Assessment of successes and lessons learned for biofuels deployment

Report Work package 4 | Lessons learnt in supply chains

Sustainable biomass supply chains for international markets

IEA Bioenergy TCP

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Assessment of successes and lessons learned for biofuels deployment

Report Work package 4

Sustainable biomass supply chains for international markets

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Executive summary

Improving the utilization of bio-based feedstocks for the production of renewable energy is vital for the meeting sustainability goals and making progress on reducing greenhouse gas emissions. However, a ramped-up production of low carbon advanced biofuels remains well below the levels needed to achieve the IEA's sustainable development scenario (SDS). This inter-task project assesses successes and lessons learned for conventional/advanced biofuels deployment and seeks to analyze international progress and experiences to identify which approaches are proving to be most effective so they can be expeditiously and more broadly deployed to get transport decarbonization back on track with SDS goals.

The report presents case studies for feedstock supply chains that have been evaluated from multiple viewpoints as these are vital for successful development of advanced biofuels. The report highlights lessons from biorefineries and pulp mills using consistent feedstock (Brazil), European experiences in development of bio-based supply chains for torrefied woody biomass, pioneer biorefineries in the US (traditional feedstock pre-processing for herbaceous feedstocks) and conceptual depots producing conversion-ready feedstock and co-products. The report closes with lessons learned from the development of sustainability standards and certification in international supply chains.

KEY MESSAGES

- Biofuels will be important to achieve climate targets and facilitating the shift and scale up of (advanced) biofuels from road transport to aviation and maritime sectors will remain a challenge notwithstanding technical innovations and economies of scale that can result in substantial cost reductions.

- Feedstock quality considerations, emanating from impurities and contaminants as well as feedstock moisture content are important, yet mitigation methods such as feedstock blending can help deploy advanced feedstock processing systems effectively.

- Biomass harvesting and processing can be accomplished with a wide array of equipment and collection systems, modified foragers and/or in-field chopping can provide an effective alternative across different feedstock systems.

- Torrefied biomass does behave superior to untreated densified biomass, saves energy and costs along the supply chain, and will open up new markets for biomass to substitute hydrocarbons and coal not only in energy.

- Development of sustainability certification schemes and their benchmarking are important and necessitating transparency and verification of the auditing process from qualified professionals to ensure quality and robustness of a certification scheme are vital.

1 Introduction

1.1 BACKGROUND

There are major challenges associated with achieving a CO_2 (GHG) emissions neutral society by 2050, fulfilling sustainable development goals (SDGs) and the IEA's SDS. Among societal sectors, transport is proving to be an extremely difficult sector to decarbonize – from fossil carbon to renewable carbon-based fuels, with IEA analysis (SDS) showing the rate of progress is lower than what is needed to sufficiently contribute to the SDGs. Ramped up production of low carbon advanced biofuels remains well below the levels needed to achieve the SDS. Stronger policy support and a greater rate of innovation are required to reduce the costs of development and scale up of sustainable advanced biofuel production, particularly for sectors like heavy duty transport, aviation and marine which are especially hard to decarbonize.

The inter-task project assesses successes and lessons learned for conventional/advanced biofuels deployment and seeks to analyze international progress and experiences to identify which approaches are proving to be most effective so they can be expeditiously and more broadly deployed to get transport decarbonization back on track with SDS goals.

1.2 OUTLINE: LESSONS LEARNT IN SUPPLY CHAINS

The lessons learnt in supply chains, sustainability certification, standards and developments of markets of biodiesel, methanol, wood chips and wood pellets are highly relevant for new biomass markets including bio-based chemicals and advanced biofuels. Cost-effective, reliable and sustainable feedstock supply chains are crucial to a successful development of advanced biofuels. Advanced biofuels will develop in an increasingly internationalized market with respect to tradeable feedstocks as well as international end-use markets such as shipping and aviation. The main goal of this report is to describe and analyze well-functioning infrastructure and stakeholder engagement of all actors in the supply chain.

The main objectives are:

- Provide insight about future potential developments of international (advanced) biofuel trade and its interaction with local/domestic markets
- Assess successes, failures and learnings of existing feedstock supply chains by presenting case studies from different IEA Bioenergy member countries. Compare the failures of large-scale mobilization and utilization of agricultural residues by pioneer biorefineries and successes of plantations supplying woody biomass to large pulp mills.
- Assess potential development of biomass fractionation methods to provide conversion-ready feedstocks and co-products.
- Describe lessons and successes in sustainability standards and certification of international supply chain.

The following chapters address and analyse the stated objectives above. Thereby, established biomass feedstock supply chains or value chains are at the core of the consideration. Developing a better understanding of supply systems is crucial for designing reliable and resilient frameworks that leverage on strategic planning processes to accomplish ascertained end goals (Dashtpeyma and Ghodsi, 2021). A **biofuel supply chain** covers all processes and actors from the production of biomass, feedstock logistics, conversion, distribution and end-use. The focus of this report is on **biomass feedstock supply chains** which includes all logistic operations to move biomass from the supply origin, for example field or forest, up to the 'throat' of the biorefinery.

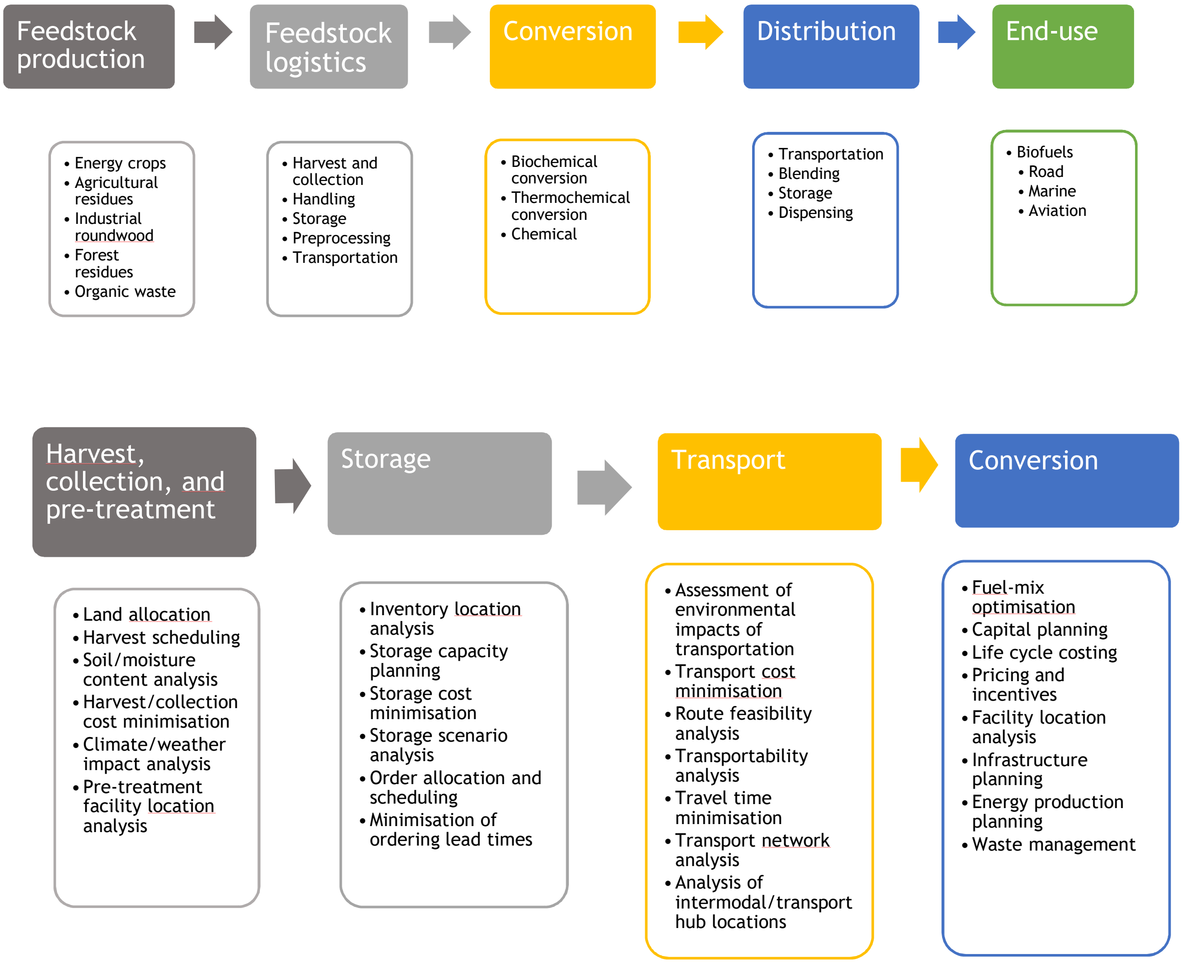


Figure 1 Biomass supply chain operations, adapted from (Mafakheri and Nasiri, 2014)

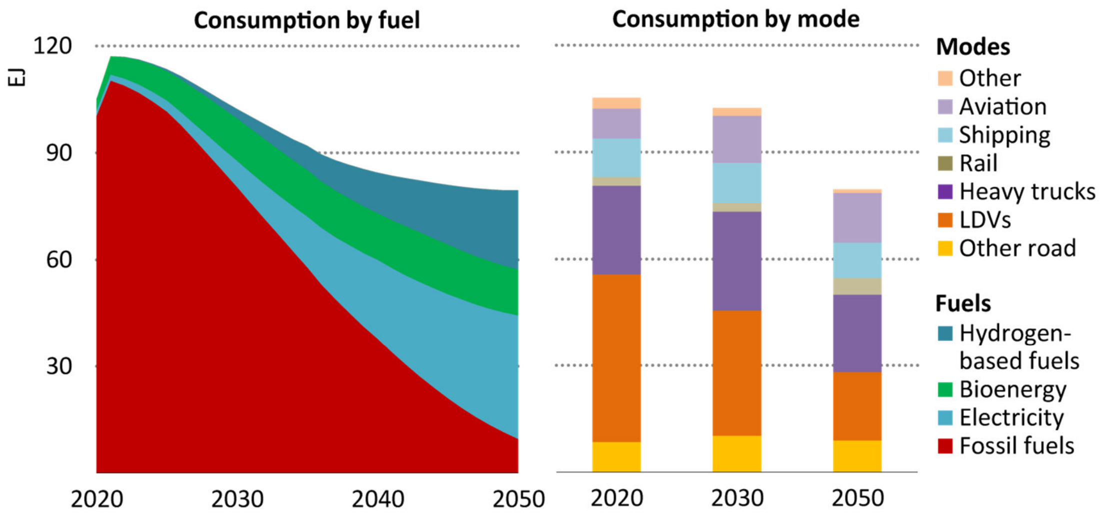
The case studies selected in this report, intended to encompass different types of biomass feedstocks as well as insights from different regions of the world. Here, 2 main types of biomass can be considered especially when addressing the question of feedstock handling and logistics, namely woody and herbaceous biomass. The cultivation of short rotation energy crops has been a huge success in Brazil. The country has demonstrated its ability to emerge as one of the lowest cost destinations for woody feedstocks and continues to strengthen its position in the global supply chain of bio-based resources.

We then highlight European experiences in development of bio-based supply chains for torrefied woody biomass. Torrefied biomass provides distinct advantages compared to untreated densified biomass and can present multiple opportunities in the form of economic and environmental benefits. Our next set of examples focus on herbaceous feedstocks in the U.S wherein we compare and contrast traditional baled biomass systems and advanced feedstock handling and storage alternatives. These include chopping of biomass using modified harvesters within the field and storage in ensiled piles, as well as more advanced methods involving application of amendments for stable storage and quality of harvested biomass.

2 Future potential developments of international (advanced) biofuel markets

2.1 INTRODUCTION

Despite the rapid developments of biofuels and electrification of road transport, oil products still dominate energy supply in the transport sector with over 90% in 2020. Bioenergy is currently the largest source of renewable energy in transport (4 % in 2020). According to IEA's Net Zero by 2050 scenario (IEA 2021), electricity (45%) and hydrogen and hydrogen-based fuels (30%) are projected to dominate future energy supply in transport (Figure). However, biofuels will grow substantially in the future. They expect that around 15 % of total fuel supply in transport will be from biofuels by 2050 (around 43 EJ). Furthermore, they expect that the use of biofuels will shift from road transport to shipping and aviation, with 45 % of fuel use supplied from biofuels in 2050 in the same scenario and that almost 90% (around 38 EJ) will be supplied from advanced biofuels.



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Electricity and hydrogen-based fuels account for more than 70% of transport energy demand by 2050

Note: LDVs = Light-duty vehicles; Other road = two/three wheelers and buses.

Figure 2 Global transport final consumption by fuel type and mode in the Net Zero by 2050 scenario (IEA 2021

These scenario projections show that advanced biofuel markets will need to grow substantially to achieve climate targets while current production is still limited. The most prominent barrier to developing advanced biofuels is the high production cost compared to fossil fuels and mature conventional biofuel technologies. A recent study from IEA Bioenergy identified the cost reduction potential of advanced biofuels and the conditions that could make these fuels affordable (Brown et al.2020). They found that significant cost reductions of capital and operational expenditures are possible due to technical learning, potentially up to 50 % in the most optimistic scenario. As a result, feedstock cost could become more prominent in the total production cost of advanced biofuels, while scaling up of certain biorefineries can only be achieved when sufficient feedstock is readily available. Developing cost-effective, reliable and sustainable feedstock supply chains is essential for the successful market deployment of advanced biofuels.

2.2 AVIATION

The global aviation sector contributes to about 2-3% of global GHG emissions, but has faced a sharp decline in 2020 due to the COVID-19 pandemic. Nevertheless, the International Civil Aviation Organization (ICAO) expects that demand for cargo and passenger markets will return to 2019 levels by 2022 – 2024. Despite efficiency measures, global jet fuel consumption will be 1.6 to 2.6 times higher compared to 2019 levels (ICAO 2022).

As a global harmonized and coordinated response to climate change, ICAO introduced the Carbon Offsetting Scheme for International Aviation (CORSIA) to stabilize CO_2 emissions at 2020 level. Sustainable aviation fuels (SAF) that are produced from biomass or waste or electricity (power-to-liquid) and meet ICAO's sustainability criteria are eligible to meet this target. The life-cycle greenhouse gas (GHG) emissions are considered to calculate the effectiveness of fossil jet fuel replacement with SAF. ICAO allows for using default values for CORSIA eligible fuels, or calculating the actual values based on the CORSIA methodology for actual life cycle emissions values. These types of policies can stimulate the development and production of advanced biofuels with a low carbon intensity (Ebadian et al. 2020), such as Fischer Tropsch (FT) fuels from biomass residues and lignocellulosic energy crops (ICAO 2021).

Various regional and national policies stimulate the development of biofuels in aviation. At the EU level, the revised Renewable Energy Directive (RED II) does not have a specific blending mandate for renewable energy in aviation but stimulates the use of renewable fuels in aviation or shipping with a multiplier of 1.2 times the energy content of fuel supplied. Even though aviation biofuels have to meet strict requirements and higher production costs compared to road transport fuels, such a multiplier could effectively shift biofuels to aviation from 2020 to 2030 (de Jong et al. 2018). However, the same study shows that the multiplier does not directly stimulate the development and production of advanced biofuels from lignocellulosic biomass due to the lower cost and commercial availability of hydrotreated esters and fatty acids (HEFA).

The EU Emission Trading System (EU ETS) includes emissions from aviation since 2012 for airlines operating in the EU. However, the current EU ETS does not directly stimulate the development of advanced biofuels. Firstly, in contrast to CORSIA, all RED compliant biofuels are counted as net zero emission fuels, excluding life cycle GHG emissions. Secondly, GHG emission abatement is difficult in aviation, making it more attractive to buy emission allowances from other ETS sectors. However, the aviation rules of the EU ETS are currently being revised in line with the 55% GHG reduction target of the Fit-for-55 package of the European Commission, including the phase out of free allowances for aviation and the implementation of CORSIA (EC 2022). Furthermore, the Fit-for-55 package's ReFuelEU Aviation regulation proposal introduces SAF blending mandates, including advanced biofuels and synthetic aviation fuels, of minimum 5% at EU airports by 2030 increasing to 63% by 2050 (CE 2021).

2.3 MARITIME SHIPPING

The global maritime shipping sector accounts for 2.5- 3% of global GHG emissions. Future trends in emissions are uncertain depending on macro-economic development and trade projections and the development of the shipping fleet, but similar to the aviation sector, shipping fuel demand could still increase substantially. The United Nations agency International Maritime Organization (IMO) regulates the sector at the global level. In 2018, IMO adopted a strategy to reduce the average carbon intensity by 40% by 2030, towards 70% by 2050 compared to 2008, and reduce the total carbon footprint by 50% by 2050. Few studies have explored the role of conventional and advanced biofuels in meeting these GHG reduction targets A study by Mukherjee et al. (2020) explored the potential of different advanced biofuel options and identified methanol and pyrolysis bio-oil as the most suitable candidates for the shipping sector. According to DNV, 30-40% of total shipping energy demand will need to be supplied from carbon neutral fuels, including biofuels and other renewable fuels (DNV 2021), but technical and economic measures are necessary, and feasible, to transition the sector to a more ambitious decarbonization pathway (DNV 2023).

2.4 CONCLUSIONS

Although electricity, hydrogen and hydrogen-based fuels are expected to play a leading role in GHG abatement of the transport sector, biofuels and in particular advanced biofuels remain quite important to achieve climate targets. One of the main challenges will be to facilitate the shift and scale up of (advanced) biofuels from road transport to the aviation and maritime sectors. Technical innovations and economies of scale can still result in substantial cost reductions of advanced biofuel production which may well put advanced biofuels to be more competitive than e.g., fuels from green hydrogen for aviation and maritime transport. The development of reliable and cost-effective feedstock supply chains is essential to enable advanced biofuel production at a commercial scale. Nevertheless, high production cost and competitiveness with fossil fuels remains one of the key challenges, in particular in aviation and shipping sectors, as long as the CO_2 abatement costs are not sufficiently addressed. The development of advanced biofuels therefore requires stable and strengthened long term policy support that needs to be implemented well before 2030.

3 Case studies - Overview on successes, failures and learning of existing feedstock supply chains

3.1 WOODY BIOMASS

Along the various stages of feedstock harvesting and collection, it is necessary to minimize impurities that can be inadvertently introduced into the system so that the quality of material is not impacted resulting in unfavourable conditions for downstream operations. For forestry-based biomass systems, the harvesting and collection process can broadly categorized into 1. Cut to length systems 2. Tree length systems, and 3. Chip Lines (Pacenka et al. 2016; WBA, 2018). In cut to length systems, trees are felled and processed in the forest itself. The residues (branches and tops) are spread out in the forest or collected in rough piles and left to dry naturally. The collection of these residues for potential use in bioenergy markets is likely to have additional costs, however, the biomass can be chipped on site using mobile chippers and then transported to either biorefineries for storage or to collection terminals like depots. Under tree length systems the whole trees are brought out from the forest, thus the additional step for collecting residues is not required. Finally, in chip lines, the trees are chipped by the harvesting machine itself – which can be beneficial for high-density short rotation woody crops.

3.1.1 Wood chips

In the market for global wood fiber supply, Brazil has been a dominant player owing to a range of advantages including conditions suitable for growing large quantities of biomass and cost competitiveness of inputs like labour (Schmid, 2017b). The country has made progress not only in terms of expanding pulp production and related infrastructure, but also explored short-rotation woody crops (such as Eucalyptus) with a view to increase biomass availability in the near term (van der Mark and Haggith, 2017).

3.1.1.1 Experiences in Production

Eucalyptus plantations with less spacing have been developed to maximize biomass yields, whilst evaluating the socioeconomic and environmental sustainability dimensions of such expansion (Stape et al., 2010; Moya et al. 2019). Chip lines with cutter chippers provide an advantage by minimizing process steps as moving, chipping, and conveying of chips onto a transport unit can be performed by a single equipment, in effect achieving low production costs (Pacenka et al. 2016). However, harvesting of biomass in high-density short-rotation energy plantations necessitates modifications to conventional harvesting systems to prevent blockages and maintain productivity.

Guerra et al. (2016) evaluated the performance of the Holland 9060 forager equipped with a 130 FB header. The header is designed for harvesting large- size short-rotation coppice wherein the header is fitted with two large diameter circular saws at the bottom of the shafts that carry the vertical crop collectors and a horizontal paddle roll (Guerra et al. 2016). The sawed stems are fed to the chipping unit that blows the chipped materials through an outlet pipe. The chip length can be adjusted to between 5-30 mm. The study provided evidence for the performance of energy wood plantations in Brazil – comparing favourably with similar systems for other woody feedstocks in North America and Europe. Finally, drying behaviour under different storage systems for young Eucalyptus chips from short-rotation coppice was evaluated under varied conditions (Junior et al., 2016). With covered storage, moisture content below 35% were obtained as well as lower temperatures in the covered piles which could contribute to lower biological degradation of the feedstock. These outcomes portend well for feedstock properties recommended for biomass use in biofuel conversion pathways.

3.1.1.2 Experiences in Transportation

There are only a few companies dedicated to producing wood chips in Brazil, and chips are typically produced only when no other higher valued market or already established industry is available for the feedstock (Schmid, 2017b). Pulp mills have been traditionally established in the South and Southeast of the county, in regions that are industrialized, have fertile lands, and proximate to the coasts (van der Mark and Haggith, 2017). With expansion, the need for exploring new areas is increasing, but Brazil faces supply chain challenges emanating from infrastructural challenges around biomass transportation. Biomass resources are spread across its vast territorial expanse; however, poor quality of roads made some areas inaccessible particularly in the rainy season, which increases transportation costs making biomass more expensive (da Silva et al. 2018).

3.1.1.3 Economics

In the case of pine-based feedstocks, while wood costs in Brazil are lower compared to the US South, high logistics costs erode some of the cost competitiveness highlighting that locational advantages are an important factor for enabling lower overall delivered cost in Brazil.

Table 1: Cost of Pine Wood Chips in Brazil and Southern United States

	Brazil		Southern United States	
	USD / Green Metric Ton	USD / Dry Metric Ton	USD / Green Metric Ton	USD / Dry Metric Ton
Delivered Pine Pulpwood Price	$28 - $33	$55 - $64	$34 - $42	$66 - $81
Production and Manufacturing	$5 - $7	$8 - $15	$5 - $7	$8 - $15
Chip Drying and Handling	$ 0	$13 - $20	$ 0	$13 - $20
Potential Fumigation	$5 - $6	$11 - $13	$5 - $6	$11 - $13
Storage, Loading, and Certification	$4 - $8	$8 - $16	$4 - $8	$8 - $16
Ex Mill Freight	$2 - $28	$3 - $56	$4 - $9	$8 - $19
General and Administrative Expenses	$2 - $4	$3 - $6	$2 - $4	$3 - $6
Operating Margin (Calculated Using Average Cost)	$1 - $3	$2 - $4	$1 - $3	$2 - $4
FOB Port Price (Calculated Using Average Cost)	$67 - $69	$147 - $149	$63 - $71	$139 - $154

Source: Schmid, A. (2017a, 2017b)

Wood chips are untreated biomass and hence subject to phytosanitary regulation, meaning that wood chips need to undergo inspection and depending on species and location harvested to undergo special treatment. Fumigation is the most simple of those but may not be sufficient for all delivery destinations. Namely Europe has built up much more stringent requirements for thermal treatment of wood chips imported from North America, but this is not limited to this geographical region.

It should also be noted that IMSBC (International Maritime Solid Bulk Cargoes) requires a moisture content of wood chips as a minimum for transport in bulk vessels in order to classify the goods as non-hazardous.

3.1.1.4 Conclusion

Although biomass harvesting and processing can be accomplished with a wide array of equipment and collection systems, modified foragers provide an effective alternative especially in high-density short-rotation woody feedstock systems. Feedstock quality considerations, emanating from impurities and contaminants as well as feedstock moisture content, are important, yet mitigation methods such as feedstock blending can help deploy advanced cut-and-chip systems effectively.

3.1.2 Torrefied wood pellets

There are 2 reasons to process biomass further than just drying, grinding and re-densifying it into standard pellets or briquettes.

1. Improvement in handling, storage, transport and combustion
2. Change in molecular chain structure and concentration of individual biomass fractions

While the case 1 improves the market position of biomass in energy applications, case 2 is opening the door for biomass to numerous other utilizations and applications.

If the biomass is only lightly to medium devolatilized (30-50%), industry refers to it as torrefaction, while products of higher devolatilization (>70%) are often referred to as biocarbon or high temperature torrefaction (C_{tot}>70%).If the goal is only to achieve advantages in handling, storing, transport and combustion, the industry has settled with a mild form of carbonization under the name of torrefaction as the ideal set point of process. Using thermal treatment, 30-50% of the mass is driven out as torrefaction-gas which itself is reinjected as process-heat utilized for drying and torrefaction. By this thermal recycling, the mass and energy (M&E)balance of the torrefaction process becomes very similar to the one of the white wood pellet production (Source IBTC M&E balance), while still producing product with advantages along the supply chain.

3.1.2.1 Experiences in Production

Industrial scale production (>4t/h) is established on basis of rotary drum, cyclone and vibrating belt reactors. Other reactors, such as screws, multiple hearths, moving bed, fluidized bed and combined systems have been proven on demonstration scale (<4t/h). Development and operation companies report self-ignition issues in their first approaches but all report to have mastered these problems relatively quickly. All production lines have integrated densification units in form of pelleting or briquetting lines. Although the extraction of Volatile Organic Compounds (VOCs) during the torrefaction process is making densification increasingly difficult, the higher the intensity of torrefaction, problems have been mastered by combining measures like uniform torrefaction to the core of the particles and narrowest particle size distribution possible. In connection with the introduction of biological binders which may be a (by)product of biorefineries, also highly torrefied biomass can be densified with satisfying results. The integrated process of torrefaction and densification has reached TRL 9 and industrial scale implication has started in recent years (Futerra, Perpetual Carbon, National Carbon, Borealis, and others) (Distler, T. and Sitzmann, W. 2018, Agar et.al. 2021)

Surprisingly good results in terms of durability have also been achieved with applying torrefaction on already produced wood pellets, thus after densification. However, the resulting low bulk density of the products has restricted this approach to the establishment of torrefaction lines close to the consumer supplying the line with wood pellets. (Alan Sherard 2018). In such case, torrefaction could also be seen also as a pretreatment for cheaper storage at power plant and easier grinding.

3.1.2.2 Experiences in Transportation

Today traded formats of torrefied biomass include pellets with cylindrical shapes and diameters from 6-10mm produced in flat or ring die pellet presses, briquettes in cylindrical shape produced in extruder briquetting presses or mechanical / piston briquetting presses or pillow, egg or puck shaped briquettes produced by roller briquetters.

Figure 3: Torrefied biomass pellets and briquettes

Aside of these shapes, minor quantities are traded in form of powder. This happens on short distance in special tanker trucks connecting the torrefaction plant directly with a carbonized biomass dust consumer, which is equipped to handle the powder safely and without any hazards to health. Proper and complete cooling of the torrefied product prior or after densification is absolutely necessary, and if not carried out completely, risk for self-ignition has materialized in unwanted combustion in interim bins, as reported by almost all producers openly.

3.1.2.3 Properties

Proven bulk densities of densified products vary between 650 and 750kg/m^3 with briquettes rather in the lower half of this range (Wild, M., 2021). Table 2 impressively highlights the substantially increase bulk energy density of thermally processed biomass.

Table 2: Comparison of transport relevant parameters of different solid biogenic fuels and steam coal

	Wood Chips	Wood Pellets WWP	Torrefied Pellets	Bio-Carbon Pellets/Briquettes	Steam Coal NEWC coal
Calorific value (MJ/kg)	9 - 12	16 - 17	20 - 23	28 - 32	25-26
Volatiles (% dry basis)	70 - 75	70 - 75	50-60	10 - 25	27-35
Fixed carbon (% dry basis)	20 - 25	20 - 25	40-50	75 - 90	<73
Bulk density (kg/m^3)	200 - 250	650 - 680	650– 750	650– 750	650– 750
Energy density (GJ/m^3)	2,0 - 3,0	10,4 - 11,0	13,5 - 17,0	18,2 - 24	16,9 - 19,5

Source: M.Wild (2020)

Companies involved in shipment of torrefied pellets so far confirm that they have achieved increased energy contents of loads and following reductions of specific transport costs, and in many cases even overcompensating eventual extra processing costs (Wild, M., 2021).

Mechanical durability (DU ISO 17831 - 1), a key product parameter in all the handling along the supply chain, had been an issue in the very first phase. Nowadays, all key suppliers mentioned above meet or exceed the durability requirement of 97,5% for best quality stated in ISO TS 17225-8. Same with fines (F, ISO 18846) which are limited to 1 respectively 2% in the stated TS. Fines are disliked for at least two reasons: they cause dust and dirt during handling and the dust causes the hazard of explosiveness.

Generally, dust of torrefied biomass is slightly less or similar explosive as the dust of the untreated feedstock to torrefaction (Explosivity class St1) (Carl Wilén, Perttu Jukola, Timo Järvinen, Kai Sipilä, Fred Verhoeff & Jaap Kiel, Wood torrefaction - pilot tests and utilisation prospects, Espoo 2013. VTT Technology 122 Espoo 2013. VTT Technology 122; also ECN, Michiel Carbo), however, the fraction of generally explosive fines (<500 microns) is likely to be higher with torrefied biomass because of its brittle character. It therefore is even more important to avoid unnecessary mechanical stress for the pellets/briquettes along the supply chain, i.e. avoiding dropping heights, passing of sharp edges, vacuum transport etc. Use of shoots and other mechanical, stress reducing means should be applied.

Figure 4: Loading torrefied pellets to MV Henny by New Biomass Energy in 2013. Although DU of pellets was above 98%, the unnecessary dropping height caused some breakage and dust which, different to white, beige or grey dust, becomes visible immediately. Pictures courtesy Carl Rheuban, New Biomass Energy LLC.

Another important parameter is water resistance. The missing of a determination standard has made clear testing and comparable expression almost impossible so far. In all tests, torrefied biomass did behave significantly better than white wood pellets. Durability was reduced only in top layers of heaps, if the product was stored outside in the rain. However, only the newly developed and from now on to be applied Water sorption (Wsorp) and post-immersion durability reduction (DURpi), ISO23443-1 will result in comparable results and categorization of product according to water resistance.

Based on a “master” MSDS (Material Safety Data Sheet) for torrefied biomass developed by the SECTOR project partners and IBTC, companies have developed their individual SDS accompanying their products. In the IMO 4.1 and IMO 4.2 test for the transport of dangerous goods it was concluded that torrefied pellets are not flammable neither in pellet shape nor crushed and they show no self-heating properties (criteria laid down in the United Nations Recommendations on the Transport of Dangerous Goods, Manual of Tests and Criteria, fifth revised edition). However, the continuous control of temperature (from proper cooling at plant to control of load at transport means or warehouses) is recommended. For wood pellets, the maximum temperature specified for loading is 60°C. It is to be expected that this safe loading temperature limit will be higher for torrefied biomass, but too few large-volume loads have been carried out so far to allow to make definitive statements. No complications have arisen during any of the ship or train transports carried out to date.

Figure 5: Checking for self-heating of torrefied pellets

REACH registration in the EU. To clarify if torrefied biomass is to be registered under REACH if brought to market in the EU the IBTC has initiated a Substance Information Exchange Forum (**SIEF**). The SIEF concluded after evaluation of all information collected that under the REACH legislation the materials that are present in the final torrefied biomass are also materials that are present in nature and present, in the most part, in the original wood; therefore, a specific REACH registration will not be required.

Charcoal, which is similar to high carbonized biocarbon is required to be registered under REACH and a number of different registration dossiers are already completed which can be joined individually by supplying companies[1].

3.1.2.4 Economics

The success hoped for by the sector only materializes with a very long-time lag. Some of the factors leading to delays in implementation are classic problems of new technologies, such as lack of experience in system integration or simply excessive demands on management. More important troubles that affected all actors equally were those of thermal power generation capacity that Europe is facing in general (while a Northern Europe based utility was talking publicly about an upcoming demand for 15 million tons of biomass pellets, preferably black, till 2012, two years later it started to tender many of its thermal power plants for sale), as well as the availability of a proven commodity biomass fuel - wood pellets. Risk assessment on suppliers simply did not favor torrefied biomass supply chains, despite the potentially large advantages offered by the product and the chain.

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[1] Compare: https://www.sector-project.eu/

[2] Compare: https://echa.europa.eu/substance-information/

The most typical comment of a buyer for power plant application indicated a willingness to sign a purchase contract for the product provided the supplier could prove flawless operation of a 200,000 t/a plant for 2 years (Wild, M., 2021). This is despite the fact that it was clear from various leaked bids that the torrefied biomass prices offered on a GJ CIF basis would have resulted in large overall cost benefits to consumers.

The technology developers and operators today describe the long focus on power plant operators and steam coal substitution as less than ideal. Although they still see potential in the European and Japanese power and district heating markets for their fuel, their focus is shifting towards higher values application than fuel only, e.g., as a reduction agent, as an additive and usages of higher-grade torrefied char for carbon capture.

3.1.2.5 Conclusion

In a nutshell, all of the expectations have been fulfilled by now: torrefied biomass does behave superior to untreated densified biomass, saves a lot of energy and costs along the supply chain and will open up new markets for biomass to substitute hydrocarbons and coal not only in energy. In handling torrefied biomass, all lessons learned with wood pellets shall be applied likewise.

3.2 HERBACEOUS BIOMASS

In the United States the commercialization pathways for most cellulosic biorefineries using herbaceous feedstocks have, thus far, focused on utilizing corn stover. The availability of corn stover in the Midwest has presented opportunities to exploit scale economies and minimize the cost of biofuel production. Energy crops can complement stover-based biofuel/bioproduct supply chains by enhancing supply security and feedstock quality characteristics, given their relatively higher carbohydrate content. However, variability in feedstock quality, especially soil/dirt sticking to the feedstock owing to harvesting/field storage techniques, can cause significant problems in downstream processes. The following sections synthesize key insights for different pathways for feedstock supply chains using herbaceous feedstocks based on Mann et al. 2019, which also provides details on assumptions and in-depth analysis.

3.2.1 Baled Logistics

3.2.1.1 Experiences in Production

The typical procedure for baling of agricultural residues, such as corn stover, takes place after the primary product (corn grain) has been harvested. Round and square bales need to be processed on separate lines because the equipment for destacking, destringing, and the net-wrap remover (for round bales) are designed specifically for the type of bale being processed. However, per current experience, the bale destacker and the plug screw feeder are the rate-limiting equipment in the preprocessing system. If the weight of the bale is higher than the target weight set by the operator, it indicates that the bale contains too much moisture or dirt. As a result, such bales are pushed to the reject area for drying or to be sold as livestock feed.

The biomass is then passed through a first-stage grinder to reduce the particle size making it suitable for finer second-stage grinding. The first-stage grinder also helps in loosening the bale structure, to remove large contaminants like rocks and metal objects. The removal of large contaminants is critical for reducing the risk of fire and explosion before the second stage of size reduction due to the relatively higher dust emissions at that stage. The materials conveyed from second stage grinding to the surge bins using pneumatic equipment are coupled with dust collection systems and fire and dust explosion suppression systems for risk mitigation.

The surge bins have storage capacity of several hours to provide system resilience in case of equipment upsets upstream or downstream of the bin. Finally, materials from the surge bin are automatically conveyed to the live bottom metering bin to precisely discharge material into the collection screw conveyor through to the feed box of the pretreatment reactor plug screw feeder.

Several equipment manufacturers compete in the market for preprocessing systems as the requirements of the biorefineries are akin to those in the forestry, paper and pulp, and agricultural sectors. Yet, the composition of corn stover makes it one of the most difficult types of biomass for handling and preprocessing. The quality of feedstock is not actively managed resulting in variations in properties of the final feedstock emanating from varying properties of the incoming feedstock.

As a result, pioneer biorefineries have experienced frequent plugging of equipment, high rate of abrasive wear and capacity constraints due to inconsistent feedstock quality, including high ash content and wide particle size distribution. A critical requirement for successful preprocessing supply chain operations hinges on collaboration between equipment manufacturers, conversion technology developers, and biorefinery operators to modify existing designs that can increase system reliability and produce processed feedstock that meets conversion specifications.

3.2.1.2 Experiences in Transportation

The type of machinery used varies depending on the biomass and location, however, the feedstock collection and transportation processes are well understood based on the experiences at existing pioneer cellulosic ethanol projects in the United States. Stover is delivered to the biorefinery following one of several pathways: 1. immediately following harvest (just-in-time), 2. after being temporarily stored on the roadside of fields, 3. stored for several months at an intermediate storage site. In the latter case, stored bales might have to be covered with tarps, or under sheds depending on the climate conditions and duration to minimize dry matter losses. Round bales are less efficient from handling and storage perspectives. A biorefinery typically holds between 3-5 days of feedstock in inventory.

3.2.2 Chopped logistics

3.2.2.1 Experiences in Production

Using energy crops instead of agricultural residues presents advantages ranging from cost competitiveness to feedstock quality. This supply chain system facilitates process intensification resulting from one-pass harvesting and chopping, potentially leading to fewer fines and lower dirt contamination in the harvested feedstock.

Furthermore, compared to baled biomass, feedstock properties are found to be more consistent, more moisture is preserved in the harvested biomass, which not only reduces the water footprint of the biorefinery, but also provides opportunities for pretreatment or utilization of coproducts in high-moisture ensiled storage. Finally, using biomass chopped in the field reduces preprocessing needs at the biorefinery improving operational reliability and lowering expenditure.

3.2.2.2 Experiences in Transportation

In this system, the biomass, such as switchgrass or miscanthus, is chopped in the field itself using a forage harvester, following which the chopped biomass is blown into a wagon or a silage truck for transportation either directly to a biorefinery or to an intermediate storage site. The biomass is delivered to depots adjacent to a biorefinery where ensiled storage piles are built, compacted, and covered with tarps. Ensiled storage of biomass has been practiced in the animal feed industry, as a result, equipment and operators are typically available in biomass producing areas. Utilization of ensiled storage also helps with minimizing dry matter loss, biomass degradation and risk of fire.

Biomass reclaimed from ensiled piles is screened to remove contaminants and any oversized particles are size reduced in shredders or choppers. The screened and chopped materials are conveyed to a day storage pile which are subsequently fed into a live bottom surge bin that discharges the material to a collection screw feeding a metering weight belt. The biomass is then transferred to a pretreatment reactor feeder. Nguyen et al. 2020 provide a qualitative comparison between baling and chopping logistics for herbaceous biomass. Their research validates the advantages of the chopped logistics system compared to the traditional baling logistics.

While chopped logistics systems are less common, barring for silage production, they also require less storage space and can be strategically located closer to biomass sources to reduce transportation costs. Another factor that works in favour of chopped logistics systems from a storage and handling standpoint is the relatively lower risk of fire. Compared to bale stacks that have to be stored apart, to prevent fire from spreading, chopped biomass tends to have high moisture levels and anaerobic conditions.

For the chopped logistics system, the harvesting and collection is also less likely to be impacted by weather compared to baling operations in which field drying and baling can be impacted by wet and cold weather. Finally, chopped logistics systems can facilitate the production of multiple products, including conversion-ready feedstocks, by applying biological and chemical treatments to the stored biomass.

3.2.2.3 Economics

Wendt et al. (2018) compared a chopped feedstock logistics supply chain with a baled logistics system using a technoeconomic analysis to conclude that a chopped logistics system is cost competitive costing only 10% more than the baled logistics system. However, the chopped logistics system performed better from energy consumption and greenhouse gas emission perspectives indicating that the system could be an economically viable alternative when dry bales are not available.

Table 3: Comparison of costs in chopped and baled logistics systems (2015 US$ per dry tonne)

	Chopped logistics system	Bale logistics system (30% moisture bales)
Grower Payment	$37.64	$37.64
Harvest and Collection	$15.61	$21.04
Field Side Storage	-	$5.05
Transportation	$29.07	$15.86
Refinery Storage	_	$1.12
Refinery Handling	_	$2.06
Preprocessing	$46.88*	$24.29
Centralized Storage		-
Dockage	$8.84	$18.62
Credits	($0.19)	-
Total	$137.86	$125.70

Source: Wendt et al., (2018). *represents combination of refinery storage, handling, preprocessing, and centralized storage

3.2.3 Conversion-ready feedstock

3.2.3.1 Experiences in Production

Fractionation of corn stover either during prepreocessing or before the components are mixed and compacted together to form a bale could also help overcome some of the biomass heterogeneities (Quang et al., 2020). This is typically achieved by separating corn plants into fractions comprising stalks and leaves and a fraction comprising husk and cobs.

Biomass is typically collected during a relatively short harvesting window and is then stored in order to facilitate year-round operations at the biorefinery. When storage conditions are not optimal, microbial degradation results in biomass loss which cascades into mechanical challenges associated with biomass handling, preprocessing, size reduction, and ultimately conversion (Wendt and Zhao, 2020). Lack of understanding of how to stably store biomass for long durations, and difficulties around chemical deconstruction in biomass during pretreatment operations are two primary challenges that have inhibited the success of pioneer cellulosic based biorefineries in the U.S (Dale, 2017).

Application of amendments to promote the formation of a low pH environment that result in stable storage and maintenance of desirable qualities for forage feedstocks have been recorded in the literature (Muck et al., 2018). Wendt and Zhao, (2020) highlight the most widely used amendments including microbial, acidic and alkali amendments that can be effective in reducing storage losses. High-moisture storage with bacterial inoculants have been demonstrated to increase sugar release across a range of feedstocks. Meanwhile, acid amendments have been effective in improving ensiling performance and aerobic stability, which might lead to their increased utilization in commercial biorefineries.

Similarly, alkali treatments have shown to reduce chemical recalcitrance of biomass to deconstruction and have been used for stabilizing wet harvested biomass. Alkaline pretreatments to biomass have also been effective in increasing carbohydrate release after anaerobic storage (Wendt et al., 2018). Anaerobic and chemically treated pile storage can also reduce dry matter loss as compared to bale and ensiled storage systems. As a result, alkaline pretreatment has the potential for transforming storage from a cost-center to a value-added operation.

3.2.3.2 Conclusion

Feedstock variability and timing of harvest necessitate long term storage in order to provide a steady supply of feedstock to the biorefinery thought the year. This problem is less pronounced for energy crops, opposed to a commodity crop such as corn, as they have more flexibility in terms of the harvest window.

Optimizing the storage systems can not only reduce operational downtime but also help with managing expenditures that can at times be cost prohibitive for a biorefinery. Wet storage systems, such as those with chopped biomass, makes material handling more costly as compared to baled biomass.

However, size reduction during harvest that is common in wet logistics systems can reduce preprocessing costs downstream. Storage amendments present a potential pathway to utilize long term storage to the benefit of a biorefinery but also presents trade-offs from cost and feedstock management perspectives.

4 Lessons and successes in sustainability standards and certification of international supply chain

4.1 CERTIFICATION

The large-scale implementation of biofuel strategies in several countries across the world has partly led to increasing demands for biofuel feedstocks, resulting in aspects such as intensification in agricultural processes or expansion of cropland. Several publications have described potential risks associated with an unsustainable production of biofuels, highlighting for example risks for deforestation, loss of biodiversity and other risks for potential ecological and social risks sustainability impacts. As a consequence, sustainability requirements are increasingly being incorporated into biofuels policies in different parts of the world. The respective sustainability requirements do cover aspects such as GHG emission reduction thresholds, socio-economic sustainability requirements and additional environmental sustainability requirements, such as for example the definition of “no go areas” for biofuel feedstock production (van Dam and Ugarte 2022).

Furthermore, in several countries, sustainability requirements have become an important element in biofuel policies, with their fulfilment being a precondition of policy support for biofuel producers. Certification is one instrument among others used by policy frameworks to ensure that these requirements are complied with. Compliance is thereby usually verified by an objective and independent third party, checking the fulfilment of the standards and criteria of a recognized voluntary certification system that operationalises the sustainability requirements of a policy framework. Once an economic operator (e.g., a biofuel or a biomass producer) is certified against the defined set of principles and criteria of a certification scheme, the respective products are considered to be in compliance with the sustainability requirements (Majer et al. 2023, van Dam and Ugarte 2022, Stickler et al. 2018, ISEAL Alliance 2018).

4.1.1 Lessons & successes

Following the implementation of biofuel policies across the world and the general increasing attention for biofuels, a significant number of sustainability certification schemes have been developed within the biofuel sector over the last decade. This is especially the case for markets operating under the framework of target-oriented policy instruments which are combined with sustainability requirements, such as for example the Renewable Energy Directive (RED). In the case of the EU policy framework or national policies for biofuels and bioenergy, certification schemes which can be used to demonstrate compliance with existing sustainability requirements are being recognised by the national or international authorities in a recurring process. Mai-Moulin 2019, Majer et al. 2018, Mai-Moulin 2018 present overviews for existing schemes and the sustainability aspects included in certification frameworks like e.g., ISCC and REDcert (both mainly focusing on liquid biofuels), SBP and SWAN (focus on solid biomass) or Biogasdoneright (biogas and biomethane).

Additionally, certification is used in voluntary markets (e.g. markets in which no policy requirements have to be fulfilled in order to participate), mostly with the intention to communicate specific product characteristics (e.g. low GHG emissions or sustainable feedstock production) to potential customers and stakeholders.

Given the aforementioned risks of a large-scale implementation of biofuels described in various publications, also the development of sustainability certification schemes for biofuels has become subject to various publications analysing and benchmarking the robustness and performance of these schemes (e.g. Mai Moulin 2018, WWF 2013, van Dam et al. 2012). Existing criticism towards the instrument of sustainability certification for biofuels often addresses two levels: i) the conceptual design of the certification schemes under review and ii) specific cases of non-compliance or fraud.

Since the general concept of certification is based on an independent verification of the sustainability criteria, especially the qualification of the respective auditor and the general quality of the audit process are important parameter for the latter. In that sense, auditor qualification as well as the general transparency of the auditing process and the audit information are crucial aspects regarding the general quality and robustness of a certification scheme.

4.1.2 Outlook

The first level includes aspects related to the governance of a scheme, the involvement of stakeholders, the robustness of the criteria and indicator of the scheme as well as the “completeness” of the included sustainability topics. In general, it can be stated that existing certification schemes for biofuels have partly also evolved over time according to these parameters (Majer et al. 2018). Schemes can in general adapt to new or additional requirements from policy frameworks or stakeholders. Examples are the integration of new elements in certification schemes, such as for example modules for the certification of ‘low iLUC risk biofuels’, new sustainability criteria for biodiversity, etc. Furthermore, developments for new governance elements such as integrity programmes or industry-specific best practice standards (e.g., Code of Practice approaches from the ISEAL Alliance) can help to increase the robustness and credibility of the certification approaches.

Potential future evolution in the setup and internal organisation of sustainability certification schemes may also be driven by changes in biofuels process chains, e.g., related to new feedstocks with a higher focus on waste and residue materials and corresponding changes regarding conversion processes. While in general, the instrument of sustainability certification can be applied to a wide range of products, the respective changes in the feedstock or technology focus might require the consideration of other risk areas (e.g. biodiversity, loss of soil organic carbon, substitution effects, etc.).

4.2 CARBON FOOTPRINT

The large-scale market deployment of advanced biofuels is considered essential to reduce the carbon footprint of the transport sector. Indeed, under the right conditions, advanced biofuels can mitigate the main sustainability concerns associated with biofuels produced from food-based crops. Advanced biofuels often yield higher life cycle greenhouse gas (GHG) reductions when replacing fossil fuels than conventional biofuels and avoid direct competition with food markets (IEA 2020).

Most lignocellulosic energy crops require fewer agrochemical inputs, including fertilizers, and can deliver higher yields on less suitable land compared to food-based crops (Lewandowski et al. 2015, Vera et al. 2021). Nevertheless, advanced biofuels are not per definition sustainable, and similar to conventional biofuels and other bioenergy systems, the climate change mitigation performance of advanced biofuels varies substantially.

These variations result from the context-specific conditions of the locations where biomass is cultivated or collected, potential displacement effects, transportation distances, conversion systems and end-use. The different drivers for climate impacts of bioenergy can be categorized as follows (EC 2016):

- Supply chain GHG emissions, covering emissions from all stages of the life cycle (biomass cultivation, harvest, collection, transportation, conversion, distribution and use) and emissions resulting from direct land use change (DLUC);
- Biogenic CO_2 emissions that are captured during biomass growth and released during combustion;
- Indirect emissions related to market-mediated effects. These include indirect land use change (ILUC) and other displacement effects such as the displacement of wood from material markets to bioenergy.

Life cycle assessment (LCA) is an effective tool to assess the potential environmental impact of bioenergy over their life cycle. The environmental LCA method is internationally standardised (ISO14040/44:2006) with further detailed specifications on climate change impacts, or carbon footprint in ISO 14067:2013, PAS 2050:2011 and GHG protocols. Furthermore, LCA-based methodologies are implemented in national and international policies, for example as compliance check to minimum life cycle GHG saving criteria in the European Renewable Energy Directive (EU) 2001/2018 and the USA Renewable Fuel Standard (RFS 2013). Despite that GHG emission assessments are more easy to perform compared to comprehensive LCAs, the choice of method between different standards, protocols and calculation rules, but also between studies based on the same standard or protocol creates a significant variation in outcomes for the same supply chain (Cherubini et al 2009, Kendall et al 2013, Wang et al 2018).

Bioenergy is multifaceted and linked to several issues including indirect effects, counterfactual uses of biomass or land, and biogenic carbon that are difficult to capture in general norms and specifications, even those that are focused on carbon footprints (van der Hilst et al. 2019). Nevertheless, the LCA community has made significant progress to tackling these issues and how the results of LCAs on bioenergy should be interpreted and used (Camia et al. 2018). At least part of the variation can be explained by different goals of studies that require different scopes and modelling approaches and, therefore, leading to different results and conclusions. In fact, flaws in the interpretation phase of LCA rather than a lack of harmonized modelling approaches is seen as a primary reason for the divisive debate about bioenergy sustainability (Agostini et al. 2020).

On the other hand, if LCAs serve the same goal, such as providing globally accepted and recognized sustainability performance indicators, harmonization of LCA models could be necessary. The modelling approach depends on the goal of the study and is either at commodity level (attributional, or “accounting LCA”) with known uncertainties and higher precision or at system level (consequential, or “change-oriented LCA”), which is more comprehensive, but also more complex and uncertain (van der Hilst et al. 2019). For bioenergy, that uses constraint resources such as land or forest biomass, consequential elements can be added to attributional LCA. Such an advanced attributional LCA allows for detailed supply chain assessments while considering important change-related effects such as the displacement of straw (Camia et al. 2018).

This section provides an overview of the supply chain GHG performance of advanced biofuels including DLUC and shortly discusses the issues of biogenic CO_2 emissions and ILUC and its relevance for advanced biofuels. Note that other important aspects for the sustainability appraisal of advanced biofuels, including socio-economic conditions and other important environmental impact categories, for example water use, and biodiversity, are beyond the scope of carbon footprint and therefore covered in this section.

4.2.1 Supply chain GHG emissions of advanced biofuels

To facilitate a harmonized assessment of the supply chain GHG emission of biofuels, different GHG calculation tools for biofuels have been developed. Most of these tools were developed consistent with to the methodology for calculating GHG emissions embedded in policies. For example, the Harmonised Calculations of Biofuel Greenhouse gas Emissions in Europe (BioGrace-I) was developed consistent with the sustainability criteria of the 2009 RED (20009/28/EC) but has become outdated with the implementation of the RED II. Other important tools include the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (USA), GHGenius (Canada) and Virtual Sugarcane Biorefinery (VSB) model (Brazil). IEA Bioenergy Task 39 made a detailed comparisons of GHG calculation tools for FAME and HVO/HEFA (Bonomi et al 2018) and advanced ethanol production and distribution (Bonomi et al. 2019).

They identified significant variety in outcomes for exactly the same supply chains, resulting from both methodical choices, for example system boundaries and allocation procedures, but also due to the input data used to develop the inventories. They also demonstrated that a few selected harmonization steps regarding input parameters and methodological assumptions can reduce the variation of GHG emission calculations for conventional and advanced biofuels substantially (Bonomi et al. 2019, de Souza et al. 2021).

The ADVANCEFUEL project used the GHG calculation methodology of the RED II to compare different advanced biofuel supply chain on a consistent basis and evaluate spatial aspects in the GHG performances of different supply chains. These spatial aspects include lignocellulosic energy crop cultivation under location specific biophysical conditions in the European Union and the impact of variations in feedstock transport distances. Because multiple pathways require hydrogen, different sources of hydrogen supply were included in the analysis. The assumed feedstock transport distances and sources of external hydrogen production are summarized in Table .

To assess the GHG performance of advanced biofuels from lignocellulosic crops cultivated on marginal land in the European Union under RED II sustainability criteria, 8 different crop types were assessed taking locations-specific characteristics into account, including emissions from DLUC. The supply chains and system boundaries are shown in Figure . To calculate supply chain emissions, the Excel tool BioGrace-I was updated with input values from the RED II (JRC 2017) and extended with inventory data from the selected advanced biofuel conversion routes. The selection of conversion routes in was based on production pathways that are in demonstration stage and near to commercialization (technology readiness levels of 5-9) and include ethanol from lignocellulosic biomass, the production of renewable jet fuels (RJF) from ethanol through alcohol-to-jet upgrading (ATJ), fast pyrolysis followed by catalytic upgrading to diesel, gasoline and RJF, and gasification and synthesis pathways including Fischer-Tropsch (BTL), methanol and dimethyl ether (DME) synthesis. The detailed calculation methodology and input data is presented in detail in ADVANCEFUEL D4.5 (Vera et al. 2020) and Vera et al. (2021).

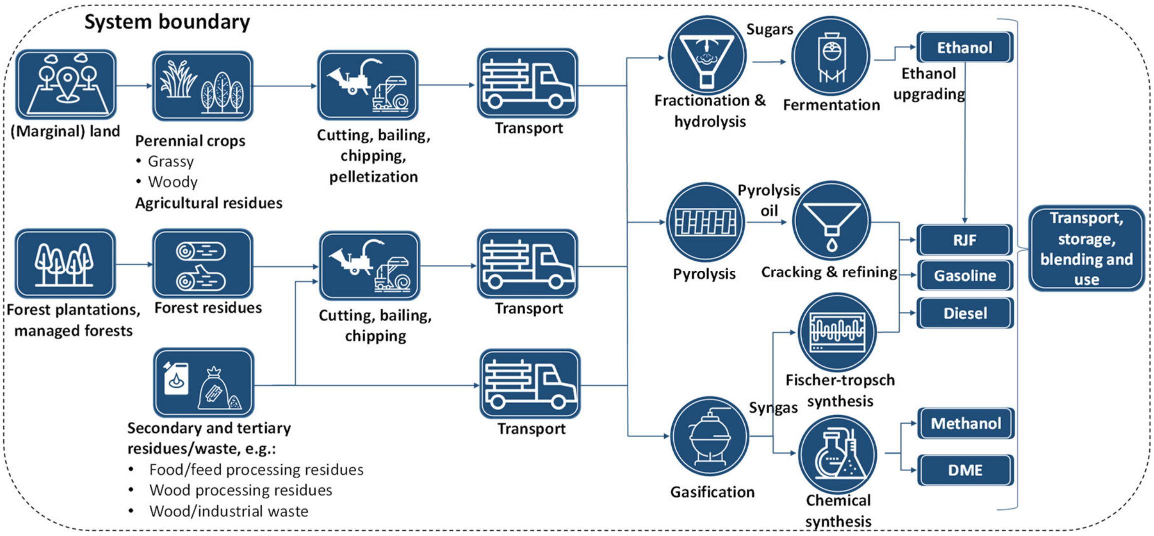

Figure 6 Advanced biofuel supply chains covered in the analysis, adapted from Vera et al. (2021). Ethanol can be catalytically upgraded to renewable jet fuel (RJF) with the alcohol-to-jet process. The pyrolysis and Fischer-Tropsch pathways produce road transport and renewable jet fuels.

Table 4 Main assumptions of feedstock transportation and external hydrogen supply (Vera et al. 2020)

	Base	Best	Worst
Transport mode and distance (one way) per type of feedstock			
Straw (bales)	500 km by truck	50 km by truck	1000 km by truck
Grassy crops (bales)			
Forest residues (chips)	250 by truck, 2000 by ship	50 km by truck	250 by truck, 8000 by ship
Woody crops (chips)			
External (ex-situ) hydrogen supply for ATJ and pyrolysis pathways			
Process type	Steam methane reforming (SMR) of natural gas	E-PEM (Proton Exchange Membrane), electricity supply: renewable, medium voltage MV	SOEC (Solid Oxide Electrolysis Cells), electricity supply: EU mix, MV
Inputs ($MJ_{input}/MJ_{hydrogen}$)	Natural gas: 1.375	Natural gas: 0	Natural gas: 0.421
	Electricity: 0.033 (EU mix)	Electricity: 0.033 (renewable mix)	Electricity: 0.033 (EU mix)

Figure shows the supply chain GHG emissions of different advanced biofuel pathways excluding emissions from land use change. The results show that each feedstock conversion combination could, in principle, meet the minimum GHG saving threshold of the RED II (65%) with GHG savings of well over 70% for most pathways. For biofuels used in aviation (RJF), thermochemical conversion through fast pyrolysis + upgrading or BTL is more efficient compared to fermentation followed by upgrading (ATJ).

When ATJ is produced from woody crops require fertilizers for cultivation in overseas regions (long distance transportation), and hydrogen is supplied from the current average electricity mix in the EU, total supply chain GHG emissions are up to 69 g CO_2eq/MJ. Pathways that use forest residues or straw perform better compared to energy crops because of the required agricultural inputs (mainly fertilizers) and direct and indirect N_2O emissions from cultivation of these crops.

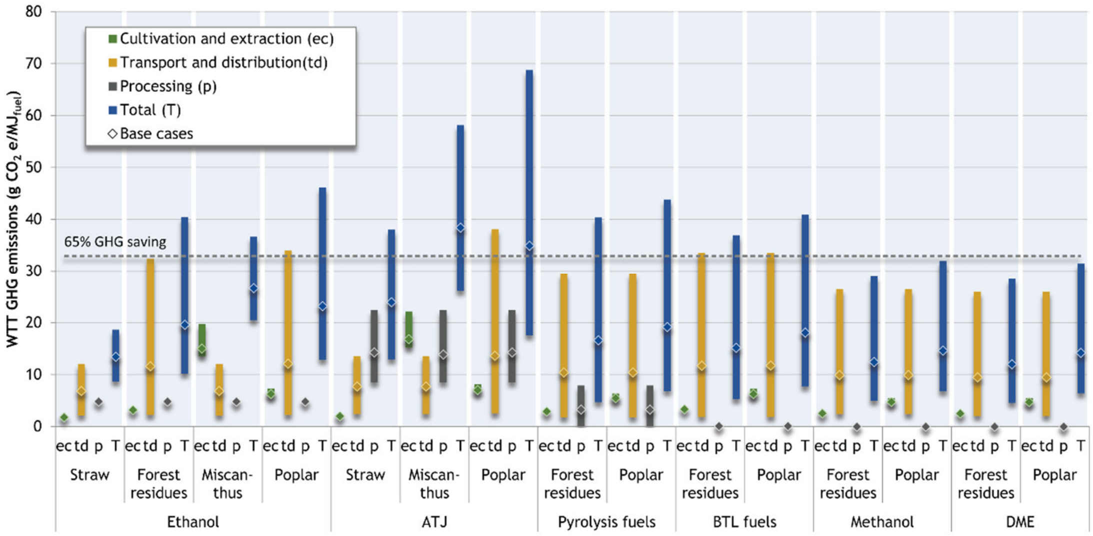

Figure 7 Attributional life cycle greenhouse gas emissions of advanced biofuel pathways. Land use-related net changes in carbon stocks and land management impacts are excluded. Markers represent the default results, the ranges describe the alternative scenarios, compared to the 65% GHG saving requirement of the RED II (32.9 g CO2e/MJ) (Vera et al. 2020).

When crops are cultivated to produce biofuels, the conversion of land to energy crops will lead to a direct change of land use from previous land uses (DLUC). These land use changes affect carbon pools that are stored in above- and belowground biomass, litter and deadwood and soil organic carbon (SOC) and could potentially lead to a net increase in GHG emissions. The highest risks for large releases of carbon by changes in carbon pools are associated with natural land, such as forests or especially wetland soils, converted to intensely managed annual cropland (Hilst et al. 2018). However, when marginal land is converted to the managed cultivation of lignocellulosic crops, it could result in a net carbon sink as a result of the increased carbon pools. The net positive impact (carbon sink) or negative impact (carbon source) of marginal land conversion is location specific and requires a spatial explicit evaluation.

Figure combines the average GHG emissions (base cases) from Figure with DLUC emissions for lignocellulosic energy crops cultivated on marginal land compliant with the EU RED II sustainability criteria. The results show that, indeed, net carbon sequestration is achieved in most cases when marginal land is converted resulting in negative LUC emissions. However, results vary substantially between crop types and locations in the EU as shown by the ranges in Figure . Despite of meeting RED II land-related sustainability criteria, GHG saving criteria cannot be met if DLUC emissions are considered for several locations (Vera et al. 2021).

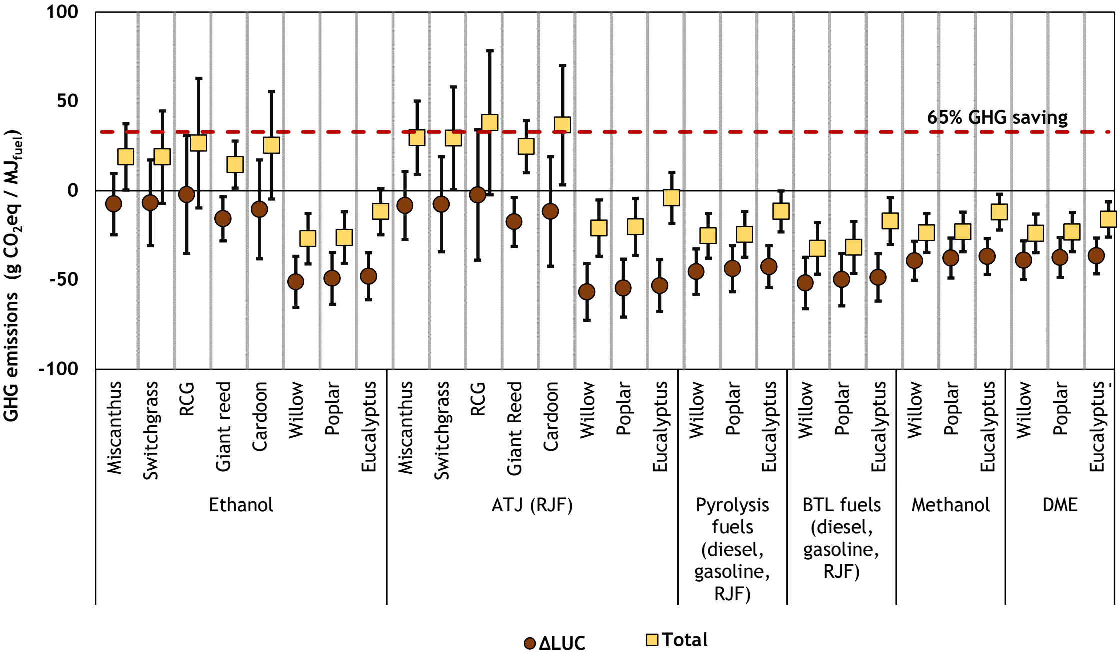

Figure 8 Average GHG emissions of advanced biofuel pathways from lignocellulosic energy crops cultivated on marginal land in the European Union including emissions from direct land use change. Ranges reflect the values within two standard deviation from the average for all possible locations taking site specific biophysical conditions into account (Vera et al. 2021).

4.2.2 Climate impacts beyond supply chain: biogenic carbon and indirect market mediated effects

Attributional LCA studies on the supply chain GHG emissions of advanced biofuels provide valuable insights in the contribution of individual processes and overall GHG performance of different pathways. They do however ignore several complex issues linked to bioenergy including indirect effects, counterfactual uses of biomass or land, and biogenic carbon, (van der Hilst et al. 2019). As a result of progress made by the LCA community in the past decade, there is an improved understanding on how to deal with these issues (Camia et al. 2018).

- **Biogenic carbon accounting.** It is a common practice in attributional LCAs of bioenergy to exclude CO_2 emitted from the combustion under the implicit assumption that the emitted biogenic carbon is captured during plant growth. However, such a temporal imbalance between carbon uptake and release can become increasingly relevant when forest biomass with long growth cycles and slow growth rates is used. Today’s concerns regarding the contribution of biogenic carbon are mainly the result of increased demand of forest biomass for heat and electricity.

- It is however expected that advanced biofuels will become one of the largest future markets for lignocellulosic biomass, including forest biomass. To assess the climate change mitigation potential of advanced biofuel pathways from forest biomass, biogenic carbon and counterfactual scenarios of biomass and land (what would have happened without bioenergy production) becomes increasingly important.

- **Indirect land use change (ILUC).** When agricultural land is converted, the displacement of the original land use activity it can drive the conversion of land in other places, or ILUC. The issue of ILUC is mainly linked to the production of conventional biofuels from crops that are cultivated on arable land and directly compete with food and feed commodity markets. Advanced biofuels are often considered and promoted to mitigate ILUC risks. Nevertheless, there is a risk that advanced biofuel companies might target productive agricultural land for crop cultivation (Mohr and Raman, 2013). One of the main challenges with ILUC is that indirect displacement effects cannot be measured. It requires integrated, complex modelling at system level and allocation procedures if one is interested in the impact at the commodity or product level. And while these methods lead to high uncertainties, the potential magnitude of ILUC risks, increased understanding in the drivers and mitigation options of ILUC and associated GHG emissions and other impacts are important. LUC factors have been calculated for advanced biofuels, including FT biodiesel from residues and ethanol from corn stover and energy crops (Taheripour and Tyner 2013, Valin et al. 2015, Field et al. 2020, Vera et al. 2021).

- Case studies for the EU and US show that LUC related carbon stock changes, often dominate total GHG emissions of advanced biofuel supply chains use scenarios. The conversion of abandoned crop land leads, in most cases, to negative GHG emissions (Field et al. 2020, Vera et al. 2021). The conversion of forest land to perennial crops will, however, in most cases lead to long term carbon debts unless CCS is applied (Jong et al. 2019, Field et al. 2020).

- **Other market mediated effects.** The use of residues from agriculture, forestry, and processing industries and organic wastes for advanced biofuels could improve resource efficiency, divert landfilling and generate net positive environmental and socioeconomic impacts (Cherubini et al. 2010, IRENA, 2019, Sailer et al. 2020). However, under high demand scenarios and in absence of effective sustainability policies, forest bioenergy can potentially displace wood from material markets (EC 2016, Visser et al. 2022). Also, straw removal could be shifted from other markets, for example, soil enhancement or animal bedding.

4.2.3 Lessons learned

The carbon intensity of fuels, including biofuels, is becoming an increasingly relevant metric in GHG mitigation policies of the transportation sector. Supply chain GHG emission calculations at the commodity level can be used to demonstrate compliance with sustainability criteria or compare the GHG performance of different pathways. A spatial explicit evaluation provides additional insights to investigate the potential contribution of DLUC related GHG emissions.

However, these results provide limited insights for strategic decision and cannot identify potential indirect impacts, which requires a system-level analysis. While advanced biofuels have the potential to mitigate risks associated with conventional biofuels, including ILUC, advanced biofuel markets are still in their infancy and their potential impacts are still highly uncertain.

Furthermore, other sustainability impacts and important trade-offs, for example, between climate and other impacts such as water use, biodiversity and socio-economic impacts are also essential to consider. Important lessons learned from the challenges and controversies from conventional biofuels (for example ILUC), and electricity and heat (for example biogenic carbon issues), assessment tools, and efforts to safeguard sustainable production are therefore relevant to facilitate the sustainable deployment of advanced biofuels (Mohr and Raman, 2013).

5 Synthesis of lessons and successes, future outlook, and conclusions

Consistency of feedstock quality is an important consideration for the development of reliable feedstock preprocessing systems. Moreover, since there is a time lag between the harvest and use of biomaterials, issues related to degradation, feedstock losses, and inconsistencies in quality emerge, which in turn adversely impact yield and throughput at the biorefinery. Approaches including in-field preprocessing, alternate storage designs, and utilization of feedstock blending can help overcome some of the challenges faced by pioneer biorefineries. In addition, if biomass is shipped in large units along the main shipping routes the specific costs in $US per GJ are moderate. But once off these main routes and especially when only smaller quantities are transported the share of transport costs in full costs of product is very significant. This situation disadvantages resources in remote areas and even cuts off some of the possibly valuable resources from biofuel markets.

Torrefied biomass does behave superior to untreated densified biomass, saves energy and costs along the supply chain and will open up new markets for biomass utilization. Increasing the energy density of resources through further processing such as torrefaction therefore can provide substantial advantages. With the reduction of the specific transport cost share, catchment areas expand and, above all, the risk of price changes in transport during contract periods decreases.

The processing of raw feedstock into water-resistant solid or liquid bioenergy carriers naturally also has a significant influence on the design of the transport chains. Enabling the use of existing infrastructure, such as the coal chain, reduces investment need, increases transport efficiency and further reduces specific costs. And even if the willingness to invest in infrastructure increases with the importance of biofuels in international trade, it is probably much cheaper overall to trim biofuels so that existing infrastructure can be used instead of replacing it at high cost.

Torrefied biomass products so far had been concentrating mostly on substituting coal in pulverized coal (PC) power plants. Hence the sweetspot of production was at around 30%-50% devolatilization. Recent developments show rapidly increasing demand from other applications of thermally treated biomass such as pulverized coal injection (PCI) and sintering coal substitution in steel mills. Especially for products of high temperature torrefaction an array of new markets is currently opening.

However, experience and feedback from manufacturing companies to date show that wherever torrefied biomass is used in production processes other than purely as an energy source, there is much less flexibility with regard to the composition of the feedstock, i.e. the torrefied biomass, than there is in the combustion processes in power plants, which can be adapted within limits (Wild, M., 2021). In the last two years there has been an intensification of testing and deployment trials, e.g. at Arcelor Mital, Voest, SSAB or Vale and other companies in the steel industry. Projects such as TORERO (Arcelor Mital, Torrocal) or TOCANEM are in their final stages and ground-breaking results for the entire industry can be expected. (: Fabritius T, Oulu University; Tocanem-Towards Carbon Neutral Metals, presentation at ISO TC238 TG1.) However, challenges to be faced in a biobased circular economy where energy-related utilisation is (often) seen at the end of the utilisation chain in case no further material use is possible can have an impact on the set up of existing supply chains.

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7 Glossary

Item	Explanation
Biofuels	Biofuels are fuels derived directly or indirectly from biomass. Biofuels used for non-energy purposes are excluded from the scope of energy statistics (for example wood used for construction or as furniture, biolubricant for engine lubrication and biobitumen used for road surface). Usually three categories are used: Solid biofuels (e.g. fuelwood, wood residues, wood pellets, animal waste, vegetal material) Liquid biofuels (e.g. transport fuels like biodiesel/FAME, HVO/HEFA, ethanol) Gaseous biofuels (e.g. biogas from anaerobic fermentation, hydrogen from thermal processes)
Fuel Readiness Level (FRL)	The Fuel Readiness Level is a scale used to describe the maturity of a fuel. It ranges from 1 to 9, being: 1st to 4th levels: Development of the production process at level lab, typical production reaches 30-40 Liters/year until FRL 4 5th to 6th levels: Scale up to pilot production to about 800-900 Liters/year and beginning of fuel validation 7th to 8th levels: Fuel fulfill international standards. Validation of commercialization and business 9th level: Scale up to industrial environmental and market competitiveness confirmation
Technology Readiness Level (TRL)	The Technology Readiness Level is a scale used to describe the maturity of a technology. It ranges from 1 to 9, being: 1st to 4th levels: Initial lab steps (from principles observation to lab validation) 5th to 6th levels: Scale up to pilot production 7th to 8th levels: Scale up to demonstration plant and validation of operation 9th level: Scale up to industrial environmental and market competitiveness confirmation

8 Abbreviations

GHG	Green House Gas
IEA	International Energy Agency
IBTC	International Biomass Torrefaction Council
MSDS	Material Safety Data Sheet
PC	pulverized coal
PCI	pulverized coal injection
RED	Renewable Energy Directive
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
SDG	Sustainable Development Goals
SDS	Sustainable Development Scenario
SIEF	Substance Information Exchange Forum
VOC	volatile organic compounds

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