The future of biomass and bioenergy deployment and trade: a synthesis of 15 years IEA Bioenergy Task 40 on sustainable bioenergy trade

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Abstract

Current biomass production and trade volumes for energy and new materials and bio-chemicals are only a small fraction to achieve the bioenergy levels suggested by many global energy and climate change mitigation scenarios for 2050. However, comprehensive sustainability of large scale biomass production and trading has yet to be secured, and governance of developing biomass markets is a critical issue. Fundamental choices need to be made on how to develop sustainable biomass supply chains and govern sustainable international biomass markets. The aim of this paper is to provide a vision of how widespread trade and deployment of biomass for energy purposes can be integrated with the wider (bio)economy. It provides an overview of past and current trade flows of the main bioenergy products, and discusses the most important drivers and barriers for bioenergy in general, and more specifically the further development of bioenergy trade over the coming years. It discusses the role of bioenergy as part of the bioeconomy and other potential roles; and how it can help to achieve the sustainable development goals. The paper concludes that

it is critical to demonstrate innovative and integrated value chains for biofuels, bioproducts, and biopower that can respond with agility to market factors while providing economic, environmental, and societal benefits to international trade and market. Furthermore, flexible biogenic carbon supply nets based on broad feedstock portfolios and multiple energy and material utilization pathways will reduce risks for involved stakeholder and foster the market entry and uptake of various densified biogenic carbon carriers.

1. Introduction

Biomass has been traded internationally for food, feed, fodder and material purposes for millennia, and trade has been increasing strongly as part of a globalizing world. A recent development is the trade of "modern" bioenergy commodities, e.g. wood pellets, ethanol, and biodiesel. The further development of sustainable and stable, international markets for such biobased commodities for energy and material purposes is an ongoing process with continuous advancements in demand and supply, as well as sustainability certification.

In fact, current biomass production and trade volumes for energy and new materials and bio-chemicals are only a fraction of what they may need to become in order to achieve the bioenergy (often combined with carbon capture and storage) levels suggested by many global energy and climate change mitigation scenarios for 2050. Eventually, biomass products for energy and modern biomaterials may develop into large-scale commodity markets, which could have multiple benefits, such as much improved market stability and competitive prices – if externalities were taken into account.

On the other hand, comprehensive sustainability of large scale biomass production and trading has yet to be secured, and governance of developing biomass markets is a critical issue, with the use of both food crops and woody biomass strongly scrutinized by some policy makers and NGOs. At this moment, fundamental policy choices by both developed and developing countries still can – and should - be made on how to develop sustainable biomass supply chains, and how to develop and govern sustainable international biomass markets.

For the past fifteen years, IEA Bioenergy Task 40 has done significant work to address these issues. Its core objective is to support the development of sustainable, international markets and international trade of biomass, recognizing the diversity in biomass resources and applications for bioenergy, biochemicals and biomaterials in the biobased economy. The aim of this paper is to highlight much of this work, and provide a vision of how it integrates with the wider (bio)economy, sustainability frameworks and thus the widespread deployment of biomass for energy purposes.

This paper is organized as follows. First, we provide a brief overview of past and current trade flows of the main bioenergy products. Second, we discuss the most important drivers and barriers for bioenergy in general, and more specifically the further development of bioenergy trade over the coming years. We then discuss the role of bioenergy as part of the bioeconomy and how it can help to achieve the sustainable development goals. Next, the potential future of bioenergy is highlighted and the role that trade may play is discussed. The paper concludes with recommendations for further work.

2. Overview of past and current trade of solid and liquid biomass

2.1 Global trade of solid biofuels

2.1.1 Wood pellets

The wood pellet market is one of the most dynamically developing solid biofuel markets in the energy sector [1] . The leading wood pellet producing regions are the US, Canada and the EU-28, which produced over 14 million metric tonnes (Mt) of wood pellets in 2015, see Table 1. The EU is also the main consumer of wood pellets with about 20 Mt. Italy, UK and Denmark have the largest consumption of wood pellet in the EU. In 2015, the total world import and export of wood pellets was 15.6 Mt and 16.0 Mt respectively, see also Figure 1 for the main trade flows.

Table 1. Global wood pellet production between 2010-2015 (in ktonnes), Source: [1], [2]

Country/years	2010	2011	2012	2013	2014	2015
USA	3 000	4 000	4 500	4 900	6 900	7 500
Germany	1 700	1 800	2 200	2 350	2 080	2 000
Canada	1 300	1 400	1 500	1 750	1 900	1 900
Sweden	1 700	1 400	1 400	1 300	1 500	1 600
Latvia	615	725	1 050	1 105	1 380	1 380
Russia	750	850	880	810	890	1 050
France	450	520	680	900	1 030	1 030
Austria	820	920	850	950	945	1 000
Estonia	425	365	500	580	995	890
Poland	430	600	600	600	620	870
Rest of the World	3 010	4 420	6 140	7 755	8 610	8 780

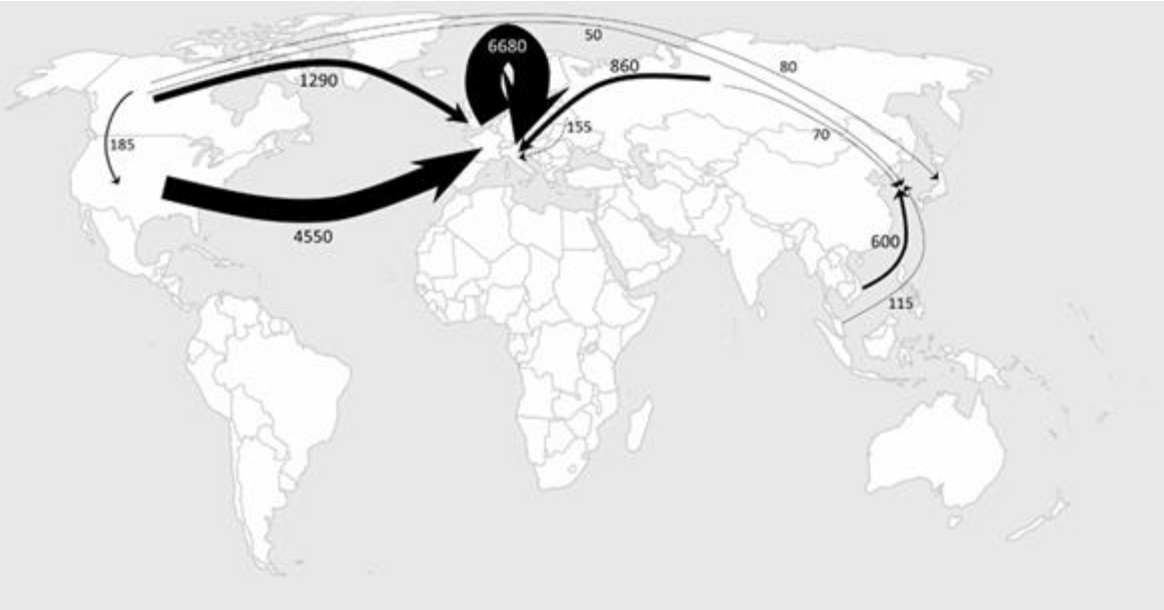


Figure 1. International net wood pellets streams (≥30 ktonnes), (in ktonnes) in 2015. Sources: [1], [3], [4]

2.1.2 Industrial roundwood, wood chips and particles

Industrial roundwood is mainly traded for material uses, e.g. for construction, furniture, paper and pulp. The leading industrial roundwood producers are USA, the EU-28 and Russia, see Table 2. The largest importers of industrial roundwood are China and the EU, see Figure 2. In the EU, the main markets of industrial roundwood are located in Denmark, Finland, Sweden, Germany, Estonia, Latvia, Lithuania and Poland. China imports high volumes of roundwood; this could be explained by the fact that China is a major exporter of wood-based panel products. From a bioenergy perspective, trade of industrial roundwood is important to emphasize as a number of by-products after trade and post consumption can be used indirectly for energy purposes, see more in Proskurina S et al. (2018) [5]. Similarly, wood chips and particles are also traded for material purposes and then can be used for energy purposes in a form of a by-product. However, wood chips and particles are mostly local product and traded for a short distance.

Table 2. Global roundwood production between 2006-2015 (in Mm^3), Sources: [3]

Country/years	2006	2010	2011	2012	2013	2014	2015
USA	410	335	355	350	355	355	370

Russia	175	160	175	175	180	190	190
Canada	180	140	145	145	150	150	150
China	95	160	160	160	170	160	165
EU-28	340	340	340	330	335	345	350
Rest of the World	535	570	595	605	610	620	650

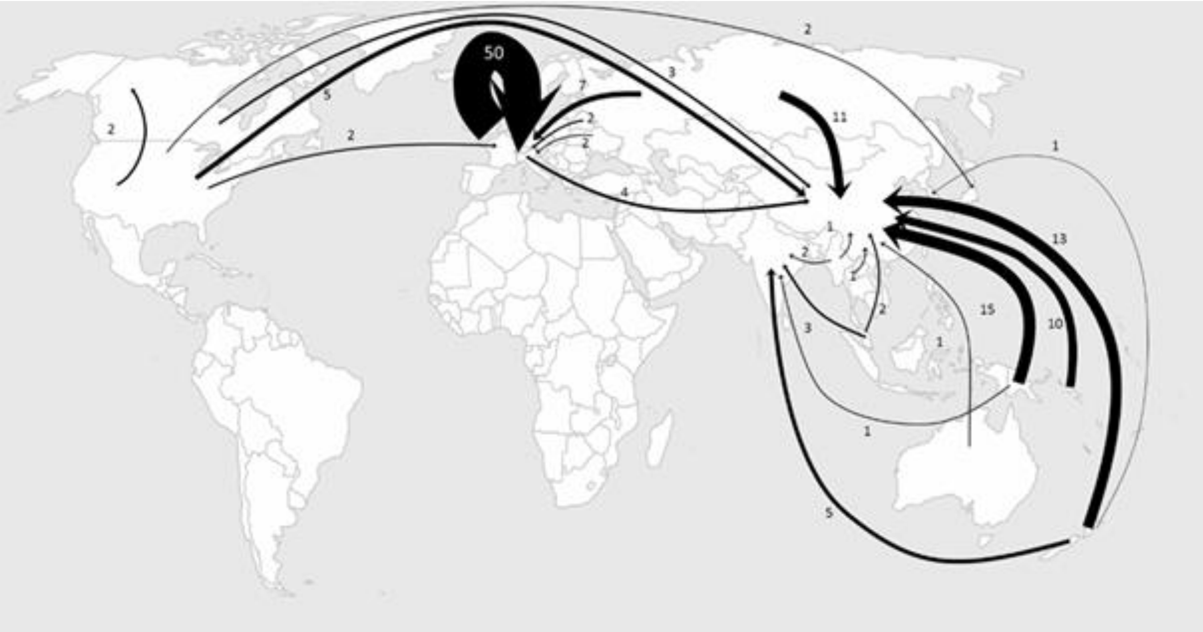


Figure 2. Main net global trade streams of industrial roundwood (≥ 1 Mm^3), (in Mm^3) in 2014. Sources: [3].

2.1.3 Charcoal

Whereas wood pellets are a fairly recent phenomenon, charcoal is a form of bioenergy with a very long history, and still widely used globally. Trade in charcoal doubled between 2008 and 2015, which can be partly explained by the increase of charcoal use for cooking in Africa, the Middle East and Asia, as well as the increase of export to the EU e.g. from Nigeria, see Figure 3. In 2015, world production of charcoal was about 52 Mt and export of charcoal was slightly more than 2 Mt. Given the contribution of charcoal production to deforestation in many developing countries and extremely high greenhouses gas (GHG) emissions linked to the traditional production of charcoal, this trade is deemed unsustainable [6], [7].

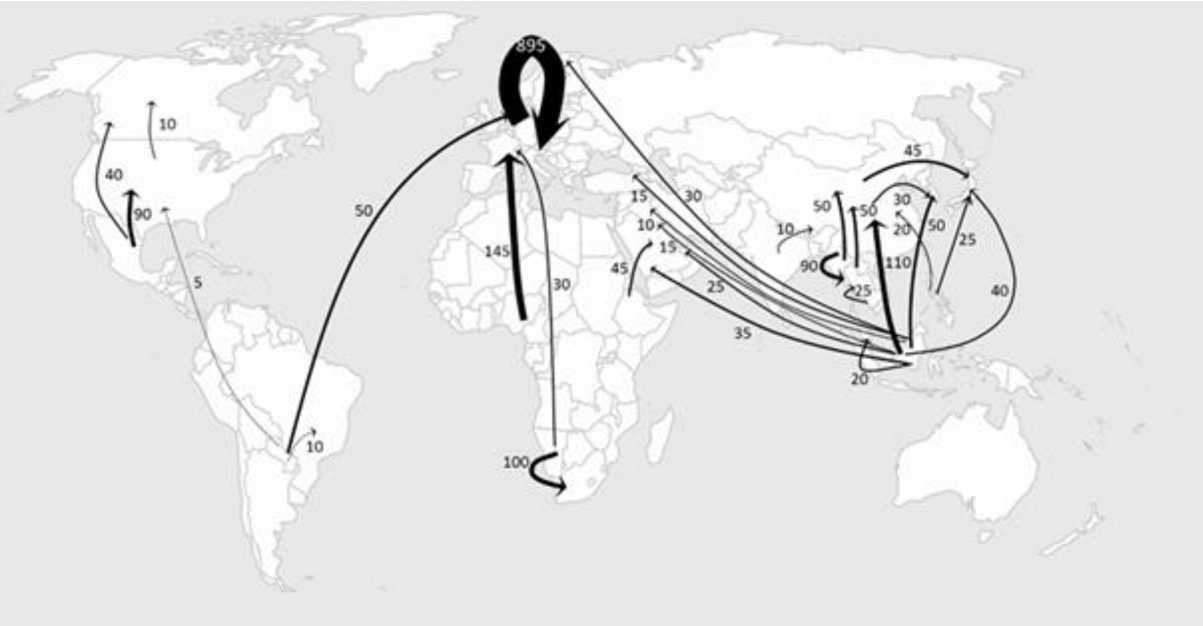


Figure 3. Major charcoal trade streams (≥5 ktonnes), (in ktonnes) in 2015. Sources: [3] , [4]

2.2 Global trade of biodiesel and bioethanol

Bioethanol and biodiesel production has increased significantly over the last ten years. In 2015, the primary exporters of ethanol were the US (1.7 Mt) and Brazil (1.5 Mt), see Table 3. The US, Caribbean countries and Sweden mainly import ethanol from Brazil for fuel usage, whereas Japan, South Korea and several other importing countries, including the EU Member States, import Brazilian ethanol for industrial and other uses, see Figure 4. Overall, more than 90% of the global ethanol consumption is used as biofuel, see more in [5]. With regard to biodiesel, Argentina is the main exporter to the US, whereas Malaysia and Indonesia are the exporters to the EU, see Figure 5. Compared to previous years, export of biodiesel from many non-European countries to the EU is relatively small due to a EU anti-dumping policy [8] . However, this is partly circumvented by the import of vegetable oils, which are then converted to biodiesel within the EU.

Table 3. Global ethanol and biodiesel production between 2006-2015 (in ktonnes). Sources: [9], [10], [11], [12]. A density of 785 kg/m^3 and 885 kg/m^3 was assumed for bioethanol and biodiesel respectively.

Country/Years	**2006**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Ethanol							
United States	15 070	41 090	43 035	40 850	41 320	44 920	44 585
Brazil	14 070	21 645	17 850	18 450	21 955	22 160	23 660
China	4 935	6 500	6 740	7 005	6 090	5 895	6 010
EU-28	2 700	4 940	5 215	5 205	5 500	5 535	5 900
India	1 220	1 265	1 570	1 515	1 600	1 785	1 780
Rest of the World	4 280	6 195	6 725	7 690	8 325	9 030	9 565
Biodiesel							
EU-28	4 870	9 580	9 120	9 725	10 380	10 645	12 000
United States	840	1 150	3 250	3 390	5 150	5 130	4 005
Brazil	60	2 110	2 365	2 405	2 580	3 290	3 990
Indonesia	55	655	1 345	1 595	1 800	2 035	3 020
Argentina	0	2 415	2 440	2 470	2 010	2 335	2 350
Rest of the World	485	1 860	2 230	2 715	2 895	3 325	3 135

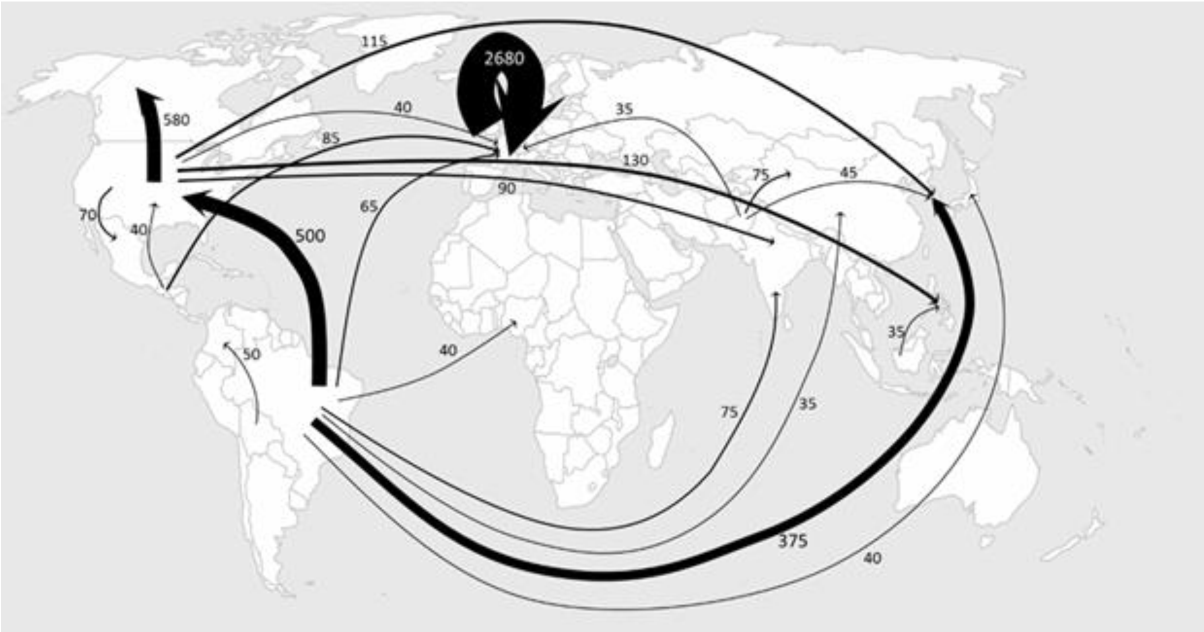


Figure 4. Net ethanol trade streams (≥35ktonnes) used for all end-uses, (in ktonnes) in 2015. Sources: [4], [12], [13]

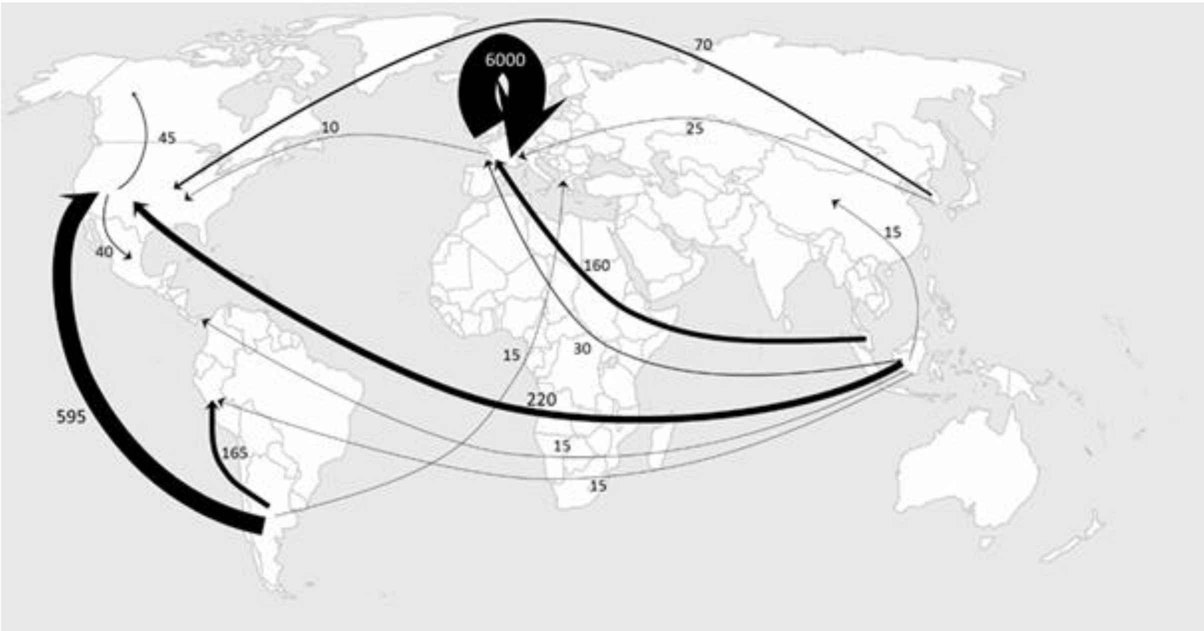


Figure 5. Major net biodiesel trade streams (≥10 ktonnes), (in ktonnes) in 2015. Sources: [4], [11], [12]

2.3 Estimated scale of total international bioenergy trade and possible other trade streams

It is estimated that total international trade of biomass for energy has almost doubled from around 785 PJ (2004) to 1,250 PJ (2015), see Table 4. This is about 2% of the total bioenergy use globally. Indirect trade has remained stable around 600 PJ. Direct trade has increased from about 200 PJ (2004) to 600 PJ (2015), and is likely going to overtake indirect trade volumes in the near future [2] .

Table 4. Estimated scope of international trade of some products between 2004–2015 (in PJ). Source: [2]

Year / product	2004	2008	2011	2012	2013	2014	2015
Indirect trade of biomass (post consumption used for for energy in the importing country):	585	610	575	550	650	625	640
Industrial roundwood	450	435	390	375	470	440	450
Wood chips and particles	135	175	185	175	180	185	190
Direct trade:	200	385	560	580	615	610	610
Charcoal	30	40	50	50	50	55	65
Fuel wood	35	40	65	65	70	70	50
Wood pellets	30	55	135	125	170	200	220
Biodiesel	20	25	80	85	75	45	50
Ethanol as biofuel	60	155	150	160	140	130	120
Palm oil for bioenergy use	25	70	80	95	110	110	105
Total (end up for energy)	785	995	1135	1130	1266	1235	1250

2.3.1 International trade in biogas and biomethane

Biogas is a gaseous fuel typically produced via anaerobic digestion of wet biomass resources such as agricultural residues (e.g. manure), and organic wastes, and - decreasingly - from energy crops. In some countries, an increasing - but yet small - share comes from intercropping, landscape maintenance, and grass cuttings. In addition to the stationary application as fuel for generating heat and power, biogas can be a substitute for existing applications of natural gas, e.g. as vehicle fuel or for local heat generation. Biogas can be distributed to the consumer via the existing natural gas grid, which is available in many countries. However, in order to inject biogas into the gas grid it has to be upgraded to natural gas quality. Biogas is then referred to as biomethane or also renewable natural gas. During the last decade the number of biomethane plants has increased significantly; with Europe as the worlds' leading producer of biomethane, with 459 plants in the EU producing 1.2 billion m^3 biomethane annually [14] , which implies an increase by a factor of 17 since the year 2011[15] . Most of the plants were built in Germany, the UK and Sweden. Only 6% of biogas is upgraded to biomethane in Europe. However, due to its properties, biomethane can be traded transnationally. So far, trade of biomethane using the gas grid has only been realized in small amounts and between neighboring countries in Europe. First trade activities are stated between Germany and Switzerland, the Netherlands and Sweden [16] . Because biomethane is delivered via the gas grid, an appropriate "track and trace" system is necessary to guarantee the biobased origin. Due to the fact that additional requirements and also support schemes for sustainable biomethane differ between the countries, additional information on the feedstock is necessary [17] . Europe has established a "renewable gas registry" called ERGaR in December 2017, which works based on the cooperation with national biogas/ biomethane/ renewable gas registries. Currently, this registry covers 10 European countries and brings together expertise to establish an independent, transparent and trustworthy documentation scheme for cross border transfer and mass balancing of renewable gas injected into the European natural gas network [18]. Within the recently amended Renewable Energy Directive (RED II), biomethane is classified as an advanced fuel. In consequence, a stronger biomethane use for transport - based on residues and waste materials - may be expected, especially in countries with existing natural gas infrastructure. This might also lead to an increasing trade activity from 2020 onwards. Outside Europe, grid-based biomethane trade has not been started yet, but interest in e.g. Africa (for city grids), and Latin America as well as parts of Asia is rising.

2.3.2 International and EU trade in wood waste

International trade in post-consumer biomass waste is a topic that has received relatively little attention in the research community. Such fuels straddle the border between the energy and the waste management sector and consequently their markets are affected by policy measures from both the energy and waste management policy spheres. Notably, waste management legislation has created "push" factors (in the form of e.g. bans on landfilling of organic materials) while energy-related legislation has created "pull" factors [19], [14] .

When it comes to solid waste fuels, there is very little research available that does deeper analysis of the practices of and mechanisms behind international trade in waste for energy purposes. Different sub-categories are traded within Europe, graded according by the extent to which they are sorted or mixed with a common denominator being that the fuels are negatively priced, in the sense that waste to energy (WtE) facilities are paid to receive them [20] .

One subcategory among waste-based fuels that stands out is waste wood, also known as recovered wood or post-consumer wood [21] . Waste wood is in turn classified depending on if and how it has been chemically treated (preservatives, paints etc.). The number of energy facilities that can use waste wood as fuel decreases with the level of contamination to the point where highly contaminated wood can only be managed by a selected few facilities [19] .

Trade in waste wood among EU member states is concentrated in the north and north-western parts of Europe with Sweden and Germany being the largest importers of waste wood, with Germany receiving its largest volumes from the Netherlands, whereas Sweden has been importing especially from Norway and the UK, see Figure 6. Transboundary shipments of non-hazardous wood waste in Northwestern Europe in 2016. Source: [19] .Figure 6.

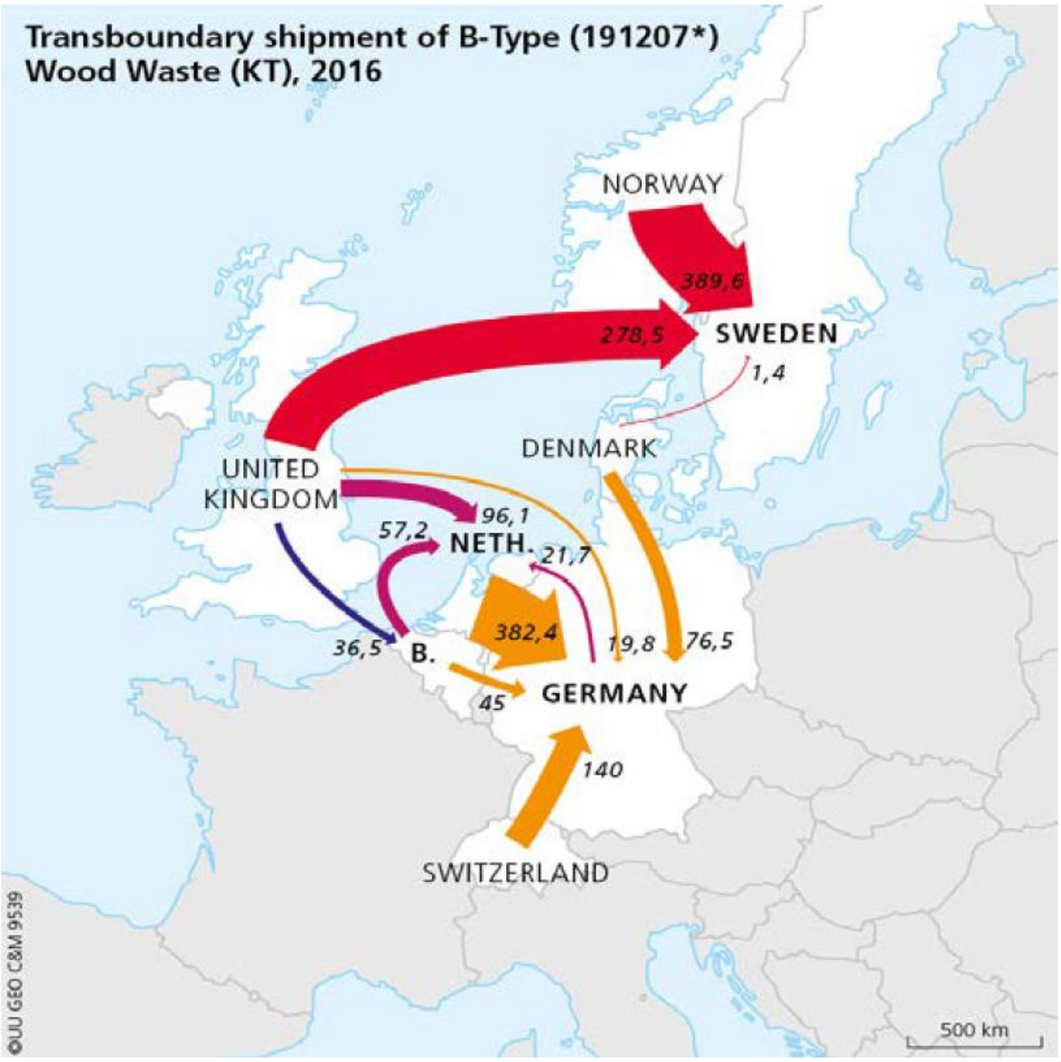


Figure 6. Transboundary shipments of non-hazardous wood waste in Northwestern Europe in 2016. Source: [19] .

Notably, Swedish imports are primarily driven by demand in the country's district heating sector, where waste wood is an inexpensive fuel compared to residues and by-products from the country's forestry and forest industry sectors, see Figure 7. It is important to note that price data pertaining to waste wood is otherwise rare.

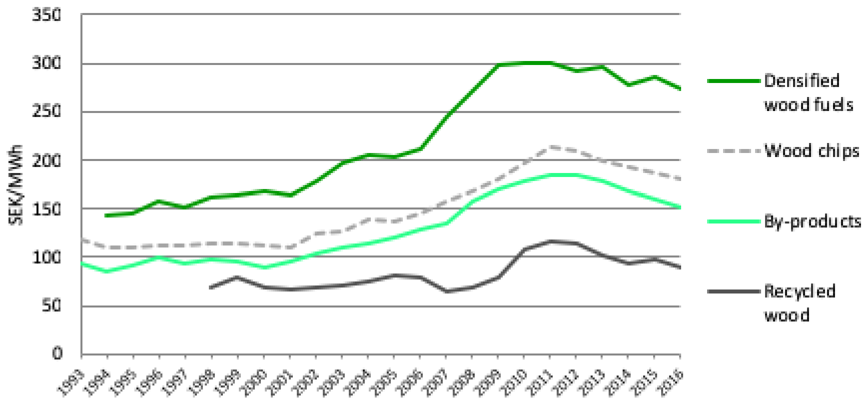


Figure 7. Prices of different fuels used in the Swedish district heating sector 1993-2016. Source: [22]

2.3.3 Other emerging biomass trade flows

New trade streams of biomass for energy can emerge, often triggered by either technological advancements (e.g. advanced pretreatment technologies) or regulatory changes that, linked to GHG or sustainability profiles, create preferred feedstocks. For example, torrefied biomass pellets are very attractive for long distance transportation attributed to advanced handling characteristics and reduced GHG emissions [23] . However, no major trade flows for industrial use have occurred yet. On the other hand, fats, oils and greases (FOG) including used cooking oil (UCO) are collected all over the world and often used to produce biodiesel (fatty acid methyl ester: FAME) or renewable diesel (hydro-processing: HEFA or HVO). Traded volumes have increased, triggered by the fact that some countries in the EU (e.g. the Netherlands) promote the use of this sustainable feedstock (as it is a waste stream) through a double counting mechanism. Other novel trade flows that might emerge are road, marine and aviation biofuel (biomass-derived jet fuel).

With regard to gaseous biomass, trade of upgraded biogas from anaerobic digestion based on certificates is already occurring (see above). In the future, syngas production from gasification of lignocellulosic biomass might become an interesting option. The syngas can be injected into the gas grid after upgrading, or even converted to bio-hydrogen for the utilisation in fuel cells through steam-reforming [24] . Other potentially upcoming tradeable bioenergy commodities include biocoal from hydrothermal carbonisation (HTC-coal) and pyrolysis oil for further refining, gasification or combustion for heat and power production [25].

3. Preconditions for bioenergy deployment and trade

3.1. Challenges related to logistics chains and markets

Biomass to bioenergy is making significant progress and technology advancement in the past decades, but there are hurdles and challenges that need to be addressed for cost reduction and reliability, scale-up and integration, and investment so as to realize a sustainable bioeconomy. To compete with petroleum-derived gasoline and other hydrocarbon fuels, biofuels must be produced at low cost while simultaneously safeguarding sustainability criteria/standards. The US Department of Energy (DOE) has set targets to reduce the Minimum Fuel Selling Price (MFSP) of lignocellulosic biofuels by developing technologies to produce biofuels at US$3 per gallon of gasoline equivalent (gge, equal to about 3.8 liters or 120 MJ) by 2022, $2.5/gge by 2030 and ultimately reduce the MFSP to $2/gge [26] . Results from research, development and deployment projects and integrated biorefineries have provided real-world information about the challenges associated with biomass supply chain, feedstock quality, cost and availability, necessary equipment and unit operations, changes in the marketplace, and sustainability. Furthermore, scale-up and integration of new technologies into pioneer commercial-scale biorefineries is a challenging and high risk undertaking. These major challenges and opportunities are discussed below.

3.1.1 Challenges and opportunities on feedstock supply and logistics

A critical driver of biomass mobilization is to reduce the delivered feedstock cost and risks associated with feedstock quality and volume to accelerate widespread commercialization of sustainable biomass supply chains for a broad range of markets. As an example of biomass utilization for production of biofuels, bioproducts and biopower, the US DOE's 2016 Billion-Ton Report estimates potential biomass availability within the US based on assumptions about current inventory and future projection, production capacity and feedstock availability, and conversion technology [27] . The vision and goal is to sustainably produce and mobilize close to 1 billion dry tonnes of renewable feedstocks annually by 2040 and displace 25% of all transportation fuel needs in the US. Mobilizing large volumes of untapped resources will require establishing new supply chains, as well as significant changes to agricultural and forestry practices. Costs of grower inputs, competing uses for biomass supplies, and costs of establishing new supply infrastructure constrain the cost reduction potential for biomass. Research and development (R&D) on biomass supply and logistics will need to sufficiently address uncertainties and build a compelling case for growers and suppliers to risk disrupting existing operations to serve new markets. There are a variety of technical, operational and economic uncertainties in the availability of consistent and affordable quality feedstocks supplies. R&D work is also required to improve the efficiency of feedstock logistics operations, and develop fundamental understanding of the interactions between feedstock quality properties and conversion performance, so as to improve the equipment performance, throughput and reliability, as well as the process economics. Optimizing logistic chains and reducing related transportation and handling costs is of particular importance for long-distance, international bioenergy trade, as these typically contribute a larger share in these supply chains than for local bioenergy projects.

Energy density affects e.g. the required capacities of fuel storage, handling, and feeding equipment, as well as transport capacity and costs. Figure 8 shows a comparison of the energy densities of different fuels from the perspective of the amount of space required. If coal use is replaced with pellets, one and a half time more logistical capacity is needed, i.e. storage space, conveyor capacity at plant and transport capacity (vehicles). With forest chips, the capacity need is six-fold to keep the energy volume at the same level. In practice, the storage levels (measured in energy units) at plant will be lower with biomass compared to coal because of limited storage capacity for pellets or chipped fuel. This may cause some logistical challenges to keep the supply security at an adequate level. Coal is typically stored at the yard of power plant whereas pellets need covered storages and silos. Black pellets made by torrefaction or steam explosion may ease the logistics, but their market is just developing. In addition, long-term storing of forest chips at yards should be avoided because of self-ignition risk and solid content losses. Therefore, forest based biomass is mostly stored as uncomminuted near harvesting sources at forests and terminals. This may add to the logistical challenges to keep up the supply security year around.

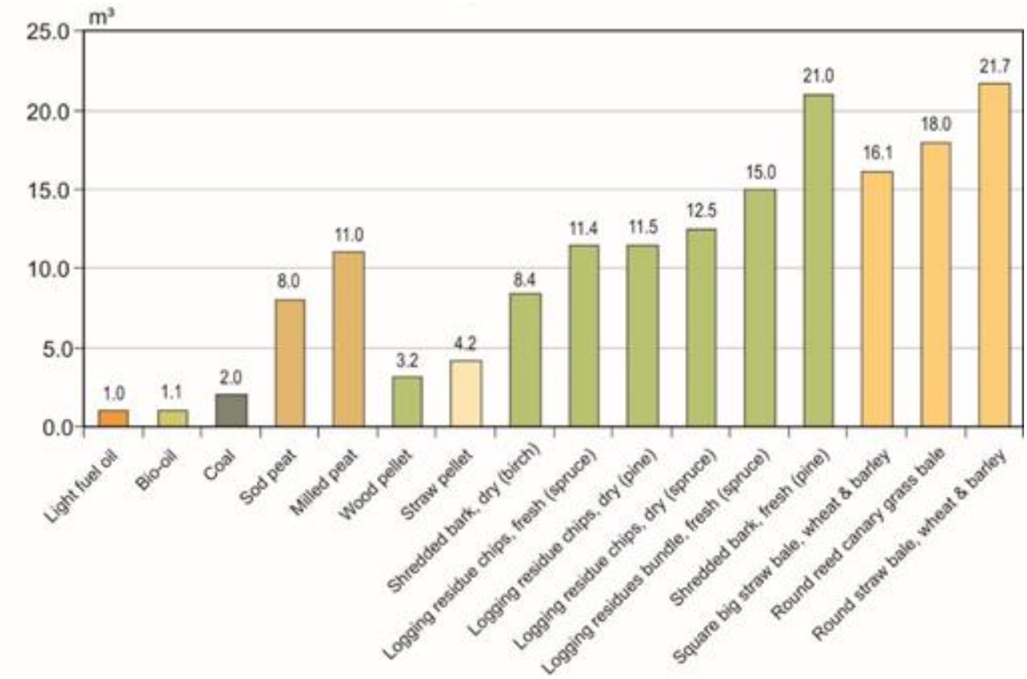


Figure 8. Volume required by different fuels for an amount of primary energy of 10 MWh (36 GJ). Source: [28]

With increasing trade volumes, efficiently measuring the quality becomes more important, but this typically a laborious task, especially for forest chips. Their quality is mainly depending on energy content (moisture content), impurities (ash content) and particle size distribution. Moisture is the most important quality parameter of biomass fuel, strongly influencing its lower heating value, combustion control and consequently fuel price determination. Typically, the supply logistics are based on truck transportation, where the moisture content of each load should be measured. The overall precision of moisture measurement by sampling of a load is dependent on the number of samples collected and on how many loads are tested. If sampling is done by fuel load, at least two increments per 50m^3 frame volume of fuel must be taken.

Delivery lot as a frame volume for truck transportation is 100-200 m^3, railways 2,600-4,600 m^3 and vessels 20,000 – 30,000 m^3. International fuel trade of forest chips is based on the latter, i.e. bulk dry vessels. Traditional sampling (preparation) methods used for truck loads are inappropriate for such large-scale deliveries. One option is to use a continuous automatic quality measurement system, e.g. by x-ray scanning of the moving forest fuel stream. This allows measuring volume, moisture content, heating value and impurities such as stones and other foreign matters [29], see Figure 9.

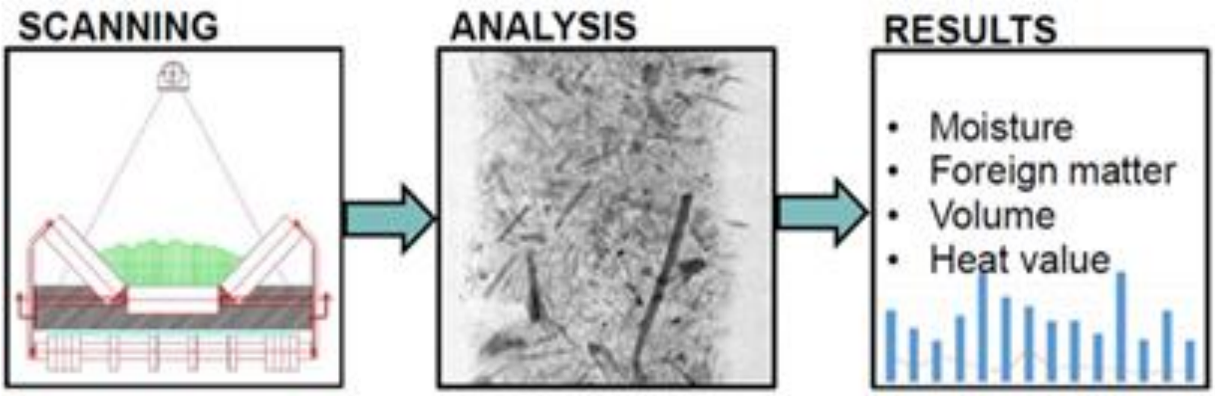


Figure 9. Continuous x-ray scanning and analysis.

3.1.2 Challenges and opportunities on feedstock conversion and scale-up

Reducing the costs of individual process steps along the value chain from feedstock to end products is paramount if bioenergy and biobased products are to be accepted into the market. R&D development needs to focus on developing a variety of conversion technologies that can be combined into pathways from diversified feedstocks to multiple products with desired performance and end-products quality. High capital cost of cellulosic biofuels and bioproducts facilities remain a significant concern. Capital expenditures (CAPEX) can be as high as $500 million, limiting participation from potential investors [26]. R&D work is required on process intensification and performance improvements to drive down capital costs, minimize resource, and minimize/eliminate release. In addition, recent pioneer biorefineries development and operation have suffered from failing to account for the complexity and variability of lignocellulosic biomass, inconsistent feeding and handling, improper equipment design, and flawed integration for conversion and process scale up. To reach cost-effective operation, biorefineries need to operate at a design capacity of at least 90% on-stream reliability. R&D is needed to identify the feedstock quality and operation factors affecting conversion performance yields, system throughput and reliability, so as to develop technologies to address contributing factors, and develop process or operational strategies to mitigate remaining factors. Resource analysis needs to ensure the sufficient quantity and quality feedstock supply to biorefineries all year round. International biomass supply could become an important feedstock buffer or back-up for biorefineries, in addition to regional supply, to diversify the sourcing portfolio and limit price fluctuations.

3.1.3 Challenges and opportunities on markets and investments

International trade of biomass is not only helping the security of supply in regions with lesser resource availability. Trade may also be a very important stimulus in the development of local and regional markets with abundant but not yet utilized biomass supplies. Many cases show that a local understanding of the opportunities biomass is providing was only developed after export chains caused attention and demonstrated steady availability of biomass volumes. One prominent example is the mobilisation and export of palm kernel shells (PKS) from Indonesia. This agricultural residue stream is available at each palm oil mill. But only after European traders purchased and exported PKS, mill and refinery operators became aware of the energetic value of the material and started using them in their coal boilers. Export opportunities are also a proof to local project finance of bioenergy projects requiring security of fuel supply.

Similarly, there are numerous examples where export of wood chips or pellets helped to create local markets. Almost every pellet mill in Eastern Europe and the Balkans was initially set up to export; contributing to supply security in other regions/countries with local sales sometimes 5% or less in their start-up years. Availability of local supplies subsequently triggered local demand. Customers considered switching to the cheaper fuel, local stove manufacturers establish business and foreign boilers and stoves were imported. Nowadays, some Balkan countries are turning from exporter to importer. Producers in Czech Republic, Slovakia, Romania sell increasing shares of production for better prices locally than the price they could get for export.

But the use of biomass for energy alone may in many cases not be sufficient to mobilize markets. When the price of oil dips to a level that biofuels cannot compete with, and federal and state renewable fuel incentives are uncertain, companies wishing to enter the fledgling advanced biofuels industry might find these external challenges insurmountable. Concerns have been raised by stakeholders that new biofuels producers need portfolio diversity and alternative revenue sources to ride out market fluctuations. For example, as a complement to biofuels, there is significant opportunity for the industry to produce and capitalize on bioproducts, which generally include nonfuel chemicals that are produced from biomass. For a bioproduct to displace a petroleum product, it must offer the same (or better) quality and performance at a competitive price. If successful, bioproducts can represent early market adoption in the bioeconomy as a whole. In addition, recovering and extracting the highest possible value from all fractions generated in various steps of value chain will reduce the overall cost of operations and foster the development of multiple markets to accelerate mobilization by enabling coproduct and value-added technologies. R&D needs to focus on market analysis including assessments on the barriers, risks, potential cost, commercialization time, and market demands for candidate biofuels, biopower, and bioproducts to focus technology development priorities in the near-, mid-, and long-term. Strategies that foster market development can be characterized as "technology push" and "market pull." Broadly, strategies that increase biomass supply, decrease biomass cost, or increase biomass value, are considered technology push. Strategies that increase market demand are considered market pull. If advancements can be made in both technology push and market pull, then biomass production and use will increase. Global trade of biomass and commoditization of intermediates (such as pellets, pyrolysis oil etc.) may open up new opportunities for biorefineries and broader market deployment

A strong bioeconomy will need to overcome challenges and realize: 1) sustainable production and supply of quality biomass feedstocks and capture of usable wastes; 2) development of innovative and efficient technologies that reliably transform lignocellulosic biomass and waste materials into high value intermediates and products at scale; 3) expansion of the market for biofuels, biochemicals, biopower, and other biomass-derived products. It is critical to develop and demonstrate innovative and integrated value chains for biofuels, bioproducts, and biopower that can respond with agility to market factors while providing economic, environmental, and societal benefits to international trade and market.

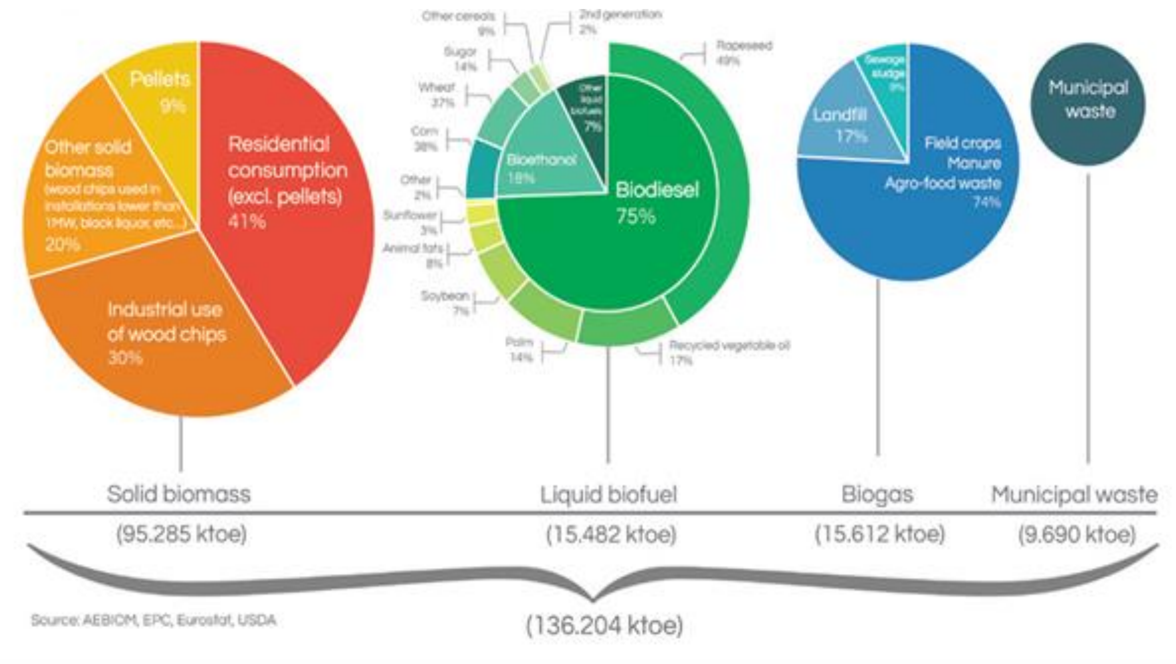
3.2 Sustainability as a precondition for biomass trade - stakeholder views

Ever since its creation, IEA Bioenergy Task 40 carried out significant work on the sustainability of bioenergy, aiming at clarifying concepts, facilitating dialogue among its members and relevant stakeholders, and fostering governance and implementation to avoid trade barriers. Many of this has been in close collaboration with other IEA Bioenergy Tasks, especially Task 38 (Climate Effects), and 43 (Biomass Feedstocks for Energy Markets).

In the past 20 years, the sustainability governance of many bioenergy supply chains has increased. The discussion about the sustainability of bioenergy supply chains emerged in the early 2000s, when no or few dedicated systems existed to monitor the sustainability of bioenergy supply chains. In comparison, by 2017, in the EU, 91% of the total transport biofuels are sustainably certified due to the establishment of RED sustainability criteria for liquid biofuels [30] , see **Virhe. Viitteen lähdettä ei löytynyt.**. In the heat and power sector, given the lack of EU wide sustainability requirements for solid biomass, Belgium, the UK, the Netherlands, and Denmark, the main importing countries of wood pellets for industrial use, have established sustainability criteria under national support and voluntary schemes [31] .

Note that given the variety of criteria and verification requirements, it is not yet possible to distinguish between all solid biomass (wood pellets and wood chips) that are certified with existing sustainable forest management schemes, and which part (and which criteria) have been verified by an independent auditor. Thus, the degree of sustainability may vary significantly.

With the inclusion of mandatory sustainability criteria for solid biomass on the EU level under the RED II, sustainable bioenergy trade is expected to increase in the coming years.



Bioenergy 2016 (ktoe)	Solid biomass	Liquid biofuels
Total consumption	8,243	15,482
Sustainably certified	2,672	14,158

Figure 10. Overview of total consumption o bioenergy and the estimated sustainably certified share in the EU. Source: [1], [30] .

The important role of bioenergy in the current and future energy landscape is recognized by the EU and several other large economies [32], [33], [34]. However, at a stakeholder level, the role of bioenergy is seen quite differently by various groups, especially regarding sustainability concerns, and scientific debate around e.g. climate effects. A number of studies have been carried out to assess positions, perception and vision of diverse stakeholders at a local, national and global level [31], [35], [36], [37] as well as to indicate under which conditions the bioenergy sector should be supported in its current and future development.

Existing challenges

The consultation with the stakeholder groups has indicated that the bioenergy sector has grown rather in "isolation", i.e. has not (yet) cooperated with other sectors and external stakeholder groups efficiently [38] . The general public has not yet had a role in designating policy and in implementation of bioenergy projects, and their position needs to be recognized. The bioenergy, biochemical and biomaterial sectors have not communicated actively although they are – conceptually and economically - integrated parts of the bioeconomy. Social acceptance to bioenergy projects is not apparent in some regions, as bioenergy projects still raise concerns for local community regarding worker rights and land rights, human health impacts, and related issues.

There are also other challenges for the bioenergy sector to overcome [38] . The barriers of bioenergy market uncertainties and unresolved sustainability issues need to be addressed adequately. As the sustainable mobilization of biomass feedstocks and global trade may well have to be further expanded in the medium and long term, biomass sustainability is a prerequisite [39] . The consultation with the stakeholders also underlined that subsidies for bioenergy to assist its competitiveness against fossil fuels may create an unlevel playing field for other sectors using the same feedstocks, and competition with material use.

Conditions to gain support and future of bioenergy

Stakeholders consider the establishment of adequate sustainability requirements as one of the key conditions to support the development of the bioenergy sector [38] . The sustainability requirements that are already implemented in some EU Member States include reduction of GHG emissions, under stringent criteria with regard to air and water pollution; reuse and recycling of materials; improvement of soil and forest management; and conservation of biodiversity and ecosystem services. Those requirements should be implemented in other countries. Also, the sustainability requirements covering social, and additional economic and environmental aspects should be ideally implemented for all types of biomass, regardless of end use, and feedstock origin.

Sustainability certification by third parties is another condition for external stakeholders to support the bioenergy sector [38]. It is important that sustainability certification is transparent in its assurance of compliance. Quantifying sustainability criteria whilst assuring a transparent and effective certification is challenging, but increasingly, issues such as land use and land use changes will be governed better – at least more transparently - when implementing the Paris Climate Agreement and the Sustainable Development Goals (see next section).

Communication and continued dialogue with external stakeholders on bioenergy benefits, if proven by scientific evidence, could help find win-win solutions for all parties [38] . The positive tracks of bioenergy and its contributions to climate change mitigation, environmental improvements as well as social and economic development need translation into simple and clear messages. This would assist long-term decision making in the bioenergy sector and inform the general public and other stakeholder groups.

A competitive sector independent from subsidies is another condition for gaining support of the external stakeholders. Bioenergy should consider mobilizing sustainable resources, advancing further processing technologies, developing more effective supply chains, and ultimately reducing bioenergy costs to strengthen the sector competitiveness. Yet, a “fair” price competition with fossil fuels must reflect their externalities also.

In addition to current accepted feedstocks used for bioenergy, additional sustainable bioenergy crops and forest biomass could potentially be mobilized. Those feedstocks harvested on surplus lands and by afforestation with low land-use change (LUC) risks, available through increased yield, better supply chain integration and higher efficiency are already demonstrated, and a number of cases is described in scientific papers.

Collaboration with the bioeconomy sub-sectors is also considered to enhance support [38] . Bioenergy is no longer a stand-alone sector; mutual solutions for bioenergy and other sector using biomass feedstocks are of importance. Collaborations beyond national borders are required to create a global and sustainable bioenergy market.

4. Sustainable bioenergy in the wider context of the bioeconomy and sustainable development goals

4.1 A circular bioeconomy?

Historically, the use and trade of biomass for various material uses has been well established for many centuries. However, by the turn of the century, increasing awareness for climate change and the limits of fossil reserves, the use of biomass for bioenergy caught increasing attention of policy makers; much more so than biomaterials or biochemicals. In Europe, for example, first the Renewable Electricity Directive [40] , next the Biofuel Directive [41] and finally the Renewable Energy Directive [42], [43] brought biomass back to the attention as a renewable energy source. In parallel, biomass was re-established as a resource for biobased products.

In consequence, a more holistic concept of the "bioeconomy" appeared, challenging fossil supremacy. For example, Europe's Bioeconomy Strategy describes the multiple biomass functions that can coexist: "…the bioeconomy encompassing food, feed, bio-based products and bioenergy" [44] .

However, despite the potential coexistence of functions, bioenergy is referred to a specific place in the functional hierarchy: "Biorefineries should adopt a cascading approach to the use of their inputs, favoring highest value added and resource efficient products, such as bio-based products and industrial materials, over bioenergy [44] .

With the introduction of the cascading principle and its adoption in various policy frameworks, bioenergy was (and still is) finding its place in the new bioeconomy. This is a challenge because, as the bioeconomy is complex, so is the cascading approach. Olssen et al. [45] acknowledge for that matter that "the cascading principle is valuable and should be treated as a guiding principle, but not as an end in itself".

Depending on viewpoints, bioenergy can be a competitor or integrator in the bioeconomy: Bioenergy is interlinked with other sectors for all steps of the production, processing and utilization chain. It can use wastes and residues of other bioeconomy activities in a cascading approach, but it may also compete for feedstocks with other sectors [46].

Regardless its position at the lower end of the cascading hierarchy, bioenergy is not expected to disappear when the bioeconomy emerges to its full potential in years to come. On the contrary, bioenergy is likely to keep being a necessity in e.g. future biorefineries. After higher value added products have been extracted, a significant fraction of high volume and/or low value biomass by-products will remain. These by-products cannot be left as an open end in the biorefinery concept. After all, biobased economy should offer a holistic solution which includes processing its by-products. Using these by-products as feedstock, bioenergy can remain playing its essential role as an integrated part of the bioeconomy. Not only offering the cornerstone to the holistic solution, but additionally producing valuable energy-products in doing so. "Advanced bioenergy and biofuels will be a cornerstone of the European bioeconomy, as well as the energy system, during the coming decades" [46].

Increasing amounts of traded biomass feedstocks could on the one hand create opportunities for the exporting countries, but also entail risks that - without appropriate governance - are largely outside the control of biomass users and policy makers who incentivized trade.

4.2 Sustainability of bioenergy within the bioeconomy

Since the early 2000s, many IEA countries started using quota systems and tax incentives to introduce liquid biofuels for transport into their markets, and the EU domestic target of 10% for 2020 (and, to a lesser extent, the US biofuel policy) stirred up an intense debate on the sustainability of biofuels, especially regarding potential effects from imports, and from displacing domestic food & feed production. Issues raised concerned biodiversity, climate and water effects, and food and land tenure security. This discussion overshadowed positive opportunities discussed earlier, e.g. employment, energy security, rural development etc.

IEA Bioenergy contributed to the discussion in providing scientific information, focusing on appropriate calculation of GHG balances, consistent sustainability metrics, and certification and monitoring systems to verify sustainability claims.

Meanwhile, Europe implemented its Renewable Energy Directive [42] with mandatory renewable fuel quota in the transport sector of all Member States, combined with mandatory sustainability criteria required to count biofuels under the quota.

But not only the EU reacted: In response to the 2005-2010 global discussion around biofuels ("food vs. fuel", "land grab", "indirect land use change" etc.), a large number of governmental and non-governmental initiatives worked on approaches and concepts to prove that biofuels and bioenergy can be produced sustainably.

On a global level, the Global Bioenergy Partnership (GBEP) developed sustainability indicators for bioenergy to guide analysis at national levels, to inform decision making, and facilitate sustainable development of bioenergy [47] . The indicators were derived in consensus among a broad range of national governments and international institutions, and have been tested in a number of countries at both regional and national level, to evaluate their feasibility and enhance their practicality as a tool for policymaking.

The GBEP work was taken up by the standard ISO 13065:2015 (Sustainability criteria for bioenergy), and in many non-governmental schemes, e.g. Roundtable on Sustainable Biomaterials (RSB), and the International Sustainability & Carbon Certification (ISCC). Furthermore, sustainability schemes for specific bio-based commodities such as palmoil, soy and sugar were developed, building on earlier work for timber (e.g. FSC, PEFC, SFI).

Despite these certification schemes, there is an ongoing scientific debate on carbon neutrality, payback time, iLUC and appropriate calculation metrics. The sustainability of internationally traded wood pellets has been questioned by critics, especially for pellets produced from pulp-quality logs in the US Southeast [48] . And even more fundamentally, mitigating GHG emissions by burning wood from forests ("carbon debt", see e.g. [49]), and the resource efficiency of burning biomass (instead of more "cascading") are being doubted by many [50] . Last but not least, concerns about availability of sustainable biomass for all uses (food & feed, chemicals, construction materials, energy, fibers…) and respective possibilities of use competition have been raised , e.g. see in Chen, X. et al. [51].

All this is partly caused by the fact that sustainability criteria included in certification schemes can usually only assess local impacts on e.g. water, soil and carbon stocks, whereas issues related to indirect land use change and carbon neutrality typically play on a landscape or "macro"/whole system level.

To overcome the critique, it is necessary to see bioenergy and biomass trade in the broader context of the bioeconomy, as part of a larger cross- and inter-sectoral global approach.

This extension of the scope allows to consider: the multiple outputs of (agricultural and forest) landscapes; the beneficial role of bioenergy development in dealing with forest and land degradation; the integration of segmented product markets into a broader view, to avoid "leakage", "indirect" effects, and other problem shifting.

From a bioeconomy viewpoint, setting only sustainability requirements for bioenergy is compromised by leakage effects – if e.g. wood and palm oil only have to meet sustainability requirements for energy purposes, all the unsustainably produced feedstocks will go to material and food purposes. Eventually, but preferably soon, sustainable production should be required for all products of the bioeconomy and governmental regulations will be needed.

In this more holistic view, bioenergy must be developed and utilized in the context of ecosystem services to limit adverse environmental impacts, not disrupting existing land uses and markets, and ensuring feasibility for all participants in the value chain.

Opportunities for increased and yet sustainable production differ around the world. For example, areas with large amounts of forests and underutilized forestry residues and resources, such as Canada, the US South-East and Russia have the opportunity to export woody biomass to regions with a deficit. Also, areas with surplus agricultural (or degraded) land could offer opportunities to mobilize and grow more biomass and the products could be utilized by the rest of the world [52] . When done right, this can entail both socio-economic and environmental benefits.

Local production of biomass can have a lower footprint, due to reduced transport emissions, but on the other hand, there are areas around the world that can have a higher production per hectare, requiring less fertilizer or irrigation, compensating for the increased transport.

There is also a socio-economic dimension, as biomass feedstock production in lower-income countries can improve the livelihood of – often rural - smallholders by producing biobased goods for international markets. In this way trade of biomass can support sustainable development and can be a driver for biomass production in the bioeconomy, with more renewable and sustainable products and energy and an increase income for the rural farmer.

A better, more integrated governance of a sustainable bioeconomy will be beneficial for trade, with a consistent and transparent mix of regulations that take into account the ecological, social and economic differences among regions.

This is especially important considering the global trade of bioenergy feedstocks, which is only going to increase in coming years. It is also important that the evolution of governance mechanisms occurs to allow smaller-scale operators to enjoy the same benefits of certification without facing undue economic hardships as a result of obtaining certification.

The IEA's Bioenergy Technology roadmap [39] identifies the development and implementation of an internationally recognized sustainability governance systems that cover all bio-based products and which supports sustainability best practices and stimulate innovation as a key action.

Industry and policy makers look for clear guidance on what is sustainable biomass, and effective governance mechanisms are needed for consumer confidence. As these are partly lacking, at present, many legislators choose for a low-risk approach and limit the use of biomass for energy to low-risk materials, and/or have developed very comprehensive sustainability requirements for biomass used for energy purposes [31] .

In parallel to all of this dynamic, sustainability – not only for biomass, but as a general issue - became more acknowledged in global policies. Significant progress has been made after the 1992 and 2012 Rio conferences [53], and in September 2015, the UN General Assembly formally adopted the universal, integrated and transformative 2030 Agenda for Sustainable Development, along with a set of 17 so-called Sustainable Development Goals (SDGs) which are – for the first time – to be implemented in and reached by all countries until 2030 [54].

The central role of bioenergy with regard to SDG7 (sustainable energy) has been described [47], and recent work underlined the close relation of the GBEP sustainability indicators with the SDG indicators [55]. Other research showed that the SDGs have strong interlinkages [56], [57] , implying that biomass sustainability could significantly influence other SDGs [58], see also Figure 11.

SDG	Key wording	Driver	Safeguard
1	End poverty in all its forms everywhere	(✓)	(✓)
2	**End hunger, achieve food security and improved nutrition and promote sustainable agriculture**	✓	✓
3	Ensure healthy lives and promote well-being for all at all ages	(✓)	(✓)
4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all		
5	Achieve gender equality and empower all women and girls	(✓)	(✓)
6	Ensure availability and sustainable management of water and sanitation for all	(✓)	(✓)
7	**Ensure access to affordable, reliable, sustainable and modern energy for all**	✓	(✓)
8	**Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all**	✓	(✓)
9	**Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation**	(✓)	
10	Reduce inequality within and among countries	(✓)	(✓)
11	Make cities and human settlements inclusive, safe, resilient and sustainable	✓	(✓)
12	**Ensure sustainable consumption and production patterns**	✓	(✓)
13	**Take urgent action to combat climate change and its impacts**	✓	✓
14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development	(✓)	(✓)
15	**Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss**	✓	✓
16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels		(✓)
17	Strengthen the means of implementation and revitalise the global partnership for sustainable development	(✓)	(✓)

Figure 11. Role of the SDGs for Sustainable Biomass Supply and Use; Source: [55]*.* **Bold text:** SDG related to energy; (✓) = partially relevant

Strong links of biomass sustainability to SDGs – beyond sustainable energy (SDG 7) – concern: food (SDG 2), as biomass influences food security - negatively or positively [59] ; water (SDG 6), as bioenergy can be provided from waste water treatment, and biomass cultivation can improve water supply [60], but may also interfere with access to clean water [61]; growth and employment (SDG 8), sustainable consumption and production patterns (SDG 12), combat climate change (SDG 13), and life on land (SDG 15).

Using the SGDs as a normative framework for the sustainability of biomass [62], [63]; [6], [53], [64] implies not only strong interlinkages, but also that the goals should be achieved in an integrated way to avoid tradeoffs. This will require to move beyond the "pillar" concept, and to consider the SDG interlinkages in a positive way: biomass – with bioenergy as part of the overall bioeconomy – should be seen as a means to implement the SDGs. This in turn implies that only those biomass systems are sustainable which comply with (at least the majority of) the SDGs. To assess these opportunities, the issue of measuring sustainability becomes relevant [65].

5. The anticipated role of bioenergy in the 21st century

Long term energy and land-use strategies seeking to meet strict climate change mitigation targets have consistently highlighted the importance of bioenergy [33], [66], [67]. Scenarios consistent with a warming by the end of the century of no more than 2°C, project bioenergy making up 23% of total primary energy supply in 2050 (10th to 90th percentile: 18-27%), equivalent to 138 EJ/yr (83-195) [68], [69], [66]. This compares to 51 EJ, or 10% of primary energy supply, in 2015 [39]. This result is consistent, even when adopting pessimistic assumptions on biomass availability and the development of advanced technologies such as 2nd generation biofuels of bioenergy with carbon capture and storage (BECCS) [70], [71].

Within these scenarios, bioenergy is overwhelmingly used in combination with BECCS (>90% of scenarios meeting at least a 2°C target). Models project the adoption and scaling up of these technologies in order to take advantage of so-called "negative emissions". These are important in mitigation scenarios in order to compensate for GHG emissions in other sectors such as CH_4 in agriculture, residual fossil fuel use in certain transport modes, etc., which are extremely difficult to mitigate [33, 66]. In this context, BECCS is part of a portfolio of "negative emission" options such as afforestation and direct air capture, however, the trade-offs concerning these options are still poorly understood [72]. Scenarios which do not adopt any BECCS either have a less than 50% probability of staying within 1.5°C [68], or heavily depend on emission mitigation through significant technological and behavioral changes such as low population growth, severely reduced consumption, high energy efficiency, and systemic changes in energy demand [73, 74].

Nonetheless, there is significant disagreement across scenarios concerning biomass deployment strategies. Models show very different deployment levels and technology portfolios for biomass conversion. While few models project production of biogas or bio-hydrogen, there is no consistent pattern concerning the adoption of bio-based electricity, gases, liquids or solids, see Figure 12 and [70]. Recent analysis has highlighted that the reason for this is due to differences across models concerning differing technology portfolios (i.e. availability of BECCS in electricity production but not in liquids) and assumptions concerning the ease of integration of variable renewable electricity generation options in the power system [75]. It is important to note that global long-term models used in such projects tend to under-represent the use of biomass in chemicals and material production, which could contribute to BECCS by locking carbon in long-lifetime products, however the potential contribution of this option has been downplayed [76]. Also, it needs to be pointed out that that models often disagree quite substantially - some pick only electricity, others only liquids, some a mixture (solids are rarely picked alone).

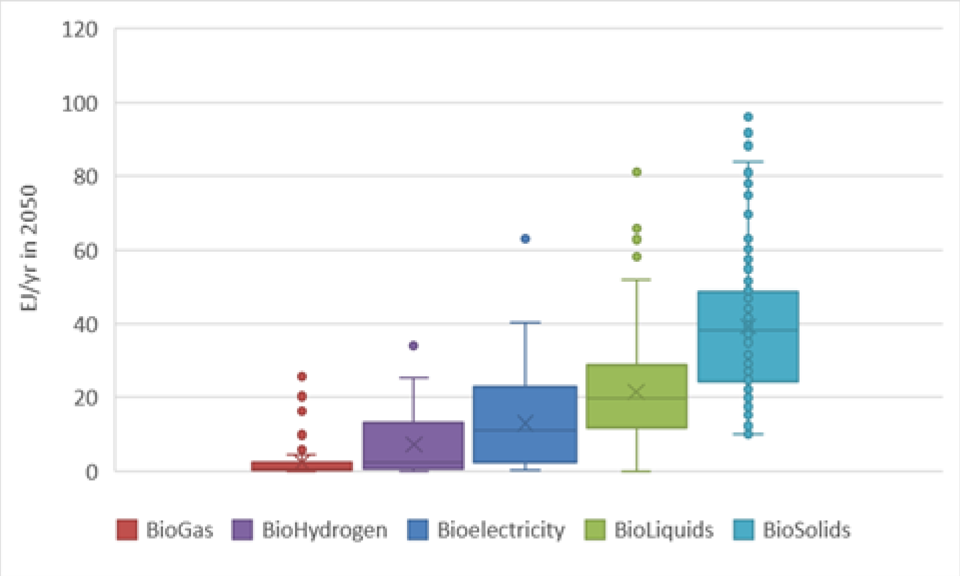


Figure 12. Use of different bioenergy conversion technologies in 2050 in scenarios that meet a 2°C climate target (N=213). Note that values of each boxplot cannot be summed as they represent different modelled bioenergy strategies.

Long-term climate change mitigation scenarios have also highlighted that the expected growth in bioenergy use also leads to a significant ramp-up of international bioenergy trade [77], [78] . There is no consensus across model projections concerning the main exporters and importers, as this depends on varying bioenergy use strategies, as well as how supply is modelled. Nonetheless, the projections agree that up to 25% of global bioenergy demand in traded across major world regions [1] in 2050, with growth rates of international trade being in the range of 5-8% per year [71] . There is modest agreement across models that Latin America and Sub-Saharan Africa are the main exporting regions due to the perceived availability of land and the possibility to achieve significant improvements in yields. Interestingly, while it is projected that multiple regions are likely to depend on imported biomass, it is unlikely that this will lead to significant energy security concerns. This arises from the fact that climate change mitigation strategies are likely to lead to an increase in energy diversity, with bioenergy (or any primary source for that matter) not making up more than a quarter of primary energy supply, as noted above.

[1] Defined here as EU, USA, Rest OECD, East Asia, rest Asia, Brazil, Rest Latin America, Former USSR, Middle East, and Africa

Furthermore, models highlight that multiple regions can act as supplier, adding to diversity of supply.

The projected growth of bioenergy use and the associated increase in its international trade raise sustainability issues. Of particular concern are those relating to food security, impact on biodiversity, water stress and LUC emissions from biomass production [79], [78], [80], see also section 3.2. While modelled climate change mitigation strategies factor in global LUC emissions, in practice, there is significant risk of international trade leading to such emissions due to inconsistent land use policies across world regions [81], [82]. Overall, optimizing carbon benefits from bioenergy use requires consistent global sustainability frameworks together with efficient production and use of bioenergy. This favors integrated agricultural and energy systems that co-produce useful bioenergy streams alongside a number of useful materials and chemicals.

6. Conclusions and recommendations

Biomass will continue to play an important role as a feedstock for renewable energy (SDG7) and materials. In-line with an emerging industry, the past decades have largely focused on establishing and evaluating specific supply chains and/or use cases. Future top challenges and research opportunities however are the integration and optimization of bioenergy on multiple levels:

Feedstock production for the (global) biobased economy will have to be part of integrated landscape management and should contribute to achieving other SDGs as well (e.g. food, water, growth and employment). A further harmonization of sustainability analysis, certification frameworks and evaluation criteria is important to ensure carbon and other co-benefits of bioenergy deployment.

A significant share of agricultural, forestry, and food residue streams remain unused, even when taking into account others existing uses (e.g. fodder) and environmental removal constraints, e.g. to prevent erosion and preserve soil organic carbon and nutrients. Integrated concepts are required to create value-add for actors along the supply chain to ensure their mobilization.

On the user side the number of biobased-products is increasing and an expansion of the market for biofuels, biochemicals, biopower, and other biomass-derived products can be noted. Moreover, the optimal use of biomass for electricity, heat, transport fuels and materials will shift over time, also with increasing emphasis of cascading biomass, increasing shares of other renewables, and the need for negative emission technologies and the potentially significant role that BECCS and BECCU can play.

Therefore, we conclude that it is critical for industry to develop and demonstrate innovative and integrated value chains for biofuels, bioproducts, and biopower that can respond with agility to market factors while providing economic, environmental, and societal benefits to international trade and market. This requires development of innovative and efficient technologies that reliably transform lignocellulosic biomass and waste materials into high value intermediates and products at scale. Furthermore, flexible biogenic carbon supply nets based on broad feedstock portfolios and multiple energy and material utilization pathways will reduce risks for involved stakeholder and foster the market entry and uptake of various densified biogenic carbon carriers.

The role of international biomass trade in all of this is very likely to increase. With increasing deployment of biomass in the bioeconomy, the need to link regions with abundant biomass supply with those requiring increasing amounts will likely grow – based on various scenarios form integrated assessment models, on the longer term, traded volumes in the same order as oil and coal today may be reached. However, this will only be possible under global sustainability frameworks to ensure amongst others carbon benefits, food security and contributions or other SDGs. Only under such circumstances, stakeholder support is likely to develop such supply chains. Also, this will also depend on the development of fungible bio-commodities/intermediates that can both handle the diverse set of feedstocks and multiple energy and material utilization pathways.

In light of these expectations, also IEA Bioenergy Task 40 will continue in the coming years, focusing on various issues around the further deployment of bioenergy. The above-mentioned emerging issues and concepts are considered and further developed, in close collaboration with other IEA Bioenergy TCPs (especially the new “Sustainability Task, see www.task45.ieabioenergy.com), and opening up to more stakeholders from the bioeconomy, and civil society. In these tasks, new biomass deployment concepts such as provision of high-temperature industrial heat, the role of renewable gases as well as the requirements and suitability of BECCS and BECCU applications will be looked at.

The design and impact of globalized sustainable biobased value chains and the respective synergies between bioenergy and the broader bioeconomy play a key role in the further bioenergy deployment. It all needs to be framed by the role of bioenergy in a well-below-2 °C/SDG world, i.e. a future in which not only climate change mitigation is paramount, but the Sustainable Development Goals are met simultaneously. Sustainable bioenergy within the broader bioeconomy will be instrumental to deliver on that.

References

1. Thrän D, Peetz D, Schaubach K, Backéus S, Benedetti L, Suani LB, et al., Global Wood Pellet Industry and Trade Study 2017 Global Wood Pellet Industry and Trade Study 2017 Lead authors. (2017).

2. Proskurina S, Junginger M, Heinimö J, and Vakkilainen E, Global biomass trade for energy - Part 1: Statistical and methodological considerations. Biofuels, Bioproducts and Biorefining (2017).

3. Faostat, Food and agriculture organization of the United Nations Statistics Division [Internet]. (2015) [cited 2018 Jul 25]. Available from: http://www.fao.org/faostat/en/#search/Faostat%2C Food and agriculture organization of the United Nations Statistics Division

4. ITC, List of supplying markets for a product imported by country. TRADE MAP - International Trade Statistics [Internet]. (2016) [cited 2016 Jul 22]. Available from: http://www.trademap.org/tradestat/Country_SelProductCountry_TS.aspx

5. Proskurina S, Junginger M, Heinimö J, Tekinel B, and Vakkilainen E, Global biomass trade for energy- Part 2: Production and trade streams of wood pellets, liquid biofuels, charcoal, industrial roundwood and emerging energy biomass. Biofuels, Bioproducts and Biorefining (2018).

6. FAO, The charcoal transition: greening the charcoal value chain to mitigate climate change and improve local livelihoods. (2017).

7. Huitink CL, Burning Nigerian forests on European barbecues. A carbon footprint and cost comparison between imported Nigerian charcoal and sustainably produced charcoal in the European Union [Internet]. (2018). Available from: https://dspace.library.uu.nl/handle/1874/365907

8. European commission, Trade, Anti-damping [Internet]. (2014) [cited 2018 Jul 25]. Available from: http://ec.europa.eu/trade/policy/accessing-markets/trade-defence/actions-against-imports-into-the-eu/anti-dumping/

9. OECD, OECD-FAO agricultural outlook 2015–2024 [Internet]. (2016) [cited 2016 Dec 8]. Available from: https://stats.oecd.org/Index.aspx?DataSetCode=HIGH_AGLINK_2015

10. RFA, Fueling a high octane future. (2016).

11. AgMRC, An Overview of the Biodiesel Market: Production, Imports, Feedstocks and Profitability. Agricultural Marketing Resource Center. [Internet]. (2017) [cited 2017 Feb 18]. Available from: http://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/

12. USDA, EU Biofuels Annual 2016 [Internet]. (2016). Available from: https://gain.fas.usda.gov/Recent GAIN Publications/Biofuels Annual_The Hague_EU-28_6-29-2016.pdf

13. EIA, total energy, Fuel ethanol overview [Internet]. (2016) [cited 2017 Jan 8]. Available from: http://www.eia.gov/totalenergy/data/browser/?tbl=T10.03#/?f=A&start=1981&end=2015&charted=7-18

14. Scarlat N, Dallemand JF, and Fahl F, Biogas: Developments and perspectives in Europe. Renewable Energy. (2018).

15. EBA, EBA Statistical Report 2017. European biogas association [Internet]. Available from: http://european-biogas.eu/2017/12/14/eba-statistical-report-2017-published-soon/

16. Kovacs A, Discussion Paper #2. Working Group on Biomethane Trade. In: GreenGasGrids Project [Internet] (2013). Available from: http://www.greengasgrids.eu/fileadmin/greengas/media/Downloads/Documentation_from_the_GreenGasGrids_project/GGG_discussion_paper_Trade_2013.pdf

17. Thrän UFZ D, Billig Tobias Persson E, Svensson M, Daniel-Gromke J, Ponitka J, Seiffert John Baldwin M, et al., Biomethane-status and factors affecting market development and trade. (2014).

18. ERGaR, PRESS RELEASE-The European Renewable Gas Registry submitted application to EC [Internet]. (2017). Available from: www.ergar.org

19. Junginger, M., Järvinen, M., Olsson, O., Hennig, C., Dadhich P, Transboundary flows of woody biomass waste streams in Europe [Internet]. (2019). Available from: http://task40.ieabioenergy.com/wp-content/uploads/2019/01/IEA-Bioenergy-2019.-Wood-waste-trade-study-FINAL.pdf

20. Fråne A, Youhanan L, Ekvall T, and Jensen C, Avfallsimport och materialåtervinning [Internet]. (2266). Available from: www.ivl.se

21. Hillring, B., Canals, G. and Olsson O, Market for recovered wood in Europe–an overview. *Manag Recover wood Univ Stud Press Thessaloniki* : 201–13 (2007).

22. Swedish Energy Agency, Wood Fuel and Peat Prices, per Quarter Excl Taxes, from 1993, SEK/MWh, Current Prices. [Internet]. (2018). Available from: http://pxexternal.energimyndigheten.se/pxweb/en/Trädbränsle- och torvpriser/Trädbränsle- och torvpriser/EN0307_1.px/table/tableViewLayout2/?rxid=60be56aa-047e-4e6a-8760-2bf0be1d332a.

23. IEA Task 40 - Wild M, Deutmeyer M, Bradley D, Hektor B, Hess JR NL et al., Possible Effects of Torrefaction on Biomass Trade. (2015). Available from: http://task40.ieabioenergy.com/wp-content/uploads/2013/09/t40-torrefaction-2016.pdf

24. Miltner A, Wukovits W, Pröll T, and Friedl A, Renewable hydrogen production: A technical evaluation based on process simulation. *J Clean Prod Sustain Hydrog from Biomass* [Internet] **18**: S51–S62 (2010). Available from: https://doi.org/10.1016/j.jclepro.2010.05.024

25. KIT, Biomass based energy intermediates bossting biofuel production - A European Research project on renewable energies. (2014).

26. USDoE, STRATEGIC PLAN FOR A THRIVING AND SUSTAINABLE BIOECONOMY. (2016).

27. USDoE, Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks [Internet]. (2016). Available from: http://energy.gov/eere/bioenergy/2016-billion-ton-report

28. Alakangas, E., Hurskanen, M., Laatikainen-Luntama, J., Korhonen J, Properties of indigenous fuels in Finland. *VTT Technol* **272** (2016).

29. Ranta, T., Korpinen O-J. AM, Improvement of forest chip quality and supply chain performance by means of a continuous quality measurement system. In: 26th European Biomass Conference and Exhibition [Internet] Copenhagen, Denmark; (2018). Available from: http://dx.doi.org/10.5071/26thEUBCE2018-1AO.7.1

30. Bioenergy Europe, Statistical Report - European Biomass Outlook. (2017).

31. Mai-Moulin T, Armstrong S, van Dam J, and Junginger M, Toward a harmonization of national sustainability requirements and criteria for solid biomass. *Biofuels, Bioprod Biorefining* (2017).

32. IPCC, Global warming of 1.5oC [Internet]. (2018). Available from: https://www.ipcc.ch/sr15/

33. IEA, World Energy Outlook 2017 [Internet]. (2017). Available from: https://www.iea.org/weo2017/

34. EC, Sustainable and optimal use of biomass for energy in the EU beyond 2020. (2017).

35. Poudyal NC, Butler BJ, and Hodges DG, Spatial analysis of family forest landownership in the southern United States. *Landsc Urban Plan* [Internet] -**October**: 1–8 (2018). Available from: https://doi.org/10.1016/j.landurbplan.2018.10.018

36. Sutor, C., Schaubach, K., Horschig, T., Thrän D, Don`t hate the player, change the rules: Stakeholder Perceptions and Influence in the German Biogas Sector. (2018).

37. Kulisic, B., Thiffault, E., Lakhdhar, I., Bouthillier, L., White, B. Krolik C, Uncharted territories: Expectations towards bioenergy in Canada, a case study in La Tuque (QC). (2019).

38. Mai-Moulin T et al., (under review) Positions, perception and vision of stakeholders towards bioenergy. : 1–39 (2019).

39. IEA, Technology Roadmap: Delivering Sustainable Bioenergy. In Paris, France: International energy Agency; (2017).

40. EC, Directive on the promotion of electricity produced from renewable energy sources in the internal electricity market. (2001).

41. EC, Directive on the promotion of the use of biofuels or other renewable fuels for transport. (2003).

42. EC, Directive on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. (2009).

43. Parliament E, and Union C of the E, (RED) 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). **2018-November** (2018).

44. EC, Innovating for A Bioeconomy for Europe Sustainable Growth – A Bioeconomy for Europe. (2012).

45. Olsson et al., Time to tear down the pyramids? A critique of cascading hierarchies as a policy tool. *WIREs Energy Environ* **7**-**2** (2018).

46. JRC, JRC Science for Policy Report Bioeconomy. (2016).

47. GBE, The global bioenergy partnership sustainability indicators for bioenergy. (2011).

48. Schlesinger W, Are wood pellets a green fuel? *Science (80-)* **359**: 1328–9 (2018).

49. EASAC, Commentary by the European Academies' Science Advisory Council (EASAC) on Forest Bioenergy and Carbon Neutrality [Internet]. (2018). Available from: https://easac.eu/fileadmin/PDF_s/reports_statements/Carbon_Neutrality/EASAC_commentary

_on_Carbon_Neutrality_15_June_2018.pdf

50. Böttcher H, Study on Impacts on Resource Efficiency of Future EU Demand for Bioenergy Task 4: Resource efficiency implications of the scenarios [Internet]. (2016). Available from: http://ec.europa.eu/environment/enveco/resource_efficiency/pdf/bioenergy/Task 4.pdf

51. Chen, Xiaoguang & Önal H, Renewable energy policies and competition for biomass: Implications for land use, food prices, and processing industry. *Energy Policy* **92**: 270–8 (2016).

52. Fritsche UR et al., Energy and land. [Internet]. (2017). Available from: https://global-land-outlook.squarespace.com/s/Fritsche-et-al-2017-Energy-and-Land-Use-GLO-paper-corr.pdf

53. Fritsche UR, Sustainability of Bioenergy - State of the art. In: Lago, Carmen; Caldes, Natalia & Lechon Y, editor. The Role of Bioenergy in the Emerging Bioeconomy - Resources, Technologies, Sustainability and Policy Academic Press. ; p. 225–41(2019).

54. UN, Sustainable Development Goals [Internet]. (2015). Available from: https://sustainabledevelopment.un.org/?menu=1300

55. Fritsche U et al., Linkages between the Sustainable Development Goals (SDGs) and the GBEP Sustainability Indicators for Bioenergy (GSI) [Internet]. (2018). Available from: http://www.globalbioenergy.org/events1/events-

56. Griggs D et al. -eds., A Guide to SDG Interactions: from Science to Implementation. [Internet]. Paris; (2017). Available from: http://www.icsu.org/cms/2017/05/SDGs-Guide-to-Interactions.pdf

57. Nilsson G, Allison EH, William WL, Dey MM, Halpern S, Mccauley DJ, et al., SDG interactions, Nilsson, Griggs. (2016).

58. Pradhan P, Costa L, Rybski D, Lucht W, and Kropp JP, A Systematic Study of Sustainable Development Goal (SDG) Interactions. *Earth's Futur* (2017).

59. Kline K et al., Reconciling food security and bioenergy: priorities for action. *GCB Bioenergy* **9**: 557–76 (2017).

60. GBEP & IEA Bioenergy, Examples of Positive Bioenergy and Water Relationships. *Glob Bioenergy Partnersh* [Internet] -**March**: 21–4 (2016). Available from: file:///C:/Users/Premkumar/Downloads/AG6_Examples_of_Positive_Bioenergy_and_Water_Relationships_Final.pdf

61. Bonsch M et al., Trade-offs between land and water requirements for large-scale bioenergy production. *GCB Bioenergy* **8**: 11–24 (2016).

62. Aguilar, Alfredo; Wohlgemuth, Roland & Twardowski T, Perspectives on bioeconomy. *New Biotechnol* **40**: 181–4 (2018).

63. El-Chichakli B et al., Policy: Five cornerstones of a global bioeconomy. *Nat* **535-7611**: 221–3 (2016).

64. Lamers P, Mai-Moulin T, and Junginger M, Challenges and Opportunities for International Trade in Forest Biomass [Internet]. Mobilisation of Forest Bioenergy in the Boreal and Temperate Biomes: Challenges, Opportunities and Case Studies. Elsevier Inc.; 127-164 p.(2016). Available from: http://dx.doi.org/10.1016/B978-0-12-804514-5/00008-1

65. GBEP & IEA Bioenergy, Clean Energy for Sustainable Development. *Clean Energy Sustain Dev* [Internet] : 3–27 (2017). Available from:

http://www.sciencedirect.com/science/article/pii/B9780128054239000016

66. ROGELJ J, SHINDELL D, JIANG K, FIFITA S, FORSTER P, GINZBURG V, et al., Mitigation pathways compatible with 1.5°C in the context of sustainable development. In: Global Warming of 15°C Geneva, Switzerland: Intergovernmental Panel on Climate Change; (2018).

67. CLARKE L, JIANG K, AKIMOTO K, BABIKER MGB, FISHER-VANDEN K, HOURCADE JC, et al., Assessing Transformation Pathways. In: EDENHOFER O, PICHS-MADRUGA R, SOKONA Y, FARAHANI E, KADNER S, SEYBOTH K, et al., editors. Climate change 2014: Mitigation of Climate Change Contribution of Working Group III to the Fifth assessment Report of the Intergovernmental Panel on Climate Change Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.; (2014).

68. HUPPMANN D, KRIEGLER E, KREY V, RIAHI K, ROGELJ J, ROSE S, et al., IAMC 1.5°C Scenario Explorer and Data hosted by IIASA. In Laxenburg, Austria: IIASA & IAMC; (2018).

69. HUPPMANN D, ROGELJ J, KRIEGLER E, KREY V, and RIAHI KJNCC, A new scenario resource for integrated 1.5° C research. **1** (2018).

70. BAUER N, ROSE S, FUJIMORI S, VAN VUUREN D, WEYANT J, WISE M, et al., Global energy sector emission reductions and bio-energy use: overview of the EMF-33 model comparison. *Clim Change* (2018).

71. Daioglou V, Doelman JC, Wicke B, Faaij A, and Van Vuuren DP, Integrated assessment of biomass supply and demand in climate change mitigation scenarios. (2019). Available from: https://doi.org/10.1016/j.gloenvcha.2018.11.012

72. HARPER AB, POWELL T, COX PM, HOUSE J, HUNTINGFORD C, LENTON TM, et al., Land-use emissions play a critical role in land-based mitigation for Paris climate targets. **9**-**2938** (2018).

73. VAN VUUREN DP, STEHFEST E, GERNAAT DEHJ, VAN DEN BERG M, BIJL DL, DE BOER HS, et al., Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. *Nat Clim Chang* (2018).

74. GRUBLER A, WILSON C, BENTO N, BOZA-KISS B, KREY V, MCCOLLUM DL, et al., A low energy demand scenario for meeting the 1.5° C target and sustainable development goals without negative emission technologies. **3**-**515** (2018).

75. DAIOGLOU V, MURATORI M, LAMERS P, FUJIMORI S, KITOUS A, BAUER N, et al., forthcoming-a. Implications of climate change mitigation scenarios on international bioenergy trade. *Clim Chang*.

76. IEA, The Future of Petrochemicals. In Paris, France: International Energy Agency; (2018).

77. MATZENBERGER J, KRANZL L, TROMBORG E, JUNGINGER M, DAIOGLOU V, SHENG GOH C, et al., Future perspectives of international bioenergy trade. *Renew Sustain Energy Rev* **43**: 926–41 (2015).

78. Daioglou, V., Doelman, J.C., Stehfest, E., Müller, ., Wicke,B., Faaij, A., van Vuuren D., Greenhouse gas emission curves for advanced biofuel supply chains. *Nat Clim Chang* **7**: 920–4 (2017).

79. SEARCHINGER TD, ESTES L, THORNTON PK, BERINGER T, NOTENBAERT A, RUBENSTEIN D, et al., High carbon and biodiversity costs from converting Africa’s wet savannahs to cropland. *Nat Clim Chang* **5**: 481–6 (2015).

80. HASEGAWA T, FUJIMORI S, HAVLÍK P, VALIN H, BODIRSKY BL, DOELMAN JC, et al., Risk of increased food insecurity under stringent global climate change mitigation policy. **8-699** (2018).

81. POPP A, HUMPENÖDER F, WEINDL I, BODIRSKY BL, BONSCH M, LOTZE-CAMPEN H, et al., Land-use protection for climate change mitigation. *Nat Clim Chang* **4**: 1095–8 (2014).

82. OTTO SAC, GERNAAT DEHJ, ISAAC M, LUCAS PL, VAN SLUISVELD MAE, VAN DEN BERG M, et al., Impact of fragmented emission reduction regimes on the energy market and on CO2 emissions related to land use: A case study with China and the European Union as first movers. *Technol Forecast Soc Change* **90**: 220–9 (2015).