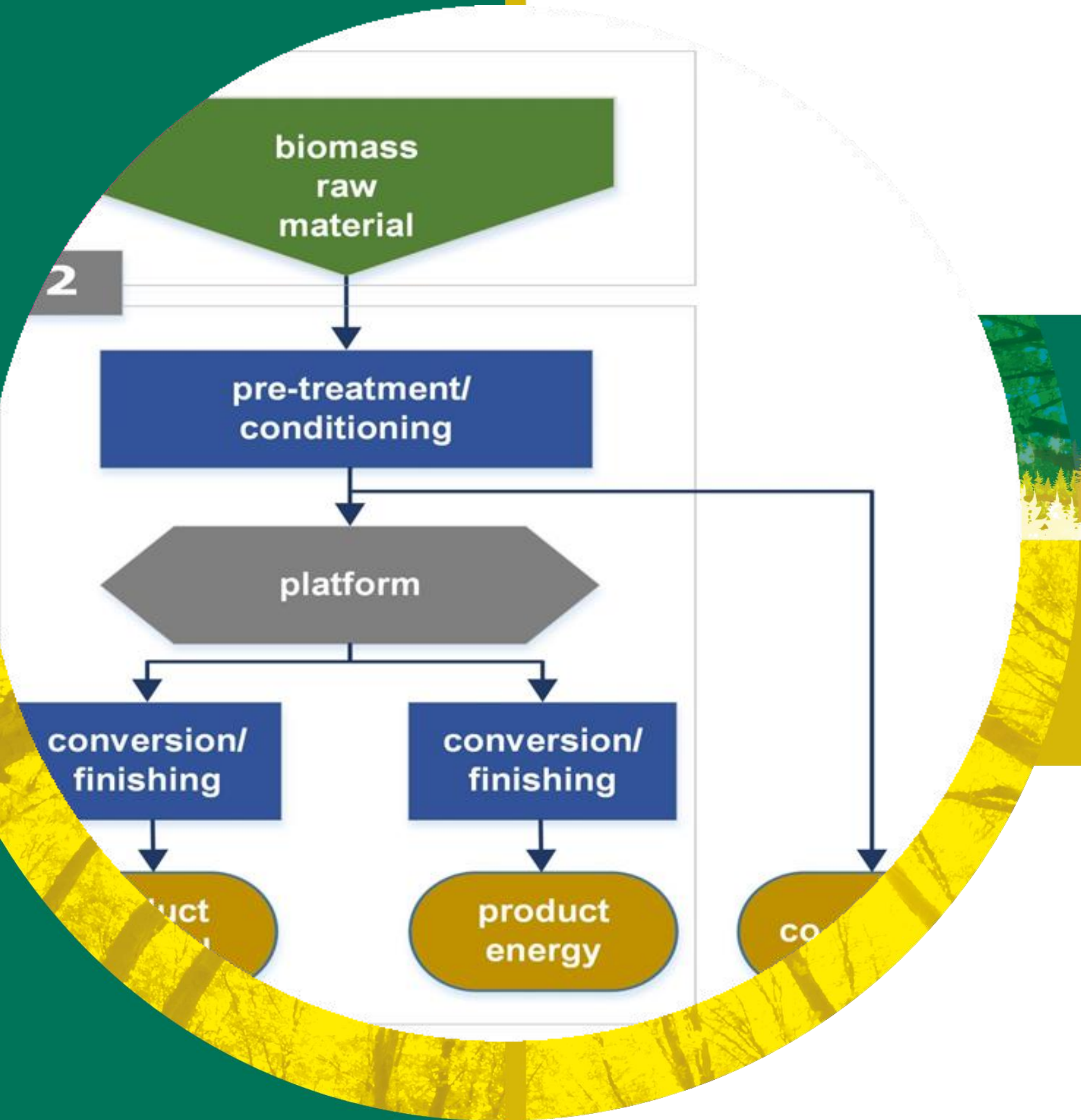
Technical, Economic and Environmental Assessment of Biorefinery Concepts

Developing a practical approach for characterisation



IEA Bioenergy

IEA Bioenergy: Task 42:2019:01

Technical, Economic and Environmental Assessment of Biorefinery Concepts

Developing a practical approach for characterisation

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We gratefully acknowledge the contribution of James J. Leahy (University of Limerick) for proof reading.

ISBN: 978-1-910154-64-9

Published by IEA Bioenergy

Executive Summary

The idea of biorefining in general is considered a promising concept for the processing of biomass into a spectrum of bio-based products and bioenergy. It is seen as one of the **enabling technologies** of the circular economy, closing loops of streams and aiming at the valorisation of multiple outputs. Due to its **complexity and diversity** there is a demand for quantitative, scientifically sound and transparent data on the technical, economic and ecological added-value of biorefining.

The International Energy Agency (IEA) **Task 42 Biorefining in a future bioeconomy** aims to contribute to the development of sustainable value chains. However, the assessment of emerging biorefining processes from an environmental and economic perspective face two main challenges: data availability and stakeholder participation. The data availability in technology development projects is typically low due to the immaturity of the processes and confidentiality. In a stepwise approach these drawbacks are now encountered. The polyhierarchical classification in the VDI-Standard 6310 and formal vocabulary for the implementation of different biorefinery processes were operationalised in a flowchart. Based on the input/output balances for representative technologies, set-up indicators for **GHG emissions, cumulated energy demand and economic values** like net present value, operating profit, specific products costs are generated based on published data.

In order to promote the implementation of biorefineries, IEA Bioenergy Task 42 presents a basis of classifying biorefinery concepts and provides an overview of available concepts along with their basic environmental performance and economic feasibility. The assessment is based on available generic data and its objective is to establish an **open access approach** containing the assessment methodology and primary data origin to create a knowledgeable community within the biorefinery sector. This supports an easy and comprehensible adaptation of existing biorefinery pathways for actual value calculations by any expert stakeholder to consider the case specific character of a biorefinery. Furthermore, this leads to the possibility of creating new pathways based on generic data and information. Therefore, the **multidimensional approach for a transparent procedure for biorefinery assessment** and the resulting **fact sheets** were developed and will be presented in this report in order to:

- make the calculations and primary data transparent, accessible and updateable;
- keep the results summary in a compact, illustrative form for information dissemination to a broader public;
- facilitate stakeholder involvement to accelerate information exchange on an international level

In this report **four case studies on biorefinery pathways** are investigated via a technical, economic and environmental (TEE) assessment. The results will be presented in the structure of biorefinery fact sheets.

Contents

1 INTRODUCTION

Possible shortage of fossil resource and GHG reduction constraints may emphasise a shift towards biobased resources. Biomass in general is considered as the main future alternative feedstock to replace fossil, providing a variety of material and energy products. In line with the vision of the bioeconomy, biorefineries are seen as the key to implement a future knowledge-driven and environmentally sound biobased economy (Hess et al., 2016; Meyer, 2017). Biorefineries enable the **transformation of biomass into a wide spectrum of products and energy carriers**. Products may include both intermediates and final products, and include food, feed, materials and chemicals. The provision of energy includes fuels, power, and/or heat (de Jong and Jungmeier, 2015).

> ***"Biorefining is the sustainable processing of biomass into a spectrum of marketable products and bioenergy"*** (IEA Task 42)

Sustainability throughout the entire value chain is a main consideration in the targeting the establishment of biorefineries. The assessment of sustainability aspects, including environmental, economic and social aspects should consider a variety of environmental impacts, such as GHGs and energy efficiency into account (de Jong and Jungmeier, 2015). It is thus recommended that the development and implementation of biorefinery concepts consider reliable processing units combined with environmentally friendly and economically feasible production chains (de Jong and Jungmeier, 2015). The definition of biorefineries implies that the products provided, and energy carriers demonstrate reduced environmental impacts compared to conventional products (Saraiva, 2017). In the scientific literature an increased interest and the derived need for a systematic assessment of the newly developed biomass-based value chains has been observed (e.g. Cherubini and Strømman, 2011; Ivanov et al., 2015; Saraiva, 2017; Zhang, 2008). Current limitations (e.g. methodological choices, transparency, etc.) of environmental assessments of biorefinery systems are leading to poor comparability and inconsistency among studies (Ahlgren et al., 2013). Besides these methodological limitations, the need to bring together key stakeholders to benefit from multidisciplinary knowledge is the main limitation of biorefinery assessment (de Jong and Jungmeier, 2015). The **Biorefinery fact sheets** (Jungmeier, 2014) consist of a brief description of the biorefinery concept including information about mass, energy balances as well as economic and environmental aspects. Providing such a format enables an improved the understanding of the value chains and the allows comparison of the different biorefinery concepts.

However, many biorefinery concepts are still under development, consequently, the present data availability for quantitative, scientifically sound and understandable **characterisation of some technical, economic and ecological aspects** is very limited, especially for technologies at low Technology Readiness Levels (TRL). Therefore, traditional life cycle analysis approaches currently deliver only aggregated and project specific results. In this context, the concept of biorefineries still offers a lot of possibilities for further research and development for representative and harmonised characterisation. The potential of all biorefinery technologies can be comprehensively evaluated and enhanced, if a large number of possible products meet the quality and price requirements of the market. In addition, identification and optimisation of site-adapted biorefinery technologies and recycling paths from the multitude of potentially available raw materials and conversion paths as well as the implementation of a continuous improvement process potentially will fuel an accelerated market diffusion of biorefinery cases. This approach potentially supports the future realisation of selected technology paths and products on the market and leads to economically viable and ecologically sustainable processes and products. Considering these objectives, a scientifically sound assessment based on the premise of "life-cycle thinking" of new biobased products and their functionalities compared to reference systems (for example conventional and / or petrochemical-based) can be of significant benefit to decision making.

In order to foster the implementation of biorefineries, IEA Bioenergy Task 42 provides the basis to classify biorefinery concepts and give an overview of available concepts and their basic environmental performance and economic feasibility. The assessment is based on available generic data and its objective is to establish an open access approach containing the assessment methodology and primary data to foster a strong knowledge community in the biorefinery sector. This supports an **easy and comprehensible adaptation of existing biorefinery pathways** for actual value calculations by any expert stakeholder to consider the case specific character of a biorefinery. Furthermore, this facilitates creating new pathways based on generic data and information. Therefore, the **multidimensional approach** for a **transparent procedure** for biorefinery assessment and the resulting fact sheets were developed and will be presented in this report in order to:

- make the calculations and primary data transparent, accessible and updateable;
- keep the results summary in a compact, graphic form for information dissemination to a broader public;
- facilitate stakeholder involvement to accelerate information exchange on an international level

In this report, **four case studies** on biorefinery pathways are investigated via a **technical, economic and environmental (TEE) assessment**. The results will be presented as biorefinery fact sheets.

2 BIOREFINERY ASSESSMENT

2.1 Current status and development trends of biorefineries

The idea of biorefining itself is not new (e.g. production of vegetable oils, paper production, starch production, etc.). However, advanced biorefinery concepts aim at valorising a wide variety of biomass—from forestry, agriculture, and aquaculture as well as many residues—into a broad range of products and energy. At the moment, different biorefinery concepts are under development, showing different stages of development (technology maturity). Therefore, the concept itself is subject to constant flux and change, leading to challenges in standardizing and assessing the various concepts (VDI, 2016). Table 1 summarises different concepts of biorefineries, their feedstocks (de Jong and Jungmeier, 2015) as well as the assigned TRL.

Table 1 Overview of feedstocks and TRL of different biorefinery concepts.

Concept	Feedstock	TRL*
Conventional biorefineries	Starch (corn, wheat, cassava) and sugar crops (sugarcane, sugar beet), wood	9
Whole crop biorefineries	Whole crop (including straw) cereals such as rye, wheat and maize	7-8
Oleochemical biorefineries	Oil crops	7-9
Lignocellulosic feedstock biorefineries	Lignocellulosic rich biomass: e.g., straw, chaff, reed, miscanthus, wood	6-8
Green biorefineries	Wet biomass: green crops and leaves, such as grass, Lucerne and clover, sugar beet leaf	5-7
Marine biorefineries	Aquatic biomass: microalgae and macroalgae (seaweed)	5-6

* Federal Government of Germany, 2012

The implementation of any kind of biorefinery concept requires reliable **processing of various feedstocks**, providing environmentally superior products compared to their conventional counterparts and economically profitable production chains. In addition, support from government and market pull initiatives are an important factor in determining the type and rate of deployment of biorefineries (de Jong and Jungmeier, 2015).

The establishment of **environmentally friendly and economically feasible** commercial scale biorefineries are challenged by numerous technical, strategic and sustainable challenges (Rudie, 2009). Current technical barriers for using biomass are mainly associated with the costs of production and challenges in harvesting and storing of the material. Non-technical barriers include restriction or prior claims on use of land (e.g. food, energy, housing, industry, etc.) as well as the environmental and ecological effects of large areas of monoculture. Cascading biomass utilisation according to the biorefinery principles can partly overcome these issues by satisfying several demands in different sectors (food and feed ingredients, chemicals, materials, fuels, energy etc.). In addition to the **technical challenges** of commercializing advanced biorefineries, there are also significant **infrastructural barriers**. These barriers are for example, associated with the development of new agricultural infrastructure for the collection and storage of the biomass and residues/wastes. An integrated feedstock supply system is required in order to provide feedstock in a sustainable way at reasonable cost. Another challenge is the heterogeneity of the biomass that is converted into bio products in a multi-feedstock biorefinery which requires the use of different pre-treatment/valorisation processes. Multiple process examples, combination options and products exist in this respect (e.g. de Jong and Jungmeier, 2015; Rudie, 2009; Stichnothe et al., 2016). In this context, the concept of biorefineries still offers many possibilities for further research and development for representative and harmonised characterisation. The potential of all biorefinery technologies can be comprehensively evaluated and enhanced. Key to this is the large number of possible products that meet the **quality and price requirements** of the market. In addition, identification and optimization of site-adapted biorefinery technologies and recycling paths from the various potentially available raw materials and conversion paths as well as the implementation of a continuous improvement process will potentially stimulate an accelerated market diffusion of the various biorefinery cases. This approach supports the future realization of selected technology paths and products on the market and leads to economically viable and ecologically sustainable processes and products. Considering these objectives, an assessment based on the premise of **life-cycle thinking** of new biobased products and their functionalities compared to reference systems (for example conventional and / or petrochemical-based) can assist decision-making (Venkatachalam et al., 2018).

2.2 Incentives for and barriers to the implementation of biorefinery concepts

There are a lot of **technical and nontechnical gaps and barriers** related to the implementation and commercialization of biorefineries in general. Current technical barriers associated with the use of energy crops are related to the **cost of production** and difficulties in harvesting and storing the biomass, especially for crops that have to be harvested within a narrow time period. Transportation costs are of high importance when calculating the overall cost of the biomass feedstock, hence especially in small scale biorefineries a local or regional production of biomass can be of significant economic benefit.

The major nontechnical barriers in highly populated countries are restrictions or prior claims on **use of land** (food, energy, amenity use, housing, commerce, industry, leisure, or designated areas of natural beauty, special scientific interest, etc.), as well as the environmental and ecological effects of large areas of monoculture. For example, vegetable oils are a renewable and potentially high-volume source of energy with an energy content close to that of diesel fuel.

However, extensive use of vegetable oils may cause other significant problems such as competition for food and feed production. **Cascading biomass utilisation** according to the biorefinery principles can partly overcome these issues and satisfy the various demands in different sectors (food and feed ingredients, chemicals, materials, fuels, energy etc.).

Established biorefineries, like the ones in the pulp & paper sector and the sugar industry followed the concept of oil refineries, using a single feedstock (e.g. for oil refineries: crude oil) in large processing facilities to achieve maximum economy of scale. Applied to biomass this approach has led to the development of a broad spectrum of different large-scale biorefineries that are using a single feedstock and produce market competitive products.

In rural areas, barriers, such as high capital costs and the sustainable supply and distribution of biomass, are limiting the realisation of such large-scale biorefineries. **Small-scale biorefineries** require a significantly lower investment (capital expenditure, CAPEX) and thus solve several challenges that their larger competitors are facing. However, there are still numerous technological and strategic challenges that hamper the commercial development of small-scale biorefineries.

Further research is needed in order to systematically **enhance the technological, economic and environmental aspects** of emerging biorefineries. The development of various biorefinery concepts is considered as a key to the realisation of the bioeconomy.

2.3 Current challenges of assessing biorefineries

In general the methodological choices and assumptions made are strongly influencing the results of the assessment (Larson, 2006). Considering Life Cycle Assessment (LCA) as an established method to assess the environmental impacts of a product (ISO 10400) the choice of **allocation** is one of the most discussed issues (Heijungs and Guinée, 2007). Additionally, the choice of **functional unit** (e.g. Weidema et al., 2004), **system boundaries** and whether the LCA is accounting or consequential are key issues for LCAs of biorefineries (Ahlgren et al., 2015; Saraiva, 2017). Before going into detail on these issues it is worth noting that there are many LCA standards and guidelines available, which may be relevant in the context of biorefineries (Ahlgren et al., 2015). The case studies in this report follow the existing standards and guidelines that are relevant to the LCA of biorefineries to the case specific applicable extent, examples include:

- ISO 14040 Series: As a common reference point the assessment will be carried out in accordance with the ISO standard for LCA;
- International Reference Life Cycle Data System (ILCD): As a complement to the ISO standard the ILCD is used especially in terms of methodological key issues;
- EU Renewable Energy and Fuel Quality Directives (RED): The assessment follows the calculations rules for GHG accounting for biofuels;
- US Environmental Protection Agency statutes and regulations promulgated under the Renewable Fuel Standard (RFS) program[1]
- Environment and Climate Change Canada, Clean Fuel Standard regulatory design[2]

[1] For more information see https://www.epa.gov/renewable-fuel-standard-program/statutes-and-regulations-under-renewable-fuel-standard

[2] For more information see https://www.canada.ca/content/dam/eccc/documents/pdf/climate-change/clean-fuel-standard-regulatory-design-paper-2018-en-1.pd

- CEN Sustainability Criteria for Biomass: The covering criteria and indicators for biomass for energy application, including GHG are followed;
- CEN TC 383 Sustainably produced biomass for energy use: The principles, criteria and indicators including their verification and auditing schemes for biomass for energy use are followed;
- ISO/TS 14067 Greenhouse gases - Carbon footprint of products: Special considerations in terms of increasing transparency in quantifying and reporting GHG emissions are given;
- VDI 6310 Part 1 Classification and quality criteria of biorefineries: The classification system is applied for the presented fact sheets.

However, the target of this study is not to extensively list or examine the applicability of existing standards and guidelines or the harmonisation of methods and standards.

Functional unit and allocation

A limitation of many LCA studies, especially when assessing new technologies or products, is that the functional unit is often reflected by the reference material flows (e.g. amount of output) rather than the function (e.g. heat value). This is mainly due to high uncertainties of the actual function and continuous product development (Lettner et al., 2018). In terms of biorefineries, different approaches for defining the functional units can be found in the scientific literature. For instance, the targeted output (González-García et al., 2011) or the total annual input of biomass (Cherubini and Ulgiati, 2010). The importance of the choice of functional unit for comparing and interpret results is unquestionable (Cherubini and Strømman, 2011). Biorefineries producing multiple outputs increases the difficulty of identifying one main function (Ahlgren et al., 2013). The **multifunctionality of biorefinery concepts** are also leading to the common challenge of allocating the environmental impacts to various outputs. Different outputs from a biorefinery can actually have different functional units and physical attributes leading to a core question in LCA for biorefineries (Cherubini et al., 2011a; Ekvall and Finnveden, 2001; Heijungs and Guinée, 2007; Weidema, 2000). Further discussion about the influences of the allocation on the results of biorefinery system can be found in Cherubini et al. (2011).

The **partitioning method** is based on the artificial splitting up of multifunctional processes into a number of independently operating mono-functional processes (Heijungs and Guinée, 2007), and it allocates the impact between the co-products using a specified criterion as shown in Figure 1. In the case of biorefinery systems, it is necessary to distinguish between processes with and without an underlying physical relationship between the outputs and the emissions (see also ISO 14040 section 4.3.4.2).

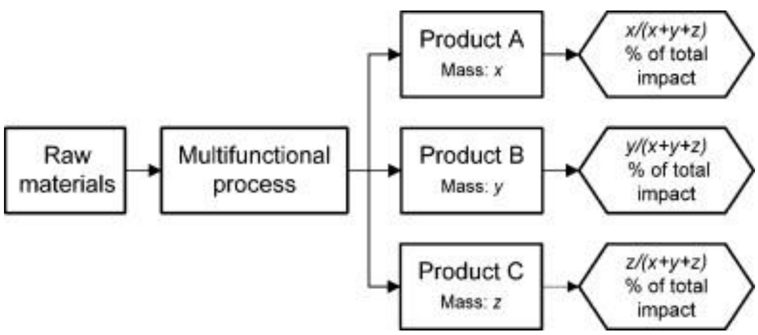

Figure 1 Basic scheme of mass allocation (Cherubini et al., 2011b).

With the partitioning method of allocations, the emissions (e.g. CO_2-eq) that are calculated within the assessment can be shared among the different factors using. Equation 1:

$$w_i = \alpha_i * W_{tot}$$ **[Equation 1]**

Where
w_i = emissions
α_i = allocation
W_{tot} = total emissions

with w_i as factor specific emissions, α_i as a factor specific allocation and W_{tot} as total emissions (Cherubini et al., 2011a). The partitioning method was found as most useful for the current assessment of different case studies. Nevertheless no general recommendation can be anticipated for this topic.

System boundaries

Using **quality criteria** helps to determine whether and to what extent a biorefinery can be seen as advantageous compared to conventional fossil-based processing and product portfolios. The choice of system boundaries (or balancing scope) strongly influences the result of value-based biorefinery quality evaluation (VDI, 2016). For instance, the quality of a biorefinery is dependent on:

- economic values;
- environmental values and;
- social values

Saraiva (2017) conducted a review on the influence of system boundary settings in the LCA's of biorefineries and the need for further investigations (Saraiva, 2017). It is recommended that one considers the entire cradle-to-grave life cycle (VDI, 2016). However, from a practical point of view, due to limitations in data availability, especially in terms of the use and end of life phase, the assessments often follow a cradle-to-gate or gate-to-gate approach. The considered life cycle stages as shown in Figure 2 include:

- biomass cultivation;
- process steps upstream and inside the biorefinery;
- consumer use of biorefinery products;
- product disposal

Although there is a distinction between biobased and non-biobased value chains, it is worth noting, that a purely biobased value chain may have connections/interactions in common with non-biobased value chains (VDI, 2016).

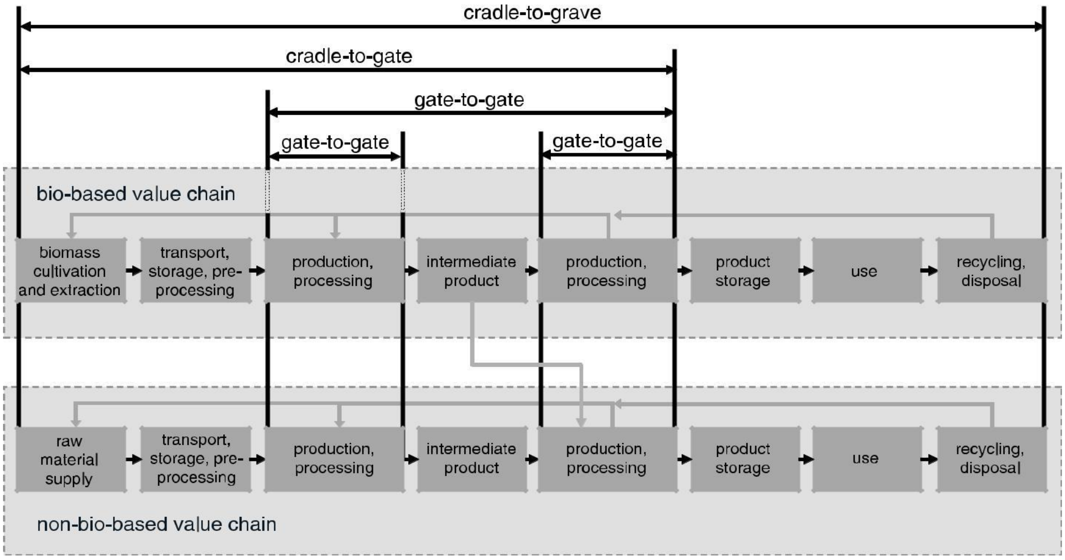

Figure 2 Definitions of system boundaries for biobased and non-biobased value chains (VDI, 2016).

The system boundaries of the case studies in this report are **cradle-to-gate**. The use and disposal phase is often not covered as operators and developers of biorefineries have only limited data and influence on the use and disposal of products. Based on the wide options for using biobased products, case specific assessments are hardly comprehensible by a generic approach. Nevertheless, life cycle thinking that refers to a cradle-to-grave approach utilising biobased products explicitly reveals their positive environmental potential, especially when substituting for fossil-based reference products and services or end of life phase related to the biogenic origin of product bound carbon (Pawelzik et al., 2013).

2.3.1 Classification of Biorefineries

As highlighted by Cherubini et al. (2009) there is a need for a common classification approach for biorefinery systems. The problem of classification has been frequently discussed in literature (e.g. Kamm & Kamm 2005, van Ree & Annevelink 2007, Axegard et al. 2007, etc.). The purpose of the IEA Task 42 classification system is to classify each biorefinery system according to **four main features: Platforms, Products, Feedstock, and Processes** (listed in order of importance). Each of the features consist of several potential subgroups, as shown in Table 2.

Table 2 Features and subgroups for classification system (adapted from Cherubini et al. 2009).

Platform		C5 sugars; C6 sugars; Oils; Biogas; Syngas; Hydrogen; Organic juice; Pyrolytic liquid; Lignin; Electricity and heat
Products	Energy products	Biodiesel; Bioethanol; Biomethane; Synthetic biofuels; Synthetic biofuels; Electricity and heat
	Material products	Food; Animal feed; Fertilizer; Glycerine; Biomaterials; Chemicals and building blocks; Polymers and resins; Biohydrogen
Feedstocks	Dedicated crops	Oil crops; Sugar crops; Starch crops; Lignocellulosic crops; Grasses; Marine biomass
	Residues	Lignocellulosic residues; Organic residues & others
Processes (selected)	Thermochemical	Combustion; Gasification; Hydrothermal upgrading; Pyrolysis; Supercritical
	Biochemical	Fermentation; Anaerobic digestion; Aerobic digestion; Aerobic conversion; Enzymatic processes
	Chemical processes	Catalytic processes, Pulping, Esterification; Hydrogenation; Methanisation; Steam reforming; Water electrolysis
	Mechanical/physical	Extraction; Fiber separation; Mechanical fractionation; Pressing/disruption; Pretreatment; Separation

Figure 3 illustrates a schematic depiction of the biorefinery classification system and associated elements. The method for classification and characterization of biorefineries was developed in Task 42 (Cherubini et al., 2009; Jungmeier et al., 2015). This categorisation uses raw material, platform, product and process as structural elements. The classification and quality criteria for biorefineries are summarized in the German **VDI standard 6310**. This provides a standardized basis for the classification of biorefineries in terms of technical aspects and environmental, economic and social criteria (VDI, 2016) based on the systematic classification system and formal vocabulary according to Cherubini et al. (2009). The classification system is open for extension and the processes are the connection between the platforms with the raw materials and the products or other platforms. It is possible to introduce additional product lines as well as add entire platforms, for example if a product should serve as the base material for further syntheses in the biorefinery (Cherubini et al., 2009).

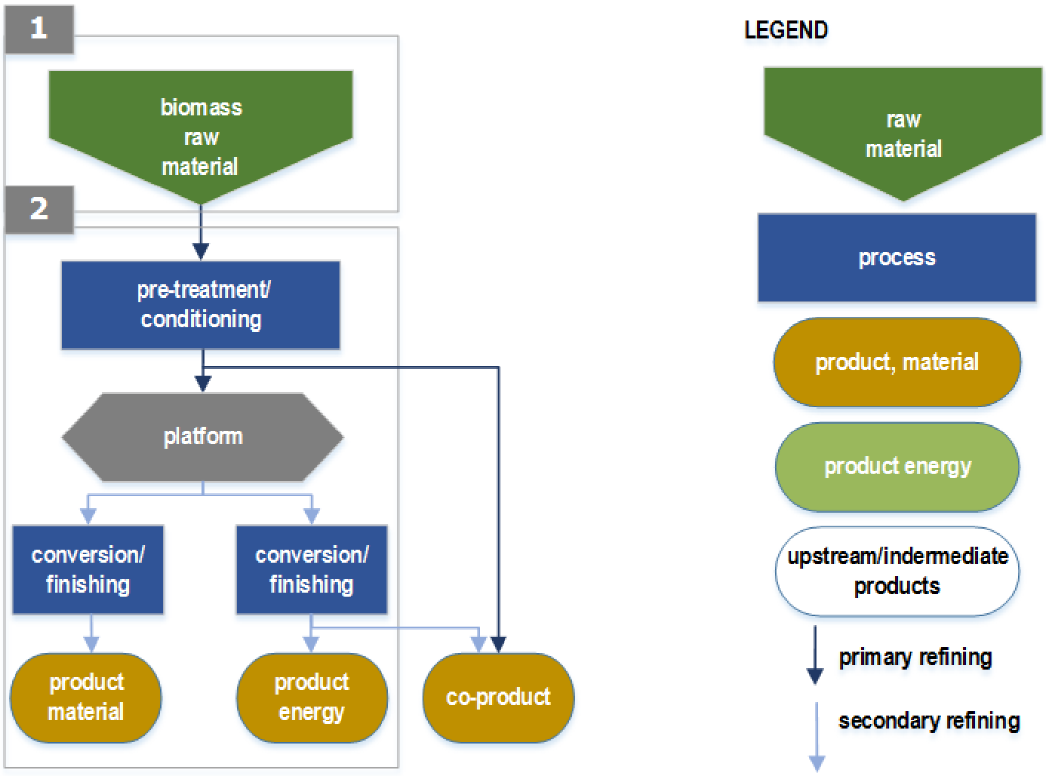

Figure 3 Schematic depiction of the biorefinery classification system and associated element (VDI 6310).

For practical implementation, the following procedure is proposed to allocate an arbitrary biorefinery to the classification schema:

- list all relevant incoming material streams (raw materials);
- list all processes involved;
- list all internal material streams (intermediate products);
- specify the resulting platform(s);
- list all outgoing material streams (products);
- prepare the associated diagram

Based on this structural classification from feedstock to products a network graph for bioenergy and biofuel oriented biorefinery systems was compiled (Figure 4). An important characteristic of this classification approach is that it can be expanded to include future developments of biorefineries concerning new feedstocks, platforms, processes or products. That can be added to features of a specific element of a value chain or diversified options of a biobased production value chain (Cherubini et al., 2009).

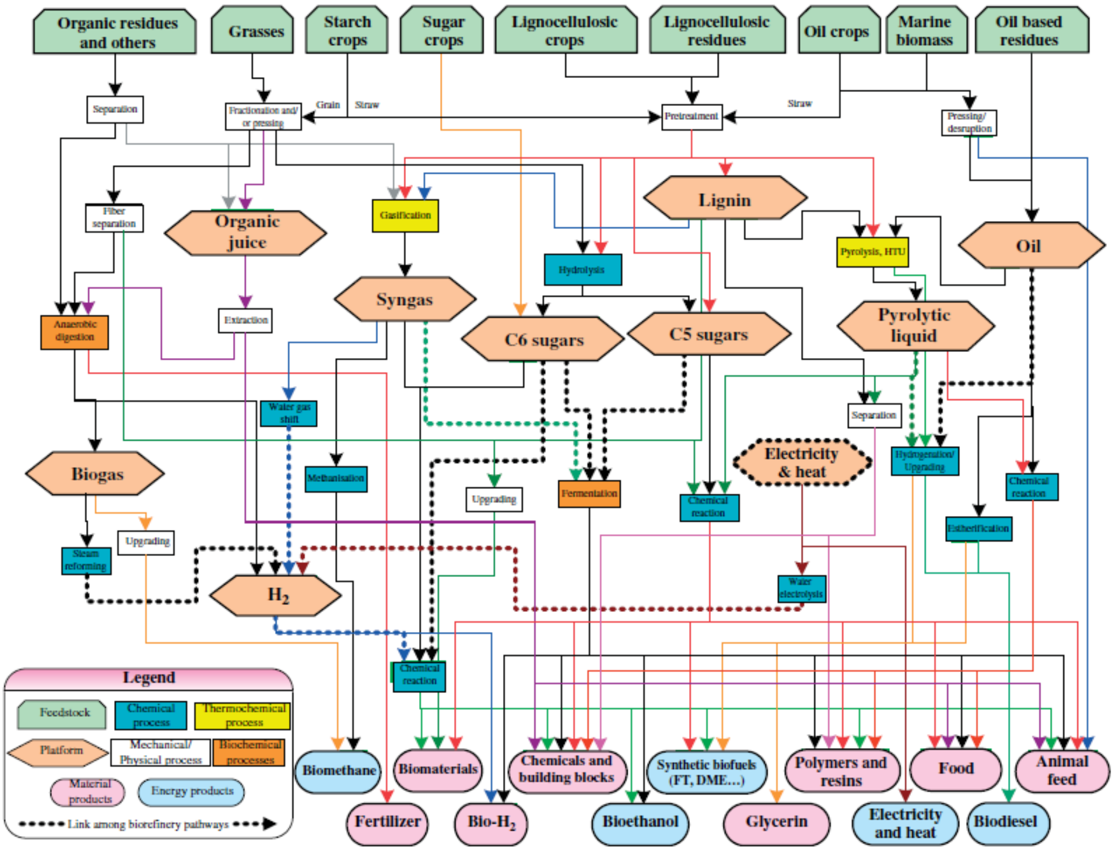

Figure 4 Network where the individual biorefinery systems are combined (Cherubini et al., 2009).

The method for **classification and characterization** of biorefineries developed in Task 42 (Cherubini et al., 2009; Jungmeier et al., 2015) is applied. This will be continuously refined into the future. It is expected, that a corresponding extension of the methodology will be needed in the future due to technological "cases" and development progress of biorefineries towards further diversification.

For conducting the assessment of selected biorefineries by means of **TEE assessment** on the one hand, the already existing technologies and biorefinery concepts are highlighted. On the other hand, systems under development are characterized together with relevant actors, since ultimately a comparison of the biorefinery systems is targeted against reference product systems. The results are summarized in a tabulated form and graphically presenting a comparison of the biorefinery pathway against predominantly fossil based technologies and reference systems. In the context of the energy efficiency assessment, the conversion losses and the use of process energy are discussed. In addition to the achievable GHG emission savings, other environmental impact categories such as primary energy demand are also taken into account. In combination with the quantification of product cost from key economic data, a comprehensive performance assessment is possible.

2.3.2 Economic assessment

As stated above economic evaluation is one important criterion for evaluating the quality of the biorefinery systems. It helps to identify promising processes, evaluate investment projects and secure financing (VDI, 2016). Table 3 briefly summarises parameters and values for the economic evaluation of biorefineries. A detailed description of each parameter can be found in VDI 6310. If possible (i.e. depending on data availability) the **net present value method** is applied to consider values that vary over time. All costs and revenues are then discounted up or down, using a discount rate that is specified at the decision time. An investment can be considered as beneficial if the net present value is positive. The calculation method of the net present value for biorefinery systems can be found in VDI 6310. Methods and instruments for dynamic evaluation of capital goods and plants may be taken from VDI 6025.

Table 3 Parameters and values for the economic evaluation of biorefineries (VDI 6310 and 6025).

No	**Parameter**	**Description**	**Unit**
1	Investments*		
1.1	Investment sum	Sum of plant investments including auxiliary plants, additional costs (e.g. financing, land fees), plus extension or optimisation	€
2	Investment costs**		
2.1	Write-offs	Under consideration of the respective technical service life	€/a
2.2	Imputed interest	Capital return	€/a
2.3	Maintenance	Costs for service and maintenance, as well as a maintenance reserve for the biorefineries	€/a
2.4	Taxes	Property taxes related to the investment	€/a
2.5	Insurance	Biorefinery plant insurance costs	€/a
2.6	Administration	Administration costs associated with the investment	€/a
3	Material and energy stream costs		
3.1	Raw material supply	Sum of raw material costs, including delivery, storage and any necessary pre-treatment	€/a
3.2	Auxiliary and operating materials	Sum of auxiliary and operating costs, including delivery, storage and any necessary pre-treatment	€/a
3.3	Energy supply	Costs for the own electricity use in the biorefinery	€/a
3.4	Disposal costs	Waste disposal cots	€/a
3.5	Transport costs	Any additional incurred transport costs	€/a
4	Material and energy stream costs		
4.1	Material (products)	Profits attainable from the sale of material products (gaseous, liquid, solid) and energy sources	€/a
4.2	Electricity	Profits attainable from the sale of electricity	€/a
4.3	Heat	Calculated based on the supplied quantity of heat and the sale price	€/a
5	Labour costs	Labour costs for operations, maintenance and management	€/a
6	Other costs	Other costs not recorded elsewhere	€/a
7	Overheads	Additional costs for overhead	€/a
8	Overall evaluation		
8.1	Operating results	Revenues minus costs (if necessary under consideration of other calculated costs)	€/a
8.2	Net present value	Sum of all discounted net payments (income minus expenses) attributable to the investment at this time	€

* refer to CAPEX … capital expenditure

** refer to OPEX … operational expenditures related to placed investments

For a detailed assessment, the production cost factors are ideally provided for each part of the system, e.g. raw material sourcing, pre-treatment/conditioning and biorefinery conversion to multi-product output. If, due to confidentiality constrains and data availability, a detailed assessment is impossible, aggregated values related to the relevant physical biorefinery inputs and outputs can be used to provide an assessment with lower granularity.

The input factors enable calculating the write-offs I_W and the imputed interest I_{Int} as in Equation 2 and Equation 3.

$$I_W = \frac{I}{T}$$ **[Equation 2]**

where
I_W = wirte-offs
I = investment costs
T = consideration duration in periods

$$I_{Int} = I * i$$ **[Equation 3]**

where
I_{Int} = imputed interest
i = discount rate

Following the operating result *O* and the net present value C_0 is calculated as in Equitation 4 and Equation 5, where I_n describes the different type of investments related costs and C_n the different type of operational related costs (VDI, 2016). In principle, Equation 4 provides a simple income versus expenditure comparison over the period considered.

$$O = E_t - \left(\sum I_n + \sum C_n\right)$$ **[Equation 4]**

where
$\boldsymbol{O}$ = operating results
$\boldsymbol{E_t}$ = sum of revenues in the period t
$\boldsymbol{I_n}$ = sum of investment related costs in the period t
$\boldsymbol{C_n}$ = sum of operation related costs in the period t

$$C_0 = -I + E_t * A_t * (1+i)^{-T} + T * A_t * (1+i)^{T}$$ **[Equation 5]**

where
C_0 = net present value
A_t = sum of payments in the period t

In the net present value method, all costs and revenues associated with an investment project are discounted up or down using a discount rate to be specified at the decision time. If the net present value is positive, then an investment is beneficial. If multiple investment alternatives are available, then the criteria specify that those with the highest net present value should be chosen.

In addition to the net present value estimate, the costs of different biorefinery pathways can be evaluated based on the **specific costs of the product portfolio**, which are calculated considering the total annual cost. This is related to the annual amount of products generated, which is comparable to the levelized cost calculation of electricity (LCOE) (de Visser and Held, 2014, Nuclear Energy Agency, 2015). Total annual costs are calculated using the so-called annuity method (VDI, 2012) taking into account that values vary over time and this method explicitly addresses periodically changing payment flows, comparable to the approach in Equation 4. The total annual cost consists of: investment related A_K, energy/material related A_V, operational A_B and additional cost A_S. These are deducted from the specific revenue A_E for by-products which gives the annuity of the total annual payments A, which can be related to the annual product output (Equation 6).

$$A = A_E - (A_K + A_V + A_B + A_S) \quad \textbf{[Equation 6]}$$

where
A = total annual cost of operations
A_E = specific revenue AE for by-products
A_K = investment related costs
A_V = energy/material related cost
A_B = operational costs
A_S = additional costs

Specific full product costs can help to determine the potential economic feasibility and marketability of biobased products in respect to fossil counterparts and its marginal revenues without considering specific price structures and economic boundary conditions. With the help of such basic calculations, a trend can be provided for the mid- to long-term perspective for process concepts at low TRLs and to elaborate which major reductions in the costs structures are required in order to be competitive and economically feasible.

Beside the calculation of the net present value of a biorefinery concept, the economic assessment can significantly benefit from **sensitivity analysis** as part of the results interpretation. Within this analysis e.g. the various parameter investment costs (including write offs, imputed interest, maintenance, taxes, insurance and administration), raw material supply, energy costs, administration and other (e.g. transport costs) are varied in a systematic range of e.g. minus 100% and plus 100% or in a case specific realistic range of the calculated base case value. The results of the sensitivity analysis are given as a percentage change relative to the specific cost value. This can provide an indication how the uncertainty in the output of the assessment can be apportioned to the different sources of uncertainty in the inputs. This is done because the applied generic values hardly represent the high variety of process specific conditions. For an improved evaluation of the presented results it can be stated that the conducted case studies are intending to inform a broader public about the potential benefits and to support decision making. However, results based on generic data are not suitable for business case development or likewise without case specific adaptation and review of the considered input data.

2.3.3 Environmental assessment

Sustainability assessment in the context of biorefineries and their multiple outputs is not straight forward (Diaz-Chavez et al., 2016). Nevertheless biorefineries are responsible for a range of direct as well as indirect impacts on the environment, requiring a systematic assessment of the impacts (VDI, 2016). In the environmental assessment conducted, the focus is on **greenhouse gas emissions (GHG) and cumulated energy demand (CED) as key indicators**. Other environmental impact categories such as eutrophication, acidification, ozone depletion potential, etc. are currently excluded in the assessment due to the high variety of characterization models and a lack of international harmonization.

The method of choice for deriving environmental indicators for biorefineries is **Life Cycle Assessment (LCA) based on ISO 14040 methodology** encompassing the four steps: goal and scope definition, inventory analysis, impact assessment as well as interpretation. This procedure is not strictly consecutive. There are interrelationships between the individual steps. This means that each step is co-determined by the others. Accordingly, this is an iterative process. If all necessary input and output streams cannot be collected within the framework of Life Cycle Inventory due to a lack of valid data, this can result in a retroactive redefinition of the system boundaries. The sensitivity analysis can also show the necessity to refine the system boundaries. On the other hand, in the course of evaluation and interpretation it can be determined that additional data must be generated in order to arrive at representative results. Therefore, the data required for the Life Cycle Inventory is of particular importance within the LCA. As stated above, the representativeness of data and factors data needs to be verified in a case specific way for every biorefinery pathway assessment.

The LCA methodology used in this context refers to the **European Renewable Energy Directive (RED)** (RED 2009/28/EC, RED II 2018/2001) which aims to establish a simple and unified life cycle based calculation of GHG savings of biofuels compared to their fossil counterparts. Nevertheless, the approach is not suitable for investigating the life cycle of product systems in every detail. LCA according to the RED methodology is a simplified LCA approach. Within the RED the basic criteria for environmental sustainability assessments including greenhouse gas (GHG) emissions are characterised. Moreover within this legal framework for renewable energy (especially biofuels) several standards are applied practically in the EU (European Commission, 2015) as voluntary standards for certification of biomass products in the USA (e.g. Sustainable Forestry Initiative (SFI), Forest Stewardship Council (FSC) and Council on Sustainable Biomass Production (CSBP); ISO standards (e.g. ISO 13065) and other standards (e.g. CEN/TC411, …) for production systems related to the circular economy. In terms of environmental assessment, it is not only a question of processing the biomass, it is also recommended that one considers upstream biomass cultivation and biomass recovery. Depending on the system boundaries, the assessment includes all processes from cradle-to-gate, as well as if possible, following a cradle-to-grave approach (VDI, 2016). Concerning the case studies presented in this report, all life cycle stages from biomass production to the final product are taken into account following RED for the calculation of considered impact indicators.

The major advantage of this simplified approach is that the equation is easy to understand and transparent and the results for different products are easily compared. Direct comparison of results is possible without considering methodological choices.

The key methodological differences of a full LCA approach according to ISO 14040 and the simplified RED methodology can be summed up as follows:

- the ISO 14040 approach provides a range of methodological recommendations of how to set up a life cycle model and is more stringent on taking into account the whole life cycle of e.g. auxiliary materials used in the production process and more environmental impact categories of versatile product systems.
- the RED follows a cradle-to-use approach focussing on the dedicated application towards calculation of greenhouse gas savings associated with renewable energy deployment, especially biofuels.
- the RED simplifies LCA to a single formula, the methodology is stringent and the degree of freedom is limited.

The life cycle steps are implemented in different modules of the assessment—from the feedstock generation to the standardized products. Furthermore, the modules gather the input's consumption and calculate the emissions of the three main greenhouse gases—CO_2, CH_4 and N_2O and primary energy demand. The following parameters are considered for each production step of the biorefinery as input factors for the assessment:

- agro inputs;
- field work;
- field emissions;
- use of (fossil) energy sources;
- conversion inputs;
- transport efficiencies;
- emissions from steam production;
- electricity production;
- multi product outputs and residues

There are two categories of input parameters: emission driving parameters and process parameters; e.g. the input of the field emissions needs the process parameter of the field work to calculate the exact amount of emissions. The emission driving parameters are linked to emission coefficients. Applying representative emission factors is a significant challenge and the application of default values and non-specific data e.g. on energy-mixes, can impose strong divergences concerning the representativeness of results.

The use and disposal phase can only be covered partly as operators and developers have only limited data and influence on the use and disposal of products. Based on these limitations, the results can only be interpreted as estimates. Further, the overall emissions of the different biorefinery operations and process steps can be calculated, and in a second step the emissions are converted to a specific value with regard to the functional units like e.g. the annual products quantity.

In addition, the need to apply cut-off criteria arises from the fact that any seemingly simple product system is integrated into a larger global system, resulting in a variety of links to subsystems. In order to be able to evaluate the product system of interest using LCA, parts of this network must be excluded from the total consideration to reduce complexity. Cut-off criteria should ensure that this procedure is not purely arbitrary. Non-relevant life cycle stages including the associated material and energy flows are excluded based on these cut-off rules. Cut-off rules are quantified by the percentage of the module not considered measured against the total environmental impact or mass. It is difficult to determine the whole, the 100 %, which serves as a reference basis. These references are often only estimates. The handling of cut-off rules must also be very carefully considered, as these lead to considerable uncertainties in the result if too many material and energy flows are excluded from the LCA. Nevertheless, life cycle thinking is referring to a maximum balancing scope (e.g. cradle-to-grave) as biobased products strongly reveal their positive environmental potential especially in the use phase by substituting fossil-based reference products and services or end of life phase related to the biogenic origin of product bound carbon.

2.4 TEE assessment approach

The objective of the work in activity area AA1 "Biorefinery system assessment" within IEA Bioenergy Task 42 is to provide a **standardized methodology resulting in an open access fact sheet approach**. In this report, **four case studies of biorefinery pathways** are investigated via a technical, economic and environmental (TEE) assessment, following a structured approach which is illustrated in Figure 5. Mainly **published information** from LCA and techno-economic studies, BAT (Best available technology) documents, national inventories/statistics and various open access databases for default/standard values (e.g.: USDA, BIOGRACE, GEMIS, AGRIBALISE; PROBAS; ELCD; openLCA, BIOENERGIEDAT) are used for the TEE assessment. The results are presented in the well-known structure of the biorefinery fact sheets. The overall aim was to establish an **open access approach containing the assessment methodology and primary data** origin to enable the creation of a strong knowledge community in the biorefinery sector.

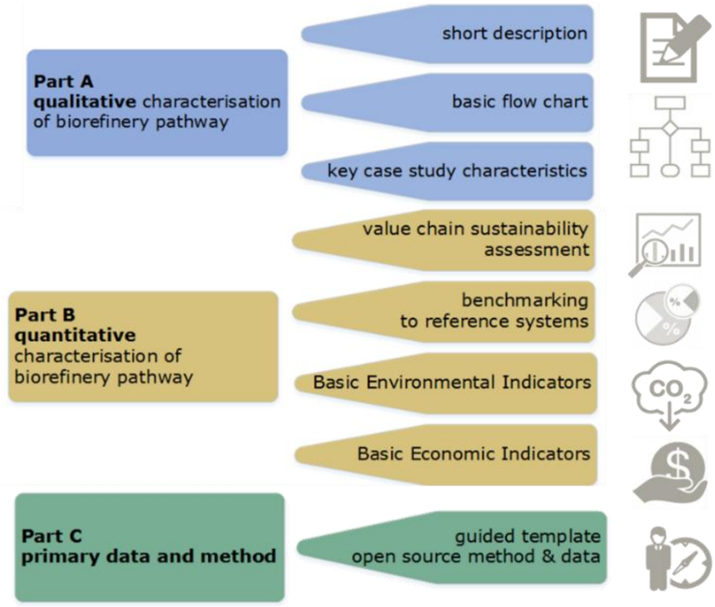

Figure 5 Structured approach of the TEE Assessment in IEA Bioenergy Task 42.

The assessment is available to all involved or interested participants with various levels of expertise to cover a wide ranging and diversified public and enable a broad dissemination. For this reason MS Excel was used to set up the data and results template. The template includes **different calculation sheets** (see screenshots in annex), supporting details of the exact and comprehensive methodology and the relevant data sources applied in an **open access manner**. The worksheets consist of:

- the first sheet provides a short process description and results overview, explains the scope, general information, disclaimer and vocabulary;
- the second sheet provides a table of contents and hyperlinks to the excel sheets with individual biorefinery pathways;
- third & fourth sheet: the user will find the calculations sheets as well as the standard values for the calculations;
- the last sheet presents the result numbers and graphs

The character of the TEE assessment provides the potential for adapting the given pathways in an easy and comprehensible way. It is therefore possible to integrate input data on feedstock input, conversion efficiencies, economic values, and thus creating new case-specific fact sheets. However, it is worth noting that the platform does not include optimization approaches or detailed modelling.

3 CASE STUDIES FOR TEE ASSESSMENT OF BIOREFINERY PATHWAYS (2016-2018)

The next section presents an extract from the open access assessment platform for the four case studies as shown in Table 4. Please note that the results demonstrated in the report and the fact sheets are snapshots of each TEE assessment, meaning that any change in the assessment platform results in a different outcome and fact sheet output.

This report considers the following biorefinery systems:

- **Case Study 1:** 2-platform (C5&C6 sugars, lignin) biorefinery to produce bioethanol, electricity & heat from corn stover
- **Case Study 2:** 2-platform (C5&C6 sugars, biogas) biorefinery to produce the biopolymer PHB, electricity & heat from sugar beet or sugar cane
- **Case Study 3:** 3-platform (C6 sugar, animal feed, lipids) biorefinery to produce the biopolymer PLA, animal feed & lipids from food waste
- **Case Study 4:** 3-platform (pulp, lignin, energy) biorefinery to produce pulp, lignin and energy from wood chips

Table 4 Overview of considered case studies.

Case study	**# 1**	**# 2**	**# 3**	**# 4**
Raw material	Corn stover	Sugar cane	Food waste	Wood
Platform	Sugar	Sugar	Sugar	Black liquor
Process	Lignocellulosic biomass conversion	Fermentation	Fermentation	Lignocellulosic biomass conversion
Product, material	Ethanol	PHB	PLA, animal feed, lipids	Lignin
Product, energy	Electricity, heat	Electricity, heat, biogas	-	Electricity, heat
Concept (VDI 6310)	Lignocellulose biorefinery	Sugar biorefinery	Waste biorefinery	Lignocellulose biorefinery
Balancing scope	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate	Cradle-to-gate

The results are presented in the structure of the Biorefinery fact sheets (Jungmeier, 2014) as shown in Figure 6 and provided by previous assessment within Task 42.

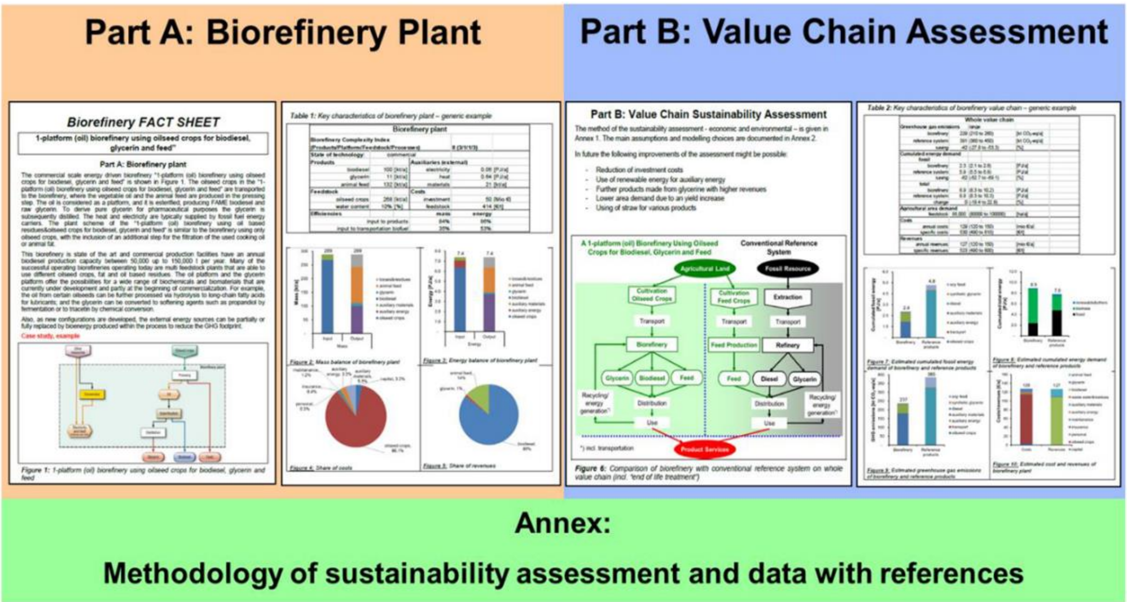

Figure 6 Biorefinery fact sheets (Jungmeier, 2014).

The biorefinery fact sheets consist of the following parts:

Part A: Biorefinery plant: the key characteristics of the biorefinery, including a short description, mass and energy balances, information about costs and revenues and the classification scheme

Part B: Value chain assessment: including information on the system boundaries, reference system, cumulative energy demand, greenhouse gas emissions and cost and revenues

3.1 Case study # 1: 2-platform (C5&C6 sugars, lignin) biorefinery to produce bioethanol, electricity & heat from corn stover

3.1.1 Introduction

This case study is characterising a lignocellulosic biorefinery using residual corn stover to produce ethanol as fossil fuel substitute (or alternatively for materials synthesis). It has on-site process energy generation via lignin combustion in a boiler and electricity production with steam from combustor. Additionally biogas is generated on-site by anaerobic digestion of waste water. No external energy supply is needed, depending on the operation mode excess electricity is generated. The lignocellulosic biorefinery has on-site cellulase enzyme production. The case study is literature based but highly relevant based on the international promotion of biofuels from residues. The biorefinery system is addressed "cradle-to-gate" (Figure 7).

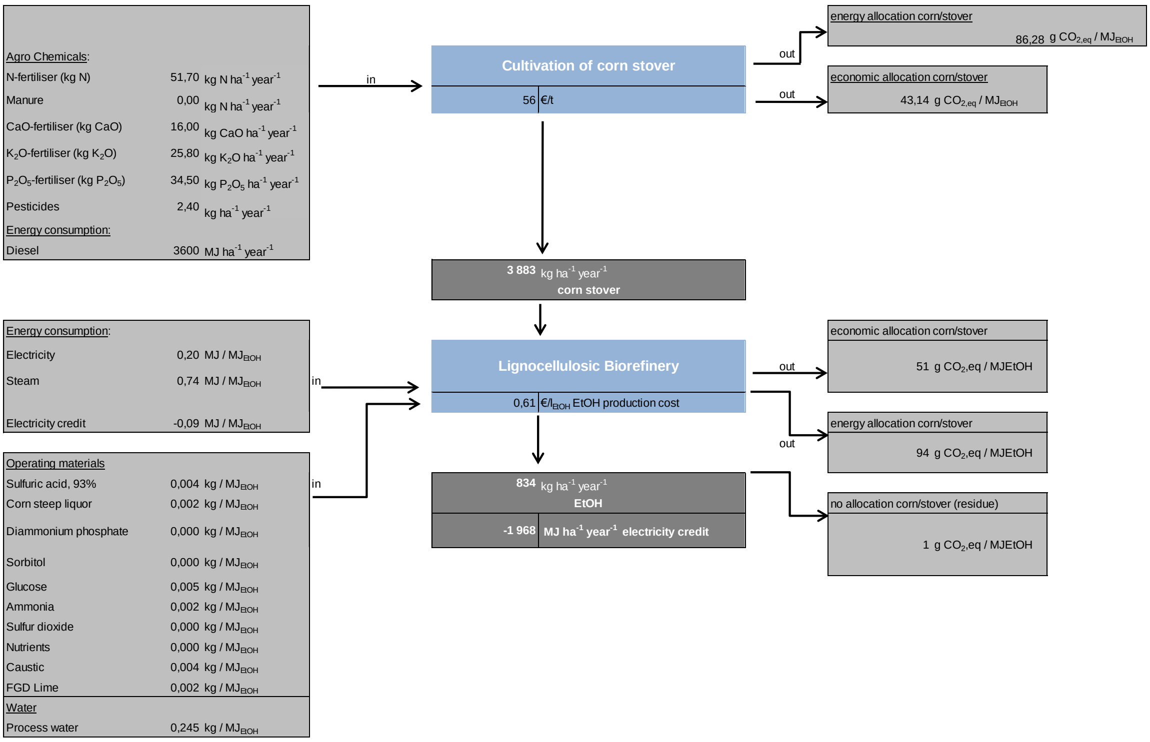

Figure 7 Overview TEE assessment: process pathways ethanol synthesis from corn stover.

The biorefinery process described in the following section is designed for a capacity of approximately 104 t dm/h corn stover, operating 24 hours, 6 days a week. This corresponds to approx. 7,500 plant operating hours per annum. The ethanol production capacity of the biorefinery is about 164,000 t/a. Humbird et al. (2011) provides a valid and transparent data base for the techno-economic analysis of a lignocellulosic biorefinery at commercial scale. The data from the techno-economic analysis is a simulation listing all CAPEX and OPEX in detail, which is publicly available. Therefore, this work was chosen to be the basis for the factsheet of the lignocellulosic biorefinery process in this case study, as it displays a realistic, technically and economically feasible process model.

3.1.2 Part A: Biorefinery plant

Ethanol is produced based on corn stover. The process route corresponds to the corn stover based ethanol biorefinery process described by (Humbird et al., 2011). The milled corn stover is pre-treated in a dilute-acid pre-treatment process (18 mg sulphuric acid/gdry biomass). Enzymatic hydrolysis is used to convert the hemicellulose and cellulose into monomeric C5 and C6 sugars and lignin, which are the platform in the described ethanol biorefinery. Cellulase is produced on-site. The C5 and C6 sugars are fed into fermentation tanks. The fermentation uses metabolically engineered strains of Saccharomyces cerevisiae microorganisms that are capable of co-fermenting xylose and glucose to ethanol, whereas a separate hydrolysis and fermentation process (SHF process) is applied. Finally, the fermentation broth is fed into a distillation process. Distillation columns and molecular sieves are used to produce 99.5 % ethanol. There are two main by-products in this biorefinery concept: lignin used for energy generation and stillage used for energy production via anaerobic digestion and as fertilizer. The lignin is fed into a CHP plant in order to produce thermal energy and electricity which is used as process energy for the biorefinery process. Additionally, the stillage by-product from the distillation process is used as an agricultural fertilizer. If the stillage is dried, it may also be used as energy carrier. The cultivation of corn stover was taken into account for the environmental part of the case study whereas three different allocation approaches are chosen (energetic allocation, economic allocation and no-allocation to corn stover as it is a residue). The basic process pathway is illustrated in Figure 8.

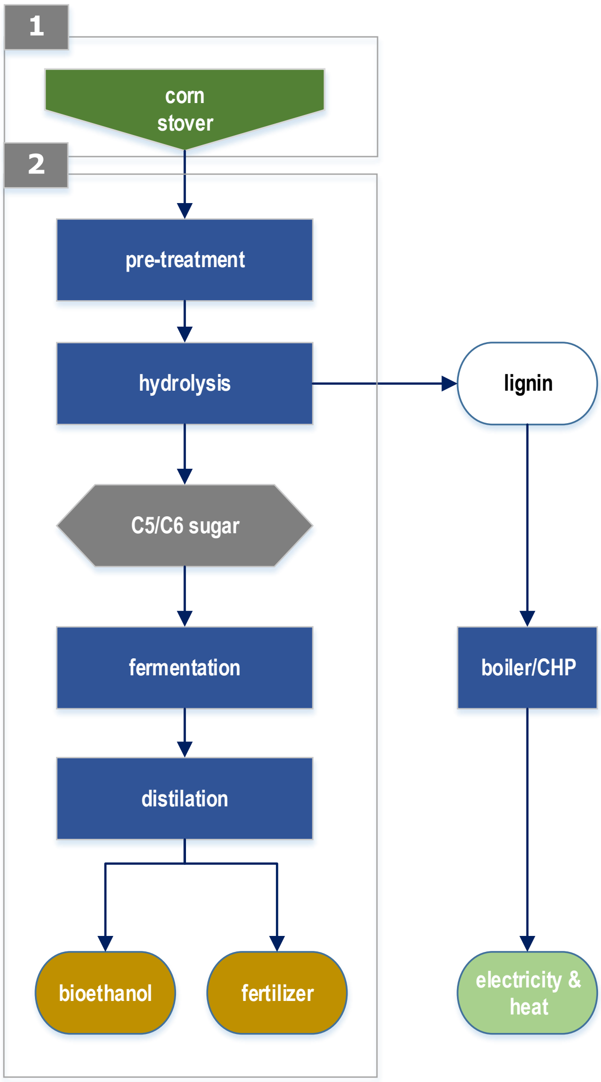

Figure 8 Case study #1: Lignocellulosic ethanol biorefinery pathway.

Furthermore, Table 5 summarizes the key characteristics for the considered case study.

Table 5 Key characteristics case study 1 ethanol.

2-platform (C5&C6 sugars, lignin) biorefinery to produce bioethanol, electricity & heat from corn stover							
State of technology		commercial / concept					
Country		US, EU 27					
Main data source		literature (technical report Humbird et al., 2011)					
Products				**Auxiliaries**			
	Ethanol	4,400	TJ/a		Heat	3,273	TJ
	Electricity	387	TJ/a		Chemical inputs	82,727	t/a
Costs				**Feedstock**			
	Investment	422	Mio. €		Corn stover	1,535	TJ/a
	Feedstock	48	Mio. €			764	kt/a
	Operating	26	Mio. €	**Conversion rates (Efficiencies)**			
	Labour	3	Mio. €		Corn stover to EtOH	0.35	MJ_{EtOH}/MJ
					By-products to CHP	0.46	MJ_{EtOH}/MJ

The mass balance (Figure 9) for the considered process pathway illustrates the feedstock intensity of the lignocellulosic biorefinery. Various pre-treatment processes are applied in the field. Typical for all biochemical conversion pathways is the high water turnover in these processes, which deserves special attention and optimal design. Based on the feedstock the proportion of lignin varies and its utilisation is a key aspect influencing the environmental performance of the value chain.

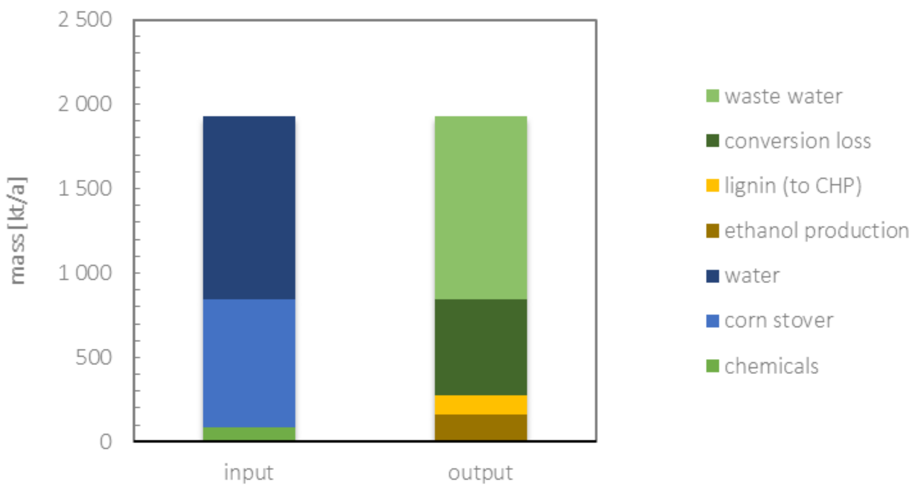

Figure 9 Mass balance case study 1.

The data on process economics is also based on (Humbird et al., 2011). The CAPEX and OPEX presented in table 5 reflect the aggregated process economics for the process route and plant capacity of the case study. To analyse the economic feasibility of the biorefinery within the TEE assessment more detailed economic data as presented in Table 5 was used. With this data, it was possible to calculate the fixed and variable production costs of the 2nd generation ethanol biorefinery. Based on this evaluation the variable costs provide a higher share on the overall costs than the fixed costs. This effect originates from the high amount of raw material supply needed for the process. The raw material supply costs have a significant impact on the techno-economic analysis and its results.

The results of the economic analysis as shared of total annual cost is shown in Figure 10. It can be seen, that the variable costs (raw material supply, auxiliary and operating material, disposal costs and water supply costs) provide a higher share on the overall costs than the fixed costs (write-offs, imputed interest, maintenance and insurance). This effect originates from the high amount of raw material supply needed for the process. The cost structure of feedstock supply chains that differs significantly between geographic regions following the raw material supply costs, has a significant impact on the techno-economic performance of a lignocellulosic biorefinery. Other main cost drivers in this case study are related to auxiliary and operating materials as well as imputed interest based on the significant investments required. This interpretation is confirmed by the sensitivity analysis conducted and present in Figure 11– with up to 200% product specific cost variation based on raw material input cost variation followed by the total investment costs – with up to 100% cost variation. Please note, that the costs of energy, others and administration have a deviation of 0%. The self-sustained energy supply within the biorefinery via the by-products imposes benefits on the environmental and economic perspective.

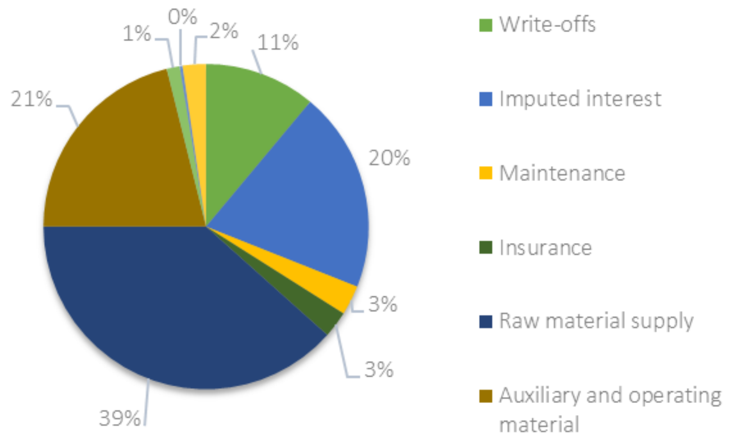

Figure 10 Share of costs case study 1.

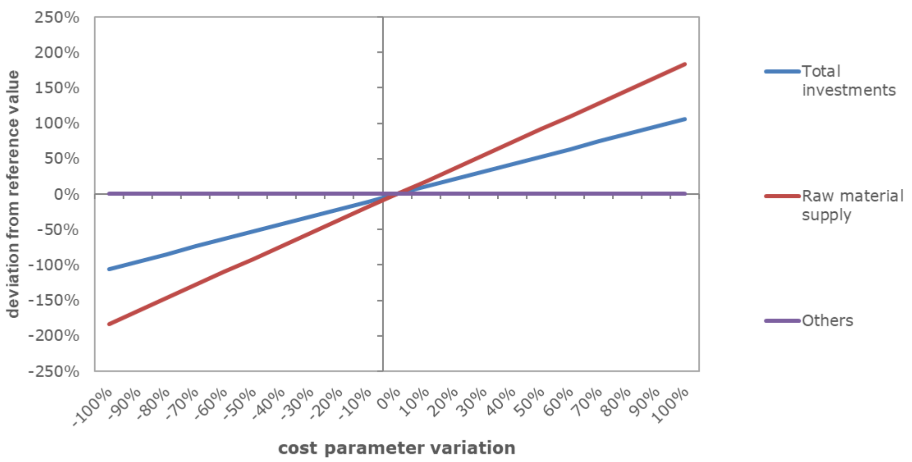

Figure 11 Sensitivity analysis of the cost structure in case study 1.

Based on the self-sustained energy supply within the biorefinery especially no effect on the sensitivity of the overall cost structure is related to the energy costs.

3.1.3 Part B: Value Chain Environmental Assessment

The environmental impacts of 2nd generation ethanol biofuel production are comprehensively examined in the literature. Most studies apply a life cycle assessment approach (Wang et al., 2012; Spatari et al., 2010; Uihlein and Schebek, 2009; Slade et al., 2009; Karlsson et al., 2014; Koponen et al., 2013; González-García et al., 2009). Currently the LCA methodology is applied in varying forms for evaluating environmental impacts of biofuel production. In a European context especially, the methodology defined in the RED has to be highlighted as it aims to establish a unified life cycle based calculation of greenhouse gas savings of biofuels compared to their fossil equivalents (Whittaker et al., 2011) and is also applied in this comparison of the lignocellulosic biorefinery with fossil reference production system. The systems are analysed based on the system boundary cradle-to-gate (also called well-to-tank) and the functional unit of MJ fuel produced (Figure 12).

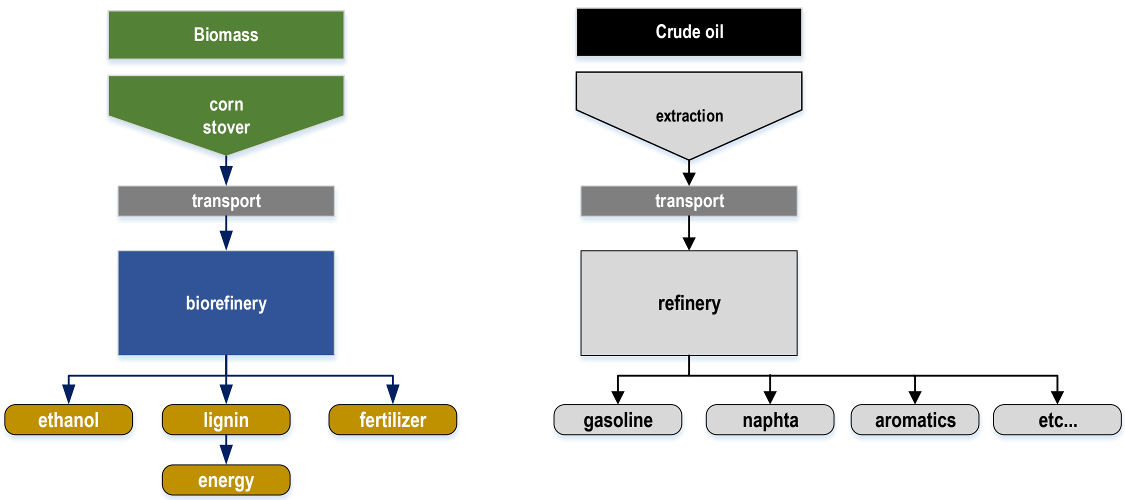

Figure 12 Biorefinery and reference system – value chain case study 1 (cradle-to-gate).

Table 6 summarises the main results from the TEE assessment. If the corn stover raw material is defined as residual agricultural by-product with no allocation of GHG emissions from major agricultural operations, then the biorefinery operations provide the strongest impact on the results. If credits for excess energy are applied in other product systems, GHG emission from biorefinery operations can be compensated and the carbon footprint of the product system decreases significantly and the considerable advantages become apparent from implementing a biorefinery. Figure 13 and 14 show the GHG emissions and CED comparison with fossil reference systems of case study 1.

Table 6 Overview TEE assessment results case study 1.

Greenhouse gas emissions			
Raw material sourcing (corn stover)		2,651	$t_{CO2,eq}$
Biorefinery		35,017	$t_{CO2,eq}$
Reference system		368,751	$t_{CO2,eq}$
Savings		331,083	$t_{CO2,eq}$
Cumulated energy demand			
Fossil (material transports,..)		30	TJ
Renewable (corn stover, …)		12,609	TJ
Reference system		5,302	TJ
Difference	+	7,337	TJ
Costs			
Annual costs		127	Mio. €
Specific costs		0.61	€/l_{EtOH}
Investment costs		422.5	Mio. €
Revenues			
Revenues Ethanol		140.7	Mio. €
Specific Revenues		~ 0.68	€/l_{EtOH}

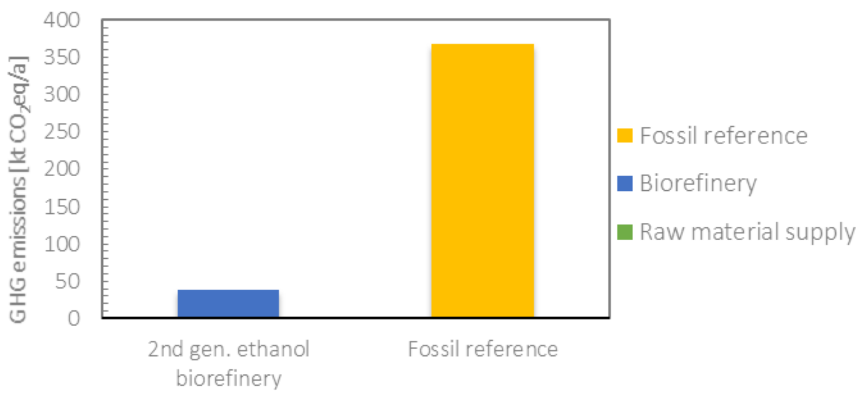

Figure 13 Greenhouse gas emissions of biorefinery compared to reference – case study 1.

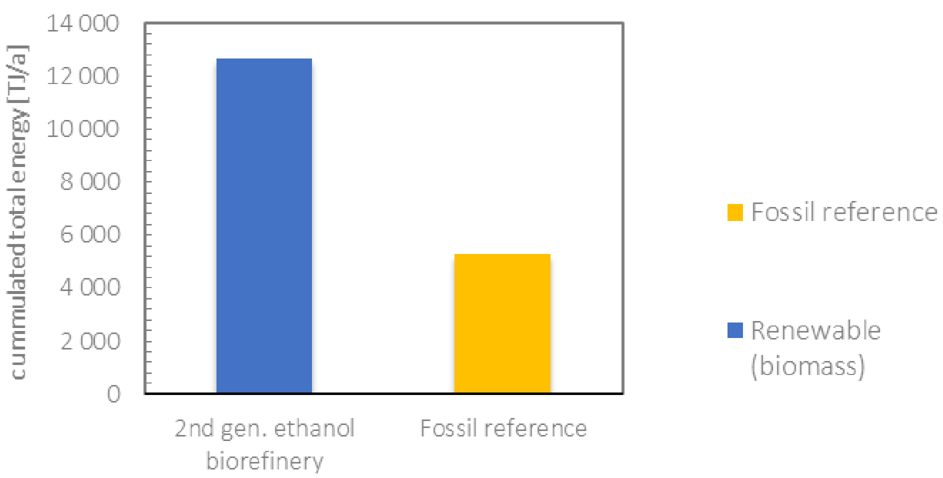

Figure 14 Cumulative energy demand of biorefinery compared to reference – case study 1.

As stated above the assessment follows a cradle-to-gate approach. The assessment of the GHG emissions considers the detailed chemical use in the corn stover based ethanol biorefinery process, use of electricity and steam from by-product utilisation (lignin and biogas from on-site anaerobic digestion of waste water) and direct emissions of the product system. In comparison with the reference system under the given assumption within case study 1 the cumulated fossil energy demand and the GHG emissions are significantly lower for the biorefinery systems compared to the reference system. Nevertheless the cumulated total energy demand of the biorefinery operations is significantly higher than for the fossil reference based on feedstock input and conversion efficiency. Efficiency improvements in this regard can potentially leverage the deployment of the biorefinery system. The GHG emissions and cumulated (fossil) energy demand are strongly dependent on the primary energy input to the conversion process. If e.g. natural gas for thermal energy and electricity from local grids is used instead of by-products the environmental performance of the bioethanol usually significantly decreases. Concerning the raw material input, corn stover is an agricultural residue whereas the agricultural operations are allocated to the main product corn, if alternatively the corn is converted to ethanol instead of the residual stover a significant proportion of the biorefineries environmental impacts originate from these agricultural inputs (e.g. fertilizer, tillage, etc.).

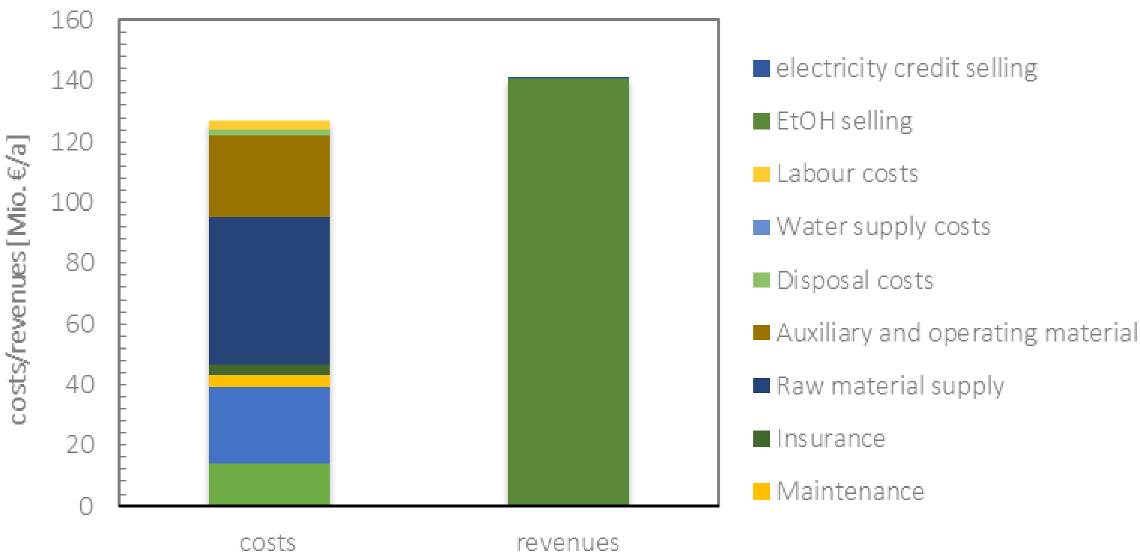

Figure 15 Costs and revenues - case study 1.

The assessment of costs and revenues (Figure 15) are highly challenged by the case specific relevance of generic data, which cannot be achieved. Under the given assumptions the revenues are solely determined by the bioethanol sales, which is strongly determined by international biofuels policies, promotion and price volatilities in world market. The lignin by-product is not shown as it is accounted for in the energy provision in the integrated biorefinery approach. If the lignin could be marketed as a product, the cost and revenue structure changes but consequently alternative energy supply is inevitable. Additional economic impacts on e.g. fertilizer provision from anaerobic digestate is not considered based on limited data availability. Detailed assumptions can be found in the supplementary data of the case study.

3.2 Case study # 2: 2-platform (C5&C6 sugars, biogas) biorefinery to produce the biopolymer Polyhydroxybutyrate (PHB), electricity & heat from sugar beet or sugar cane

3.2.1 Introduction

PHB is a product based on sugar cane via the biochemical fermentation route. The biopolymer PHB (other terms: polyhydroxybutyric acid, poly-(R)-3-hydroxybutyrate, P(3HB)) is a polyhydroxyalkanoate (PHA). The polyolester PHB is isotactic and absolutely linear. It belongs to the group of thermoplastic polyesters and can therefore be formed under heat potentially substituting applications currently served via fossil based plastics (e.g. polypropylene). 1st generation sugar is the feedstock of the biorefinery, by-products from raw material processing are sugar cane bagasse and biogas from PHB fermentation. An overview is provided in Figure 16.

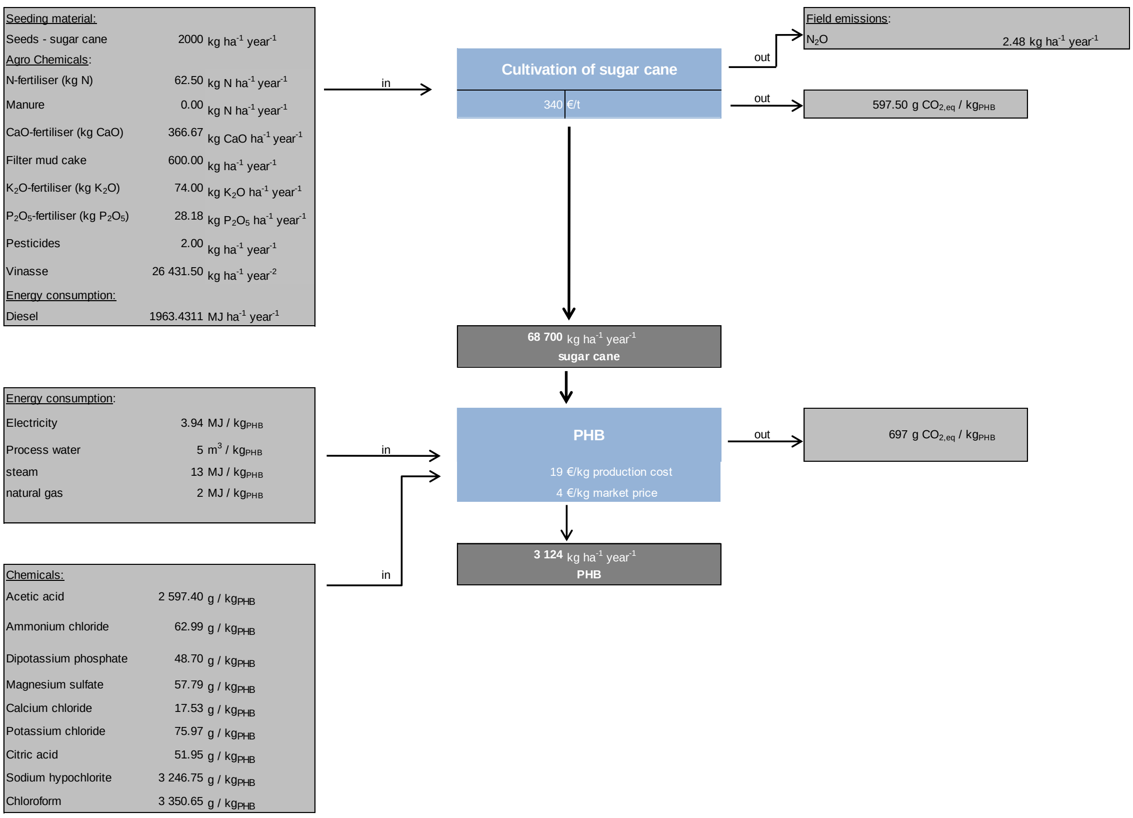

Figure 16 Overview TEE assessment: process pathway PHB from sugar cane.

The mass and energy flows as well as the process economics are based on available literature. The data on mass and energy flows are predominantly based on (Mudliar et al., 2007, Harding et al., 2007), Align biofuel GHG emission calculations in Europe (BioGrace 2018, Haddad et al., 2018) and the process economics are based on (Mudliar et al., 2007, Thrän and Pfeiffer, 2015, Compressed Air Solutions Ltd, 2018, Levett et al., 2016, Harding et al., 2007). Data for sugar cane cultivation is based on the BioGrace tool. The EU approves this database for the harmonized calculation of biofuels greenhouse gas emissions. The PHB biorefinery process described is designed for a capacity of processing 100 m^3 fermentation broth per day with a PHB yield of 44 % - an up-scaling from small scale to industrial is required for future assessments. The sugar extraction from sugar cane is a state-of-the art process.

The conversion efficiency of sugar to PHB is assumed to be 2.68 $kg_{sucrose}/kg_{PHB}$ (Haddad et al., 2018). Downstream processing of sugar is performed as a batch fermentation process – batch time is 96 h - using four fermentation tanks in order to guarantee a continuous operation. The fermentation broth is fed into a separation process where the PHB rich biomass is harvested. For the harvesting step a decanter centrifuge is utilized and the resulting biomass cake is brought to a lysis tank where the biomass cake is treated with a solvent to crack the cell walls. The PHB is then extracted from the biomass cake. After a filtration and evaporation step, the PHB is ready for storage (Mudliar et al., 2007). By-products of the biorefinery process such as bagasse from sugar extraction as well as the residual biomass are used for process energy production. Bagasse is fed into a CHP plant to generate electricity and thermal energy and the residual biomass from the PHB extraction is valorised in an anaerobic digestion plant.

3.2.2 Part A: Biorefinery plant

The PHB biorefinery process described in the following fact sheet is designed for a capacity of processing 100 m^3 fermentation broth per day with a PHB yield of 44 %.

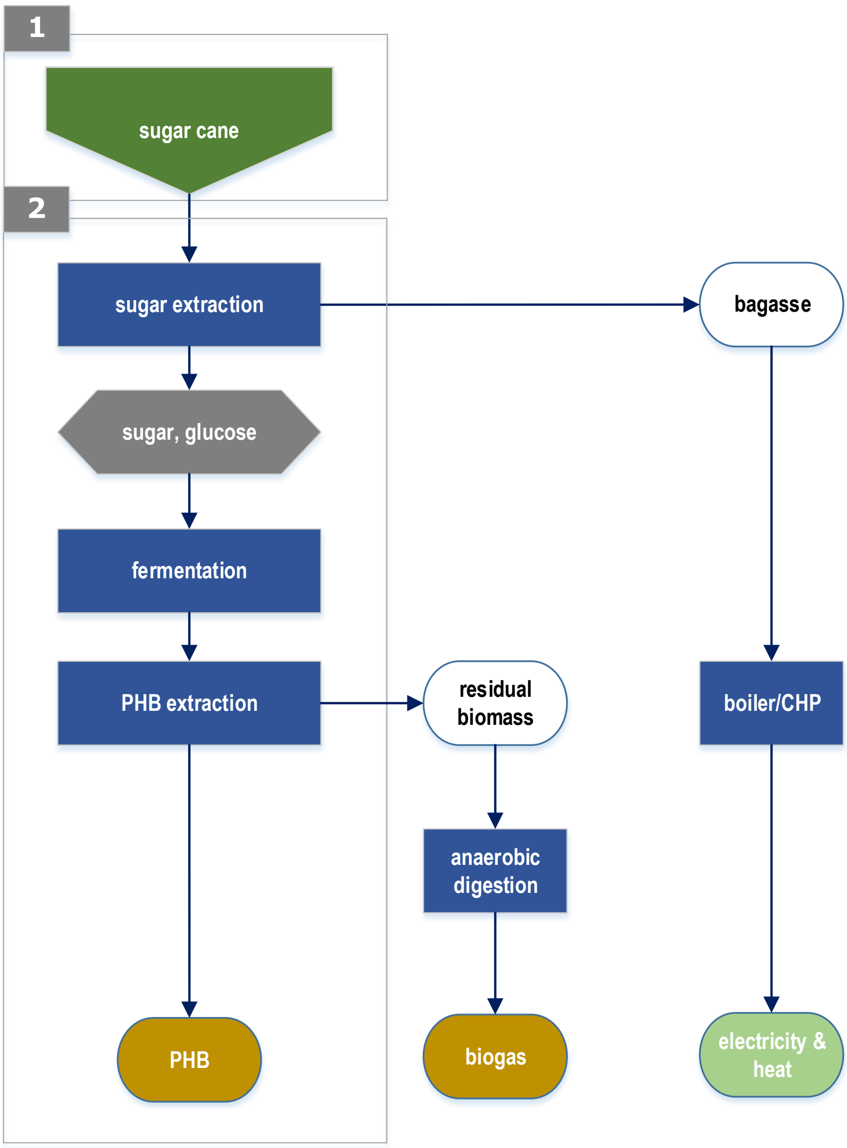

Figure 17 Poly-hydroxybutyrate (PHB) biorefinery pathway.

Table 7 Key characteristics case study 1 PHB.

2-platform (C5&C6 sugars, biogas) biorefinery to produce the biopolymer PHB, electricity & heat from sugar cane							
State of		Demonstration					
Country		EU 27					
Main data		literature					
Products				**Auxiliaries**			
	PHB	46,200	kg/a		Energy	309,007	MJ
					Chemical	407,668	kg/a
Feedstock				**Costs**			
	Sugar	1,015,938	kg/a		Investment	606,673	€
					Feedstock	345,419	€/a
PHB extraction rate				**Efficiencies**			
		5%			Sugar cane to PHB	22	kg/kg

Considering a comparison between the minimum selling price and the market price, the results of the analysis the conventional process seems favourable. The biorefinery minimum selling price is ~5 times higher than the market price. PHB production is currently not economically feasible compared to the fossil based reference systems on a simple cost calculation basis for the small scale case study examined. A biorefinery based PHB production system is consequently dependent on the willingness to pay a green premium or receive public subsidies. It has to be mentioned that the economic analysis for PHB production is based on a scaled-up process. The production cost decrease as the plant capacity increases (economies of scale) and as the PHB yield increases (learning effects). The lowest PHB production costs are reported to be at 5.40 €/kg for a fermentation capacity of 1,000 m^3 and a PHB yield of 70 % is applied (Mudliar et al., 2007). Technical and economic process development appears to have significant potential for improvement towards broad market penetration of biobased polymers such as PHB.

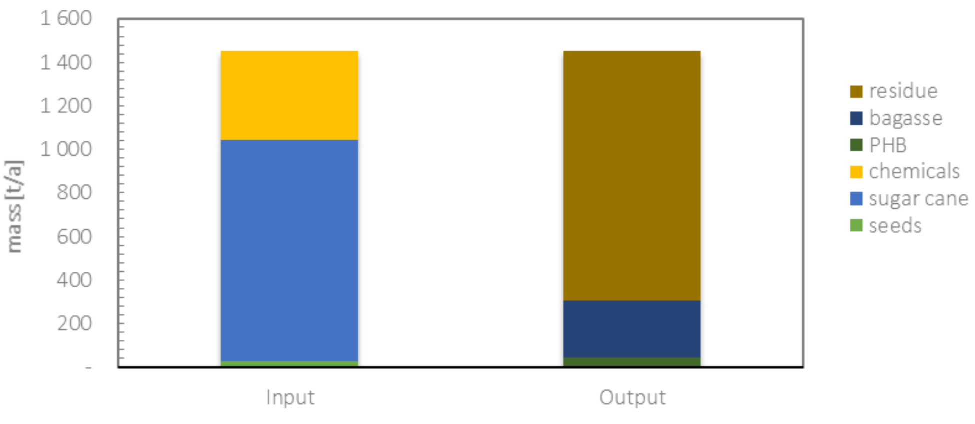

Figure 18 mass balance - case study 2.

The results of the techno-economic estimations are shown in Figure 19. It can be seen that the variable costs provide a higher share on the overall costs than the fixed costs. This effect originates from the amount of raw material supply needed for the process. Other main cost drivers in this case study are related to auxiliary and operating materials as well as imputed interest on the amortization of infrastructure (CAPEX) based on the significant investments required.

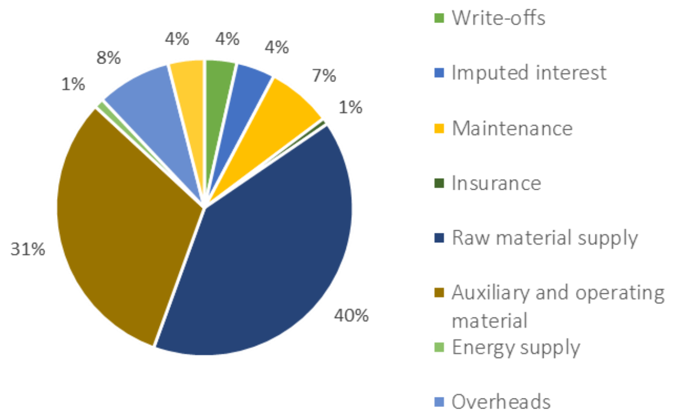

Figure 19 share of costs - case study 2.

3.2.3 Part B: Value chain Environmental Assessment

Figure 20 provides an overview of the reference system considered, following a cradle to gate approach. Based on that, the TEE assessment helped to identify the cumulated energy demand of the biorefinery compared to the reference model, as shown in Figure 21 and the GHG emissions as shown in Figure 22.

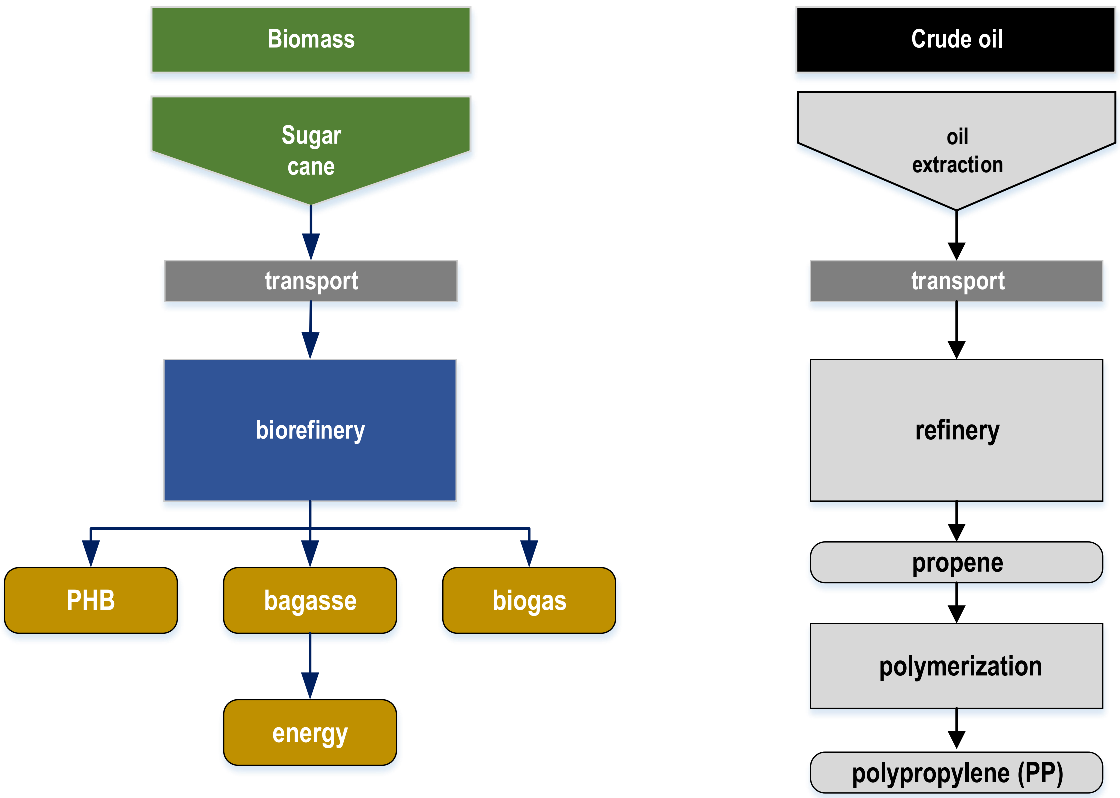

Figure 20 Biorefinery and reference system – value chain case study 2 (cradle to gate)

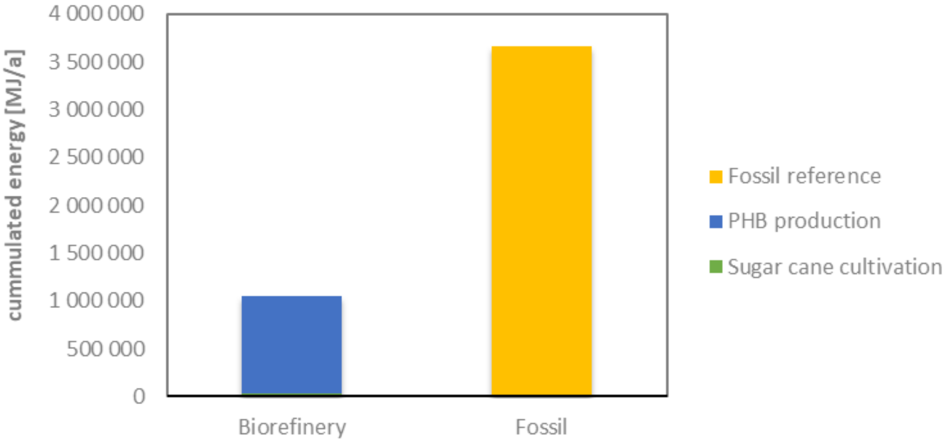

Figure 21 Cumulated energy demand of biorefinery compared to reference plant – case study 2.

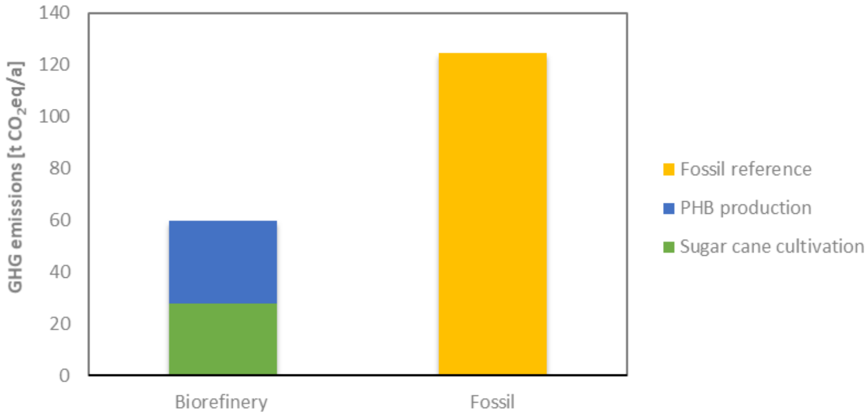

Figure 22 Greenhouse gas emissions of biorefinery compared to reference plant - case study 2.

The overall results of case study #2 can be found in Table 8

Greenhouse gas emissions		
Sugar cane cultivation	27,605	$kg_{CO2,eq}$
Biorefinery	32,199	$kg_{CO2,eq}$
Reference system	124,740	$kg_{CO2,eq}$
Savings	64,936	$kg_{CO2,eq}$
Cumulated energy demand		
Sugar cane cultivation	29,035	MJ
Biorefinery	1,016,400	MJ
Reference system	3,670,590	MJ
Savings	2,625,155	MJ
Costs		
Annual costs	862,080	€
Specific costs	19	€/kg_{PHB}
Investment costs	606,673	€
Revenues		
Revenues PHB	172,788	€
Specific Revenues	3.74	€/kg_{PHB}

Table 8 Overview TEE assessment results - case study 2.

3.3 Case study # 3: 3-platform (C6 sugar, animal feed, lipids) biorefinery to produce the biopolymer PLA, animal feed, lipids from food waste

3.3.1 Introduction

Case study 3 is based on a study for the valorisation of mixed food wastes from the domestic sector. That is to ferment the C6 sugars after pre-treatment to lactic acid and valorise the remaining solids to a lipid enriched faction and animal feed. Polylactides, also called polylactic acids (PLA), are synthetic polymers that belong to the group of polyesters. They are composed of many chemically bound lactic acid molecules and are promising biobased building blocks. Figure 23 shows the biorefinery pathway for polylactic acid (PLA) production.

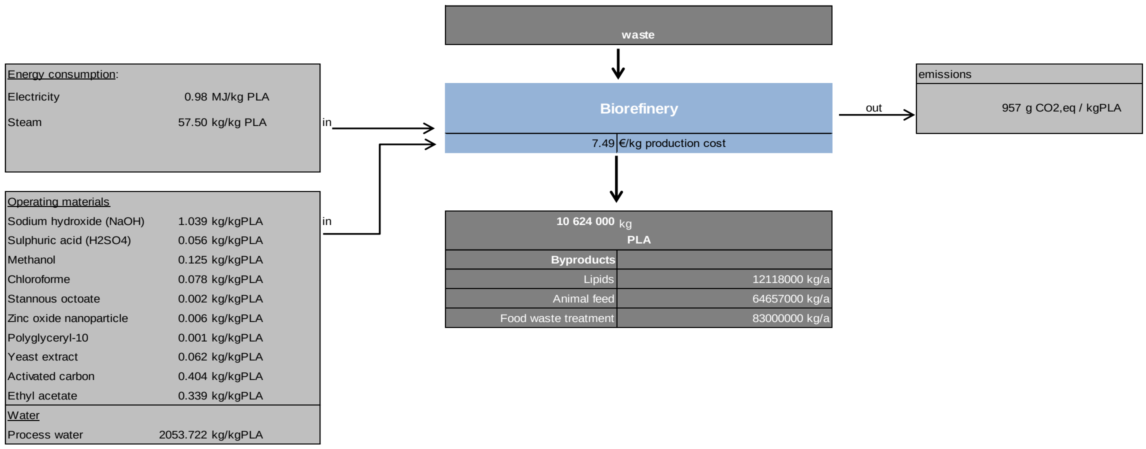

Figure 23 Overview TEE assessment: process pathway Polylactic acid (PLA).

3.3.2 Part A: Biorefinery plant

Food waste is the feedstock for PLA production, as shown in Figure 24. Accordingly, no up-stream process for feedstock supply is considered. The fact sheet for the PLA biorefinery is based on literature data (Kwan et al., 2018). The assumed biorefinery plant has the capacity to process 10 t food waste powder per hour. Assuming 8,300 plant working hours per year, the biorefinery processes up to 83,000 t food waste powder per year. The platform for the biorefinery is glucose obtained from the carbohydrate rich food waste. The glucose yield is at 0.32 gglucose/gfood waste powder. The food waste powder is the result of pre-treatment with a commercial food waste treatment plant. Pre-treatment is followed by fungal hydrolysis in order to extract the sugar from the food waste. Aspergillus awamori and Aspergillus oryzae are used for the hydrolysis step. Hydrolysis takes 36 h in a bioreactor. The fungal biomass is produced on-site in a solid-state fermentation step. Hydrolysis if followed by a fermentation step of 36 h duration using lactobacillus. After an extraction process, lactic acid is obtained from the fermentation broth. Lactic acid is an important intermediate product of the PLA biorefinery which is ready for market. Downstream processing of lactic acid comprises of lactide synthesis mixing lactic acid with a zinc oxide nanoparticle dispersion. Lactide is the second intermediate product of the biorefinery process which potentially could be sold on the market. The Lactide is polymerized in order to obtain PLA. The remaining solids are utilized as animal feed as it contains valuable carbohydrates, proteins and lipids. Lipids are another by-product of the PLA biorefinery (Kwan et al., 2018). These lipids can be utilized as platform for further biorefinergy products (e.g.: fatty acids for polymerization and bio-plastic production; biodiesel production). Accordingly, the current process model of the PLA biorefinery focusses more on material production than on producing energy carriers.

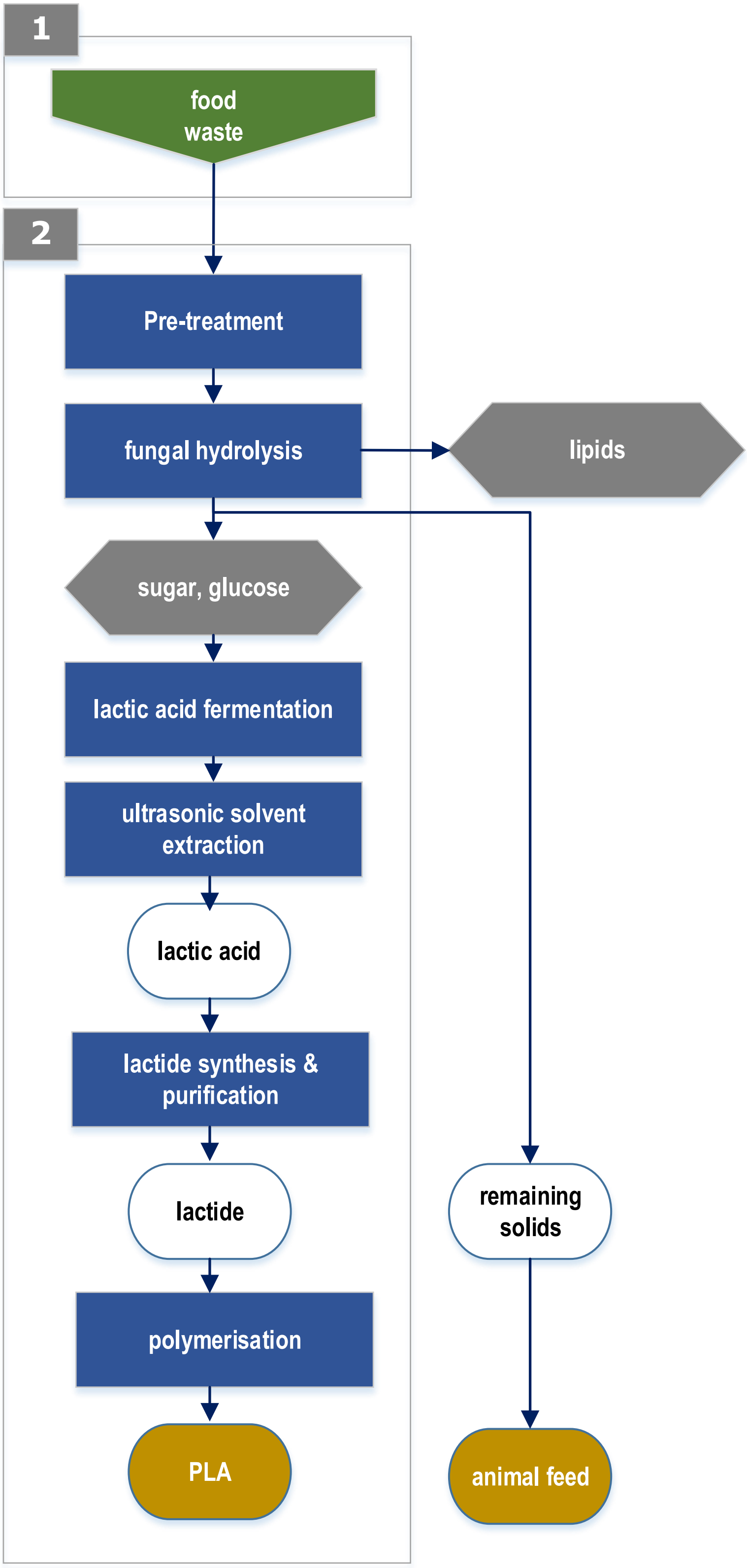

Figure 24 Process pathway PLA from waste.

The bioconversion process from food waste to high-value PLA was developed in laboratory scale und simulated for a technical feasibility (Table 9).

Table 9 Key characteristics case study 3 PLA.

3-platform (C6 sugar, animal feed, lipids) biorefinery to produce the biopolymer PLA, animal feed, lipids from food waste							
State of technology		commercial / concept					
Country		China					
Main data source		literature					
Products				**Auxiliaries**			
	PLA	10,624	t/a		Electricity	10,439	GJ
	Lipids	12,118	t/a		Chemical inputs	22,438	t/a
	Animal feed	64,657	t/a				
Feedstock				**Costs**			
	Food waste	83,000	t/a		Investment	116.5	Mio. US$
					Feedstock costs	16.2	Mio. US$

From an input of 83,000 tonnes per year of food waste from domestic collection such as kitchen waste, whey, coffee mucilage, brewer's spent grains 10 624 t of PLA, 12 118 t of lipid and 64.657 t of animal feed fraction are produced (Figure 25).

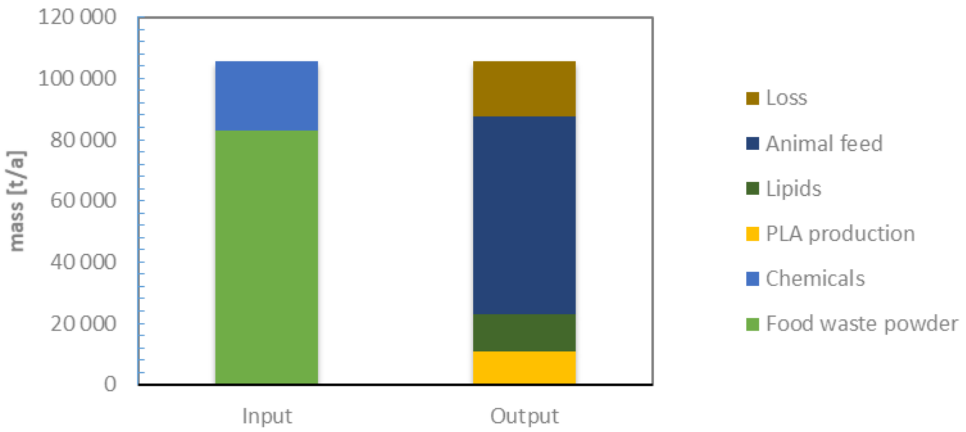

Figure 25 mass balance - case study 3.

The total capital cost was calculated by addition of fixed capital investment costs and working capital costs. The estimated operating cost includes the total variable production cost, fixed charges, plant overhead costs and general expenses (Figure 26).

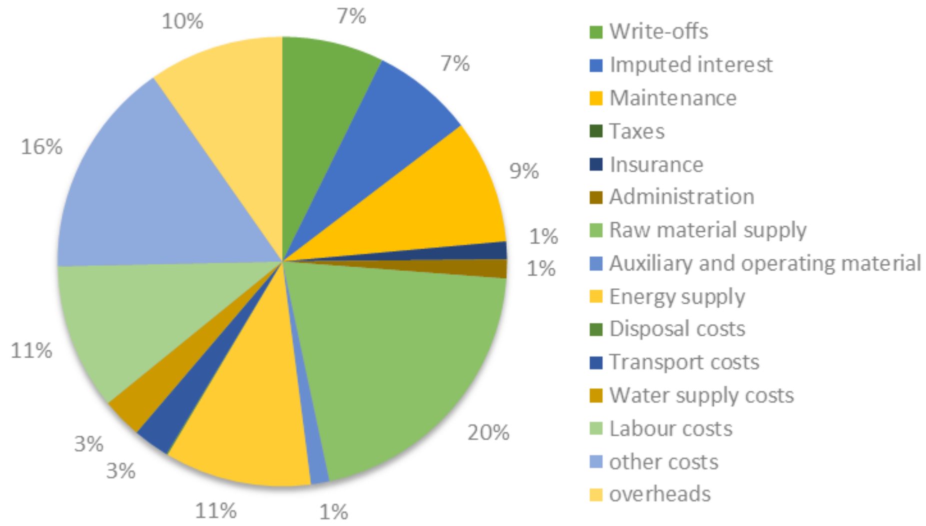

Figure 26 share of costs - case study 3.

PLA is best compared to PET-and can be, in principle, processed with comparable techniques (e.g. blow moulding, thermoforming, etc.). Higher grades are also available for injection moulding applications and can be used as an alternative to polystyrene (PS). This biopolymer is also suitable for fibre extrusion where it can be used as a substitute for polypropylene (PP) which is selected as reference system in this case study (Figure 27).

3.3.3 Part B: Value Chain Environmental Assessment

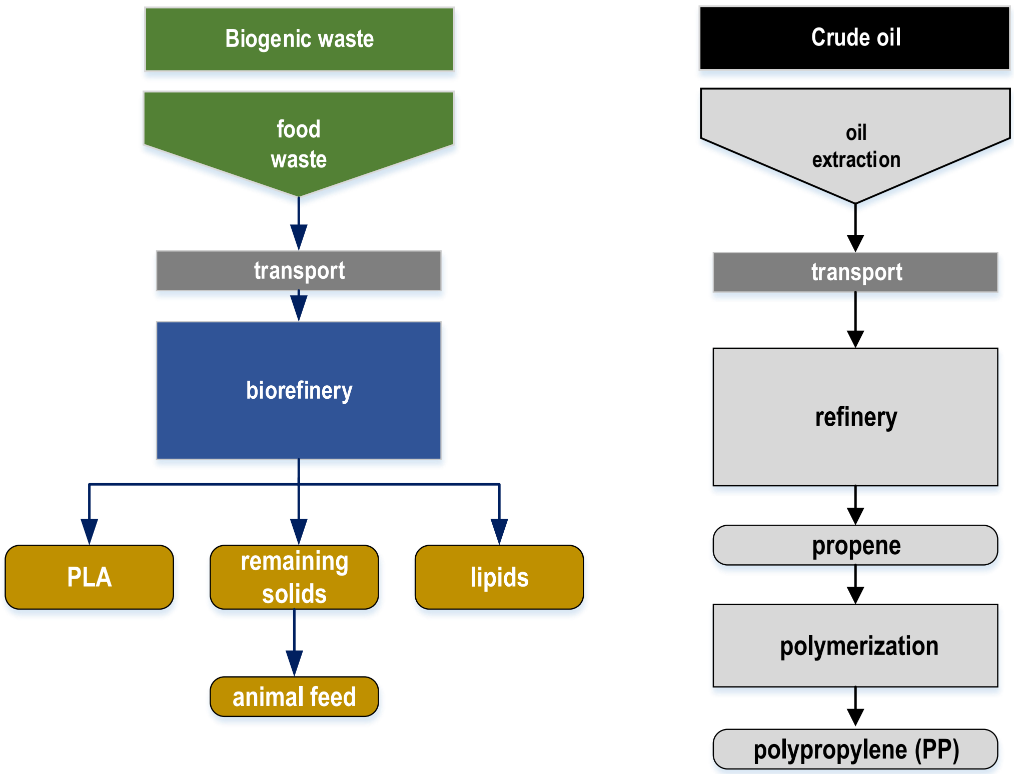

Figure 27 Biorefinery and reference system – value chain case study 3 (cradle to gate).

The overview of major results of the TEE assessment is provided in Table 10

Table 10 Overview TEE assessment results – case study 3.

Greenhouse gas emissions		
Biorefinery	10,164	$t_{CO2,eq}$
Reference system	28,685	$t_{CO2,eq}$
Savings	- 8,521	$t_{CO2,eq}$
Cumulated energy demand		
Biorefinery	10,439	GJ
Reference system	844,077	GJ
Savings	- 3,638	GJ
Costs		
Annual costs	79.5	Mio. US$
Specific costs	7.49	US$/$kg_{PLA}$
Investment costs	116.5	Mio. US$
Revenues		
Revenues PLA	55.4	Mio. US$
Revenues lipids	6.1	Mio. US$
Revenues animal feed	29.1	Mio. US$
Food waste treatment	6.4	Mio. US$
Specific Revenues	9.13	US$/$kg_{PLA}$

Results are presented from an environmental assessment based on GHG emissions and cumulated energy demand. A comparison of the food waste based biorefinery with the production of PLA, and value adding mass fractions of lipids and animal feed indicate a significantly better performances compared to the fossil reference system based on the input data of the case study (Figure 28 and Figure 29).

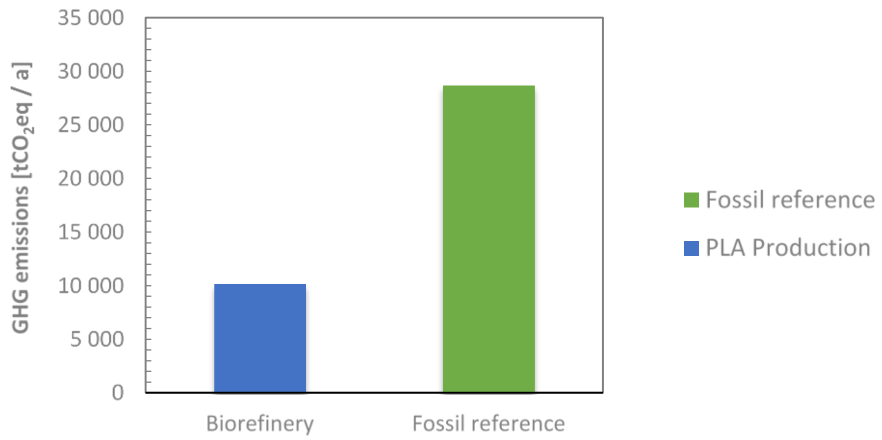

Figure 28 Cumulated energy demand of biorefinery compared to reference plant - case study 3.

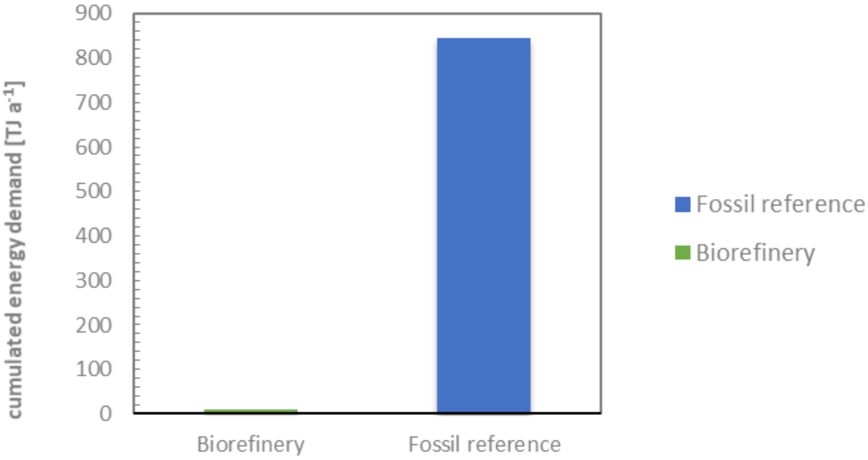

Figure 29 Greenhouse gas emissions of biorefinery compared to reference plant - case study 3

The cost and revenues comparison (Figure 30) and sensitivity analysis indicate that the prices of PLA significantly affect the economic performance of the biorefinery case study. The price attainable is in turn strongly dependent on the achievable purity of precursor lactic acid and the associated suitability for food, drug and other use whereas this biorefinery case study assumes a technical polymer grade is produced. Additionally, the lipid fraction is designated as a feedstock for biodiesel production.

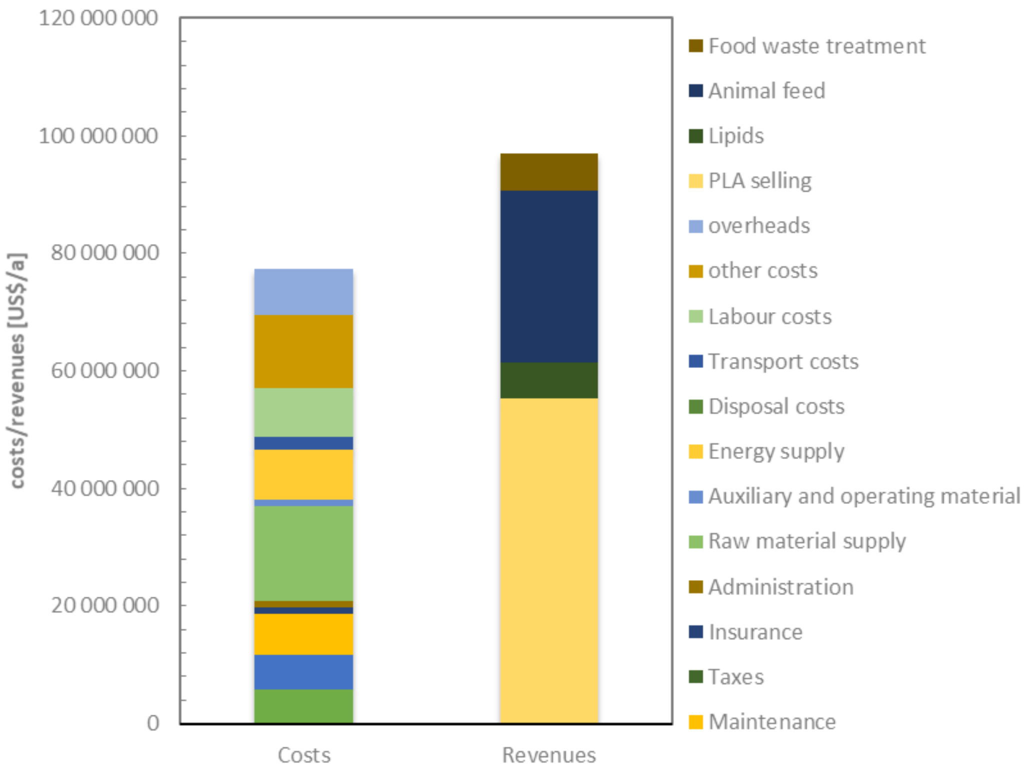

Figure 30 Costs and revenues - case study 3.

3.4 Case study # 4: 3-platform (pulp, lignin, energy) biorefinery to produce pulp, lignin and energy from wood chips

3.4.1 Introduction

In general, a lignocellulose biorefinery can process any type of annual and perennial grass, residues from agriculture as well as any wood and wood-like biomass. The primary refining consists of mechanical pre-treatment steps as well as physical-chemical pulping of the lignocellulose, followed by fractionation steps. Secondary refining contains further processing steps for the raw products of cellulose, hemicellulose and lignin. Depending on the type of processing, mixtures of raw products and by-products can be generated (VDI, 2016). Case study 4 refers to a lignocellulose biorefinery, focusing on the provision of kraft lignin as the by-product of a kraft pulp process. The assessment covers the production of pulpwood (spruce & pine), the kraft pulping process and the LignoBoost process (Figure 31). It is assumed that all processes take place in Europe.

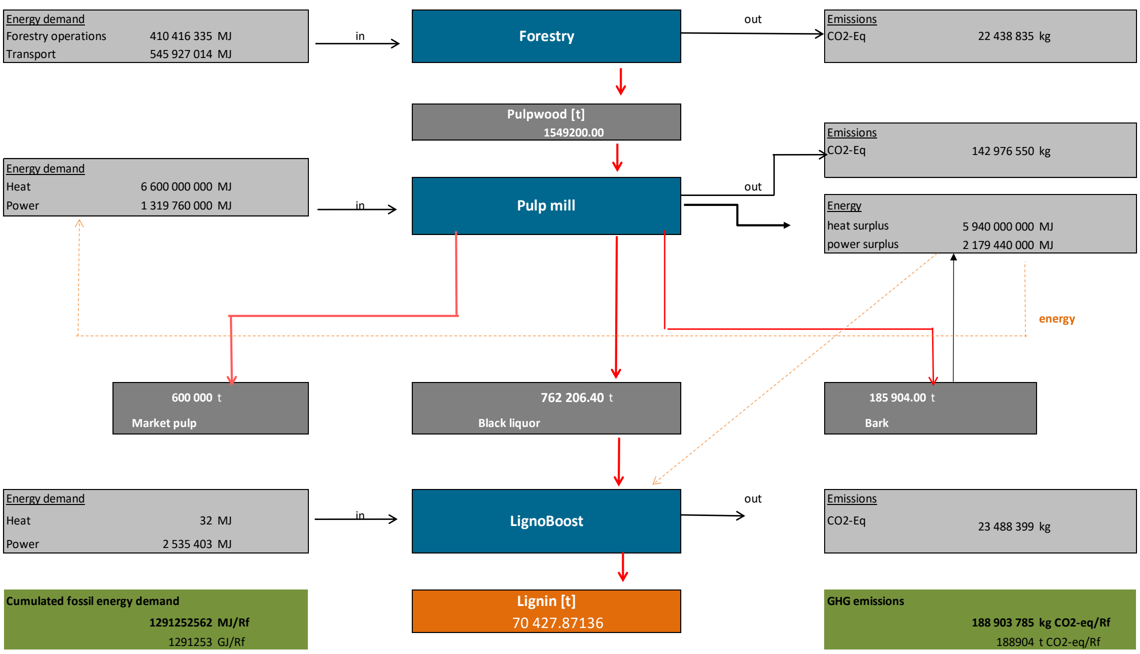

Figure 31 Overview TEE assessment: process pathways lignin from wood chips.

3.4.2 Part A: Biorefinery plant

Using wood (round wood) in a kraft pulp mill at commercial scale, provides Kraft pulp, Kraft lignin and energy, as shown in Figure 32. The system boundaries are set as cradle-to-gate, starting at the forest operations (incl. planting, thinning, harvesting etc.), the pulping process and the lignin extraction via the LignoBoost process. The products considered are: pulp as main product and reference flow, lignin as by-product and an energy surplus (electricity to the grid). The assumptions are based on a state of the art Kraft pulp mill, with an annual capacity of 600 000 Adt pulp. The lignin extraction is assumed to be 15% in order to still be able to provide enough energy to cover the mill's energy needs. Natural gas is assumed as an auxiliary fuel. The system boundaries are set as cradle to gate and the development status of the biorefinery is (depending on the specific case) between TRL 6 and TRL 9.

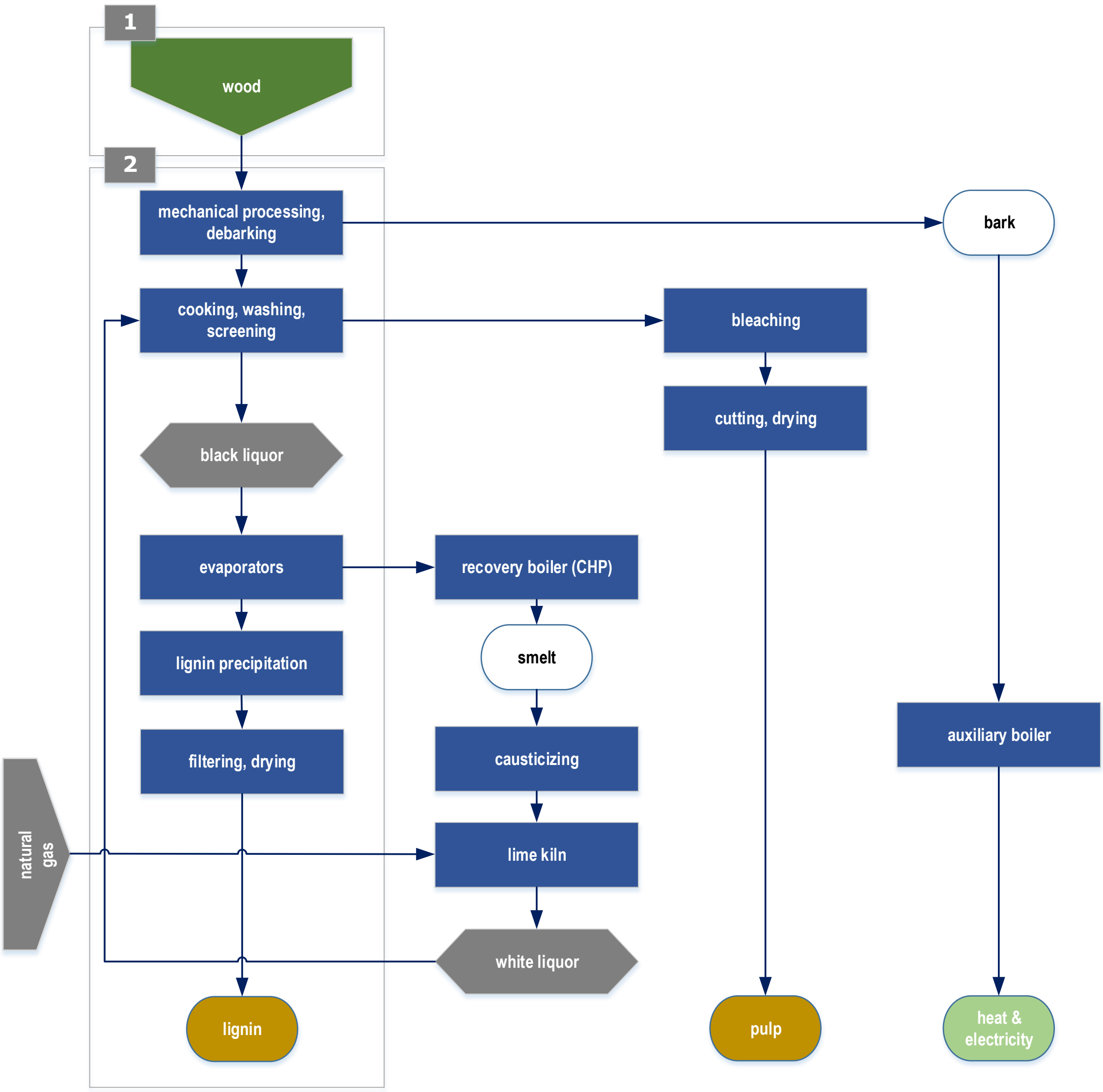

Figure 32 Lignocellulosic biorefinery pathway.

The forest operations involve the procurement of spruce and pine wood from the forest and is transported to the pulp mill. The inputs consist of 80% spruce and 20% pine. The Biorefinery plant itself consists of the production of Kraft lignin as a by-product of pulp production, using a state-of-the-art Kraft pulp mill. The pulp mill is divided into the fibre line, the recovery line and the lignin recovery process. As a multi-output process, this system is typically challenged by the required allocation procedure. The assessment assumes that the energy demand of the LignoBoost process (31.5 MJ/kg extracted lignin) can be covered by the energy surplus of the pulp mill.

Table 11 summarises the key characteristics of the considered biorefinery. In considering the production of 600 000 Adt kraft pulp/a, it is assumed that about 70 000 t lignin can be separated via the LignoBoost process without compromising energy self-sufficiency. Additional energy input is only required for the lime kiln (Natural gas). In terms of chemical inputs, it is considered high with (up to 99%) of the cooking chemicals recovered. The assumed investment costs refer to the integration of the LignoBoost process. The number of employees is estimated based on a state of the art Kraft pulp mill with a production capacity of 600 000 Adt pulp/a. The total amount of black liquor was calculated at around 760 000 t/a. All background data are based on the literature and on the ecoinvent 3.2 and ProBas database. In the case of primary data collection, in addition to numerical data, descriptive data was also collected, such as any potential upscaling-effects and chemical recovery issues.

Table 11 Key characteristics case study 4 lignin.

3-platform (pulp, lignin, energy) biorefinery using wood chips for the production of Kraft pulp, Kraft lignin and energy							
State of technology	commercial/concept						
Country	EU 27						
Main data source	Literature, Wood K plus						
Products				**Auxiliaries (external)**			
Pulp		600,000	t	Energy		780,000	GJ
Lignin		70,427	t	Chemical inputs		139,453	t
Heat		1,478,632	GJ				
Feedstock				**Costs**			
Round wood		1,549,200	t	Investment costs		11	Mio €
				Feedstock costs		1,5	Mio €
Lignin extraction rate		15	%	Number of employees		135	#
Efficiencies							
Pulp to lignin		8.5	t/t lignin	**Reference flow**		**600,000**	**t pulp**
Black liquor to lignin		10.8	t/t lignin				

The mass balances depicted in Figure 33 show that the main input is the feedstock (i.e. the pulp wood itself, followed by chemical requirements for pulping and the LignoBoost process). Please note that water input was excluded in this case. The main outputs are pulp and black liquor. Additionally, bark was considered as an output which can be used on-site to generate energy for the process. As stated above it is assumed that the state of the art pulp mill is energy self-sufficient. Auxiliary energy is only required for the lime kiln. Depending on the conversion process, either heat and/or power surplus is available. Energy balances as well as the share of costs are shown in Figure 34 and 35 respectively.

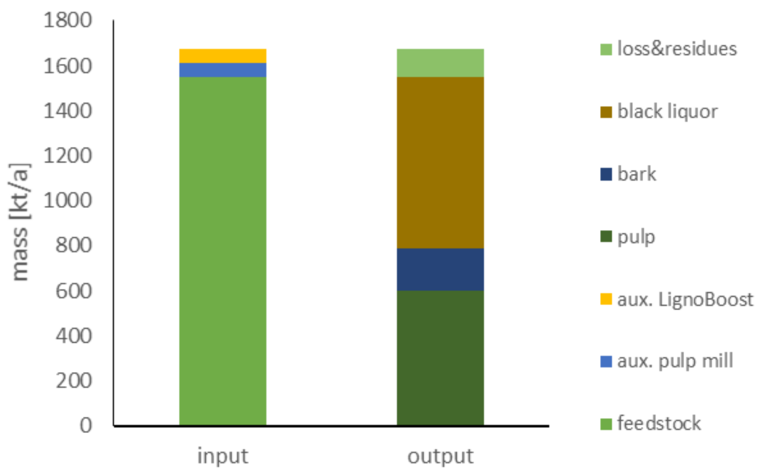

Figure 33 mass balance - case study 4.

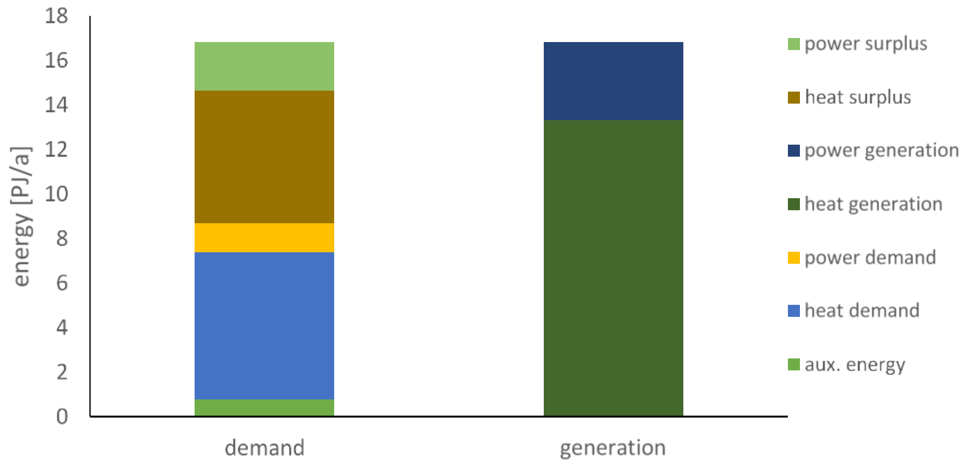

Figure 34 energy balance - case study 4.

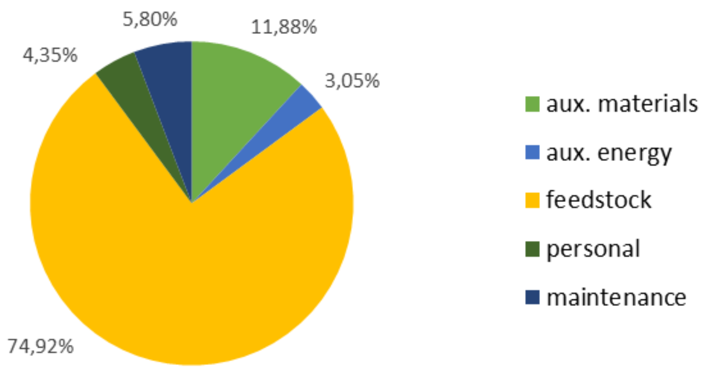

Figure 35 share of costs - case study 4.

The feedstock (i.e. spruce and pine wood) account for the main costs, followed by aux. materials, such as cooking and bleaching chemicals. The feedstock is also in terms of quantities the main input. The assessment of the revenues is shown in figure 39.

3.4.3 Part B: Value Chain Environmental Assessment

As shown in various studies (Ghorbani et al., 2017; Kalami et al., 2017; Lettner et al., 2018; Solt et al., 2018), lignin could be an interesting alternative to current fossil based adhesives, especially as a replacement for phenol in phenol formaldehyde (PF) resins. The reference system is shown in Figure 36.

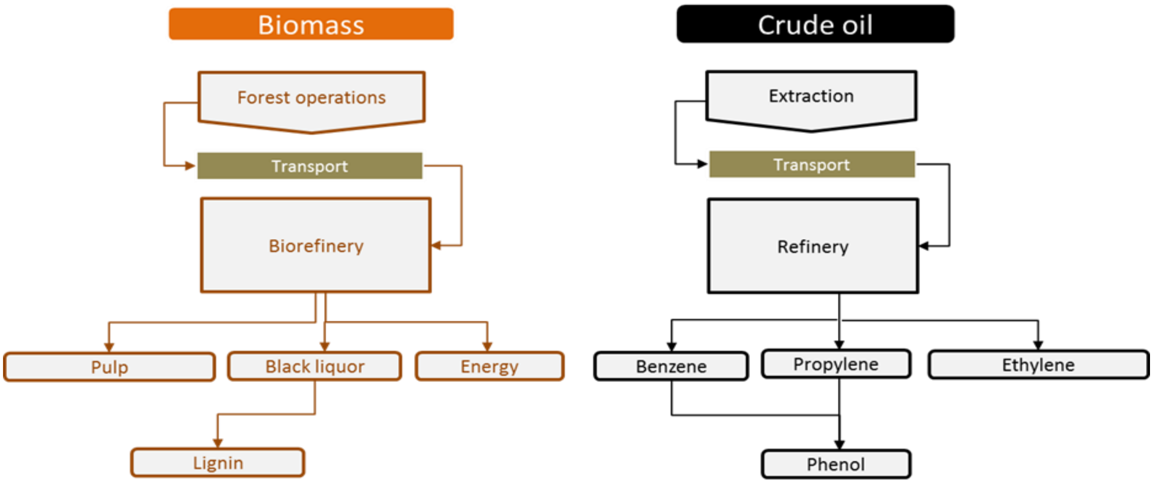

Figure 36 Biorefinery and reference system - value chain (cradle to gate).

Key characteristics of biorefinery value chain

Table 12 provides an overview of the environmental and economic assessment carried out for the case study.

Table 12 Overview TEE assessment results - case study 4.

Greenhouse gas emissions		
Forestry	22,438	t CO_2-eq
Biorefinery	142,976	t CO_2-eq
Lignin extraction	23,488	t CO_2-eq
Reference system	309,882	t CO_2-eq
Savings	-120,978	t CO_2-eq
Cumulated energy demand		
Fossil		
Forestry	956	TJ
Biorefinery	0,0014	TJ
Lignin extraction	334	TJ
Reference system	8,240	TJ
Savings	-6,948,808	TJ
Costs		
Annual costs	207	Mio €
Investment costs	11	Mio €
Revenues		
Specific revenues	633	€/t Reference flow

As stated above the assessment follows a cradle-to-gate approach. The assessment of the GHG emissions considers the use of natural gas in the lime kiln, the main chemicals inputs and direct emissions (CO2, CH4 and N2O) of the pulp mill. In a comparison with the reference system under the given assumptions within case study 4, the cumulated fossil energy demand and the GHG emissions are lower for the biorefinery systems compared to the reference system (Figure 38 & 38).

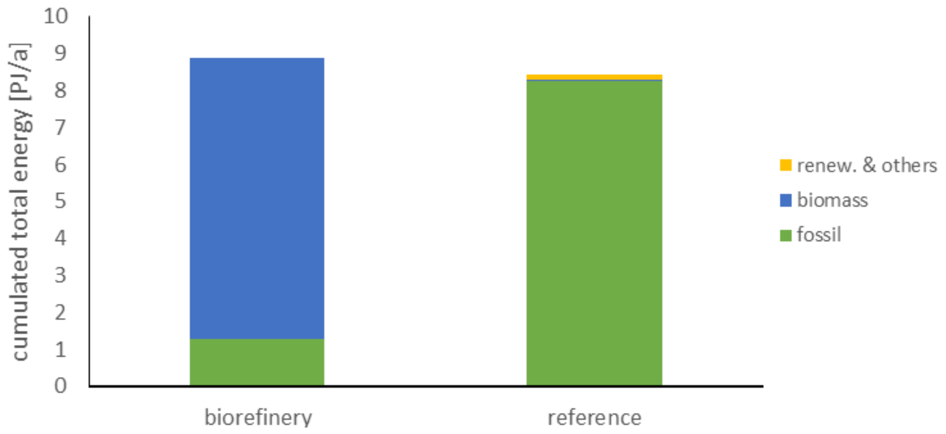

Figure 37 Cumulated energy demand of biorefinery compared to reference plant - case study 4.

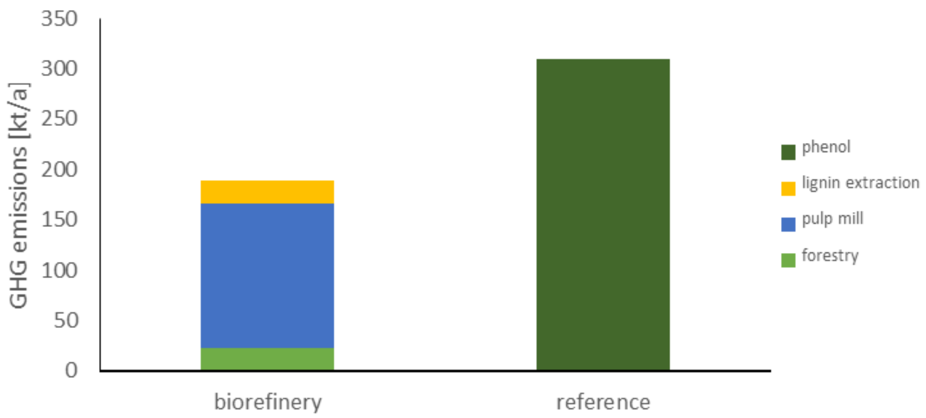

Figure 38 Greenhouse gas emissions of biorefinery compared to reference plant - case study 4.

The assessment of costs and revenues is highly challenged by limited data availability. Detailed assumptions can be found in the supplementary data of the case study. Under the given assumptions the revenues are mainly determined by the pulp, which is understandable due to the differences in quantities and the uncertainties of the actual lignin price, as shown in Figure

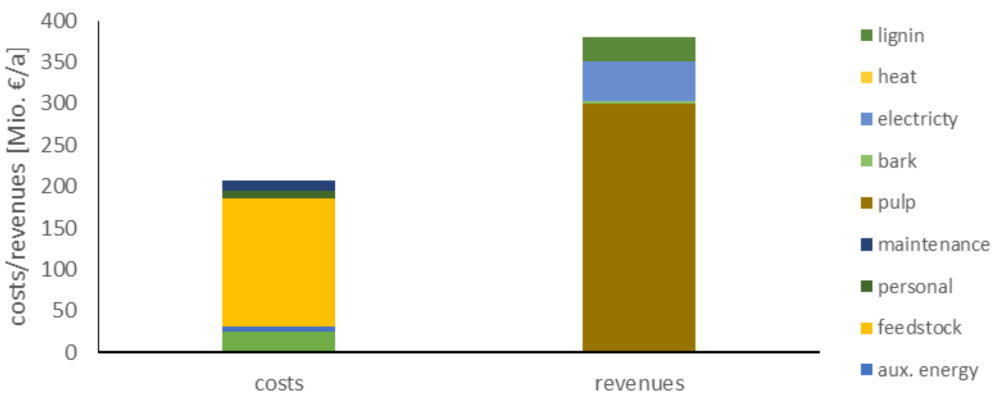

Figure 39 Costs and revenues - case study 4.

4 CONCLUSIONS & OUTLOOK

Biorefinery concepts are an important building block for establishing a vital bioeconomy. This is because biorefinery concepts address some of the most important aspects of the bioeconomy strategy. The cascade-use of biomass for the production of biobased materials and energy in closed loop process designs is the core principle that is addressed by the biorefinery pathways. These pathways were investigated via a technical, economic and environmental assessment (TEE) tool, as documented in this report.

The four case studies depicted showed the potential environmental benefits of biobased products from biorefinery processes. However, at the moment the economic feasibility of those products is still partly questionable as their fossil counterparts are available on the market at much lower cost. Furthermore, today´s biorefinery processes still show significant optimisation potential while the production processes of fossil-based products are technically mature and optimised. Technical developments in the biorefinery sector continue to generate new knowledge and as they are commercialised and deployed these are likely to lead to further improvements via economies of scale. As a result, it is expected that the production cost for biorefinery products will decline in the (near) future and that the products will become more competitive over time. Until this is achieved, biorefinery pathways will continue to rely on targeted policy measures and public support programs to drive the development. The wide implementation of biorefinery technologies requires, that a large number of possible products meet the quality and price requirements of the market. In addition, it is necessary to identify and optimise the site-adapted biorefinery technologies and recycling paths from the multitude of potentially available raw materials and conversion paths.

However, it is questionable if there will be a "one-fits-all" solution comparable to fossil based refineries. The biorefinery concepts have to consider regional situations and take into account available raw material mixes and the resulting platforms that are based upon the biorefinery products. Furthermore, research and development should address these aspects in order to develop a regionally adapted decentralized biorefinery solution. Technical research on biorefinery concepts has to be accompanied with systemic and structural research in order to design biorefinery pathways of the right scale, right raw material mix, right platforms, etc. for their specific site location. The IEA Task 42 provides the basis for doing so as it classifies biorefinery concepts and gives an overview of available concepts and their environmental performance and economic feasibility based on available generic data in an "open access" approach concerning assessment methodology and primary data origin to enable a strong knowledge-based community within the biorefinery sector.

Future research will include further TEE-assessments of different types of biorefinery by Task 42 in close cooperation with other Tasks. For example, thermochemical liquefaction based biorefineries (cooperation Task34), anaerobic digestion based biorefineries (cooperation Task37) or advanced biofuel based (biochemical) biorefineries (cooperation Task39) will be analysed and assessed. Appropriate biorefinery pathways will be selected for further TEE-assessment. The discussion and evaluation of preliminary biorefinery data collected on various biorefinery set-ups will be done by exchange with experts. This will enable to integrate academic and industrial experts and stakeholders in order to further define and select biorefineries for the detailed assessment and the consequent compilation of a comprehensive fact sheets.

5 REFERENCES

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Appendix - Screenshots template TEE assessment

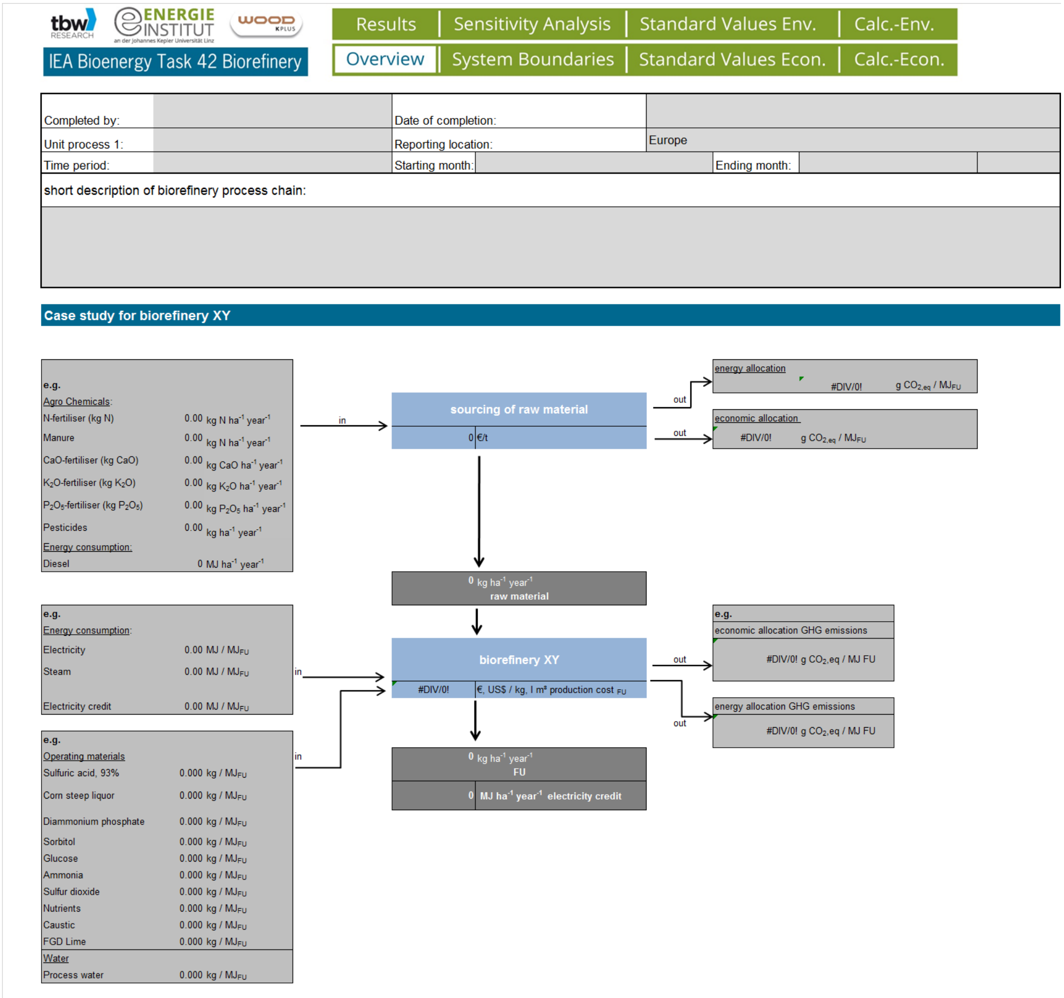

Figure 40: First template sheet. Process description and Overview

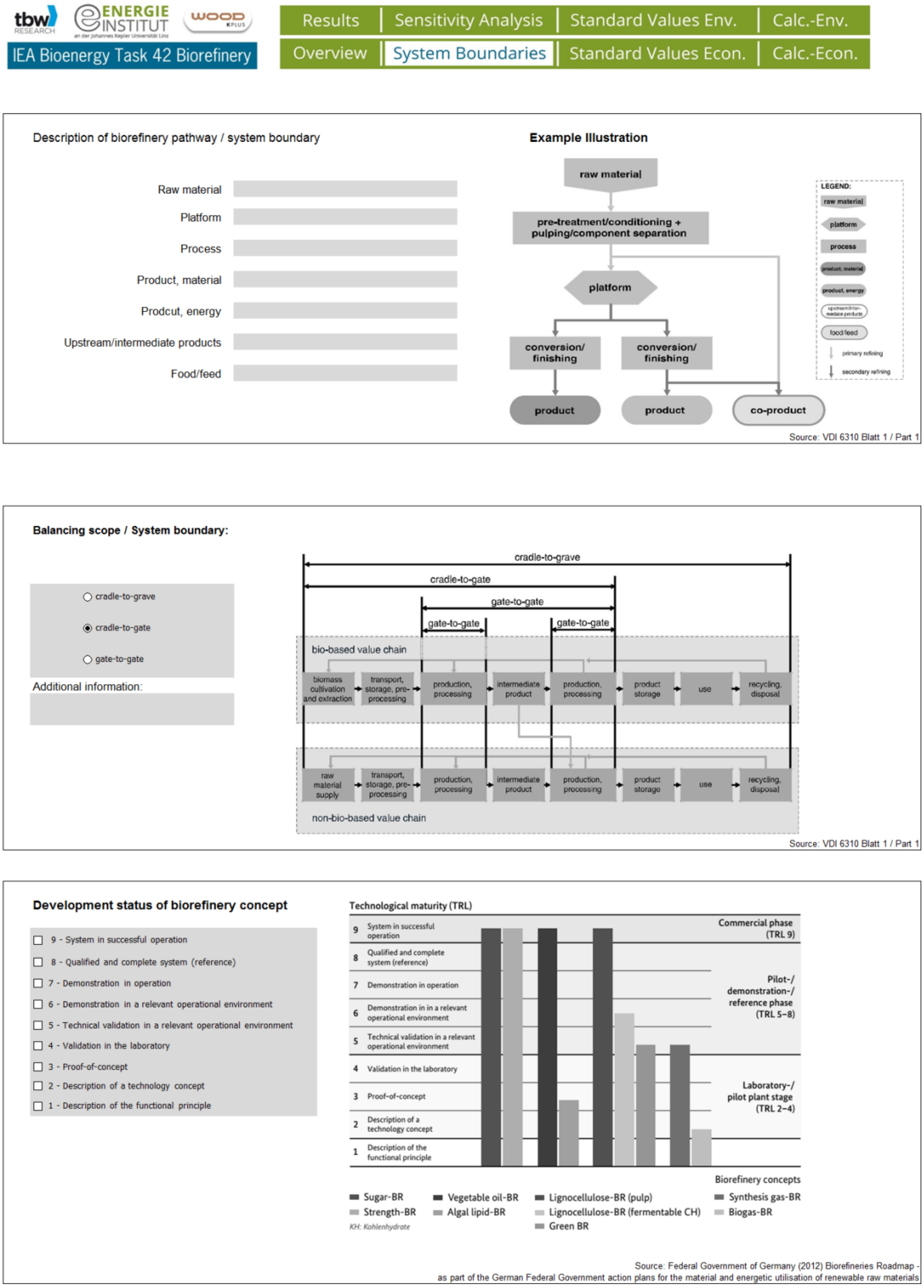

Figure 41: Second template sheet Information about system boundaries and TRL

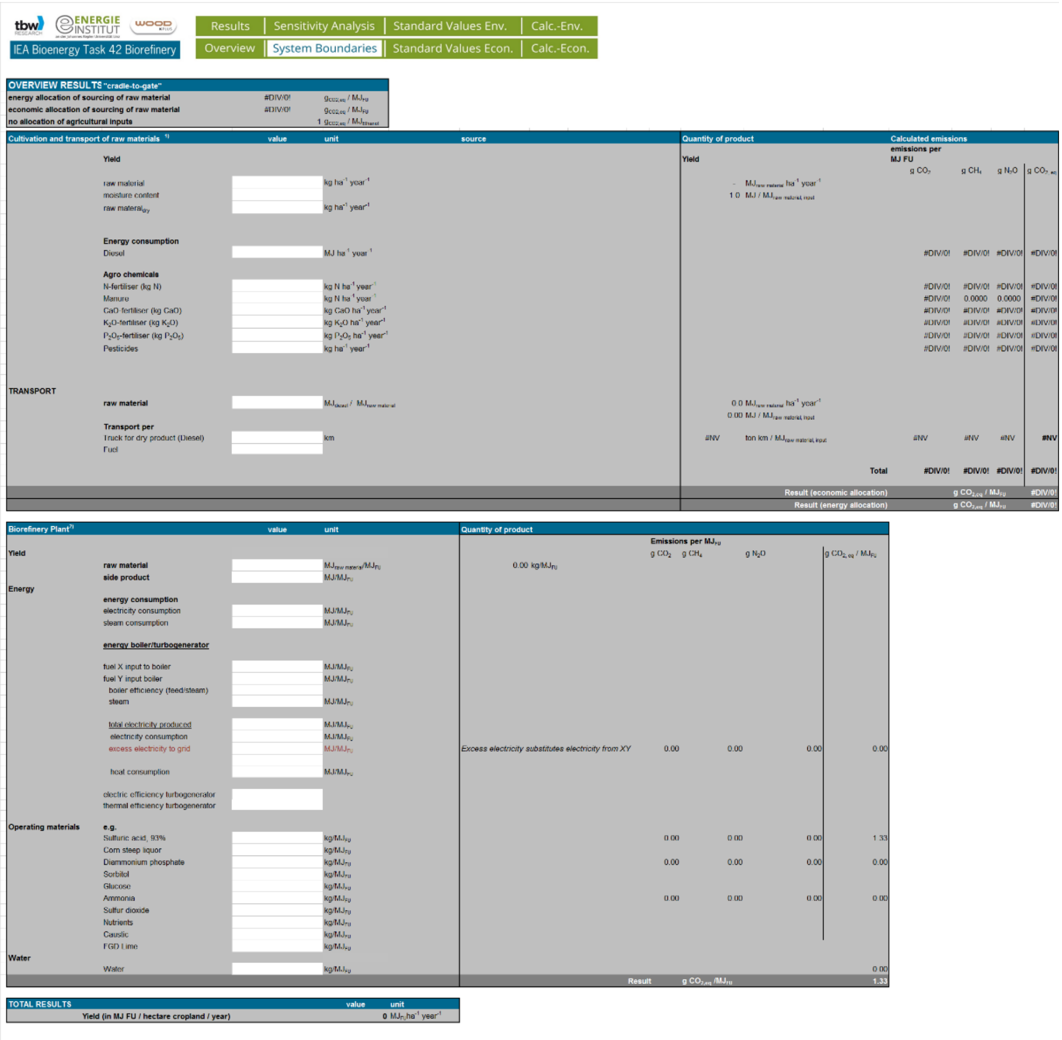

Figure 42: Third template sheet environmental assessment

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Results	Sensitivity Analysis	Standard Values Env.	Calc.-Env.
Overview	System Boundaries	Standard Values Econ.	Calc.-Econ.

OVERVIEW RESULTS	operating result	unit	FU production cost	unit
	#DIV/0!	€/a	#DIV/0!	€/l

No.	Biorefinery CAPEX & OPEX[1]	value	unit		value	unit
No.	*Parameter*					
A	**Investments**					
A.1	Investment sum		€	duration period		a
				revenues		€/a
B	**Investment costs**			discount rate		
B.1	Write-offs	#DIV/0!	€/a	FU production		MJ/a
B.2	Imputed interest	0	€/a	FU production		kg/a
B.3	Maintenance		€/a	FU production		l/a
B.4	Taxes		€/a			
B.5	Insurance & Tax		€/a			
B.6	Administration		€/a			
	Fixed Operating Costs	#DIV/0!	€/a			
C	**Material and energy stream costs**					
C.1	Raw material supply		€/a			
C.2	Auxiliary and operating material		€/a			
C.3	Energy supply		€/a			
C.4	Disposal costs		€/a			
C.5	Transport costs		€/a			
C.6	Water supply costs		€/a			
E	**Labour costs**		€/a			
F	**other costs**		€/a			
G	**overheads**		€/a	*overheads are insurance & mainteanance*		
H	**overall evaluation**					
H.1	operating result	#DIV/0!	€/a			
H.2	overall FU production cost	#DIV/0!	€/a			
H.3	specific FU production cost	#DIV/0!	€/l			
H.4	specific by-product production cost		€/l			

Figure 43: Fourth template sheet economic assessment

Further Information

IEA Bioenergy Website
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