ADVANCEFUEL

Sustainability criteria and certification for lignocellulosic biorefinery systems: Harmonisation possibilities and trade-offs

D4.2

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ADVANCEFUEL at a glance

ADVANCEFUEL (www.ADVANCEFUEL.eu) aims to facilitate the commercialisation of renewable transport fuels by providing market stakeholders with new knowledge, tools, standards and recommendations to help remove barriers to their uptake. The project will look into liquid advanced biofuels – defined as liquid fuels produced from lignocellulosic feedstocks from agriculture, forestry and waste – and liquid renewable alternative fuels produced from renewable hydrogen and CO_2 streams.

In order to support commercial development of these fuels, the project develops a framework to monitor the current status, and future perspectives, of renewable fuels in Europe in order to better understand how to overcome barriers to their market roll-out. Following this, it investigates individual barriers and advanced new solutions for overcoming them.

The project will examine the challenges of biomass availability for advanced biofuels, looking at non-food crops and residues, and how to improve supply chains from feedstock providers to conversion. New and innovative conversion technologies will also be explored in order to see how they can be integrated into the energy infrastructure.

Sustainability is key to ensure the market uptake of renewable fuels. And ADVANCEFUEL looks at socio-economic and environmental sustainability across the entire value chains. Ultimately, ADVANCEFUEL aims at providing sustainability criteria and policy-recommendations to ensure that renewable fuels are truly sustainable fuels. A decision support tools will be created for policy-makers to enable a full value chain assessment of renewable fuels, as well as useful scenarios and sensitivity analysis on the future of these fuels.

Stakeholders will be addressed throughout the project to involve them in a dialogue on the future of renewable fuels and receive feedback on ADVANCEFUEL developments to ensure applicability to the end audience, validate results and ensure successful transfer and uptake of the project results. In this way, ADVANCEFUEL will contribute to the development of new transport fuel value chains that can contribute to the achievement of the EU's renewable energy targets, and reduce carbon emissions in the transport sector to 2030 and beyond.

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Executive Summary

Sustainability criteria and proof of compliance by certification have become important tools to address concerns and safeguard the sustainability of bioenergy along the supply chain (feedstock production, logistics, conversion and end use) (Scarlat, Nicolae and Dallemand, 2011). The revised Renewable Energy Directive (RED II) aims to improve sustainability. The coverage of binding sustainability criteria is extended to all bioenergy sectors and covers biofuels, solid biomass and biogas used for electricity and heating, and it adds new criteria to forest and agriculture biomass. Although the RED II is a major step forward critical issues still remain in the context of mitigating barriers to the commercialisation of advanced biofuels.

This report investigates the development of lignocellulosic biorefineries, which serve as production facilities to process biomass feedstocks into multifunctional bio-based products of the bioeconomy including renewable transport fuels, heat, electricity and bio-based materials. Lignocellulosic biorefineries are expected to play an important role in reducing significant GHG emissions of various products as well as contributing to the European climate and renewable targets. However, lignocellulosic biorefineries need to comply with sustainability criteria defined in the RED II, for example if their electricity or heat generation capacity goes beyond the defined thresholds or if biofuels are produced. And, although biofuels sustainability criteria are harmonised at the EU level, EU member states are allowed to implement additional and more strict criteria to heat and electricity from biomass. Furthermore, bio-based materials are exempted from binding sustainability criteria at the EU level. To this purpose, this deliverable identifies possible concerns of the RED II linked to sustainability performance of lignocellulosic biorefineries and the bioenergy sector and it identifies harmonisation possibilities and trade-offs to demonstrate the sustainability compliance of multi-output biorefineries.

The results of this deliverable show that the EU wide environmental sustainability criteria are binding for bioenergy while sustainability performance which covers environmental, social and economic aspects is voluntary for lignocellulosic biorefineries. Since the sustainability performance is voluntary for lignocellulosic biorefineries, using various sustainability initiatives and voluntary schemes to demonstrate sustainability performance creates complexities of using diverging standards and ultimately may lead to higher costs and time requirements in regard to performing sustainability compliance.

The results also show some harmonisation possibilities for some sustainability aspects while other sustainability issues need to consider certain trade-offs. Harmonisation is possible for a number of sustainability criteria and requirements: protection of high biodiversity; landuse, landuse change and forestry; sustainable forest management; risk-based approach; chain of custody and most elements of social and economic criteria. These sustainability criteria are commonly used by the bioenergy sector and they are relevant for lignocellulosic biorefineries as well. Other sustainability criteria which cannot be harmonised but important to be kept separately: chemical and toxicity which is more relevant for lignocellulosic biorefineries but not for bioenergy; ILUC is only relevant for bioenergy production but less appropriate for lignocellulosic biorefineries which process feedstocks of no competition with food.

Two sets of sustainability criteria which are not yet possible to be harmonised but important to be considered for a future harmonisation. One of the criteria is the reduction of GHG emissions which are used for all the bioeconomy sectors. Calculation methods of GHG emissions and emission allocation are not yet aligned between the bioenergy sector and lignocellulosic biorefineries. Discussion on the methods used to calculate GHG emissions of various value chains needs to be carried out and more guidance for involved actors is also required so that appropriate calculations can be agreed upon. The other criteria, which should also be considered for the whole bioeconomy sector is the protection of air, soil and water. Although environmental impacts are different from one sourcing region to the others, more detailed guidance for imported lignocellulosic feedstocks or for regions which do not have stringent environmental laws are of importance. Given the situation, there will likely be a need for a harmonised sustainability framework to guide the bioeconomy sectors to demonstrate sustainability performance.

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Abbreviations

CAP	Common Agriculture Policy
CoC	Chain of Custody
EC	European Commission
EU	European Union
FSC	Forest Stewardship Council
GHG	Greenhouse gas emissions
GRI	Global Reporting Initiative
GWP	Global warming potential
iLUC	Indirect Land Use Change
ILO	International Labour Organisation
ISCC	International Sustainability & Carbon Certification
MSs	Member States
PEFC	Programme for the Endorsement of Forest Certification
RED II	Revised Renewable Energy Directive
RO	The UK Renewable Obligation
RSB	Roundtable of Sustainable Biofuels
SDE+	Stimulering Duurzame Energieproductie (The Dutch Promotion of Sustainable Energy Production)
SFM	Sustainable Forest Management

1. Introduction

The overarching goal of the Horizon 2020-funded EU project ADVANCEFUEL is to facilitate the market rollout of advanced liquid biofuels and other liquid renewable fuels (further jointly addressed as "RESfuels") between 2020 and 2030. The project will provide market stakeholders with new knowledge, tools, standards and recommendations to remove the most prominent barriers and detect development opportunities for their commercialisation.

Sustainability criteria and proof of compliance by certification have become important tools to address concerns and safeguard the sustainability of bioenergy along the supply chain (feedstock production, logistics, conversion and end use) (Scarlat and Dallemand, 2011). The development of certification systems by various stakeholders has been stimulated in particular for liquid biofuels used in the European Union (EU) as a result of mandatory sustainability criteria set by the Renewable Energy Directive (RED I) (EC, 2009). Electricity and heat were exempted from binding criteria at the EU level which led to the development of diverging national sustainability schemes in member states that imposed sustainability criteria at the national level for these bioenergy sectors. The lack of harmonised criteria between different bioenergy sectors was identified as a prominent barrier to the market rollout of advanced biofuels (Uslu, Detz and Mozaffarian, 2018), a barrier to biomass trade and a risk to the EU internal market(EC, 2016b). Furthermore, lack of harmonised regulations on sustainable forest management and sustainable farming practices, particularly regarding the residues (i.e. removal of straw), are seen as barriers to advanced biofuel feedstock supply (Uslu, Detz and Mozaffarian, 2018).

The revised Renewable Energy Directive (RED II) (European Parliament and Council, 2018a) aims to address the abovementioned issues. The coverage is extended to all bioenergy sectors and covers biofuels and solid biomass and biogas used for electricity and heating and it adds new criteria to forest and agriculture biomass. It also stimulates the production of advanced biofuels by restricting crop-based biofuels and by introducing a sub-target for advanced biofuels produced from listed feedstock types (Annex IX part A of the RED II). Although the RED II is a major step forward in the context of mitigating barriers to the commercialisation of advanced biofuels, critical issues remain.

- Firstly, EU member states cannot set additional or stricter sustainability criteria to biofuels, but they can set additional criteria for biomass used in electricity and heat. Current bioenergy markets have so far developed in relative isolation with limited interaction (Junginger *et al.*, 2019). Advanced biofuels produced from lignocellulosic biomass are different, however, from conventional biofuels. Next to traditional fibre sectors (for example pulp, timber) they share feedstock markets with heat and electricity from solid biomass that could be subject to national diverging criteria.

- Secondly, the conversion of lignocellulosic biomass to advanced biofuels used in road transport, marine and aviation is often most efficient in multi-output biorefineries that produce, next to biofuels, also electricity and heat or integrated biorefineries that combine the production of bio-based materials and bioenergy in an integrated manner (de Jong *et al.*, 2012). Bio-based materials are not part of the renewable energy targets and sustainability criteria set in the RED II, but could be subject to standards, national criteria or industry requirements that are not aligned with bioenergy markets.
- Thirdly, international shipping and aviation sectors are becoming increasingly relevant markets for advanced biofuels because of their lack of feasible alternatives to mitigate GHG emissions. Poor harmonisation of sustainability criteria at the global level hampers the development of these markets.

To this purpose, this report aims to assess actions aiming at harmonisation of national standards, certification schemes and sustainability initiatives for all types of products. These products are derived from lignocellulosic biomass (including fuels) located in the EU. Other liquid renewable fuels that do not use a feedstockof biological origin, such as power-to-liquids, are not covered in this report. . The research is part of ADVANCEFUEL WP4 that aims to assess the current and future sustainable production of RESfuels and test their performance against sustainability criteria, as laid down in certification schemes and standards to safeguard and stimulate sustainable production of RESfuels. To meet this objective, WP4 has been organised in 4 tasks, with Tasks 4.1 and 4.2 focusing on sustainability criteria and certification and Tasks 4.3 and 4.4 focusing on quantifying potential sustainability impacts of advanced biofuel supply chains (Figure 1). This report presents the results of Task 4.2.

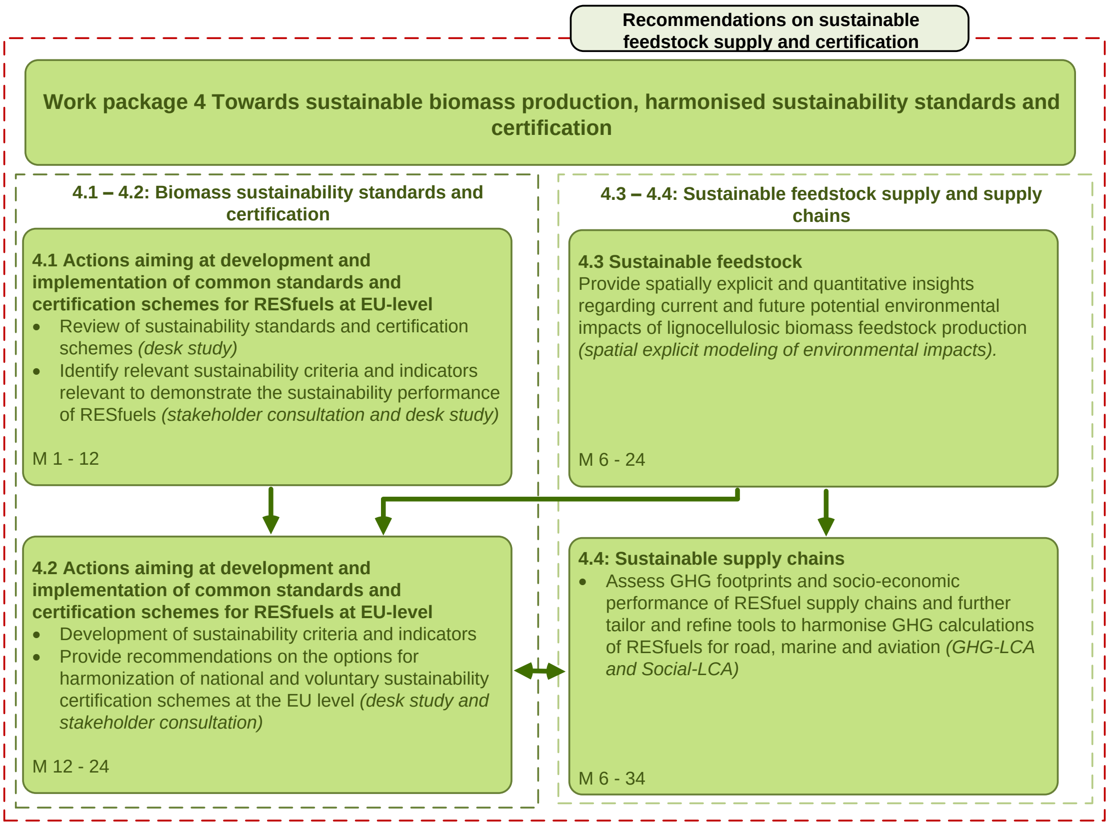

Figure 1. Overview of ADVANCEFUEL Work Package 4

The report consists of six chapters. Chapter two describes the role of multiproduct biorefineries in the European Union (EU) as well as the development lignocellulosic biorefineries given the implementation of new EU policies including the revised Renewable Energy Directive (RED II) and European Bioeconomy Strategy. Chapter two also convers an outlook of lignocellulosic biorefineries development until 2030. Chapter three discusses sustainability of various sectors of the bioeconomy, pending challenges and the objectives of this report. Chapter four provides an assessment of possible sustainability concerns of the RED II implementation for lignocellulosic biorefinery. It also discusses sustainability performance of the bioenergy sector and lignocellulosic biorefineries. Chapter five shows an investigation of sustainability performance of bioeconomy sectors. Chapter six discusses harmonisation possibilities for the bioenergy sector as well as other possible trade-offs. Chapter seven presents discussion on prevailing points from the results conclusions based on the review and assessment of the study.

2. Lignocellulosic biorefineries

2.1 Definition of biorefineries

The bioeconomy covers various sectors encompassing production of renewable biological resources and conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy. Bioeconomy includes sectors such as agriculture, forestry, fisheries, food, pulp and paper production, plastics, as well as parts of chemical, biotechnological and energy industries (EC, 2018). Bioeconomy strategies are thus established to unlock the productive potential of those biological resources through innovation (Meyer, 2017).

Biorefining is often identified as a key technology for successful bioeconomy deployment (Hess, 2016). Biorefineries enable the transformation of biomass into a wide spectrum of marketable food and feed ingredients, bio-based products (chemicals, materials) and bioenergy (biofuels, power and heat) (IEA Bioenergy Task 42, 2014). Biorefineries are also envisioned as a possibility for more efficient conversion of biomass into valuable products, thus providing substitutes for fossil-based products and energy within the current infrastructure. Non-food biomass and organic waste should be preferred as raw materials in order to avoid competition with the food supply (Meyer, 2017). Sustainable resource use is a main driver for implementation of biorefineries.

A lignocellulosic biorefinery is based on the utilization of dry biomass, woody energy crops used by modern-day fiber-line and pulping industries as well as various waste for the production of bio-based fuels and chemicals via thermochemical conversion (Konwar L. et al., 2018). Lignocellulosic biorefineries are therefore considered to improve resource efficiency and close material cycles, novel technological, organisational and product solutions are required including integrated biorefinery concepts (Gawel, Pannicke and Hagemann, 2019).

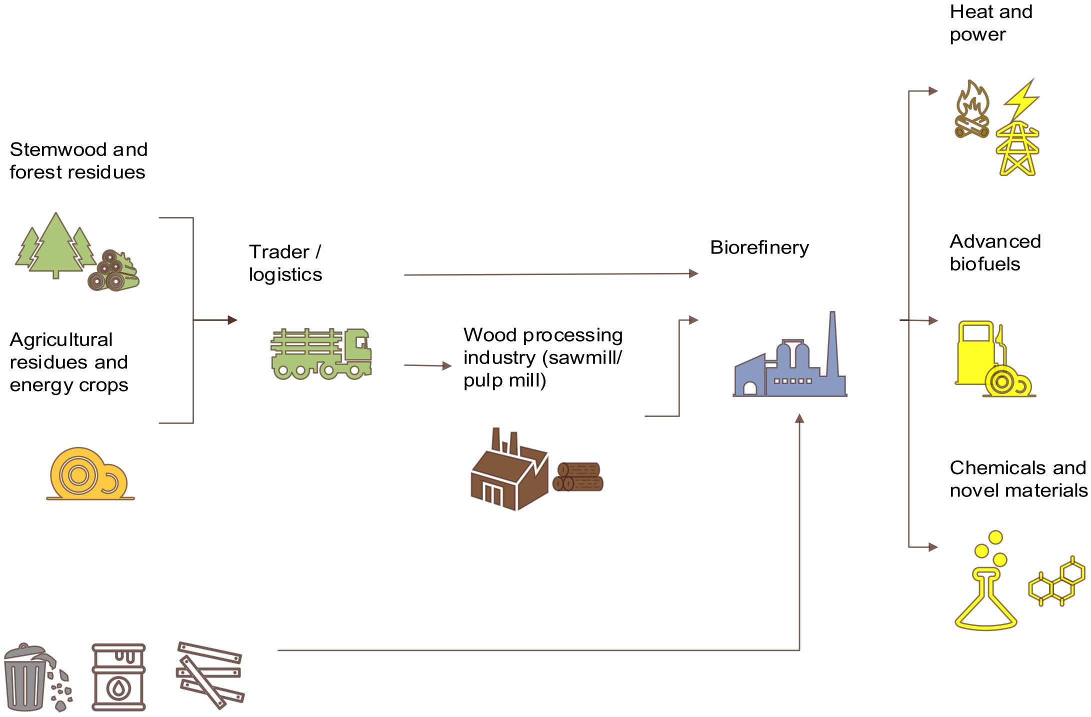

Figure 2. Visualisation of biorefinery supply chain

2.2 Current biorefineries in the EU

The current bio-based industry and biorefinery capacity in the EU is recently mapped by JRC and includes facilities that produce bio-based chemicals, liquid biofuels and bio-based composites and fibres. In total, 803 biorefineries were identified in by JRC (Parisi, 2018). Most biorefineries are located nearby chemical clusters and ports and produce chemicals (507) followed by liquid biofuels (363) and bio-based composites and fibres (141). The number of facilities should not be confused with production capacities. Liquid biofuel production volumes are substantially larger still and produced in larger plants compared to bio-based chemicals and bio-based composites and fibres Most biorefineries in the EU use agriculture biomass, apart from Scandinavian countries where forest biomass is the main feedstock (Figure 4). It is not possible to identify advanced biorefineries from the available data.

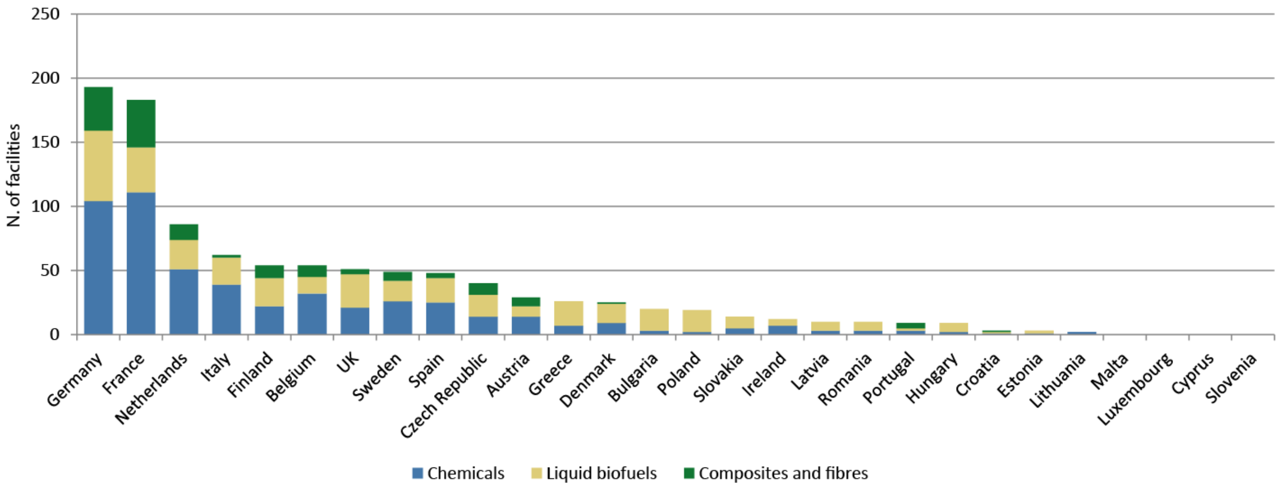

Figure 3. Distribution of biorefineries in the EU per type of output (Parisi, 2018)

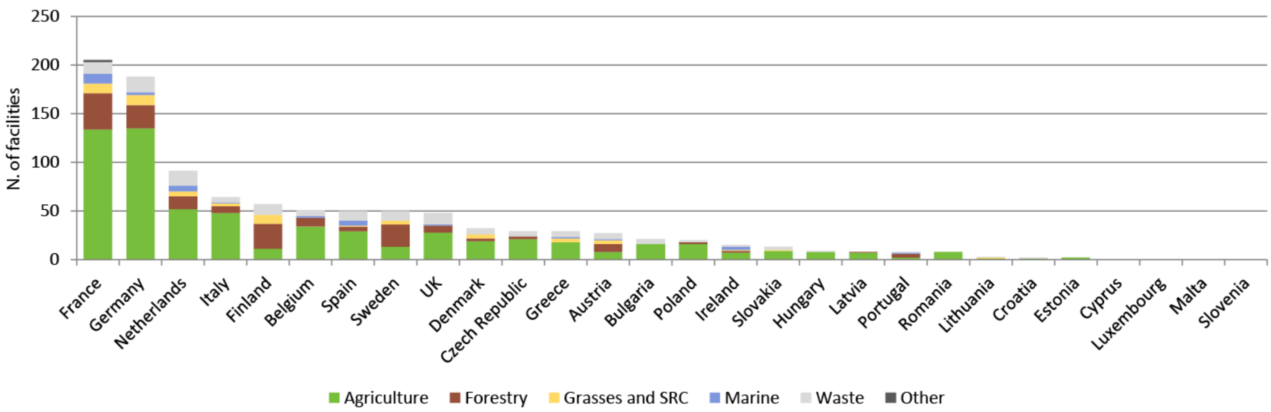

Figure 4. Distribution of biorefineries in the EU per type of feedstock (Parisi, 2018)

2.1 Outlook of lignocellulosic biorefineries

In the bioeconomy, agricultural biomass has been widely used and most feedstocks and their current applications are still "non-lignocellulosic"(JRC, BBI JU and IEA Bioenergy, 2018) such as vegetable oils, sugar and starch crops, animal fats, and used cooking oil. In the European Union (EU), lignocellulosic biomass has been mainly used in traditional sectors such pulp and paper, wood processing, pulp and paper, as well as heating in residential buildings and for industrial purposes. Since the launch of the European Bioeconomy strategies in 2012, the European bio-economy has developed swiftly and its turnover has reached 2.29 trillion Euro in 2015 (Piotrowski, Carus and Carrez, 2016). The bioeconomy development benefits from various European policies which aim to reduce climate change impacts, stimulate sustainable energy and promote resource efficiency (EC, 2016a), (EC, 2018), (European Parliament and Council, 2018a). Thus, lignocellulosic biomass has potentials to grow further and expand in new markets.

Development of the European bioeconomy requires mobilisation of domestic biomass feedstocks in a sustainable and resource efficient manner and the transition to advanced conversion technologies and lignocellulosic feedstocks (S2Biom, 2016). However, the bio-based value chains and products are not per se sustainable. Issues such as land use, deforestation, water use, emissions, health and energy demand are important for an overall assessment of sustainability (EC, 2019). Considering increasing pressure on our planet and nature, the bioeconomy and its involved stakeholders will have to prioritise use of finite bio-based resources to uses that delivers the best environmental and economic benefits.

Lignocellulosic biomass, such as wood, straw, agricultural residues, is a crucial feedstock for energy and fuels and, in the long run, for biobased products and materials. It is widely available and well suited to a range of conversion routes and applications (S2Biom, 2016). Lignocellulosic biorefineries refine lignocellulosic biomass into intermediate outputs including cellulose, hemicellulose, lignin which are then processed into a spectrum of products. Lignocellulosic biomass is expected to become the future's most important source of biomass and be widely available at moderate costs showing less competition with food and feed production (de Jong and Jungmeier, 2015).

S2Biom model-based projections conclude that a total of 476 million dry tonnes of lignocellulosic biomass will be needed to fulfil expected demand for energy, fuels and biobased materials in the EU by 2030. Lignocellulosic biorefineries in Europe will provide significant potential for synergies and facilitate further mobilisation of lignocellulosic biomass by 2030.

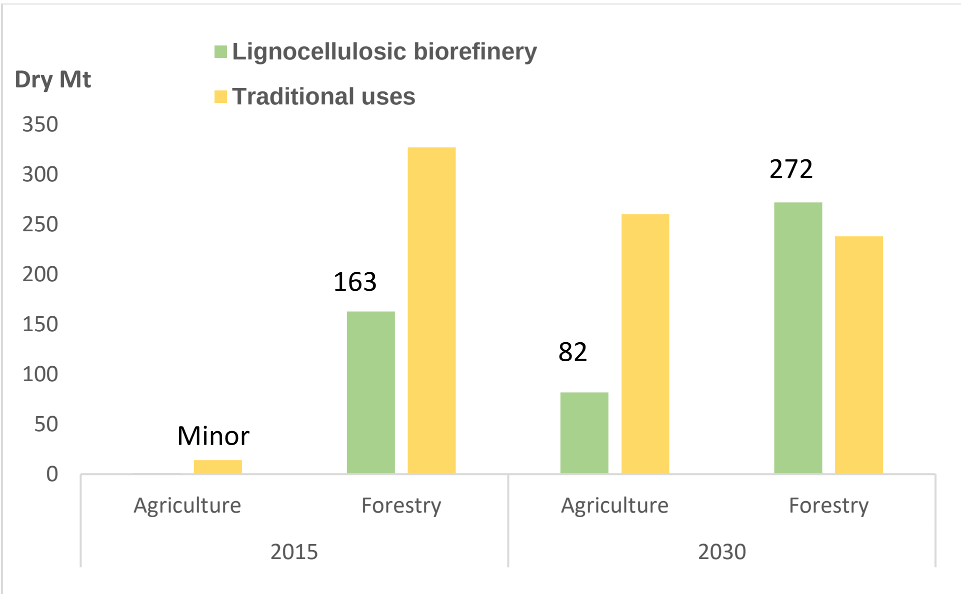

Figure 5. Sustainable feedstock mobilisation for lignocellulosic biorefineries from agricultural and forest sectors. Others are used for pulp, paper and traditional sectors (figure adopted from S2BIOM report data, (S2Biom, 2016))

The S2BIOM results indicate evidence that at least 1 billion tonnes of lignocellulosic biomass will exist in Europe on an annual basis across various supply sectors (agriculture, forestry, bio-wastes and dedicated perennial crops). Part of it is now exploited by respective industries but there are still numerous opportunities for improvements across all value chains. The recent S2Biom estimates for the 2030 base potential (which includes the sustainability criteria as stated within the Renewable Energy Directive I) amount to 1,093 million tonnes of dry lignocellulosic biomass per year. An outlook for the mobilisation of sustainable feedstocks for lignocellulosic biorefineries until 2030 is presented in Figure 3.

3. Sustainability of bioeconomy sectors and pending challenges

3.1 Sustainability performance

The bioeconomy needs to include sustainability and circularity in order to be successful (EC, 2018). In the EU, sustainability of the bioeconomy is considered not only a legal obligation, but also an opportunity for society and underpins most EU action priorities (EC, 2016a). Sustainability performance is important and sustainability certification is needed to implement targets in view of a sustainable development both from public to private sectors and to increase and preserve the general societal acceptance of the bioeconomy (Majer et al., 2018).

The sustainability performance of biorefineries is often assessed over its entire life-cycle by life cycle assessments (LCA). These assessments focus mainly on environmental issues such as GHG emission performance, soil organic carbon and water footprint (Schaidle J.A. et al., 2010), (Ahlgren S. et al., 2015), (Silva C.A.M et al., 2015). LCA can be carried out at an early stage of development to understand the potential environmental benefits, impacts and trade-offs whilst products are still in research and development (Broeren M. et al., 2017). LCA results thus can help process designers optimise new production processes towards a sustainable track. LCA can also be carried out as a full assessment for biorefineries which are commercially operational. The full assessment measures and compares the environmental performance of commercial products.

Lignocellulosic biorefineries generate multiple outputs that include for example bioenergy, feed, biochemicals and biomaterials. Furthermore, feedstock supply to a biorefinery is often part of an existing production system, for example straw produced during harvest of grains. All relevant emissions of inputs and outputs of a biorefinery supply chain should be accounted for. It is argued that emissions and removals of biogenic carbon from biomass used in the production of food, feed, biofuels heat and electricity, even if that biogenic carbon does not become part of the product, it should be accounted for (Ahlgren S. et al., 2015). It is also stated that if allocation is applied to deal with multiple outputs, it should consider other methods such as mass or economic value rather than energy content as is applied in the RED II (Karlsson, 2014), (Ahlgren S. et al., 2015).

The sustainability performance of operational biorefineries is regularly demonstrated in corporate sustainability reports where various environmental, economic and aspects are considered.

The sustainability performance was found in the reports of a number of lignocellulosic biorefineries including Borregaard (Borregaard, 2018), UMP (UPM Biofore-Beyond Fossils, 2018), Lenzing Group (Lenzing Group, 2018), (Rain Forest Alliance, 2017) and Metsa Fibre (Metsa Group, 2018). Sustainability performance of other corporates including NEOT (NEOT, 2018), Neste (Neste, 2018) and Eni (Eni, 2018). These corporates consisting of biorefineries involve approaches to assess sustainability compliance and measurements of sustainability indicators. They are considered relevant for lignocellulosic biorefineries, therefore they were also assessed in this study.

3.2 Challenges toward sustainability

The use of lignocellulosic biomass, derived from agricultural and forest residues up to industrial wastes, is considered more sustainable than the use of dedicated energy crops (Hassan, 2019). It is found that most of the short-term investments would likely consider lignocellulosic and forestry based value chains such as transitioning from first-generation to second-generation ethanol production and expanding second-generation technologies to chemical building blocks (Piotrowski, Carus and Carrez, 2016).

With the same lignocellulosic feedstocks used for the co-production of bioenergy, feed, biochemicals and biomaterials, the supply chains should be virtually similar and comparable (Silva C.A.M et al., 2015). Thus, sustainability criteria and indicators, which are used to demonstrate sustainability compliance, should be all considered for those products, as for the whole bioeconomy.

Sustainability criteria, which have been widely used for sustainability assessment of the bioenergy sector, can be considered for other bioeconomy sectors and the application of those criteria is considered most practical at the biorefinery scale (Diaz-Chávez, 2016). Sustainability assessment needs to be comprehensively accomplished not only at the harvesting stage but also on the process and delivery of products. Sustainability assessment for biorefineries can serve multiple purposes, but there is no consensus yet for a harmonized assessment framework. A common framework may help governments and industry to identify, evaluate performance, and support the development of a more sustainable bioeconomy (Diaz-Chávez, 2016). A comprehensive review of biorefineries-related key issues and recommendations in existing standards and guidelines is currently lacking. Harmonisation of sustainability requirements is considered needed for feedstocks regardless of end-uses (Mai-Moulin *et al.*, 2017).

New EU policies such as the RED II (European Parliament and Council, 2018a) will limit the share of conventional energy crops and are expected to accelerate the rate of lignocellulosic exploitation for advanced biofuels, heat and electricity. Another policy, the EU Updated Bioeconomy Strategy (EC, 2018) also aims strengthen and scale-up the bio-based sectors using lignocellulosic feedstocks as well as unlock investments and markets in those sectors. Bioenergy is so far the only sector where EU wide binding sustainability criteria are required. The RED II, which considers the new EU waste criteria (European Parliament and Council, 2018b), defines that bioenergy produced from waste and residues (other than agricultural, aquaculture, fisheries and forestry residues), is required to fulfil only the GHG emissions saving criteria. This means up-stream environmental impacts and emissions (cultivation, harvesting and transport to the processing points) are omitted.

Given the perspective that the RED II will be effective soon, there still exist sustainability challenges such as the difficulty to measure indirect land use change (ILUC), or exclusion of social and economic impacts which are considered important to guarantee sustainability compliance. In practice, certain social and economic criteria are already implemented in various voluntary schemes (Mai-Moulin, Hoefnagels and Junginger, 2019).

Given this current context, the first objective of this study is to investigate possible concerns of the RED II implementation with the sustainability demonstration of lignocellulosic biorefineries. The second objective is to investigate harmonisation possibilities and trade-offs of sustainability compliance for multiple outputs in lignocellulosic biorefineries. The study also aims to addresses sub-objectives:

- *Assess how bioenergy produced in lignocellulosic biorefineries may comply with the RED II sustainability criteria;*
- *Investigate sustainability performance of lignocellulosic biorefineries and how far they are subject to other/voluntary sustainability initiatives;*
- *Discuss the most relevant and harmonised sustainability criteria for biorefineries and bioenergy.*

4. Possible sustainability concerns of the RED II implementation

Sustainability compliance for bioenergy (as a possible product of biorefineries) has been established in the EU. Binding sustainability criteria have been defined and implemented for biofuels used in the transport sector since 2009 (European Parliament and Council, 2009). Sustainability for biofuels is demonstrated through voluntary schemes recognised by the EC which verify whether or not biofuels are sustainably produced and comply with the EU sustainability criteria. Sustainability of solid biomass used for heat and electricity generation is binding in some EU Member States including Belgium, the Netherlands and the United Kingdom; is voluntary in Denmark. It can be demonstrated by direct reporting from economic operators or sustainability certificates issued from voluntary schemes which are recognised by national authorities. The RED II establishes overarching and binding sustainability criteria which will be applied in the whole bioenergy sector by 2020 (European Parliament and Council, 2018a). Compliance with the EU wide binding sustainability criteria indicates that more biofuels, heat and electricity production need to be sustainably certified.

Sustainability performance

The RED II generally addresses sustainability concerns for bioenergy, however it does not include specific requirements for bioenergy produced from lignocellulosic biorefineries. The RED II covers sustainability criteria which are mostly encountered during early stages of feedstock harvesting, mobilisation and transportation: no agricultural biomass obtained from land with high biodiversity values, high carbon stock, peatland; risk minimization of using forest biomass derived from unsustainable production; compliance with landuse, landuse change and forestry requirement; avoidance of ILUC. Only GHG emissions saving criteria are included for the whole supply chains, also at the conversion stage.

In lignocellulosic biorefineries in the EU, sustainability performance for feedstock harvesting, mobilisation and transportation are all considered. Our review of existing biorefineries shows that social and economic criteria are also included in voluntary corporate sustainability reports, notably worker rights, local rights and international treaties, human health impacts and job creation. Feedstocks mobilised from agricultural crops and forestry within the EU already complies with Common Agricultural Policy (CAP) and forest management regulated at national level (EC, 2010). Sustainability criteria are more effective when included in these policies as they cover the whole forest and agriculture sectors within the EU rather than bioenergy exclusively. They do however not apply to biomass imported from third countries and are still subject to debate regarding sustainability concerns within the EU, for example on biodiversity criteria.. Unlike bioenergy sector, lignocellulosic biorefineries may need to deal with concerns at the conversion stage due to chemical uses for the production of feed, biomaterials and biochemicals as well as the impacts from those chemical uses to the environment. Pollution which may potentially lead to atmospheric acidification, water eutrophication, ozone depletion, freshwater acidification, and freshwater salinity is commonly assessed.

Coverage of the RED II: Total rated thermal input

The RED II establishes sustainability criteria for biofuels, bioliquids and biogas and biomass fuels. Bioenergy that fulfils sustainability compliance, contributes towards the EU target and renewable energy shares of MSs, is eligible for financial support. Sustainability compliance is required for installations producing electricity, heating and cooling or fuels with a total rated thermal input equal to or exceeding 20 MW in the case of solid biomass fuels; and with a total rated thermal input equal to or exceeding 2 MW in the case of gaseous biomass fuels. However, it is also indicated in the RED II that MSs may apply the sustainability criteria and requirement of emissions to installations with lower total rated thermal input. The sustainability and the GHG saving criteria apply irrespective of the geographical origin of the biomass.

Sustainability approaches for biorefineries are different. It is found that there are currently 43 lignocellulosic biorefineries in operation in the EU which produce multiple products including bioenergy, feed, biochemicals and or biomaterials (Hassan, 2019). This means main products may cover a variety of bioeconomy products rather than solely bioenergy. In the coming years new large-scale lignocellulosic biorefineries may be built with a high production capacity of lignocellulosic feedstock inputs (Biorefineria, 2018). This indicates a possible need of compliance with binding sustainability criteria defined in the RED II for large-scale lignocellulosic biorefineries have a production capacity higher than the equivalent total rated thermal input defined in the

RED II. Thus it is not clear how to apply a total rated thermal input in lignocellulosic biorefineries producing multiple output products and bioenergy.

GHG emissions

In the RED II, there are two methods to calculate GHG emissions of energy from 1) the production and use of transport fuels, biofuels and bioliquids biofuels, bioliquids and 2) from the production and use of biomass fuels. The methods to account GHG emissions for energy are binding in the whole EU, therefore harmonized at the EU level. There are various tools which have been developed to calculate GHG emissions for various types of bioenergy.

At the EU level, the Biograce tools were developed to calculate GHG emissions of biofuels, heat and electricity production to comply with the RED I (RED, 2009/28/EC) and the Fuel Quality Directive (FQD, 2009/30/EC) as well as national sustainability criteria. The Biograce tools are however no longer supported and unlikely to be updated or used in the future. At the national level, the UK Biofuels Carbon Calculator, and the UK Solid and Gaseous Biomass Carbon Calculator are developed with calculation approaches in compatibility with the RED II methodologies. They cover defined values provided by the Joint Research Centre (JRC) for different stages of the supply chains. The UK tools allow economic operators employ their own operation data to feed in the tools to estimate GHG emissions.

In all the tools and methods used for bioenergy, biogenic carbon emissions are not counted for. However they are considered for feedstocks used in biorefineries following Greenhouse Gas Protocol and GRI sustainability initiative. This indicates another obstacle to be overcome to calculate GHG emissions for bioeconomy sectors.

Multifunctionality and allocation

Similar to RED I, the RED II uses energy allocation to deal with multi-functionality. Exergy allocation is used when heat is co-generated to address for the temperature difference and 'quality' of the heat output. However biorefineries include a complexity of biorefining processes with various outputs with diverse functions that also include material uses. The RED II, as an energy directive, does not provide solutions to properly deal with multifunctionality of materials rather in lignocellulosic biorefineries.

Social and economic criteria are excluded in the RED II; however, they were assessed in corporate sustainability reports of lignocellulosic biorefineries. Table 1 compares sustainability demonstration for bioenergy following the RED II guidance as well as for lignocellulosic biorefineries. It shows that sustainability performance is not similar and inconsistent for all bioeconomy sectors although using the same feedstocks. To align the focused aspects of various bioeconomy sectors, topics were rearranged into sub-groups which reflect better similar sustainability focuses and which better indicate harmonisation possibilities in the subsequent section.

Table 1. RED II sustainability criteria for bioenergy and common sustainability performance of other bio-economy sectors

	Bioenergy sustainability criteria (as defined in the RED-II)	Common sustainability criteria for biochemicals & biomaterials (as encountered in corporate sustainability reporting)
ENVIRONMENTAL PERFORMANCE:		
Reduction of GHG emissions (Mitigation of climate change)	*- GHG emissions saving*	- Energy use - Air emissions - Potential climate impacts
Biodiversity and ecosystem conservation	*- Protection of high biodiversity*	- Water use & pollution - Chemicals use and toxicity - Feedstock sourcing
LUC measurements ***LULUCF requirement***	*- ILUC measurement* *- LULUCF & carbon stock preservation*	
Sustainable forest management	*- Risk minimization of sustainable forest management*	- Feedstock sourcing - Sustainable materials
Resource protection	*Monitoring of air, soil and water*	
Discharge and pollution	-	Chemicals use and toxicity
Risk based approach	*Risk based approach*	
Chain of custody	*Mass balance*	- Mass balance - Physical segregation
ECONOMIC PERFORMANCE:		
Resource efficiency	*Not available*	- Water consumption - Reuse, recycling of feedstock and materials
Job creation		Job creation
SOCIAL PERFORMANCE:		
- Worker rights		- Worker rights - Training & education
- Human health impacts		Human health impact
- Compliance with local law and international treaties	*Not available*	Compliance with local law & international treaties

5. Sustainability performance of lignocellulosic biorefineries

This section shows a voluntary sustainability performance of lignocellulosic biorefineries and their corporates. The sustainability performance was found in sustainability reports and demonstrated beyond the RED II's requirements. Not only environmental criteria were assessed, but also social and economic criteria were presented for lignocellulosic biorefineries. Various impacts occurred during the production, harvesting, mobilisation and conversion phases were assessed. In these reports, there was an prevailing emphasis on environmental evaluation of GHG emissions reduction, protection and efficient use of resources: water consumption, energy and chemical use, toxicity and resource efficiency.

Sustainability of operational biorefineries was performed through life cycle assessment and inclusion of other sustainability approaches. Global Reporting Initiative (GRI), widely used at a corporate level, covers topic-specific standards used to report information on an organization's material impacts related to environmental, social and economic aspects. CanopyStyle, Rainforest Alliance initiatives, used by corporates processing wood and wood based materials, aim to ensure sustainable forest product supply chains, reduce deforestation and improve innovative conservation of forest. Voluntary schemes were also used to certify and verify feedstocks and products of biorefineries. The schemes widely used include Forest Stewardship Council (FSC), Programme for the Endorsement of Forest Certification (PEFC), International Sustainability & Carbon Certification (ISCC) and Roundtable of Sustainable Biomaterials (RSB).

Sustainable sourcing was assessed by Canopy Style, Rain Forest Alliance and GRI initiatives but it was mainly conducted at corporate level. Sustainability verification by Canopy Style and Rain Forest Alliance was applied for a low risk of sourcing wood from ancient and endangered forests. In the EU, they were found to be used mainly for wood sourced from Central Europe. PEFC was used based on enforced national forestry laws, whereas FSC certification of forests is not widespread in those regions. ISO standards were also applied for fiber and dissolving wood pulp production sites in accordance with ISO 9001, ISO 14001, and OHSAS 18001 system certifications.

5.1 Production capacity

The RED II shows that whilst biofuels need to be sustainably certified to fulfill sustainability compliance, biomass fuels only need a sustainability demonstration for high production capacity plants, see chapter 4.

Currently in some MSs, requirements for production capacity, which might be considered by lignocellulosic biorefineries, vary. The UK legislation requires operators of generating plants using bioliquids, and operators of generating stations with a total installed capacity ≥1MW using solid biomass and biogas, to report against, and meet, the sustainability criteria to get support under the Renewable Obligation scheme. The Dutch Energy Agreement instructs the formulation of sustainability criteria for the categories of new and existing co-firing and co-gasification of biomass in coal-fired power plants ≥ 100 MW and large-scale heat projects where steam is generated from the burning of wood pellets ≥ 5 MW, supported by means of an SDE+ subsidy. The Danish Industry Agreement identifies that only plants whose rated thermal input exceeds 20 MW will be subject to voluntary documentation requirements. In other MSs, it is not yet known what production capacity would be applied for bioenergy plants as well as for lignocellulosic biorefineries producing electricity and heat.

5.2 Environmental performance

a. Greenhouse gas emission

Various GHG Protocol tools can be used to calculate GHG emissions such as country-specific tools, sector-specific tools or tools for countries and cities. The most relevant tool for lignocellulosic biorefineries is cross-sector tools which are applicable to many industries and businesses regardless of sector. GHG Protocol covers direct GHG emissions in consideration with generation of electricity, heating, cooling and steam, physical and chemical processing as well as transportation of materials, products and waste, fugitive emissions from methane leakages (of gas transport). Energy indirect GHG emissions include, but are not limited to, the emissions from the generation of purchased or acquired electricity, heating, cooling, and steam consumed. Emissions of ozone-depleting substances are also considered. Reporting is required for biogenic emissions of CO_2 from the combustion or biodegradation of biomass separately from the gross direct GHG emissions.

A variety of allocation methods were also used in other calculation tools to partition GHG emissions in biorefineries including energy allocation, mass allocation, economic allocation, or a combination of several approaches. In lignocellulosic biorefineries, a complexity exists due to high number of refining processes. Mass allocation is relevant for mass products such as feeds, biochemicals and biomaterials but less relevant for bioenergy. Energy allocation is suitable for bioenergy products but less appropriate for mass products. The exergy allocation, as defined in the RED II, is considered complicated as defining exergy values for some products is not yet possible (Njakou Djomo et al., 2017). In practice, another approach to deal with allocation – substitution- was also used for GHG emissions in biorefineries. With this approach, the environmental impact of the main products was calculated as the emissions from the main production system minus the avoided emissions from the production systems replaced by the co-products on the market. But biorefinery processes are integrated and might not be easily divided into subprocesses and processing feedstocks into final products requires a synergy in the production. Economic allocation have also been used to split burdens among bioenergy and biorefinery products, considers the financial incentives (Broeren, 2018). It can be seen different allocation method were considered relevant and applied for lignocellulosic biorefineries depending on targeted output products.

b. Chemical use and toxicity

These sustainability criteria are mainly applied in the processing phase of lignocellulosic biorefineries using wood feedstocks but they are not considered for the bioenergy sector. Utilization of additive and process chemical in the kraft paper process or for the production of biomaterials and biochemicals may lead to negative health and environmental impacts. Treated wastewater from those biorefineries discharging to the environment may still bear some micro nutrients which potentially lead to eutrophication. In addition, production of feedstocks used in lignocellulosic biorefineries may link to potential ecotoxicity impacts due to chemical use. Therefore substances used as input factors were in principle assessed to identify potential risk and toxicity and ensure safe use of chemicals and additives.

For bioenergy systems and lignocellulosic biorefineries using agricultural feedstocks, the concerns of those impacts are minor.

c. Other environmental criteria

- Biodiversity protection and ecosystem conservation

These sustainability criteria are mainly applied for the feedstock harvesting of lignocellulosic biorefineries using wood and forest feedstocks. For agricultural residues, these criteria are not relevant.

Protection of land with high biodiversity value and ecosystem conservation were assessed for sustainability performance of lignocellulosic biorefineries and presented in their corporate sustainability report. Using voluntary schemes recognized by the EC such as ISCC, RSB, Better Biomass to demonstrate compliance was found popular for biofuel production. Using SFM schemes such as FSC and PEFC was more favored by heat and electricity operators in some MSs as well as in lignocellulosic biorefineries. FSC and PEFC involve comprehensive and robust criteria for biodiversity protection and ecosystem conservation and therefore their criteria were found widely used in the EU.

- Sustainable forest management

These sustainability criteria were also commonly used for feedstock harvesting of lignocellulosic biorefineries using wood and forest feedstocks. For agricultural residues, these criteria are inappropriate.

In SFM schemes such as FSC and PEFC, legal sourcing, maintenance of forest productivity & ecosystem & nature conservation, biodiversity production and ecosystem conservation are required to ensure sustainable forest management. FSC Controlled Wood, FSC Mix, PEFC Controlled Source were used to certify forest feedstocks harvested in the EU, whilst FSC was more popularly applied for forest feedstocks harvested in other world regions. These two schemes have already benchmarked in some MSs, and they are accepted to be used for all SFM criteria (Mai-Moulin *et al.*, 2017).

- Chain of custody:

Chain of custody (CoC) is used for the traceability of forest feedstocks throughout the supply chains, verifying that certified materials are identified or kept separated from non-certified materials. CoC is also used to avoid double counting. FSC CoC and PEFC CoC were reported in sustainability reporting for lignocellulosic biorefineries.

5.3 Social and economic performance

Social and economic criteria have been established and implemented in a number of voluntary schemes which verify sustainable biofuels (Mai-Moulin, Hoefnagels and

Junginger, 2019). Social and economic performance was also found in certain peer-reviewed articles assessing sustainability of biorefineries as well as in sustainability report of many lignocellulosic biorefineries. Frequently assessed social and economic aspects included in voluntary sustainability reporting of lignocellulosic biorefineries include worker rights, human health impacts, compliance with local law and international treaties, contributions to local development, job creation and resource efficiency.

Worker rights were assessed by aspects including child labour avoidance, work conditions, human rights, and non-discrimination policies. Lignocellulosic biorefineries were found to demonstrate a compliance with national regulations, the EU's Working Time Directive (2003/88/EC) and the ILO (International Labour Organisation) Declaration of Fundamental Principles and Rights at Work. Several lignocellulosic biorefineries which source feedstocks from outside the EU, demonstrated a Supplier Code of Conduct which is used to protect fundamental human rights, dignity and equality through the value chains. The voluntary schemes used by the bioenergy sector and lignocellulosic biorefineries also adopted the requirements for worker rights based on ILO Declaration of Fundamental Principles and Rights at Work.

Human health impacts was performed by an assessment of annual accidents, sick-leaves, and injuries using different indices. In some lignocellulosic biorefineries the total recordable injury frequency (TRIF), or process safety event rate (PSER) were used. In the others, total recordable incident rate (TRIR), or lost time injury (LTI) were adopted.

Compliance with local law and international treaties Lignocellulosic biorefineries reported a compliance with local law and international treaties. In all reports, compliance with international standards regarding human rights and sustainability schemes were mentioned. Land rights and contributions to local community with indicators such as social development and protection of local community rights and indigenous people's rights were not often directly stated in the respective reports. A sustainability assessment by voluntary schemes, however indicated a protection of land rights. Social development is regarded as the active engagement of improving local livelihoods Regarding worker rights, some corporates reported a personnel well-being through internal measures such as supporting facilities, well-being campaigns, flexible work place and work hours. Training & education initiatives for employees were rather diverse. All corporates provided trainings on work safety and personal security. Additional trainings were given on code of conduct, personal data protection, anti-corruption, competition law, confidentiality, etc.

Economic aspects were considered in most lignocellulosic biorefineries. **Job creation** was mentioned by all reports. However, some referred to number of employees, and some to full-time equivalent. This sustainability criteria were consistent through most assessments and reports, since almost all the companies reported employees by work contract, gender, and age groups. Also the distributed economic value via tax was the most standardised. **Resource efficiency** was considered in a number of sustainability reports with the aim to optimize resource use and improve recovery rates of feedstock and material uses. These criteria ultimately aim to minimize GHG emissions, water consumption and waste.

6. Options for harmonisation of sustainability performance

This study has shown that the EU wide sustainability approach is used for bioenergy following the RED II guidance as sustainability criteria are binding for bioenergy. Divergent sustainability approaches are used by lignocellulosic biorefineries processing products of various bioeconomy sectors. Given this situation, there will likely be a need for a harmonized sustainability framework. Complexities of diverging standards and sustainability requirements may lead to higher cost and time requirements to perform sustainability compliance. This section discusses harmonisation possibilities and trade-offs of sustainability requirements for bioenergy and also for other products of lignocellulosic biorefineries. The findings are based on results of Chapters four and five.
To facilitate the harmonisation investigation, sustainability criteria established for solid biomass in some MSs was considered anticipate sustainability compliance of lignocellulosic biorefineries in the near future given sustainability criteria of the RED II are not yet implemented for biomass fuels.

6.1 Production capacity

The results of production capacity as total rated thermal input defined in the RED II and its implementation at Member State level show that there are already some different terminologies and threshold requirements. Member States are found to consider this criterion based on plants operated specifically at national level, thus harmonisation is not possible.

6.2 Environmental performance

a. GHG emissions

- Calculation method: The methods used for calculating GHG emissions for energy defined in the RED II are harmonised at the EU level. However, calculation methods used by lignocellulosic biorefineries vary. If lignocellulosic biorefineries need to comply with the

RED II's criteria, it is logical that the RED II's methods should be used and as a result, guidance of calculation methods need to be provided for lignocellulosic biorefineries. Given the situation, the harmonisation cannot be yet revealed.

- Data collection: Data inputs to calculate GHG calculations will affect final GHG emission results therefore they need to be compared and verified. Data to be considered include global warming potentials (GWP), yields, process efficiency, emission factors in cultivation and harvesting stage, use of fertilisers, pesticides and herbicides for nutrient compensation, transport mode throughout the supply chains of biorefinery products. Current findings reveal that there is still a lack of data available for various biorefinery products, therefore it is difficult to harmonise this aspect.

- Emission threshold: GHG emission thresholds have been defined for solid biomass used for heat production and electricity generation at the Member States level. Following the RED II's guidance, the Netherlands and Denmark currently establish the most ambitious targets, requiring emission reduction of 70% for heat and electricity produced from solid biomass. Whilst the UK requires a lower threshold of 60%. It is not yet know what emission threshold to be applied for lignocellulosic biorefineries at national level. Therefore harmonisation is unlikely for this aspect.

- Allocation approach:

The methods used to allocate GHG emissions for bioenergy following the RED II approach as well as for various products in lignocellulosic biorefineries vary. Harmonisation is therefore unlikely regarding allocation method.

b. Chemicals and toxicity

The assessment of chemical and toxicity shows that the impacts vary depending on feedstock types. There are no sustainability requirements defined for bioenergy as chemicals and additives are rarely used in bioenergy production. Thus, harmonised sustainability criteria are unlikely. It is obvious that requirements for controlled chemical use and toxicity should be placed and separated for the other bioeconomy sectors rather than bioenergy as they are important to ensure low environmental impacts of specific sectors.

c. Biodiversity protection and ecosystem conservation

The investigation reveals both lignocellulosic biorefineries and the bioenergy sector considered and implemented sustainability criteria of biodiversity protection. However, ecosystem conservation was only assessed in some sustainability reports for lignocellulosic biorefineries. The investigation also finds that FSC sustainability criteria and certification is widely used. Some voluntary schemes recognised by the EC accept FSC approach and include international conventions designed for biodiversity and ecosystem conservation in their certification. Some other recognised voluntary schemes define a less strict biodiversity criteria and or does not require ecosystem conservation. Harmonisation might be possible but needs an agreement on consistent requirement and measurement for the protection of high biodiversity value. Harmonisation for ecosystem conservation is unlikely as its application is not yet popular so that a harmonisation possibility could be considered.

d. Land use change

The RED II defines an ILUC measurement and an ILUC delegated regulation has been issued to assess high ILUC risks. ILUC is considered occurred when pasture or agricultural land previously destined for food and feed markets is diverted to biofuel production. It is less relevant for lignocellulosic biorefineries because lignocellulosic biomass used either for the production of bioenergy, biochemicals and biomaterials are not mobilised from energy crops or from agricultural land producing food and feed feedstocks. However, to avoid any ILUC conflicts, mobilisation of residues from crops of high ILU risks such as oil palm need to be carefully verified. Thus, these criteria are not appropriate for a harmonisation discussion.

e. Landuse, landuse change and forestry

These criteria are found in the RED II and relevant to ensure that changes in carbon stock associated with biomass harvesting are accounted so that reduce or limit GHG emissions in the sourcing regions. Countries which have signed the Paris Agreement are in principle committed to protecting carbon stock and EU countries have all signed the agreement. For other countries, national or sub-national laws can be used to assess the carbon stock protection.

Land use change was mentioned in sustainability reporting of several lignocellulosic biorefineries but measuring land use change was considered a challenge because a consistent measurement is not yet established. Harmonisation would be possible if a common methodology to measure LULUCF is defined and agreed upon.

f. Protection of water, soil and air

The protection of soil, water and air is mentioned in the RED II but only a monitoring is required. This requirement is not relevant for lignocellulosic biorefineries because no obvious risks are found for both forest biomass and agricultural residues. Thus harmonisation possibility is unlikely.

g. Risk based approach:

Risk based approach (RBA) is a method to be considered for a compliance with SFM criteria when sustainability certification is not always available. Thus RBA needs to be established based SFM principles. RBA is alreadt implemented by FSC, PEFC and other SFM schemes. With lignocellulosic biorefineries and bioenergy systems using forest biomass, FSC and PEFC are already applied. In the EU, RBA is defined in the RED II, and is already implemented under the UK Renewable Obligation (UK OFGEM, 2018) as well as in the Dutch Stimulation of Sustainable Energy Production (SDE+) under the Verification Protocol in the Netherlands (RVO, 2015). At national level, RBA approaches slightly vary but since FSC and PEFC are both accepted by those Member States, harmonisation would be possible for this sustainability measurement.

6.3 Social and economic performance

Social and economic impacts of lignocellulosic biorefineries operating in the EU are not priority in discussions on the application and harmonisation of certification schemes as they are already addressed via other EU regulations (European Parliament, 2019). The RED II does not include social and economic criteria, therefore harmonisation for these criteria is not possible. However, they can still be considered among voluntary schemes for aligning better voluntary performance. Social and economic criteria established in voluntary schemes vary and harmonisation of those criteria can be considered by a common agreement on how they are defined and assessed. Regarding the social and economic performance for lignocellulosic biorefineries, harmonisation level depend on national sustainability guidance for a sustainability reporting.

Worker rights in lignocellulosic biorefineries were performed based on recognised international treaties including ILO Declaration of Fundamental Principles and Rights at work. The agreement on these criteria in voluntary schemes would be likely and harmonisation is therefore possible. **Human health impacts** was performed by varying indicators, harmonisation would still be possible but requires agreement on reporting units. **Compliance with local law and international treaties** were also assessed by diverse indicators including human rights, land rights, contributions to social development and protection of local community rights and indigenous people's rights. Although indicators vary, harmonisation would be at some level feasible because definition of compliance is similar, only the compliance level differs. **Job creation** is one of the key objectives identified in sustainability reporting, harmonisation is therefore possible but needs an agreement of performing indicators.

Cascading use of biomass/ resource efficiency was considered more relevant in term of efficient use of resources in the circular economy context that maximises the added value of the products. But given the perspective of market prices, high quality of feedstocks are in principle used for processing high-value products. Whilst bioenergy costs are low compared to biomaterials and biochemicals in view of economic term, it is unforeseeable that high quality of feedstocks are used for bioenergy production. In addition, cascading use of biomass is only defined in a number of Member States such as Sweden and Belgium, and there is not yet a concrete definition agreed at the EU level. Therefore harmonisation of this criterion is low.

Table 2. Focused topics and indication for harmonisation and trade-offs

	Indicators	Harmonisation possibilities	Harmonisation level	Trade-offs
PRODUCTION CAPACITY:		N		
ENVIRONMENTAL PERFORMANCE:				
Reduction of GHG emissions (Mitigation of climate change)	*Calculation method*	N		Y
	Allocation	N		Y
	Data collection	Y	Medium	
Biodiversity and ecosystem conservation	*Protection of high biodiversity*	Y	Low	
	Conservation of ecosystem	N		
LUC measurements	*LUC measurement*	N		
	ILUC measurement	N		
LULUCF requirement	*- LULUCF*	Y	High	
	- Carbon stock preservation	Y	Low	
Sustainable forest management	*- Legalisation*	Y	Medium	
	- Forest productivity & well-functioning	Y	Medium	
Resource protection	*- Monitoring and quality control of air, soil and water*	N		Y
Chemical use and toxicity		N		Y
Risk based approach		Y	Low	
Chain of custody	*- Mass balance*	Y	Medium	
	- Physical segregation	Y	Medium	
ECONOMIC PERFORMANCE: harmonisation assessed at scheme level				
Job creation		Y	Medium	
Cascading use of biomass/ Resource efficiency		Y	Low	
SOCIAL PERFORMANCE: harmonisation assessed at scheme level				
Worker rights		Y	High	
Human health impacts		Y	Medium	
Compliance with local law rights & international treaties		Y	Medium	

7. Discussion and Conclusions

This study investigates sustainability criteria required in the RED II for bioenergy and sustainability performance relevant to lignocellulosic biorefineries. Sustainability performance of lignocellulosic biorefineries indicates their role for a better efficient distribution and use of resources. In the meantime their efforts to demonstrate a voluntary sustainability performance to tackle environmental challenges and reduce impacts is acknowledged. However a sustainability performance of various output products following EU wide regulation for bioenergy and bioeconomy is yet be consistent.

The findings on sustainability concerns of the RED II implementation and their implication for lignocellulosic biorefineries can be considered by LCA practitioners when investigating sustainability performance of lignocellulosic biorefineries. They also provide sustainability considerations for scientists and policy makers in the field of bioenergy and bioeconomy sustainability. Policy makers in MSs may consider the existing sustainability concerns of lignocellulosic biorefineries for a more comprehensive transposition of the RED II into national legislation. Guidance of sustainability compliance from policy makers is important for actors involved in the development and operation of lignocellulosic biorefineries. The study results also benefit the actors of lignocellulosic biorefineries to consider various sustainability aspects for the sustainability performance of multifunctional products they produce. The specific points are to be considered as below:

Feedstock use and involved processes

Sustainability criteria should be considered depending on feedstock use and involved technological processes. The study reveals that most of the sustainability criteria can be omitted for agricultural residues except requirements for GHG emissions reduction and a consideration for including biogenic carbon emissions if data are available. The results find out that certain sustainability considerations are relevant for agricultural residues such as wheat straw but additional sustainability should be applied for forest residues to ensure sustainable harvesting from forest regardless of origin.

With feedstocks mobilised within the EU, sustainability proof can be considered via a compliance with laws and regulations such as CAP and Forest Europe. For feedstocks mobilised from outside the EU, they should be subject to additional sustainability criteria to avoid any incurred sustainability risks. Social and economic criteria should be included.

Social acceptance and credibility

Voluntary reporting of sustainability performance of lignocellulosic biorefineries is a good practice which should be maintained and encouraged. Sustainability reporting involves time and resources but transparency and credibility are crucial for the development of lignocellulosic biorefineries, their roles to process multifunctional products as well as for the bioeconomy expansion. The products of lignocellulosic biorefineries are new in the market or only available in negligible quantities. Thus their sustainability reporting which responds to sustainability concerns of society, informs any impacts but also opportunities to customers, ultimately helps gain trust for their development.

Lesson learnt from actors of combined heat and power plants

One of the challenges is that development of lignocellulosic biorefineries is still in an early stage, not much data is available for investigation of sustainability performance. With the implementation of sustainability criteria for bioenergy, lessons can be learnt to deliver meaningful sustainability guidance for current and future operational lignocellulosic biorefineries.

Sustainability criteria have been already implemented for high capacity plants producing heat and electricity in some MSs. Therefore, the involved actors already have experience to deal with sustainability concerns and how to performance compliance with various sustainability requirements. With similar processes and product outcomes, the actors of lignocellulosic biorefineries can learn from both mistakes and successes of combined heat and power plants to demonstrate sustainability compliance. The lessons can help them avoid confusion and facilitate the sustainability compliance more rapidly and successfully.

Selection of sustainability initiatives

In practice, there are hundreds of sustainability initiatives and voluntary schemes which are used to certify and verify sustainability compliance for bio-based products. Thus selecting suitable schemes which are relevant for lignocellulosic biorefineries is also of importance. For feedstocks mobilised outside the EU, selection of sustainability initiatives would help to identify and solve sustainability issues such as land rights and contributions to local development. Already covered by certain voluntary schemes, the protection of land rights and social development are regarded as the active engagement of improving local livelihoods. Within those criteria, indicators such as social development and protection of local community rights and indigenous people's rights should be included in the sustainability reporting.

Harmonisation possibilities and trade-offs

Through sustainability assessment and performance for lignocellulosic biorefineries, potential benefits of sustainability performance and trade-offs of lignocellulosic biorefineries have been identified. For lignocellulosic biorefineries located in the EU, the harmonisation is not seen as necessary for certain sustainability criteria since these aspects are already regulated on EU or national level, e.g. human and labour rights. The biorefineries mainly need to deal with health and safety of workers as in bioenergy plants. As conversion to final energy carrier is usually accomplished in the EU, and these aspects are already covered in other EU laws.

Sustainability reports have shown that some indices were measured quantitatively whilst others were measured qualitatively which ultimately makes them less comparable. Thus, the selection and measuring of a set of criteria should follow a transparent and consistent approach. In terms of harmonisation, it is also essential to be able to make a well-founded statement about certification quality. One way to do so is to assess the reliability of information. For instance, working hours in the contract might vary to actual working hours. Assessing corporate sustainability reports revealed that reporting on socio-economic impacts show a level of harmonisation among voluntary schemes. The reason is that a majority on the investigated corporates report following GRI sustainability approach. Reflection on such initiative is important, since it enables us to see what types of data are feasible to be collected. And we found that the level of harmonisation is higher among those GRI reports. However, GRI is indicated in some studies that it is less efficient because of general requirements and without detailed information needed, some companies may disguise their unsustainable activities (Fonseca, McAllister and Fitzpatrick, 2012). Moreover, a high number of criteria required by GRI are not fully relevant for certain sectors (Silva et al., 2017).

A harmonised sustainability scheme would be ideal to assess not only apparent but also unwanted effects. Efroymson, Dale, & Langholtz (2017) have shown that the validity of criteria is stakeholder dependent. Consequently, there should be a common agreement of certain sustainability criteria which need to be prioritised (Martin, Røyne, et al., 2018). In current literature, workers are the prioritised stakeholder group which is in line with the priority given to workers' rights and health. Harmonised criteria should include distributional effects in term of costs and benefits, in order to avoid that benefits are taken by only certain actors and sectors.

However, establishment of harmonised sustainability criteria is considered challenging due to the inclusion of all social dimension which is case-specific (Martin, Royne, Ekvall, & Moberg, 2018). Some criteria are also easier to model since they are less time and location dependent (Efroymson, Dale and Langholtz, 2017). Another challenge harmonising socioeconomic criteria is that only a limited set of criteria has standardised data collection methods, while e.g. there is still no common framework available to assess food security (Dale et al., 2013). An overarching harmonisation still requires substantial effort, since some criteria are highly diverse, irrelevant for certain scopes, or face lack of data availability (Siebert et al., 2018).

Summary

Lignocellulosic biorefineries process feedstocks of often low environmental impacts; therefore, they can play a role in reducing significant GHG emissions and contributing to the climate and renewable energy targets. The sustainability performance is however more than only its GHG performanceand include diverse environmental, social and economic aspects. The results from this study show that harmonisation of sustainability criteria is possible for some sustainability aspects,. This is an important for future policy design across bioeconomy sectors. Integrating policies for the whole bioeconomy can help transform trade-offs into synergies.

The results show harmonisation possibilities for a number of sustainability criteria and requirements: protection of high biodiversity; landuse, landuse change and forestry; sustainable forest management; risk based approach; chain of custody and most of social and economic criteria. These sustainability requirements are commonly used by the bioenergy sector and relevant for lignocellulosic biorefineries. Other sustainability criteria which cannot be harmonised but important to be kept separated: chemical and toxicity which is more relevant for lignocellulosic biorefineries; ILUC remains relevant for bioenergy but might be less appropriate for lignocellulosic biorefineries using low-risk feedstocks such as agriculture residues. At the same time, displacement risks can still occur when biomass is used for non-food markets or when crop land is converted to cultivate dedicated energy crops.

Two set of sustainability criteria that cannot yet be harmonised, but important to be considered for harmonisation. One of the criteria is the reduction of GHG emissions that are used for all the bioeconomy sectors. Calculation method and emission allocation are not yet consistent from the bioenergy sector to lignocellulosic biorefineries. Discussion on calculating GHG emissions on various options needs to be carried out and more guidance for involved actors is also required so that appropriate calculations can be implemented. The other criteria, which should also be considered for the whole bioeconomy sector is the protection of air, soil and water. Although environmental impacts from one sourcing region to the others are different, more detailed guidance is of importance for imported lignocellulosic feedstocks or for regions which do not have stringent environmental laws.

This deliverable has been carried out by a desk study and a review of scientific articles on sustainability of the bioenergy sector, biorefineries and other bioeconomy industries. Although we aimed for a comprehensive review and detailed findings, more insights on sustainability compliance of lignocellulosic biorefineries are still needed. In particular, consultation with actors of lignocellulosic biorefineries, policy makers is important to understand their concerns, what bottle necks and what solutions they consider for the future sustainability performance. Future studies are recommended to examine this aspect as well as investigate further other case studies outside the EU and envisage lessons to be learnt from those.

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Annex: List of sustainability initiatives relevant to lignocellulosic biorefineries

1. Global Reporting Initiative: CONSOLIDATED SET OF GRI SUSTAINABILITY REPORTING STANDARDS 2018
   https://www.globalreporting.org/standards/gri-standards-download-center/consolidated-set-of-gri-standards/
2. Greenhouse Gas Protocol: Corporate Standard and Calculation Tools
   https://ghgprotocol.org/corporate-standard
   https://ghgprotocol.org/calculation-tools#cross_sector_tools_id
3. Forest Stewardship Council: FSC Controlled Wood, FSC Mix and Chain of Custody:
   https://www.fsc.org/en/page/forest-management-certification#controlled-wood
   https://www.fsc.org/en/controlled-wood-FSC-MIX
   https://www.fsc.org/en/page/chain-custody-certification
4. International Sustainability & Carbon Certification: certification scopes
   https://www.iscc-system.org/process/certification-scopes/
5. Programme for Endorsement of Forest Certification: Standards and Guides
   https://www.pefc.org/standards-implementation/standards-and-guides
6. Roundtable on Sustainable Materials: Certification and related documents
   https://rsb.org/certification/about-certification/
   https://rsb.org/certification/certification-documents/