Izaias Pinheiro Lisboa, Maria Regina Gmach, Letícia Leal Varanda, Maristela Calvente Morais, Lucas Santos Satiro, Gustavo Vicentini Popin, Sílvia Rodrigues de Paiva, Arthur Klebson Belarmino dos Santos, Ana Luisa Soares de Vasconcelos, Paul Lineker Amaral de Melo, Carlos Eduardo Pellegrino Cerri, and Carlos Clemente Cerri. 2018. Crop residue harvest for bioenergy production and its implications on soil functioning and plant growth: A review. *Scientia Agricola* 75 (3): 255–272. doi: 10.1590/1678-992X-2016-0459.

[94] Hiloidhari, Moonmoon, Dhiman Das, and D. C. Baruah. 2014. Bioenergy potential from crop residue biomass in India. *Renewable and Sustainable Energy Reviews* 32:504–512. doi: 10.1016/j.rser.2014.01.025.

anaerobic decomposition. Also, the organic fraction of MSW can be exploited for the production of bio-oil through hydrothermal liquefaction or synthetic fuels through gasification and chemical conversion of syngas. Another relevant residue from municipality is sewage, which is still eligible for digestion to biogas. The sludge resulting at the end of digestion could be incinerated to produce power – although increased processing costs are expected for drying e stabilization –, but pyrolysis is also an option to produce even more biogas from the same raw material.

2.3.4 Algae as a new feedstock

With the term algae we refer to a broad group of autotrophic organisms, which can be coarsely divided into "macroalgae", including larger species like kelps, and "microalgae", referring to both smaller species and cyanobacteria, a different prokaryotic species. Algae are conventionally classified as a separate, third generation group of biomasses owing to some specific features. They are not in competition with food as for 2G feedstocks, but they are also characterized by fast growing rate, high lipid content and more accessible carbon source compared to lignocellulosic materials. Most algae typically flourish in aquatic environments, but there are also some terrestrial species, which are still fitting to grow in non-arable lands.

Algae are able to produce biomass using CO_2 as a carbon source through photo-biochemical processes. Such conversion is performed at a faster rate compared to terrestrial plants: roughly 2 g of CO_2 are required per gram of generated biomass.[95] Lipids stored inside algae are no different from many plant lipids, except for a consistent amount of fatty acid components with higher degrees of unsaturation, and their amount can be increased by putting the algae culture under nutrients (e.g. Nitrogen) stress.[96] Selection of the best strains is a crucial point for the feasibility of the process. As estimated, there are one to ten million microalgal species on the Earth and more than 40,000 species have been identified.[97] The preferred strains will display high lipid content and fast growth rate.

2.4 Advanced Biofuels: technologies

Such feedstocks can be exploited according to three different platforms. The biochemical platform, featuring the conversion of lignocellulosic biomass to ethanol via fermentation. The oleochemical platform, where FOG (fats, oils and grease), microbial oils and algae oils are converted to FAME or HVO/HEFA. Finally, the thermochemical platform entails the conversion of different 2G/3G biomasses to syngas through thermochemical treatments and then to different fuel and chemicals, including methanol, MTBE, synthetic Fischer-Tropsch fuels. In 2018 all these novel technologies accounted only for 9% of biofuel production, corresponding to 13.5 billion L.[98] This limited share is mainly due to the low maturity and poor know-how of most advanced technologies, resulting in increased production costs and high risk for the deployment at the commercial scale. Moreover, the majority of such biofuels (12 billion L) came from hydrotreating of 2G feedstocks to jet-fuel, while lignocellulosic ethanol and thermochemical processes only accounted for 1% of the global biofuel production.[99]

[95] Pienkos, Philip T., and Al Darzins. 2009. The promise and challenges of microalgal-derived biofuels. *Biofuels, Bioproducts and Biorefining* 3 (4): 431–440. doi: 10.1002/bbb.159.

[96] Hu, Qiang, Milton Sommerfeld, Eric Jarvis, Maria Ghirardi, Matthew Posewitz, Michael Seibert, and Al Darzins. 2008. Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances. *The Plant journal : for cell and molecular biology* 54 (4): 621–639. doi: 10.1111/j.1365-313X.2008.03492.x.

[97] Wang, Bei. 2010. *Microalgae for biofuel production and CO2 sequestration.* Hauppauge N.Y.: Nova Science Publishers.

[98] International Energy Agency. (2019). Transport biofuels. In *Renewables 2019: Analysis and forecast to 2024*.

[99] Ibid.

2.4.1 Cellulosic Bioethanol

Many lignocellulosic feedstocks from the agri-food industry can be exploited for advanced fermentation. This includes woody and fast-growth plants, whose main components are lignin, hemicellulose and cellulose. The latter is usually the major component in lignocellulosic biomass and it is the main carbon source for biochemical conversion. However, due to the refractory nature of the feedstock, fermentation of the raw feedstock is not possible, as lignin and lignocellulosic fractions have an inhibitory effect on the yeasts.

As a result, pre-treatment of the biomass is required to make sugars available for conversion. This is recognized as the most crucial step and the main challenge for technology implementation. The complex lignocellulose structure must be break-down to make cellulose and hemicellulose available for the fermentative step and allow lignin removal. Several chemical and mechanical solutions are available, such as dilute acids, ammonia extraction and steam explosion, but there is no consensus on a preferred technology. The removal efficiency can vary widely in the range 30-75%.[100] Moreover, most of these processes are conducted in harsh conditions (high temperature or pressure) and they usually make up for 30-40 % of the total cost of the process.[101] Lignin is broken-down to smaller, soluble fragments, which can be removed. However, care must be taken in the possible production of lignin-derived inhibitors, including some aldehydes, weak organic acids and phenolic compounds, which can hinder the fermentative process.[102]

The biomass is then subjected to enzymatic hydrolysis. This stage is more demanding compared to 1G starchy crops, mainly due to the complexity and variety of hemicellulose structure, and a large ensemble of enzymes is exploited to convert long-chain polymers to simple monomeric sugars, namely glucose from cellulose and hexose/pentose (e.g. xylose) from hemicellulose. The main side-product up to this point is lignin, which can be valorized for polyester production or it could be converted to liquid biofuels through thermochemical processes (see corresponding section). Finally, the biomass is converted to bioethanol. The most common yeasts for ethanol production (i.e. *S. Cerevisiae*) are not very effective in converting pentose. This may significantly reduce the process yield, as pentose often makes up a large share of the biomass, especially feedstocks rich in hemicellulose. Microbial engineering is a possible way to increase both the yeast ability to degrade pentose and its tolerance to ethanol and lignin. However, such approaches are still far from maturity and further research is required. As for 1G bioethanol, extensive concentration of the product is required through evaporation, distillation, and dehydration. Again, this is the most energy-intensive stage of the process, raising greatly the operating costs and reducing its profitability.

Table 2.5 reports some illustrative figures for biomass productivity and ethanol yield for different 2G feedstocks. Agri-food residues and woody feedstocks display great potential thanks to their relatively high yield. In the case of sugarcane bagasse, a side-product of either sugar industry or 1G ethanol plants, integration with conventional biofuel plants is also possible. In this way, side-products like cellulose could be used for supplying thermal energy for the main conversion. Clearly, this also entails investments for the additional pre-treatment stages and

[100] S. Vieira, M.V. Barros, A.C.N. Sydney, C.M. Piekarski, A.C. de Francisco, L.P.d.S. Vandenberghe, E.B. Sydney, Sustainability of sugarcane lignocellulosic biomass pretreatment for the production of bioethanol, Bioresour. Technol. 299 (2020) 122635. https://doi.org/10.1016/j.biortech.2019.122635.

[101] Soetaert, Wim, and Erick J. Vandamme. Ü2009. *Biofuels.* Hoboken, N.J: Wiley.

[102] E. Palmqvist, B. Hahn-Hägerdal, Fermentation of lignocellulosic hydrolysates. II: inhibitors and mechanisms of inhibition, Bioresour. Technol. 74 (2000) 25–33. https://doi.org/10.1016/S0960-8524(99)00161-3.

adapting the microbial consortium. Another approach to reduce capital investments for advanced bioethanol is conducting simultaneous saccharification and fermentation (SSF), thus cutting the costs related to the two separate units. Still, the production costs for 2G bioethanol are rather high and cannot compete with conventional fuels. For instance, production costs of lignocellulosic ethanol from softwood in the US were estimated as 0.90 USD/L, almost twice the average costs for US corn or Brazil sugarcane ethanol.

TABLE 2.5. Biomass productivity (as tons of dry solids per hectare per year) and ethanol yield for some relevant 2G feedstocks.[103]

FEEDSTOCK	BIOMASS PRODUCTIVITY (TON DS. HA^{-1} Y^{-1})	ETHANOL YIELD (M^3 HA^{-1})
Corn stover	3	0.9
Sugarcane bagasse	10	3
Miscanthus	15-40	4.6-12.4
Poplar	5-11	1.5-3.4
***Agave* spp.**	10-34	3-10.5

Nonetheless, some industrial solutions for advanced bioethanol production are already available. Cellulosic bioethanol started to be commercialized in January 2013 by Beta Renewables in Crescentino (Italy), producing 40,000 tons of ethanol per year.[104] Other notable application of lignocellulosic ethanol at an industrial scale include DuPont (Nevada, Iowa, USA), Abengoa (Hungton, Kansas, USA), and Poet/DSM (Emmetsburg, Iowa, USA), with capacity in the range 90-113 million liters per year. However, lignocellulosic ethanol is still a risky and demanding market, also considering the fierce competition of cheap gasoline and/or corn ethanol. Both Abeongoa and DuPont plants have been closed and sold - the latter in 2018 to the German company VerBio, to be used for the production of biogas -, while Poet/DSM has been operating at reduced capacity for many years and has reverted to R&D to improve process efficiency. Moreover, these ventures accounted for a minimal share in global biofuel production. In fact, in 2018 lignocellulosic bioethanol and thermochemical processes (see corresponding section) only accounted for 1% of global biofuel production (1.4 billion L).[105]

In addition, some varieties of sugarcane were genetically modified to improve productivity and resilience (energy cane). Such crops display the ability to effectively grow in areas not suited for sugar cane cultivation, thus reducing

[103] C. Somerville, H. Youngs, C. Taylor, S.C. Davis, S.P. Long, Feedstocks for lignocellulosic biofuels, Science 329 (2010) 790–792. https://doi.org/10.1126/science.1189268.

[104] Balan, Venkatesh, David Chiaramonti, and Sandeep Kumar. 2013. Review of US and EU initiatives toward development, demonstration, and commercialization of lignocellulosic biofuels. *Biofuels, Bioproducts and Biorefining* 7 (6): 732–759. doi: 10.1002/bbb.1436.

[105] IEA. (2019). Transport biofuels. In Renewables 2019: Analysis and forecast to 2024.

competition with food and exploiting degraded/unused lands. Examples of energy canes are EunergyCane by Alkol Biotech and Cana Vertix by GranBio[106], which are effectively exploited for cellulosic ethanol production.

2.4.2 Advanced bio-oils

Algae are a rich source of lipids, which can be recovered (typically via hexane extraction) and exploited for transesterification to FAME and/or hydrotreated to drop-in HVO. At the same time, the high content of sugars in the residual biomass makes it viable for conversion to bioethanol. Also, the remaining feedstock can be exploited for anaerobic digestion to biogas.

Thus, algae make a rather versatile feedstock for biofuel production. However, their industrial scalability is currently hampered by the energy demands related to both cultivation and harvesting phases. Farming can be achieved both in open ponds and dedicated bioreactors. Open ponds are attractive because they are cheap and easy to operate, but they require large extensions of land and provide lower productivity. Thus, the application of open ponds should be considered in regions where there is high availability of land and limited or no competition with arable lands.[107] On the other hand, bioreactors can achieve higher cultivation density (e.g. vertical columns layout) and higher productivity, but both capital and operational costs are substantially increased due to the complexity of the configuration.

Moreover, the harvesting and dewatering of the biomass are recognized as the major bottleneck, especially for microalgae systems where they account for 20-30% of the total production costs.[108] Macroalgae harvesting is generally based on mechanical systems with lower requirements.[109] Conversely, microalgae recovery is achieved through different separation processes, including filtration, centrifugation, flotation and electrophoresis .[110]
The selection of a specific treatment will depend on the feedstock characteristics, such as strains fragility (centrifugation) or the density range (flotation). Moreover, flotation and flocculation require the addition of flocculants (i.e. ferric and aluminum chlorides), which may pose environmental concerns and limit the use of side-products. A comparative study by Norsker et al. reported that for the most economic cultivation system the biomass production cost was 4.15 €/kg[111], much higher than common feedstocks like soybean, wheat or corn.

Currently, biofuel production from algae requires further optimization before reaching the proper industrial scalability, as the overall capital and operational costs are still relatively high compared to other solutions. Process profitability may be increased through co-production of value-added products (e.g. fertilizers, food additives, cosmetics), which can sustain the main production line, or by exploiting flue gas and wastewaters as

[106] GranBio, "What is energy cane?". http://www.granbio.com.br/en/conteudos/energy-cane. Accessed October 2020.

[107] Singh, Jasvinder, and Sai Gu. 2010. Commercialization potential of microalgae for biofuels production. *Renewable and Sustainable Energy Reviews* 14 (9): 2596–2610. doi: 10.1016/j.rser.2010.06.014.

[108] Uduman, Nyomi, Ying Qi, Michael K. Danquah, Gareth M. Forde, and Andrew Hoadley. 2010. Dewatering of microalgal cultures: A major bottleneck to algae-based fuels. *Journal of Renewable and Sustainable Energy* 2 (1): 12701. doi: 10.1063/1.3294480.

[109] Roesijadi, G., S. B. Jones, L. J. Snowden-Swan and Y. Zhu. 2010. Macroalgae as a biomass feedstock: a preliminary analysis. Pacific Northwest National Laboratory.

[110] Uduman N, Qi Y, Danquah MK, Forde GM, Hoadley A. 2010. Dewatering of microalgal cultures: a major bottleneck to algae-based fuels. J Renew Sustain Energy 2:012701.

[111] N.-H. Norsker, M.J. Barbosa, M.H. Vermuë, R.H. Wijffels, Microalgal production--a close look at the economics, Biotechnol. Adv. 29 (2011) 24–27. https://doi.org/10.1016/j.biotechadv.2010.08.005.

source of carbon and nutrients.[112] Still, the production costs of micro algae biodiesel was estimated to be 2–3 times higher than 1G and 2G counterparts, ranging from 1.6-2.2 USD/L for open ponds and around 4.7 USD/L for photobioreactors.[113]

Bio-oils can also be harvested from selected strains of yeasts, which are able to convert the excess carbon in their culture medium to lipids and store in their cells in the form of lipid droplets. This behavior is common to both oleaginous and non-oleaginous yeasts (e.g. *S. Cerevisiae*), but oleaginous yeasts can store high amounts of lipids (at least 20% by weight) in their cells, while other microbial species are typically limited to a maximum of 10% of their dry weight. The selection of a proper feedstock is relevant, as it strongly influences the final content of the lipid fraction and accounts for most of the process cost, up to 85%.[114]

Most of the sugar industry by-products, such as sugarcane molasses, bagasse and husks are low-cost, viable carbon sources for yeasts growth.[115] Also, lignocellulosic materials can be exploited such as wheat and rice straws or corn stover. After cultivation, the yeasts can be harvested either by settling or centrifugation and the lipid fraction is recovered through hexane extraction. The obtained oils are converted to FAME through transesterification and the resulting biodiesel can be used for blending or further upgraded with hydrotreating.

2.4.3 Biogas from wastes

2G biomasses can be converted to biogas through anaerobic digestion similarly to agricultural crops. A great variety of feedstocks may be exploited, including animal manure, agri-food residues, wastewater sludge, and lignocellulosic crops. In the EU, biogas production is currently dominated by agricultural crops, crop residues and animal manure.[116] The latter is also very relevant in China, where it is the predominant source for household digesters in rural areas (roughly 70% of the total installed capacity in China).[117] Conversely, US biogas comes mainly from municipal solid wastes, with landfill gas collection making up for nearly 90% of US production.[118]

Every feedstock has some inherent drawbacks for the process, such as suboptimal carbon to nitrogen ratio (C/N) or low availability of carbon source. To partially overcome this issue, co-digestion of many raw materials is possible. Lignocellulosic feedstocks are attractive due to their high yield, but their usage is hindered by the need of costly pre-treatments (e.g. dilute acids) as for 2G fermentation. Crop residues and animal manure are the largest sources worldwide and, in many cases, they are nearly zero-cost or even negative if disposal of the

[112] Peng, Licheng, Christopher Q. Lan, Zisheng Zhang, Cody Sarch, and Matt Laporte. 2015. Control of protozoa contamination and lipid accumulation in Neochloris oleoabundans culture: Effects of pH and dissolved inorganic carbon. *Bioresource technology* 197:143–151. doi: 10.1016/j.biortech.2015.07.101.

[113] R. Davis, A. Aden, P.T. Pienkos, Techno-economic analysis of autotrophic microalgae for fuel production, Applied Energy 88 (2011) 3524–3531. https://doi.org/10.1016/j.apenergy.2011.04.018.; J. Hoffman, R.C. Pate, T. Drennen, J.C. Quinn, Techno-economic assessment of open microalgae production systems, Algal Research 23 (2017) 51–57. https://doi.org/10.1016/j.algal.2017.01.005.

[114] Leiva-Candia, D. E., S. Pinzi, M. D. Redel-Macías, Apostolis Koutinas, Colin Webb, and M. P. Dorado. 2014. The potential for agro-industrial waste utilization using oleaginous yeast for the production of biodiesel. *Fuel* 123:33–42. doi: 10.1016/j.fuel.2014.01.054.

[115] Freitas, Cláudia, Teresa Margarida Parreira, José Roseiro, Alberto Reis, and Teresa Lopes da Silva. 2014. Selecting low-cost carbon sources for carotenoid and lipid production by the pink yeast Rhodosporidium toruloides NCYC 921 using flow cytometry. *Bioresource technology* 158:355–359. doi: 10.1016/j.biortech.2014.02.071.; Yousuf, Abu. 2012. Biodiesel from lignocellulosic biomass--prospects and challenges. *Waste management (New York, N.Y.)* 32 (11): 2061–2067. doi: 10.1016/j.wasman.2012.03.008.

[116] IEA 2020, "Outlook for biogas and biomethane: prospects for organic growth".

[117] Ibid.

[118] Ibid.

waste is required by law. This does not affect the biogas costs dramatically, though, as installing the digesters usually make up for 70-95% of the total costs. Moreover, integration with other biofuel technologies is possible, for instance when exploiting the residual fermentation mash from bioethanol plants. In Table 2.6 the average energy yield in biogas for different types of feedstock are synthetized. They are provided as tons of oil equivalent, corresponding to the energy released by burning one ton of crude (about 42 GJ). For comparison, it is recalled that bioethanol and biodiesel heating values are roughly 27 GJ/ton and 38 GJ/ton respectively - with some variability according to the considered feedstock.

TABLE 2.6. Average biogas yield (as ton of oil equivalent per ton of feedstock type).[119]

FEEDSTOCK	BIOGAS YIELD (TOE TON^{-1})
Industrial waste	0.361
Food and green[120]	0.222
Wood residues	0.178
Sugar beet	0.254
Corn	0.208
Oilseeds, soybean and rice	0.181
Wheat and sugarcane	0.160
Poultry and pig	0.039
Sheep and cattle	0.008

The biogas yield lies in a wide range. Industrial waste provides the highest yield, but landfill gas is a very low-cost source. Animal manure yield is quite low, but it can be exploited in house-hold digesters with limited capital investments. In fact, landfill gas recovery and basic household digesters average costs were estimated respectively around 8 USD/MWh and 11 USD/MWh. Implementation of digestion in wastewater plants is possible, but high investments are required resulting in average costs of about 50 USD/MWh.[121] According to this general picture, a huge potential for biogas production is available around the world. However, most of the viable feedstocks are currently neglected or utterly underused. In fact, the worldwide biogas production in 2018 was 35 Mtoe, a very small fraction of the estimated overall potential of biogas (570 Mtoe) and biomethane (730 Mtoe).[122] Full utilization of the biogas sustainable potential could cover some roughly 20% of today's worldwide gas demand.[123]

[119] Ibid.

[120] "Food and green" represents food and garden waste (e.g. leaves and grass) disposed of as MSW.

[121] Ibid.

[122] Ibid.

[123] Ibid.

2.4.4 Thermochemical processes

Pyrolysis

Pyrolysis is a thermochemical process featuring the conversion of biomass to solid, liquid and gaseous products at high temperature and in absence of oxygen. The feedstock is progressively reduced to carbonaceous solids (char), liquid bio-oil (tar) and a gaseous mix of mainly hydrogen, CO, carbon dioxide and methane. Pyrolysis can be exploited to make recalcitrant biomasses like lignocellulosic crops and residues viable for gasification. Alternatively, the resulting bio-oil can be upgraded through transesterification to FAME or possibly hydrotreating to HVO, while the gaseous products can be purified and exploited for synthetic fuel production.

The product distribution can be adjusted by properly tuning the operating conditions. Currently, the most common set-up relies on fast pyrolysis, where the biomass is treated in the temperature range of 400-550 °C with very short vapor residence times (down to 1-2 s). What makes this option particularly attractive is the possibility to achieve a high yield of bio-oil (up to 75% by weight) compared to other conditions. The obtained bio-oil is a viscous, brownish mixture of oxygenated organics – including alcohols, esters, phenolic compounds and lignin oligomers – and thus its oxygen content is rather high (up to 40%).[124] This implies that bio-oil is quite reactive (i.e. not very stable) and requires upgrading through hydrotreating before its application either as biodiesel or as bio-jet. Still, non-negligible amounts of the other phases are produced, calling for side-processes for their valorization. This would be desirable to raise the economic profitability of the main process - according to a biorefinery approach -, but one should also take into account the regional constraints (market demand, logistics).

Provided that fast pyrolysis is an endothermic process and very short residence times are required, very high heating rates are required (up to 1000 °C/s), negatively affecting the overall energy balance. Still, it is possible to exploit the biochar for partial or complete oxidation to provide energy to the main process. Alternatively, zeolites can be used to catalyze the reaction. The catalyst allows reducing the operating temperature to less than 500 °C and delivering bio-oil with a lower oxygen content. This variation of the process is generally referred to as in-situ catalytic pyrolysis.

To properly operate the process, the feedstock needs to be extensively dried and grounded to fine particles. This adds significant operating costs and may hinder the exploitation of some advanced feedstocks when the pre-treatments are excessively costly. In this respect, intermediate pyrolysis may be a sound alternative, at least to overcome the grounding issue. In fact, this process implies lower heating rate (i.e. higher residence time) in the order of 300 °C/min and it works fine even with coarse particles. These milder conditions imply a lower yield of bio-oil, though, typically around 50% by weight.

To date, some industrial scale facilities performing pyrolysis are already operational. Some relevant examples include Fortum in Joensuu (Finland), Ensyn plants in Ontario (Canada) and BTG in Hengelo (the Netherlands), with capacity ranging from 50 to 300 tons per day roughly. Yearly production is still limited compared to other

[124] Bridgwater, A. V. 2012. Review of fast pyrolysis of biomass and product upgrading. *Biomass and Bioenergy* 38:68–94. doi: 10.1016/j.biombioe.2011.01.048.

advanced bioprocesses and most of the generated bio-oil is not employed for drop-in fuel production, but rather as co-feed for refineries and combined heat and power (CHP) or for food flavoring manufacturing.

Hydrothermal Liquefaction (plus HTC, HTG)

Hydrothermal processes imply the treatment of the biomass in presence of hot water in sub-critical, near critical or supercritical conditions. In hydrothermal liquefaction (HTL) the biomass is liquefied at high pressure (50-250 bar) and moderate temperature of 250-550 °C, delivering an oily stream, sometimes referred to as bio-crude.[125]

The greatest advantage of the HTL process is the ability to deliver a single, liquid output. In addition, it is possible to process wet biomass, which removes the costs related to drying and enables the exploitation of a wider variety of feedstocks (wastewaters, manure, and municipal/industrial sludges). HTL yield in bio-oil is lower compared to fast pyrolysis, but the bio-crude is more stable and displays much lower oxygen content compared to pyrolysis oil, usually in the range 5-10%.[126] Nonetheless, upgrading through hydrotreating is still required for drop-in application, especially in the case of bio-jet, but the hydrogen consumption is typically lower. Despite being a very promising technology, little attention has been paid to HTL thus far and only few demonstrations with pilot plants were attempted globally.[127]

Other hydrothermal processes exploit different operating conditions to switch the main output to either solid or gaseous products. Hydrothermal carbonization (HTC) is performed at mild conditions (less than 220 °C and 30 bar) and yields in a solid carbon source, akin to coal. Apart from the application as primary biofuel (i.e. direct burning), the biochar can also be exploited for gasification and conversion to synthetic fuels. By contrast, treatment in supercritical conditions at 600-700 °C allows converting most of the feedstock to mainly hydrogen and carbon dioxide, with or without the addition of catalysts.[128] The production of a gas rich in methane is also possible by varying process conditions and applying proper catalyst.[129]

Gasification (Biomass to Liquid)

In the gasification process the raw materials (solid or liquid) are converted to gases using air/oxygen at high temperature. The output is a mixture of hydrogen, carbon monoxide, CO_2, methane, and minor impurities. Such stream is generally referred to as syngas, synthesis gas or producer gas and it can be exploited, after cleaning and conditioning, for the conversion to synthetic fuels (e.g. Fischer-Tropsch fuels). This route for biomass conversion is usually labeled as 'Biomass-to-Liquid' (BtL) processes.

[125] Akhtar, Javaid, and Nor Aishah Saidina Amin. 2011. A review on process conditions for optimum bio-oil yield in hydrothermal liquefaction of biomass. *Renewable and Sustainable Energy Reviews* 15 (3): 1615–1624. doi: 10.1016/j.rser.2010.11.054.

[126] Elliott, Douglas C., Patrick Biller, Andrew B. Ross, Andrew J. Schmidt, and Susanne B. Jones. 2015. Hydrothermal liquefaction of biomass: developments from batch to continuous process. *Bioresource technology* 178:147–156. doi: 10.1016/j.biortech.2014.09.132.

[127] Gollakota, A.R.K., Nanda Kishore, and Sai Gu. 2018. A review on hydrothermal liquefaction of biomass. *Renewable and Sustainable Energy Reviews* 81:1378–1392. doi: 10.1016/j.rser.2017.05.178.

[128] Chakinala, Anand G., Derk W. F. Brilman, Wim P.M. van Swaaij, and Sascha R. A. Kersten. 2010. Catalytic and Non-catalytic Supercritical Water Gasification of Microalgae and Glycerol. *Industrial & Engineering Chemistry Research* 49 (3): 1113–1122. doi: 10.1021/ie9008293.

[129] Stucki, Samuel, Frédéric Vogel, Christian Ludwig, Anca G. Haiduc, and Martin Brandenberger. 2009. Catalytic gasification of algae in supercritical water for biofuel production and carbon capture. *Energy & Environmental Science* 2 (5): 535. doi: 10.1039/b819874h.

Gasification is suitable for all biomasses coming from the agri-food sector, wood residues, municipal solid or liquid wastes, and aquatic biomasses. According to the reactor configuration, pre-treatment of the feedstock is required to a greater or lesser extent. For instance, biomass feed to entrained flow gasifiers requires raw materials fine grained with a maximum grain size of 1 mm.[130] This is not a great issue when dealing with coal-like materials, but it can become quite a challenge for lignocellulosic feedstocks, increasing the costs significantly. Further increase in the overall process costs may come from difficulty in feedstock handling (e.g. straw) or from high moisture feeds (> 30%), requiring extensive drying prior to gasification.[131] An alternative way to overcome such issues is the use of pyrolysis as a pre-treatment for gasification. In this case, raw biomass is converted to a bio-slurry, which is easier to handle during gasification.

The process is typically carried out at 800-1200 °C and it is endothermic. A stream of air is required for the partial combustion of the biomass, which is accounting for the required energy (autothermal mode). However, this will result in a strongly diluted product, due to the presence of Nitrogen in the air. Alternatively, pure oxygen can be used for the combustion, avoiding the issues related to Nitrogen dilution. In this case, an air separation unit (ASU) will be required to provide the oxygen stream, increasing the overall process costs. Still, the low cost of electricity, which accounts for most of ASU operating costs, make this extra unit generally feasible.

The composition of the output gases is strongly influenced by the operating condition. Apart from the operating temperature, addition of steam to the oxygen stream will favor the water-gas-shift reaction, resulting in an increased generation of hydrogen. This is particularly beneficial when gasification is exploited for Fischer-Tropsch synthesis, as syngas with a high H_2/CO ratio is required for the process. Conversely, addition of hydrogen will boost the production of methane, making the output stream viable for biomethane production. Along with the main gaseous products minor amounts of *tar* and *char* are produced as well.

In any case, the obtained syngas will require further processing before conversion to synthetic fuels. For instance, the catalysts employed for Fischer-Tropsch synthesis are vulnerable to poisoning from Sulphur and Nitrogen.[132] Regardless of the syngas use, such species should still be removed from the stream to prevent the formation of NO_x and SO_x during combustion of the synthetic biofuel. Separation of residual *tar* and *char* are also required to prevent catalyst deactivation and to meet biofuel specifications. There are several approaches to mitigate the production of *char* and *tar*, but they all come at a cost, like addition of steam (worsened energy balance), increase air/biomass ratio (more biomass lost for combustion), or increase the temperature (higher capital and operational costs). If the syngas is destined for catalysis to liquid fuels, the gas cleanup technologies may also separate CO_2, which then dominates the byproduct gas stream and is suitable for geologic storage.

[130] A. van der Drift, H. Boerrigter, B. Coda, M.K. Cieplik, K. Hemmes, Entrained flow gasification of biomass—Ash behaviour, feeding issues, and system analyses. Report ECN-C--04-039, 2004.

[131] Brammer, J. 2002. The influence of feedstock drying on the performance and economics of a biomass gasifier–engine CHP system. *Biomass and Bioenergy* 22 (4): 271–281. doi: 10.1016/S0961-9534(02)00003-X.; Cummer, K. 2002. Ancillary equipment for biomass gasification. *Biomass and Bioenergy* 23 (2): 113–128. doi: 10.1016/S0961-9534(02)00038-7.

[132] Dayton, David C., Brian Turk, and Raghubir Gupta. 2019. Syngas Cleanup, Conditioning, and Utilization. In *Thermochemical processing of biomass: Conversion into fuels, chemicals and power*, ed. Robert C Brown and Robert C. Brown, 125–174. Hoboken, NJ: Wiley.

For all these reasons, syngas cleaning can be one of the most demanding but also rewarding steps along the Biomass-to-Liquid route.

Even though gasification of biomass is widespread around the globe, it is mainly devoted to the production of energy via co-firing in furnaces or CHP plants rather than production of biofuels for transport. Nonetheless, few commercial facilities are available. Enerkem gasifier in Westbury (Quebec, Canada) convert treated wood, wood residues and municipal solid wastes to syngas for alcohols production (4000 t/y of ethanol). ThermoChem Recovery International has successfully deployed a fully integrated biorefinery (Durham, North Carolina, USA), where organic residues and municipal solid wastes are gasified, and the obtained syngas is converted to Fischer-Tropsch liquid products (1 t/y). Karlsruhe Institute of Technology (KIT) demonstration plant combines pyrolysis pre-treatment, gasification and chemical synthesis to convert straws into DME (608 t/y) and synthetic gasoline fuels (360 t/y).

2.4.5 Synthetic biofuels (Biomass-to-Liquid)

The syngas from gasification can be exploited for a sound variety of synthetic biofuels. Each synthesis has its own requirements in terms of operating conditions (temperature, pressure) and catalyst, but the lower quality of bio-derived syngas is surely a key issue, which is hampering the deployment of BtL platform. Methanation was already mentioned earlier as a possible route for conversion of syngas to methane through a high temperature, catalyzed reaction (see crops digestion to biogas).

In addition, two relevant conversion routes, namely methanol/DME and Fischer-Tropsch synthesis, are presented in the following sections. These are consolidated processes in the chemical and fossil fuels industry, whose chemistry is well-known and industrial-scale infrastructure are available. Thus, when syngas from biomass is fed, little adjustments are expected compared to the conventional conditions of the processes.

Methanol and DME Synthesis

Methanol production is a consolidated technology, based on the exothermic conversion of syngas. It is conducted at 220-280 °C and 50-100 bar in presence of a catalyst based on Copper, Zinc and Aluminum oxides. Hence, syngas must be cleaned from Sulphur and halogens to prevent poisoning of the catalyst. Methanol is the main product of the process, but methane, ethane, ethers, higher alcohols, and DME are also obtained as by-products. Furthermore, the conversion per pass is quite low and recycling of the unreacted syngas is required to achieve high yield. Consequently, distillation of products is conducted to separate methanol from lighter and heavier species, increasing energy costs. A variation of the process, where reaction is operated at 260-525 °C and 30-300 bar, allows producing mixed alcohols, but further research is required to make commercialization feasible.[133]

The obtained methanol is not eligible as a drop-in biofuel, but it can be used for blending in gasoline along with ethanol. Notably, ENI and FCA have launched a new fuel made up of 15% methanol and 5% bio-ethanol.

[133] Fang, Kegong, Debao Li, Minggui Lin, Minglin Xiang, Wei Wei, and Yuhan Sun. 2009. A short review of heterogeneous catalytic process for mixed alcohols synthesis via syngas. *Catalysis Today* 147 (2): 133–138. doi: 10.1016/j.cattod.2009.01.038.

Commercialized with the brand name "A20", the fuel is reported to provide 3% less CO_2 emissions due to its peculiar formulation.[134] Alternatively, it can be converted to dimethyl-ether (DME) and gasoline. This is possible through catalytic dehydration of methanol at 250-300 °C and 15-30 bar in presence of alumina or zeolites catalyst. The reaction is exothermic and water is the main by-product. DME is viable as fuel for heavy-duty transport due to its high cetane number, but it will need compression before end-use being gas at standard conditions. By pushing dehydration further, DME can be converted to gasoline. The process is conducted at 250-300 °C and 30 bar under zeolite catalyst and the output consists of gasoline-range hydrocarbons (44 wt.%) and water (56 wt.%).[135]

Fischer-Tropsch (F-T) Synthesis
Syngas can also be exploited for the production of synthetic liquid fuels through the Fischer-Tropsch (F-T) synthesis. This process involves the conversion of syngas to hydrocarbons and water through catalytic hydrogenation. The reaction is carried out at 200-350 °C and pressure up to 275 bar, it is strongly exothermic and proceeds via the addition of $-CH_2-$ building blocks to form short-/long-chain hydrocarbons.

Straight-chain alkanes and alkenes are the main reaction products, but some isomers, methane, alcohols, and other oxygenated products are also obtained in smaller amounts. The product distribution can be adjusted by properly tuning the operating conditions, selecting the most suited catalyst, and adjusting the hydrogen over CO ratio (usually around 2.2-2.5). Iron-based catalysts and higher temperature typically shift the distribution to gasoline-range hydrocarbons and methane, while Cobalt-based catalysts, lower temperature and high pressure are preferred to obtain long-chain hydrocarbons (mainly diesel, but also naphtha cuts).

As some oxygenated products are also formed, a downstream unit for water separation is to be included. Also, lighter products (i.e. LPG) must be separated to allow recycling unreacted syngas. Removal of Sulphur, Nitrogen and *tar* from the syngas is fundamental to preserve the catalyst, while adjustment of the H_2/CO is necessary to obtain the desired product distribution. The latter may not be required in the presence of Iron-based catalysts due to their activity towards water-gas-shift reaction. The synthetic liquids obtained from F-T synthesis require upgrading through hydrotreating to meet specifications as drop-in biofuels or can be blended with fossil cuts.

The great advantage of Fischer-Tropsch synthesis compared to other processes is certainly the possibility to tune the product distribution depending on regional market needs. Moreover, little adjustment is expected when switching to biomass feed, except for feed purification against poisoning. Table 2.7 summarizes some techno-economic assessment of biofuel production through gasification and F-T synthesis. The liquid fuel cost varies widely depending on the feedstock, but it could be competitive with fossil fuels depending on the considered region. This is especially true for low cost feedstocks like switchgrass and woody biomasses.

[134] "Eni And FCA Have Developed A20, A New Fuel That Pairs Emissions Reduction With Energy Efficiency". 2021. Eni.Com. https://www.eni.com/en-IT/media/press-release/2019/04/eni-and-fca-have-developed-a20-a-new-fuel-that-pairs-emissions-reduction-with-energy-efficiency.html.

[135] S.D. Phillips, J.K. Tarud, M.J. Biddy, A. Dutta, Gasoline from Wood via Integrated Gasification, Synthesis, and Methanol-to-Gasoline Technologies, Report NREL TP-5100-47594, 2011.

TABLE 2.7. Production capacity (as barrel per day) and liquid fuel production cost for gasification and F-T synthesis of some relevant 2G feedstocks.

FEEDSTOCK	PRODUCTION CAPACITY (BPD)	LIQUID FUEL COST (USD L^{-1})	REFERENCE
Switchgrass	4630	0.52	[136]
Residual wood straw	5500	1.57	[137]
Corn stover	2362	1.39	[138]
Woody biomass	1700	0.81	[139]
Woody biomass	2180	0.40	[140]

2.5 Perspectives

2.5.1 Overview of biofuels technologies

The biochemical platform comprises the conversion of sugar-containing crops to ethanol and the production of biogas through anaerobic digestion. Regarding fermentation, the process is well-established, but the low concentration of obtained ethanol is the choke point. The purification of bioethanol is costly and energy-intensive and significant investments are required for the realization of new, dedicated infrastructures. Moreover, the pre-treatment of recalcitrant feedstocks (i.e. lignocellulosic biomasses) further increases the overall costs of the process, making it less attractive than the biomass-to-liquid route. As a result, gasification of the biomass, especially for 2G, may be more convenient compared to its hydrolysis for ethanol production.

As for biogas production, digestion is a mature technology, but it is susceptible to biomass characteristics and requires significant pre-treatment, especially for some advanced feedstocks. Co-feeding of different biomasses may mitigate this issue, while centralized, large-scale plants are preferred to optimize the process and reduce operating costs. However, this may not be feasible when the logistics is poor, increasing excessively handling and transportation costs. Furthermore, separation of CO_2 and impurities is required to meet biomethane quality standards. Thus, significant investments are required to provide basic infrastructures for biomass handling, pre-treating and integration in the natural gas grid.

[136] E.D. Larson, H. Jin, F.E. Celik, Large-scale gasification-based coproduction of fuels and electricity from switchgrass, Biofuels, Bioprod. Bioref 3 (2009) 174–194. https://doi.org/10.1002/bbb.137.

[137] F. Trippe, M. Fröhling, F. Schultmann, R. Stahl, E. Henrich, A. Dalai, Comprehensive techno-economic assessment of dimethyl ether (DME) synthesis and Fischer–Tropsch synthesis as alternative process steps within biomass-to-liquid production, Fuel Processing Technology 106 (2013) 577–586. https://doi.org/10.1016/j.fuproc.2012.09.029.

[138] H. Boerrigter, Economy of Biomass-to-Liquids (BTL) plants.: An engineering assessment, 2006. Available at http://www.ecn.nl/docs/library/report/2006/c06019.pdf from the Energy research Centre of the Netherlands (http://www.ecn.nl/), Postbus 1, 1755 ZG Petten (NL). Accessed November 2020.

[139] L. Tock, M. Gassner, F. Maréchal, Thermochemical production of liquid fuels from biomass: Thermo-economic modeling, process design and process integration analysis, Biomass and Bioenergy 34 (2010) 1838–1854. https://doi.org/10.1016/j.biombioe.2010.07.018.

[140] M. Shahabuddin, M.T. Alam, B.B. Krishna, T. Bhaskar, G. Perkins, A review on the production of renewable aviation fuels from the gasification of biomass and residual wastes, Bioresour. Technol. 312 (2020) 123596. https://doi.org/10.1016/j.biortech.2020.123596.

The oleochemical platform comprises both FAME and HVO/HEFA production. The FAME process is well-known, but the poor quality of the obtained biodiesel (requiring extensive upgrading) as well as the susceptibility to biomass variations make it less attractive than hydrotreating. Indeed, FAME profitability at commercial scale is still dubious, also bearing in mind that huge amounts of glycerin are obtained, whose valorization is not always straightforward. Conversely, HVO was successfully scaled-up to industrial level and provides high quality biofuel, which is also eligible for jet-fuel application. This is particularly relevant as electrification of the aviation segment is not yet attainable, thus making HVO the only practicable route for decarbonization of the sector. Moreover, repurposing existing infrastructure and/or co-feeding is possible, cutting the capital investments and the risks connected to technology deployment.

The thermochemical production of biofuels passes through the conversion to syngas. This solution is undoubtedly advantageous in terms of product flexibility, as syngas is eligible for conversion to either gasoline, diesel, methanol or even methane under proper catalyst and operating conditions. Moreover, syngas with H_2/CO ratio close to 3 can also be exploited for ammonia production. Many different biomasses are reduced to the same intermediate (i.e. syngas) and then the most fitting conversion route can be selected, depending on the regional context. Furthermore, small capital investments are required compared to other technologies, as repurposing of existing infrastructure is possible for both gasification and syngas conversion. This is the main reason making biomass-to-liquid more convenient for lignocellulosic feedstocks – especially the most recalcitrant or low-density ones – compared to a less maturity technology like 2G fermentation to ethanol.

The overall picture clearly shows that biofuels can be a more or less valuable asset depending on many variables, notably the regional context. There is no global optimum in terms of technology profitability, but many local optima according to the local needs and feedstock availability. Framing Table A tries to summarize the key elements for all technologies.

FRAMING TABLE A. Key features of traditional and advanced biofuel technologies.

PROCESS	TYPE	INPUT	OUTPUT	APPLICATIONS	READINESS
Bioethanol from fermentation	Bio-chemical	Sugar-, amidaceous-, lignocellulosic crops; agrifood residues	Diluted bioethanol solution to distillation/ dehydration units	Drop-in fuel or blending for gasoline engine; alcohol-to-jet for aviation	Consolidated, but energy-intensive; infrastructure is required
Biogas from digestion	Bio-chemical	Agricultural crops; lignocellulosic crops; agrifood and municipal wastes; algae	Biomethane; CO_2	Blend with natural gas for transportation;	Significant investments for basic infrastructure and CO_2 removal; grid is required
Esterification (FAME) to biodiesel/jet	Chemical	Vegetable oils; oleaginous residues; microbial oils; algae oils	Fatty acid methyl esters (FAME); glycerol and soaps	Drop-in fuel or blending for diesel engine	Sensitive to biomass variability; commercial profitability is questionable
Hydrotreating (HEFA/HVO) to jet-fuel	Chemical	Vegetable oils; oleaginous residues; microbial oils; algae oils	Hydroprocessed esters and fatty acids/ hydrogenated vegetable oils (HEFA/HVO); propane	Drop-in fuel for diesel or jet-fuel engines	Flexible to biomass variability; existing infrastructures can be repurposed
Thermo-chemical platform (mainly gasification)	Thermo-chemical	Agricultural crops; lignocellulosic crops; agrifood and municipal wastes; algae	Syngas ($CO+H_2$); methane; light hydrocarbons	Synthetic fuels through FTS; methanol/DME; methanation to feed the natural gas grid	Well-established; existing infrastructure can be exploited
Synthetic fuels from Fischer-Tropsch synthesis (FTS)	Chemical	Syngas	Biodiesel; gasoline; jet-fuel; alcohols; LPG	Hydrotreating of liquids for drop-in biofuels or blending	Well-known; existing infrastructure can be used without major adjustments
Methanol/ DME synthesis	Chemical	Syngas	Methanol; ethers; lower and higher alcohols; DME	Blending for gasoline engine or conversion to DME; drop-in fuel for heavy-duty (DME)	Well-known; existing infrastructure can be used without major adjustments

2.5.2 Competition/synergy with alternative platforms

A sound and wide-ranging assessment of biofuel technologies profitability should take into account other platforms relevant for transport. This includes both electrification of transport segments and use of hydrogen as a fuel.

Electrification appears as the most promising route for substantial reduction of transport GHG emissions on the long term, with a greater potential growth in urban areas. In 2019 sales of electric cars topped 2.1 million globally, surpassing 2018, and raising electric car share to 2.6% of global car sales and 1% of global car stocks.[141] This is the result of a strong policy effort in recent years to push electric car sales and use. However, substantial increase of the current grid is required. Indeed, most of the charging is currently done at home and works with slow chargers. In 2019 chargers reached about 7.3 million worldwide, but 6.5 million of them were private, light-duty vehicle slow chargers in homes, multi-dwelling buildings and workplaces.[142] Instead, public, accessible chargers only accounted for 12% of global light-duty vehicle chargers.[143] Expansion of the grid will be relevant for sustaining the electric car market, electrification of heavy-duty segment and highways.

Such intervention may require huge effort and time, leaving room for biofuels in the meantime. In fact, when no major change in the infrastructure is required, biofuels may act synergistically to foster the shift to full electrification. They could be seen, in this respect, as an intermediate platform before the electric grid is able to step in. Moreover, the high infrastructure costs related to electrification may reduce its profitability compared to some biofuel technologies. This is particularly true for methane, for which the infrastructure is fully available, and for developing, rural areas, where the effort required for deploying the grid is still too high. Finally, electrification of the aviation sector is still critical. Despite the rapid increases in battery energy densities in the past decade, battery chemistries would enable at most all-electric fly distances of around 1000 km, covering only about 20% of jet-fuel demand.[144] This implies that HVO/HEFA are still the only viable solution to achieve decarbonization of the aviation segment. The technology for hydrotreating is mature and the repurposing of existing infrastructure is possible, thus making HVO as the most attractive solution for replacing fossil jet-fuel.

Hydrogen is also gaining increasing attention as an alternative source of "clean energy" both in the public debate and for private and public investments. Hydrogen reacts in presence of oxygen to form water, releasing energy, without any CO_2 emission. It should be stressed, though, that when reaction is achieved with air NO_x are also produced. It has been successfully employed as an energy source in fuel cell vehicles (FCV), typically passenger car, and in fuel cell buses. The global FCV stock nearly doubled to 25,210 units at the end of 2019 (12,350 new vehicles), more than doubling the 5,800 purchased in 2018.[145] Traditionally, hydrogen is obtained from fossil sources, namely steam reforming of methane or coal gasification, which are still the dominant feedstock. Biomass gasification could be an alternative way for H_2 production, but the low content of hydrogen in biomasses (usually below 10%) is a very strong constraint. Electrolysis of water is also possible when a proper water source is

[141] IEA 2020, "Global EV Outlook: entering the decade of electric drive?".

[142] Ibid.

[143] Ibid.

[144] Ibid.

[145] IEA (2020), Hydrogen, IEA, Paris https://www.iea.org/reports/hydrogen. Accessed November 2020

available. Indeed, the projects and the installed electrolyzer capacity have increased from less than 1 MW in 2010 to more than 25 MW in 2019.[146]

However, the major constraints on hydrogen exploitation lies in the storage and utilization rather than the manufacturing process. Since the volumetric energy density of hydrogen is low, storage under compression is required and tank volume is large compared to conventional fuels. This clearly pose many issues to safety, as hydrogen is very reactive, flammable and it tends to leak easily. Moreover, hydrogen is very aggressive with conventional construction materials, including high-strength low-alloy steel, inducing the so-called hydrogen embrittlement. As a result, existing infrastructure cannot be exploited for pure hydrogen transport. The methane grid, for instance, could only carry mixture with low hydrogen fraction.

Accordingly, biofuels can be seen not just in competition with hydrogen and especially electricity, but mainly as a synergistic resource. They could be seen as a sort of battery, allowing easy and reliable storage of energy for when the need comes. For instance, biofuels could be exploited for modulating electricity consumption during peak demands. Moreover, this approach is a fortiori suitable for inherently intermittent sources of energy like wind or solar power. Framing Table B synthesizes the main advantages/disadvantages of biofuel technologies compared to electricity and hydrogen.

FRAMING TABLE B. Main pros and cons for traditional/advanced biofuel technologies compared to electricity and hydrogen platforms.

TECHNOLOGY	PROS	CONS
Bioethanol from fermentation	Old and consolidated technology Lignocellulosic biomasses to avoid competition	Low yield of ethanol (yeasts poisoning) Energy-intensive infrastructure Usually not a drop-in
Biogas from digestion	Can be fed to natural gas grid Wide variety of wastes to avoid competition Already deployed in wastewater treatment plants	High CO_2 content (separation/conversion) Contaminants must be removed to allow methanation Logistics can hinder centralized production

[146] Ibid.

TECHNOLOGY	PROS	CONS
Esterification (FAME) to biodiesel/jet	Recycled frying oils and animal fats can be valorized Side-products to pharma/food chemical	Strong gap in performance according to feedstock Side-products conversion is not always profitable Usually not a drop-in
Hydrotreating (HVO) to jet-fuel	High-performance drop-in biofuel Existing infrastructure viable for repurposing	Hydrogen required as feed
Biogas from thermochemical platform	Can be fed to natural gas grid Wide variety of wastes to avoid competition Well-established infrastructure	May be energy-intensive Purification is crucial for catalyst
Synthetic fuels from B-t-L platform	High quality synthetic fuels Different cuts available (gasoline, diesel, naphtha) Well-known with existing infrastructure	Purification is crucial for catalyst Catalyst may be costly for some cuts
Hydrogen (from biomass)	Wide variety of feedstocks for production “Clean” energy	Costly, new infrastructure is required Emissions of NO_x when fed with air Low energy content per unit of volume Low hydrogen content in the biomass (below 10%)
Electric grid	Carbon footprint is low during operation Electricity low cost	Infrastructure deployment is slow and costly Cannot easily supply rural areas

Chapter III

3. THE NEXUS: WATER-LAND-BIOFUELS

Lead Author: Maria Cristina Rulli, Politecnico di Milano
With the collaboration of: Paolo D'Odorico, University of California, Berkeley; Nikolas Galli, Politecnico di Milano.
Paragraph 3.6 by Monia Santini, Euro-Mediterranean Center on Climate Change Foundation
Paragraph 3.7 by Jampel Dell'Angelo, Vrije Universiteit Amsterdam
Paragraph 3.8 by Joaquim E. A. Seabra, Universidade Estadual de Campinas

The UN Sustainable Development Goals (SDGs) state access to affordable, clean, and reliable energy as a major challenge of our century.[147] Achieving this goal entails the transformation of the current systems of energy production and distribution which may ultimately also increase the competition for natural resources (*i.e.* water and land) with the food system. Land, water, and energy are interconnected, both in terms of the natural resources directly used for energy production, and also as a result of land use change and alterations of the carbon and hydrological cycles. In addition, the availability of natural resources, such as water, might be a limiting factor in the implementation of some of the new energy technologies aimed at decarbonizing the power sector. Technologies such as biofuel production, concentrated solar power, and carbon capture and storage require large amounts of water and land.

To curb the increasing atmospheric GHG concentrations in recent years, energy policies have mandated a certain degree of reliance on renewable energy sources as alternatives to fossil fuels.[148] The synthesis of biofuels from plant biomass (mostly crops) provides the opportunity to rely on energy from geologically recent carbon as an alternative to fossil fuel, especially in the transport sector.[149] The ability to produce and consume renewable energy locally can help achieve energy independence, and thus energy security,[150] particularly in countries that lack direct access to fossil fuel deposits.

However, the production of biofuel crops, especially crops for the production of first generation bioethanol and biodiesel, can also have negative impacts on the environment, particularly through land use change and deforestation.[151] Although bioethanol consumption is for the most part domestic, at least one third of the global biodiesel use is available through international trade, mostly associated with palm oil from Indonesia and

[147] United Nations (2015). Transforming our world: The 2030 agenda for sustainable development. New York: United Nations, Department of Economic and Social Affairs.

[148] US CONGRESS 2007; European Union (2009). Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Official Journal of the European Union, 5, 2009.

[149] D'Odorico, P., Davis, K. F., Rosa, L., Carr, J. A., Chiarelli, D., Dell'Angelo, J., Gephart, J., MacDonald, G. K., Seekell, D. A., Suweis, S., & Rulli, M. C. (2018). The Global Food-Energy-Water Nexus. Reviews of Geophysics, 56(3), 456–531. https://doi.org/10.1029/2017RG000591

[150] U. S. Congress (2007). Senate. 2007. Biofuels Security Act of.

[151] Carlson, K. M., Curran, L. M., Ratnasari, D., Pittman, A. M., Soares-Filho, B. S., Asner, G. P., ... & Rodrigues, H. O. (2012). Committed carbon emissions, deforestation, and community land conversion from oil palm plantation expansion in West Kalimantan, Indonesia. Proceedings of the National Academy of Sciences, 109(19), 7559-7564.; Fargione, J., Hill, J., Tilman, D., Polasky, S., & Hawthorne, P. (2008). Land Clearing and the Biofuel Carbon Debt. 319(February), 1235–1239.;
Fitzherbert, E.B., Struebig, M.J., Morel, A., Danielson, F., Bruhl, C.A., Donald, P.F. et al. 2008. How will oil palm expansion affect biodiversity? Trends Ecol. Evol., 23, 538–545.;
Lima, M., M. Skutsch, & de Medeiros Costa G. 2011. Deforestation and the social impacts of soy for biodiesel: perspectives of farmers in the south Brazilian Amazon. Ecology and Society16(4): 04.http://dx.doi.org/10.5751/ES-04366-160404.

Malaysia for the European market. Moreover, biofuels require water and land resources that may otherwise be used for food production.[152] Therefore, the competing needs for land and water resources by food and biofuel sectors is at the forefront of the energy-food debate.[153] As a result, a number of outstanding questions on the water-energy-food nexus have arisen, including those related to the effects on food security, environment, and the displacement of land use due to the reliance on the trade of biofuel feedstock.[154]

3.1 Energy Security and Food Security: The Role of Biofuels

During the second half of the 20th century, rapid population growth and changes in diets generated increasing concerns about the ability of the limited renewable resources of the planet to meet the food and energy needs of humanity.[155]

For over 1.3 billion people with no access to electricity, bioenergy can help improve energy security and can be available in rural areas to decrease poverty.[156] Access to reliable and affordable energy is essential for economically and environmentally sustainable development, as emphasized by the SDGs (SDG 7 specifically). Although not the focus of this report, it is important to note that today 2.8 billion people in the world burn wood and agricultural waste (solid fuels) for cooking and heating.[157] This is an inefficient 'traditional' bioenergy source, which causes respiratory illness and approximately 1.6 million deaths per year, mainly of women and children. In India, solid fuels contribute to about 63% of the total household energy consumption, having great impacts significantly to both CO_2 emissions and hazardous indoor air quality. Cambodia, with an estimated 1,304 deaths per million people and India, with some 954 deaths per million, occupy the top two positions in deaths attributed to indoor pollution, one of the leading causes of mortality in the world.[158]

[152] Cassidy, E. S., West, P. C., Gerber, J. S., & Foley, J. A. (2013). Redefining agricultural yields: From tonnes to people nourished per hectare. Environmental Research Letters, 8(3), 034015. https://doi.org/10.1088/1748-9326/8/3/034015; Gerbens-Leenes, P. W. (2017). Bioenergy water footprints, comparing first, second and third generation feedstocks for bioenergy supply in 2040. In European Water (Vol. 59).; Gerbens-Leenes, P.W., Hoekstra, A.Y. & Van der Meer Th.H. 2009. The water footprint of bioenergy. Proceedings of the National Academy of Science 106(25): 10219-10223.;
Gerbens-Leenes, P.W., Lienden, A.R.v., et al. 2010. Biofuel scenarios in a water perspective: the global blue and green water footprint of road transport in 2030. Global Environmental Change 22 (3), 764–775.;
FAO-OECD. 2011.Food and Agriculture Organization/Organization for Economic Co-operation and Development: Price Volatility in Food and Agricultural Markets: Policy Responses. Food and Agriculture Organization of the United Nations, Rome, Italy.

[153] Cassidy et al., Redefining agricultural yields.; Smith P, Gregory PJ, Van Vuuren DP, Obersteiner M, Havlík P, Rounsevell M, Woods J, Stehfest E & Bellarby J. 2010. Competition for land. Phil Trans R Soc B: Biol Sci 365:2941–2957.

[154] Lambin, E. F. & Meyfroidt, P. 2011. Global land use change, economic globalization, and the looming land scarcity. Proc. Natl Acad. Sci. USA 108, 3465–3472.

[155] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.;
Carr, J. A., D'Odorico, P., Laio, F., & Ridolfi, L. 2013. Recent History and Geography of Virtual Water Trade. *PLoS ONE*. https://doi.org/10.1371/journal.pone.0055825.;
Chapagain, A. K., & Hoekstra, A. Y. (2008). The global component of freshwater demand and supply: An assessment of virtual water flows between nations as a result of trade in agricultural and industrial products. *Water International*. https://doi.org/10.1080/02508060801927812.;
Falkenmark, M., & Rockström, J. (2006). The new blue and green water paradigm: Breaking new ground for water resources planning and management. In *Journal of Water Resources Planning and Management*. https://doi.org/10.1061/(ASCE)0733-9496(2006)132:3(129).;
Peter, G. 1993. World'S Fresh Water Resources. In *Water In Crisis - A Guide to the World`s Fresh Water Resources*.;
Rockström, J., Falkenmark, M., Lannerstad, M., & Karlberg, L. (2012). The planetary water drama: Dual task of feeding humanity and curbing climate change. *Geophysical Research Letters*. https://doi.org/10.1029/2012GL051688.;
Varis, O., Keskinen, M., & Kummu, M. (2017). Four dimensions of water security with a case of the indirect role of water in global food security. *Water Security*. https://doi.org/10.1016/j.wasec.2017.06.002.

[156] Souza, G.M., Victoria, R.L., Joly, C.A., Verdade, L.M., 2015. Bioenergy & sustainability: bridging the gaps. Scientific Committee on Problems of the Environment (SCOPE), Paris Cedex.

[157] Ekouevi, Koffi; Tuntivate, Voravate. 2012. Household Energy Access for Cooking and Heating : Lessons Learned and the Way Forward. A World Bank Study. Washington, DC: World Bank. © World Bank. https://openknowledge.worldbank.org/handle/10986/9372 License: CC BY 3.0 IGO.

[158] Ibid.

In addition to improving indoor air quality, modern bioenergy can potentially help improve food security by maximizing land productivity and agricultural management, building cooperation throughout the biomass and food supply chain. Modern bioenergy production, however, requires post-farm processing and related infrastructure (e.g., biorefineries) that is often lacking in rural areas across the developing world, suggesting the existence of a gap between biofuel crop production and its use to meet local energy needs. Around 70-80% of food insecurity occurs in rural areas, where energy insecurity or energy poverty are also concentrated. Bioenergy might also play a part in sustainable energy supplies, even with increasing food demands from rising urbanization. The bioenergy sector can also create a new market for producers while at the same time offering new kinds of employment which will spur economic growth, increasing rural incomes and lowering poverty rates. Opportunities could arise in the areas of biofuel production, processing, transportation, trade and distribution. Employment can grow both geographically and in related sectors. IRENA reports liquid biofuels as one of the major employers in the renewable sector, with jobs concentrated in feedstock supply. Brazil, China, the United States and India are key bioenergy job markets.[159] In addition, the provision of power generated from biomass sources can contribute to rural development by improving the energy access for rural communities who lack grid connectivity, though biofuel crops are often hardly usable for local energy needs. Energy access can enhance agricultural productivity, food preservation, and access to markets, all of which have direct consequences for food security. Nevertheless, bioenergy can add an element of competition for certain food stocks which then changes incomes and food prices. Income influences both the quantity and quality of food consumed by households. In general, higher food prices hurt net food consumers but farmers who are net food producers are likely to benefit from higher prices and increase their incomes.

Hence, questions have arisen about the sustainability of biofuels and their potential role in energy security because of the tradeoffs that biofuel production generates in terms of food, water, and land consumption.[160] Biofuels can affect food security through two principal pathways. First, they compete for the same natural resources used to support food production. Second, they may compete with traditional agricultural commodities and affect food security outcomes (Figure 3.1).[161]

Additionally, biofuel production and food security are linked through food prices, employment and incomes, rural development, and poverty reduction .[162] However, some studies in the existing energy literature (e.g., Da Silva, 2005; Billen et al., 2015; Nelson et al., 2009; West et al., 2014) show the possibility to increase resilience in the food-energy-water nexus, minimizing the exploitation of water and land resources through the use of green technologies and "sustainable intensification" of food production, as discussed later.[163]

[159] IRENA, 2017. Renewable Energy and Jobs. Annual Review 2017.

[160] Araújo, K., Mahajan, D., Kerr, R., & Silva, M. Da. 2017. Global biofuels at the crossroads: An overview of technical, policy, and investment complexities in the sustainability of biofuel development. *Agriculture (Switzerland)*, *7*(4). https://doi.org/10.3390/agriculture7040032.

[161] Food and Agriculture Organization of the United Nations. Bioenergy, & Food Security Project. 2010. Bioenergy and food security: the BEFS Analytical Framework (No. 16). Food & Agriculture Org.

[162] Food and Agriculture Organization of the United Nations, Bioenergy and food security.

[163] Davis, K. F., Rulli, M. C., Seveso, A., & D'Odorico, P. (2017). Increased food production and reduced water use through optimized crop distribution. Nature Geoscience, 10(12), 919-924.; Erb, K. H., Lauk, C., Kastner, T., Mayer, A., Theurl, M. C., & Haberl, H. (2016). Exploring the biophysical option space for feeding the world without deforestation. Nature communications, 7, 11382.; Foley, J. A., Ramankutty, N., Brauman, K. A., Cassidy, E. S., Gerber, J. S., Johnston, M., ... & Balzer, C. (2011). Solutions for a cultivated planet. Nature, 478(7369), 337-342.; Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Bloomer, P., ... & Herrero, M. (2013). Sustainable intensification in agriculture: premises and policies. Science, 341(6141), 33-34.

3.1.1 Food and Energy Trade-Offs: Biofuel Competition with Food

This section addresses food and energy trade-offs considering the Food and Agriculture Organization's (FAO) ***four pillars of food security*** (i.e. availability, access, utilization, stability) and the interconnections among them.[164] It considers the impact of competition amongst finite natural resources, first on food *availability* and *utilization*, then on price variations (affecting *access*), and finally on food *stability* through analyzing market trends.

Availability

Biofuel production can have direct and indirect effects on food availability.[165] On the one hand, first generation biofuel crops can be used directly as food; on the other, feedstock production implies the use of water and land resources that could be available for additional food production.[166] Therefore, first generation biofuels are at the core of the food-energy-land-water nexus because of the destination of edible crops as fuel for energy production rather than as food for reducing malnutrition.[167] In this regard, analysis made by Brown shows that the fuel that fills a regular car tank could feed one person for one year.[168] The interlinkage between food security and first generation biofuels has been analysed by Rulli et al. in terms of food unavailability.[169] In particular, Table 3.1 shows that about 200 million people could be fed with crops (in terms of calories) used for bioethanol and 70-80 million people with the caloric content of total biodiesel production. Although second and third generation biofuels do not have a direct impact on food availability, they can potentially have indirect impacts since they could be used as animal feed, e.g. wheat, barley, and oat straw.[170] Greater availability of food, however, could also result in the aftermath of investments in bioenergy as a result of positive spillovers that could increase food supplies through intensification (i.e., increasing crop yields), such as mechanization, hydraulic infrastructures and technology in general.[171] This issue is explained in detail later.

Access

Food can be available but not accessible to the poorest groups of the population.[172] Food access is strictly related to the volatility of commodity prices and to population income.[173] Hence, access depends on the equilibrium of food supply and demand over time. In case of increases in food crop demand for alternative uses than food, crop

[164] Food and Agriculture Organization of the United States. (2013). The State of Food Insecurity in the World, 2013: The Multiple Dimensions of Food Security. Food and Agricultural Organization of the United Nations.

[165] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.

[166] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.; Rulli et al., The water-land-food nexus.

[167] Mohr, A., & Raman, S. (2015). Lessons from first generation biofuels and implications for the sustainability appraisal of second generation biofuels. Efficiency and Sustainability in Biofuel Production: Environmental and Land-Use Research, 63, 281–310. https://doi.org/10.1016/j.enpol.2013.08.033

[168] Brown, L. R. (2012). Full planet, empty plates: the new geopolitics of food scarcity. WW Norton & Company.

[169] Rulli et al., The water-land-food nexus.

[170] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.; Mohr & Raman, Lessons from first generation biofuels.

[171] Achterbosch, T. J., Meijerink, G. W., Slingerland, M. A., & Smeets, E. M. W. (2013). Combining bioenergy production and food security. NL Agency.; Naylor, R. L., Liska, A. J., Burke, M. B., Falcon, W. P., Gaskell, J. C., Rozelle, S. D., & Cassman, K. G. (2007). The ripple effect: biofuels, food security, and the environment. Environment: Science and Policy for Sustainable Development, 49(9), 30-43.;
Food and Agriculture Organization of the United Nations, Bioenergy and food security.

[172] Naylor et al., The ripple effect.; Sen, A. (1982). The food problem: Theory and policy. Third World Quarterly, 4(3), 447-459.

[173] Achterbosch et al., Combining bioenergy production; D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.; Naylor et al., The ripple effect.

prices can rise if supply does not keep pace with the demand.[174] In fact, Naylor et al. have observed that combining energy and food sectors led to food price spikes after a long time of declining prices.[175] For example, in 2006, 20% of corn was diverted from food use to biofuels production, resulting in the increase in food prices registered between 2003 and 2008.[176] Moreover, Hochman et al. suggest that biofuels have contributed to a 25% increase in corn prices in 2011 with respect to 2001.[177] Considering FAO estimates, the food price indexes of cereals, oils and sugars more than doubled in 2011 compared to the 2002-2004 average.[178] In general, biofuels production could favour crop producers (e.g. rural farmers) and damage food consumers, since producers may enjoy higher profits from biofuels production rather than food production and the consequent lower crop supply to the food system would result in higher food prices for consumers.[179] However, several studies assert the opposite suggesting that over time food prices could drop[180] because investments in mechanization and other management practices aimed at increasing biofuel production to maximize profits could boost crop production, allowing the crop demand to be met, thus balancing the market.[181] Furthermore, investments in the bioenergy sector (e.g. production, processing, transportation) may lead to the creation of new job opportunities and rural development.[182] Higher incomes may improve food security when they benefit rural livelihoods, especially small-scale bioenergy producers therefore allowing for rural development, and thus greater food access from the consumer's side.[183] In conclusion there is no consensus in the scientific arena on the role played by biofuel production on food access, calling for more in-depth cost-benefit analysis at different scales accounting also for environmental externalities.

Stability

Food stability is closely linked both to market trends of crop prices and to the availability of crop supply over time. In fact, the FAO's fourth pillar of food security states that people should have *enough and nutritious food at all times*.[184] On the one hand, biofuel markets can improve the security of farmer incomes and energy self-sufficiency; on the other hand fluctuations in food supply can exacerbate food insecurity conditions.[185] Biofuel energy markets can divert food crops from the food sector to the energy sector making the food system less resilient to shocks. Moreover, potential shortfalls in food supply can lead countries to import commodities, hence

[174] Naylor et al., The ripple effect.

[175] Ibid.

[176] EIA, Energy Information Administration, 2007. Biofuels in the US Transportation Sector. Published in Annual Energy Outlook 2007, February 2007; Mitchel, D. (2008). A note on rising food prices. The World Bank.; Sorda, G., Banse, M., & Kemfert, C. (2010). An overview of biofuel policies across the world. Energy Policy, 38(11), 6977–6988. https://doi.org/10.1016/j.enpol.2010.06.066

[177] Hochman, G., Kaplan, S., Rajagopal, D., & Zilberman, D. (2012). Biofuel and food-commodity prices. Agriculture, 2(3), 272-281.

[178] Sorda et al., An overview of biofuel policies across the world.

[179] Naylor et al., The ripple effect.; Rulli et al., The water-land-food nexus.

[180] Naylor et al., The ripple effect.; Food and Agriculture Organization of the United Nations, Bioenergy and food security.

[181] Naylor et al., The ripple effect.; Food and Agriculture Organization of the United Nations, Bioenergy and food security.

[182] Food and Agriculture Organization of the United Nations, Bioenergy and food security.

[183] Ibid.

[184] Vitousek, P. M., Naylor, R., Crews, T., David, M. B., Drinkwater, L. E., Holland, E., ... & Nziguheba, G. (2009). Nutrient imbalances in agricultural development. Science, 324(5934), 1519-1520.

[185] Achterbosch et al., Combining bioenergy production.; Rulli et al., The water-land-food nexus.

reducing their self-sufficiency making them more dependent on international trade and less stable in the face of market fluctuations.[186]

Considering trade-offs among finite resources, the expansion of first generation biofuels endangers the capacity to ensure adequate and sufficient food, especially in the case of external shocks (e.g. floods, droughts, pandemics) to the food system. Deprived of its surplus, the food system is less resilient to external catastrophes and shortages, and food stability over time is threatened.

Stability can be achieved with direct state intervention in the food economy through tariffs, subsidies, and governmental policies in order to restore balance between supply and demand.[187] For this reason, the sustainability of biofuel production and energy infrastructure and technologies must be addressed together with food security.[188]

TABLE 3.1 People that could be fed with the caloric content of the food crops used as biofuels feedstock, in absolute terms and for each TJ of produced biofuel.[189]

	PEOPLE¹ (10^6)	PEOPLE² (10^6)	PEOPLE¹ (CAP/TJ)	PEOPLE² (CAP/TJ)
BIOETHANOL				
United States	143.3	147.9	123	127
Brazil	29.1	28.6	57	56
Canada	9.3	8.8	134	126
World total/mean	203.9	206.7	113	111
BIODIESEL				
United States	9.6	11.1	76	88
Brazil	9.9	9.9	97	97
France	6.8	7.5	71	79
World total/mean	73.5	81.3	89	99

¹Consumer country diet, ²Producer country diet. World total is computed for People (10^6), mean for People (cap/TJ)

[186] Achterbosch et al., Combining bioenergy production.

[187] Ibid.

[188] Ibid.

[189] Rulli et al., The water-land-food nexus.

3.2 The Pressure of Biofuels on Land

The environmental effects of first-generation biofuel production expansion have led to criticism and debate. The increasing demand for ethanol implies a consequent increase in demand for crops such as corn in the United States and sugarcane in Brazil, causing concerns over land use change.[190] The effects can be direct or indirect in countries such as Brazil, with biofuel crop plantations replacing pastures, and new pastures replacing forested areas.[191] Similarly, the use of corn-based ethanol to replace gasoline in the United States could cause an increase in CO_2 emissions as a result of land cover change, within and outside of the country borders (e.g., expanding cropland area particularly on more marginal lands, including grasslands and wetlands).[192] Likewise, the boom of oil palm plantations in Southeast Asia, in response to biofuel and oil crop markets, is having important impacts on the high biodiversity of old-growth forests, including substantial emissions of GHGs from deforestation and particularly drainage of carbon-dense tropical peatlands.[193] Depending on the previous land cover and its carbon storage, the effects of negative net GHG emissions, which are considered to be the potential advantage of biofuels over conventional fossil fuels, can be nullified for decades (and even centuries). This positive carbon balance (i.e., positive greenhouse gas emissions) will persist until the "carbon debt" from the increased GHG emissions caused by deforestation has been paid off.[194]

3.2.1 Current Land Use for Biofuels Production

Cropland area covers more than 1.56 billion hectares worldwide. These include – among others – areas cultivated for the production of grain, oilseeds, protein, sugar, fibres, fruits, and vegetables. The FAO estimates that 34% percent of the total global land surface is "to some extent" prime and good land for rainfed agriculture (4.5 Bha). Of this area, 1.56 Bha is already in crop production and 1.8 Bha is classified as forest, protected areas, or urban. Thus, there are about 1.2 Bha of additional land that could be used for crop production, likely at the expense of savannas, grasslands, pastures, and ranges, which provide unique habitat to a variety of plant and animal species. About 26% of this land is in Latin America, 32% in Sub-Saharan Africa and most of the remainder in Europe, Oceania, Canada, and the USA.[195] Union zur Förderung von Oel und Proteinpflanzen (UFOP) (2020) estimates most cropland is used for food production, while only 5% of cropland is dedicated to biofuels production.[196] Excluding the commercial co-products from the gross biofuel land area, only 2.4% of arable land is used for

[190] De Oliveira, F. C., & Coelho, S. T. (2017). History, evolution, and environmental impact of biodiesel in Brazil: A review. *Renewable and Sustainable Energy Reviews*, *75*(October 2016), 168–179. https://doi.org/10.1016/j.rser.2016.10.060.

[191] Hermele, K. (2013). The Appropriation of Ecological Space: Agrofuels, unequal exchange and environmental load displacements. Routledge.

[192] Hertel, T. W., Golub, A. A., Jones, A. D., O'Hare, M., Plevin, R. J., & Kammen, D. M. (2010). Effects of US corn ethanol on global land use and greenhouse gas emissions: Estimating market-mediated responses. BioScience, 60(3), 223–231. https://doi.org/10.1525/bio.2010.60.3.8; Lark, T. J., Salmon, J. M., & Gibbs, H. K. (2015). Cropland expansion outpaces agricultural and biofuel policies in the United States. Environmental Research Letters, 10(4), 044003.; Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D., & Yu, T. H. (2008). Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science, 319(5867), 1238–1240. https://doi.org/10.1126/science.1151861.

[193] Carlson, K. M., Curran, L. M., Ratnasari, D., Pittman, A. M., Soares-Filho, B. S., Asner, G. P., ... & Rodrigues, H. O. (2012). Committed carbon emissions, deforestation, and community land conversion from oil palm plantation expansion in West Kalimantan, Indonesia. Proceedings of the National Academy of Sciences, 109(19), 7559-7564.; Rulli, M. C., Casirati, S., Dell'Angelo, J., Davis, K. F., Passera, C., & D'Odorico, P. (2019). Interdependencies and telecoupling of oil palm expansion at the expense of Indonesian rainforest. Renewable and Sustainable Energy Reviews, 105, 499-512.; West, P. C., Gerber, J. S., Engstrom, P. M., Mueller, N. D., Brauman, K. A., Carlson, K. M., Cassidy, E. S., Johnston, M., MacDonald, G. K., Ray, D. K., & Siebert, S. (2014). Leverage points for improving global food security and the environment. *Science*, *345*(6194), 325–328. https://doi.org/10.1126/science.1246067.

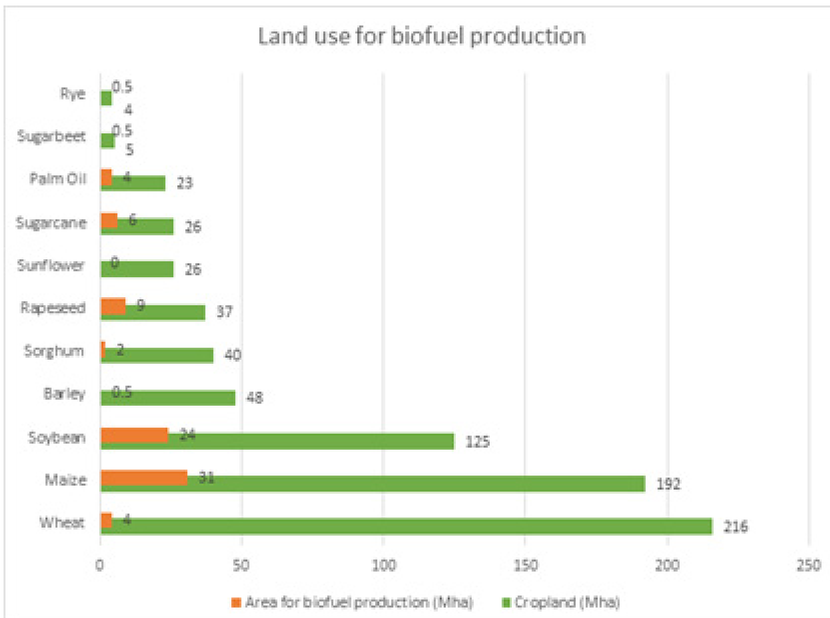
[194] Rulli et al., The water-land-food nexus.

[195] Souza et al., Bioenergy & sustainability: bridging the gaps.

[196] UFOP. 2020. *UFOP Global Supply Report 2019/2020*.

biofuel production.[197] On a global scale, corn and soy are the most cultivated crops for the production of biofuels, contributing to 67% of the total cropland area for biofuel. Figure 3.2 shows the amount of cultivated land for each type of crop for biofuel production. Between 2000 and 2010, the net 'increased area' (net of co-products) associated with biofuels was 13.5 Mha (24.9 Mha in total, where 11.4 was associated with co-products). This area is evenly used for the production of bioethanol (6.8 Mha) and biodiesel (6.7 Mha). The additional area necessary for co-products is roughly 6 Mha for bioethanol (almost all dried distillers grains with solubles (DDGS) in the USA) and 5.4 Mha with biodiesel (mostly EU rapeseed and then US soy).[198]

FIGURE 3.2. Total Cultivated area used to produce Crops for Global Biofuel Production (OECD, USDA, Oil World (2018)).



Biofuel yield varies among crops and planting regions. Ethanol has generally higher yields than biodiesel and sugary feedstocks are more productive when compared with starchy ones (Table 3.2).

[197] Langeveld et al., Biofuel cropping systems: carbon, land, and food.

[198] Souza et al., Bioenergy & sustainability: bridging the gaps.

TABLE 3.2 Biofuel Past and Future Yields 2005-2030 (IEA)

REGION-BIOFUEL	FEEDSTOCK	YIELD 2005 (L HA^{-1})	YIELD 2030[A] (L HA^{-1})
EU-ethanol	Wheat	2500	2980
EU-ethanol	Sugar beet	5000	5950
EU-biodiesel	Rapeseed	1200	1430
US-ethanol	Corn	3000	3570
US-biodiesel	Soybean/rapeseed	800	952
Brazil-ethanol	Sugarcane	6800	8100
Brazil-biodiesel	Soybean	700	900
RoW-ethanol[b]	Sugarcane	5500	7050
RoW-ethanol	Grain[c]	2000	2560
RoW-biodiesel	Oil palm	2500	3200
RoW-biodiesel	Soybean/rapeseed	1000	1200
World-ethanol	Ligno-cellulose	4300	5940
World-BtL diesel	Biomass[d]	3000	4140

[a] Calculated by Regis et al. (2012), based on International Energy Agency (2010).
[b] RoW: Rest of the World.
[c] Essentially corn and wheat.
[d] Ligno-cellulosic material.

3.2.2 Land Use Change and Greenhouse Gasses Emissions

Given the different pressures on finite natural resources, biofuels production can contribute directly or indirectly to land use change (respectively dLUC and iLUC).[199]

dLUC includes changing cropping systems on existing agricultural land or through extensification of biofuel feedstock production on available land for cultivation.[200] At the same time, a controversial aftermath of biofuel production is iLUC which includes the indirect expansion of food crops on high value ecosystems in order to keep

[199] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.; Harvey, M., & Pilgrim, S. (2011). The new competition for land: Food, energy, and climate change. Food policy, 36, S40-S51.; Hermele, The Appropriation of Ecological Space.; Hughes, S. R., & Qureshi, N. (2014). Biomass for Biorefining: Resources, Allocation, Utilization, and Policies. In Biorefineries(pp. 37-58). Elsevier.; Searchinger et al., Use of U.S. croplands for biofuels increases greenhouse gases.

[200] Van Stappen F., Brose I., Schenkel Y. 2011. Direct and indirect land use changes issues in European sustainability initiatives: State-of-the-art, open issues and future developments. Biomass and Bioenergy, 35, 12, https://doi.org/10.1016/j.biombioe.2011.07.015; Gawel, E., & Ludwig, G. (2011). The iLUC dilemma: How to deal with indirect land use changes when governing energy crops?. Land Use Policy, 28(4), 846-856.

pace with food and feed demand.[201] This is exemplified by the rise in food prices after the shift in end use (e.g. crops produced for fuel instead of food) in 2008 and the consequent expansion of crop production in pastureland or forests.[202] These land use changes may lead to the release of CO_2, potentially enhancing climate change. An example of the exact impact of two crop expansions in Brazil for biofuel production is demonstrated in table 3.3.

TABLE 3.3 Land Use Change in Brazil[203]

CROP	DLUC (10^6 HA)	ILUC (10^6 HA)	LUC (10^6 HA)
Sugarcane	5.7	7.8	13.6
Soybean	10.8	10.8	21.6

A widely used argument in favour of biofuel expansion is the need to reduce GHG emissions by replacing emission intensive fossil fuels.[204] The direct CO_2 emissions are lower for biofuels than for traditional fossil fuels, mainly because the crop cultivation phase of biofuel production contributes to carbon sequestration through the photosynthetic process, which compensates the emissions of the processing and utilization stages.[205]

However, carbon sequestration can be overwhelmed by indirect emissions of biofuel production due to land use change (e.g. in response to the biofuel expansion plans in Brazil or through the European oil palm demand in Malaysia and Indonesia).[206] The CO_2 emissions associated with deforestation to make room for biofuel crop cultivation, are the results of burning or decomposition of forest biomass, and the oxidation of organic soil are high and. The magnitide and lifetime of such emissions to may nullify the benefits of biofuel production, especially in the medium and long term.[207] Fajardy & Mac Dowell report land conversion factors by Fargione et al. in terms of tons of CO_2 produced for each hectare of native land that is converted to biofuel production.[208] The values, reported in Table 3.3, vary strongly depending on the type of native ecosystem and on the biomass produced: oilseed plants for biodiesel production produce roughly 600 tons of CO_2 per hectare of converted tropical rainforest; this can more than double when peatland is converted, and the latter value can increase up to $3452t_{CO2}$/ha.[209] Corn and sugarcane for ethanol production range around $150t_{CO2}$/ha depending on the crop, the location, and the converted native ecosystem. This effect can be mitigated by converting abandoned cropland

[201] Searchinger et al., Use of U.S. croplands for biofuels increases greenhouse gases.

[202] Ibid.

[203] Lapola DM, Schaldach R, Alcamo J, Bondeau A, Koch J, et al. 2010. Indirect land-use changes can overcome carbon savings from biofuels in Brazil. P Natl Acad Sci USA 107(8): 3388-3393.

[204] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.; Rulli et al., The water-land-food nexus.; Searchinger et al., Use of U.S. croplands for biofuels increases greenhouse gases.

[205] Naik, S. N., Goud, V. V., Rout, P. K., & Dalai, A. K. 2010. Production of first and second generation biofuels: A comprehensive review. In Renewable and Sustainable Energy Reviews (Vol. 14, Issue 2, pp. 578–597). Pergamon. https://doi.org/10.1016/j.rser.2009.10.003

[206] Lapola et al., Indirect Land-use changes; Rulli et al., Interdependencies and telecoupling of oil palm expansion.

[207] Tilman, D., Socolow, R., Foley, J. A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., & Williams, R. (2009). Beneficial biofuels - The food, energy, and environment trilemma. Science, 325(5938), 270–271. https://doi.org/10.1126/science.1177970

[208] Fajardy, M., & Mac Dowell, N. (2017). Can BECCS deliver sustainable and resource efficient negative emissions?. Energy & Environmental Science, 10(6), 1389-1426.; Fargione, J., Hill, J., Tilman, D., Polasky, S., & Hawthorne, P. (2008). Land Clearing and the Biofuel Carbon Debt. 319(February), 1235–1239.

[209] Ibid.

or marginal land, lowering the conversion factors to $6t_{CO2}$/ha and even 0-70kg_{CO2}/ha respectively.[210] This is more viable for second generation biofuels because energy crops require less agricultural inputs than food crops to attain acceptable yields.

Direct land use change may not take place for first generation biofuels when already cultivated land is diverted to biofuel production; instead it triggers indirect land use change. Converting food crops to biofuel production reduces the availability of land for food production and increases the price of food crops.[211] Thus, rangeland and cropland are expanded through conversion of native ecosystems, in response to the market alteration.[212] One study found that, "By using a worldwide agricultural model to estimate emissions from land-use change…corn-based ethanol, instead of producing a 20% savings, nearly doubles greenhouse emissions over 30 years and increases greenhouse gases for 167 years." The magnitude of the effect is such that the replacement of fossil fuels with ethanol from corn results in a 20% decrease in GHG emissions not including indirect land use change but a 97% increase in GHG emissions when accounting for indirect land use change (Table 3.8).[213] The use of trade and of second generation biofuels from residues can be a step in the right direction, but it may not be enough. Hertel et al. find that resorting to market and by-product use to produce corn ethanol reduces GHG emissions per unit energy by 75% with respect to previous estimates, but this reduction is still not enough to reach a non-positive net GHG balance.[214]

The areas where land and water are available for biomass production are not necessarily those where biofuel demand originates or where fossil fuel production occurs. Thereby, an expansion of biofuel production able to meet future energy demand scenarios, be it first or second generation, would require the setup of an international supply chain for biofuels comparable to the one currently available for fossil fuels, with the consequent CO_2 emissions.[215]

Another issue is that CO_2 absorption effects are longer term than the almost immediate GHG emissions derived from land conversion. This generates a 'carbon debt' whose payback times often exceeds the life cycle of cars and power plants.[216] Payback times have been estimated to range between 2 and 9 decades for bioethanol and 1 and 4 centuries for biodiesel.[217] Table 3.4 reports carbon debt per unit area and payback time for direct and indirect land use change of different ecosystems in Brazil, Indonesia and Malaysia, and the U.S.

[210] Ibid.

[211] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.; Searchinger et al., Use of U.S. croplands for biofuels increases greenhouse gases.

[212] Hertel, Effects of US corn ethanol on global land use and greenhouse gas emissions.; Searchinger et al., Use of U.S. croplands for biofuels increases greenhouse gases.

[213] Searchinger et al., Use of U.S. croplands for biofuels increases greenhouse gases.

[214] Hertel, Effects of US corn ethanol on global land use and greenhouse gas emissions.

[215] Fajardy & Mac Dowell. Can BECCS deliver sustainable and resource efficient negative emissions?

[216] Ibid.

[217] Fargione et al., Land Clearing and the Biofuel Carbon Debt.; Lapola et al., Indirect land-use changes can overcome carbon savings.

In summary, first generation biofuels may produce more GHG emissions than they could mitigate if agricultural expansion is not well planned.[218] The fact that the consequences of indirect land use change are delayed in space and time generates a variety of spillover effects and socio-economic externalities. The land claimed to expand rangeland and cropland in response to food crop diversion from food to biofuel production displaces the effect on people and ecosystems to other locations from those that could benefit from biofuel production. Moreover, the marginal land that can be used for low-emission land conversion may be vital for subsistence farmers.[219] Further comments on the possibility to sustainably expand biofuel production using marginal land can be found later in this chapter. Use of crops residues seems again to be the most sustainable option for biofuel expansion, but whether residual biomass alone will be able to meet future bioenergy demand remains an open question.

[218] For additional information on this topic, please see: Berndes et al. 2015. Soils and water. In: Bioenergy & Sustainability: bridging the gaps / edited by Glaucia MendesSouza, Reynaldo L. Victoria, Carlos A. Joly and Luciano M. Verdade. SCOPE 72.; Mello et al. 2014. Payback time for soil carbon and sugar-cane ethanol. Nature Climate Change (4): 605-609.; Bordonal et al. 2015. Greenhouse gas balance from cultivation and direct land use change of recently established sugarcane (Saccharum officinarum) plantation in south-central Brazil. Renewable and Sustainable Energy Reviews (52): 547-556.

[219] Mohr & Raman, Lessons from first generation biofuels.

TABLE 3.4 Carbon debt per unit area and payback time for direct and indirect land use change of different ecosystems in Brazil, Indonesia and Malaysia, and the U.S.

COUNTRY	LAND USE CHANGE	CONVERSION	CROP	CARBON DEBT (MG/HA)	PAYBACK TIME (YR)	REF.
Brazil	DLUC	Rangeland to biofuel	Sugarcane	75	4	a
		Rangeland to biofuel	Soybean	75	28	a
		Cerrado grassland to biofuel	Soybean	85	37	b
		Other natural to biofuel	Soybean	120	0	a
		W. Savanna to biofuel	Soybean	165	1	a
		Cerrado wood to biofuel	Sugarcane	165	17	b
		Forest to biofuel	Soybean	680	6	a
		Tropical rainforest to biofuel	Soybean	737	319	b
Brazil	ILUC	Other natural to rangeland	Sugarcane	66	1	a
		Rangeland to cropland	Sugarcane	70	0	a
		Other natural to rangeland	Soybean	70	5	a
		Rangeland to cropland	Soybean	78	3	a
		W. Savanna to rangeland	Soybean	144	7	a
		W. Savanna to rangeland	Sugarcane	150	1	a
		Forest to rangeland	Soybean	689	196	a
		Forest to rangeland	Sugarcane	690	38	a
Indonesia/ Malaysia	DLUC	Tropical rainforest to biofuel	Oil palm	702	86	b
		Peatland rainforest to biofuel	Oil palm	1294	423	b
US	DLUC	Marginal cropland to biofuel	Prairie	0	0	b
		Abandoned cropland to biofuel	Prairie	6	1	b
		Abandoned cropland to biofuel	Corn	69	48	b
		Central grassland to biofuel	Corn	134	95	b

a) Lapola et al., Indirect land-use changes can overcome carbon savings.
b) Fargione et al., Land Clearing and the Biofuel Carbon Debt.; D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.

3.3 The Pressure of Biofuels on Water

Biofuels have received increasing attention and support by policy makers as an instrument for sustainable development to ensure economic growth while reducing fossil fuel dependency and increasing the renewable share of energy consumption.[220] However, the impact of biofuel production on freshwater resources has only been evaluated recently, despite the much greater rates of water consumption for biofuels with respect to traditional fossil fuels.[221] An often overlooked, yet interesting explanation for the difference in water consumption between biofuels and fossil fuels is that fossil fuel water consumption only accounts for extraction and processing water inputs. Indeed, the biomass that generated fossil fuels was produced in past geological eras by the same transpiration process that is needed to sustain biomass today, and thus fossil fuel production likely required the consumption of similar amounts of water.[222] This water is not accounted for because it was consumed in previous geological eras. Conversely, biofuel production adds stress to currently available water sources. Considering the water crisis the world is facing, with two thirds of the global population living in conditions of water scarcity for at least a part of the year, additional pressure on water resources for the biofuel industry and its competition for water with the food industry is a problem that needs to be addressed thoroughly.[223]

3.3.1 Current Water Use for Biofuels Production

Globally, irrigation water used for biofuel production is estimated by the World Water Assessment Programme at 44 km3, or 2% of all irrigation water in 2014.[224] With the existing production technologies it takes an average of roughly 2,500 litres of water (about 820 litres of irrigation water) to produce 1 litre of liquid biofuel.[225]

The share of irrigation water used for biofuel production is negligible in Brazil and the European Union, where crops are mostly rainfed, while it is estimated to be 2% in China and 3% in the United States. Analysis by Jeeam in 2014 showed that implementing all current national biofuel policies and plans would take 30 million hectares of cropland and 180 km3 of additional irrigation water, almost four times the current water demand.

Water is required in most stages of biofuel production. Most water use for biofuel production – roughly 99% - is for the cultivation of crops, but it is also important, especially in a policy context, to consider both water withdrawal and consumption in the processing stage, which might have more intense local effects.[226]

Water in the cultivation stage is essentially needed to support the plant evapotranspiration process. Evapotranspiration depends on climate and weather conditions, principally air humidity, radiation, wind speed and temperature; the potential value rendered by the atmospheric demand of water is then modulated by the needs of the specific crop in each of its

[220] Sorda et al., An overview of biofuel policies across the world.

[221] Dominguez-Faus, R., Powers, S. E., Burken, J. G., & Alvarez, P. J. (2009). The water footprint of biofuels: A drink or drive issue? In Environmental Science and Technology (Vol. 43, Issue 9, pp. 3005–3010). https://doi.org/10.1021/es802162x.; Fingerman, K. R., Torn, M. S., O'Hare, M. H., & Kammen, D. M. (2010). Accounting for the water impacts of ethanol production. Environmental Research Letters, 5(1), 014020. https://doi.org/10.1088/1748-9326/5/1/014020

[222] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.

[223] Mekonnen, M. M., & Hoekstra, A. Y. (2016). Sustainability: Four billion people facing severe water scarcity. *Science Advances*, *2*(2), 1–7. https://doi.org/10.1126/sciadv.1500323.

[224] "Fact 22: Water & Biofuels | United Nations Educational, Scientific And Cultural Organization". 2014. *Unesco.org*. http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/facts-and-figures/all-facts-wwdr3/fact-22-water-biofuels/.

[225] Ibid.

[226] Fingerman et al., Accounting for the water impacts of ethanol production.

growing phases.[227] Plants use photosynthesis to chemically convert water and carbon dioxide into primary and secondary metabolites: primary metabolites are simple organic molecules such as glucose, cellulose, and starch, while secondary metabolites are less abundant, more complex, and more valuable.[228] These secondary metabolites are the feedstock that is refined to produce biofuels. Photosynthesis relates to transpiration through stomatal regulation in that, as plants open the stomata to sequester atmospheric carbon, they lose water vapor (transpiration). Plants capture water primarily from the ground through the root apparatus. When the water required by the plant's vital processes is more than what the plant can currently abstract (i.e., relying on soil moisture naturally replenished by precipitation), additional water can be supplied by means of irrigation to avoid crop water stress and subsequent yield reduction.[229] Moreover, especially for food crops (thus for first generation biofuels), N and P fertilizers are used to increase yield, which requires substantial amounts of water (grey water) to dilute pollutants, in addition to having energy- and carbon-intensive supply chains.[230]

The principal feedstock sources for bioethanol are corn and sugarcane, followed by wheat, sugarbeet, and sorghum, but other starch-rich crops such as potato and cassava or other cereals such as barley, rye, and rice are also used.[231] Sugarcane is the highest ethanol biomass contributor, whereas corn is the most yielding, most water-intensive, and the most used bioethanol feedstock, accounting for two thirds of world bioethanol production.[232] Oilseed plants such as soy, oil palm, and rapeseed are the main sources for biodiesel.[233] Oil palm is the most water-demanding feedstock when compared to soy, however soy yields are smaller per unit of land.[234] Any local deficit in biomass production is compensated by trade of biomass (and thus essentially a virtual water trade), by importing the biomass from exporters. This traded biofuel accounts for 3% of world bioethanol production and up to 20% of the OECD+EU27 countries' biodiesel production - thus, bioethanol is produced and used mostly domestically; biodiesel is also produced and used mostly domestically but is traded internationally at higher levels.[235]

The main energy crops for second generation biofuels production are herbaceous plants such as miscanthus or ligneous plants such as pine or eucalyptus.[236] Energy crops have generally lower water requirements than food crops, and provide satisfying yields with low inputs, but they present usually low biomass-to-biofuel yield.[237]

[227] Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). FAO Irrigation and Drainage No. 56. Crop Evapotranspiration (guidelines for computing crop water requirements). https://doi.org/10.1016/j.eja.2010.12.001

[228] Naik et al., Production of first and second generation biofuels.

[229] Allen et al., FAO Irrigation and Drainage No. 56.

[230] Fajardy, M., & Mac Dowell, N. (2017). Can BECCS deliver sustainable and resource efficient negative emissions? Energy and Environmental Science, 10(6), 1389–1426. https://doi.org/10.1039/c7ee00465f.;Wu, M., Chiu, Y., & Demissie, Y. (2012). Quantifying the regional water footprint of biofuel production by incorporating hydrologic modeling. Water Resources Research, 48(10). https://doi.org/10.1029/2011WR011809

[231] Gerbens-Leenes, Bioenergy water footprints, comparing first, second and third generation feedstocks for bioenergy supply in 2040.; Rulli et al., The water-land-food nexus.

[232] Rulli et al., The water-land-food nexus.

[233] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.

[234] Rulli et al., The water-land-food nexus.

[235] Ibid.

[236] Gerbens-Leenes, Bioenergy water footprints, comparing first, second and third generation feedstocks for bioenergy supply in 2040.; Mohr & Raman, Lessons from first generation biofuels.;Mohr, A., & Raman, S. (2015). Lessons from first generation biofuels and implications for the sustainability appraisal of second generation biofuels. Efficiency and Sustainability in Biofuel Production: Environmental and Land-Use Research, 63, 281–310. https://doi.org/10.1016/j.enpol.2013.08.033

[237] Gerbens-Leenes, Bioenergy water footprints, comparing first, second and third generation feedstocks for bioenergy supply in 2040.; Mohr & Raman, Lessons from first generation biofuels.; Mohr, A., & Raman, S. (2015). Lessons from first generation biofuels and implications for the sustainability appraisal of second generation biofuels. Efficiency and Sustainability in Biofuel Production: Environmental and Land-Use Research, 63, 281–310. https://doi.org/10.1016/j.enpol.2013.08.033

Residues for second generation biofuels are typically agricultural and forestry byproducts such as leaves and straw or solid organic wastes.[238] The water input for residues are low, as they share the water requirement of the primary product they derive from.[239] Leaving crop residues on the field to increase the soil organic content and to reduce soil evaporation and erosion is a common and advisable farming practice, but using some of them for farming and bioenergy is also a viable option.[240] However, removing straw and agricultural byproducts from food crop fields creates the need for additional fertilizer, generating additional grey water outputs.[241] Some competition may arise as residues are also used for livestock feeding, but given the increasing global meat demand, livestock production systems are getting more and more industrialized, thus moving away from this market.[242] This demonstrates the complexities of even advanced biofuel production and its impact on direct and indirect water usage.

Biomass is converted to biofuels or bioenergy by thermochemical or biochemical processes, depending on the source and the final product. The grain product must be ground and mixed with water to enable the cleavage of polysaccharides into glucose by yeast.[243] The bacteria then anaerobically digest the glucose generating ethanol and carbon dioxide. The mixture is then distilled to separate the ethanol: water is lost in this process (though in amounts much smaller than water losses in the field by transpiration), mainly through the heating and cooling process, incorporation in the final product, and in the DDGS (distiller's dried grains with solubles) by-product.[244] Beside the direct loss of water due to evaporation or system efficiency, cooling water generates a grey water footprint due to side production of ammonia and sulfuric acid as well as thermal pollution.[245]

Second generation bioethanol is produced from lignocellulosic biomass with a hydrolysis-fermentation process analogous to first generation bioethanol, but the complex structure of lignocellulosic biomass requires some additional pre-treatment that can be water- and heat-intensive, such as steam explosion to disintegrate biomass.[246] Water consumption in the processing phase for first generation bioethanol has been estimated as 3 liters of water per liter of bioethanol (L/L), excluding the water consumption associated with the treatment plant setup, whereas for second generation bioethanol the value rises to 9.8 L/L.[247]

[238] Searchinger et al., Use of U.S. croplands for biofuels increases greenhouse gases.; Tilman, D., Socolow, R., Foley, J. A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., & Williams, R. (2009). Beneficial biofuels - The food, energy, and environment trilemma. Science, 325(5938), 270–271. https://doi.org/10.1126/science.1177970.; Wu, M., Mintz, M., Wang, M., & Arora, S. (2009b). Water consumption in the production of ethanol and petroleum gasoline. Environmental Management, 44(5), 981–997. https://doi.org/10.1007/s00267-009-9370-0.

[239] Wu et al., Water consumption in the production of ethanol and petroleum gasoline.

[240] Tilman et al., Beneficial biofuels.

[241] Fajardy, M., & Mac Dowell, N. (2017). Can BECCS deliver sustainable and resource efficient negative emissions? Energy and Environmental Science, 10(6), 1389–1426. https://doi.org/10.1039/c7ee00465f

[242] Cassidy et al., Redefining agricultural yields.

[243] Gerbens-Leenes, Bioenergy water footprints, comparing first, second and third generation feedstocks.

[244] Fingerman et al., Accounting for the water impacts of ethanol production.; Wu, M., Mintz, M., Wang, M., & Arora, S. (2009a). Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline. ACS National Meeting Book of Abstracts, 1–77. www.anl.gov.

[245] Wu et al., Quantifying the regional water footprint of biofuel production.; Wu et al., Water consumption in the production of ethanol and petroleum gasoline.

[246] Naik et al., Production of first and second generation biofuels.

[247] Wu et al., Water consumption in the production of ethanol and petroleum gasoline.

Whole-crop biorefineries are the plants dedicated to the conversion of biomass into a range of products, including biodiesel, through a stepwise process analogous in principle to traditional crude oil refineries.[248] In biorefineries, vegetable oil is extracted from oil crops and converted into biodiesel through transesterification, a chemical reaction that requires alcohol as a reagent.[249] Water use and loss in the biorefinery process include washing water to remove residual catalyst and condensation water to recover solvents.[250]

Third generation biodiesel is obtained from algae, also through a biorefinery process. The extraction process of fatty biomass is easier for algae than for oil crops, and the by-products are still marketable.[251] Water consumption in biorefineries is about 1 L/L, regardless of the feedstock.[252]

3.3.2 Water Footprint of Biofuels

The 2016 World Energy Outlook by the International Energy Agency (IEA) states that, while agriculture is and remains the most water-intensive sector, energy production and power generation are projected to have substantially increased impacts on water resources by 2040, with water withdrawal and consumption rising by 2% and 60% respectively.[253] This stronger relative growth of water consumption to withdrawals is also related to the aforementioned policy-driven boosting of the biofuel sector and is caused by the water demands of the crops cultivated to generate biomass.[254] The best and most widely used approach to assess water consumption by a process or a product (in this case, biofuels) is the water footprint approach proposed by Hoekstra et al.[255] The water footprint is made up of 3 components: a green, blue, and grey water footprint. The green water footprint is an indicator of the use of water originating from rain that does not generate runoff, but is instead stored in the soil or in plant biomass and eventually evaporates or transpires. The blue water footprint is water withdrawn from a surface or subsurface water body and consumed in a given process, e.g. irrigation water for non-rainfed crops.

The grey water footprint is an indicator of pollution representing the volume of water necessary to absorb the water pollution load associated with a given process. In the case of biofuels, not only the water footprint itself, but also its repartition among its green, blue, and grey components is strongly dependent on the crops used; the location, in terms of climate and soil; and on the type of biofuel generated - first, second, or third generation biofuels.[256]

[248] Ibid.

[249] Ibid.

[250] Subhadra, B. G., & Edwards, M. (2011). Coproduct market analysis and water footprint of simulated commercial algal biorefineries. Applied Energy, 88(10), 3515–3523. https://doi.org/10.1016/j.apenergy.2010.12.051.

[251] Ibid.

[252] Harto, Christopher, Robert Meyers, and Eric Williams. 2010. "Life Cycle Water Use Of Low-Carbon Transport Fuels". *Energy Policy* 38 (9): 4933-4944. doi:10.1016/j.enpol.2010.03.074.

[253] IEA. (2016). World Energy Outlook 2016 - LubaValby7566.pdf.

[254] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.

[255] Hoekstra, A. Y., Chapagain, A. K., Aldaya, M. M., & Mekonnen, M. M. (2012). The Water Footprint Assessment Manual. In The Water Footprint Assessment Manual. https://doi.org/10.4324/9781849775526

[256] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.; Fingerman et al., Accounting for the water impacts of ethanol production.; Wu et al., Water consumption in the production of ethanol and petroleum gasoline.

Table 3.5 shows water footprint values for a range of first and second generation biofuel feedstocks. First generation biofuels have an average water footprint ranging between roughly 40 and 150m3/GJ, 80% of which is green water.[257] Second generation biofuels from crop residuals have a much lower green water footprint, since only a small part of crop evapotranspiration goes into the production of the residual biomass used for producing this type of biofuels.[258] In fact, water footprints of crop residuals in Table 3.5 are lower both in terms of feedstock mass and energy production, meaning that, even when the processing stage is more complex than for first generation biofuels, the lower water footprint in the cultivation stage propagates along the whole producion chain. For second generation biofuels, energy crops are not usually irrigated nor fertilized, so their biomass water footprint has no blue or grey component.[259] Although their water footprint per ton of feedstock is comparable, if not lower, than that of first generation biofuels, their green water footprint per unit energy is often higher, as can be seen in Table 3.5. This is because the conversion process is more water intensive and the caloric yield of energy crops is lower. Moreover, the longer life cycle of energy crops may alter the groundwater recharge system for longer periods, and their processing stage is water-intensive.[260] Nonetheless, the second generation biofuel water footprint does not directly compete with food, as their biomass has no alternative food-related use.[261]

However, competition may be possible for energy crops in case of future biofuel expansion, as they would use water and land resources that could otherwise be destined to food crops for food production.[262] Third generation bioenergy presents complementary issues. Since third generation bioenergy is derived from algae, it has only a blue water footprint, ranging from 8 to 35 m3/GJ, but if bioenergy production were to expand through third generation biofuels, the increase in blue water consumption to fulfill future demand as given by the 2040 IEA energy scenario would pose serious challenges to global freshwater reserves.[263] The effects of water consumption, especially if compared with greenhouse emissions, are typically dependent on where and when water is consumed.[264] First, volumes of consumed water that have a negligible marginal effect on the global freshwater availability may have significant impacts on a regional or local scale.[265] Second, differences between distribution in space and time of biofuel demand and water availability would be compensated by virtual water trade, resulting in market alterations as explained by Rulli et al. in the "3.1.1.Competition with food section" of this chapter.[266] From a water footprint perspective, a more viable strategy to tackle the increasing demand of biofuels, and bioenergy in general, without entering competition with food seems to be the employment of second generation biofuels from crop residuals.

[257] Gerbens-Leenes, Green, Blue and Grey Bioenergy Water Footprints, a Comparison of Feedstocks for Bioenergy Supply in 2040.; Rulli et al., The water-land-food nexus.

[258] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.; IEA. (2016). World Energy Outlook 2016 - LubaValby7566.pdf.

[259] Fajardy & Mac Dowell, Can BECCS deliver sustainable and resource efficient negative emissions?

[260] Mohr & Raman, Lessons from first generation biofuels.

[261] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.

[262] Mohr & Raman, Lessons from first generation biofuels.

[263] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.; Gerbens-Leenes, P. W. (2018). Green, Blue and Grey Bioenergy Water Footprints, a Comparison of Feedstocks for Bioenergy Supply in 2040. Environmental Processes, 5, 167–180. https://doi.org/10.1007/s40710-018-0311-x; IEA, World Energy Outlook 2016.

[264] Fingerman et al., Accounting for the water impacts of ethanol production.

[265] Mohr & Raman, Lessons from first generation biofuels.

[266] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.; Rulli et al., The water-land-food nexus.

TABLE 3.5 World average water footprint (WF) per unit mass of feedstock and unit energy for different types of biofuel.

	CROP	WF (M3/TON)	WF (M3/GJ)	REF.
BIOETHANOL				
1st generation	Sugar beet	132	50	a,c
	Sugar cane	210	90	
	Potato	287	90	
	Cassava	564	110	
	Corn	1222	120	
	Barley	1423	140	
	Rye	1544	150	
	Paddy rice	1673	160	
	Wheat	1827	180	
2nd generation energy crops	Pine	1299	491	b
	Eucalyptus	1305	160	a,b
	Mischantus	708	80	a,b
2nd generation residues	Sugar cane bagasse	130.4	18.3	b
	Corn stover	205.4	28.3	
	Paddy rice straw	128.7	21.7	
	Wheat straw	140	25.3	
	Sugar beet pulp	36.9	6.3	
	Cassava stalks	86.6	23.1	
	Rapeseed straw	205.2	40.9	
	Cotton stalks	154.5	61.2	
	Sunflower straw	636.3	61.3	

contiues >

BIODIESEL AND PYROLOYSIS OIL				
1st generation	Oil palm	1098	155	a,c
	Rapeseed	2271	195	
	Soybean	2145	345	
	Pine	1299	200	a,b
	Eucalyptus	1305	100	
	Mischantus	708	62.5	
2nd generationn energy crops	Sugar cane bagasse	130.4	8	b
	Corn stover	205.4	20.1	
	Paddy rice straw	128.7	28.5	
	Wheat straw	140	24.1	
	Sugar beet pulp	36.9	8	
	Cassava stalks	86.6	7.1	
2nd generation residues	Soybean straw	187.7	12.3	
	Rapeseed straw	205.2	27.1	
	Cotton stalks	154.5	12.9	
	Sunflower straw	636.3	191.3	

a) Gerben – Leenes, 2018; b) Mathioudakis et al., 2017; c) Mekonnen & Hoekstra, 2012

3.4 Land and Water Availability without Competing with Food and Causing Unwanted Ecological Impacts

In the face of a steadily increasing world demand for food, the two rooted complementary strategies for increasing agricultural production are intensification and expansion.[267] Agricultural intensification is the increase in land productivity through increased inputs, such as water and fertilizers, or optimized practices, whereas extensification is the increase in production through expansion into uncultivated areas.[268] These two approaches should not be practiced without consideration for spillover effects and sustainability factors, since, as Table 3.6 shows, we are already pushing the limits of our planet in terms of water and land resources, and fertilizers can

[267] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.; FAO. (2008). The State of Food and Agriculture. http://www.fao.org/catalog/inter-e.htm.; Rosa, L., Rulli, M. C., Davis, K. F., Chiarelli, D. D., Passera, C., & D'Odorico, P. (2018). Closing the yield gap while ensuring water sustainability. Environmental Research Letters, 13(10). https://doi.org/10.1088/1748-9326/aadeef

[268] FAO, The State of Food and Agriculture.

have significant negative environmental impacts.[269] Several studies, for example Tilman et al., analyzed the extent of these combined effects according to present trends, finding that there could be an increase in 1 billion hectares of land and in nitrogen use of 250 Mt per year by 2050.[270] To meet future demand within planetary boundaries it is widely recognized that the only viable solution is the sustainable intensification of agriculture.[271]

TABLE 3.6 Natural Resources use and Planetary Boundaries

TYPE	BLUE WATER (KM^3)	LAND (10^6 HA)	REFERENCE
Total crop use	7400[1]	1500[2]	a
Biofuel use	11	41.3	b
Planetary boundaries	2500	1200	c

a) [1] Mekonnen et Hoekstra, 2011; [2] Sachs, 2015; b) Rulli et al., The water-land-food nexus.; D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.;c) Willett et al., 2019

Therefore, finding the combination of interventions able to increase agricultural production in a sustainable way is not only a core issue for the biofuel sector, but for the whole food system, and thus requires comprehensive policies.

3.4.1 Surplus from Boosting Feedstock Productivity (Intensification)

Intensification can help in ensuring increased productivity through irrigation, mechanization, and regionally specific inputs including fertilizers and seeds, but it may also generate several externalities including water scarcity, freshwater resources pollution, the emergence of dead zones, biodiversity losses, and large-scale land acquisition (LSLAs).[272] For example, intensification through increased inputs is sustainable only if this increase does not generate additional environmental costs. Sustainable intensification allows water to be withdrawn for irrigation only where the withdrawal does not generate water scarcity. Likewise, in sustainable intensification practices the environmental optimum for fertilizer use must be sought, although it may not coincide with the

[269] Stehfest, E., G. B. Woltjer, A. G. Prins, B. Eickhout, and M. Banse. 2009. First and second generation biofuels up to 2030: possible scenarios and their environmental impacts. Paper presented at the AGSAP conference, 10–12 March 2009, Egmond aan Zee, The Netherlands.; Stehfest, E., Bouwman, L., Van Vuuren, D. P., Den Elzen, M. G. J., Eickhout, B., & Kabat, P. 2009. Climate benefits of changing diet. Climatic Change, 95(1–2), 83– 102. https://doi.org/10.1007/s10584-008-9534-6

[270] Tilman, D., Balzer, C., Hill, J., & Befort, B. L. (2011). Global food demand and the sustainable intensification of agriculture. Proceedings of the national academy of sciences, 108(50), 20260-20264.

[271] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.; Erb et al., Exploring the biophysical option space.; Foley et al., Solutions for a cultivated planet.; Garnett et al., Sustainable intensification in agriculture: premises and policies.; Tilman et al., Global food demand.; Mbow, C., C.Rosenzweig, L.G.Barioni, T.G.Benton, M.Herrero,M.Krishnapillai,E.Liwenga,P.Pradhan,M.G.Rivera-Ferre, T. Sapkota, F.N. Tubiello, Y. Xu, 2019: Food Security. In: Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press.

[272] Diaz, R. J., & Rosenberg, R. (2008). Spreading dead zones and consequences for marine ecosystems. science, 321(5891), 926-929.; D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.; FAO, The State of Food and Agriculture.; Jägermeyr, J., Pastor, A., Biemans, H., & Gerten, D. (2017). Reconciling irrigated food production with environmental flows for Sustainable Development Goals implementation. Nature Communications, 8(1), 1-9.; Vitousek, P. M., Naylor, R., Crews, T., David, M. B., Drinkwater, L. E., Holland, E., ... & Nziguheba, G. (2009). Nutrient imbalances in agricultural development. Science, 324(5934), 1519-1520.

economic optimum.[273] Alternative approaches to yield boosting can be achieved through improved management practices, and through optimizing choices in crop varieties. Irrigating crops that are currently rainfed can raise yield and boost production: adding about 400 km3 of irrigation water on currently rainfed agricultural land could feed 2.8 billion people.[274] Additional water inputs, if well calibrated and combined with fertilization, can increase the production of biomass in a way that the GHG emissions per unit of biofuel-generated energy are substantially lowered.[275]

Fertilizers, in particular nitrogen (N), are popular and established instruments for yield boosting but their efficiency depends on the agricultural practices they are combined with.[276] Moreover, only a carefully tuned fertilization rate can increase yields without negating the positive environmental effects of biofuels.[277] Tilman et al. points out the need for a global improvement in management practices of fertilizers for sustainable intensification.[278] There is a need for farming practices that can sustainably boost yields worldwide through crop replacement, efficient management practices, and improved seeds.[279]

Sustainable intensification can be also obtained by growing crops in the most suitable place for their cultivation, in order to save water and inputs while boosting crop yields.[280] For example, it is possible to plant crops that use less water and do not induce water scarcity conditions. Therefore, it is crucial to define the suitability of a certain crop considering different environmental boundary conditions (e.g. temperature, soil slope, texture).[281]

Improved technologies and mechanization can produce higher yields both directly for biofuels cultivation and indirectly for the other crops grown in the area with the same machinery.[282] Therefore, yield gap closure can be achieved by bringing technology to biofuel producing countries.[283] The study by Johnston et al. shows that closing the yield gap at the 50th percentile for 20 crops can increase biofuel production by more than 100 billion liters of ethanol and roughly 9 billion liters of biodiesel.[284] However, mechanization, besides altering the life cycle of the soil, requires investments in the agricultural sector that small farmers cannot afford that could lead to LSLAs[285] and environmental and social issues, as discussed later in section 3.8.

[273] Rosa, L., Rulli, M. C., Davis, K. F., Chiarelli, D. D., Passera, C., & D'Odorico, P. (2018). Closing the yield gap while ensuring water sustainability. Environmental Research Letters, 13(10). https://doi.org/10.1088/1748-9326/aadeef; van Noordwijk, M., Khasanah, N., Dewi, S., 2017. Can intensification reduce emission intensity of biofuel through optimized fertilizer use? Theory and the case of oil palm in Indonesia. GCB Bioenergy 9, 940–952. https://doi.org/10.1111/gcbb.12398

[274] Ibid.

[275] Yang, Y., Tilman, D., Lehman, C., Trost, J.J., 2018. Sustainable intensification of high-diversity biomass production for optimal biofuel benefits. Nat. Sustain. 1, 686–692. https://doi.org/10.1038/s41893-018-0166-1

[276] Spiertz, J.H.J. Nitrogen, sustainable agriculture and food security. A review. Agron. Sustain. Dev. 30, 43–55 (2010). https://doi.org/10.1051/agro:2008064

[277] van Noordwijk etal., Can intensification reduce emission intensity of biofuel through optimized fertilizer use?

[278] Tilman et al., Global food demand and the sustainable intensification of agriculture. 2011.

[279] Harvey & Pilgrim, The new competition for land: Food, energy, and climate change.; Mbow et al., Food Security.

[280] FAO, The State of Food and Agriculture.

[281] Ibid.

[282] Ibid.

[283] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.; Tilman et al., Global food demand.

[284] Johnston, M., Licker, R., Foley, J., Holloway, T., Mueller, N. D., Barford, C., & Kucharik, C. (2011). Closing the gap: global potential for increasing biofuel production through agricultural intensification. Environmental research letters, 6(3), 034028.

[285] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.

Gap closure is efficient especially in countries where there is a big difference between the maximum attainable yield and the present yield (e.g. sub-Saharan Africa).[286] Changing the crop used for biomass generation can push the attainable yield to higher values where the gap is small. Moderately fertilized high-mixture grasslands can provide overall satisfying biomass yields, on areas that would yield much less with food crops, such as abandoned or degraded lands, as reported in the next section.[287]

Sustainable intensification of agriculture can have positive effects not only on the biofuel production chain, but on the food system as a whole; however a necessary condition to that is the employment of fine-tuned, mixed-approach strategies that are policy-driven. There could be negative social and environmental impacts because of the shift from subsistence farming to high-input and industrialized agriculture, as previously said.[288] However, sustainable intensification can also help in reducing the competition among resources, therefore increasing the efficiency of water and land use and contributing to maintaining higher environmental quality.[289]

3.4.2 Surplus from Activating Under-Utilized Low Carbon Land (Especially Degraded Land) for Feedstock Production

Strategies to increase feedstock production for biofuel expansion include intensification, as explored in the previous section, and extensification, which is the focus of this section.

Using marginal land has often been invoked as a potentially successful strategy to produce biofuels without competing with food systems.[290] Often touted as a win-win solution to this coupled food-energy problem, this approach hinges on a myopic and anthropocentric perspective that does not recognize the environmental value of "marginal land" because of its perceived lower primary productivity and biodiversity. It also ignores possible uses that local indigenous communities often make of that land (e.g., for fuelwood collection, grazing, hunting) by simply labeling "marginal lands'' as "unused".

Marginal lands include areas that are unsuitable or unproductive for conventional crops because of the soil characteristics, climatic conditions, or due to contamination or degradation.[291] Marginal lands may also be exposed to erosion, salinization, and nutrient depletion.[292] Therefore, they may not be suitable for food crops unless substantial irrigation and fertilization are adopted, thereby offsetting the positive environmental effects of producing biofuels on marginal lands. In order to use marginal lands for biofuel production, we need to consider the consequences of the use of these lands from an environmental, economic, and social lens. Second generation biofuels from residues do not have a direct impact on land, as they share it with the main product(s) from which they derive. Agricultural residues play a role in maintaining the carbon balance and the fertility of the soil, and

[286] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.; Mueller, N. D., Gerber, J. S., Johnston, M., Ray, D. K., Ramankutty, N., & Foley, J. A. (2012). Closing yield gaps through nutrient and water management. Nature, 490(7419), 254-257.

[287] Yang et al.,Sustainable intensification of high-diversity biomass production for optimal biofuel benefits.

[288] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.

[289] D'Odorico et al., The Global Food-Energy-Water Nexus. Reviews of Geophysics.; FAO, The State of Food and Agriculture.

[290] Fajardy & Mac Dowell, Can BECCS deliver sustainable and resource efficient negative emissions?

[291] Mehmood, M. A., Ibrahim, M., Rashid, U., Nawaz, M., Ali, S., Hussain, A., & Gull, M. (2017). Biomass production for bioenergy using marginal lands. Sustainable Production and Consumption, 9, 3–21. https://doi.org/10.1016/j.spc.2016.08.003

[292] FAO. (2008). The state of food and agriculture 2008: Biofuels: Prospects, risks and opportunities (Vol. 38). Food & Agriculture Organization.

thus removing them for biofuel production can significantly reduce crop yields and soil health.[293] Sacrificing the land's natural yield to increase productivity for a secondary product would not have a net positive outcome in terms or sustainable land management.

Urban residues and residual oil are not constrained from this point of view, as they have no such alternative value. The main problems in this case remain technologic and logistic, as conversion of such complex biomasses is costly and energy demanding, and the supply chain for such feedstock should be integrated from the household level to the biorefinery.[294] Thus, for extending biofuel production on marginal lands, the focus is on energy crops. The yield of energy crops varies substantially among species, climates, and soils.[295] Perennial grasses such as Miscanthus and Switchgrass have low agricultural requirements, are drought resistant and, thanks to their developed root system, help in reclaiming soil and preventing erosion, thus eventually improving the soil conditions of marginal lands.[296] Miscanthus, in particular, requires half of the land and one third of the water used by corn to produce the same amount of biofuel.[297] Yet, cellulosic crops work best if irrigated, so policies to incentivize feedstock production from energy crops may induce farmers to irrigate permanent grasses, zeroing one of the positive environmental effects these crops had in the first place.[298]

Another interesting perspective is offered by succulent crops such as Agave. The advantages here are that the water requirements are notoriously low, and that the leaves present high content of soluble non-structural carbohydrate at the expense of lignin content, therefore being much easier to convert, but the global availability of suitable marginal lands for agave is uncertain.[299] In order to define a comprehensive framework, numerous local studies should be integrated in a global analysis to map the marginal lands and determine their suitability for food crops or energy crops.[300]

Extensification of feedstock production on marginal land also has a range of secondary effects, both positive and negative. A careful selection of the cultivated species can improve water quality, prevent erosion, and help restore biodiversity.[301] Moreover, many herbaceous energy crops are almost completely dried out at their harvesting date, reducing the costs associated with transport and drying.[302]Marginal lands could attain their productive potential if properly managed; a non-invasive management would avoid the carbon costs of conversion, and a minimal and well calibrated fertilizer input may increase the field productivity more than it would increase the GHG emissions

[293] Ibid.; Tilman et al., Beneficial biofuels.

[294] Naik et al., Production of first and second generation biofuels.

[295] Gelfand, I., Sahajpal, R., Zhang, X., Izaurralde, R. C., Gross, K. L., & Robertson, G. P. (2013). Sustainable bioenergy production from marginal lands in the US Midwest. Nature, 493(7433), 514–517. https://doi.org/10.1038/nature11811

[296] Mehmood et al., Biomass production for bioenergy.; Wu et al., Consumptive Water Use in the Production of Ethanol and Petroleum Gasoline.

[297] Ibid.

[298] Fajardy & Mac Dowell, Can BECCS deliver sustainable and resource efficient negative emissions?; Fingerman et al., Accounting for the water impacts of ethanol production.

[299] Mehmood et al., Biomass production for bioenergy.; FAO. (2008). The state of food and agriculture 2008: Biofuels: Prospects, risks and opportunities (Vol. 38). Food & Agriculture Organization.

[300] Ibid.

[301] Mohr & Raman, Lessons from first generation biofuels.; FAO. (2008). The state of food and agriculture 2008: Biofuels: Prospects, risks and opportunities (Vol. 38). Food & Agriculture Organization.

[302] Mehmood et al., Biomass production for bioenergy.

associated with the fertilizer use.[303] However, not all marginal lands are ready and available to be used for the production of herbaceous feedstocks. As noted earlier, land classified as "marginal" is often grazed or used by subsistence farmers in rural poor areas; in these cases, the positive impact on GHG emissions may be questioned, and the legal nature of the acquisition process of these lands would be critical for its socio-economic effects on the local population.[304] Moreover, not all marginal lands are close enough to biorefineries or to areas that could potentially host one.[305] Sacrificing one ecosystem or the socio-economic equilibrium of one community to obtain marginal benefits at a global scale may not be a sustainable pathway. Therefore, the *conditio sine qua non* for biofuel expansion on marginal land is a leap in agricultural practice research, land management policies, feedstock conversion technology, and logistics. There are several studies underway in the U.S. to better understand how to use marginal lands to *sustainably* produce biofuels, as showcased in the final chapter of case studies in this report.

3.5 Impacts of Biofuels Expansion on Ecosystems

The environmental impacts of European palm oil imports from Malaysia and Indonesia have been highlighted by a number of recent studies. Such impacts from oil palm plantations include high deforestation rates and large carbon emissions in Malaysia and Indonesia as well as losses of habitat and threats to biodiversity.[306] In response, the European Union has taken some action to limit these unwanted effects on the environment.[307] For instance, biofuels produced from feedstocks grown on land with "high biodiversity value" (e.g., primary forests, peatlands, wetlands, certain woodlands and grassland) are not accepted under EU renewable energy mandates. The direct and indirect effects of biofuel production on these ecosystems, however, remain difficult to verify.[308]

In addition to the environmental impacts, biofuel production has important societal implications that can be better understood by examining the energy-food-water nexus of biofuels as discussed in section 3.7. A variety of biofuel production schemes are showcased in the last chapters of this report to highlight real world challenges and successes in the global biofuel marketplace.

[303] Gelfand et al., Sustainable bioenergy production from marginal lands in the US Midwest.

[304] Ibid.; Mohr & Raman, Lessons from first generation biofuels.; FAO. (2008). The state of food and agriculture 2008: Biofuels: Prospects, risks and opportunities (Vol. 38). Food & Agriculture Organization.

[305] Ibid.

[306] Carlson, K. M., Curran L.M., Ratnasari D., Soares-Filho B.S., Rodrigues H.O., McDonald Pittman A., Asner G. P., Trigg S. N., Lawrence D. & Gaveau D. L. 2012. A. Expanding oil palm plantations in West Kalimantan, Indonesia: Impacts on land cover change and carbon emissions. *Proceedings of the National Academy of Sciences*. doi/10.1073/pnas.1200452109.; Fargione, J., J. Hill, D. Tilman, S. Polasky, & P. Hawthorne. 2008. Land clearing and the biofuel carbon debt. *Science* 319:1235–1238.; United Nations Environment Programme. 2009. *Towards sustainable production and use of resources: Assessing Biofuels*, UNEP, Division of Technology Industry and Economics, Paris.

[307] European Union. 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*, European Commission, Bruxelles.

[308] Hermele, K. 2014. *The Appropriation of Ecological Space. Agrofuels, unequal exchange and environmental load displacements*, Rutledge ed. pp. 158, New York.

3.6 Impacts of Climate Change on Bioenergy Crop Cultivation

Monia Santini, Euro-Mediterranean Center on Climate Change Foundation

While there is robust consensus on the need of biomass for bioenergy according to various national and global energy pathways, future estimates of biomass availability are highly uncertain, especially for those concerning dedicated energy crops.[309] Among various sources of uncertainty, including the competition for lands, production costs, and sustainability factors, one must also consider the potential effects on crop growth due to a changing climate, which modifies temperature and precipitation patterns. In particular, increasing global water stress, due to rising water demands and reduced supplies, can be further exacerbated in some locations by climate change, with evaporative requirements of plants rising with temperature as vapor pressure deficit rises.[310]

However, climate change impacts depend on several factors: the crops and regions in question, the modelling approach used, and the consideration of land-use constraints and CO_2 fertilization effects.[311] This is why evaluations based on model ensembles are often adopted in order to consider a range of likely outlooks, by averaging results and/or labeling them based on likelihood. For example, Cronin et al. created a land suitability approach for a range of future climate and land-use conditions under which the suitability for energy crops could change.[312] They applied five general circulation models (GCMs) driven by two GHG Representative Concentration Pathways - RCP 2.6 and RCP 8.5 - representing a low and high climate change scenario respectively. The models were also driven by two pathways of socio-economic development, one assuming medium population growth, urbanization and land-use for food agriculture (SSP2) and the other assuming high levels of fossil-fuel driven development, high population and GDP growth, and food consumption with a high share of meat and waste generation (SSP5). Results suggest that the area of marginally suitable land has increased globally but the area of optimal land has decreased, with very different impacts between northern and southern latitudes as described below.

Considering the variety of pathways and models considered in this report, climate change would result in North America and Northern Asia (including China) increasing their global share of suitable land area suitable for biofuel production from 17 to 26-35%, while a decrease from 58% to 39-43% is projected for Sub-Saharan Africa, Brazil, Australia, and Southeast Asia. The same authors also project the suitability for different energy sources (wood, grass, oil, sugar/starch crops) under different climate change scenarios, revealing that the largest increase in crop suitability is expected to occur by the end of the century for grass, sugar/starch, and oil crops in the northernmost

[309] Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., …, Yongsung, C. (2016). Biophysical and economic limits to negative CO_2 emissions. Nature Climate Change, 6(1), 42–50. https://doi.org/10.1038/nclim ate2870

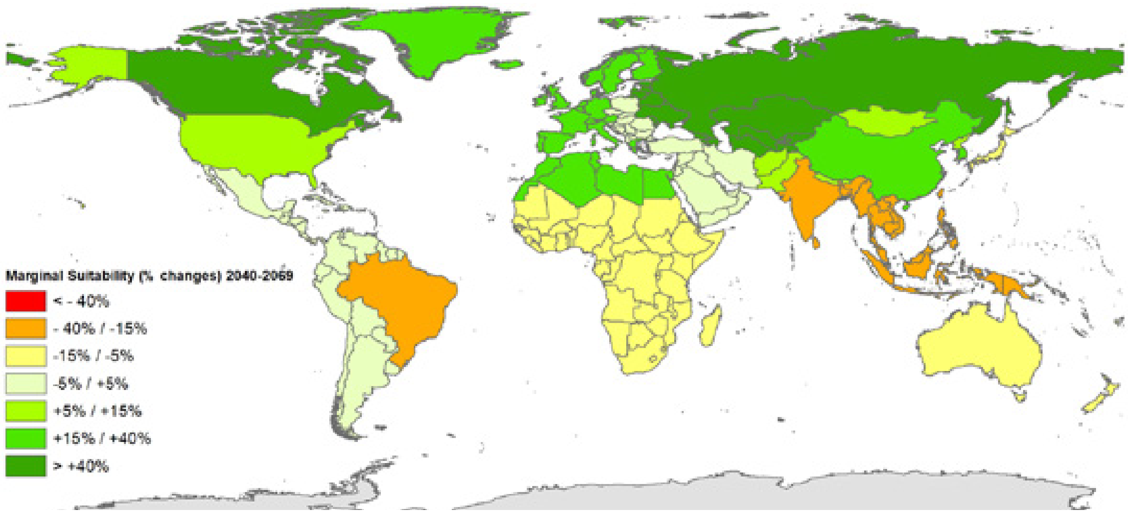
[310] Vörösmarty, C. J. Global water resources: vulnerability from climate change and population growth. Science 289, 284–288 (2000).

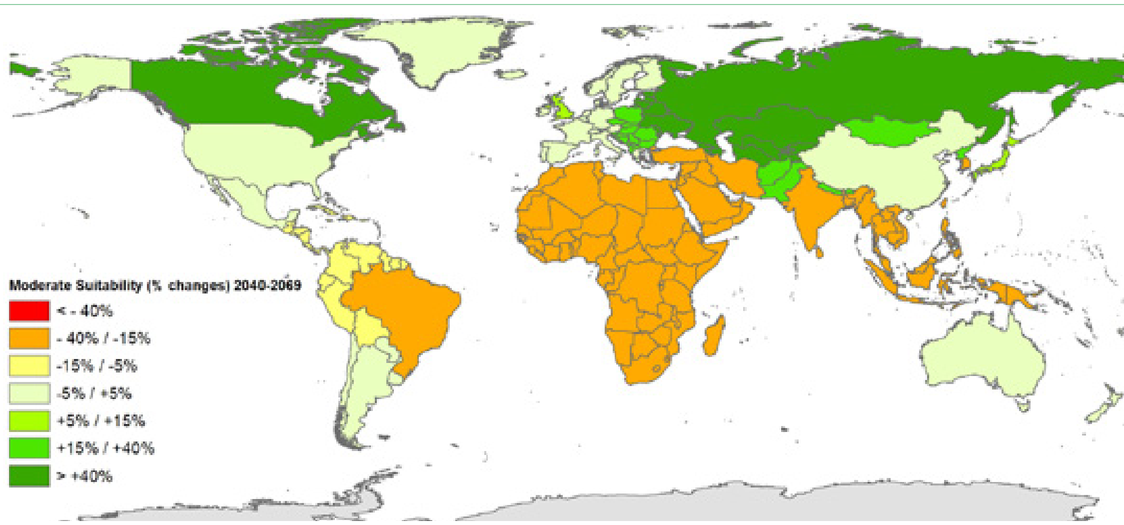
[311] Beringer, T., Lucht, W., & Schaphoff, S. (2011). Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. GCB Bioenergy, 3(4), 299–312. https://doi.org/10.1111/j.1757-1707.2010.01088.x; Haberl, H., Erb, K.-H., Krausmann, F., Bondeau, A., Lauk, C., Müller, C., …, Steinberger, J. K. (2011). Global bioenergy potentials from agricultural land in 2050: Sensitivity to climate change, diets and yields. Biomass and Bioenergy, 35(12), 4753–4769. https://doi.org/10.1016/j.biomb ioe.2011.04.035; Kahsay, A., Haile, M., Gebresamuel, G., & Mohammed, M. (2018). Land suitability analysis for sorghum crop production in northern semi-arid Ethiopia: Application of GIS-based fuzzy AHP approach. Cogent Food & Agriculture, 4(1), 1–24. https://doi.org/10.1080/23311 932.2018.1507184; Kyle, P., C. Müller, K. Calvin, and A. Thomson (2014), Meeting the radiative forcing targets of the representative concentration pathways in a world with agricultural climate impacts, Earth's Future, 2, 83–98, doi:10.1002/2013EF000199.

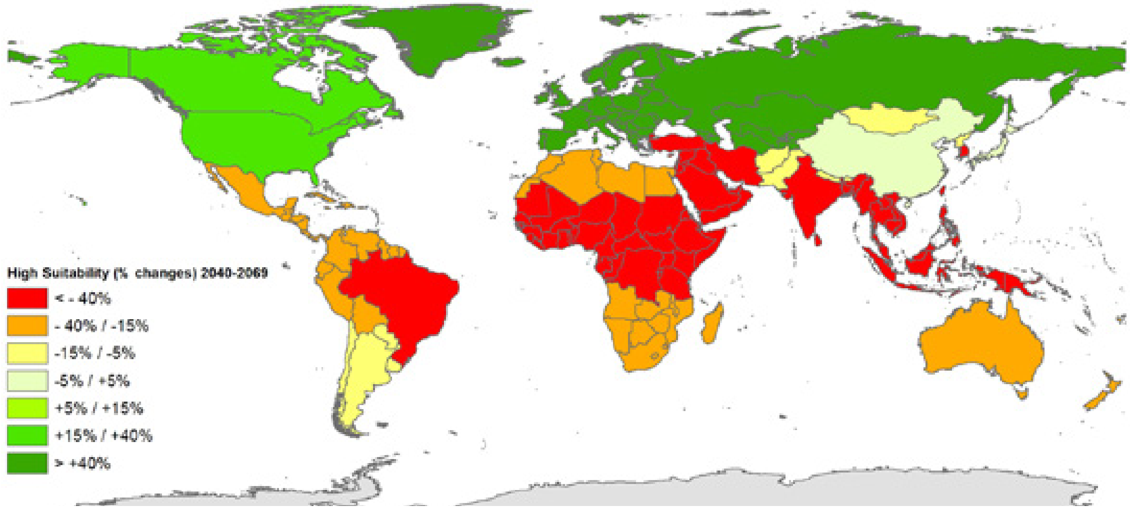
[312] Cronin, J., Zabel, F., Dessens, O., Anandarajah, G. (2019) Land suitability for energy crops under scenarios of climate change and land-use. DOI: 10.1111/gcbb.12697

regions and under the strong climate change scenario (SSP5-RCP8.5), while the highest absolute losses are projected for all crops in Central Africa and Brazil.

FIGURE 3.3. Maps of percent changes in land suitability classes (marginal-*top*; moderate-*centre*; high-*bottom*) across countries for 2040-2069 vs. 1980-2009. The values are averaged among scenarios SSP2-RCP2.6, SSP5-RCP2.6 and SSP5-RCP8.5 considering land availability restrictions (i.e. excluding - from land availability - urban, forest, protected and food agricultural lands). (Source: author's elaboration from Cronin et al. 2020).







Using an ecological niche model driven by temperature and precipitation variables aggregated at the monthly, seasonal and annual level, *Hu (2017)* found even more concerning results for Jatropha (*Jatropha curcas*), a biodiesel) feedstock which is commonly grown without irrigation in subtropical regions.[313] *Hu*'s results project, under the same RCPs assumptions as above but using a only one GCM, an overall reduction in land suitability by more than 35% and 45% under RCP2.6 and RCP8.5, respectively. Under the same RCPs but using five climate models, Jatropha was also included among the nine crops analyzed by *Yan et al. (2021)* for China with a multi-factor analysis approach. In each climate change scenario, marginal suitable land increases for seven out of nine crops in the medium-term (2050-2059), - including Jatropha. This confirms the findings of *Hu (2017)* over southern China. The potential production of these crops is projected to reach just one fourth of the current values due to both climate change and the poor yield that results from using marginally suitable lands to grow energy crops.

Jaime et al (2018) conducted species distribution modelling under five GCMs, driven by both RCP8.5 and RCP4.5 (high and intermediate climate scenarios respectively) to compare two oilseed crops - *Brassica napus* and *Sinapis alba* - in their suitability to the Mediterranean basin and other western European countries.[314] Due to decreased resilience of *B. napus* under the arid conditions expected for the area, the study confirmed *S. alba* a good alternative bioenergy crop better preadapted to future climatic conditions.

By using a vegetation model, *Gernaat et al. (2021)* analyzed likely modifications in the potential for bioenergy for the end of this century (2070-2100) with respect to the reference period (1970-2000). They found contrasting results when CO_2 increase is considered or not in the model to account for CO_2 fertilization effects, in addition to changes in climate variables, confirming that CO_2 fertilization effects are an important source of uncertainty.[315]

[313] Hu, J., 2017. Decreasing desired opportunity for energy supply of a globally acclaimed biofuel crop in a changing climate. *Renewable and Sustainable Energy Reviews*, 76, pp.857-864.

[314] Jaime R, Alca´ntara JM, Manzaneda AJ, Rey PJ (2018) Climate change decreases suitable areas for rapeseed cultivation in Europe but provides new opportunities for white mustard as an alternative oilseed for biofuel production. PLoS ONE 13(11): e0207124. https://doi.org/10.1371/journal.pone.0207124

[315] Gernaat, D.E.H.J., de Boer, H.S., Daioglou, V. et al. Climate change impacts on renewable energy supply. Nat. Clim. Chang. 11, 119–125 (2021). https://doi.org/10.1038/s41558-020-00949-9

The above-mentioned findings suggest that the possible effect of climate change and variability on energy crops must not be neglected for robust planning and investments in biofuel pathways' development. Although future projects inherently maintain some level of uncertainty, this can be addressed by adopting the likelihood and confidence approach as used by IPCC.[316]

3.7 Social Impacts and Controversies of Biofuel Expansion

Jampel Dell'Angelo, Vrije Univeristeit Amsterdam

Biofuel expansion through large-scale agricultural land investments

Biofuel production expansion plays a fundamental role in shaping the direction of global agrarian development. Supported by environmental narratives on decarbonization policy and driven by financial incentives and financial returns on investment, the recent expansion of biofuels in Sub-Saharan Africa, Latin America, South-East Asia and Eastern Europe, has been tightly associated with the phenomenon of large-scale land investments and a driving force of the redefinition of the agrarian landscape in these countries.[317] Over 90 million hectares of arable land, approximately the size of Pakistan, have been acquired by foreign investors in the last 20 years.[318] In many instances, the land that is being appropriated through these investments is transformed from small-scale, semi-subsistence, traditional farming, to large-scale industrialized commercial agriculture.[319]

The extent of this phenomenon, in terms of both the dimension of land property reconfigurations, and also in terms of the socio-political impacts produced, leads scholars to describe it as a new 'global land rush'[6], evoking images of neo-colonial dispossession.[320] A variety of scholars have pointed at the development of the biofuels industry as one of the key drivers of this process.[321]

In addition to the environmental trade-offs that have been exposed in the previous parts of this chapter, agrarian scholars have highlighted a number of concerning socio-political transformations that can be associated with this agricultural transition, with biofuel expansion playing a driving role.

[316] Mastrandrea, M.D., C.B. Field, T.F. Stocker, O. Edenhofer, K.L. Ebi, D.J. Frame, H. Held, E. Kriegler, K.J. Mach, P.R. Matschoss, G.-K. Plattner, G.W. Yohe, and F.W. Zwiers, 2010: Guidance Note for Lead Authors of the IPCC Fifth Assessment Report on Consistent Treatment of Uncertainties. Intergovernmental Panel on Climate Change (IPCC).

[317] Rulli, M. C., Casirati, S., Dell'Angelo, J., Davis, K. F., Passera, C., & D'Odorico, P. (2019). Interdependencies and telecoupling of oil palm expansion at the expense of Indonesian rainforest. *Renewable and Sustainable Energy Reviews*, *105*, 499-512.; Garrett, R. D., Rueda, X., & Lambin, E. F. (2013). Globalization's unexpected impact on soybean production in South America: linkages between preferences for non-genetically modified crops, eco-certifications, and land use. *Environmental Research Letters*, *8*(4), 044055.

[318] Muller et al., 2021) Impact of transnational land acquisitions on local food security and dietary diversity. *Proceedings of the National Academy of Sciences of the United States of America*. 118 (4).

[319] Anseeuw W, Alden Wily L, Cotula L, Taylor M. 2012a. In Land rights and the rush for land: Findings of the global commercial pressures on land research project, Bending T, Wilson D (eds). International Land Coalition: Rome. ISBN 978-92-95093-75-1.; Nolte K, Chamberlain W, Giger M. 2016. International land deals for agriculture. Fresh insights from the Land Matrix: Analytical Report II. https://doi.org/10.7892/boris.85304.

[320] Cotula, L. (2012). The international political economy of the global land rush: A critical appraisal of trends, scale, geography and drivers. *The journal of peasant studies*, *39*(3-4), 649-680.

[321] Scheidel, A., & Sorman, A. H. (2012). Energy transitions and the global land rush: Ultimate drivers and persistent consequences. *Global Environmental Change*, *22*(3), 588-595.

Commodification of agriculture. Biofuels are produced following the logic of commercial opportunity and profit. Large investments seek financial returns that are competitive on international commodity markets. This commoditization and commodification of agriculture is particularly accentuated by the logic of 'flex crops', a term which describes investment in a product that can satisfy different types of financial and economic demands. The system allows for the same type of crop to be sold for bioenergy purposes, for feed, and for food. The finality of agricultural production in this context is completely driven by commercial and financial aims.[322] Agricultural values that have traditionally been associated with the land, emic values, and the perspective on land as a transgenerational family asset are lost and substituted by the logic of land as a mere factor of production which needs to be exploited for commercial purposes.[323] There are a variety of ethical, cultural, and anthropological implications that result from this type of transition.

Transformation of systems of agricultural production. Biofuel production is associated with a process of industrialization and intensification that drastically changes the modes of agricultural production. Traditional systems of rural production, in many areas where biofuels are being developed through large-scale land acquisitions, are being fundamentally transformed. Small-scale farming, semi-subsistence agriculture, and pastoralist systems are affected by the imposition of new agricultural models which entail a multidimensional radical transformation of the agrarian landscape. The transformation of these systems entails a change in the way land is cultivated, the types of fertilizers, pesticides, nutrients, tillage, rotation, and crop diversity, very often moving from organic to fossil-based agriculture. Moreover, traditional ecological knowledge and cultural practices are affected as well as drastic reconfiguration of property rights, land tenure, and access to land resources.[324]

Impact on labor and working relations. The impact of the development of commercial agriculture for biofuels can be understood by looking at the labor market effects of large-scale agricultural investments. A common narrative supporting these types of agricultural investments is that they favor the development of new employment opportunities. Nevertheless the extent to which these types of investments provide employment benefits for local communities is very strongly debated. A recent global empirical study addressing the question of whether large-scale agricultural investments create or destroy employment found that these investments massively crowd out smallholder farmers. This effect is mitigated to a very small extent by the cultivation of labor-intensive crops and contract farming schemes.[325]

Reconfiguration of property relations and access. Large-scale land acquisitions (LSLAs) have a direct impact on land access and they fundamentally alter property rights and land tenure in the targeted areas. Most contemporary large-scale land investments in Sub-Saharan Africa, Latin America, Southeast Asia and Eastern

[322] Leguizamón, A. 2016. Disappearing nature? Agribusiness, biotechnology and distance in Argentine soybean production. The Journal of Peasant Studies, 43(2), 313-330.; Isakson, S. R. 2014. Food and finance: The financial transformation of agro-food supply chains. The Journal of Peasant Studies, 41(5), 749-775.

[323] Elliott, B., Jayatilaka, D., Brown, C., Varley, L., & Corbett, K. K. 2012. "We are not being heard": Aboriginal perspectives on traditional foods access and food security. Journal of Environmental and Public Health, 2012.; Clapp, J., & Isakson, S. R. 2018. Risky returns: The implications of financialization in the food system. Development and Change, 49(2), 437-460.

[324] Ruiz-Mallén, Isabel, and Esteve Corbera. "Community-based conservation and traditional ecological knowledge: implications for social-ecological resilience." Ecology and Society 18.4. 2013..; Wilkinson, J., Reydon, B., & Di Sabbato, A. (2012). Concentration and foreign ownership of land in Brazil in the context of global land grabbing. Canadian Journal of Development Studies/Revue canadienne d'études du développement, 33(4), 417-438.

[325] Nolte, K., & Ostermeier, M. (2017). Labour market effects of large-scale agricultural investment: conceptual considerations and estimated employment effects. *World Development*, *98*, 430-446.

Europe are implemented through land concessions that attribute exclusive access and use rights to investors.[326] In many instances, this reconfiguration of land titles is directly developed and enforced by national governments and a large body of literature has pointed at dynamics of dispossession, eviction, and coercive imposition of new institutional arrangements.[327] A common narrative in the reallocation of land titles for commercial agricultural development is the one of "idle", "empty", or "unused" lands. It has been denounced as a developmentalist narrative that pushes forward a system of legalized dispossession at the expense of traditional communities, such as the pastoralist and other rural communities that directly rely on natural resources, the so-called 'marginal lands'. This process is also happening with clear negative implications for the ecosystems.[328]

Dispossession of commons. The frontier of expansion of large-scale land acquisitions for industrial agriculture is being pushed in territories with traditional land use and institutional arrangements. In many of these instances it has been reported that land governed through customary common property systems is appropriated and privatized by land investors.[329] LSLAs are happening at the expense of the commons which represent a fundamental system for the subsistence and maintenance of social norms and traditions of small-scale farmers, indigenous people, pastoralists, and other rural groups. Often governed in a sustainable way, the commons exhibit a variety of positive socio-ecological features. Their dispossession affects rural communities in multiple ways including productive security, food security, and employment.[330]There is strong evidence that land investors are specifically targeting common systems as often governments step in to favour land investments and grant concessions on lands that de facto are managed through traditional common property systems. The users of the commons are often evicted and a meta-study of the literature demonstrated that this is happening with high levels of coercion and violence.[331]

Violence, coercion and repression. It has been denounced that the dynamics of commons grabbing are inherently characterized by violence, power imbalance, and coercion [Dell'Angelo et al,. 2017]. A recent synthesis paper added novel information and characterizations about the ways in which coercion and violence manifest more frequently in these types of land claim confrontations. What emerges is an oppressive dynamic that begins with the violation of communities and collective interests, and leads to collective reactions that eventually are suppressed through coercion and violence. There are several studies that show that, when communities organize to oppose these types of agricultural land acquisitions they face conditions of oppression and violence. Repression, displacement, violent targeting, criminalization, and assassination of activists are more common than other non-violent social outcomes such as legislative and institutional changes.[332]

[326] Tura, H. A. (2018). Land rights and land grabbing in Oromia, Ethiopia. *Land Use Policy*, *70*, 247-255.

[327] Cotula, L. (2012). The international political economy of the global land rush: A critical appraisal of trends, scale, geography and drivers. *The journal of peasant studies*, *39*(3-4), 649-680.

[328] Borras Jr, S. M., Hall, R., Scoones, I., White, B., & Wolford, W. (2011). Towards a better understanding of global land grabbing: an editorial introduction. *The Journal of Peasant Studies*, *38*(2), 209-216.

[329] De Schutter, O. (2011a). Green Rush: The global race for farmland and the rights of land users. Harvard International Law Journal, 52, 503.; Fuys, A., Mwangi, E., & Dohrn, S. (2008). Securing common property regimes in a globalizing world. Rome: The International Land Coalition.; Wily, L. (2011b). The tragedy of public lands: The fate of the commons under global commercial pressure. Rome: The International Land Coalition.

[330] Agrawal, A. (2001). Common property institutions and sustainable governance of resources. World Development, 29(10), 1649–1672.;

[331] Dell'Angelo, J., D'odorico, P., Rulli, M. C., & Marchand, P. (2017). The tragedy of the grabbed commons: coercion and dispossession in the global land rush. *World Development*, *92*, 1-12.

[332] Jampel Dell'Angelo, Grettel Navas, Marga Witteman, Giacomo D'Alisa, Arnim, Scheidel, Leah Temper (2021) Commons grabbing and agribusiness: violence, resistance and social mobilization. *Ecological Economics* (forthcoming)

3.8 Life Cycle Analysis

Joaquim E. A. Seabra, Universidade Estadual de Campinas

The growing societal concern with sustainability requires appropriate tools to inform decision-making. In this regard, life cycle assessment (LCA) methods have been increasingly used in the private and public sectors to provide a conceptual basis for identifying and understanding the impacts associated with a given process or product, from the extraction of raw materials up to final disposal and recovery.

A traditional LCA study addresses the environmental aspects and their potential impacts throughout a product's life cycle. The comprehensive scope of LCA aims to avoid shifting problems, for example, from one phase of the life cycle to another, from one region to another, or from one environmental problem to another.[333]

Different from the other renewable technologies, bioenergy is a part of the terrestrial carbon cycle. The CO_2 emitted due to biofuels use was earlier sequestered from the atmosphere and will be sequestered again if the bioenergy system is managed sustainably, although emissions and sequestration are not necessarily in temporal balance with each other (e.g., due to long rotation periods of forest stands).[334] Therefore, opposed to the typical case of fossil fuels, the net contributions to the biofuels life cycle emissions are not associated with their final use, but with non-CO_2 GHG and fossil CO_2 emissions from auxiliary energy use in the supply chain, as well as carbon from land use change (LUC).

Even though LCA studies usually employ methodologies in line with ISO 14040:2006 and 14044:2006 standards, there is no single method for conducting an LCA. Examples of key issues related to the evaluation of biofuels are product system definition (including spatial and dynamic boundaries) and the method for considering energy and material flows across system boundaries.[335] Furthermore, many processes create multiple products, which result in significant data and methodological challenges because environmental effects can be distributed over several decades and in different geographical locations.[336]

[333] Finnveden, Göran, Michael Z. Hauschild, Tomas Ekvall, Jeroen Guinée, Reinout Heijungs, Stefanie Hellweg, Annette Koehler, David Pennington, and Sangwon Suh. 2009. "Recent Developments in Life Cycle Assessment." Journal of Environmental Management 91 (1): 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018.

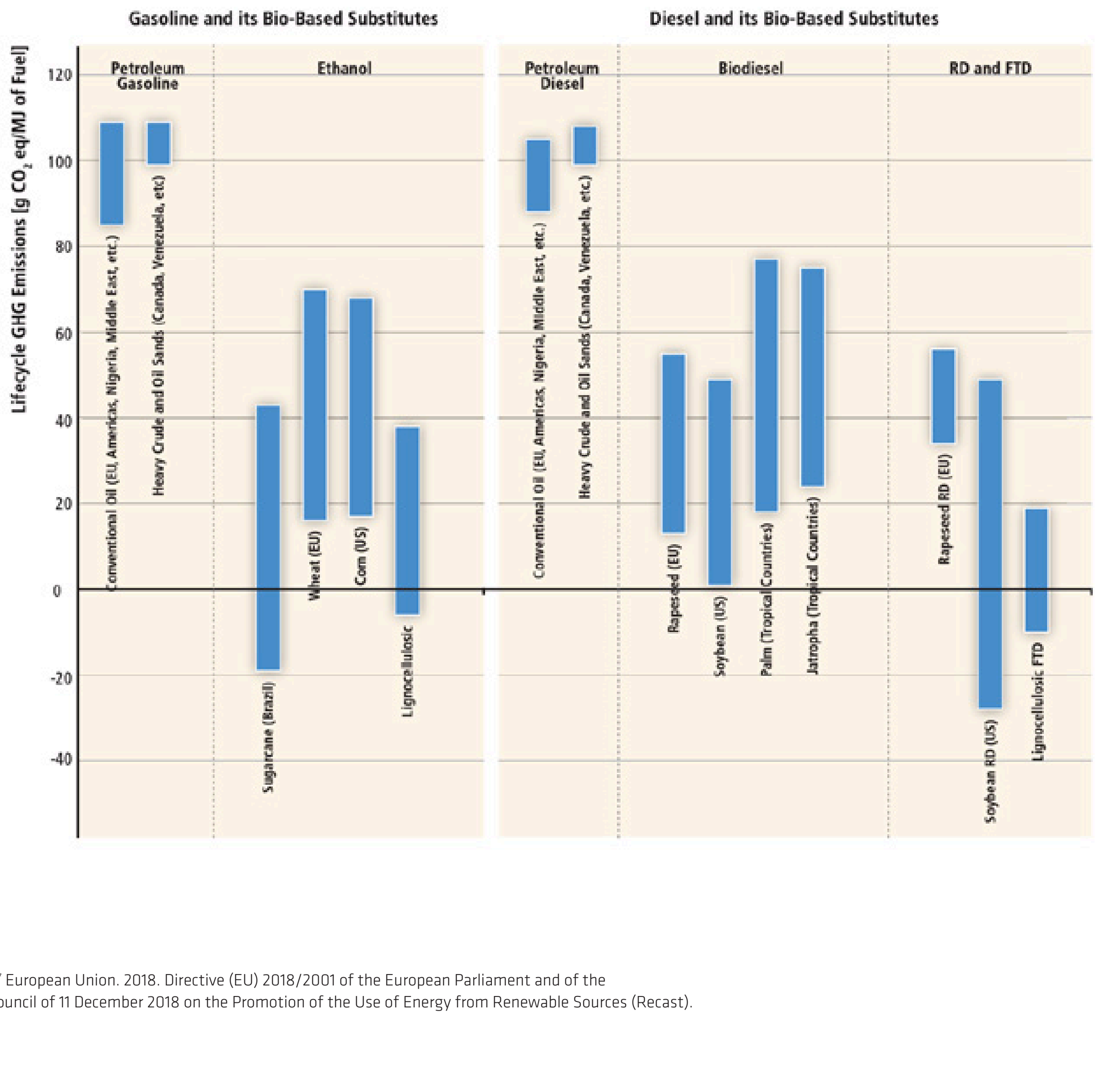
[334] Edenhofer, Ottmar, Ramón Pichs Madruga, Y. Sokona, United Nations Environment Programme, World Meteorological Organization, Intergovernmental Panel on Climate Change, and Potsdam-Institut für Klimafolgenforschung, eds. 2012. Renewable Energy Sources and Climate Change Mitigation: Special Report of the Intergovernmental Panel on Climate Change. New York: Cambridge University Press.

[335] Most bioenergy LCAs are designated as attributional to the defined boundaries, as they describe the impacts of an average unit of a bioproduct. Consequential LCAs, on the other hand, analyze bioenergy systems beyond these boundaries, in the context of the economic interactions, chains of cause and effect in bioenergy production and use, and effects of policies or other initiatives that increase bioenergy production and use. In summary, consequential LCAs investigate the responses to bioenergy expansion and have hence become a common approach in the regulatory context of biofuels. Indirect land use change (iLUC), for example, is typical impact evaluated in consequential LCAs.

[336] Cherubini, Francesco, Neil D. Bird, Annette Cowie, Gerfried Jungmeier, Bernhard Schlamadinger, and Susanne Woess-Gallasch. 2009. "Energy- and Greenhouse Gas-Based LCA of Biofuel and Bioenergy Systems: Key Issues, Ranges and Recommendations." Resources, Conservation and Recycling 53 (8): 434–47. https://doi.org/10.1016/j.resconrec.2009.03.013.; Edenhofer, et al., Renewable Energy Sources and Climate Change Mitigation.

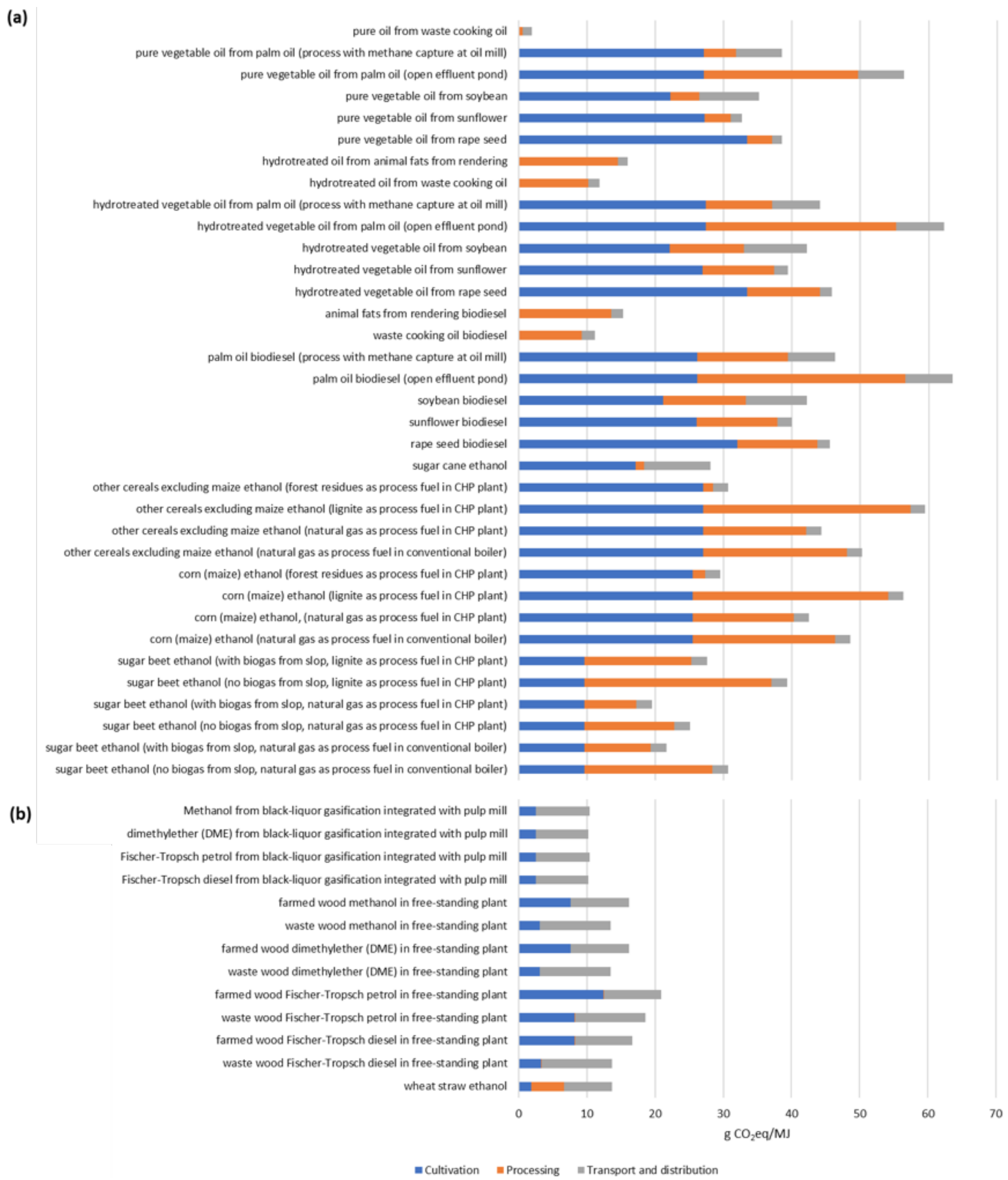
Figure 3.4 illustrates the ranges of life cycle GHG emissions for biofuels and their fossil alternatives per unit energy output. Given the wide variation in cultivation conditions as well as methodological differences between studies, estimates of life cycle emissions for the same bioenergy options vary over a wide range, even for the same temporal and spatial considerations. A broader comparison of biofuels options is shown in Figure 3.4 for the specific context of the EU's Renewable Energy Directive.[337]

FIGURE 3.4. Ranges of life cycle GHG emissions of petroleum fuels, first-generation biofuels and selected next-generation lignocellulosic biofuels without considering land use change (Edenhofer, et al., Renewable Energy Sources and Climate Change Mitigation).



[337] European Union. 2018. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources (Recast).

FIGURE 3.5 EU's Renewable Energy Directive estimations of typical life cycle GHG emissions of (a) biofuels and (b) future biofuels that were not on the market or were only on the market in negligible quantities in 2016 (European Union, Directive (EU) 2008/2001).



Of particular relevance for the biofuels life cycle performance are the LUC effects, the nitrous oxide (N2O) emissions, the methods used for handling the co-products, the process efficiency, and the fuel used in the biomass conversion step. The hydrogen supply is another special point of concern for the cases involving hydrotreatment, such as in several pathways dedicated to the production of aviation biofuels.[338] Table 3.7 illustrates the GHG emissions breakdown for four mature, commercial biofuels. Usually, feedstock production dominates life cycle emissions, but process fuel can drastically reduce the climate benefit of biofuels. For example, Wang, Wu, and Huo showed that GHG emissions for US corn ethanol can vary significantly – from a 3% increase if coal is the process fuel to a 52% reduction if wood chips are used.[339] Brazilian sugarcane ethanol plants, in turn, use bagasse as process fuel to meet their own energy demand, and modern mill configurations can actually export large quantities of surplus electricity to the grid.[340]

[338] Capaz, Rafael S., Elisa M. de Medeiros, Daniela G. Falco, Joaquim E.A. Seabra, Patricia Osseweijer, and John A. Posada. 2020. "Environmental Trade-Offs of Renewable Jet Fuels in Brazil: Beyond the Carbon Footprint." Science of The Total Environment 714 (April): 136696. https://doi.org/10.1016/j.scitotenv.2020.136696.

[339] Wang, Michael, May Wu, and Hong Huo. 2007. "Life-Cycle Energy and Greenhouse Gas Emission Impacts of Different Corn Ethanol Plant Types." Environmental Research Letters 2 (2): 024001. https://doi.org/10.1088/1748-9326/2/2/024001.

[340] Macedo, Isaias C., Joaquim E.A. Seabra, and João E.A.R. Silva. 2008. "Green House Gases Emissions in the Production and Use of Ethanol from Sugarcane in Brazil: The 2005/2006 Averages and a Prediction for 2020." Biomass and Bioenergy 32 (7): 582–95. https://doi.org/10.1016/j.biombioe.2007.12.006.;
Seabra, Joaquim E. A., Isaias C. Macedo, Helena L. Chum, Carlos E. Faroni, and Celso A. Sarto. 2011. "Life Cycle Assessment of Brazilian Sugarcane Products: GHG Emissions and Energy Use." Biofuels, Bioproducts and Biorefining 5 (5): 519–32. https://doi.org/10.1002/bbb.289.

TABLE 3.7 Breakdown of GHG emissions per life cycle stage for four commercial biofuels (gCO_{2eq}/MJ) (Souza et al., Bioenergy & Sustainability).

	CORN ETHANOL[a]	SUGERCANE ETHANOL[a]	SOYBEAN BIODIESEL[b]	RAPESEED BIODIESEL[c]
Feedstock Farming	30.8	22.5	34.2	57.5
Fertilizer production	10.1	3.8[d]	Not separated	Not separated
N_2O emissions in field	16.7	6.7[e]	20.1[e]	Not separated
Farming	4.0	12.0[f]	14.1	Not separated
Fuel Production	31.0	2.6	9.6	15.2
Transport and distribution	4.5	1.8	1.9	1.9
Co-product credit	-13.7	-6.4	Not separated	-20.8[g]
Total without credit	66.3	27.7[h]	45.7	74.6
Total with credit	52.6	21.3	16.8[i]	53.8

a) Wang et al, (2012); Seabra et al. (2011). Displacement method was used to address co-products of bio-ethanol. b) Pradhan et al. (2012). Allocation method was used to address co-products of biodiesel. c) Edwards et al. (2013). Displacement method was used to address co-products fo biodiesel. e) Includes other agrichemicals. f) Includes CO_2 emissions from lime and N_2O emissions from nitrogen fertilizer in field. GHG emissions of lime in field are included in all four studiees. In Wang et al. (2012) and Edwards et al. (2013), lime GHG emissions are included in farming emissions. For sugarcane ethanol, it also includes emissions from residues. f) Includes emissions from trash burning. g) Includes a GHG credit of 14.6 g/MJ for meal and 6.2 g/MJ for glycerin. h) Includes tallpipe emissions. i) Calculated by the mass allocation method that was used by the original authors. The mass shares between soubean meal and soy oil are 81.6% and 18.4%; between biodiesel and glycerin are 89.9% and 10.1%.

As discussed in Chapter 3, LUC has been the most contentious issue in the evaluation of GHG effects of biofuels, which can lead to significant reduction or increase of carbon stocks in biomass and soil. Even though there are large uncertainties about the overall carbon stock changes, the dLUC effects can be measured and observed with time, while iLUC implications result from projections using economics models, which are only able to capture both effects (dLUC and iLUC) together.

The more recent studies of iLUC report a lower effect than the earlier studies (Table 3.8). For example, estimates for new land brought into cultivation by the expansion of corn ethanol have been reduced by an order of magnitude and by threefold for sugarcane ethanol. These exercises therefore indicate that the land use sectors are able to accommodate a significant part of the projected bioenergy expansion without claiming new land.[341]

[341] Souza, Glaucia Mendes, Reynaldo L Victoria, Carlos A Joly, and Luciano M Verdade. 2015. Bioenergy & Sustainability: Bridging the Gaps. Paris Cedex: Scientific Committee on Problems of the Environment (SCOPE).

TABLE 3.8 Summary of iLUC factors (Souza et al., Bioenergy Sustainability).

	CORN	SUGARCANE	SUGAR BEET	PALM OIL	RAPE OIL	SOY OIL	METHODOLOGY
Searchinger et al. 2008	104.0	111.0	n.a.	n.a.	n.a.	n.a.	FAPRI
CARB 2009	30.0	46.0	n.a.	n.a.	n.a.	62.0	GTAP
EPA 2010	26.3	4.1	n.a.	n.a.	n.a.	43.0	FAPRI w/Brazilian model, FASOM
Hertel et al. 2010	27.0	n.a.	n.a.	n.a.	n.a.	n.a.	GTAP
E4Tech 2010	n.a.	8.0-27.0	n.a.	8.0-80.0	15.0-35.0	9.0-67.0	Causal-descriptive approach
Tyner et al. 2010	15.2-19.7	n.a.	n.a.	n.a.	n.a.	n.a.	GTAP
Al-Riffal et al. 2010	n.a.	17.8-18.9	16.1-65.5	44.6-50.1	50.6-53.7	67.0-75.4	MIRAGE
Laborde 2011	10.0	13.0-17.0	4.0-7.0	54.0-55.0	54.0-55.0	56.0-57.0	MIRAGE
Marelli et al. 2011	13.9-14.4	7.7-20.3	3.7-6.5	36.4-50.6	51.6-56.6	51.5-55.7	MIRAGE and JRC emissions model
Moreira et al. 2012	n.a.	7.6	n.a.	n.a.	n.a.	n.a.	Causal-descriptive approach
GREET1_2013	9.2	n.a.	n.a.	n.a.	n.a.	n.a.	GREET
CARB 2014	23.2	26.5	n.a.	n.a.	n.a.	30.2	GTAP
Laborde 2014	13.0	16.0	7.0	63.0	56.0	72.0	MIRAGE and JRC emissions model
Elliott et al. 2014	5.9	n.a.	n.a.	n.a.	n.a.	n.a.	PEEL
Harfuch et al. 2014	n.a.	13.9	n.a.	n.a.	n.a.	n.a.	BLUM

Agricultural intensification, and particularly double cropping, has been suggested as a practical strategy to reconcile biofuel feedstock production with other land-use priorities. Moreira et al. assessed the case of corn ethanol production under representative conditions of the current practice in the west central region of Brazil: corn grown as a second crop with soybean on land that formerly grew a single soybean crop, and energy processed from a combined heat and power plant using plantation-grown eucalyptus chips.[342] They found that although indirect conversion of natural vegetation is identified, this effect is more than counterbalanced (in terms of GHG emissions) by the expansion of planted forests and a smaller expansion of soybean area on pastures.

Negative LUC emissions have also been anticipated for cellulosic biofuels; Field et al., for instance, showed that on land transitioning out of crops or pasture, switchgrass cultivation for cellulosic ethanol production has per-hectare mitigation potential comparable to reforestation and several fold greater than grassland restoration.[343] Relevant impacts may as well be expected from alterations in crop cultivation management. For sugarcane in Brazil, studies have indicated the trend for carbon sequestration under unburned cane management, though it is conditioned by several factors.[344]

Furthermore, bioenergy with carbon capture and sequestration (BECCS) technologies can be an important option for improving life cycle emissions of biofuels. When applied to ethanol plants, the process would be converted into a net carbon absorber, since CO_2 emissions in the biorefinery largely exceed the amount of GHG emissions of ethanol life cycle. For 1G ethanol, Chagas et al. estimated that capturing CO_2 from fermentation would reduce life cycle emissions to -8.8 g CO_{2eq}/MJ, while for 1G+2G (i.e. sugarcane + bagasse/straw) integrated plants, emissions would drop to -17,2 g CO_{2eq}/MJ.[345] For US corn ethanol, a large potential exists. Sanchez et al. found that 216 existing US biorefineries emit 45 Mt CO_2 annually from fermentation, of which 60% could be captured and compressed for pipeline transport for under $25/t CO_2.[346]

Although the capacity of mitigating GHG emissions is a critical element for biofuels, other environmental aspects can also play important roles in a biofuel-fossil fuel trade-off analysis. Usually, biofuels perform better in terms of global impacts, but biomass cultivation may lead to some higher regional impact emissions, whereas the advantages of waste-based biofuels are naturally more clear.[347] In a direct comparison between gasoline, ethanol and blends, Luo, van der Voet, and Huppes concluded that in terms of abiotic depletion, GHG emissions, ozone layer depletion, and photochemical oxidation, ethanol fuels are better options than gasoline, whereas gasoline

[342] Moreira, Marcelo M. R., Joaquim E. A. Seabra, Lee R. Lynd, Sofia M. Arantes, Marcelo P. Cunha, and Joaquim J. M. Guilhoto. 2020. "Socio-Environmental and Land-Use Impacts of Double-Cropped corn Ethanol in Brazil." Nature Sustainability 3 (3): 209–16. https://doi.org/10.1038/s41893-019-0456-2.

[343] Field, John L., Tom L. Richard, Erica A. H. Smithwick, Hao Cai, Mark S. Laser, David S. LeBauer, Stephen P. Long, et al. 2020. "Robust Paths to Net Greenhouse Gas Mitigation and Negative Emissions via Advanced Biofuels." Proceedings of the National Academy of Sciences 117 (36): 21968–77. https://doi.org/10.1073/pnas.1920877117.

[344] Walter, Arnaldo, Marcelo Valadares Galdos, Fabio Vale Scarpare, Manoel Regis Lima Verde Leal, Joaquim Eugênio Abel Seabra, Marcelo Pereira da Cunha, Michelle Cristina Araujo Picoli, and Camila Ortolan Fernandes de Oliveira. 2014. "Brazilian Sugarcane Ethanol: Developments so Far and Challenges for the Future: Brazilian Sugarcane Ethanol." Wiley Interdisciplinary Reviews: Energy and Environment 3 (1): 70–92. https://doi.org/10.1002/wene.87.

[345] Chagas, Mateus, Otavio Cavalett, Bruno Klein, Rubens Maciel Filho, and Antonio Bonomi. 2016. "Life Cycle Assessment of Technologies for Greenhouse Gas Emissions Reduction in Sugarcane Biorefineries." Chemical Engineering Transactions 50 (June): 421–26. https://doi.org/10.3303/CET1650071.

[346] Sanchez, Daniel L., Nils Johnson, Sean T. McCoy, Peter A. Turner, and Katharine J. Mach. 2018. "Near-Term Deployment of Carbon Capture and Sequestration from Biorefineries in the United States." Proceedings of the National Academy of Sciences 115 (19): 4875–80. https://doi.org/10.1073/pnas.1719695115.

[347] Capaz, et al., "Environmental Trade-Offs of Renewable Jet Fuels in Brazil.

performs better when it comes to human toxicity, ecotoxicity, acidification, and eutrophication.[348] However, it is important to remark that technological progress in biomass cultivation and processing is expected to bring significant improvements for first generation biofuels.[349]

3.9 Biofuels Sustainability Certification

Despite the large appeal of bioenergy as a strategy to mitigate emissions, reduce dependency on fossil fuels, and spur economic development in rural areas, various concerns regarding bioenergy sustainability have been raised. As bioenergy policies emerged in the mid-2000s, environmental groups pressured governments to ensure that mandates produced environmental and social gains over the business-as-usual baseline.[350] As a consequence, policy makers decided to implement sustainability initiatives that set conditions for commercializing liquid biofuels in the most important consumer markets.

These sustainability initiatives can be classified as: (1) technical regulations, technical standards or conformity assessment procedures, according to their scope; (2) public, private or mixed, considering their nature; (3) voluntary or mandatory, according to the flexibility; and (4) aiming at guidance, verification or certification, considering the purpose.[351]

Examples of technical regulations are the Renewable Energy Directive of European Union (EU-RED), the Renewable Fuel Standard (RFS-2) in the United States, and the Californian Low Carbon Fuel Standard (LCFS). The Global Bioenergy Partnership (GBEP) and the standard ISO 13065 – Sustainability Criteria for Bioenergy – are examples of technical standards that aim at informing governments, producers, and consumers about how the production has occurred, its impacts, and what is important in order to verify a product's sustainability. In both cases the adoption of these technical standards is voluntary.[352]

Conformity assessment procedures aim at verification or certification, and these schemes are mostly private and always voluntary. Examples are the certification schemes recognized by the European Commission, in the context of the EU-RED, such as the RSB standard (Roundtable on Sustainable Biomaterials), the Bonsucro Production Standard, and the ISCC (International Sustainability & Carbon Certification) standard.[353]

[348] Luo, Lin, Ester van der Voet, and Gjalt Huppes. 2009. "Life Cycle Assessment and Life Cycle Costing of Bioethanol from Sugarcane in Brazil." Renewable and Sustainable Energy Reviews 13 (6–7): 1613–19. https://doi.org/10.1016/j.rser.2008.09.024.

[349] Silva, Cinthia R. U. da, Henrique Coutinho Junqueira Franco, Tassia Lopes Junqueira, Lauran van Oers, Ester van der Voet, and Joaquim E. A. Seabra. 2014. "Long-Term Prospects for the Environmental Profile of Advanced Sugar Cane Ethanol." Environmental Science & Technology 48 (20): 12394–402. https://doi.org/10.1021/es502552f.

[350] Endres, J.M., Diaz-Chaves, R., Kaffka, S.R., Pelkmans, L., Seabra, J.E.A., Walter, A., 2015. Sustainability certification, in: Bioenergy & Sustainability: Bridging the Gaps. Scientific Committee on Problems of the Environment (SCOPE), Paris Cedex, pp. 660–681.

[351] Walter, A., Seabra, J.E.A., Machado, P.G., Correia, B. de B., Oliveira, C.O.F. (Eds.), 2018. Sustainability of Biomass, in: Biomass and Green Chemistry. Springer International Publishing, Cham, pp. 191–220. https://doi.org/10.1007/978-3-319-66736-2

[352] Ibid.

[353] European Commission, 2020. Voluntary schemes [WWW Document]. URL https://ec.europa.eu/energy/topics/renewable-energy/biofuels/voluntary-schemes_en#approved-voluntary-schemes.; European Union, 2018. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast).

The understanding is that the sustainability initiatives cover, somehow, the general concerns regarding bioenergy production on a large scale.[354] Compared with more general agricultural certification systems, alternative fuel specific standards are particularly required to address GHG emissions because of the regulatory requirements for life cycle emissions mitigation in comparison to their petroleum counterparts. Additionally, other principles frequently shared among the certification schemes for biomass, alternative fuels and bioenergy include:[355]

- Sustainable production: Raw materials for biofuels may not come from land that has been converted (e.g. primary forest, protected area, highly biodiverse grassland, areas with high stocks of carbon, or peatlands) and must come from legal sources.

- Other environmental impacts: The production, conversion, and logistics may not lead to negative impacts on soil, water, and air quality.

- Efficient energy conversion: Bioenergy chains should strive for maximum energy efficiency in feedstock production, conversion, and logistics.

- Protection of biodiversity: The production of biomass should not negatively affect biodiversity.

- Contribute to local prosperity and welfare: Bioenergy chains should contribute towards social well-being for employees and local population.

As an example, Table 3.9 summarizes the environmental aspects addressed by EU-RED, GBEP and ISO 13065. In the case of EU-RED and ISO 13065, all aspects should be accomplished by the economic operator (e.g., a biofuel producer), while in the case of GBEP the aspects/indicators are guidance for assessing the impacts of bioenergy production at regional or national level.

[354] Walter, A., et al., 2018.

[355] ICAO, 2018. Sustainable aviation fuels guide, Version 2. ed, Transforming Global Aviation Collection. ICAO, UNDP, GEF.; Pelkmans, L., Goovaerts, L., Smith, C.T., Joudrey, J., Stupak, I., Englund, O., Junginger, M., Goh, C.S., Chum, H.L., Cowie, A., 2013. Recommendations for improvement of sustainability certified markets, Strategic Inter-Task Study: Monitoring Sustainability Certification of Bioenergy. IEA Bioenergy.

TABLE 3.9. Environmental aspects addressed by three selected sustainability initiatives[356]

ASPECT	EU-RED	GBEP	ISO 13065
GHG emissions (to be evaluated in life-cycle basis)	Set thresholds of required avoided emissions	Assessment of GHG emissions from bioenergy production and use	GHG emissions should be reduced; no threshold is defined
Soil	The Common Agricultural Policy shall be observed in case of production in EU	Soil quality, in terms of soil organic carbon, to be preserved	Soil quality and productivity shall be preserved
Water	The Common Agricultural Policy shall be observed in case of feedstock production in EU	Assessment of impacts on water resources, considering water use and efficiency, and on water quality	Water resources shall be preserved (water availability and water quality shall be observed)
Air	The Common Agricultural Policy shall be observed in case of feedstock production in EU	Assessment of non-GHG emissions along the whole supply chain; to be compared with other energy sources	Air emissions shall be controlled in order to maintain air quality
Biodiversity	Define that biomass production cannot occur in areas of high biodiversity value	Address: (a) conversion of high biodiversity value areas for feedstock production; (b) introduction of invasive species; and (c) use of recognized conservation methods	Actions to identify potential impacts on biodiversity; Actions for protecting biodiversity; Biomass removal from areas designated as biodiversity-protected areas to be reported
Land use and land use change	Define that biomass production cannot occur in areas with high carbon stock; in biannual basis each Member State should report land use changes due to bioenergy	Aspects mentioned: areas used for feedstock production; bioenergy production without pressure on agricultural land; land use changes caused by bioenergy feedstock production	Aspect not addressed
Harvest level of wood resources	Aspect not addressed	Annual harvest (volume and as a percentage of net growth or sustained yield), plus the amount used for bioenergy	Aspect addressed in one of biodiversity criteria
Energy efficiency	Aspect not addressed	Aspect not addressed	Energy consumption to be monitored
Wastes	Aspect not addressed	Aspect not addressed	Waste management is required

[356] Walter, A., et al., 2018.

As for the social aspects, it must be noted that social principles and criteria required in the sustainability initiatives cannot go beyond what is established by the United Nations Declaration on Human Rights and by the ILO Conventions (International Labor Organization), provided the country has ratified them.[357] The cases of CBEP and ISO 13065 are presented in Table 3.10. These aspects do not perfectly match, as they are applicable to different contexts (regional or national, in the case of GBEP, and at the operator level in the case of ISO 13065).

TABLE 3.10. Social aspects addressed by GBEP and ISO 13065[358]

ASPECT	GBEP	ISO 13065
Human rights	Aspect not addressed	Respect human rights
Labor rights	One indicator related to unpaid time spent by women and children and another indicator related to occupational injury, illness and fatalities in the production of bioenergy	Respect labor rights (i.e., avoiding forced and child labor, allowing collective bargain, and assessing working conditions)
Jobs creation	Assessment of net job creation as a result of bioenergy production, plus and indicator about jobs quality	Aspect not addressed
Changes in income	Contributions of bioenergy production on wages and income	Aspect not addressed
Land use rights	Land title and procedures for change of land title shall be observed	Consent of local people for feedstock production
Water use rights	Aspect not addressed	Identification of potential impacts on water availability and on water quality; consent of people affected
Food price and food supply	Changes in prices (including price volatility), production, imports and exports should be observed	The criteria related to land use rights and water use rights have specificities for food insecure regions
Access to modern energy services	Impacts of bioenergy to be assessed	Aspect not addressed
Impacts of phasing-out indoor smoke	Impacts of bioenergy to be assessed	Aspect not addressed

[357] Walter, A., et al., 2018.

[358] Ibid.

Economic sustainability aspects are not mentioned in EU-RED, while ISO 13065 has only two economic criteria that address the economic and financial feasibility of bioenergy production and trade, besides financial risk management. On the other hand, due to the motivation of assessing impacts at the regional or even national level, GBEP has an extensive list of economic indicators, although some of the indicators are not strictly economic.

Despite the overwhelming proliferation of different standards and certification approaches, there is still no global definition of how sustainability as a concept should be translated into practice, i.e. how to measure sustainability and which criteria and indicators should be included.[359] Yet, the sustainability initiatives can still be an important tool for the promotion of more sustainable biofuels, even though the compliance with certification schemes does not necessarily translate into a sustainable production. Risks of greenwashing exist, while further investigation is needed to gauge the implications on trade, new producers, and ultimately the effective promotion of sustainable development. To that end, research and development, good governance (helped by appropriate certification schemes), and innovative business models will be essential to address knowledge gaps and foster innovation across the value chain.[360]

[359] ICAO, 2018. Sustainable aviation fuels guide, Version 2. ed, Transforming Global Aviation Collection. ICAO, UNDP, GEF.

[360] Endres, J.M., et al. 2015.; Walter, A., Seabra, J.E.A., Machado, P.G., Correia, B. de B., Oliveira, C.O.F. (Eds.), 2018. Sustainability of Biomass, in: Biomass and Green Chemistry. Springer International Publishing, Cham, pp. 191–220. https://doi.org/10.1007/978-3-319-66736-2; Walter, A., et al., 2018.

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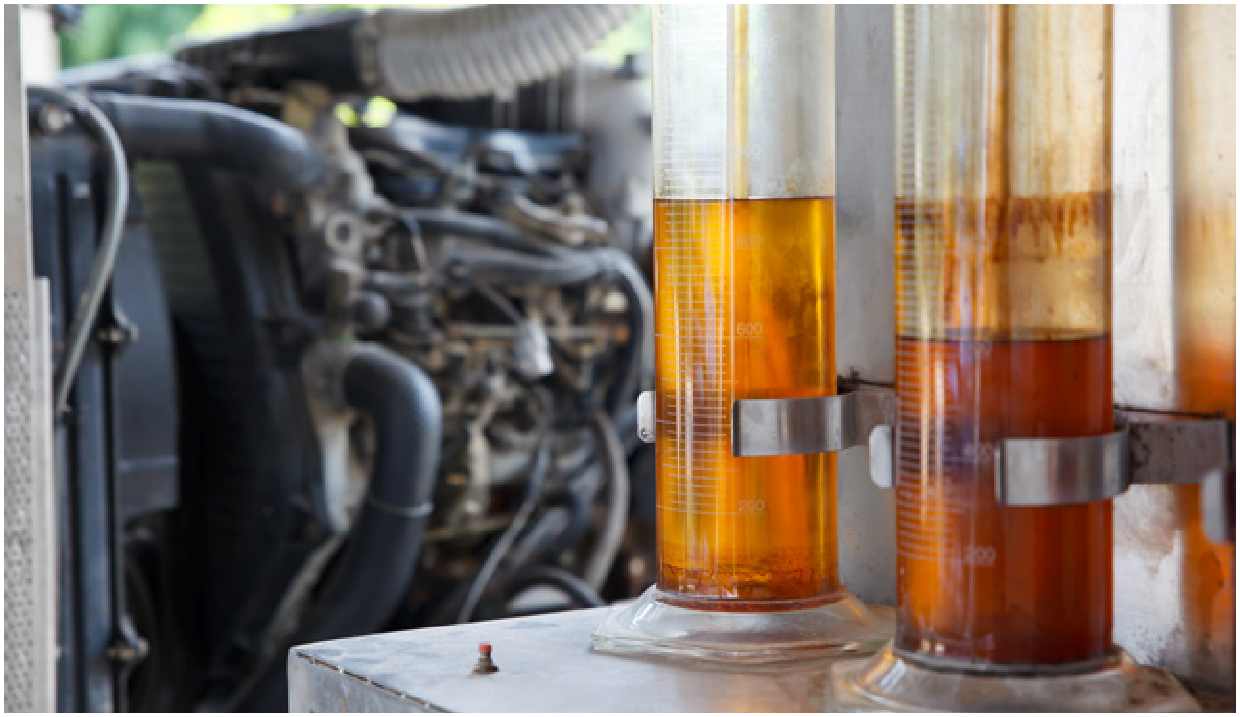
Chapter IV

4. CASE STUDIES

4.1 The Case of Malaysia and Indonesia: Rethinking Biofuel Policies for Sustainability and Flexibility

Lead Author: Chun Sheng Goh, Jeffrey Sachs Center on Sustainable



In Malaysia and Indonesia, the use of local bio-resources for energy purposes is not only perceived as an option to ease the stress of energy security but also an opportunity to create new jobs and income for farmers and the general rural population. Most of the time, the latter is perceived as a more important motivation for biofuel development as both countries are in fact large oil and gas producers. Initially in the 2000s, biofuel development was championed by trade and investment departments. Ambitious, mega-scale targets were set without carefully considering the vital links between economic, environmental, and social elements. Later, both countries gradually adjusted their targets to recognise that biofuel development needs to cover combinations of policy interventions across multiple sustainable development goals, especially economic growth (SDG 8), industrialization (SDG 9), energy (SDG 7), climate change (SDG 13), land-use (agriculture and forestry) (SDG 2 and SDG 15) and rural development (SDG 8). Evaluating the role of biofuels in achieving sustainable development in these countries would require more holistic thinking beyond just 'land' or 'energy' and instead covering multiple aspects of a place or territory. Evaluating the sustainability of biofuels in these countries, therefore, must carefully consider the regional and local context.

4.1.1 Palm Oil

Palm oil is the major cash crop in Malaysia and Indonesia. The palm oil industry, following the rubber industry, was developed as a means to jumpstart the economy in many parts of the countries. It plays a key role in economic development, contributing a significant percentage of the countries' revenues. A dominant feature of the palm oil industry is the extent to which exports of primary products, i.e. crude and refined palm oil, still loom large. However, due to a scarcity of suitable land resources and labour forces, Malaysia has lost its comparative advantage in furthering oil palm expansion. In Indonesia, the unsustainable mode of oil palm expansion has also greatly increased risk of environmental degradation and social conflicts. In the next few decades, it is unlikely that both countries will continue to see similar low-cost expansion as in the past due to biophysical, economic, and social factors.

4.1.2 Downstream Development

Historically, countries would pull out of low-cost, unsustainable land exploitation when they were able to diversify away from primary production. As incomes from downstream expand, land-based economies likely enter a transitional period towards more advanced, and possibly more sustainable forms of development, gradually reducing the rate of resource exploitation. As such, creating new added value through developing, upgrading, and diversifying the value chain is deemed an essential move to secure long-term economic interests. This has been regarded as a key step to transform Malaysia and Indonesia from primary producers to advanced bio-economies, as well as a turning point to relieve the countries from rampant timber extraction and agricultural expansion while improving the welfare of local population. Moving the local industries up in the commodity value chain requires advancement in manufacturing technologies, with products spanning from base oleo like fatty acids to end products like polymer and cosmetic products, and possibly in the future high-end products from advanced biorefineries. Biofuel is among the low hanging fruits in the eyes of producers as it involves relatively less complicated processing technologies.

However, there are still concerns over sustainability of the palm oil industry in attempts to move from primary production to secondary development. In the past, oil palm is often labelled as the culprit of extensive land-use change that involves massive carbon stock loss. Many organizations or movements, especially in Europe, have advocated excluding palm oil from the market, translating into policies or actions such as the 'No Palm Oil' label in France and Belgium. Among the different palm-based products, palm-based biofuels probably received the most criticism, involving numerous debates, discussions, research, movements, and even legal actions.
To better understand the sustainability of palm oil biofuels, it is necessary to place the discussion in different contexts.

4.1.3 Scale

First, it is important to understand the scale of biofuels in the context of the vegetable oils market. Figure 4.1 shows the trend in the global consumption of vegetable oil for technical purposes (i.e., not food or feed) in comparison to its other uses. In 2011, about a quarter of the global vegetable oil demand was fulfilled by palm oil, and about two-thirds of the total palm oil was used for technical purposes. Most of this palm oil was consumed in the chemical industry, with a relatively small amount devoted to biofuel production.

FIGURE 4.1 Amount of Vegetable Oils Consumed Globally

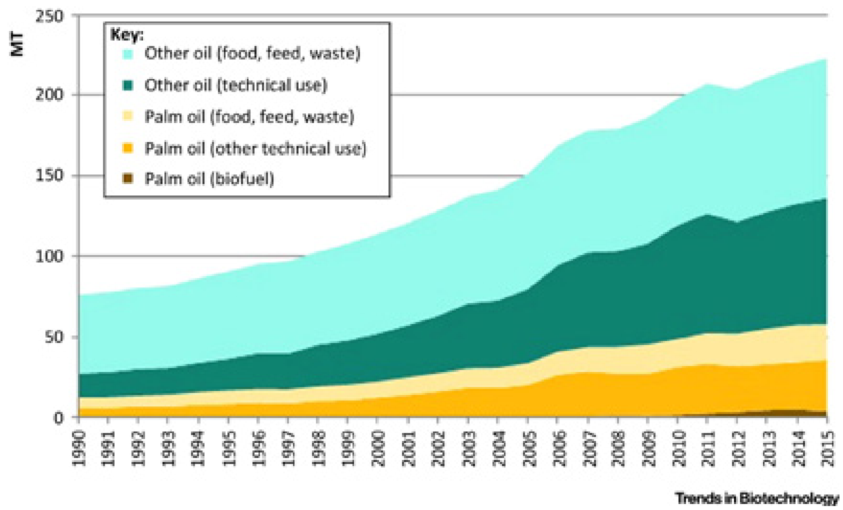
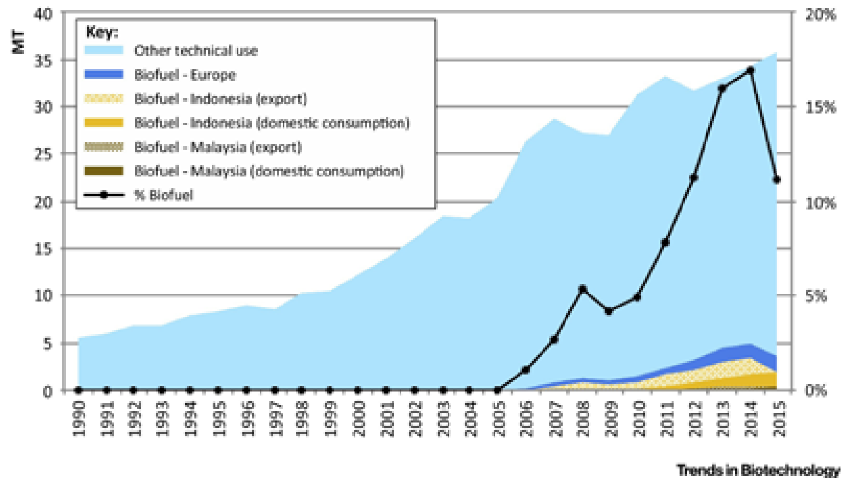


Figure 4.2 illustrates the use of palm oil for biofuel and other technical purposes. Palm oil has been used for biofuel production since 2007, especially in Europe. Indonesia and, to a lesser extent, Malaysia have historically produced palm-based biofuel for export purposes until they started to create domestic markets in 2011. In 2014, domestic consumption in these two countries had reached about half of what is consumed in Europe, while there was a sharp fall in Indonesian exports due to antidumping duties imposed by the EU. Outside of the biofuel industry, palm oil is actually much more widely used in personal care and cosmetics products, as well as in pharmaceutical ingredients. In fact, the volume of palm oil used for these purposes is more than six times that used for biofuel. Based on these figures, at first glance, the impact of palm-based biofuel is likely much lesser compared to other end-uses considering the scale of the market.

The scale of palm-based biofuel reflects that the biofuel policies in Malaysia and Indonesia are designed in a way to create a buffer for their primary commodity, i.e. palm oil. They carry the objectives of artificially creating a domestic biodiesel market for excessive stock of CPO resulting from the fluctuating prices. This is especially important in certain years when the demands for palm oil and palm-based products drop substantially.[361] Although emission reduction was often emphasized, the current domestic biodiesel market functions more as a back-up for the oil palm industry, providing more economic flexibility, especially considering that both countries are also major petroleum producers. This is also a reason why the palm-based biofuel industry in both countries is unstable, as the primary objective is to supplement the palm oil industry and less about emission-reduction or energy security. Recognising the practical challenges, governments have adopted more flexible approaches in setting blending targets, avoiding making ambitious goals for energy security and emission reduction. The competition between food and technical uses, when taken in this context, may be less of a concern.

[361] Goh, C. S. & Lee, K. T. 2010. Will biofuel projects in Southeast Asia become white elephants? *Energy Policy,* 38, 3847-3848.

FIGURE 4.2 Amount of Palm Oil Consumed Globally for Technical Purposes



4.1.4 Under-Utilized Low Carbon Land

Moving upstream, when biofuel production involves the use of under-utilized land, the risk of food-vs-fuel must be carefully evaluated. In reality, many idle, non-forested, and low carbon lands will remain unused for food production with or without biofuel development. This involves complex interactions between economic, agricultural, and international trade policies as well as food markets and distribution mechanisms. In many places, the incentives from biofuel production are perceived as a key to activate these land resources for productive use, thus providing new income sources for local communities. Multiple studies show that there is still plenty of non-forested, degraded land in Indonesia that remains under-utilized.[362]

4.1.5 Deforestation

Encouraging the use of under-utilized, low carbon land resources with the right incentives and rules may also prevent unsustainable expansion and conversion of forests. On a landscape scale, the new income provided by biofuel production may contribute to sustainable agrarian transitions in developing countries like Indonesia. While legislation and subsidies could protect the remaining forest, alternative funding and long-term income sources for local communities, e.g. provided by biofuels, are needed as an additional safeguarding measure. Potentially, this may be combined with incentives from the carbon tax or credit system for both land carbon restoration and emission reduction. Such combinations are still largely missing today, despite some small-scale experiments.

4.1.6 Land Availability and Readiness

Accompanying risks must also be properly understood in different regional contexts. Various names e.g. 'abandoned', 'degraded', and 'marginal' land, have been proposed to quantify land available for future expansion

[362] Jaung, W., Wiraguna, E., Okarda, B., Artati, Y., Goh, C., Syahru, R., Leksono, B., Prasetyo, L., Lee, S. & Baral, H. 2018. Spatial Assessment of Degraded Lands for Biofuel Production in Indonesia. *Sustainability*, 10.

depending on local interpretation.[363] Their definitions or criteria may be different, and some are not entirely clear, e.g. abandoned land is not necessarily degraded, and vice versa.[364] A study by Gibbs and Salmon shows that global estimates of 'degraded' land based on different databases and methodologies can vary widely from 1 billion ha to over 6 billion ha.[365] Furthermore, the conditions of land may change significantly from time to time, complicating the monitoring efforts. At the moment, high-resolution monitoring on a landscape scale is still too costly to be implemented. On this basis, it is crucial to understand how future expansion can take place on these lands considering the multiple factors and perspectives of various stakeholders. Importantly, mobilization of under-utilized lands needs to be safeguarded from unwanted environmental impacts, with measures like regulations or market-based voluntary sustainability standards.

4.1.7 Socio-economic Factors

Furthermore, adversarial relationships between local communities, private companies, and governments, especially in terms of land rights, have been frequently cited as one of the most serious problems discouraging land development in developing countries. Navigating a biofuel production system characterized by small-scale farming is ongoing, but strong external interventions are required to protect and support such a system, as well as regulate and ensure the sustainability of the entire landscape. Importantly, the development plan must consider how the different types of land-use – from small household mixed farming to industrial monoculture – can co-exist and interact.

4.1.8 Final Remarks

In short, the general impressions of food-fuel competition and indirect land-use impacts may turn out to be very different by countries or regions. The potential risks mentioned above may also be mitigated with better policymaking, business model designs, and law enforcement. **In the era of digital revolution, the emergence of new technologies like real-time monitoring of landscape and bioremediation of degraded soils may make biofuel production more sustainable.** These provoke decision-makers to rethink the role of biofuel development from a broader perspective. Importantly, it must be placed in a wider canvas of sustainable development that cuts across multiple SDGs beyond individual sectors, disciplines, institutions, and countries. The best outcome may only be achieved through co-learning and co-design among all stakeholders across sectors and scales, capitalizing on the synergies generated from integrating various transformative strategies across sectors.

Points for policy discussion:

- More holistic thinking beyond just 'land' or 'energy' but covering multiple aspects of a place or territory.

- One objective is creating new added value through developing and upgrading downstream diversification to relieve the countries from rampant timber extraction and agricultural expansion while improving the welfare of the local population.

[363] Ahmed Et Al., Using The Ecosystem Service Approach.; Goh, C. S., Wicke, B., Potter, L., Faaij, A., Zoomers, A. & Junginger, M. 2017. Exploring Under-utilised Low Carbon Land Resources From Multiple Perspectives: Case Studies On Regencies In Kalimantan. *Land Use Policy,* 60, 150-168.

[364] Smit, H. H., Meijaard, E., Van Der Laan, C., Mantel, S., Budiman, A. & Verweij, P. 2013. Breaking the Link between Environmental Degradation and Oil Palm Expansion: A Method for Enabling Sustainable Oil Palm Expansion. *PLoS ONE,* 8.

[365] Gibbs & Salmon, Mapping The World's Degraded Lands.

- More flexible approaches in setting the blending targets, avoiding making ambitious goals for energy security and emission reduction.

- Encouraging the use of under-utilized, low carbon land resources with the right incentives and rules may also prevent unsustainable expansion and conversion of forests.

- Understand how future expansion can take place on under-utilized, low carbon lands considering the multiple factors and perspectives of various stakeholders.

- Importantly, mobilization of under-utilized lands needs to be safeguarded from unwanted environmental impacts, with measures like regulations or market-based voluntary sustainability standards.

- Consider how the different types of land-use – from small household mixed farming to industrial monoculture – can co-exist and interact.

- The emergence of new technologies like real-time monitoring of landscape and bioremediation of degraded soils may make biofuel production more sustainable.

4.2 The Case of Brazil: Evidence that Sustainable Biofuels are an Effective and Immediate Solution for Decarbonizing Transport

Lead Author: Prof. Luiz A Horta Nogueira, Universidade Federal de Itajubá

Starting with ethanol blending mandates in gasoline in 1931, Brazil has been undertaking a long and persistent journey to successfully displace fossil fuels with biofuels. Biofuels are currently distributed in all the 41,700 gas stations in the country, in the form of gasohol (E27), pure hydrous ethanol (E100) or diesel/biodiesel blend (B12). The volumes are enough to displace about 600 thousand barrels of oil per day, thereby avoiding the emission of 69 million tonnes of CO_2 per year. All Brazilian vehicles (i.e., more than 47 million units), from motorbikes to heavy trucks, use some type of biofuel, either neat or in blends with oil products. The local production of these biofuels reduces energy imports, improves the national energy security, and brings social and environmental benefits.

4.2.1 Current Status of Biofuels Production and Use

Figure 4.3 presents the evolution of blending mandates of biofuels and Figure 4.4 presents the progressive contributions of biofuels, in energy terms. In 2019, ethanol replaced 45% of gasoline consumption, while biodiesel replaced 9% of fossil diesel, although legislation aims to reach 15% by 2023. Currently, most of the Brazilian light duty fleet is powered with flex-fuel engines, which are able to burn, with good performance, any blend from E100 to E27, hence explaining why ethanol participation is higher than the blending mandate. The remarkable reduction of ethanol consumption in the 2008-2012 period was essentially due to the elevated subsidies applied to gasoline in this period, moving consumers to fossil fuels.

FIGURE 4.3 Evolution of biofuel blending in gasoline and diesel in Brazil (% in volume)

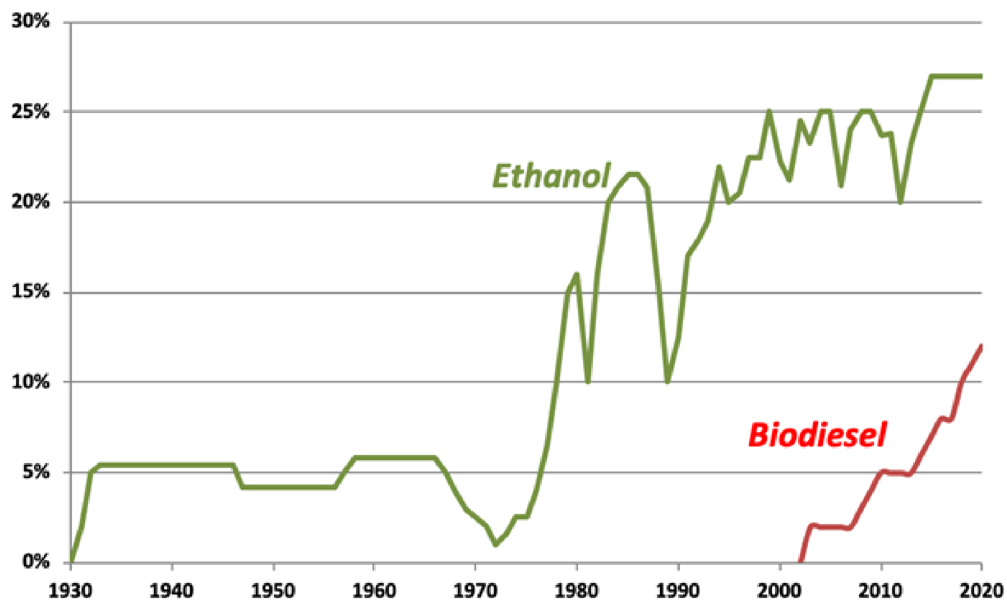
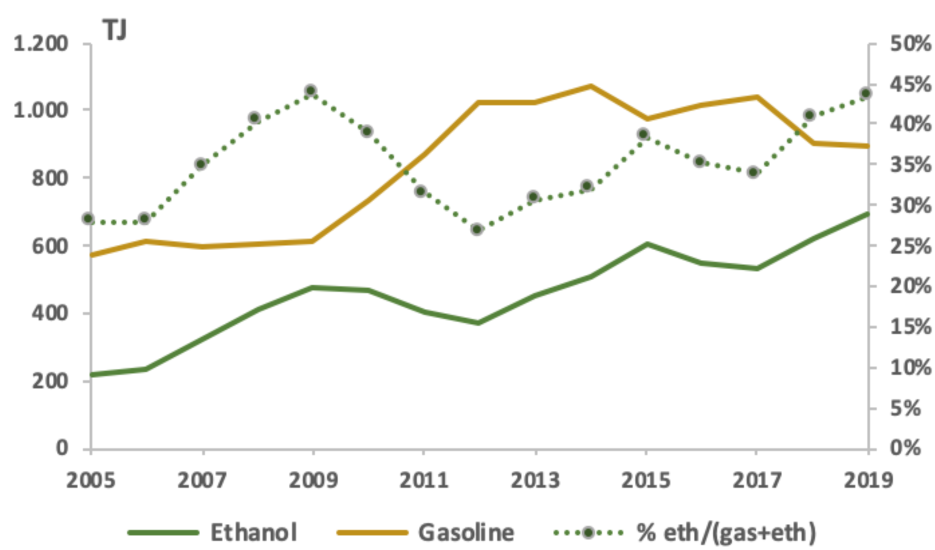
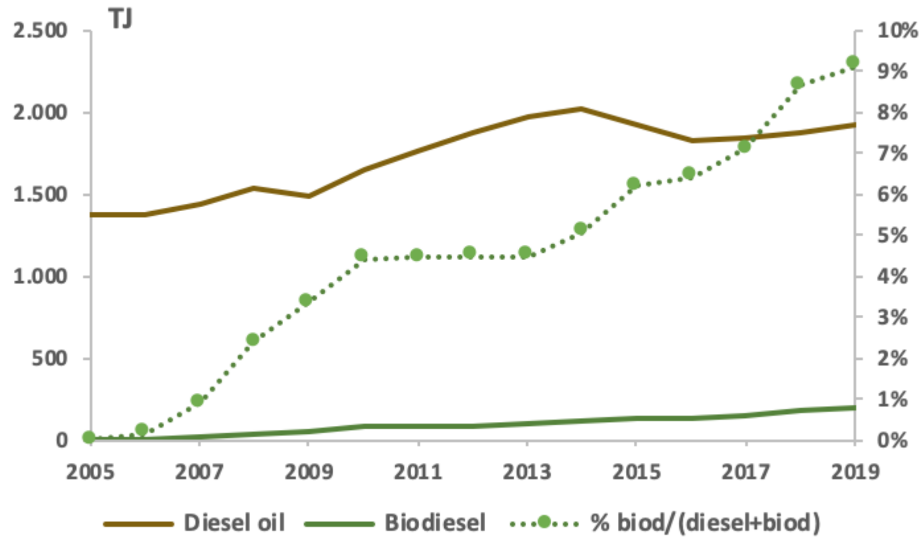


FIGURE 4.4 Fossil fuels and biofuels consumption and biofuels participation in Brazil

a) Gasoline and ethanol

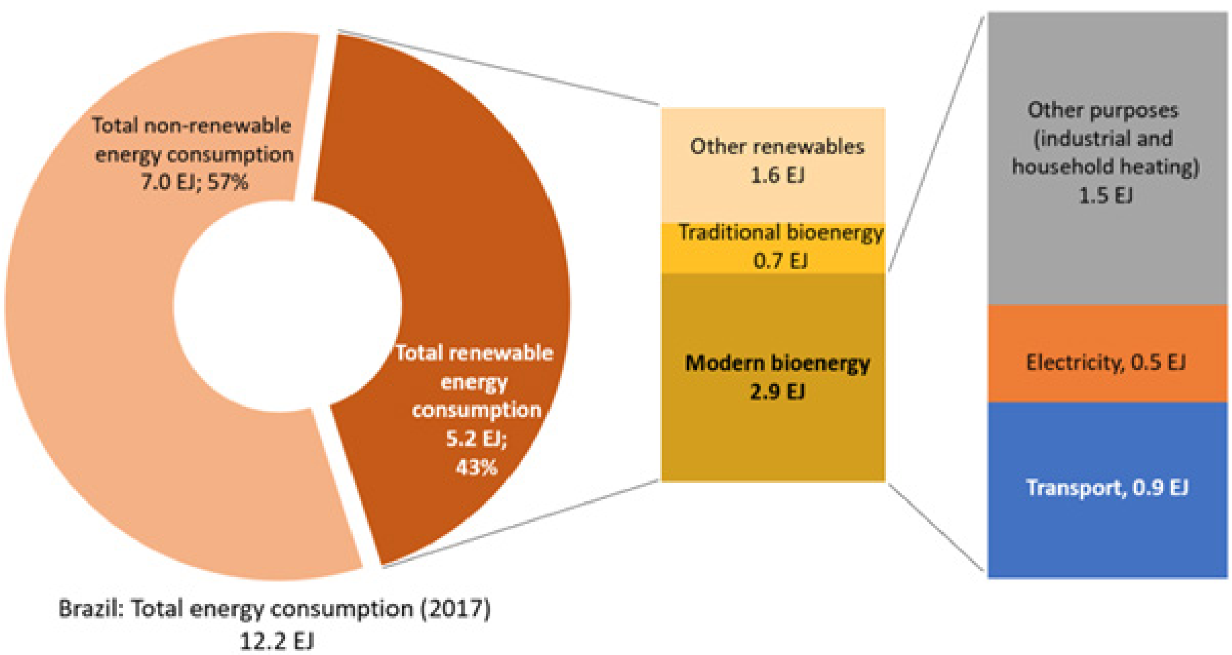


b) Diesel oil and biodiesel



Modern liquid biofuels are part of the bioenergy production in Brazil, whereas biomass such as sugarcane bagasse, black liquor, and wood processing residues, are used as fuel for heat and power applications. In 2019, electricity from biomass reached 52.5 GWh, i.e. 8.2% of the total electricity generation in Brazil. Overall, bioenergy is the most important renewable energy source in the country (Figure 4.5).

FIGURE 4.5 Bioenergy in the Brazilian Energy Matrix

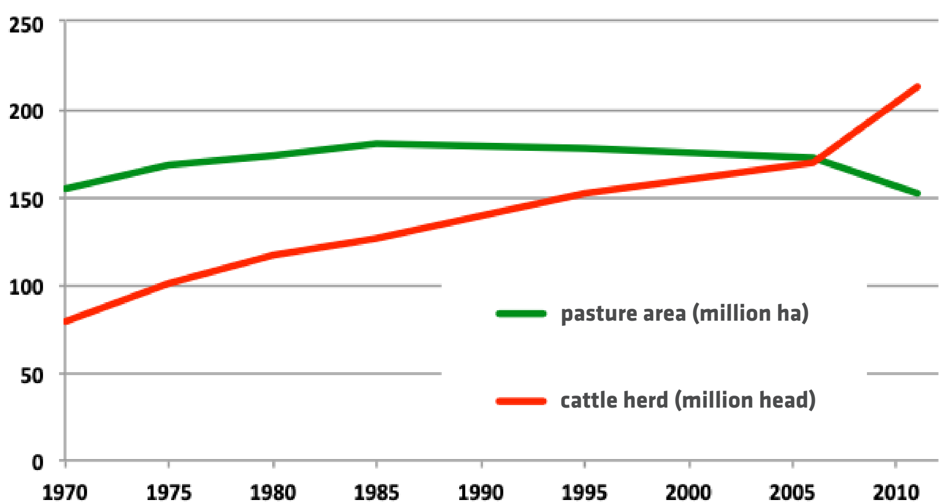


4.2.2 Biofuels Impacts and Land Use

As important as the energy contribution and emissions effects of biofuels, significant social and economic benefits can also be associated with their production and use. The sugarcane agroindustry alone, mostly adopting mechanized harvesting operations and modern cultivation practices, employs 870,000 workers and creates 2.5 million indirect jobs. It has been shown that sugarcane improves life conditions in regions where it is produced, as supported by a higher HDI compared to the neighboring regions. Furthermore, the accumulated savings of 3.15 billion barrels in gasoline imports avoided by ethanol production since 1975 was valued at 540 billion USD.

The modern bioenergy agroindustry, applying advanced technology and sustainability-oriented management in feedstock production and processing, allowed high yields and efficiencies, which resulted in a reduced land requirement. In Brazil, ethanol is produced mainly from sugarcane, complemented with corn, while biodiesel comes basically from soybean oil and tallow, with minor contributions from other vegetable oils. These feedstocks combined occupy about 11.2 Mha, i.e. 1.3% of national area. In fact, there is still a large room for promoting bioenergy on a sustainable basis, without affecting the production of other agricultural goods, neither harming natural forests nor biodiversity, especially through productivity gains and densification in livestock production. As indicated in Figure 4.6, cultivated and natural pastures occupy about 150 Mha in Brazil, 18% of the national territory, where the adoption of better practices has allowed an increase in production and freed land for other activities. Even marginal productivity gains in this large area can significantly expand the bioenergy supply. For instance, considering current best practices in Brazil, annual energy productivities of about 0.29 TJ/ha or 47 boe/ha has been obtained.

FIGURE 4.6 Evolution of pasture area and cattle herd in Brazil



As a good indicator of the space for sustainable bioenergy expansion, in the Brazilian agroecological zoning for sugarcane, approximately 65.0 Mha are considered suitable for expansion, more than six times the current area. Among other restrictions, the following areas were excluded for this estimation: (a) land with slopes greater than 12% (unsuitable for mechanical harvesting), (b) areas with native vegetation, (c) Amazon and Pantanal biomes, (d) environmental protection areas, and (f) indigenous lands.

Therefore, the sustainable production of relevant volumes of biofuels can be well developed in areas of low productivity pastures with no need to use lands in the Amazon biome. It must be noted, however, that there is an urgency to promote (sustainable) economic activities in the Amazon, generating jobs and income distribution. In that sense, the production of oil palm in the currently degraded areas is an interesting option, as this can achieve high productivity while helping to recover the land. This means that the production of sustainable biofuels does not rely on the Amazon, but the desired development of the region may have biofuels as an important component. However, in order to be socially effective, governance and effective public policies (some already in place) must avoid undesired socioeconomic impacts, such as land grabbing, which may be one of the most delicate aspects for local communities and is not limited to biofuels initiatives.

4.2.3 The Essential Role of R&D

The remarkable evolution of efficiency and productivity of bioenergy production and use in Brazil was strongly supported by local R&D efforts, along the whole supply chain, from agriculture to final use, including process improvement, product diversification, and environmental impacts reduction. During the last decades, after initial studies and trials in Brazilian research centers and universities, a large set of new technologies were launched and progressively adopted. Some examples include the development of new plant varieties, biological control of pests, reduced tillage practices, precision agriculture, improved harvesting and transport, crop residue utilization, cogeneration, biogas production from stillage, and nutrients recycling, among several others. All of these efforts have led to less pollution and reduced consumption of chemicals and water, meaning reduced losses and more production, essentially by adopting more rational and environmentally responsible approaches, reinforcing the competitiveness of bioenergy production. With impressive results in ethanol agroindustry, after 30 years, energy productivity (in MJ/ha) increased by threefold and water consumption in the sugarcane mills was reduced to 5% of the original figures.

Additional relevant achievements can be expected in the forthcoming years, as indicated by the research results already available in Brazil. For example, new sugarcane varieties, selected and improved to yield more fiber and sugar, (also known as energy cane) have been introduced, doubling the conventional energy production per cultivated area. Also, second generation technologies are in pre-commercial operation. Several other innovations are under development, evolving the current agro-energy plants towards biorefineries, aligned with the broader concept of the modern bioeconomy. Particularly interesting for tackling climate change, assessments of CCS integration to ethanol mills are underway to make use of CO_2 rich streams to enable negative GHG emissions from bioenergy, for example at ADM Illinois Industrial Carbon Capture and Storage (ICCS) project in Decatur, Illinois.

Complementing the R&D efforts and outcomes in biofuels production, their final use in road vehicles has also received attention In Brazil. Thus, new concepts have been introduced, such as electric turbocharging and flex fuel hybrid electric vehicles, increasing the efficiency of internal combustion engines; and fuel cell electric cars, fed with hydrogen produced on board by ethanol catalytic reform, which are currently in tests and demonstration on Brazilian roads. These improvements reinforce the advantage of biofuels.

4.2.4 Renovabio Program: An Environmental Breakthrough

Beyond the improvement of air quality in large cities, such as observed in São Paulo and Rio de Janeiro, the lower carbon footprint of biofuels allowed a significant reduction in GHG emissions in the Brazilian transport sector, representing an important contribution to the Brazilian NDC pledge in COP21. This positive effect has been acknowledged by the new Brazilian biofuels policy RenovaBio, launched in 2017. RenovaBio is a federal policy intended to reinforce the role of biofuels in the Brazilian energy matrix, in order to enhance energy security and mitigate GHG emissions, hence contributing to fulfill the Brazilian commitments under the Paris Agreement. The program establishes annual decarbonization targets for the transport sector and includes sub-targets for fuel distributors. The objective is to create a market-driven mechanism to promote the expansion of biofuels in final energy demand, including land, sea, and air transport, based on sustainable practices and increased energy-environmental efficiency. The mechanism relies on a voluntary certification system through which biofuel producers can issue decarbonization credits (CBIOs) based on their respective carbon footprint. Financial institutions issue CBIOs which are freely negotiated at the stock exchange, and public policy will only be in charge of defining the long-term carbon reduction targets. Current decarbonization targets approved under RenovaBio will reduce the emission of 700 million tons of carbon from energy in the transport sector by 2029, making it one of the largest decarbonization programs in the world.

RenovaBio incorporates zero deforestation as one of the eligibility criteria for certification of biofuel producers. This means that biofuel production cannot be based on feedstocks coming from deforested areas, and all areas under cultivation must be registered under Brazil's strict Forestry Code's CAR (Rural Environmental Registry) requirements. More than a model of low carbon energy production, RenovaBio has consolidated a project of integrated economic development, using the potential for expansion of bioenergy production.

4.2.5 Final Remarks: A Vision of Future

Brazil offers a consistent example of the potential of biofuels, improved over decades in real large-scale systems, supplying competitive and low carbon fuels for a large vehicle fleet, with social and environmental advantages. Brazil has certainly succeeded in displacing fossil fuels by solar energy through biofuels, and in all scenarios forecasted for the forthcoming decades, this option is present.

This Brazilian experience has been successfully replicated in other countries as well; however, it can still be replicated/adapted in many other wet tropical countries, enabling a reduction of carbon emissions in the short term and increasing the sustainability of the energy sector as a whole. For this, land availability for expanding biomass production is more than enough and there is a large room for improvement in the production and use stages, assuring that it is possible and feasible to foster significant biofuel production and use in the short and long term. Indeed, biofuels can play an immediate and decisive role to decarbonize the transport sector, employing essentially the existing liquid fuel logistic infrastructure and the current vehicles fleet. However, although the Brazilian experience indicates that modern bioenergy can significantly reduce GHG emissions while promoting quality of life, it is unrealistic to expect that biofuels will solve all social and environmental problems alone. Complementary actions will certainly be necessary for the promotion of economic growth and in the pursuit of the Sustainable Development Goals.

4.3 The Case of the United States: Reimagining Biofuels as if Carbon Mattered

Lead Author: Tom Richard, Pennsylvania State University

4.3.1. The First Generation – Biofuels as a Market for Agricultural Abundance and Energy Security

Historians remind us that the past is the prologue, so in mapping the future of bioenergy it is important to understand the historical context. Putting aside the thousands of years that bioenergy via fire was the primary human energy resource, and skipping over a few short forays into biofuels for transportation by Rudolf Diesel, Henry Ford and others, the modern biofuels industry really began to gather momentum in the US in the 1970s. Although potential conflicts between food versus fuel dominate the debate about the role of biofuels in a sustainable future, it is important to note that the greatest challenge for the U.S. food system then, and arguably still today, was not scarcity but an overabundance of food. And today, as then, biofuels may offer a path toward sustainable development, but only if we learn from and address the challenges unveiled in the intervening decades.

In the mid 1970s the US beef industry started losing market share to poultry at an increasing rate, to the point that over a few decades per capita demand for beef dropped by over 30%.[366] Because poultry is much more efficient than beef at converting grains to meat, this dietary change led to a steep decline in demand for corn and soybeans. At the same time, biotechnology advances and improved crop management kept increasing grain yields year after year. Increasing supply and shrinking demand led to chronically low prices for farmers, while tight monetary prices caused farmland value to plummet.[367] During the farm crisis in the 1980s, farm bankruptcies

[366] "Agricultural Economic Insights | Pass The Meat: U.S. Meat Consumption Turns Higher". 2021. *Agricultural Economic Insights*. https://aei.ag/2016/10/31/u-s-meat-consumption-turns-higher/.

[367] Barnett, B.J. 2000. The U.S. farm financial crisis of the 1980s. Agricultural History 74(2):366-380

were at levels not seen since the Dust Bowl of the 1920s and Great Depression of the 1930s. Low crop prices and economic stress were crushing rural communities and driving young people away from farming. The U.S. also had its first "peak oil" in 1970, and in subsequent decades experienced declining domestic oil production, increasing imports, and frequent price shocks.[368] In this context corn ethanol and soybean biodiesel gained widespread political support and strong financial subsidies to address concerns of energy security, farm income, and rural economic development.[369]

The environmental attributes of biofuels were always recognized, but in a secondary role, with the first real environmental driver being the use of ethanol as an oxygenate in gasoline to improve combustion, replacing the carcinogenic petroleum-derived methyl tert-butyl ether (MTBE) that had contaminated groundwater through spills and leaking underground storage tanks.[370] That substitution resulted in a new standard that gasoline vehicles be designed for blends of up to 10% ethanol. That 10% ethanol content became a defacto "blend wall", slowing growth in demand soon after ethanol production reached 10 billion gallons per year in 2009. While subsequent testing by manufacturers and the US Environmental Protection Agency (EPA) now allows vehicles built since 2001 to use blends up to 15% ethanol, that cap has effectively constrained demand to about 15 billion gallons per year since 2015 (see figure 4.3.1).[371]

4.3.2. A Lost Decade: Cellulosic Biofuels Boom and Bust

The biofuels industry entered the first decade of the new millennium with both political and economic momentum. Climate change was gaining widespread attention, and cellulosic biofuels were recognized for their potential to reduce greenhouse gas emissions. Both private industry and federal agencies projected that the cellulosic biofuel industry was technically ready for commercialization. There was widespread belief that the primary limitation to commercialization was financing, which could be solved by guaranteed markets. Soon the U.S. Congress was ready to expand support for biofuels, passing the Energy Independence and Security Act of 2007.[372] These revisions to the Renewable Fuel Standard (RFS2) set annual fuel volume requirements that blenders and distributors of petroleum fuels had to meet, resulting in an EPA regulated market for renewable fuels and their associated Renewable Identification Numbers (RINs) by petroleum fuel distributors. Volume requirements were set for different categories of biofuels, with volumes for first generation biofuels of starch ethanol and biodiesel only expanded slightly. Of the nearly 400% growth projected for the 15 years ending in 2022, almost all would be in the categories of cellulosic and other advanced biofuels that have a greatly reduced carbon footprint relative to fossil fuels. Separate volume requirements were set for each fuel category, and thus guaranteed markets with higher prices were expected to subsidize the rapid growth of the most low carbon cellulosic and advanced biofuels.[373]

[368] Bardi, U. 2019. Peak oil, 20 years later: Failed prediction or useful insight? Energy Research & Social Science 48:257-261.

[369] Tyner, W.E. 2008. The US Ethanol and biofuels boom: its origins, current status and future prospects. BioScience 58(7):646-653. https://doi.org/10.1641/B580718.

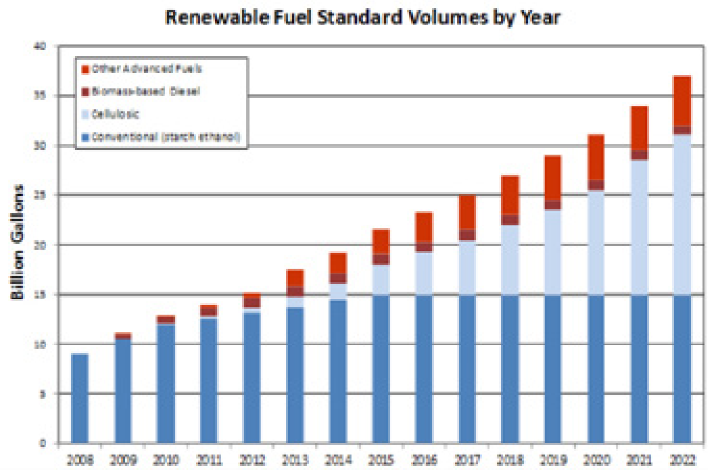
[370] Connor J.A., R. Kamath, K.L. Walker, and T.E. McHugh. 2015. Review of quantitative surveys of the length and stability of MTBE, TBA, and benzene plumes in groundwater at UST sites. Ground Water 53(2):195-206. doi: 10.1111/gwat.12233.

[371] 2021. *Eia.Gov*. https://www.eia.gov/todayinenergy/detail.php?id=40095.

[372] "H.R.6 - 110Th Congress (2007-2008): Energy Independence And Security Act Of 2007". 2021. *Congress.Gov*. https://www.congress.gov/bill/110th-congress/house-bill/6.

[373] U. S. Environmental Protection Agency, Assessment and Standards Division, Office of Transportation and Air Quality. 2010. Renewable fuel standard program (RFS2) regulatory impact analysis. United States Environmental Protection Agency, Washington, DC. https://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=P1006DXP.TXT

FIGURE 4.3.1. The U.S. Energy Independence and Security Act of 2007 legislated annual renewable fuel volume requirements for defined categories of biofuel.



Shortly after the 2007 legislation became law, several companies announced plans to build cellulosic biofuel plants, and within a few years three were fully built in the U.S. and several others started. But then came the bust, and as with the boom there were a constellation of factors involved. First, the technology was simply not ready. Processes that worked in the laboratory or small pilot facilities faced challenges at commercial scale. These challenges were exacerbated by the rush to build full-scale commercial plants that were often thousands of times larger than any proven pilot scale, despite prudent industry practice indicating that scale-up with solid feedstocks should step up by a factor of ten to twenty at most. Biomass logistics were also an issue, ranging from challenges with negotiating farmer contracts to major fires in storage depots. Not one of that first round of second generation cellulosic biofuel biorefineries is regularly operating today.[374]

Beginning in 2008 and continuing to the present, overcoming these commercialization challenges has been hindered by a softening of public and private support. Public support for biofuels was first challenged by perception that food production is in conflict with biofuels. This concern coincided with rapid growth of the starch ethanol industry in the 2000's, so that by 2008 roughly 40% of the U.S. corn crop was used for that single purpose. That year prices for corn and other grains spiked, and biofuels were blamed for grain scarcity and higher food prices, igniting a "food versus fuel" debate. While those price spikes and grain shortages were eventually found to be largely due to other factors including crop failures due to drought elsewhere in the world, the public mindset was fixed.[375] That concern about food production was reinforced by several scientific papers in 2008 and subsequent years projecting that biofuel demand induced land use change and conversion of native ecosystems including tropical rainforests that greatly diminished and might even overcome any greenhouse gas emission

[374] "Next-Gen Biofuel Dreams Fade; Developers Blame EPA". 2021. *Agri-Pulse.Com*. https://www.agri-pulse.com/articles/12894-cellulosic-ethanol-struggles-to-climb-commercialization-ladder.

[375] Zhang, Z., L. Lohr, C. Escalante, M. Wetzstein. 2010. Food versus fuel: What do prices tell us? Energy Policy 38:445-451.

benefits of biofuels relative to fossil energy.[376] Although later studies dramatically reduced those early estimates, the views of many environmental groups and much of the public had shifted to a negative view of biofuels.[377]

A second factor in reducing public support was the rapid increase in domestic oil and gas production due to hydraulic fracturing. U.S. production of natural gas began growing rapidly in 2005 and the shale oil boom followed in 2008, growing so rapidly that the previous 1972 peak in domestic oil production was surpassed in 2018 and is even higher today. The oil and gas industry became less concerned about shortages and more concerned about growing markets for fossil oil and gas. While some U.S. auto manufacturers were prepared to shift to make internal combustion engines to be more compatible with ethanol (the easiest and most efficient liquid fuel produced from biomass, including from cellulose), there was a growing call from the petroleum industry, the aviation industry (see next section) and others for "drop-in" fuels that were 100% compatible with existing engines and infrastructure, often implying that was the only way to overcome the "blend wall".[378] Not surprisingly, these drop-in fuels have proven much more difficult and more expensive to make than ethanol. In the last decade, government and academic researchers have spent over a billion dollars on research on drop-in fuels, and the only large-scale commercial successes thus far have been based on either first generation vegetable oil feedstocks or, for cellulosic feedstocks, the gasification and Fisher-Tropsch technology developed in World War II and expanded in South Africa to make liquid fuels from coal in response to sanctions during the apartheid era.[379] With limited public and political support and continuing technology challenges, renewable energy investment capital shifted to less controversial renewables like solar and wind.[380] This flight of investment capital continues to limit growth in the U.S. biofuels industry with two important exceptions – aviation fuels and renewable natural gas.

4.3.3. Aviation Biofuels

Although the commercial success of electric vehicles is a more recent phenomena than the call for drop-in fuels, they have been mutually reinforcing. With the rapid advances in batteries and electric vehicle technologies, new questions have been raised about whether there is even a need for transportation biofuels in the future. Long term projections by the U.S. Department of Energy, the International Energy Agency, and others indicate that heavy duty transportation and specifically commercial aviation will be most reliant on liquid fuels. Finding substitutes for commercial aviation is particularly challenging for several reasons: from a technical standpoint liquid fuels have a far higher energy density than batteries or even gaseous fuels on a volumetric basis, so for long distance flight fuel storage space is a major constraint; each airplane can remain in commercial service for many decades, so every airport will need to service the existing fleet with liquid fuels well past 2050 greenhouse

[376] Fargione, J., J. Hill, D. Tilman, S. Polasky, P. Hawthorne. 2008. Land clearing and the biofuel carbon debt. Science 319, 1235–1238 (2008).; Searchinger, T. et al., 2008. Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319, 1238–1240.

[377] Taheripour, F., W. E. Tyner, M. Q. Wang. 2011.Global land use changes due to the US cellulosic biofuel program simulated with the GTAP model. Argonne National Laboratory. https://greet.es.anl.gov/publication-luc_ethanol.; Dunn, J.B., S. Mueller, H. Kwon, M. Q. Wang. 2013. Land-use change and greenhouse gas emissions from corn and cellulosic ethanol. Biotechnology for Biofuels. **6**, 51.

[378] Anderson, J.E., D.M. DiCicco, J.M. Ginder, U. Kramer, T.G. Leone, H.E. Raney-Pablo, T.J. Wallington. 2012. High octane number ethanol–gasoline blends: Quantifying the potential benefits in the United States, Fuel 97:585-594, ISSN 0016-2361, https://doi.org/10.1016/j.fuel.2012.03.017.

[379] Shahabuddin M., Alam M.T., Krishna B.B., Bhaskar T., Perkins G. 2020. A review on the production of renewable aviation fuels from the gasification of biomass and residual wastes. Bioresour Technol. 312:123596. https://doi.org/10.1016/j.biortech.2020.123596.

[380] Lynd, L. 2017. The grand challenge of cellulosic biofuels. Nat Biotechnol **35**, 912–915. https://doi.org/10.1038/nbt.3976.

gas reduction targets; and jet engines are already very efficient, so there is little potential to double mileage efficiency like the automobile industry is on track to achieve.[381]

For all these reasons the commercial aviation industry has encouraged and welcomed the pivot in U.S. government research and demonstration funding to "drop-in" fuels. While many airlines are purchasing small volumes of aviation biofuels today, most current commercial processes use vegetable oil as feedstock, which has a similar cost to conventional jet fuel and limited per acre yield. There are commercial aviation biofuel alternatives based on sugars and starch (with similar food versus fuel constraints) or thermochemical technologies such as gasification and Fischer-Tropsch catalysis. Many other drop-in fuel technologies have been proposed and even demonstrated at laboratory scale, but commercial scale-up remains in its infancy.[382]

4.3.4. The Rise of Renewable Natural Gas – The Surprise Drop-In Fuel

While the legacy of the 1970s oil crisis lingers on in the policy support for liquid biofuels for transportation, in the last five years it is a gaseous biofuel that has experienced the most rapid growth. Renewable Natural Gas (RNG), or biomethane, is chemically identical to the methane molecule that comprises over 95% of fossil natural gas. While the U.S. Renewable Fuel Standard (RFS) categories of cellulosic biofuels and advanced biofuels were written with liquid fuels in mind, in 2014 the EPA made a determination to expand the cellulosic biofuel category to include the methane from landfills and anaerobic digestion, categorizing landfill waste and on-farm agricultural feedstocks as cellulosic by definition, and therefore eligible for the most lucrative subsidies in that program.[383] The state of California provides an even larger subsidy for many types of RNG through their transportation-focused Low Carbon Fuel Standard (LCFS).[384] Suddenly landfills and farms that had been converting biogas (a mixture of roughly 60% methane and 40% CO_2) to electricity found that these transportation subsidies were much more lucrative than renewable electricity, and since 2014 over 95% of the cellulosic biofuel sold in the U.S. has been RNG.[385] Both the RFS and LCSF markets are constrained by there being enough natural gas vehicles buying RNG for transportation to justify all the RNG subsidies, but thus far that usage has exceeded the supply. With shale gas continuing to be low cost and abundant, many public and commercial transportation fleets have been converting vehicles to natural gas, staying ahead of the surge in investment in RNG projects at landfills and farms.

While the initial growth of RNG in the U.S. has primarily been driven by subsidies for transportation biofuels, most fossil natural gas is used for electricity and process heat. As these sectors also shift to renewable sources, new markets for RNG are expected to expand, with the natural gas grid providing very low cost distribution to a massive customer base. Already some businesses and governments are contracting for RNG to replace their fossil natural gas in heat and power applications, allowing significant reductions in the corporate greenhouse gas footprint. As intermittent renewables like solar and wind supply even larger fractions of the electricity portfolio, RNG fueled

[381] National Academies of Sciences, Engineering, Medicine. 2016. Commercial Aircraft Propulsion and Energy Systems Research: Reducing the Global Carbon Emissions. Washington, D.C., The National Academies Press. https://www.nap.edu/23490.

[382] Díaz-Pérez M.A., Serrano-Ruiz J.C. 2020. Catalytic Production of Jet Fuels from Biomass. Molecules:25(4):802. https://doi.org/10.3390/molecules25040802

[383] "Renewable Fuel Pathways II Final Rule To Identify Additional Fuel Pathways Under Renewable Fuel Standard Program | US EPA". 2021. *US EPA*. https://www.epa.gov/renewable-fuel-standard-program/renewable-fuel-pathways-ii-final-rule-identify-additional-fuel.

[384] "Low Carbon Fuel Standard | California Air Resources Board". 2021. *Ww2.Arb.Ca.Gov*. https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard.

[385] 2021. *Eia.Gov*. https://www.eia.gov/todayinenergy/detail.php?id=33212.

gas turbine generators will compete with grid-scale batteries to provide easily stored and dispatchable electricity. Although the term "drop-in" fuel was originally intended to describe liquid biofuels for transportation, RNG can compete favorably not just for transportation but also heat, electricity, and manufacturing. With fossil natural gas now the dominant energy source across all these sectors in the U.S., meeting future goals to reduce GHG emissions may require a larger role for RNG, perhaps the ultimate drop-in fuel.

4.3.5. CO_2 Storage Arrives

RNG is not the only opportunity for bioenergy to leverage U.S. fossil energy investments. Over several decades the U.S. Department of Energy (DOE) has invested billions of dollars developing technologies for the capture and geologic storage of CO_2 from coal-fired power plants. The U.S. has suitable geology to store over a thousand years of CO_2 at current emission rates. Carbon capture from flue gas at power plants has proven technologically complex and expensive to scale-up. But most biofuel conversion processes produce concentrated CO_2, either as a byproduct of ethanol fermentation, the residual gas after RNG purification from biogas, or as a byproduct of syngas cleanup in a thermochemical biorefinery.[386]

For these reasons, a corn ethanol biorefinery owned by ADM is now the first U.S. commercial source of CO_2 to be stored underground, funded initially as a DOE demonstration project and currently injecting a million Mg of CO_2 annually. That facility overlays appropriate geology so there are no transport costs, but for more dispersed networks the costs of pipeline transport of CO_2, plus injection and monitoring of a geologic storage site, are estimated at between $30 and $60 per Mg of CO_2.[387] Federal tax incentives passed in 2017 cover most or all of those costs, and any geologic CO_2 storage associated with biofuels sold in California for transportation can earn additional incentives of nearly $200 per Mg of CO_2 through the Low Carbon Fuel Standard marketplace. As a result of these incentives and synergies, biofuel facilities are poised to dominate the near-term growth of CO_2 storage in the U.S. In early 2021, Summit Carbon Solutions announced a $2 billion pipeline that will gather CO_2 from corn ethanol facilities in several Midwestern states for geologic storage.[388]

With the right feedstocks and processing strategies, Biomass Energy Carbon Capture and Storage (BECCS) can not only reduce emissions, but actually produce net carbon negative energy. Relative to regular biomass energy systems, adding BECCS can capture an additional 33% of the biomass feedstock carbon in an ethanol fermentation, 40% in anaerobic digestion when separating biogas to RNG, 50% from thermochemical fuel catalysis, and over 95% from a bioelectricity plant.[389] BECCS has been widely viewed by the Intergovernmental Panel on Climate Change and others as the primary strategy for offsetting fossil emissions by mid-century, and is projected to be

[386] Field J.L., L.R. Lynd, T.L. Richard, E.A.H. Smithwick, H. Cai, M.S. Laser, D.S. LeBauer, S.P. Long, K. Paustian, Z. Qin, J.J. Sheehan, P. Smith, M.Q.L. Wang. 2020. Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels. Proceedings of the National Academy of Sciences 117 (36) 21968-21977. https://doi.org/10.1073/pnas.1920877117

[387] Sanchez, D.L., N. Johnson, S.T. McCoy, P.A. Turner, K.J. Mach. 2018. Near-term deployment of carbon capture and sequestration from biorefineries in the United States. Proceedings of the National Academy of Sciences. **115**, 4875–4880. https://doi.org/10.1073/pnas.1719695115.

[388] "Summit Carbon Solutions To Launch Major CCS Network To Reduce Carbon Footprint Of U.S. Biorefineries - Chemical Engineering". 2021. *Chemical Engineering*. https://www.chemengonline.com/summit-carbon-solutions-to-launch-major-ccs-network-to-reduce-carbon-footprint-of-u-s-biorefineries/.

[389] Field, et al., Robust paths to net greenhouse gas mitigation and negative emissions; Sanchez, D.L, J.H. Nelson, J. Johnston, A. Mileva, D.M. Kammen. 2015. Biomass enables the transition to a carbon-negative power system across western North America. Nature Climate Change. **5**, 230–234. https://doi.org/10.1038/nclimate2488.

drawing down atmospheric CO_2 concentrations at a gigaton scale by 2100.[390] But achieving those goals will require substantial investment in research, development, and deployment, as maximizing the climate mitigation potential of bioenergy requires advances in both sustainable feedstock production and conversion technology.[391]

4.3.6. Sustainable Feedstocks: Realizing the Potential of Carbon Negative Biofuels

At the scale of the earth system, photosynthesis captures ten times as much CO_2 as is emitted by current fossil energy production. Some of that carbon captured by photosynthesis is stored in forests, soils, and other ecosystems, and net ecosystem carbon storage at a large scale can provide a substantial "natural solution" to climate change.[392] But in most ecosystems, nearly all of that captured carbon quickly returns the atmosphere through decomposition or fire. Unfortunately, many human interventions including land clearing, cultivation and drainage associated with conventional agriculture can lead to net ecosystem carbon loss. To get to a meaningful carbon negative system, termed "additionality", requires (1) increasing photosynthetic carbon uptake and/or (2) reducing losses that normally return to the atmosphere via respiration or combustion. Recognizing that the fundamental problem of U.S. agriculture is currently abundance, not scarcity, and that the need for negative emissions is already massive and needs to grow, it is important to consider the sustainability of biomass feedstock alternatives with respect to their climate mitigation potential, their impact on ecosystem services, and potential synergies with food production systems. There are many win-win options for food and biofuel.

Increasing photosynthetic carbon capture (additionality #1) can be accomplished in several ways. In the U.S., plant breeding programs have been successful in increasing biomass yields and thus carbon capture for a range of bioenergy crops. These include first generation biofuel crops like corn, soy, and canola; cellulosic annual crops such as biomass sorghum; perennial grasses such as switchgrass, miscanthus, and energy cane; and short rotation woody crops including willow and poplar.[393] Other ways to increase photosynthesis include various strategies of sustainable intensification: planting bioenergy double crops like winter rye, which could provide over 100 million Mg yr-1 of biomass feedstock on existing cropland during times of the year the land is normally fallow;[394] precision management of water and fertilizers to optimize yields while minimizing N_2O emissions or losses to surface and groundwater; and planting robust, high yielding perennial biomass crops on marginal field or subfield areas where less resilient annual crops grow poorly some years due to flooding, drought, insects, disease or other stressors. Recent studies have found that 20% or more of U.S. cropland is economically marginal for annual food crop

[390] "IPCC – Intergovernmental Panel On Climate Change". 2021. *Ipcc.Ch*. https://www.ipcc.ch/.

[391] Field, et al., Robust paths to net greenhouse gas mitigation and negative emissions.

[392] Field, et al., Robust paths to net greenhouse gas mitigation and negative emissions; Griscom, B.W., Adams, J., Ellis, P.W., Houghton, R.A., Lomax, G., Miteva, D.A., Schlesinger, W.H., Shoch, D., Siikamäki, J.V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M.R., Herrero, M., Kiesecker, J., Landis, E., Laestadius, L., Leavitt, S.M., Minnemeyer, S., Polasky, S., Potapov, P., Putz, F.E., Sanderman, J., Silvius, M., Wollenberg, E., & Fargione, J. 2017. Natural climate solutions. PNAS, 114(44), 11645– 11650. https://doi.org/10.1073/pnas.1710465114.

[393] Owens, V.N. 2018. Sun Grant/DOE Regional Feedstock Partnership, Final Technical Report. E-Link Report/Product Number: DOE-SDSU-85041 https://www.osti.gov/servlets/purl/1463330

[394] Feyereisen, G.W., G.T.T. Camargo, R.E. Baxter, J.M. Baker and T.L. Richard. 2013. Cellulosic biofuel potential of a winter rye double crop across the U.S. corn-soybean belt. Agronomy Journal 105(3):631-642; Wolfe, M.L. and T.L. Richard. 2017. 21st century engineering for on-farm food-energy-water systems. Current Opinion in Chemical Engineering 18:69-76, https://doi.org/10.1016/j.coche.2017.10.005; Bonner, I.J., K.G. Cafferty, D.J. Muth Jr., M.D. Tomer, D.E. James, S.A. Porter, D.L. Karlen. 2014. **Opportunities for energy crop production based on subfield scale distribution of profitability.** Energies 7: 6509-6526, 10.3390/en7106509; Martinez-Feria, R.A., Basso, B. 2020. Unstable crop yields reveal opportunities for site-specific adaptations to climate variability. Sci Rep 10:2885. https://doi.org/10.1038/s41598-020-59494-2.

production.[395] Much of that land can be converted to bioenergy crops with minimal impacts of food production, and with significant improvements in ecosystem services ranging from soil carbon to biodiversity to water quality.

Other sections of this report have emphasized the "no regrets" advantage of waste materials as bioenergy feedstocks. These organic materials include food waste, wood waste, industrial sludges from food and other bioprocessing industries, as well as farm manure and crop residues. If there are any negative impacts on the environment during their production, those impacts and any associated land use change will be debited against the primary product and not the waste. If not used for bioenergy these potential feedstocks would otherwise be decomposing, with their carbon being released to the atmosphere though microbial respiration. For these feedstocks, additionality #2 can be realized in several ways. Biomass systems that divert that decomposing carbon to fuels or other energy products can earn an offset against the fossil emissions they displace. If the residues from fermentation, pyrolysis (biochar) or other processes are returned to the land some or most of that carbon can be sequestered in the soil, potentially longer and to a greater extent than if the original wastes were left on the soil surface or disposed in a landfill. BECCS is an extreme form of additionality #2, and couples well with cellulosic bioenergy crops (additionality option #1).

It is important to recognize that with current technology options, not all locations are appropriate for advanced cellulosic biofuel systems. For example, feedstock production is unlikely to be sustainable on sites or with crops that require irrigation, as the energy and environmental costs of pumping water and the depletion of surface and groundwater aquifers could exceed any carbon mitigation benefits from biofuels. With current technology, it is also difficult to justify converting healthy forests to biofuel production. In the forested landscapes of the Eastern U.S., the carbon mitigation potential of current cellulosic biofuels technologies without BECCS is roughly equivalent to carbon storage in the equivalent natural ecosystem, so there is no benefit to investment. In the temperate rainforests of the northwestern U.S., natural ecosystems can accumulate carbon for centuries before their high rates of carbon mitigation slow. In contrast, because of the much lower amount of carbon stored in a grassland ecosystem, implementing the same current cellulosic biofuel technologies could mitigate carbon emissions by 3X (300%) on a per hectare basis.[396]

Cellulosic biofuel production on marginal cropland and grassland has tremendous carbon mitigation potential, and that potential increases with higher crop yields (additionality #1), more efficient conversion technologies, and BECCS (additionality #2). But additional research, development, policy, and financial support are needed to realize that potential. Such support is needed to identify appropriate feedstock types and locations, develop and implement advanced cellulosic biofuel technologies, and create the pipeline and subsurface infrastructure needed for BECCS. With such investment, biofuels and BECCS can be a strong driver for increasing the sustainability of agricultural systems and reversing climate change through negative emissions. Relative to natural ecosystems in the eastern U.S., advanced biofuel systems using perennial grasses as feedstocks and incorporating BECCS for

[395] Bonner, et al., Opportunities for energy crop production; Muth, D.J., 2014. Profitability versus environmental performance: are they competing? J Soil Water Conserv 69:203A-206A; M.E. Jarchow, M. Liebman, S. Dhungel, R. Dietzel, D. Sundberg, R.P. Anex, M.L. Thompson, T. Chua. 2015. Tradeoffs among agronomic, energetic, and environmental performance characteristics of corn and prairie bioenergy cropping systems. GCB Bioenergy 7: 57-71, 10.1111/gcbb.12096; X. Zhou, M.J. Helmers, H. Asbjornsen, R.K. Kolka, M.D. Tolmer, R.M. Cruz. 2014. Nutrient removal by prairie filter strips in agricultural landscapes. J Soil Water Conserv 69:54-64, 10.2489/jswc.69.1.54.

[396] Field, et al., Robust paths to net greenhouse gas mitigation and negative emissions.

the byproduct CO_2 streams could provide between 5X (forest ecosystems) and 14X (grassland ecosystems) greater carbon mitigation benefits.[397] Integration of biofuels with food crops can also generate important synergies. The BiogasDoneRight approach, pioneered in Italy, uses anaerobic digestion to convert winter crops, crop residues, livestock manure, and agro-industrial wastes to biogas, which can then be used to produce either electricity or RNG. This approach is currently being piloted on farms in the U.S., and if fully implemented, could generate sufficient RNG to replace roughly 10% of current fossil natural gas supplies while also enhancing soil and water quality, improving nutrient cycling, and increasing food production.[398]

Perhaps the most important lesson from the U.S. experience is that there are both good and bad ways to implement biofuels. Winter bioenergy crops and perennial grasses can play a critical role in increasing biodiversity and improving soil health, forming a foundation for regenerative agriculture with benefits to ecosystem services, rural economies, and also with strong carbon mitigation. But there are also ways to implement biofuels poorly. Corn production, which is the dominant biofuel feedstock in the US today, can result in degraded ecosystems, eroded soils, and contaminated waterways. Policies are needed to guide project development toward the better alternatives. These policies need to be based on sound science, and backed by quantitative tools, such as life cycle analysis, to assess the many dimensions of sustainability. Performance based incentives, such as California's Low Carbon Fuel Standard, have proven effective at stimulating innovation and accelerating deployment of biofuels with a low carbon intensity. Similar incentives that reward other indicators of social and environmental sustainability, and drive biofuels from "low carbon" to "negative carbon", are also needed. In 2011 the Nuffield Council on Bioethics proposed an International Ethical Standard for Biofuels that addressed human rights, environmental sustainability, climate mitigation, fair trade, justice, and equity.[399] Because of the recognized potential of biofuels to address climate change, the last principle stated that if the other ethical criteria were met, there is an ethical responsibility to develop biofuels. Now a decade later, with global CO_2 levels continuing to climb, the imperative to develop and scale-up sustainable, carbon negative bioenergy systems is greater than ever before.

[397] Ibid.

[398] Dale B. et al. 2016 "Biogasdoneright™: Food, Fuel and Environmental Services from Agriculture: An Innovative New System Is Commercialized in Italy" Biofuels, Bioproducts & Biorefining (2016); DOI: 10.1002/bbb.1671; Dale, B.E., Bozzetto, S., Couturier, C., Fabbri, C., Hilbert, J.A., Ong, R., Richard, T., Rossi, L., Thelen, K.D. and Woods, J. 2020. The potential for expanding sustainable biogas production and some possible impacts in specific countries. Biofuels, Bioprod. Bioref. 14:1335-1347. https://doi.org/10.1002/bbb.2134.

[399] Whittall, H. 2011. Proposal for an international ethical standard for biofuels.
Biofuels 2(6): 607-609. https://www.tandfonline.com/doi/abs/10.4155/bfs.11.112

4.4 The Case of the European Union: The Untapped Potential of Wastes and Residues for Sustainable Biofuel Production

Lead Author: Emanuele Oddo, Politecnico di Milano

EU countries made a great effort in recent years to define more ambitious targets for sustainability in order to stay on track for the 2050 goals. Many countries are close to the 10% target for renewable share in transport for 2020 and some countries are even above. The same is true also for the overall share of renewable sources. Although some countries still fall short, the EU is currently the largest producer of biodiesel worldwide and among the top producers of advanced biodiesel/HVO with the US.

The deployment of advanced platforms for biofuel production is undoubtedly tied to the strong commitment of EU policies. Indeed, IEA reported that if long-term targets for novel advanced biofuels are met, they will prompt investment in new technologies and encourage biofuel feedstock diversification so that the EU will get halfway to its 2025 interim target.[400] Furthermore, one of the greatest benefits coming from the efficient conversion of wastes/residues for biofuel is in terms of land and water impact. Wastes need to be disposed of one way or the other – and owners are often willing to pay to get rid of them – and they usually do not imply land usage or water consumption to be fed to the process, thus lowering significantly the impact related to biofuel production.

[400] International Energy Agency. 2019. Transport biofuels. In Renewables 2019: Analysis and forecast to 2024.

4.4.1 The framework of EU renewable energy policies

The EU introduced over the years many policies to foster the sustainable evolution of EU countries towards climate neutrality for 2050. Such initiatives collectively fall under the frame of the European Green Deal, which is articulated in macro-areas of intervention, including sustainable mobility. In this respect, a substantial measure to foster biofuel production is surely the Renewable Energy Directive (RED II) of 2018. The directive implies demanding goals for the coming years:

- 35% improvement in energy efficiency;

- 32% share of renewable in energy consumption within EU by 2030;

- 14% share of biofuels in transport fuel consumption by 2030;

- Less than 7% food crops as feedstock for biofuel production.

The directive will have to be transposed by member states by June 2021. The 32% target of renewable energy will be achieved by EU countries collectively. As for the transport sector, fuel suppliers in each Member State are required to incorporate at least 14% of renewable energy by 2030, following the indicative guidance set by national authority. Moreover, biofuels based on feedstocks which are not meeting sustainability criteria (e.g. 1G feedstocks with food-vs-fuel or water footprint issues) are expected to be progressively phased out starting from 2023. The Renewable Energy Directive also addresses advanced biofuels and biomethane from municipal solid waste (MSW) and agri-food residues with a sub-target of 3.5% by 2030.

In addition, Annex IX-A and IX-B reports two lists of advanced feedstocks for biofuel production, namely algae, MSW, agri-food and forestry residues and municipal or industrial waste for Part A and used cooking oil (UCO) and animal fats for Part B. This is particularly relevant considering that the double count mechanism is applied to Annex IX biofuels. This means that biofuel obtained entirely from waste and residues are double counted for the purpose of determining renewable energy units (HEB). This is clearly one way to incentive the production of advanced biofuels among the Member States, even though Annex IX-B feedstocks are capped to 1.7% for the 2030 target (but Member States may request higher limits for proven feedstock availability). Moreover, these communitarian initiatives still need to be implemented by each EU country and may undergo some modifications. This is all the more true considering that the European Commission has planned a revision of the RED II by the end of 2021, to foster the EU's increased climate ambition.[401]

In addition to RED II, a set of other directives also foster waste and residues mobilization by preventing or discouraging landfill disposal. This includes the Waste Framework Directive 2008/98/EC and the Industrial Emission Directive 2010/75/EC for air and water protection, which limits landfill disposal of waste organic fraction to both encourage re-use and prevent possible threats to public health. Broadening the view, all these actions

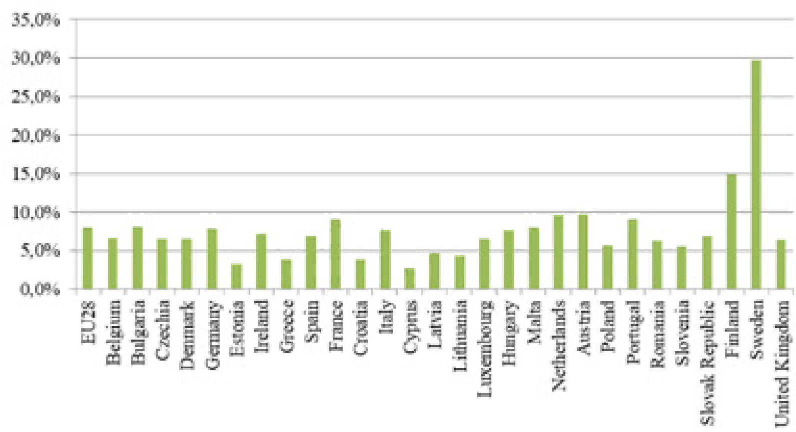
[401] 2021. *Europarl.Europa.Eu*. https://www.europarl.europa.eu/legislative-train/api/stages/report/current/theme/a-european-green-deal/file/revision-of-the-renewable-energy-directive.

are shaped within the general framework of the European Green Deal, which aims to cut 90% of GHG emissions within the transport sector by 2050.

4.4.2 Cutting edge biofuel production in Nordic countries

Northern Europe countries are the forefront of advanced biofuel technology and biofuel production in general. Indeed, the biofuel share in the transport sector for Nordic countries is very high compared to the other member states (see Figure 4.4.1), with Finland surpassing the average by at least 5% and Sweden almost reaching 30% in 2018. Such a gap is still evident for 2019 figures, where Finland energy share in transport climbed to 21.3%, compared to an EU average of roughly 9%, while Sweden raised its own share to 30.3%, retaining the highest share in the EU by a wide margin.[402] These huge achievements are also the result of very ambitious policies within Nordic countries, giving rise to a wide array of ventures for advanced biofuel production.

FIGURE 4.4.1. Share of renewable energy in the transport sector per EU Member State in 2018.[403]



In Finland, Neste is surely the leading group for sustainable fuel production with an ensemble of five refinery lines divided between Porvoo and Naantali. Although the main products in the Porvoo complex come from crude refining, the facility is also equipped with NEXBTL units, providing renewable diesel through hydrotreating of waste oils and fats. These production lines yield drop-in biofuel viable for either road or marine transport as well as renewable naphtha and propane, providing higher flexibility to the plant.[404] The renewable diesel coming entirely from waste – known as Neste MY Renewable Diesel – was launched in 2017 at Helsinki in many service stations.[405]

[402] "SHARES (Renewables) - Energy - Eurostat". 2021. *Ec.Europa.Eu*. https://ec.europa.eu/eurostat/web/energy/data/shares.

[403] Ibid, as elaborated by USDA Biofuel Annual report E42020-0032

[404] "Porvoo And Naantali". 2021. *Neste Worldwide.* https://www.neste.com/about-neste/who-we-are/production/porvoo-and-naantali.

[405] "Neste MY Renewable Diesel – High-Performing Low-Carbon Biofuel". 2021. *Neste Worldwide.* https://www.neste.com/products/all-products/renewable-road-transport/neste-my-renewable-diesel.

UPM is also operating a biorefinery in Lappeenranta, Finland. Opened in 2015 with a 179 million euros investment, the plant is converting wood residues, mainly pulp tall oil and paper mill wastes, to HVO. It is located next to a paper mill facility to ease the supply of raw materials and it provides 130,000 tons per year of biodiesel. Additionally, the plant opening guaranteed 250 new employees through direct or indirect work positions.[406] The company is also considering the opening of another plant in Kotka with a capacity of about 500 million liters, for the conversion of forest residues, like sawdust and branches, to biofuels for road and marine sectors.[407] Another company exploiting pulp residues is Södra, which began production of biomethanol in Mönsterås, Sweden. The plant is based at the pulp mill and it has a capacity of roughly 6 million liters per year.[408] The biomethanol can be used either as a transport fuel or as platform chemical (e.g. for the production of diesel). The feasibility of this route is certainly strengthened by the great versatility of methanol, which is a common brick of the organic chemistry industry, providing many industrial applications.

Another relevant production in Sweden is surely the Preem plant in Gothenburg, producing 160 million liters of HVO from tall oil. The company is also planning to expand the capacity to 1.3 billion liters in 2023. Both Preem and St1 are planning to start the production of bio-jet fuel in Gothenburg in 2022, with production capacities of 250-300 million liters. The main feedstocks will again be either UCO and waste fats, as expected considering the double counting incentive. Pyrocell, which is owned by Preem, is considering a production line for the conversion of wood residues into pyrolysis oil.[409] The plant will be located in Gävle, Sweden, and should process up to 40,000 tons of dry feedstock. Green Fuel Nordic Oy has also established a partnership with the Dutch BTG for the opening of a pyrolysis oil plant using sawmill by-products in Lieksa, Finland.[410] Finally, St1 Biofuels Oy launched a cellulosic ethanol plant with a 10 million liters capacity in 2018 and it is planning to build three 50 million liters plants in Kajaani, Pietarsaari and Follum (Norway).[411]

This large ensemble of production lines is also possible thanks to the cutting edge policies implemented in Nordic countries. In fact, Finland has established a 30% target of biofuels in transport by 2030, paired with a 10% target for advanced biofuels in the same sector. In Sweden, liquid biofuels are exempted from energy and COĐ taxation, to increase their use in the transport sector, and the European Commission has approved the prolongation of such tax exemption to 31 December, 2021.[412] Despite being the leading country for biofuel share and already well above the 10% target for 2020, Sweden has also committed the reduction of GHG reduction in the transport sector by 70% compared to 2010 level by 2030. Even though this measure does not account for the aviation segment, it is still a challenging objective. Production of HVO/HEFA is very relevant in these countries, also due to the double-counting system, which was accepted by both Finland and Sweden.

406 "UPM Lappeenranta Biorefinery". 2021. *UPM Lappeenranta Biorefinery | UPM Biofuels*. https://www.upmbiofuels.com/about-upm-biofuels/production/upm-lappeenranta-biorefinery/.

407 "Environmental Impact Assessment For UPM's Possible Kotka Biorefinery Is Ready". 2021. *Environmental Impact Assessment For UPM's Possible Kotka Biorefinery Is Ready | UPM Biofuels*. https://www.upmbiofuels.com/whats-new/news/2018/10/environmental-impact-assessment-for-upms-possible-kotka-biorefinery-is-ready.

408 "Biomethanol". 2021. *Sodra.Com*. https://www.sodra.com/en/global/Bioproducts/biomethanol/.

409 "Production". 2021. *Preem.Se*. https://www.preem.com/in-english/about/refineries/production/.

410 "Welcome :: Green Fuel Nordic Oy". 2021. *Greenfuelnordic.Fi*. https://greenfuelnordic.fi/en.

411 "Advanced Fuels From Waste". 2021. https://www.st1.com/about-st1/company-information/areas-operations/advanced-fuels-waste.

412 "State Aid: Commission Approves One-Year Prolongation Of Tax Exemption For Biofuels In Sweden". 2021. *European Commission - European Commission*. https://ec.europa.eu/info/news/state-aid-commission-approves-one-year-prolongation-tax-exemption-biofuels-sweden-2020-oct-08_en.

4.4.3 The potential of hydrotreating platform for transport

More in general, production of hydrotreated biofuels is a relevant asset for the entire EU panorama. This is due to many reasons, the first being the double-counting system. This system is implemented in many EU countries, allowing double-count biofuels produced entirely from waste and residues. Moreover, hydrotreating allows easy repurposing of existing infrastructure and it is currently the only viable way to ensure bio-jet to feed the aviation segment. As a result, many companies are operating or planning to construct/reconvert plants into full HVO production.

For instance, Total has launched in 2019 the La Mède plant in France, producing 500,000 tons each year of HVO biodiesel. The biofuel is obtained from 60-70% of vegetable oils and 30-40% of wastes, including UCO and animal fats. Total has pledged to keep palm oil consumption below 300,000 tons per year and to incorporate at least 50,000 tons of French-grown rapeseed into the raw materials. This would create the opportunity for a new domestic market.[413]

Apart from the aforementioned plants in Finland, Neste has also launched two other plants in Singapore (2010) and Rotterdam (2011), for the exclusive production of renewable products, with capacities respectively of 1.3 and 1 million tons per year [414],[415]. At the end of 2018, Neste has announced a 1.3 billion euros investment to raise the Singapore refinery capacity up to 4.5 million tons per year.[416] This intervention fits in the Neste plan to raise its renewable jet-fuel capacity from about 120 million liters to 1.2 billion liters, whose main production will be located in Singapore. The main feedstocks are again waste fats and oils, covering 80% of the feed in 2018, and Neste has pledged to reach 100% waste and residues by 2025.[417]

ENI has also strongly invested into conversion of waste to renewable diesel and jet-fuel. A former crude oil refinery in Venice was reconverted to biorefinery in 2014 in the framework of the "Green Refinery'' project. Since then it has been processing 360,000 tons per year of pre-treated vegetable oils, UCO and animal fats to renewable diesel according to the proprietary technology Ecofining™. Recently, a 500 million euros investment was made to allow direct processing of crude vegetable oils, raising the processing capacity to 560,000 tons per year and the output to 420,000 tons per year.[418] Thanks to several agreements with national consortia, Porto Marghera biorefinery is currently processing 50% of all the UCO available in Italy.[419] The Venice experience is a clear example showing that repurposing of existing infrastructure is possible for hydrotreating with relatively moderate investment costs. This will clearly reduce the risk connected to the deployment of the technology, fostering its deployment.

[413] "La Mède: A Multipurpose Facility For The Energies Of Tomorrow". 2021. *Total.Com*. https://www.total.com/energy-expertise/projects/bioenergies/la-mede-a-forward-looking-facility.

[414] "Singapore". 2021. *Neste Worldwide*. https://www.neste.com/about-neste/who-we-are/production/singapore.

[415] "Rotterdam". 2021. *Neste Worldwide*. https://www.neste.com/about-neste/who-we-are/production/rotterdam.

[416] "Singapore"., 2021.

[417] "Waste And Residues As Raw Materials". 2021. *Neste Worldwide*. https://www.neste.com/products/all-products/raw-materials/waste-and-residues.

[418] "The Venice Biorefinery". 2021. *Eni.Com*. https://www.eni.com/en-IT/operations/italy-venice-biorefinery.html.

[419] Ibid.

Another plant has been launched in 2019 in Gela, with a processing capacity of 750,000 tons per year. Again, the biorefinery comes from the repurposing of existing infrastructure with a 360 million euros investment. The plant can be fed interchangeably with many advanced 2G/3G feedstocks, including UCO, tallow and algae.[420] Given the high flexibility of such plants, ENI has pledged to totally replace palm oil with advanced feedstocks by 2023. This is a huge effort, implying mobilization of roughly 1 million ton per year of alternative raw materials.

The Gela facility also hosts a Waste-to-Fuel pilot plant, converting organic fraction of MSW into 250 tons per year of bio-oil, the result of a 3 million euros investment. This is relevant considering that hydrothermal liquefaction is generally a neglected route for biofuel production, although it provides great advantages compared to other thermochemical processes (milder conditions, one-phase output, sound efficiency). Looking at the whole country, Italy produces about 30 million tons of waste per year. 14 million tons are correctly separated and about 7 million tons make up the organic fraction. By improving waste collection, separation and management, the available organic fraction could be raised up to 10 million tons. Should this reservoir be devoted to bio-oil conversion, it would yield a billion liters per year of bio-oil, which corresponds to about 6 million barrels of crude oil per year.[421] This would be paired with a considerable production of water - it makes up roughly 80% of the process output - which could be employed for industrial purposes, possibly in integration with other processes.

As a final remark, given the available infrastructures, the two major constraints of the hydrotreating platform are essentially raw material costs and hydrogen supply. The former is typically overcome when dealing with 2G waste feedstocks. As for the latter, it has been proposed to implement the local production of green hydrogen (i.e. from electrolyzers) to directly supply the hydrotreater. The process would clearly benefit from this in terms of carbon balance, especially if the electrolyzers can be powered through bio-energy. In fact, ENI is planning in collaboration with ENEL the realization of two 10 MW pilot plants to produce green hydrogen, which could be exploited in place of conventional H_2 from steam reforming. The company is also investing to expand its facility near Ravenna, which is currently devoted to CCS and blue hydrogen, which may again be exploited to supply H_2 for hydrotreating.

4.4.4 Perspectives on the potential of wastes

The previous examples clearly highlight that there is a high potential connected to the mobilization and conversion of waste and residues. The economic profitability of such processes is evident, considering that many companies are currently investing to expand their businesses in this field. Moreover, the EU and national policies for stimulating waste-based biofuels have been effective in significantly raising the biofuel share. This is especially true in Nordic countries, where national policies are not just in compliance with the EU frame, but they are even more demanding. Although the EU is still the leading continent in such a field, a large room for improvement is available. Indeed, only a minor share of the huge reservoir of wastes have been exploited.

[420] "Gela Home To The Most Innovative Biorefinery In Europe". 2021. *Eni.Com*. https://www.eni.com/content/enicom/it/en/attivita/italia-gela-la-bio-raffineria.html.

[421] "Waste To Fuel: Biofuels From Food Waste". 2021. *Eni.Com*. https://www.eni.com/en-IT/operations/waste-to-fuel.html.

It was estimated that about 44 million tons of MSW will be available for biofuel production in the EU in 2030.[422] The organic fraction of such wastes is partially devoted to recycling or incineration, but the remaining is typically disposed of in landfills, where the decomposition to methane may have adverse climate effects if left unchecked.

As for crops residues, the production varies widely between EU countries, due to the wide differences in farming techniques, and some of these feedstocks are already exploited for other uses. However, about 122 million tons are considered to be sustainably available now and 139 million tons are expected to be disposable in 2030.[423] Forestry residues are not trivial to be mobilized for several reasons, including soil balance and low bulk density. Still, 80 million tons of forestry residues are produced each year in the EU, yielding 40 million tons sustainably available for harvesting without causing soil depletion.

Finally, more than 1.1 million tons of used cooking oil was consumed in 2013 in the EU, with substantial imports.[424] Thus, an increase in the collection efficiency of used cooking oil within the EU would be desirable to satisfy such demand. This could come from household collection, although it would imply a relevant effort in terms of behavior change, and from oil separation in wastewater treatment plants. Certifications may also play a key role in asserting a common degree of quality of processed oil and resulting biofuels.

UCO import in the EU is not the only issue related to trade. Indeed, waste displacement between EU countries is also relevant, due to the different capacities in waste management among the countries. This results in rather different gate fees for waste management and treatment, making waste processing far more convenient in some countries compared to the others (for instance, the UK may be willing to take advantage of more convenient gate fees in Germany or in the Netherlands[425]). More generally, a great disparity is still found among countries in terms of policies enactment and harmonization with the EU framework, which is probably one of the strongest barriers preventing advanced biofuel deployment throughout the continent.

[422] International Council on Clean Transportation. 2014. WASTED: Europe's untapped resource. https://theicct.org/publications/wasted-europes-untapped-resource.

[423] Ibid

[424] Ibid

[425] International Energy Agency. 2014. Bioenergy Waste to Energy.

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