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Integrated sustainability assessment of SUPRABIO biorefineries

Main results of the SUPRABIO project from an overall sustainability perspective

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(Updated version of October 31st, 2014)

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1 Publishable summary

The SUPRABIO project

The SUPRABIO project researched, developed and demonstrated a toolkit of novel generic processes that can be applied to a range of biorefinery concepts. These biorefinery concepts included a biochemical route for the production of second generation (lignocellulosic) ethanol, mixed organic acids or nanocellulose from straw and a thermochemical route for the production of Fischer-Tropsch (FT) fuels or dimethyl ether (DME) from forest residues. Furthermore, a number of so-called other routes or add-ons were investigated.

In the last couple of years, a controversial discussion on the net benefit of biofuels, bioenergy and bio-based materials has been going on, showing that the use of biomass is not sustainable *per se*, just because biomass is a renewable resource. Against this background, a comprehensive integrated sustainability assessment was conducted to validate the benefits and risks of the investigated SUPRABIO biorefinery concepts by means of a multi-criteria evaluation and, ultimately, to provide a basis for decision making processes.

Integrated sustainability assessment

In the absence of an internationally standardised methodological framework for integrated sustainability assessments, a newly developed comprehensive and streamlined approach was applied in SUPRABIO. Based on exactly the same system boundaries, potential impacts of SUPRABIO biorefineries on all major aspects of sustainability (environment, society and economy) were investigated individually, using a set of existing state-of-the-art methodologies. The latter were harmonised with the sister biorefinery projects BIOCORE and EUROBIOREF. This was supplemented by separate analyses of biomass competition and various sustainability aspects, which were not covered by the other assessments. Finally, all sustainability aspects were integrated into an overall sustainability assessment using multi-dimensional comparison metrics and a structured transparent discussion.

Essentially, all individual assessments as well as the final integrated assessment followed a life cycle approach, comparing bio-based product portfolios from a potential SUPRABIO biorefinery to conventional (mostly petroleum-based) product portfolios. Furthermore, SUPRABIO systems were compared to other biomass-based systems which are competing in terms of biomass or land use. All life cycle comparisons were based on scenarios depicting potential implementations of mature, industrial-scale biorefineries in 2025 and of current technology on smaller scale in 2015 (see Tables 1–1 and 1–2). The scenarios were finalised in late 2013 on the basis of experts' expectations and data available at that time. More recent advancements within SUPRABIO such as results of the Piteå gasifier test in May 2014 (which would lead to more optimistic expectations) could not be taken into account any more.

The newly developed integrated life cycle sustainability assessment (ILCSA) which was applied to the proposed biorefinery concepts is a practical approach capable of revealing synergies, conflicts and trade-offs associated with future implementations of biorefineries.

Results and conclusions: SUPRABIO vs. conventional systems

The analysis has shown that none of the investigated systems is necessarily superior from a sustainability point of view. Since all scenarios show both advantages and disadvantages,

positive and negative aspects have to be balanced based on individual preferences and subjective value choices. Today, the best possible compromise from a sustainability point of view would be 2nd generation ethanol, but FT fuels show an interesting potential in the future.

Products obtained via the thermochemical route in 2025 show a more advantageous environmental performance regarding eutrophication, acidification and photochemical oxidant formation. Moreover, production costs are lower and the products have a higher market maturity than products manufactured via the biochemical route. But because of low product prices, the net present value (NPV) of the thermochemical biorefineries is negative and the conversion units are not profitable without subsidies. In the biochemical route, ethanol production in 2025 shows highest primary energy and greenhouse gas savings and the lowest energy resource savings and greenhouse gas saving costs. The NPV of ethanol production chains with optimised process energy generation are the only SUPRABIO value chains achieving a positive NPV and hence can be considered economically feasible. However, ethanol as a fuel faces blending restrictions.

In general, it becomes obvious that the SUPRABIO systems need further technological improvement to be sustainable options for biofuel production. However, the sustainability of a biorefinery is not only a question of resolving technological challenges (especially important for global / regional environmental and economic impacts) but is also critically influenced by other aspects such as the availability and supply of sustainable biomass (important for all impacts), biomass production by farmers / forest owners and their involvement as stakeholders (especially important for local environmental and social impacts) and political framework (important for all impacts). In terms of biomass provision, it could be shown that the type of biomass feedstock determines the extent and magnitude of impacts. The provision of domestic biomass residues (wheat straw or forest residues) and of dedicated lignocellulosic crops (e.g. perennial crops like SRC poplar) are associated with comparatively low risks - provided that biomass residue extraction rates are sustainable and no direct or indirect land use changes are induced. Higher risks are associated with biomass which is imported from emerging / developing countries.

In general, it can be concluded, that the SUPRABIO systems are not necessarily more sustainable than conventional (mostly petroleum-based) reference systems, just because biomass is a renewable resource. All systems are showing advantages and disadvantages regarding the selected sustainability indicators. Since none of them is free of disadvantages, optimisation of all processes and close-to-optimum technical implementation is needed to obtain systems that are both environmentally friendly and economically profitable.

Results and conclusions: SUPRABIO vs. other biomass-based systems

Comparing the SUPRABIO scenarios to alternative uses of the same land, it could be shown from an environmental angle, that 2nd generation technology does not show the potential to significantly improve the land use efficiency of ethanol. The thermochemical route towards FT fuels offers higher (relative) improvements over 1st generation biodiesel, however, 2nd generation ethanol shows higher potentials for climate change mitigation per unit area than FT fuels from the same biomass feedstock. Yet, FT fuels display advantages over lignocellulosic ethanol regarding other environmental impacts (other than climate change). Comparing alternative uses of the same biomass, the fiercest competitor for SUPRABIO is direct combustion of biomass for combined heat and power generation. As long as a significant share of power is produced from coal, the stationary use of biomass is expected to mostly outperform the biofuel use of biomass by far. Nevertheless, SUPRABIO biorefineries have

the potential to become environmentally, socially and economically sustainable cornerstones of a bio-based economy.

Table 1-1 SUPRABIO main scenarios for the biochemical route
Odt BM: oven dry tonnes biomass, SHF: separate hydrolysis and co-fermentation, SSF: simultaneous saccharification and co-fermentation.

	Straw to Ethanol (2015)	**Straw to Ethanol (2025)**	**Poplar to Ethanol (2025)**	**Straw to Mixed Acids (2025)**
Feedstock	Straw	Straw	Poplar	Straw
Capacity	40,000 odt BM/a	400,000 odt BM/a	400,000 odt BM/a	400,000 odt BM/a
Pre-treatment	Steam explosion	Steam explosion	Steam explosion	Steam explosion
Main process	SHcF	SScF	SScF	Hydrolysis & anaerobic ferment.
Main product(s)	Ethanol (310 kg/odt BM)	Ethanol (340 kg/odt BM)	Ethanol (250 kg/odt BM)	Propionic and butyric acid (up to 520 kg/odt BM)
Co-product	Electricity (250 kWh/odt BM)	Electricity (350 kWh/odt BM)	Electricity (650 kWh/odt BM)	-
Assessed variants	-	Different energy recovery from processing residues	-	Different product ratios and amounts

Table 1-2 SUPRABIO main scenarios for the thermochemical route
Odt BM: oven dry tonnes biomass, FT: Fischer-Tropsch, DME: dimethyl ether.

	Forest residues to FT fuels (2015)	**Forest residues to FT fuels (2025)**	**Forest residues to DME (2025)**	**Straw residues to FT fuels (2025)**	**Poplar residues to FT fuels (2025)**
Feedstock	Forest residues	Forest residues	Forest residues	Straw	Poplar
Capacity	5 x 8,000 odt BM/a	5 x 80,000 odt BM/a	5 x 80,000 odt BM/a	5 x 80,000 odt BM/a	5 x 80,000 odt BM/a
Pre-treatment	Pyrolysis	Pyrolysis	Pyrolysis	Pyrolysis	Pyrolysis
Main process	Gasification (fed by 5 pyrolysers)	Gasification (fed by 5 pyrolysers)	Gasification (fed by 5 pyrolysers)	Gasification (fed by 5 pyrolysers)	Gasification (fed by 5 pyrolysers)
Main product(s)	FT diesel, FT gasoline (34 / 37 kg/odt BM)	FT diesel, FT gasoline (52 / 42 kg/odt BM)	DME (186 kg/odt BM)	FT diesel, FT gasoline (41 / 33 kg/odt BM)	FT diesel, FT gasoline (43 / 35 kg/odt BM)
Co-product	Electricity (110 kWh/odt BM)	Electricity (100 kWh/odt BM)	Electricity (30 kWh/odt BM)	Electricity (70 kWh/odt BM)	Electricity (80 kWh/odt BM)
Assessed variants	-	Deviating steam provision, gasification conditions and centralised pyrolysis	-	-	-

2 Introduction

2.1 The SUPRABIO project

The SUPRABIO project researches, develops and demonstrates a toolkit of novel generic processes that can be applied to a range of biorefinery concepts based on sustainable types of biomass feedstock.

In the last couple of years, a controversial discussion on the net benefit of biofuels, bioenergy and biomaterials has been going on, showing that the use of biomass is not environmentally friendly per se, simply because biomass is renewable. The discussion gained momentum in the light of increasing competition for agricultural land between the production of food, feed, fibre and fuel which might even aggravate in the decades to come and jeopardise food security.

In this context, a strict and overarching sustainability assessment is needed to validate the benefits and risks of any given biorefinery concept and, ultimately, to provide a basis for the development of policy incentives. In SUPRABIO, the sustainability of the biorefinery concepts under investigation is assessed in an integrated manner and by taking into account the entire life cycle (value chain).

2.2 Objectives and approach of the integrated sustainability assessment

In SUPRABIO, the sustainability assessment consists of a series of individual assessments that separately assess the major aspects determining the sustainability of biorefinery systems (Fig. 2-1). The results of all these individual assessments need to be united to come up with comprehensive conclusions and recommendations. This is done in the so called “integrated assessment”.

The description of work /DoW 2011/, which is the contractual basis of this project, specifies the objectives of the sustainability assessment to “provide a multi-criteria evaluation of the sustainability of the entire value chain by taking into account technological, environmental, economic, social, political and legal aspects”. Based on this comprehensive main goal, the following key questions have been specified in the “Interim report on definitions and settings” /Rettenmaier et al. 2011/.

General questions:

- What are the implications of the SUPRABIO biorefinery systems on sustainability?
- Which processes determine the results significantly and what are the optimisation potentials?
- What main products/product systems perform best regarding the replacement of fossil fuels?

- What system performs best regarding CO_2 savings per tonne of biomass input?
- What is the performance of SUPRABIO systems compared to alternative uses of the same feedstock (biomass) or cultivation area?

Specific questions within each route (biochemical, thermochemical):

- Which product portfolio performs best?
- Which co-product treatment performs best?
- How do the different add-ons and advanced technology options affect sustainability?
- What are the implications of plant capacity, e.g. on rural development?
- How does the time frame influence the results?

These questions are answered within this report; however, they are not addressed one by one. Instead, the answers form part of the overall conclusions.

The methodological approach of the integrated assessment is presented in chapter 3, followed by a description of the assessed SUPRABIO value chains in chapter 4. Subsequently, this report contains a short description of the methodological approaches of the individual assessments and the respective main findings (chapter 5), the integration of the results of the individual assessments into an integrated assessment (chapter 6) as well as conclusions and recommendations from a sustainability perspective (chapter 7).

This way, this report aims at providing a comprehensive overview of the results from the entire work package on sustainability assessment without the need to read the individual assessment reports. Nevertheless, the individual assessment reports are important sources of in-depth information on further aspects of the individual assessments.

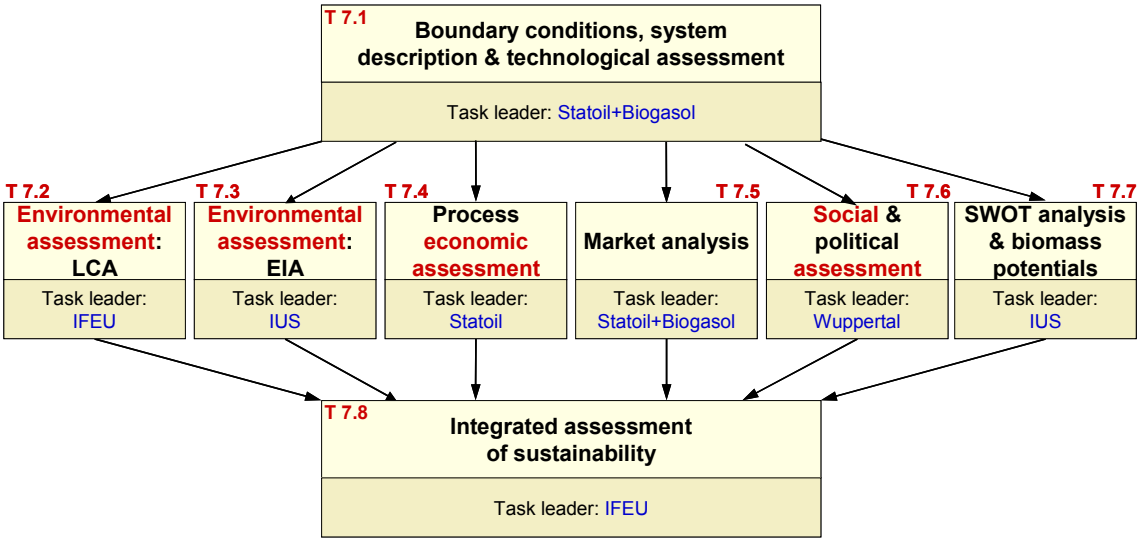


Fig. 2-1 Sustainability assessment in SUPRABIO

3 Methodology of the integrated assessment

This chapter describes the methodology of the integrated sustainability assessment, which builds on results from previous assessments of individual sustainability aspects. For the methodologies used in these individual assessments, please refer to the respective reports: /Lervik Mejdell et al. 2014/ (D 7-11, techno-economic and market assessment), /Keller et al. 2014/ (D 7-5, environmental assessment), /Schütz 2014/ (D 7-8, social assessment) and /Kretschmer et al. 2014/ (D 7-6, SWOT analysis and biomass competition analysis).

3.1 General approach

Within the SUPRABIO projects, different biorefinery value chains have been analysed. These different SUPRABIO biorefinery options as well as existing alternatives are represented in this assessment in the form of scenarios. On each scenario, various indicators from technological assessment, environmental assessment via screening LCA and LC-EIA, process economic assessment and market analysis, social assessment, biomass competition analysis and from the assessment of other sustainability aspects via SWOT analysis are made available in this study. All these aspects are integrated into an overall picture to facilitate decisions between the options.

There are two general ways of integrating this information:

Structured discussion

All pros, cons and conflicts of the options can be discussed verbally argumentatively. This can make conflicts transparent and enable their active management. Considering the amount of options and indicators, this requires a structured approach. This approach is followed in this study. This section describes the methodology used for the structured comparison and presentation of decision options based on a multi criteria analysis.

Weighting and mathematical integration

All indicators could be mathematically combined into one score using weighting factors or ranked otherwise according to a weighting algorithm. These approaches cannot be entirely based on scientific facts but depend on personal value-based choices defined beforehand. Furthermore, conflict situations do not become apparent since in many cases, one option has advantages regarding some sustainability indicators and disadvantages regarding others. Decisions regarding such conflicts depend on weighting factors, which are hard to understand for decision makers not involved in the study. Therefore, this approach is considered not sufficiently transparent and is not applied.

3.2 Collection of indicators and results from individual assessments

Indicators and results for all scenarios are provided by the individual assessments /Lervik Mejdell et al. 2014/, /Keller et al. 2014/, /Schütz 2014/ and /Kretschmer et al. 2014/. They are collected in an overview table (Table 6-1). In some cases, indicators are selected or aggregated by the authors of the respective individual assessment to focus on the most relevant aspects for decision support. No further adjustments are made except for rescaling quantitative data to a common basis if necessary. Thus, all specific settings, methodological choices including underlying estimates, and data sources apply unchanged as documented in the respective reports.

Some of the assessments provide quantitative and qualitative indicators (economic and environmental assessment), others provide only qualitative indicators (social assessment, technological assessment and SWOT analysis).

3.3 Additional indicators

The indicators taken from the individual assessments refer only to one single pillar of sustainability: either the environment, or the economy, or any other aspect. In some aspects it is interesting to provide additional indicators which aggregate aspects of different pillars of sustainability. This is a particular matter of interest if it comes to the costs of environmental protection measures.

Climate protection under the condition of limited financial resources has to use the available financial resources as efficiently as possible. Efficiency means here to achieve the highest possible greenhouse gas (GHG) emission savings with the lowest monetary expenditures necessary for that. CO_2 avoidance costs are frequently used as indicator for this purpose. CO_2 avoidance costs are defined as quotient of the differential costs for a CO_2 reduction measure and the avoided CO_2 emissions by this measure.

In analogy to CO_2 avoidance costs, similar additional efficiency indicators can be defined for other quantitative sustainability indicators. In this case, such indicators are available from the screening LCA like for example acidification (basis for SO_2 avoidance costs) or resource depletion (basis for non-renewable energy savings costs). The same methods apply for those indicators as discussed in the following for the example of CO_2 avoidance costs.

CO_2 avoidance costs are used for microeconomic decisions as well as for the decisions in energy policy. Microeconomic decisions are always based on business analyses. If political decisions like the implementation of support programmes are concerned, the valuation is often more difficult, as the macroeconomic dimension, possible external effects as well as second- and third-round effects have to be considered. For the determination of CO_2 avoidance costs, different methodological characteristics have to be considered concerning:

- the determination of a reference, which is e.g. for biofuels the use of fossil fuels,
- the inclusion of different cost items (e.g. full costs vs. additional costs),

- the inclusion of temporal dynamics of systems under consideration (e.g. developments of investment costs of systems, of prices for energy carriers, etc.),
- the different perspectives – especially microeconomic and macroeconomic approaches.

However, the sole consideration of CO_2 avoidance costs is often not sufficient to come to sustainable decisions. On the one hand, they do not contain any information about the amount of emissions that can be avoided and on the other hand, they do not take other environmental impacts into account. Therefore, CO_2 avoidance costs do not represent a single combined indicator resulting from the sustainability assessment but only one additional criterion.

CO_2 avoidance costs from a microeconomic perspective are calculated as follows:

$$\mathbf{CO_2\ avoidance\ costs} = \frac{\mathbf{costs - costs\,(reference)}}{\mathbf{GHG\ emissions - GHG\ emissions\,(reference)}}$$

CO_2 avoidance costs are expressed in Euro per tonne of CO_2 equivalents. Costs refer to the support in € maximally required to make an investment attractive (i.e. to reach an expected rate of return of 25 % without green premium product prices unless specified otherwise) and greenhouse gas emissions (GHG emissions) expressed in CO_2 equivalents.

One methodological option is to discount the avoided CO_2 emissions for the calculation of the avoidance costs as well, in order to create a preference for temporally preceding measures. Otherwise a later realisation of the measure could be reasonable for decision makers. Moreover, a discounting reflects an assumed uncertainty about the degree and the time point of the environmental impact.

$$GHG\,em - GHG\,em(benchmark) = \sum_{t=0}^{n} \frac{\Delta GHG\,em(t)}{(1+i)^t}$$

Generally, a discounting of the environmental costs results in higher CO_2 avoidance costs as without discounting. However, for further calculations in this study it is assumed that the discounting is neutralised by the fact that the environmental impact increases parallel to the so called social preference rate. The social preference rate consists of the time discounting and the growth accounting /Nordhaus 1994/, /IPCC 1996/, /Fankhauser 1995/. Therefore, the method without discounting is used.

As CO_2 avoidance costs represent an efficiency indicator, they are only defined in the case that the primary goal is met, this is, that there are greenhouse gas emission savings by the process under investigation compared to the benchmark. If the goal is not met, one obviously cannot define an indicator on how efficiently the goal is reached. This means, the CO_2 avoidance costs can be interpreted or not depending on the results of the numerator and the denominator.

Fig. 3-1 shows that out of nine possible result options only two allow an interpretation of the avoidance costs. If negative avoidance costs occur it has to be reconsidered if this results from the lower total costs or from the possibly higher emissions. Differences approaching zero make a calculation of avoidance costs impossible. If two differences are compared to

each other, it can lead to disproportional influences of uncertainties. This is especially the case if either the emissions or the costs of the compared pathways are very similar. If for example the CO_2 emissions of the two pathways differ by 10 % then a 5 % error of estimating these emissions can lead to a deviation in CO_2 avoidance costs of 100 %. Furthermore, small emission savings mathematically lead to very high and at the same time very uncertain avoidance costs. Therefore, avoidance costs are only then a reliable indicator if the uncertainties of emissions and the costs are small compared to the respective differences between the pathways.

Δ profit / Δ emissions	**> 0**	**≈ 0**	**< 0**
< 0	calculation possible (less costs than for reference)	no calculation possible	calculation possible
≈ 0	no calculation possible	no calculation possible (similar systems)	no calculation possible
> 0	no CO_2 avoidance (not defined)	no CO_2 avoidance (not defined)	no CO_2 avoidance (not defined)

Fig. 3-1 Different result options for the calculation of CO_2 avoidance costs (modified from /Pehnt et al. 2010/).

The second limitation is that avoidance costs are very prone to changes in the course of time because they can generally be very sensitive to changes as discussed above and they depend on the technological developments as well as market changes for two different systems. Therefore, it is especially important only to compare avoidance costs if they are determined for the same timeframe and under the same conditions. This makes it difficult to find comparable avoidance costs outside of this study although there is plenty of data on avoidance costs in literature. This especially applies to analyses of technologies not yet implemented for a timeframe more than a decade ahead as it is the case in this study.

Taken together, avoidance costs for environmental burdens such as greenhouse gas emissions can help to decide how mitigations of environmental burdens can be reached for the lowest price or even with profits. However, avoidance costs have to be interpreted carefully because in many situations their robustness and comparability are poor.

For further details and a critical review of the method see /Pehnt et al. 2010/.

3.4 Benchmarking

For the comparison of many different processes, a common benchmark has to be defined. This benchmark has to be chosen according to the questions to be answered and the respective perspectives of various stakeholders. In this case, the benchmark could for example be the economically or environmentally most favourable pathway, or the currently most used option.

For all quantitative indicators, the benchmarking process involves calculating the differences between the respective scenario and the benchmark. These comparisons should serve as a decision support to answer the question whether a scenario performs better than the benchmark regarding a certain indicator. Therefore, these quantitative differences are categorised into very advantageous [++], advantageous [+], neutral [0], disadvantageous [-], or very disadvantageous [--]. A certain minimum difference was chosen as a cut off value for the category neutral or very advantageous/disadvantageous respectively. These thresholds are set as percentage of the bandwidth from the best results to the worst result among all scenarios regarding a specific indicator. Here, a threshold of 10 % of the bandwidth is chosen.

For all qualitative indicators, rating of differences is done analogously but without applying minimum differences. The categories are interpreted as number with “++” interpreted as 2, “+” as 1, 0 as 0, “-“ as “-1” and “- -“ as “-2”. The indicator value of the benchmark scenario is subtracted from the indicator value for the respective scenario and the result is retranslated into the “- -“ to “++” categories.

3.5 Overall comparison

For an overall comparison, a verbal argumentative discussion of decision options is supported by structured overview tables containing the integrated assessment results.

The integrated sustainability assessment of this project is based on

- three qualitative technological indicators,
- eight quantitative and five qualitative environmental indicators,
- six quantitative and three qualitative economic indicators,
- five qualitative social indicators, six qualitative indicators taken from SWOT analysis and biomass competition analysis and
- two additional quantitative efficiency indicators.

(see Table 3-1 for an overview)

These are a subset of all possible indicators, which were assessed in previous steps of the sustainability assessment and found to be relevant for the decision process. Depending on the question to be answered, overview tables may contain all or a part of these selected indicators and scenarios. Furthermore, the unit of reference is chosen according to the question. To make the tables easily readable, indicator values deviating relevantly from the mean (in case of a comparison of SUPRABIO pathways with conventional reference pathways) or from the benchmark scenario (in case of comparisons between SUPRABIO scenarios) are marked coloured red or green respectively.

Table 3-1 Overview of sustainability indicators.

Impact category	Short description
Technology	
Net efficiency	Net energy efficiency of biomass processing plant. Calculated as: LHV Ethanol Product/ (LHV Biomass Feed – Electricity Export/0.4 + Steam deficit/0.9) /Lervik Mejdell et al. 2014/
Maturity	Technical maturity of involved conversion technologies
Complexity	Technical complexity (e.g. degree of integration) associated with the installation and operation of the biorefinery
Environment - LCA	
Resource depletion: energy	Depletion of non-renewable energy resources, i.e. fossil fuels such as mineral oil, natural gas, coal and uranium ore.
Climate change	Global warming as a consequence of the anthropogenic release of greenhouse gases. Besides carbon dioxide (CO_2), a number of other gases like methane (CH_4) and nitrous oxide (N_2O) are included.
Terrestrial acidification	Shift of the acid / base equilibrium in soils by acidifying gases like sulphur dioxide, nitrogen oxides and ammonia (keyword ‘acid rain’).
Marine / freshwater eutrophication	Input of nutrients into surface water (marine and freshwater) directly or via input into soils and gaseous emissions. E.g. nitrogen and phosphorous species contribute to this (keyword ‘algal bloom’).
Photochemical ozone formation	Formation of specific reactive substances, e.g. ozone, in presence of nitrogen oxides, volatile hydrocarbons and solar radiation in the lower atmosphere (keyword ‘ozone alert’ or ‘summer smog’).
(Stratospheric) Ozone depletion	Loss of the protective ozone layer in the stratosphere by certain gases such as CFCs or nitrous oxide (keyword ‘ozone hole’).
Respiratory inorganics (particulate matter emissions)	Damage to human health due to air pollutants such as fine, primary particles and secondary particles (mainly from NO_X, NH_3 and SO_2, keyword ‘winter smog’ or ‘London smog’).
Environment – LC-EIA	
Water	Local water availability for ecosystems and its quality.
Soil	Soil quality is affected e.g. by erosion, compaction or organic matter content.
Fauna	Local biodiversity among animals is affected e.g. by the presence of diverse habitats.
Flora	Biodiversity among plants on and around cultivated areas is affected e.g. by weed control measures.
Landscape	Characteristics and diversity of the landscape.

Table 3-1 (continued).

Impact category	Short description
Economy	
NPV (5 %)	An absolute measure and given by the sum of the discounted cash flows for all operating years: $$NPV = \sum_n \frac{C_n}{(1+r)^n}$$ where Cn is the total cash flow in year n, and r is the required rate of return (discount rate) set for the project. Thus, the project can be considered profitable if NPV > 0. Discount rate: 5 % per year (in this case).
CAPEX	Capital expenses. Sum of invested capital for the biorefinery facility including utilities per t of processed biomass.
OPEX	Operating expenses. Sum of operating costs such as salaries and wages, feedstock costs, maintenance, management, insurances and taxes etc. per t of processed biomass
Production costs	Sum of CAPEX and OPEX
Break-even price	Market price for the products produced from one t of biomass that needs to be achieved over the operating years to reach NPV = 0. The lower the break-even price, the more robust the project can be considered
Profitability index PI	Ratio between the NPV and the discounted value of all investments. It is a measure of the amount of value created per unit of investment, and can be a useful tool when comparing different potential project.
Market analysis	
Market volume	Marketable volume of the final products. The bigger the market volume, the bigger the expected growth options of innovative production concepts. .
Market maturity	A mature market that has reached a state of equilibrium marked by the absence of significant growth or innovation. SUPRBIO products are innovative products in stage of development, introduction or growth. A too immature market is a disadvantage because investments in market infrastructure and consumer awareness are needed.
Product value	The higher the product value, the higher the achievable price.
Society	
Risk of child labour	Child labour is defined by ILO as employment of children in any work that deprives children of their childhood interferes with their ability to attend regular school, and that is mentally, physically, socially or morally dangerous and harmful. Not all work by children is considered child labour in this sense.
Risk of forced labour	All work or service which is exacted from any person under the menace of any penalty and for which the said person has not offered himself voluntarily (ILO, forced labour convention, 1930)
Risk of country not passing laws to protect indigenous	Indigenous rights are those rights that exist in recognition of the specific needs and conditions of indigenous peoples. This includes particularly the preservation of their land, language, religion, and other elements of cultural heritage that are a part of their existence as a people.
Risk of not having Access to improved Sanitation - rural	Improved sanitation is defined as sanitation a facility that hygienically separates human excreta from human contact.

Impact category	Short description
SWOT analysis and biomass competition	
Direct additional land use	Arable land is a limited resource. Agricultural land use and forestry are open production systems, associated with a range of possible diffuse emissions causing environmental impacts as well as social impacts for the local populations.
Risk of indirect land use changes	Using arable land for new products can lead to a displacement of traditional crops. Such a displacement can lead to land use changes in other places because the displaced products are still demanded. Land use changes are often associated with negative social and environmental impacts. Indirect land use changes are associated with unknown and possibly severe environmental or social impacts (rain forest clearing, forced displacement of local populations etc.).
Availability of infrastructure	Effective supply chains are crucial for the success of biorefining. This indicator describes the availability of infrastructure for biomass supply.
Acceptance and experience amongst farmers /forestry	Little acceptance amongst biomass producers can be a severe obstacle for the implementation of new value chains.
Use of GMOS	GMO technologies are of little acceptance amongst the people of many European countries.
Risk of explosion and fires	This indicator describes inherent security risks of the involved technologies as a proxy for human health risks.
Additional indicators	
CO_2 avoidance cost	Quotient of the differential costs for a CO_2 reduction measure and the avoided CO_2 emissions by this measure.
Energy resource saving costs	Quotient of the differential costs for an energy resource saving measure and the avoided CO_2 emissions by this measure.

4 System description

The SUPRABIO biorefining system can be implemented in many different variants and ways. For the purpose of the sustainability assessment, scenarios were defined to reflect the most important of all possible implementations. Subchapter 4.1 describes the scenarios that are assessed and introduces general aspects of the SUPRABIO biorefining system. These scenarios include the whole life cycles of product provision and use 'from cradle to grave'. Additionally, the whole life cycles of conventional products that are replaced by SUPRABIO products are included in these scenarios as a reference.

Furthermore, any implementation of a SUPRABIO biorefinery replaces existing ways of using (or not using) land and / or biomass. These alternatives are described in subchapter 4.2

4.1 The SUPRABIO biorefining concept

This chapter describes scenarios depicting how bio-based products can be provided by a biorefinery according to the SUPRABIO biorefining concept, how these products are used, and which conventional products are replaced. Fig. 4-1 gives an overview on SUPRABIO biorefining concepts.

4.1.1 Raw material production / extraction

Biorefineries according to the SUPRABIO concept use a wide range of biogenic feedstocks depending on the conversion routes and products. The provision of these feedstocks is part of the SUPRABIO scenarios. These scenarios are assessed based on the precondition that biomass and land is available. Thus, they are compared to the reference systems of (non-wooded) idle land or not extracting residues. Environmental assessment (subchapters 5.2 and 5.3) considers also other reference systems for land use. Further aspects of land use and land use change are considered in SWOT and biomass competition analysis (subchapter 5.6).

For residues that are used as feedstocks, only those expenditures are allocated to the biorefinery, which occur additionally compared to the reference system (no extraction of residues) such as the collection of the biomass, hence no land use is allocated to the residues.

The following feedstocks are assessed:

- Poplar short rotation coppice: This feedstock represents an example of a dedicated crop used to produce lignocellulosic biomass on agricultural land.
- Oil crops (rapeseed, oil palm, soy, Jatropha): These crops are used to produce vegetable oils for certain biorefinery routes on agricultural land (see subchapter 4.1.3.3).
- Residual wood from forestry: This residue is extracted from forests during thinning or harvest operations as a co-product of stem wood extraction.

- Cereal straw (wheat): This residue is extracted from wheat fields after the harvest.

Besides main feedstocks, the provision of several inputs like phosphorous fertiliser is taken into account as well in the sustainability assessment.

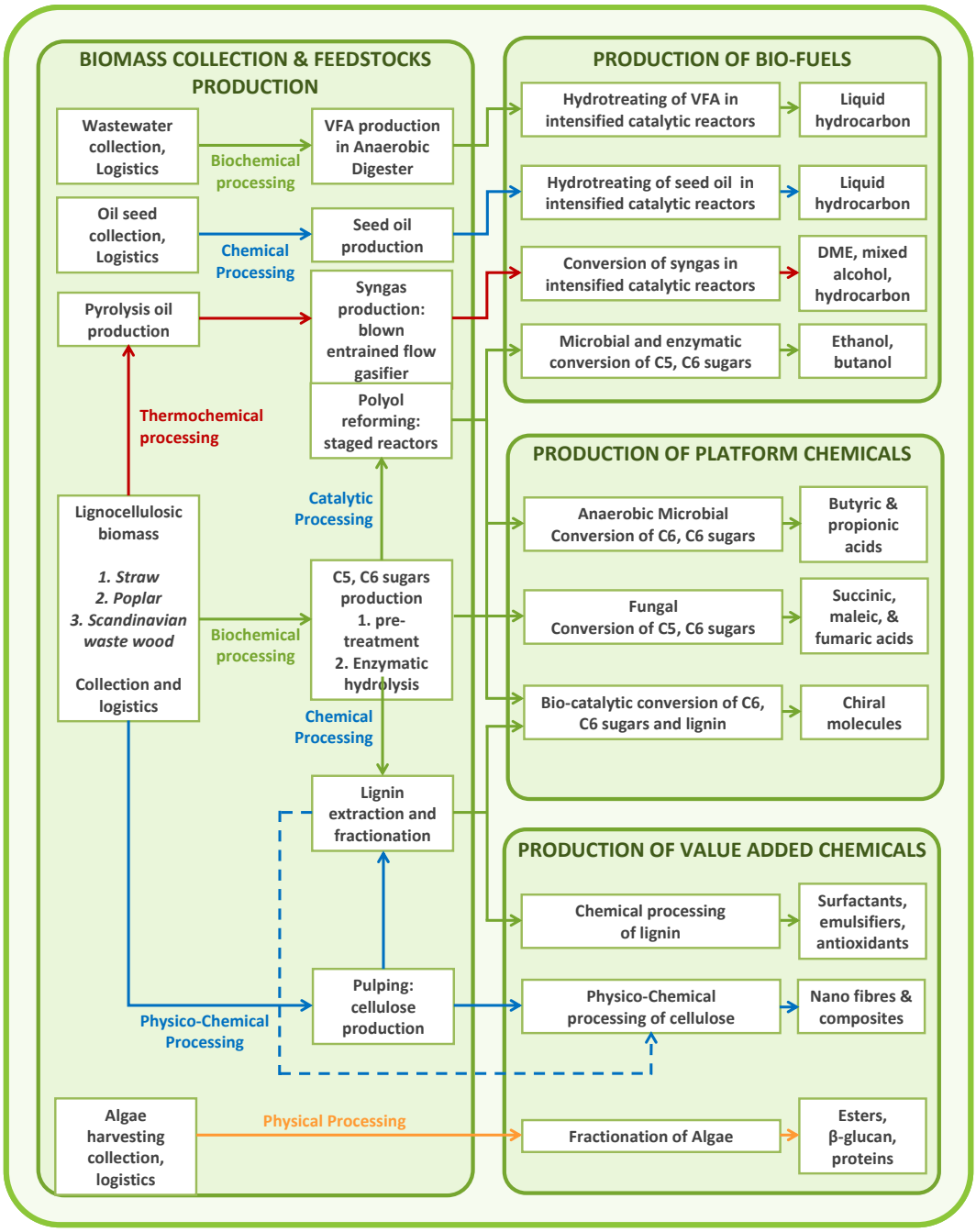


Fig. 4-1 Overview of routes within the SUPRABIO biorefining concept.

4.1.2 Transport and logistics

Transport and logistics of biogenic feedstocks face particular challenges because their energy densities are lower than those of fossil feedstocks. This leads to a higher transportation volume. One approach for a solution is to convert biomass in several distributed units into a high energy density intermediate, which saves transport costs. This strategy is followed in the thermochemical route, which is based on five distributed pyrolysis units supplying pyrolysis oil to one central biorefinery for gasification and subsequent Fischer Tropsch synthesis. In the biochemical route, however, primary biomass is transported to central biorefineries.

Additionally, biomass requires extensive storage capacity because of its low energy density and (in most cases) seasonal harvesting. SUPRABIO scenarios are mainly based on distributed storage of biomass close to the field / forest.

4.1.3 Raw material conversion (SUPRABIO biorefinery)

The SUPRABIO biorefining concept includes three classes of conversion routes:

- Biochemical routes based on a pre-treatment of lignocellulosic biomass via steam explosion and followed by enzymatic and / or microbial conversion (subchapter 4.1.3.1).
- Thermochemical routes based on pyrolysis and subsequent thermochemical (catalytic) conversion of lignocellulosic biomass (subchapter 4.1.3.2).
- Other routes / add-ons, which aim at using co-products of the core biorefinery (biochemical or thermochemical) but may also use a variety of other feedstocks via specific conversion technologies (subchapter 4.1.3.3).

Technical reference, time frame and geographical coverage

The technical reference describes the technology to be assessed in terms of plant capacity and development status / maturity. The time frame of the assessment determines e.g. the development status of biorefinery technology. Likewise, the environmental impact associated with conventional products changes over time (hopefully decreasing), e.g. greenhouse gas emissions associated with electricity generation. In this assessment, scenarios distinguish between an early implementation and a later implementation with the following differences:

Early implementation:

- 2015
- Current technology
- 40,000 tonnes / year of dry matter input to central biorefinery or 8,000 tonnes / year of dry matter input to five distributed pyrolysis units (depending on scenario)

Later implementation (all main scenarios):

- 2025
- Mature technology
- 400,000 tonnes / year of dry matter input to central biorefinery or 80,000 tonnes / year of dry matter input to five distributed pyrolysis units (depending on scenario)

Geography plays a crucial role in many sustainability assessments, determining e.g. agricultural productivity, transport systems and electricity generation. The SUPRABIO project focuses Europe and thus all parameters and reference processes are chosen based on this region (mostly EU 27). Deviating from this specification, some of the other routes / add-ons are also assessed based on imported biomass because this represents a large fraction of the production and use in Europe, e.g. in the case of hydrogenated vegetable oils (HVO).

4.1.3.1 Biochemical route

The fermentative conversion of lignocellulosic biomass pre-treated by means of steam explosion can yield a variety of products. Furthermore, a variety of feedstocks can be used and several plant configurations are possible. Out of all these options, five combinations were chosen to be modelled in detail and to be depicted in scenarios for sustainability assessment. These are:

Early implementation scenario:

I. Straw to Ethanol (2015)

Main scenarios (mature technology):

II. Straw to Ethanol (2025)

III. Poplar to Ethanol (2025)

IV. Straw to Mixed Acids (2025)
   IVa: Butyric acid
   IVb: Propionic acid

Simplified schemes of the respective life cycles of these processes, their products and the respective conventional reference processes and products are depicted in Fig. 4-2 to Fig. 4-4 for scenarios I to IV.

All biochemical processes use lignocellulosic biomass (wheat straw or poplar short rotation coppice) and share the pre-treatment process. They mainly differ in the fermentation sections, which produce various products from hydrolysed cellulose and hemicellulose. The utilisation of co-products again follows a similar strategy in all processes: Anaerobic digestion and staged gasification followed by combustion of the resulting biogas and syngas are used to produce process energy from process residues. These residues mainly consist of stillage, which is left over after product separation and also contains the lignin. The early implementation scenario on ethanol production in 2015 differs from the corresponding mature technology scenario in the configuration of the hydrolysis and fermentation section. In 2015, simpler but already available separate hydrolysis and co-fermentation (SHcF) is used, whereas simultaneous saccharification and co-fermentation (SScF) in employed in the 2025 mature technology scenarios.

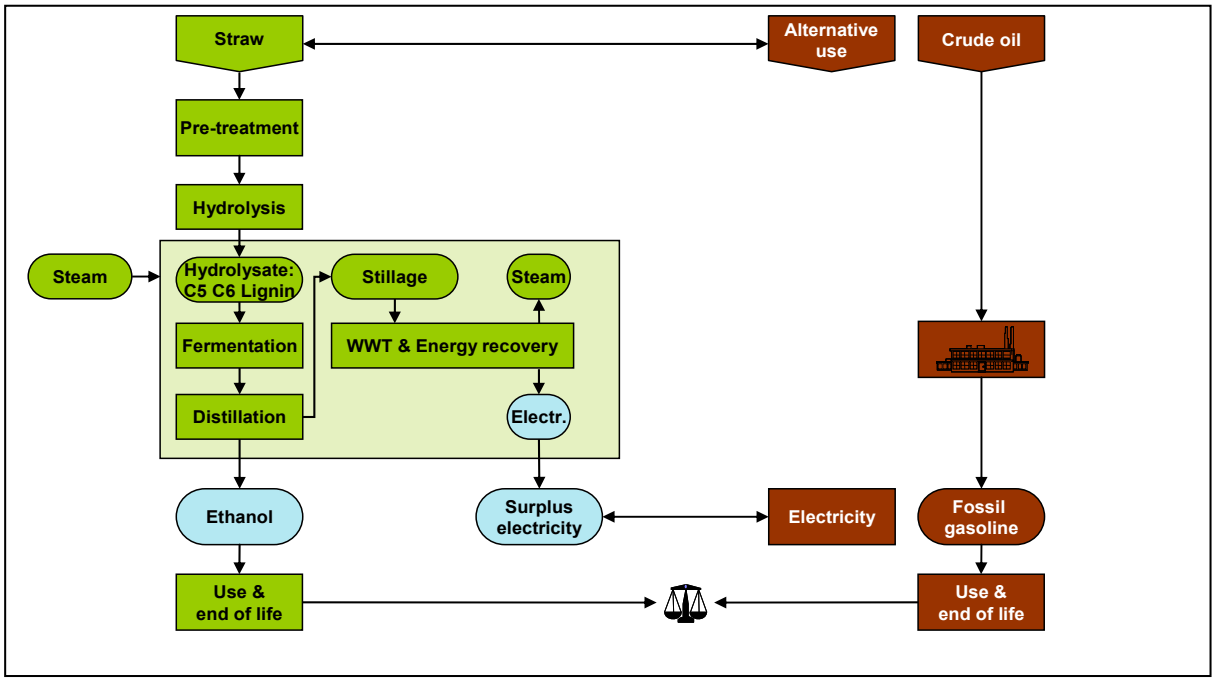


Fig. 4-2 Life cycle comparison between ethanol from straw (2015) and its reference products and processes (Scenario I). WWT: wastewater treatment.

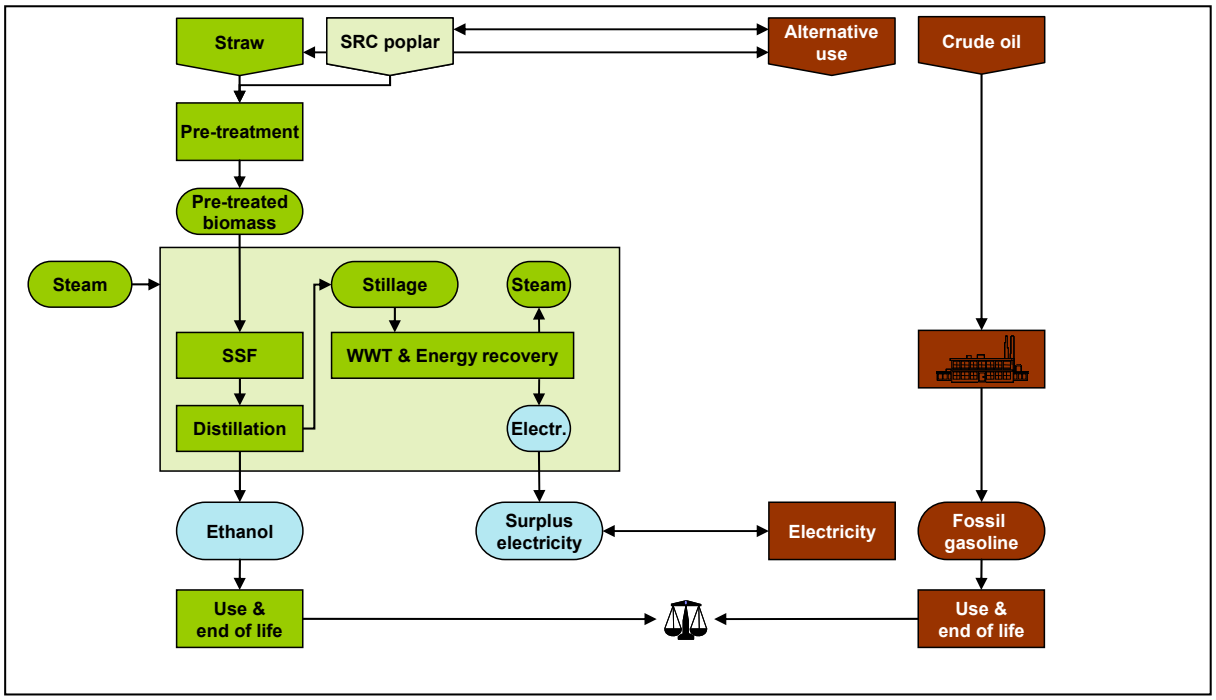


Fig. 4-3 Life cycle comparison between ethanol from straw (2025) or poplar (2025, light green) and their reference products and processes (Scenarios II and III, respectively). SSF: simultaneous saccharification and fermentation, WWT: wastewater treatment.

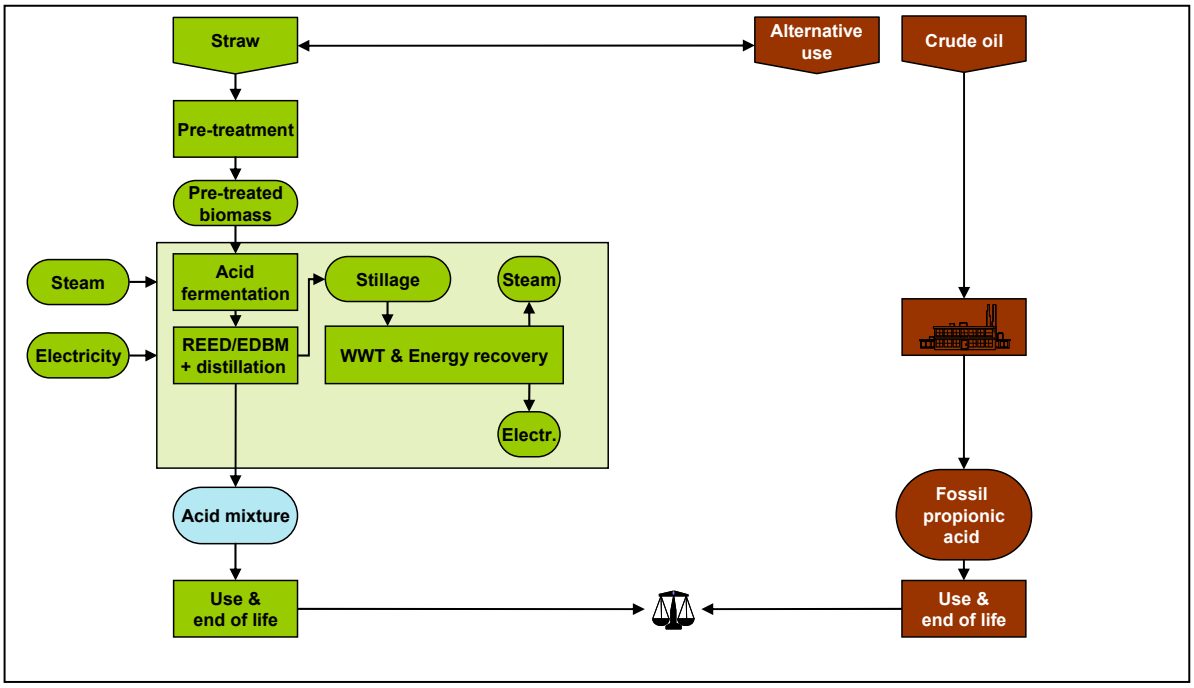


Fig. 4-4 Life cycle comparison between mixed acids from straw (2025) and their reference products and processes (Scenario IV). REED: reversed electro-enhanced dialysis, EDBM: electrodialysis using bipolar membranes.

For details on the processes including process flow sheets and mass and energy balances please refer to /Ljunggren et al. 2013/ and /Nygård et al. 2013/.

Sensitivity analysis scenarios:

The efficiency of process energy generation is a very important parameter for the overall performance of the biorefinery because it determines whether additional energy input from fossil resources is required or if excess electricity can be fed into the power grid. Therefore, this section is studied in a separate sensitivity analysis as a variation of scenario II (Fig. 4-5).

Based on scenario II: Straw to Ethanol (2025)

II-1-A. Straw to Ethanol (2025) – Gas turbine (identical to main scenario)

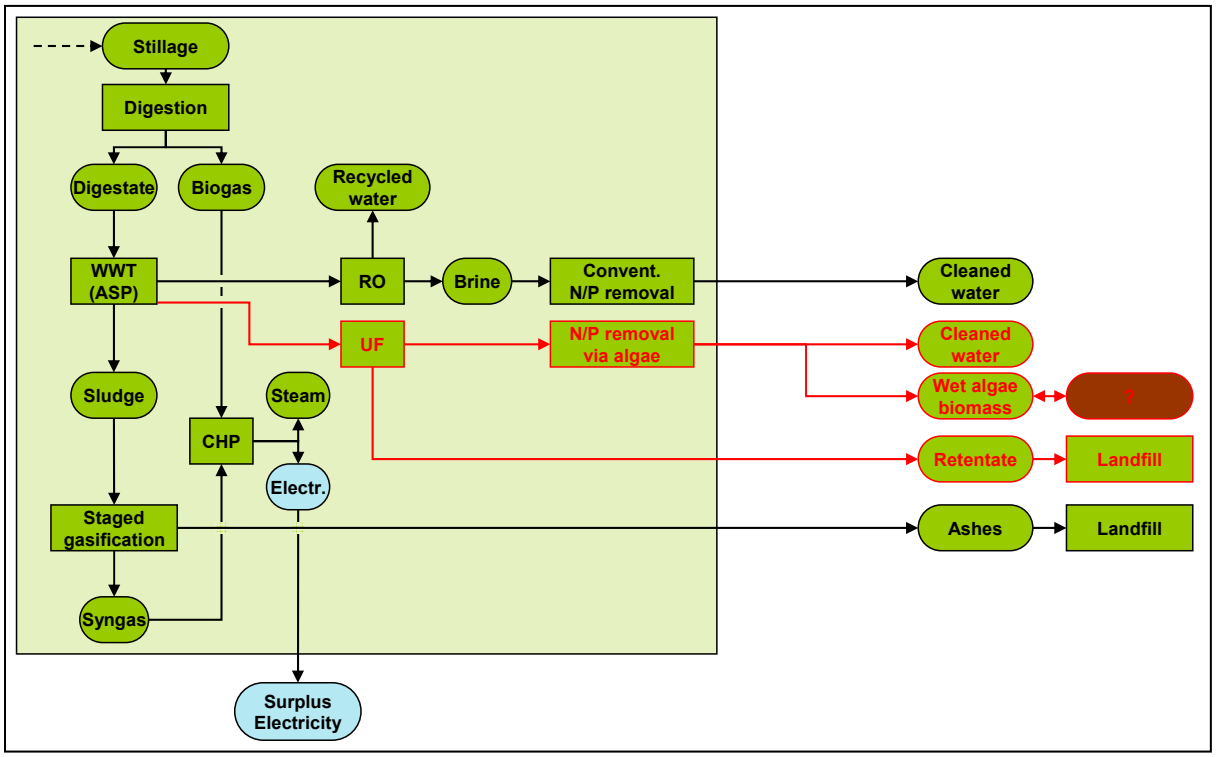
II-1-B. Straw to Ethanol (2025) – Gas engine

II-2-A. Straw to Ethanol (2025) – Gas turbine and early solids separation

II-2-B. Straw to Ethanol (2025) – Gas engine and early solids separation

II-2-C. Straw to Ethanol (2025) – Circulating fluidised bed boiler and early solids separation

One varied parameter concerns the order of process steps: Solids can be separated from the stillage stream after anaerobic digestion (sub-scenarios 1-A and 1-B) or before anaerobic digestion (sub-scenarios 2-A, 2-B and 2-C). The other difference between the scenarios in the sensitivity analysis is the kind of CHP technology used for the co-production of steam and power. This can either be a gas turbine, a gas engine (both for the co-combustion of syngas and biogas) or a steam turbine, the latter being coupled to the boiler which co-combusts solids and biogas.



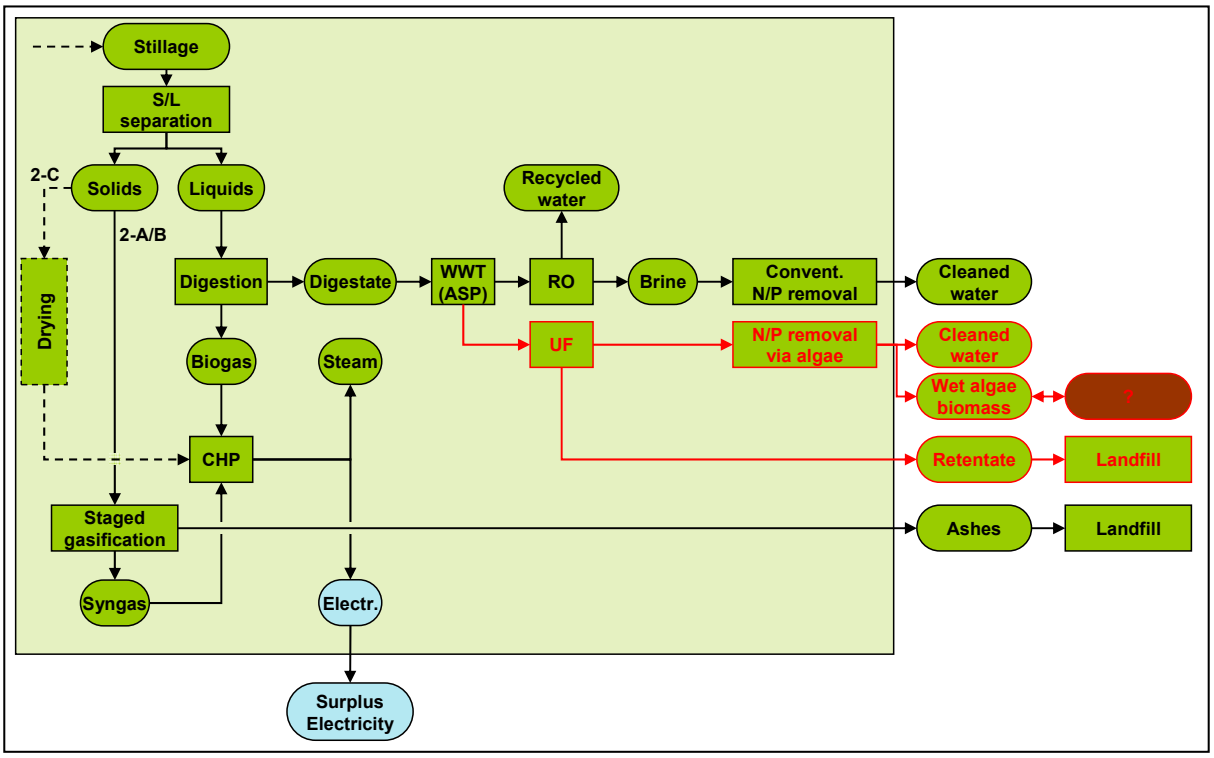


Fig. 4-5 Sensitivity analysis scenarios on co-product usage for biochemical route. Top: scenarios 1-A and 1-B; bottom: scenarios 2-A, 2-B and 2-C. Red elements indicate alternative process steps if algae production is integrated with the biorefinery. WWT (ASP): wastewater treatment by active sludge process, CHP: combined heat and power plant, RO: reverse osmosis, UF: ultrafiltration.

The standard biorefinery scenarios are based on a wastewater treatment (WWT) consisting of an activated sludge process (ASP) followed by reverse osmosis (RO), yielding recycled water (back to the biorefinery) and brine. The latter, however, still contains substantial amounts of N and P and needs further external sewage treatment before being released to a receiving water body. For details on the processes including process flow sheets and mass and energy balances please refer to /Ljunggren et al. 2013/ and /Nygård et al. 2013/.

In SUPRABIO, an alternative WWT including algae production was investigated, too. The idea was to make use of the nutrients (N and P) still contained in the biorefinery wastewater. In this scenario, pre-treated wastewater (by means of ASP) is subjected to an ultrafiltration unit (UF) before entering the algae production process in open ponds (raceway configuration) under a greenhouse. Furthermore, it was assumed that the algae production could benefit from CO_2 originating from fermentation processes, and low temperature residual heat recovered from the core processes /Le & Lépine 2011/ and /Le Borgne 2014/.

However, since /Le Borgne 2014/ was not available by 30 September 2013 (project-internal deadline), this pathway could not be considered in the process integration work by Statoil. Therefore, this scenario cannot be evaluated quantitatively in this assessment due to a lack of detailed mass and energy flow data. Nevertheless, its advantages and disadvantages are discussed qualitatively.

4.1.3.2 Thermochemical route

The thermochemical routes in the SUPRABIO concept are based on pyrolysis of lignocellulosic biomass. Scenarios differ in used feedstocks and final products. Additionally to wheat straw and poplar short rotation coppice, which can also be used by the assessed scenarios of the biochemical route, the thermochemical route can also use forestry residues as feedstock. The products of the thermochemical routes are Fischer-Tropsch (FT) fuels (synthetic diesel and a gasoline equivalent derived from bio-based naphtha) or dimethyl ether (DME), which is also used as transportation fuel.

Early implementation scenario:

I. Forest residues to FT fuels (2015)

Main scenarios (mature technology):

II. Forest residues to FT fuels (2025)

III. Forest residues to DME (2025)

IV. Straw to FT fuels (2025)

V. Poplar to FT fuels (2025)

VI. Simplified schemes of the whole life cycles of these processes, their products and the respective conventional reference processes and products can be found in Fig. 4-6 and Fig. 4-7.

VII. The early implementation scenario (2015) is very similar to the mature technology scenario (2025). It is based on a smaller scale (40 kt/year instead of 400 kt/year) and operating conditions and performance parameters do not reach industrial level yet.

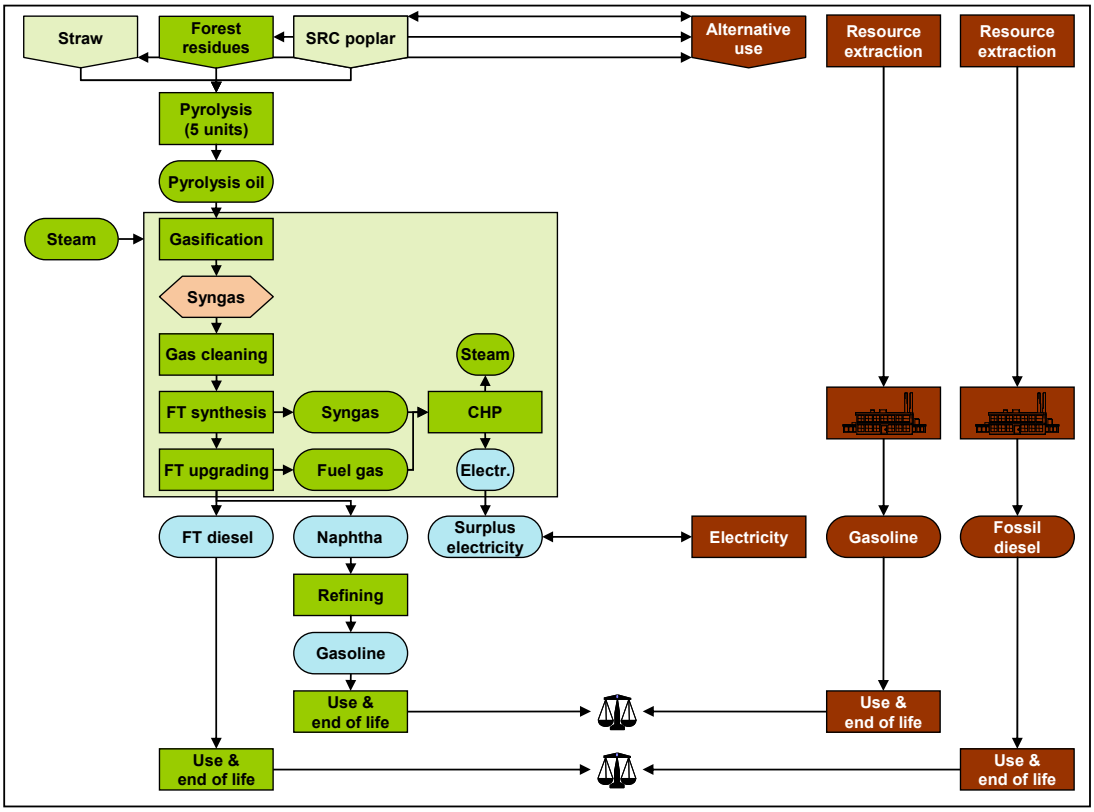


Fig. 4-6 Life cycle comparison between Fischer Tropsch (FT) fuels from forest residues, straw or poplar short rotation coppice (SRC) (2025) and their reference products and processes (Scenarios II, IV and V, respectively). CHP: combined heat and power plant.

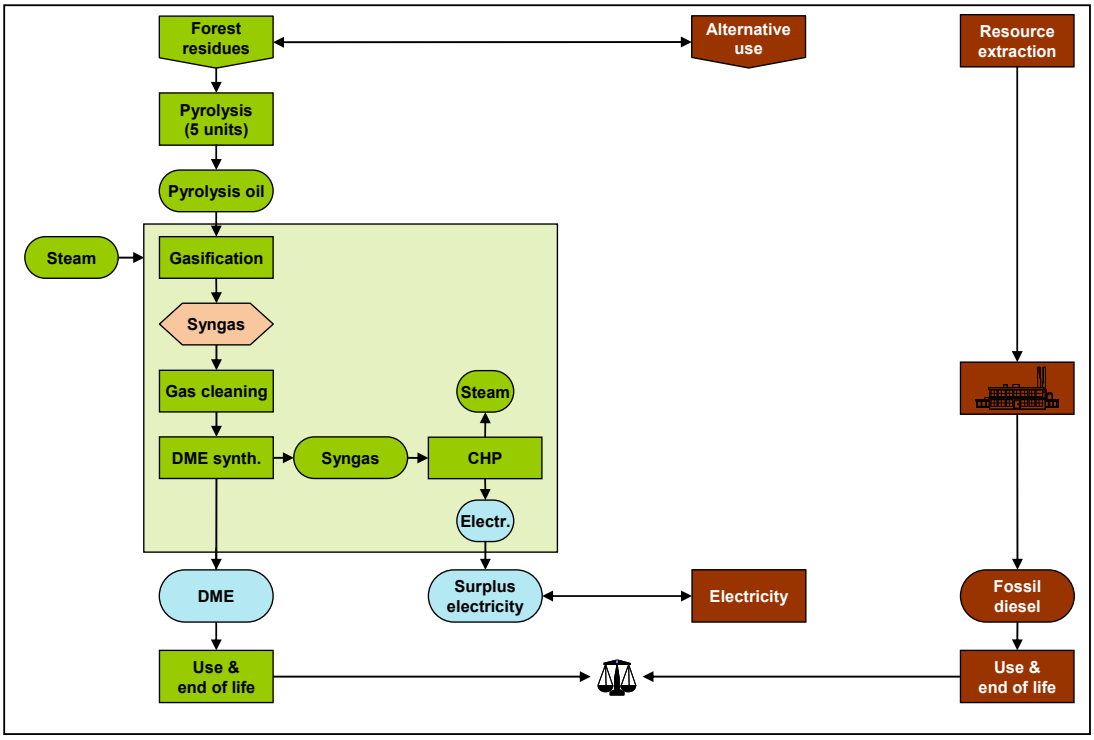


Fig. 4-7 Life cycle comparison between dimethyl ether (DME) from forest residues (2025) and its reference products and processes (Scenario III). CHP: combined heat and power plant.

Sensitivity analysis scenarios:

Several specific aspects of the thermochemical route, which are important for the overall performance of the process, are studied additionally in sensitivity analyses. One scenario investigates natural gas as an alternative energy input for the biorefinery. Another scenario analyses whether a central plant including one pyrolysis unit is better than the standard configuration with five distributed pyrolysis units. Two more scenarios concern crucial process parameters of the gasification unit within the biorefinery.

Based on scenario II: Forest residues to FT fuels (2025)

VIII. Forest residues to FT fuels (2025) – Natural Gas

IX. Forest residues to FT fuels (2025) – Centralised

X. Forest residues to FT fuels (2025) – High pressure

XI. Forest residues to FT fuels (2025) – High pressure and quenching temperature

A life cycle scheme on these scenarios can be found in Fig. 4-8.

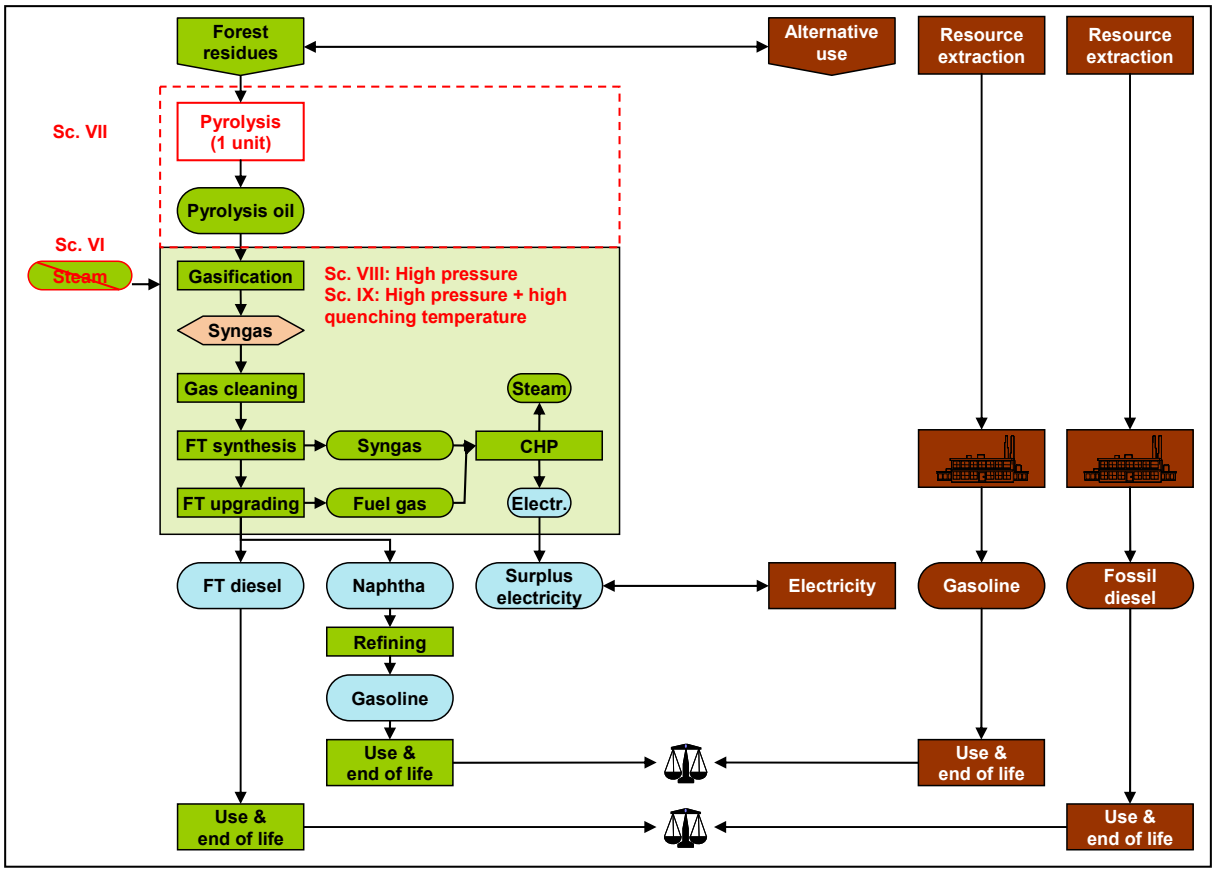


Fig. 4-8 Sensitivity analyses (Scenarios VI to IX). Differences to main scenario II (Forest residues to FT fuels, 2025) are indicated in red.

4.1.3.3 Other routes

Other routes are designed as add-ons to be integrated with the main biorefinery. They aim at using co-products of the bio- or thermochemical core biorefinery (Fig. 4-9 and Fig. 4-10) but may alternatively also use a variety of other feedstocks in a stand-alone version.

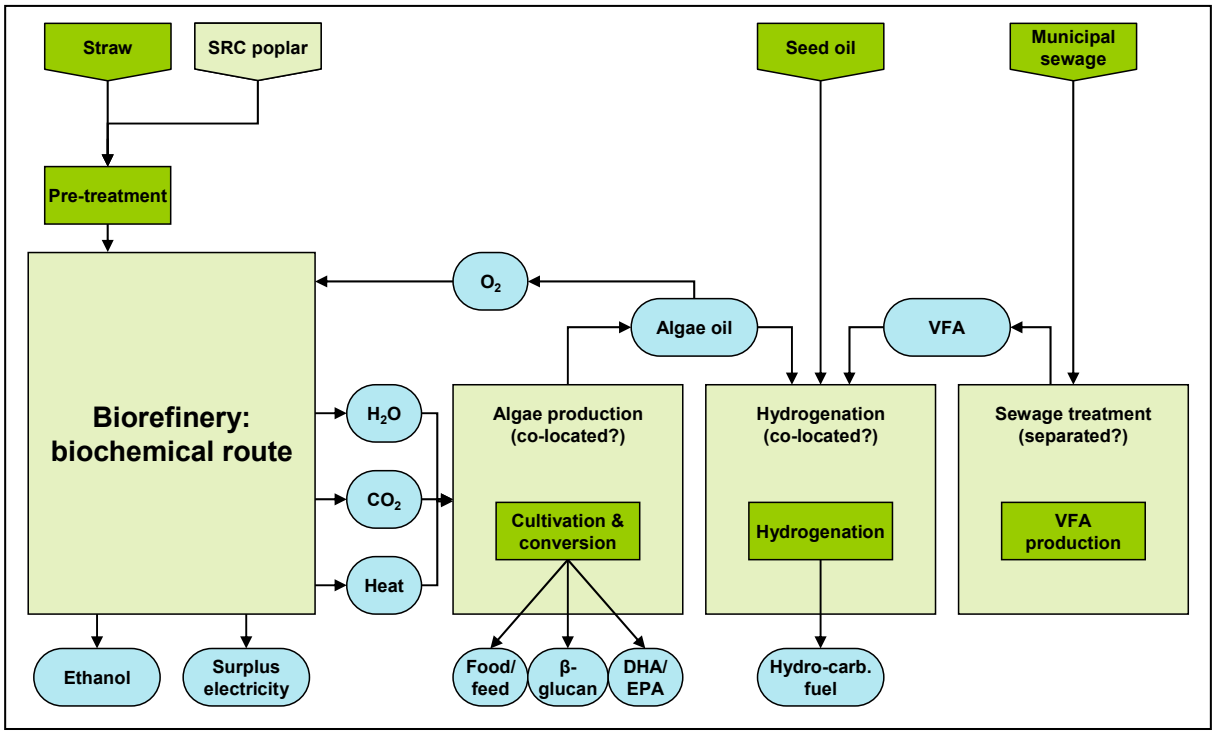


Fig. 4-9 Biochemical biorefinery and possible add-ons. For details and abbreviations please refer to the text or chapter 9.

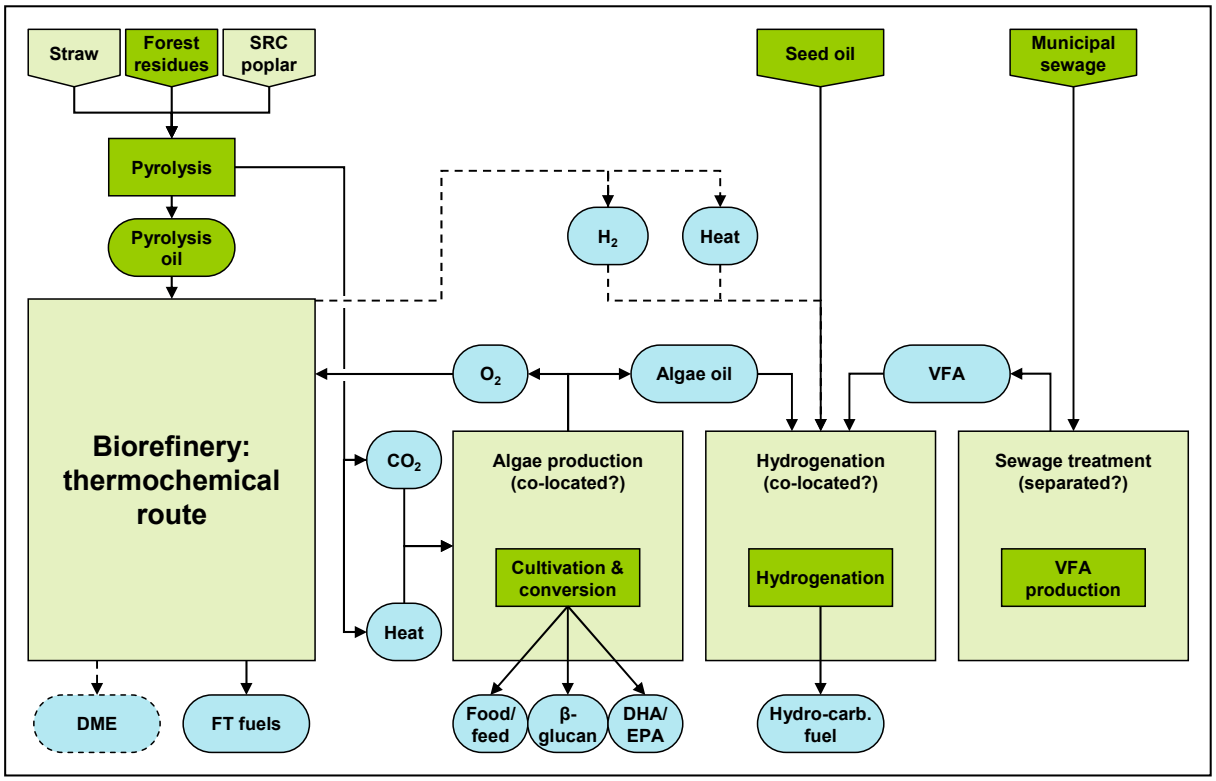


Fig. 4-10 Thermochemical biorefinery and possible add-ons. For details and abbreviations please refer to the text or chapter 9.

As there were no robust mass and energy balances available within the SUPRABIO project, these routes can only be evaluated in a qualitative way where possible. Please refer to /Nygård et al. 2013/ for technical details. The following other routes are part of the SUPRABIO biorefining concept:

Mixed alcohols from volatile fatty acids (VFA)

Short chained volatile fatty acids (VFA) are produced via fermentation from organic matter contained in municipal sewage. Then they are hydrogenated to yield mixed alcohols that can be used as biofuel. The required hydrogen was planned to be supplied by the core biorefinery. However, since /Barta 2013a/ and /Barta 2013b/ were not available by 30 September 2013 (project-internal deadline), this pathway could not be considered in the process integration work by Statoil. Therefore, this route cannot be evaluated in this assessment due to a lack of detailed mass and energy flow data.

EPA / DHA and β-glucan from algae

In SUPRABIO, the production of high-value dietary supplements from algae such as docosahexaenoic acid (DHA), its precursor eicosapentaenoic acid (EPA) and β-glucan was investigated. However, due to a change of partners, this work will only be completed by the end of the project. This means that at the time of writing this report, the algae production process and its potential links to the core biorefinery have not been defined yet. Therefore, this route cannot be evaluated in this assessment.

Seed oil hydrogenation

This route concerns the hydrogenation of seed oils (also called vegetable oils) to yield biofuels (HVO, hydrogenated vegetable oils). Feedstocks include rapeseed, oil palm, soybean or Jatropha. Hydrogenation of vegetable oils is a state-of-the-art process established at industrial scale, e.g. by Neste Oil who operates a plant in Porvoo, Finland, and a 800 kt plant in Rotterdam, the Netherlands.

The main advancement of SUPRABIO was the development of a staged introduction of hydrogen into the reactor. The required hydrogen and possibly also heat was planned to be delivered by the core biorefinery. A further integration potential was envisioned by using algae oils (see above) or volatile fatty acids (VFA, see above). However, since /Barta 2013a/ and /Barta 2013b/ were not available by 30 September 2013 (project-internal deadline), this pathway could not be considered in the process integration work by Statoil. Therefore, this route cannot be evaluated in this assessment due to a lack of detailed mass and energy flow data.

Nevertheless, seed oil hydrogenation was assessed generically from an environmental point of view as a stand-alone plant based on published data on existing HVO plants to outline the potentials and risks of this route. As there is no project-specific data involved in the assessment, this route is not listed as SUPRABIO scenario but as alternative to SUPRABIO to avoid misunderstandings.

4.1.4 Use and end of life

Use and end of life of all biorefinery products are taken into account in the sustainability assessment, too. Most SUPRABIO products are primarily used as biofuels. These are ethanol, FT diesel and dimethyl ether (DME). Hydrogenated vegetable oils (HVO), which are assessed generically in this study, are used as biofuel, too. For all fuels, combustion in a motor represents the use and end of life stage. Mixed acids are used as cereal grain preservatives. They remain on the cereals in the further animal feed production process. Therefore, there is no end of life treatment.

Depending on the scenario, co-products of SUPRABIO biorefineries can be surplus electricity and ashes from combustion of process residues. Electricity is fed into the power grid and ashes are landfilled.

4.1.5 Reference systems for SUPRABIO

The purpose of this environmental assessment is to compare the impacts of the whole life cycles of SUPRABIO biorefinery products to the impacts that would arise from alternative processes and products, which would be used if no SUPRABIO biorefinery was built. The comparison on the product level is based on equivalent utility of innovative and replaced conventional products (subchapter 4.1.5.2). Furthermore, the alternative use of resources such as agricultural land and agricultural or forestry residues has to be considered: what would happen to them if they weren't used by the biorefinery. This is described in the subchapter on reference systems (subchapter 4.1.5.1).

4.1.5.1 Reference systems for land use and biomass use

The initial part of the assessment focussing on the SUPRABIO biorefinery concept is based on the precondition that sufficient biomass or agricultural land is available. Independent of how much unused biomass or agricultural land may be available in reality in 2015 or 2025, this precondition allows to independently assess the SUPRABIO biorefinery and its optimisation options before comparing it to alternative use options of biomass or agricultural land in a second step (subchapter 4.2). Thus, the implementation of the SUPRABIO biorefinery concept is compared to not extracting agricultural residues and forestry biomass or not using the agricultural land.

Nevertheless, these reference systems can still cause environmental benefits (e.g. remaining straw serves as fertiliser reducing the demand for mineral fertiliser) or environmental burdens (e.g. nitrogen deposited from the air on idle land causes environmental burdens. These environmental impacts of the reference system are credited to the SUPRABIO biorefinery, which leads to the reduction of its environmental impacts (if burdens are avoided) or to additional impacts (if benefits are prevented). These reference systems are part of the life cycles of the SUPRABIO scenarios. An overview of SUPRABIO feedstocks and their reference systems is given in Table 4-1.

Table 4-1 Feedstocks for the SUPRABIO biorefining concept and their reference systems

Feedstock type	Feedstock	Reference system
Agricultural residues	Wheat straw	Ploughing in
Forestry residues	Residues such as branches or thin tops (non-stem wood)	Remain in forest
Agricultural biomass	Poplar short rotation coppice (SRC)	No production, land is laying idle (Europe: non-rotational fallow land without significant accumulation of carbon stocks)
	Rapeseed	Non-rotational fallow land (EU)
	Oil palm	a) Idle land b) Rainforest
	Soybean	a) Idle land b) Rainforest
	Jatropha	a) Idle land (good soil) b) Marginal land c) Woodland

4.1.5.2 Reference products

Reference products are conventional products that are replaced by biorefinery products. Their complete life cycles are assessed and compared to the complete life cycles of the SUPRABIO products.

For all biofuels, the reference products are equivalent amounts of fossil fuels. Depending on whether the biofuel is used in diesel or gasoline engines, conventional diesel or gasoline are replaced. The replaced amount is based on the distance that can be travelled using either fuel in a standard car. Mixed acids are compared to equivalent synthetic organic acids (butyric or propionic acid), which are made from fossil resources.

The co-product electric power replaces conventionally produced power in the grid. As this study follows a consequential approach and thus its influence on the energy sector has to be taken into account, power consumption is assessed following a marginal concept /Fraunhofer ISI 2009/, /UBA 2013/. According to this, additionally produced power of new plants such as biorefineries prevents either new power plants to be built or causes old power plants to be shut down earlier. Based on the assumption that renewable energies mainly compete with fossil energy sources rather than with each other due to political boundary conditions, the bandwidth of marginal energy sources ranges from natural gas to hard coal.

For all qualitative parts of the sustainability assessment, those steps in the life cycles of all reference products have to be identified, which are most relevant regarding sustainability impacts. In the case of SUPRABIO, all replaced main products are largely produced from petroleum fractions. Thus, crude oil extraction and refining are key processes for all reference products and for some also petrochemical processes are important. Furthermore, some scenarios produce electricity as a co-product. In this case, extraction and conversion of other conventional energy resources such as coal, gas and uranium are relevant for the reference products' life cycles, too.

4.1.6 Overview of scenarios

4.1.6.1 Biochemical route

Table 4-2 SUPRABIO scenarios for the biochemical route

Number	Name
Early implementation	
I	Straw to Ethanol (2015)
Main scenarios (mature technology)	
II [= II-1-A]*	Straw to Ethanol (2025)
III	Poplar to Ethanol (2025)
IVa/b	Straw to Mixed Acids (2025)
Sensitivity analysis scenarios	
II-1-B	Straw to Ethanol (2025) – Gas engine
II-2-A	Straw to Ethanol (2025) – Gas turbine and early solids separation
II-2-B	Straw to Ethanol (2025) – Gas engine and early solids separation
II-2-C	Straw to Ethanol (2025) – Boiler and early solids separation

*: All main scenarios use gas turbines for energy production from co-products.

4.1.6.2 Thermochemical route

Table 4-3 SUPRABIO scenarios for the thermochemical route

Number	Name
Early implementation	
I	Forest residues to FT fuels (2015)
Main scenarios (mature technology)	
II	Forest residues to FT fuels (2025)
III	Forest residues to DME (2025)
IV	Straw to FT fuels (2025)
V	Poplar to FT fuels (2025)
Sensitivity analysis scenarios	
VI	Forest residues to FT fuels (2025) – Natural Gas
VII	Forest residues to FT fuels (2025) – Centralised
VIII	Forest residues to FT fuels (2025) – High pressure
IX	Forest residues to FT fuels (2025) – High pressure and quenching temperature

4.1.6.3 Other routes

HVO from rapeseed, oil palm, soybean and Jatropha are assessed on a generic level as a stand-alone plant. As these processes cannot be distinguished from competitors' processes, they are listed as alternatives to SUPRABIO (subchapter 4.2).

4.2 Alternative biomass-based systems

Biomass and agricultural land are limited resources. There is considerable uncertainty regarding the extent of underutilised biomass and land potentials that are available for bioenergy, biofuels, biomaterials and bio-based chemicals production in 2025. Nevertheless, most studies agree that there will be at least some biomass and land available for these purposes but that it will not be sufficient to realise all expansion plans in the respective sectors. Therefore, SUPRABIO competes with alternative biomass-based systems for resources. These alternatives are assessed in this environmental assessment as well including their whole life cycles and the whole life cycles of the conventional (mostly fossil resource-based) products they replace (reference systems). This subchapter introduces the assessed scenarios of alternative biomass-based systems and their reference systems.

The scenarios for alternative biomass-based systems are based on the same precondition that there is sufficient biomass and agricultural land available. Competition between alternatives and SUPRABIO scenarios is analysed by comparing the assessment results of all competing scenarios (subchapters 6.4 and 6.5).

Alternative biomass use

Biomass can be used in various alternative ways besides in a SUPRABIO biorefinery. For lignocellulosic feedstocks other than solid wood, the most important alternative is direct combustion for heat and power production. This is assessed for all lignocellulosic SUPRABIO feedstocks.

Alternative land use

If cultivated biomass is used as feedstock, agricultural land is required for its production. In that case, the land could also be used for alternative purposes. The alternative scenarios for energy and fuel production in Europe listed in Table 4-4 are analysed in this study.

Table 4-4 Alternative uses of agricultural land in Europe (other than for SUPRABIO)

Feedstock	Product	Reference product
Sugar beet, wheat grains and maize grains	1st generation Bioethanol (transportation fuel)	Gasoline
Rapeseed	Biodiesel (transportation fuel)	Diesel
Rapeseed	Hydrogenated vegetable oil (HVO, transportation fuel)	Diesel
Maize (whole plant)	Biogas (CHP fuel)	Heat and power
Triticale (whole plant)	Direct combustion (CHP fuel)	Heat and power

Furthermore, production of hydrogenated vegetable oil (HVO) from following non-European feedstocks is assessed for comparison: palm oil, soy oil and Jatropha oil.

All reference products in these alternative scenarios are based on fossil feedstocks. They are assessed as described in subchapter 4.1.5.2 for the reference products of SUPRABIO products.

5 Summary of results from individual assessments

5.1 Technological assessment

The following subchapters are adopted from D 7-11 “Final report on techno-economic assessment including the market potentials of SUPRABIO products” /Lervik Mejdell et al. 2014/, where amongst others, a technical evaluation of the biorefinery concepts was conducted. For detailed results please refer to the section on the technical evaluation in the original assessment report.

5.1.1 Objective

The objective of the technological assessment was to identify potentials and technological constraints of biorefinery concepts investigated in the SUPRABIO project.

5.1.2 Methodology

To get data on the technology of the processes investigated in SUPRABIO, process flow sheeting and data collection was initiated early in the project period by developing Excel flow sheets for the processes in cooperation with the process developers. However, during the technical evaluation it was revealed that several of the processes that should have initially been investigated (see D 7-1 /Rettenmaier et al. 2011/), were very immature and some were lacking important process steps to form a complete process from feedstock to final product. Thus, unfortunately, only limited process data was received and could be used for the analysis. As described in subchapter 4.1.3, two different biorefinery concepts have also been evaluated in D 7-11, one based on the biochemical core process concept (subchapter 4.1.3.1) and the other based on the thermochemical core process concept (subchapter 4.1.3.2). In addition, the possibility to integrate so-called add-ons has been investigated (subchapter 4.1.3.3).

For the two biorefinery concepts only waste treatment integration was implemented. No other relevant integration between the proposed processes in the biochemical refinery concept has been found technically feasible so far. Each process was therefore evaluated one by one integrated with the waste treatment scenario.

Among the proposed add-ons, only the seed oil hydrogenation process was established and could potentially be connected to the biorefinery concepts via hydrogen exchange. Unfortunately, the evaluation of hydrogen extraction from different biorefinery streams was delayed making it impossible to include these results in the technological assessment.

For the biochemical process (ethanol production) and partially for the thermochemical route (FT liquids and DME production), the established Aspen Plus models create a basis for dimensioning of the equipment. For the processes lacking important data, a rough approach was used mainly to point out the main process and product challenges which will be guidance for the process developers on where to focus the development efforts.

5.1.3 Key results

The two biorefinery concepts studied perform very differently:

- The biochemical route anticipated for the year 2025 (Scenario II: straw to ethanol) has a high energy efficiency of about 55 % and 70 % LHV efficiency and net efficiency, respectively.
- The maximum net and LHV efficiency of the thermochemical refinery concept, however, is below 30 %.

In the following more detailed results for the biochemical and the thermochemical route are described.

Biochemical route

The main product of the biochemical route is ethanol. Alternatively, also mixed acids can be produced.

For the production of **ethanol**, the following key results could be identified:

- The technologies are available at demo or pilot scale if wheat straw is used as feedstock. No show-stoppers were identified.
- Nevertheless, there is still a risk of failure in technological development with regard to the performance of this pathway, in particular with respect to the development of a simultaneous saccharification and co-fermentation (SScF) concept (mature configuration, e.g. scenario II).
- The early implementation scenario (scenario I) showed somewhat lower performance compared to the mature technology scenario as anticipated for 2025 (scenario II) since the SScF process used in the mature configuration produces more energy that can be converted into electricity and exported to the grid compared to the SHcF process used in the early implementation.
- The sub-scenarios (2015 or 2025) using staged gasification combined with gas turbine (scenarios II-1-A and II-2-A) or gas engine (scenarios II-1-B and II-2-B) produce a significant amount of electricity (Table 5-1 for 2025).
- For the boiler based sub-scenario (II-2-C) all the waste is converted to steam and after supplying enough steam and electricity to the process it is depending on the maturity (2015 or 2025) if either electricity can be imported or must be exported to the grid.
- However, the different sub-scenarios perform not dramatically different and from the technical evaluation point of view (for both maturity levels 2015 and 2025) it is therefore impossible to select a preferred sub-scenario.

- Changing feedstock from straw to poplar wood significantly reduced the LHV efficiency from feedstock to fuel ethanol, while the net efficiency was still comparable.

Table 5-1 Overall energy efficiency for main Scenario II Straw to ethanol (2025) /Lervik Mejdell 2014/. LHV = lower heating value; MP = mid pressure; LP = low pressure.

	Sub-scenario 1-A (gas turbine) Energy [kW]	**Sub-scenario 1-B (gas engine) Energy [kW]**	**Sub-scenario 2-A (gas turbine / early solid separation) Energy [kW]**	**Sub-scenario 2-B (gas engine / early solid separation) Energy [kW]**	**Sub-scenario 2-C (boiler and early solid separation) Energy [kW]**
LHV Biomass Feed:	225,980	225,980	225,980	225,980	225,980
LHV Ethanol Product:	124,310	124,310	124,310	124,310	124,310
Electricity Export:	17,500	22,250	15,220	19,920	6,970
MP steam deficit:	0	290	0	0	0
LP steam deficit:	2,840	7,380	2,040	6,510	0
LHV efficiency[1]	55 %	55 %	55 %	55 %	55 %
Net efficiency[2]	67 %	69 %	65 %	68 %	60 %

[1] Calculated as: LHV Ethanol Product/ (LHV Biomass Feed)
[2] Calculated as: LHV Ethanol Product/ (LHV Biomass Feed – Electricity Export/0.4 + Steam deficit/0.9)

For the production of **mixed acids**, the following key results could be identified:

- The acid mixture separation end purification process is quite energy demanding which add a significant demand for importing electricity and steam.
- A potential challenge could be the membrane based separation of acids from the solids containing fermentation broth, but the process has according to Aalborg been proven in their laboratory with no issues regarding the membrane based separation.

Thermochemical route

The main product of the thermochemical route is FT diesel. Alternatively, also DME can be produced.

For the production of **FT liquids**, the following key results could be identified:

- The technologies are demonstrated. No show-stoppers were identified.
- Nevertheless, there is still a risk of failure in technological development regarding the performance of this pathway. That is in particular given for the following technologies:
    - Pressurised Entrained-flow Biomass Gasification (PEBG gasifier)
    - Further development of efficient and robust reactors for synthesis
- All the FT liquid scenarios result in a low net efficiency (below 30 %, Table 5-2) due to carbon losses associated to:
    - Pyrolysis section: net efficiency ranging from 60 to 67 %
    - Gasification section: cold gas efficiency ranging from 66 to 71 %

- FT section: LHV efficiency from conditioned syngas to fuel ranging from 52 to 67 %

- FT liquids produced from straw/poplar (scenario IV / V) result in a slightly lower efficiency than if FT liquids are produced from forest residues due to a slightly lower yield of pyrolysis oil from straw or poplar (Table 5-2).
- However, if the electricity export from the pyrolysis process is included in the calculations, the net energy efficiency will increase by about 1 % for forest residues and 3 % for straw and therefore both the straw and forest residues biorefineries have very similar net efficiency.
- Considerable amounts of steam are needed for the acid gas removal process and the water gas shift (WGS) reaction.
- All the FT liquid biorefinery scenarios result in a deficit of steam. Integration with the pyrolysis section (scenario VII) or introduction of natural gas (scenario VI) in order to overcome this deficit has been shown to be more energy efficient than importing steam (Table 5-2).
- The most favourable change in terms of overall performance is the operation at higher pressure (scenario VIII). Increasing the pressure results in a higher efficiency which is related to higher selectivity to heavier hydrocarbons in the FT section. However, the data related to this scenario in terms of FT performance is of high uncertainty and has not been demonstrated yet.
- Increasing the gasifier quenching temperature to 250°C results in approximately 1 - 2 % higher efficiency (scenario IX) compared to the high pressure scenario (scenario VIII) (Table 5-2).
- Producing steam on-site in the biorefinery by burning natural gas (scenario VI) in the existing gas turbine seems beneficial in terms of efficiency resulting in an increase of almost 2 % of the net efficiency. The use of natural gas also results in a larger electricity export (Table 5-2).
- Sending the incondensable pyrolysis gas and the flue gas from the char combustion of the pyrolysis process to the central CHP unit for steam production, the new configuration results in two larger pyrolysis units beside the biorefinery, instead of five smaller units distributed in the forest. The overall efficiency of the biorefinery can then be increased by 3.3 % (scenario VI, Table 5-2).
- The thermochemical biorefinery scheme producing FT liquids is a net water producer.

For the production of **DME**, the following key results could be identified (Table 5-2):

- It is too early to evaluate the ability of the microchannel technology for direct DME synthesis. New experimental campaigns using appropriate testing conditions need to be carried out in order to demonstrate highly selective one-step DME production. At the same time, a long development process is still necessary in order to optimise the catalyst formulation, maximise DME selectivity and study the long term mechanical and chemical stability of the system. In addition, as in the case of FT synthesis, a strategy for scaling up the system and management of the produced heat is still not clear.
- The production of DME from forest residues as feedstock results in an overall LHV efficiency approximately 6 % higher than the equivalent configuration for FT diesel produc-

tion. The main carbon losses are as described for FT liquids above for both the pyrolysis and gasification processes. The main difference is that higher selectivity to the final fuel product is achieved in the DME biorefinery.

- The DME biorefinery, however, results in a larger steam deficit. Still, the net efficiency of the DME biorefinery has been calculated to be approximately 2 % higher than for FT diesel.
- The thermochemical biorefinery scheme producing DME is a net water producer.

Table 5-2 Overall performance of the thermochemical biorefinery scenarios /Lervik Mejdell 2014/.

	Scen. I (2015)	**Scen. II (2025)**	**Scen. III (DME)**	**Scen. IV (straw)**	**Scen. V (poplar)**	**Scen. VI (nat. gas)**	**Scen. VII (centra-lised)**	**Scen. VIII (high pressure)**	**Scen. IX (high pressure / quench-ing)**
	2015 - FT	**2025 -FT**	**2025 - DME**	**2025 - FT - Straw**	**2025 - FT - Poplar**	**2025 - FT - NG**	**2025 - FT - Central**	**2025 - FT - HP**	**2025 - FT - HP-Quench**
	[kW]	**[kW]**	**[kW]**	**[kW]**	**[kW]**	**[kW]**	**[kW]**	**[kW]**	**[kW]**
LHV Bio-mass Feed:	128,545	257,090	257,090	231,967	236,405	257,090	257,090	257,090	257,090
LHV Natu-ral Gas	0	0	0	0	0	47,083	0	0	0
LHV FT Liquids:	22,266	59,316	74,545	46,147	48,811	59,316	59,316	65,905	67,939
Electricity Export:	2,657	5,005	1,075	3,544	4,085	20,132	7,501	5,975	4,707
LP steam import	0	0	17,220	0	0	0	0	0	0
MP steam import	7,548	27,474	35,119	20,792	22,966	0	0	4,830	0
HP steam Import:	0	0	0	0	0	0	0	2,155	0
LHV effi-ciency[1]	**17.3 %**	**23.1 %**	**29.0 %**	**19.9 %**	**20.6 %**	**23.1 %**	**23.1 %**	**25.6 %**	**26.4 %**
Net effi-ciency[2]	**17.1 %**	**21.6 %**	**23.9 %**	**18.7 %**	**19.4 %**	**23.4 %**	**24.9 %**	**26.4 %**	**27.7 %**

[1] Calculated as: (LHV FT liquids)/ (LHV Biomass Feed)
[2] Calculated as: (LHV FT liquids)/ (LHV Biomass Feed + Total steam import/0.9 – Electricity Export/0.4)

5.2 Environmental assessment: LCA

Life Cycle Assessment (LCA) is one of two parts of an environmental sustainability assessment of the SUPRABIO systems (besides LC-EIA, see subchapter 5.3). The LCA evaluates global and regional environmental impacts such as greenhouse effect, acidification of soils by airborne pollutants or the depletion of non-renewable resources. This subchapter summarizes the objectives, methods and findings of the respective part of Deliverable D 7-5 “Final report on environmental assessment of SUPRABIO biorefineries” /Keller et al. 2014/.

5.2.1 Objective

This part of the Environmental assessment provides, together with the LC-EIA part, an evaluation on the environmental sustainability of the SUPRABIO systems. The objective of the provide answers to following questions:

- What are the implications of the SUPRABIO biorefinery systems on environmental sustainability?
- Which processes determine the results significantly and where can they be optimised?
- Which systems perform best regarding greenhouse gas savings per tonne of biomass?
- What is the performance of SUPRABIO systems compared to other uses of the raw material?

More specifically, questions are answered on the basis of the assessment of the following environmental impact categories:

- Climate change
- Depletion of fossil resources and land use change
- Acidification and eutrophication
- Stratospheric ozone depletion
- Photochemical oxidant formation and particulate matter formation

5.2.2 Methods

The methodology of life cycle assessment

Life cycle assessment (LCA) addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of emissions) throughout a product’s life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal. The approach is therefore often called cradle-to-grave.

LCA methodology is laid down in important regulatory frameworks: the ISO standards 14040 and 14044 /ISO 2006/ and the ILCD Handbook /JRC-IES 2012/, part of the International

Reference Life Cycle Data System (ILCD). Both standards are taken into account. For the SUPRABIO systems, screening LCAs are applied.

Settings for the analysis

Since SUPRABIO should provide a meso/macro-level decision support, consequential modelling is chosen. Likewise, the substitution approach is used. Additionally, however, also allocation is applied in a sensitivity analysis according to Annex V of the EU RED /CEC 2009/. The environmental impacts are assessed on a midpoint indicator basis, based on the ReCiPe 2008 methods /Goedkoop et al. 2013/. Deviating from this, stratospheric ozone depletion is assessed according to /Ravishankara et al. 2009/ and the ReCiPe indicator "Fossil fuel depletion" is substituted by the indicator cumulative non-renewable energy demand. In some cases, the environmental impacts of the SUPRABIO systems are put into relation to the average environmental burden of each inhabitant in the EU 25+3. This is called normalisation, leading to the reference unit "inhabitant equivalent" (IE).

All parameters and reference processes of the systems analysed are chosen on a European basis (mostly EU27). Further to this, some hydrogenated vegetable oils (HVO) are also assessed based on imported biomass because this represents a large fraction of the HVO produced and used in Europe.

5.2.3 Key results

In the following, key results are listed for all scenarios. The results are grouped into general results, results related to the biochemical routes and results related to the thermochemical conversion routes. Subsequently both conversion systems are compared to each other and to reference systems. Finally some conclusions are drawn.

General results

- Lignocellulosic biomass can generally be provided with relatively low global / regional impacts. In contrast, its conversion into products (here mostly biofuels) requires intensive processing. Thus, an optimisation of any SUPRABIO biorefinery is paramount.
- The investigated biofuels (ethanol, FT fuels and DME) typically lead to advantages in terms of non-renewable energy use and global warming potential. The latter only applies if no direct or indirect land use changes are associated with biomass provision. At the same time, disadvantages are incurred regarding eutrophication and ozone depletion. Other impact categories show indifferent results (acidification, photochemical ozone creation and particulate matter formation). This means that from an LCA point of view, the investigated **biofuels do not show a clear advantage** over conventional fuels.

Biochemical routes

- Main scenario ethanol production:
  Provision of enzymes and nitrogen nutrients to the biorefinery causes most emissions. Depending on the scenario, electricity export can compensate for more or less all non-renewable primary energy consumed throughout the whole life cycle (including e.g. enzyme and fertiliser production). Thus, the assessed 2nd generation bioethanol process is

particularly energy efficient. Additionally, only about three tonnes of biomass dry matter are required per tonne of ethanol.

- Main scenario mixed acids production:
  Expenditures for biorefining are bigger, mainly because of a very energy-intensive product separation, outweighing the expenditures for the reference product by far. Therefore mixed acid production shows disadvantages compared to the respective conventional product in all environmental impact categories.
- Feedstock straw vs. poplar:
  Production of ethanol from straw and short rotation coppice shows the same pattern of advantages and disadvantages. However, using agricultural land for poplar cultivation may lead to indirect land use changes, which can severely affect the environment. Thus, underutilised residues should be preferred over agricultural biomass.
- Early implementation of ethanol production:
  Separate hydrolysis of cellulose and hemicellulose and fermentation (SHF) in the early implementation scenarios (2015) requires more inputs than simultaneous saccharification and fermentation (SSF) in mature scenarios (2025). Together with a slightly lower efficiency this leads to higher impacts in the early implementation scenario.
- Optimisation of ethanol production:
  Energy generation from unconverted biomass is an important parameter for optimizing the energy efficiency of the conversion process. The main scenario Straw to Ethanol (2025), which uses gasified residues in a gas turbine, shows the best results regarding climate change under standard conditions. Gasification of process residues can substantially improve the life cycle greenhouse gas balance compared to a direct combustion in a boiler. Furthermore, improvements in external enzyme production and enzyme performance can reduce environmental impacts. Additionally, a reduction of the input of nitrogen into the main process could reduce the environmental impacts. Reductions in a similar order of magnitude seem plausible if the input of nitrogen into the main process could be reduced.

Thermochemical routes

- Main scenario Fischer-Tropsch (FT) fuels:
  Depending on the scenario, the avoided environmental burdens due to electricity export from process residues can compensate for more or less all expenditures throughout the whole life cycle.
- FT fuels vs. Dimethyl ether (DME):
  The production of bio-based DME is more energy intensive than FT fuels production and less energy is produced from residues. This is not compensated for by the higher energy content of the fuel. Thus, DME production is disadvantageous compared to FT fuels production. The differences are not very big but robust.
- Feedstock:
  FT fuels from all feedstocks show rather similar results, best results are typically found where forest residues are used as feedstock. Deviations mainly result from different fertiliser demands and different ratios of the co-products FT fuels and electricity (with lower fuel production leading to higher electricity production from process residues). Thus, all feedstocks are usable unless undesired effects such as land use changes or a feedstock withdrawal from more advantageous use options occur. In terms of eutrophication, prod-

ucts from forest residues (only investigated for the thermochemical route) perform equal or better than conventional products, mainly because no compensation fertilisation of forest systems was assumed.

- Early implementation scenario do not performing much worse than the mature technology scenario.
- Optimisation of FT fuels production:
  All analysed alternative process design options leading to improvements of overall results. A central pyrolysis plant performs better than several distributed units (more efficient energy provision from residues). The required steam is best produced internally via co-production. Gasification units are operating better at higher pressures and if syngas is released at higher temperatures.

Comparison of routes and alternatives

- Thermochemical or biochemical production of biofuels from lignocellulosic biomass:
  Environmental feasibility depends on technical details of the implementation, feedstock and weighting of impacts. In the investigated example slight advantages occur for biochemical ethanol production compared to optimised thermochemical FT fuels production regarding mitigation of climate change. However, in contrast to ethanol production, FT fuels are not associated with other substantial environmental burdens e.g. regarding acidification. Thus, unless savings of greenhouse gases and non-renewable energy are strongly preferred over other environmental impacts, optimised FT fuels production is likely to be the better choice because it avoids more environmental burdens.
- Alternative biomass use options:
  Up to the near future, fuel production from lignocellulosic biomass cannot reach levels of climate change mitigation as is possible by direct combustion of the same biomass in a CHP plant since each conversion comprises a loss.
- Alternative land use options:
  Direct combustion of poplar short rotation coppice for heat and power production is the best of all assessed land use options from an environmental standpoint. SUPRABIO 2nd generation bioethanol and FT fuels show results that are more or less within the range of results of established 1st generation biofuels and biogas.

  The results for 2nd generation ethanol from poplar are in the same range as many the results for different types of 1st generation ethanol. Second generation ethanol from poplar is surpassed by 1st generation ethanol from sugar beet and also sugar cane (the latter not analysed here).

  The results for FT fuels from poplar are considerably better than the results for other diesel-type biofuels such as FAME and HVO produced from rapeseed (which is the most relevant oil crop in Europe and thus relevant for a comparison on a land use basis).

  The results for hydrogenated vegetable oil (HVO) are as poor as the results for 1st generation biodiesel (FAME) if produced from the same biomass feedstock (rapeseed being most relevant in Europe).

  From an environmental perspective, HVO and biodiesel production even from certified imported seed oil should not be expanded because of the risk of causing LUC. Therefore, also new HVO processes should not be developed if their implementation depends on seed oil imports.

- Generally, biofuels from underutilised and sustainably extracted residues should be preferred over biofuels from cultivated biomass in order to diminish the risk of iLUC. Although mostly it seems less severe than for imported seed oils, it is not negligible.
- Which residues are truly underutilised in 2025 cannot be predicted as expansion is planned for many lignocellulose-based processes such as fuels, heat and power as well as bio-based materials. In many locations, competition and thus the risk of misallocation from an environmental perspective is very likely as it can already be observed for some residues and locations today.

Conclusions

- Comparing the results presented above, it must not be concluded that biofuels generally are to be preferred over bio-based products (e.g. mixed organic acids). The fact that the biofuels investigated in SUPRABIO show less disadvantages than the investigated bio-based products cannot be generalised and only applies to the products that happened to be chosen in SUPRABIO. There are plenty of studies which show that bio-based products are on a par with biofuels: the net climate change mitigation per land used of bio-based products is in the same range as for biofuels, in some cases considerably higher /Dornburg et al. 2003/, /Reinhardt et al. 2007/, /Rettenmaier et al. 2010/. The challenge is "just" to identify these more promising pathways. The bio-based products investigated in SUPRABIO still require further R&D efforts and considerable breakthroughs are needed in the field of energy efficiency and product separation and purification.
- From an environmental angle, there is thus no reason to prefer the use of biomass for energy over the use of biomass for bio-based products as it is the case in Europe due to the current political framework (especially RED). From a supply security point of view, it would make sense to divert more biomass towards material use since biomass is the most obvious renewable carbon sources for the chemical industry (apart from power-to-gas / power-to-liquid technology), whereas renewable energy can be provided from other sources such as wind and photovoltaics and the transport sector can be electrified to a large extent.
- Nevertheless, FT fuels from forest residues investigated in SUPRABIO would safely achieve the minimum greenhouse gas emission savings of 60 % (as stipulated in the RED after 1 January 2018), provided that the processes are optimised. However, since the GHG balances according to Annex V of the RED deliver relative savings achieved by the biofuel compared to the fossil fuel comparator instead of net (or absolute) greenhouse gas emission savings, the results obtained via these calculation rules should not be taken as a basis for political decisions, but only for the regulation of economic operators.
- We conclude that 2nd generation technology does not show the potential to significantly improve the land use efficiency of ethanol. Thus, 2nd generation ethanol production from dedicated crops (even if perennial) does not live up to the high expectations connected to it in terms of environmental benefits. The thermochemical route towards FT fuels offers higher (relative) improvements over 1st generation biodiesel, however, 2nd generation ethanol shows higher potentials for climate change mitigation per unit area than FT fuels from the same biomass feedstock. Yet, FT fuels might display advantages over lignocellulosic ethanol regarding other environmental impacts (other than climate change). Moreover, FT fuels do not face any blending restrictions (in contrast to ethanol) and might be

more desirable since the demand for diesel-type and kerosene-type renewable fuels in Europe will increase in the future, whereas gasoline demand (and thus the demand for ethanol) is projected to decrease.

- Regarding other biomass-based systems which compete for the same biomass or land, the fiercest competitor for SUPRABIO is direct combustion of biomass for combined heat and power generation. As long as a significant share of power is produced from coal, the stationary use of biomass is expected to mostly outperform the biofuel use of biomass by far. However, renewable heat and power can also be provided from sources other than biomass whereas airplanes, ships and heavy trucks are unlikely to be electrified in the near future and will most probably depend on liquid or (compressed) gaseous hydrocarbons.

5.3 Environmental assessment: LC-EIA

The Life Cycle Environmental Impact Assessment (LC-EIA) is the second part of the environmental sustainability assessment in SUPRABIO. The LC-EIA contains elements of environmental impact assessment (EIA) and strategic environmental assessment (SEA) and regards particularly site-specific environmental effects for the cultivation of crops and the biorefineries. This subchapter summarizes the objectives, methods and findings of the respective part of Deliverable D 7-5 “Final report on environmental assessment of SUPRABIO biorefineries” /Keller et al. 2014/.

5.3.1 Objective

This part of the Environmental assessment provides, together with the LCA part, an evaluation on the environmental sustainability of the SUPRABIO systems. The aim is to qualitatively assess the impacts associated with each of the (hypothetical) SUPRABIO biorefinery concepts (in the sense of technological concepts) at a generic level. Some of the general questions are:

- What are the implications of the SUPRABIO biorefinery systems on environmental sustainability?
- Which processes determine the results significantly and where can they be optimised?
- What is the performance of SUPRABIO systems compared to other uses of the raw material?

More specifically, questions are answered based on the following aspects:

- Human beings, fauna and flora; biodiversity
- Soil, water, air and the landscape
- Interaction between these factors

5.3.2 Methods

For the purpose of the SUPRABIO project which does not encompass the actual construction of a biorefinery plant, it is not appropriate to perform a full-scale EIA according to the European regulatory frameworks (/CEC 1985/ and its amendments). Monitoring and auditing measures, for example, are omitted within SUPRABIO. Nevertheless, elements of EIA are used to characterise the environmental impacts associated with the SUPRABIO biorefinery concepts at a generic level. The scope of the LC-EIA encompasses all life cycle stages and is divided in the impact assessment for biomass production and the impact assessment for biomass conversion and use. For biomass production, the following impacts are assessed:

- Soil: erosion, compaction, chemistry, organic matter
- Water: nutrient leaching / eutrophication, use of water resources

- Flora, fauna & landscape: weed control / pesticides, species diversity / habitat quality

For biomass conversion and use, another set of impacts is selected, based on the following technology-related factors:

- Emission of noise and odour: human health, fauna
- Waste water and waste water treatment: water, flora, fauna
- Amount of traffic (noise and gaseous emissions): human health, fauna
- Size and height of conversion plants: soil, flora, fauna, biodiversity, landscape

Like for the LCA part of the environmental assessment, also for the LC-EIA part potential biorefinery scenarios are compared with so-called *reference systems*. The reference systems are divided into 1) reference systems for biomass production and 2) reference systems for biomass conversion and use. They are described in subchapter 4.1.5.

Following impact identification and prediction, *impact evaluation* is the formal stage at which the significance of an impact is determined. Impact significance depends on the joint consideration of its characteristics (quality, magnitude, extent, duration) and the importance (or value) that is attached to the resource losses, environmental deterioration or alternative uses. Significant negative impacts will be taken into further consideration because they could require mitigation measures.

The assessment of environmental impacts resulting from biomass production, conversion and use is carried out as a *benefit and risk assessment*. This is useful if the project is considered as a theoretical concept with uncertainty regarding the possible future location of biomass cultivation sites and conversion facilities.

Aggregated *conflict matrices* were created based on the biomass-specific benefits and risks, which summarise the impacts of biomass production, conversion and use on the selected environmental factors. For biomass residues like wheat straw and wood residues, the focus of the conflict matrices is on changes in soil organic matter content, changes in nutrient balances or changes in the composition of the litter layer in forest soils. Finally, as SUPRABIO is not aiming to a specific location, mitigation measures are omitted.

5.3.3 Key results

In this subchapter, key results for feedstock provision and feedstock conversion are provided, followed by some conclusions.

Feedstock provision

General results

- Additional area for feedstock production is rare. A potential increase in area used for provision on energy crops is possible especially by intensifying the use of grasslands and providing the released area for agriculture. An area of about 193.000-627.000 km² is predicted to be available for the provision of energy crops in 2050 representing 5-16 % of the arable land in the EC25.

- Intensified agriculture leads to several partly severe environmental impacts, e.g.
  - loss of biodiversity in cultural landscapes
  - loss of grassland with high nature conservation value especially in marginal lands
  - increase of the eutrophication of surface and groundwater bodies
  - further compaction and erosion of soils
  - further pressure on conservation areas
  - possibly increased impacts on flora, fauna and biodiversity
- Further investigations are necessary especially to quantify potential impacts on biodiversity.
- Residues used as feedstock
  - The provision of both residue feedstocks investigated (straw, wood residues) causes comparably little impacts on the environmental factors in comparison to the reference systems.
  - Straw has been used as feedstock ever since (fodder, litter) and by example it is shown that there is feedstock available to drive a plant with 75 kt of straw per year. Potential impacts for the environment arise from the intensification of land use. With a straw-driven biorefinery, a development towards intensified use is expected. This means an increased extraction of nutrients from the soil, which then has to be supplemented. A risk of decreasing biodiversity is expected in the long term.
  - The use of wood residues is bearing long-term risks compared to the reference system of traditional forestry where wood residues and thinning material usually are left onsite. The residues basically contribute to SOM balance and carbon sequestration. Current developments in forestry are opting for shorter rotation cycles and the valorisation of thinning wood and wood residues. In the long term this means a net export of nutrients and of carbon from forest soils.
- Cultivated biomass: SRC
  - Compared to the reference system of non-rotational fallow land, SRC poplar plantations on arable land perform better in respect to many environmental factors. Soil compaction and erosion is lower due to longer growing periods and reduced maintenance cycles. Low need of fertiliser supports this valuation and results in low eutrophication rates with less negative impacts on soil and groundwater. Furthermore, the variety of habitat types can be increased. Species and habitat diversity would benefit from perennial crops like SRC poplar offering additional habitat types for plants, invertebrates and vertebrates.
- Cultivated biomass: oil crops
  - The environmental value of low-input Jatropha plantations is similar to those of marginal land.
  - In case of a cultivation of Jatropha or oil palms on the expense of tropical rain forest, irreversible impacts on soil, water, biodiversity and landscape are to be expected.

- Annual crops
  - Cultivating annual crops in general results in higher impacts on the environment than in the reference system of rotational fallow land:
  - Risks on soil compaction and erosion are higher independently from the annual crop investigated.
  - Crop specific differences are comparably small and only evident as on-site effects on the field. They mainly result from crop-specific differences on soil erosion.
  - In case of sugar beet, soil erosion compared to cereals is more probable. The impact risk on groundwater and superficial water is increased due to leaching of nutrients.
  - Due to the application of fertiliser and weed control, lower numbers of species in the plantations are expected compared to perennial plantations.

Raw material conversion

- The assessment of local environmental impacts in implementing and operating refineries reveals no fundamental differences between the different technologies investigated.
- Independently from the technology, differences are not to be expected on a generic level during the construction phase and related to buildings, infrastructure and installation.
- In a “Greenfield scenario” where a potential refinery is to be built on unsealed areas, impacts can be by far higher than in a “Brownfield scenario” on e.g. former industrial zones.
- Regarding the drain of water resources, biorefineries likely exceed the demand of conventional refineries. This might be unfavourable in regions with water scarcity since potential plants when built in the vicinity of irrigated feedstock would increase the risk of droughts especially during dry seasons.
- On a generic level, bio-based refineries seem to be environmentally more favourable than refineries based on fossil feedstock. This is basically linked to the following risks:
- Emissions of gases and fine dusts. Very little differences between chemical and biorefineries. Crude oil processing and synfuels production from biomass slightly unfavourable. Coal plants unfavourable.
- Traffic. Local traffic increased in the area of biorefineries with feedstock provision from the vicinity. Impacts of Greenfield will exceed those from Brownfield scenario. Local traffic increased in central mature thermochemical plant (2025 scenario) compared to decentralised facilities.
- Disposal of waste / residues. Clear advantage for biorefineries as organic residues can be used for combustion (energy production), animal feed or fertiliser. Nuclear power plants most unfavourable.
- Risk of accidents. Considerably high in conventional refineries, comparably low in biorefineries although usually working with genetically modified organisms (GMO).

Conclusions

- In Europe, arable land is limited and competing uses can occur. In order to minimise risks, it makes sense to reduce capacities and to decentralise the locations of potential

plants. Clear recommendations for a specific feedstock or feedstock crop are not possible; however, perennial crops like SRC poplar seem to be slightly favourable. An intensified use of bio-based feedstock seems to be limited due to land use competition. However, trends towards higher agricultural yields show a possibility for extended biomass production.

- A clear preference for a specific type of conversion technology is not possible. On a generic level qualitative impacts are comparable. Quantitative differences might occur especially in terms of water use which is expected to be higher in case of the biochemical route.
- In general, local environmental impacts of SUPRABIO systems are dominated by biomass provision. However, the impacts' extent and magnitude is largely dependent on the type of biomass feedstock. Large areas of land are affected either by the extraction of agricultural or forest residues or by the cultivation of dedicated lignocellulosic crops, i.e. the extent of impacts is generally quite large, depending on the yield of biomass residues and dedicated crops, respectively. The potential impacts are mainly land-use related and affect water, soil and biodiversity. Provided that biomass residue extraction rates are sustainable and provided that no direct or indirect land use changes are induced (=main precondition underlying this assessment), it can be stated that in terms of magnitude of impacts both the provision of biomass residues (wheat straw or forest residues) and the provision of dedicated lignocellulosic crops (e.g. perennial crops like SRC poplar) are associated with comparatively low risks. Higher risks are associated with imported biomass, especially oil crops. However, from an LC-EIA point of view, a clear preference for a specific type of biomass feedstock cannot be given since all investigated feedstock show advantages and disadvantages. Regarding biomass residues, the provision of wheat straw is a slightly better option than forest residues.
- In contrast to that, transport processes are of minor importance from an environmental point of view (both biomass transport and product transport).
- We conclude that it is important to consider land use and water use (resource depletion: water) as part of the comprehensive set of environmental impact categories when evaluating biorefineries and other biomass-based systems.
- Apart from the local environmental impacts associated with the bio-based product, the impacts associated with the substituted conventional reference product are decisive. Since the type of risks associated with the biomass-based systems and conventional (mostly petroleum-based) systems are completely different in quality and quantity, a direct comparison is not possible. However, a comparison of impacts at the level of environmental factors is feasible:
- Regarding local environmental impacts, the comparison of SUPRABIO products to conventional products shows that the land use impact of biomass provision is orders of magnitude higher than the land use impact of conventional (fossil) feedstock provision – provided that crude oil extraction from conventional petroleum deposits is considered. The picture might change, though, if unconventional petroleum deposits such as oil sands were chosen as reference system.
- In general, the environmental impacts related to the provision of biomass feedstock are expected to be mostly reversible – as long as the main precondition underlying this assessment (no land use changes) is fulfilled. In contrast to that, most of the impacts from conventional (fossil) feedstock provision are expected to be long-term and non-reversible.

As regards raw material conversion, the land use impacts of SUPRABIO biorefineries and conventional refineries are comparable.

- In terms of water use, the drain of water resources by biorefineries likely exceeds the one by conventional refineries – at least in case of the biochemical route. This could cause negative impacts in water-scarce regions, especially during the hot season.
- Regarding feedstock provision, perennial lignocellulosic crops such as poplar short rotation coppice used for 2nd generation biofuels lead to fewer impacts on environmental factors than most annual crops used for 1st generation biofuels. Among the annual crops, particularly high impacts are associated with sugar beet cultivation. However, it has to be noted that sugar beet has a higher sugar yield per hectare than lignocellulosic crops. Moreover, it produces a feed co-product which reduces the net land use. In other words, there is a trade-off between magnitude and extent of impact.
- Regarding raw material conversion, differences between 1st and 2nd generation conversion technologies are very low from an LC-EIA point of view.
- Regarding different use options of biomass residues, differences between conversion technologies e.g. a biorefinery and a CHP are very low from an LC-EIA point of view. Thus, a ranking of technologies is not possible.

5.4 Process economic assessment and market analysis

The following subchapters are adopted from D 7-11 “Final report on techno-economic assessment including the market potentials of SUPRABIO products” /Lervik Mejdell et al. 2014/, where amongst others; an economic evaluation including a market analysis of the integrated biorefinery concepts was conducted. For detailed results and a precise description of the methodology please refer to the original assessment report, sections on economic evaluation and market analysis.

5.4.1 Objective

The objective of the economic assessment was to identify potentials and economic constraints of biorefinery concepts investigated in the SUPRABIO project. In a market analysis the properties, applications and market of each SUPRABIO product are evaluated.

5.4.2 Methodology

As for the technological assessment two different biorefinery concepts have been evaluated, one based on the biochemical core process concept (subchapter 4.1.3.1) and the other based on the thermochemical core process concept (subchapter 4.1.3.2). In addition, also the possibility to integrate with so-called add-ons has been investigated (subchapter 4.1.3.3). For the two biorefinery concepts only waste treatment integration was implemented. No other relevant integration between the proposed processes in the biochemical refinery concept has been found technically feasible so far. Each process was therefore evaluated one by one integrated with the waste treatment scenario. Among the proposed add-ons only the seed oil hydrogenation process was established and could potentially be connected to the biorefinery concepts via hydrogen exchange. Unfortunately, the evaluation of hydrogen extraction from different biorefinery streams was delayed making it impossible to carry out the analysis.

The economic evaluation of SUPRABIO biorefinery concepts takes into account many factors that can affect production costs, such as variable costs (OPEX) and fixed costs (CAPEX). OPEX (OPerating or OPerational EXpenditure) has been calculated by an accountant from raw materials, utilities and labour demands. CAPEX (CAPital EXpenditure) is the fixed capital investment that a company pays for all plant components. The estimation of total equipment cost has been conducted with the help of Aspen In-Plant Cost Estimator. An internal estimation tool developed from Statoil was used to calculate the total investment cost. In order to compare the economic performance of the different biorefinery concepts, suitable indicators such as the Internal Rate of Return (IRR), the profitability index and the break-even price (i.e., the price where the project NPV (net present value) becomes zero) are used.

For the market analysis different partners have been responsible of the different products and data has to a large extent been collected from open sources. An overview of SUPRABIO products and responsible partners can be found in Table 24 in /Lervik Mejdell et al. 2014/.

5.4.3 Key results of the economic evaluation

In the following key results of the economic evaluation of the biochemical and thermochemical biorefinery concepts are described.

Biochemical route

The main product of the biochemical route is ethanol. Alternatively, also mixed acids can be produced.

For the production of **ethanol**, the following key results could be identified (Table 5-3):

- The early implementation scenario showed somewhat lower performance compared to the mature technology scenario as anticipated for 2025. With the process layout change (SHcF in the early implementation to SScF in the mature technology) and expected process improvements the process became profitable for three of the five sub-scenarios (scenarios II-1-B, II-2-B, II-2-C). Thus, the gas engine and boiler technologies proved to be advantageous.
- Only the sub-scenarios with the gas turbines resulted in a negative NPV, mainly because of the necessary high investments in compressors and turbines.
- The sub-scenarios utilising gas engine and boiler result in comparable ethanol production cost. However, the gas engine based scenarios have higher capital cost, but compensate with income from the larger electricity export.
- Is poplar wood used as feedstock for ethanol production in the biochemical concept all the sub-scenarios result in a negative NPV, but sub-scenarios 1-A and 2-A have a significant lower NPV compared to the others. This is mainly due to significantly higher capital cost for sub-scenarios 1-A and 2-A, but also slightly higher fixed operational cost and slightly lower electricity export.
- The breakeven price for e.g. the main process of the biochemical route (straw to ethanol 2025, scenario II-1-A) is 307 € per t biomass input. If from one t biomass about 0.34 t ethanol can be produced, the minimum selling price for a tonne ethanol amounts to 914 € to make this process economically viable.

For the production of **mixed acids**, the following key result could be identified (Table 5-3, scenarios IV a, IV b):

- The acid mixture separation end purification process is quite energy demanding which add a significant demand for importing electricity and steam making the process strongly unviable (high negative NPV).

Table 5-3 CAPEX, OPEX, NPV, IRR, PI and minimum selling price for the biochemical biorefinery scenarios calculated per biomass input. For details regarding the numbers of sub-scenarios see subchapter 4.1.6.

Sub-scenario	Total CAPEX [M€]	CAPEX [€/tonne biomass]	OPEX [€/tonne biomass]	Production cost [€/tonne biomass]	NPV [M€]	IRR [%]	Profitability index [%]	Break-even price[1] [€/tonne biomass]
I-1-A	149	248	234	482	-144	-20.8	-93.3	606
1-B	101	168	194	362	-78	-10.5	-74.5	448
2-A	151	252	238	491	-149	-22.4	-94.7	618
2-B	106	177	202	379	-87	-12.1	-78.7	468
2-C	91	152	218	370	-78	-13.6	-82.2	446
II-1-A	682	114	136	249	-125	2.3	-17.6	392
1-B	438	73	114	187	218	11.4	47.8	286
2-A	716	119	141	260	-180	1.2	-24.2	409
2-B	470	78	120	198	161	9.5	32.8	304
2-C	383	64	128	192	218	12.3	54.7	224
III-1-A	836	139	117	257	-499	-5.5	-57.5	327
1-B	496	83	89	171	-27	4.2	-5.3	213
2-A	912	152	139	291	-669	-9.2	-70.5	367
2-B	557	93	102	194	-145	1.0	-25.0	241
2-C	442	74	116	189	-83	2.2	-18.1	226
IVa	626	104	297	401	-741	-	-113.8	454
IVb	708	118	386	504	-1,012	-	-137.3	563

[1] Break even product price scaled to dry biomass input

Thermochemical route

The main product of the thermochemical route is FT diesel. Alternatively, also DME can be produced.

For the production of **FT liquids** (Scenarios I, II and IV-IX), the following key results could be identified (Table 5-4):

- All the FT liquid scenarios result in a low net efficiency (below 30 %). The low efficiency combined with a large investment cost result in strong negative NPV estimates for all scenarios.
- FT liquids produced from straw/poplar (scenarios IV / V) result in lower production costs per t biomass input than FT liquids produced from forest residues. However, if the production costs per t FT liquids are considered, FT liquids from straw/poplar result in approximately 15 - 20 % higher production costs than from forest residues. Both results are mainly due to a lower yield of pyrolysis oil from straw and poplar which is caused by higher ash content in both feedstocks that act as undesired catalysts in the cracking of the organic liquid components. All the FT liquids biorefinery scenarios result in a deficit of steam. Integration with the pyrolysis section or introduction of natural gas (scenarios VI / VII) in order to overcome this deficit may improve the overall performance but results in higher production costs per t biomass input (5 - 10 %) than importing steam, mainly due to the higher CAPEX related to a larger CHP section. The increase in the CAPEX weights more than the efficiency improvement.

- The most favourable change in terms of overall performance is the operation at higher pressure (scenario VIII). Increasing the pressure results in reduced CAPEX costs which is related to less compression needs in the CHP unit and a smaller FT section. However, the data related to this scenario in terms of CAPEX is of high uncertainty and has not been demonstrated yet.
- Increasing the gasifier quenching temperature to 250°C (scenario IX) results only in a slight additional reduction of production costs per t biomass input compared to the high pressure scenario (scenario VIII).
- The breakeven price for e.g. the main process of the thermochemical route (wood residues to FT liquids 2025, scenario II) is 250 € per t biomass input. If from one t biomass about 0.10 t FT liquids can be produced, the minimum selling price for a tonne FT liquids amounts to approximately 2,600 € to make this process economically viable.

For the production of **DME** (Scenario III), the following key result could be identified:

- The production cost per tonne biomass input is approximately the same (Table 5-4). The production costs per tonne of DME product, however, is about 90 % lower than for FT diesel (25 % in energy basis - €/MJ). This is mainly related to the smaller CHP unit section since more of the syngas is converted to the fuel product in this case.

Table 5-4 CAPEX, OPEX, NPV, IRR, PI and minimum selling price for the thermochemical biorefinery scenarios calculated per biomass input. For details regarding scenario numbers see subchapter 4.1.6.

Scenario	Total CAPEX [M€]	CAPEX [€/tonne biomass]	OPEX [€/tonne biomass]	Production cost [€/tonne biomass]	NPV [M€]	IRR	PI	Break-even price[1] [€/tonne biomass]
I	355	118	118	237	-502	-	-136 %	296
II	561	94	109	203	-736	-	-126 %	250
III	511	85	117	202	-515	-	-97 %	245
IV	511	85	106	191	-738	-	-139 %	227
V	528	88	107	195	-746	-	-136 %	239
VI	687	114	111	225	-875	-	-123 %	283
VII	605	101	112	213	-793	-	-126 %	263
VIII	522	87	98	185	-616	-	-114 %	225
IX	520	87	100	187	-609	-	-113 %	226

[1]Break even product price scaled to dry biomass input

5.4.4 Key results of the market analysis

In the following the key results of the market analysis are described. Within SUPRABIO a wide range of processes leading to various products has been developed and evaluated. The products range from fuels, bulk chemicals to high value chemicals, including the following:

Fuels

- Ethanol
- Butanol

- FT diesel
- Hydrogenated seed oil
- Dimethyl ether
- Mixed alcohols

Chemicals

- 2,3-butanediol
- Methyl ethyl ketone
- Butyric and propionic acid
- Four carbon 1,4 dicarboxylic acids
- Lignin based products
- Glucosamine
- Sugar fatty acid esters
- Hydroxystearic acid
- Vernolic acid
- Ω-3 fatty acids
- β–glucan

Biochemicals and biofuels can potentially bring value to businesses in three ways:

- Allow existing products to be produced at a lower cost.
- Allow companies to produce products with unique properties not achievable in any other way.
- Create opportunities for nature-based products.

In general, the market for bio-based products is increasing in specific areas and the markets for bio-based chemicals and fuels will most likely grow in the future.

- In 2011 the bio-based chemical market reached a value of 3.6 billion USD (excluding biofuels) and is forecasted to grow to 12.2 billion USD by 2021.
- The main hurdle for a large expansion is in general higher costs for bio-based products compared to the competing fossil-based products.
- A premium price for most bio-based products cannot be expected for the reason of just being “green”, they would also need to show superior properties.
- For a large expansion of bio-based chemicals many of the processes which today are in the development phase must have been commercialised.
- The success of biochemicals depends on a number of factors, e.g. process and product development and demand and supply of crude oil (i.e. the cost of crude oil).

5.5 Social assessment

The social assessment investigates social, policy and employment issues regarding the SUPRABIO systems. This subchapter summarizes the objectives, methods and findings of Deliverable D 7-8 “Final report on social assessment” /Schütz 2014/.

5.5.1 Objective

The objective of the social assessment comprises the following issues:

- **Social sustainability** assessment with the focus on social hotspots assessment and specific further analysis of most remarkable findings,
- **policy based strategies** for development of biorefineries in Europe,
- **employment effects** to be expected from biorefinery development strategies.

The social assessment completes the environmental and economic assessment to a comprehensive assessment of sustainability of the SUPRABIO biorefinery systems.

5.5.2 Methods

The methods used for reaching the three objectives as above are different since the objectives are not equal in their quality.

For investigating the **social sustainability**, first an overview is given of to date existing major approaches for the assessment of social issues in the life cycle of products. Then, for practical implementation of social assessment in SUPRABIO, the approach was oriented at the social hotspots analysis of New Earth. The social assessment in SUPRABIO supply chains focuses on hotspots analysis at feedstock level and includes crude oil and its processing steps in refineries and the chemical industry as the fossil reference product chain. First, a top-down screening of potential social hotspots at country and sector levels is done using the Social Hotspot Database (SHDB) model /Benoît-Norris et al. 2012/. Finally, issues at very high and high risk level are specifically reviewed.

There are different works on life-cycle based social assessment: the rather theoretical guidelines for social-LCA and respective methodological sheets for subcategories evaluation by the UNEP/SETAC initiative /Benoît et al. 2009/ and two major approaches towards operationalisation of social assessment of products by GreenDelta and New Earth. Both have own specific methodologies for social-LCA (and recently SocialLCA+) and social hotspots analysis, respectively. The latter methodology has been applied in this project.

The European **policy based strategies** are investigated by a review of the EU’s targets and measures for surmounting the issues of climate change and energy, especially

- the Lead Market Initiative (LMI) on bio-based products in the EU /EC 2007/,
- the European strategy for a European Bioeconomy /EC 2012a/,

- the Renewable Energy Directive (RED) /CEC 2009/.

Regarding the **employment effects**, in the first line the accompanying Commission Staff Working Document to the European Bioeconomy strategy has been examined /EC 2012b/. Furthermore, different other studies worldwide on renewable energies, biorefineries, forestry products and other have been evaluated.

5.5.3 Key results

Social sustainability

- The hotspots analysis shows very high risk in the four emerging / developing economies studied – Brazil, India, Indonesia, and Mozambique. The maximum number of indications is found for the issue of access to improved sanitation. Among the second priority issues, i.e. having high social risks, the issue of risk of forced labour is by far on top. Surprisingly, this not only for the four emerging / developing economies but also for the EU countries France, Germany, UK and the four Scandinavian countries Denmark, Sweden, Norway and Finland. This and the other top-ranking issues with high risk potential are followed up by specific analysis.
- There are specifically two issues standing behind the very high and high risk potentials found in the above analysis. Very high risk potentials often concern life and working conditions in poor countries with low safety standards, and even if companies are not directly involved, their supply chains – perhaps unrecognised by themselves – may well put them into responsibility for obvious wrongs. High risk potentials for forced labour in Europe are topical according to a most recent report commissioned by the UK-based Joseph Rowntree Foundation. The report concludes that seeing forced labour in the context of trafficking leads to a focus on immigration controls, which can deter migrants subjected to forced labour from seeking assistance. It also fails to assist those who are EU nationals or not migrants at all. It would be better to approach the problem of forced labour as an extreme element of the labour market, rather than one of trafficking. As most forced labour is in undeclared or clandestine jobs, it cannot be ruled out from the beginning that forced labour contributes to companies' supply chains.
- According to /Feldt & Kerkow 2013/ governments should strive to establish a coherence of the raw material strategy with human rights obligations, risk assessment for human rights violations for trade agreements of the EU with third countries, making support programmes for projects in foreign countries dependent on due diligence for human rights, establishing raw materials partnerships with foreign countries including assessment of consequences for human rights, supporting governments in foreign countries to enact issues like right of co-determination and in particular the right for free, early and informed agreement of indigenous people to projects concerning their own environment and living.
- From the same source, it is recommended to enterprises, among others, to integrate human rights principles in their own policies at highest management level, claiming for human rights standards in supply contracts, establish an independent auditing with focus on human rights risk assessment, develop certification which addresses all relevant human rights standards, establish a material data bank including all relevant information for use in suppliers evaluation and requirements for tender formulations, establish a reporting

system on own practice and efforts to gain influence for the supply chain with regard to human rights.

- A chance for enterprises to proceed towards social risk assessment offers the Business Social Compliance Initiative – BSCI. The BSCI is a leading business-driven initiative for companies committed to improving working conditions in factories and farms worldwide. BSCI's 2014 Code of Conduct is a set of core principles and values that provides a reference point to support retail and other importing companies towards the integration of an innovative vision of business that places social responsibility at its core /FTA 2014/.

Policy based strategies

- The European Commission has made a clear commitment to the expansion of renewable energy, including bioenergy and the industrial use of renewable resources. The targets arise in large part from the EU's package of measures on the set of issues of climate change and energy, in particular
  - the Lead Market Initiative (LMI) on bio-based products in the EU,
  - the European strategy for a European Bioeconomy,
  - the Renewable Energy Directive (RED).
- The Lead Market Initiative for bio-based products was completed by the end of 2011. The Commission's action plan for this lead market integrates necessary actions in a synchronised way to favour the innovation of the new products and services. The final evaluation of the lead market initiative identified four different categories of priority policy instruments.
- The 2012 launched Communication on the European Bioeconomy, building upon the work and results of the bio-based products Lead Market Initiative, is aimed at assisting Europe in making the transition to a more resource efficient society that relies more strongly on renewable biological resources to satisfy consumers' needs, industry demand and tackle climate change. The strategy focuses on three key aspects: developing new technologies and processes for the bioeconomy; developing markets and competitiveness in bioeconomy sectors; and pushing policymakers and stakeholders to work together more closely. With regard to biorefineries, the accompanying commission staff working document to the European Bioeconomy strategy includes a clear commitment as well as a statement that "they should adapt their inputs and outputs in response to market supply of different types of biomass and wastes and to the demand for bio-based products, biofuels and bioenergy." Further, biorefineries should adopt a cascading approach to the use of their inputs, favouring highest value added and resource efficient products, such as bio-based products and industrial materials, over bioenergy. Biorefineries can thus contribute to the principles of a "zero-waste society". The biorefinery concept can be integrated in a wide range of environments, ranging from small-scale plants using agricultural residues in remote rural areas to large plants using waste from surrounding industries and municipalities in a symbiotic manner. The FP7 project Star-COLIBRI formulated a Joint European Biorefinery Vision for 2030 /Star-Colibri 2011a/ and Joint Strategic Research Roadmap for 2020 /Star-Colibri 2011b/.
- Finally, the Renewable Energy Directive (RED) includes reporting obligations for the Commission on the impact on social aspects in the Community and in third countries of increased demand for biofuels. Based on the results of these reporting obligations on so-

cial sustainability, a revision of the Renewable Energy Directive is foreseen to possibly include additional criteria ensuring the socio-economic sustainability of (biomass and) biofuels. Sustainability criteria with regard to socio-economic issues are developed in the Global-Bio-Pact project for the European Commission.

Employment effects

- The accompanying commission staff working document to the European Bioeconomy strategy reports about 22 million jobs and about 2 trillion € annual turnover for the bioeconomy in the European Union. Most of this is allocated to the more traditional sectors food, agriculture, paper/pulp, forestry/wood, and fisheries/aquaculture. The bio-based industries are split into bio-chemicals and plastics, enzymes, and biofuels. Their contributions to turnover and employment are relatively small in the context of bioeconomy performance, but in particular bio-chemicals and plastics already achieve the same level of employment as biofuels but perform economically much better with a share of 2.4 % of the annual turnover of the bioeconomy versus only 0.3 % for biofuels.
- With regard to future expected employment effects the Commission staff working document considers four scenarios to assess how to best unlock the innovation and employment creation potential of Bioeconomy research. Employment effects as well as a couple of other positive development effects are highest in a scenario where bioeconomy is given a coherent interaction framework of supportive public policies that aim at reconciling competing activities and overlapping initiatives. In total, up to 131,000 new jobs (gross) are expected by 2025, particularly in those sectors which will invest in the non-food applications of biomass, e.g. energy, chemicals, eco-innovation.
- The EmployRES study is doing model-based evaluation of economic effects including employment under different scenarios for the implementation of the renewable energy strategy of the EC /Ragwitz et al. 2009/. It analyses the past, present and future impacts of renewable energy policies in the EU on employment and the economy, looking at the gross effects (direct and indirect) as well as the net effects (including both conventional replacement and budget effects). It finds that despite the large gross figures in terms of employment and value added, net figures are significantly smaller due to replaced investments in conventional energy technologies as well as due to the dampening effect of the higher cost of renewable energies compared with conventional alternatives. In the end, net employment effects are decisive and may differ substantially from gross effects in single sectors. The study concludes with policy recommendations in order to foster future positive development effects.
- In addition, a couple of studies worldwide focussing so far on biorefinery type production estimated positive effects for employment on regional scale. Examples are for biorefineries in Sweden, United Kingdom, Netherlands and Germany, for forestry products in Minnesota, USA and for biorefineries in Australia /Karbowski 2009/.

5.6 SWOT analysis and biomass competition

The following subchapters are adopted from D 7-6 “Final report on task 7.7 (SWOT analysis and biomass competition” /Kretschmer et al. 2014/, where the strengths, weaknesses, opportunities and threats for biomass provision and biomass conversion for SUPRABIO biorefinery concepts are described. Furthermore, as biomass availability is a crucial issue for the success and failure of biomass based value chains, the results from the SWOT analysis are complemented by a short summary on biomass availability (biomass competition analysis). For detailed results and a precise description of the methodology please refer to the original assessment report, sections on SWOT and biomass competition analysis.

5.6.1 Objective

The first objective of this assessment was to analyse the key internal and external factors that will determine the success of the SUPRABIO biorefinery concepts. To do this, an analysis on strengths, weaknesses, opportunities, and threats (SWOT) was performed for the investigated pathways. The second objective of task 7.7 was to investigate the sustainable biomass potential and the competition between different uses of the same type of biomass, e.g. the competition for straw between biorefineries and conventional bioenergy pathways. In the light of this competition, biomass availability for SUPRABIO biorefineries was analysed in order to depict possible sites for biorefineries.

5.6.2 Methodology

In this subchapter the methodology of the SWOT and the biomass competition analyses are described.

SWOT analysis

A SWOT analysis is a tool to assess the performance of a project, a product or a company. It originates from business management and it is a strategic planning tool to identify and assess the Strengths, Weaknesses, Opportunities and Threats of the surveyed object. Thereby strengths and weaknesses are defined as internal characteristics of the assessed system, while opportunities and threats are external factors determining the success or failure. The results of a SWOT analysis are generally summarised in a SWOT matrix.

In the SUPRABIO project, SWOT analysis is used to describe the strengths, weaknesses, opportunities and threats of the SUPRABIO biorefinery concepts. The SWOT analysis in SUPRABIO consists of two parts: a SWOT analysis on feedstock provision and a SWOT analysis on feedstock conversion and use.

Depending on the type of processing either lignocellulosic materials or seed oils are used for **feedstock provision** in SUPRABIO. The main lignocellulosic feedstocks are wheat straw and wood residues. In addition, also poplar wood from short rotation coppice (SRC) is ana-

lysed. Furthermore, seed oils are needed that are either imported (palm oil, Jatropha oil, soy oil) or domestically grown (rape seed oil).

For **feedstock conversion and use** within SUPRABIO a set of different biorefinery concepts was analysed. The focus of the analyses was laid on the biochemical and thermochemical processing of lignocellulose to fuels. In addition, several advanced technology options (e.g. lignocellulose to mixed acids) as well as “add-ons” (e.g. hydrogenation of seed oils) that can be attached to the biorefinery were assessed. For a detailed descriptions of biorefinery pathways analysed in the final SWOT analysis of the SUPRABIO project see D 7-6 /Kretschmer et al. 2014/ subchapter 2.1.3.

Biomass potentials and competition analysis

Success and failure of biomass-based industries strongly depend on the availability of sustainable biomass supply. Therefore, a short separate investigation on biomass potentials and competition was carried out in order to depict possible sites for biorefineries.

For the analysis of biomass potentials within SUPRABIO, a literature review was conducted, which considered the output relevant studies in this area, among others the outcomes of the EC-funded projects EUWood (Real potential for changes in growth and use of EU forests), BEE (Biomass Energy Europe) and BiomassFutures.

Regarding biomass competition, the analysis focussed on land use changes as well as their consequences for the environment and human beings. Moreover, it was investigated whether sustainability criteria and certification of biomass could be a means to reduce undesired land use changes. Finally, conclusions were drawn and recommendations given.

5.6.3 Key results

In the following subsections the key results of the SWOT and the biomass competition analyses are presented. For a detailed description of results and concrete SWOT matrices see D 7-6 /Kretschmer et al. 2014/.

SWOT analysis: biomass provision

Main feedstock for the biochemical route is wheat straw. In addition, the biochemical biorefinery concept is also based on poplar wood from short rotation coppice. In the thermochemical route wood residues are mainly used as feedstock. Alternatively, also straw or poplar wood is used. For the “add-on” technology “hydrogenation of seed oils”, several vegetable oils are used as feedstock. Those include either domestically grown seeds such as rape or imported seed oils such as Jatropha, oil palm or soy.

The following key results for the use of lignocellulosic feedstock (straw, poplar wood, wood residues) and seed oils could be identified:

Lignocellulosic feedstock

- Straw and wood residues are considered as particularly sustainable feedstock. However, sustainable straw and wood residue extraction rates should be pursued.

- Compared to poplar wood, straw and wood residues do not directly compete with food production.
- Only low yields per hectare for wood residues compared to straw and SRC poplar.
- In contrast to straw, there is only little knowledge on SRC cultivation and its market opportunities amongst farmers.
- For the biochemical route, results for poplar as feedstock is only modelled for batch processes, thus there is still a great risk that this feedstock is not suitable for the biochemical route of the SUPRABIO biorefinery concept.
- For the thermochemical route all types of feedstock (wood residues, straw and poplar wood) are considered as suitable.

Seed oils

- In contrast to Jatropha, the cultivation of rape seeds, oil palm and soy directly compete with food production.
- Compared to rape seed oil production, all other investigated seed oils need to be imported, thus longer transportation distances need to be covered and greater environmental burdens are caused.
- Rape and soy can only be harvested once a year, for Jatropha and oil palm a year round harvest is possible.
- Compared to oil palm, only low yields per hectare can be achieved for rape, soy and Jatropha.
- Cultivation experience is low for Jatropha compared to the other investigated seed oils.

SWOT analysis: biomass conversion

For most important SWOT arguments, specific for the biochemical and the thermochemical route of SUPRABIO see Table 5-5 and Table 5-6. General key results are:

- The final SWOT results for biomass conversion are still very limited due to knowledge gaps especially regarding the advanced technology options (e.g. lignocellulose to mixed acids) and the add-on technologies (if integrated or as stand-alone concepts).
- Immaturity itself is a main threat since there is always the risk of a failure in development.
- For the alternative pathways, which are considered to be available in 2025, only very general specifications are available.
- Despite, only less data is often available, the SWOT analysis revealed some interesting ideas about successes and failure factors for the SUPRABIO concepts that help stakeholders and politicians in decision making.

Biomass competition analysis

The following key results for the biomass competition analysis could be identified. For a more detailed description of key results see /Kretschmer et al. 2014/.

Conclusions

The analysis of biomass potential studies has shown that the availability of land and biomass is limited, i.e. that various land and biomass uses are competing with each other. Having a bioenergy focus (results are expressed in unit energy rather than in unit [bio-]mass), land-demanding sustainability goals (e.g. biotope networks) and competing uses (particularly future material use of biomass) are only insufficiently addressed in most existing studies.

Table 5-5 Most important SWOT factors regarding biomass processing along the biochemical route (ethanol as product).

	Success factors	Failure factors
Internal factors	**Strengths** Pre-treatment • Pre-treatment is demonstrated up to demo scale (for wheat straw) Production of ethanol • Enzymatic hydrolysis is demonstrated up to pilot scale (for wheat straw; basic configuration) • Mature technology for fermentation processes (basic configuration) • Mature technology for downstream processes • SScF (mature configuration) o Compared to SHcF higher electricity export → better net efficiency Overall • Relatively high net efficiency • Based on non-food biomass (residues)	**Weaknesses** Production of ethanol • High costs for enzymes • Use of GMOs (low acceptance, high requirements for process management) • SScF (mature configuration) o Immature state o Ethanol yield and productivity are unknown → possibly too low Wastewater • High water consumption; must rely on effective wastewater treatment technology for water recycling • Technologies for the gasification of the solids from wastewater treatment are still challenging
External factors	**Opportunities** Production of ethanol • Successful development of simultaneous saccharification and co-fermentation (SScF; mature configuration) → lower enzyme demand → lower OPEX/CAPEX costs	**Threats** Pre-treatment and enzymatic hydrolysis • Failure in efficient pre-treatment of other feedstocks Production of ethanol • Microorganisms cannot be recycled → might lead to additional costs • SScF fermentation unsuccessful (mature configuration) Overall • Competitors may succeed with superior alternative 2nd generation biofuel concepts • Other transportation fuels will gain momentum in the market

Table 5-6 Most important SWOT factors regarding biomass processing along the thermo-chemical route (FT liquids as product).

	Success factors	Failure factors
Internal factors	**Strengths** Pyrolysis: • Fast pyrolysis technology: extra heat available for feedstock drying • Highly flexible towards feedstock: suitable for a large variety of biomass (residue) types Gasification • Demonstrated technology available FT diesel production • Enhanced economy at lower scale compared to conventional FT production Overall • Runs on residues (no direct competition to food) • Two-step process (pyrolysis & gasification) allows a decentralised processing of biomass and hence lower transportation expenditures Wastewater • Compared to the biochemical route no extra water is needed	**Weaknesses** Gasification and syngas cleaning • PEBG gasifier not yet commercial technology • Steam is needed for syngas cleaning FT diesel production • Potentially low catalyst lifetime due to poisoning or carbon deposition → high catalyst demand, high costs • Micro reactors not yet commercial technology • Exothermic process → difficult temperature control • Large amount of light hydrocarbons and LPG are produced Overall • Low net efficiency compared to the biochemical pathway
External factors	**Opportunities** Gasification • Commercialisation of PEBG (pressurised entrained flow gasifier) → High gasifier temperature leads to relatively clean gas → facilitates FT diesel / DME production • Fuel flexible gasifier → many different biomasses as feedstock • The produced syngas can be converted to many different chemicals, products or IGCC FT diesel production • Micro reactors increase process efficiency and stability of the process (by increased heat removal, high mass transfer rates and high pressure resistance) Overall • Route enables synthesis of a large variety of products from different feedstocks	**Threats** Pyrolysis • Failure to further develop immature technology to commercial technology FT diesel production • Failure in development of micro reactors Overall • Competitors may succeed with superior alternative 2nd generation biofuel concepts • It is not clear if PEBG will provide a superior performance advantage compared to conventional gasifiers

Even without considering these aspects, it could be shown that the European biomass potential is significantly lower than the energy demand in the EU. Europe will therefore be dependent on the import of biomass, especially from tropical countries. This immediately raises questions in terms of security of supply (e.g. number of suppliers, quality of biomass feedstock, extreme weather events) and sustainability (especially in case of weak law enforcement and governance).

Sustainability criteria and certification are definitely steps in the right direction; however, they are not a silver bullet since the problem of displacement and indirect effects are not resolved. Indirect effects have to be taken into account - not only in terms of greenhouse gas emissions, but also with regard to biodiversity and food security - until all biomass across all sectors is covered and the global land use is effectively limited.

This is because the impacts associated with the production of biomass are fairly independent of its use, i.e. whether the feedstock is used for biofuels, bio-based products or for other purposes. Therefore it is important to apply the same rules for all agricultural products irrespective of their use for food, feed, fibre or fuel. As long as only biomass used for liquid biofuels is certified 'green', undesired land use changes will continue to occur. Therefore, mandatory sustainability criteria should urgently be expanded to solid and gaseous biofuels for heat and power generation as well as by bio-based products.

Recommendations

Competition about biomass or land use between bio-based materials, chemicals, fuels and energy, as well as foodstuffs, fodder and nature conservation represents one of our most important societal challenges around biorefineries. New technologies such as 2nd generation biorefineries will increase the demand for biomass. This conflict must be actively managed with clear objectives. We specifically recommend the following measures:

- In the mid- to long-term, national and European biomass allocation and land use plans should be compiled in a participatory manner. Because environmental burdens and social impacts of resource scarcity in particular do not possess an adequate price, market mechanisms cannot replace these plans.
- Regional planning, which comprises project planning guidelines, should be based on this premise. This framework should also rule out the cultivation of cultures that are unsuited to the local conditions. For example, the quantity of agricultural or forest residues that can be extracted without impairing soil fertility, depends on the location. Moreover, regional planning is also important because market participants with individual high biomass demand and large market power are created with the aid of public funding, and may be additionally created by establishing biorefineries. Distortions in the biomass market can and must be mitigated by appropriate planning.
- As long as this is not the case, mandatory area- and cultivation-specific sustainability criteria should be uniformly defined as preventive measures for all applications, i.e. for bio-based materials, chemicals, fuels and energy, as well as for food and feed.

6 Integrated assessment

The integrated sustainability assessment joins and connects results on individual sustainability aspects to give an integrated view on sustainability of the SUPRABIO biorefining concept. Indicators and results from the assessments of individual sustainability aspects are collected and complemented by additional efficiency indicators (CO_2 avoidance costs and SO_2 avoidance costs, see subchapter 3.3).

For the main scenarios (cf. definition in subchapter 4.1.6), the findings are presented in overview tables and discussed in subchapters 6.1 (absolute results) and 6.2 (relative results). In a second step (subchapter 6.3), sensitivity scenarios and alternative settings are compared to the main scenarios, so that positive and negative impacts of the alternative settings become visible. In the third and last step (subchapters 6.4 and 6.5), the SUPRABIO concept is compared to competing alternative biomass-based systems because the supply of biomass is expected to be a limiting factor.

In all tables, the cells are filled in different colours to highlight differences. The colour code used is explained in each subchapter.

6.1 Overview: SUPRABIO main scenarios vs. conventional systems

This subchapter describes the advantages and disadvantages of the SUPRABIO main scenarios (cf. definition in subchapter 4.1.6) compared to their conventional reference systems. Only those indicators based on a full life cycle approach are suitable for this comparison. Therefore, the comparison is limited to environmental indicators, some SWOT indicators and two economic indicators. The economic indicators are NPV and PI. The other economic indicators (cost and price related indicators (CAPEX, OPEX, total costs, break-even price) do not take into account a conventional reference system. The NPV contains the discount rate (set to 5 % by /Lervik Mejdell et al. 2014/) as indirect comparator to other types of investment. PI is based on NPV calculations and hence also contains the discount rate set as a type of comparator.

Because of the high uncertainty of data, not all quantitative indicators showing results different from zero are marked in green (="advantageous compared to reference") or red ("disadvantageous compared to reference"), but only those beyond a certain threshold. The threshold is defined as 10 % of the bandwidth of all scenarios (including the sensitivity scenarios and alternative biomass and land use options).

The following table shows the performance of SUPRABIO main scenarios in comparison with their conventional reference scenarios (Table 6-1).

Table 6-1 Overview of selected indicators and results for SUPRABIO main scenarios in comparison to conventional systems under standard conditions. Functional unit: 1 t of biomass.

			SUPRABIO Scenarios									
			Biochemical route					Thermochemical route				
			2015	2025				2015	2025			
			I-1-A	II-1-A	III-1-A	IVa	IVb	I	II	III	IV	V
Area	**Indicator**	**Unit**	Straw EtOH 1-A	Straw EtOH 1-A	Poplar EtOH 1-A	Straw Butyric 2-C	Straw Propionic 2-C	For. res. FT diesel	For. res. FT diesel	For. res. DME	Straw FT diesel	Poplar FT diesel
Environment: LCA	CED (non-renewable)	MJ / t biomass (dry)	-4,757	-9,309	-12,139	6,208	19,862	-4,661	-5,022	-3,844	-6,477	-4,201
	Global warming	kg CO_2 eq / t biomass (dry)	-363	-615	-770	420	1,138	-302	-339	-302	-350	-272
	Terrestrial acidification	g SO_2 eq / t biomass (dry)	4,891	3,390	2,371	4,332	5,537	-265	-231	-70	310	-164
	Marine eutrophication	g N eq / t biomass (dry)	1,320	1,036	608	1,247	1,330	12	15	22	546	158
	Freshwater eutrophication	g P eq / t biomass (dry)	168	133	100	487	609	-7	-8	-2	69	50
	Photochem. oxidant form.	g C_2H_4 eq / t biomass (dry)	1,218	798	373	1,643	2,807	113	188	347	97	163
	Ozone depletion	g F11 eq / t biomass (dry)	6	6	3	15	16	0	0	0	3	1
	Particulate matter form.	g PM10 eq / t biomass (dry)	870	563	349	735	1,107	-50	-34	17	-8	-25
Proc. econ.	NPV [M€]	M€ / plant	-144	-125	-499	-741	-1012	-502	-736	-515	-738	-746
	PI	%	-93.3%	-17.6%	-57.5%	-113.8%	-137.3%	-136.0%	-126.0%	-97.0%	-139.0%	-136.0%
SWOT + comp.	Direct additional land use		○	○	–	○	○	○	○	○	○	–
	Risk of indirect land use change		○	○	–	○	○	○	○	○	○	–
	Availability of infrastructure		–	–	–	–	–	–	–	–	–	–

The table shows that:

- The SUPRABIO systems are not in all aspects advantageous for the environment:
  - All SUPRABIO systems except the production of organic acids show significant primary energy savings compared to the fossil reference systems and at least small greenhouse gas savings. The “Poplar to Ethanol (2025)” scenario shows significant GHG savings.
  - All biochemical scenarios increase eutrophication and acidification, photochemical oxidant formation and particulate matter formation. The thermochemical scenarios perform much better regarding these indicators, but still not better than the conventional reference system.
- All main scenarios shown in Table 6-1 are not profitable under the analysed conditions and hence need financial incentives to be put in place. However, this is not the case for the “Straw to Ethanol (2025)” sub-scenarios II-1-B, II-2-B and II-2-C which are economically viable (not shown in Table 6-1). Please refer to subchapter 6.3.1 for a comparison of biorefinery waste treatment options.

- The SUPRABIO systems based on poplar increase the demand for arable land, hence increasing the risks of land use changes.
- All SUPRABIO systems are affected by immature infrastructure and logistics for biomass supply.

In conclusion, the SUPRABIO systems need further technological improvement to become environmentally advantageous and economically viable. The only clear advantage is a contribution to primary energy savings and hence an increased independency from limited fossil resources (except for organic acid production scenarios).

In the following subchapters, it is analysed which SUPRABIO systems perform best and how SUPRABIO optimisation scenarios could increase the overall performance of the SUPRABIO systems.

6.2 Relative performance of SUPRABIO main scenarios

The following table (Table 6-2) highlights the relative performance of the main SUPRABIO scenarios. The absolute indicator values are the same as in Table 6-1, but now the colour code highlights the scenarios performing better or worse than average. It can be concluded that:

- There is no clear superiority of one or the other system from a sustainability point of view. All pathways show advantages and disadvantages.
- Thermochemical conversion pathways show a better environmental performance regarding the LCA parameters eutrophication, acidification and photochemical oxidant formation. Their products achieved already a higher market maturity. On the other hand, the use of forest products might negatively affect indigenous rights and the local environment (LC-EIA parameters soil, flora, fauna).
- The biochemical ethanol production in 2025 shows highest primary energy and greenhouse gas savings and the lowest energy resource saving and greenhouse gas saving costs.
- Production of organic acids shows higher environmental burdens and a lower economic profitability. But it has to be taken into account that these technologies are less mature and results may change with increased maturity.
- The “Poplar to Ethanol (2025)” scenario shows the best performance of all biochemical pathways with regard to LCA, but is related with higher costs and a lower profitability. Furthermore the use of cultivated biomass causes a risk of land use changes.

Table 6-2 Relative performance of SUPRABIO main scenarios. Colour code for quantitative indicators: scenarios performing at least 10 % better than average are marked green, scenarios performing at least 10 % worse are marked red. Colour code for qualitative indicators: “+” and “++” indicators are marked green and “-“ and “- -“ are marked red. Functional unit: 1 t of biomass.

			SUPRABIO Scenarios									
			Biochemical route					Thermochemical route				
			2015	2025				2015	2025			
			I-1-A	II-1-A	III-1-A	IVa	IVb	I	II	III	IV	V
Area	Indicator	Unit	Straw EtOH 1-A	Straw EtOH 1-A	Poplar EtOH 1-A	Straw Butyric 2-C	Straw Propionic 2-C	For. res. FT diesel	For. res. FT diesel	For. res. DME	Straw FT diesel	Poplar FT diesel
Tech-nology	Net efficiency		+	++	++	–	–	– –	– –	– –	– –	– –
	Maturity		○	–	–	– –	– –	–	–	–	–	–
	Complexity		–	–	–	– –	– –	–	–	–	–	–
Environment: LCA	CED (non-renewable)	MJ / t biomass (dry)	-4,757	-9,309	-12,139	6,208	19,862	-4,661	-5,022	-3,844	-6,477	-4,201
	Global warming	kg CO_2 eq / t biomass (dry)	-363	-615	-770	420	1,138	-302	-339	-302	-350	-272
	Terrestrial acidification	g SO_2 eq / t biomass (dry)	4,891	3,390	2,371	4,332	5,537	-265	-231	-70	310	-164
	Marine eutrophication	g N eq / t biomass (dry)	1,320	1,036	608	1,247	1,330	12	15	22	546	158
	Freshwater eutrophication	g P eq / t biomass (dry)	168	133	100	487	609	-7	-8	-2	69	50
	Photochem. oxidant formation	g C_2H_4 eq / t biomass (dry)	1,218	798	373	1,643	2,807	113	188	347	97	163
	Ozone depletion	g F11 eq / t biomass (dry)	6	6	3	15	16	0	0	0	3	1
	Particulate matter formation	g PM10 eq / t biomass (dry)	870	563	349	735	1,107	-50	-34	17	-8	-25
Envi: EIA	Water		○	○	○	○	○	○	○	○	○	○
	Soil		○	○	+	○	○	–	–	–	○	+
	Fauna		○	○	+	○	○	–	–	–	○	+
	Flora		○	○	+	○	○	–	–	–	○	+
	Landscape		○	○	○	○	○	○	○	○	○	○
Proc. econ. - quantitative	NPV [M€]	M€ / plant	-144	-125	-499	-741	-1012	-502	-736	-515	-738	-746
	CAPEX	€ / t biomass (dry)	248	114	139	104	118	118	94	85	85	88
	OPEX	€ / t biomass (dry)	234	136	117	297	386	118	109	117	106	107
	Production costs	€ / t biomass (dry)	482	249	257	401	504	237	203	202	191	195
	Break-even price	€ / t biomass (dry)	606	307.1	327	454	563	296	250	245	227	239
	PI	%	-93.3%	-17.6%	-57.5%	-113.8%	-137.3%	-136.0%	-126.0%	-97.0%	-139.0%	-136.0%
Market	Market volume		++	++	++	++	++	++	++	++	++	++
	Market maturity		+	+	+	+	+	++	++	+	++	++
	Product value		○	○	○	○	○	○	○	○	○	○
Society	Risk of child labor		++	++	++	++	++	++	++	++	++	++
	Risk of forced labor		–	–	–	–	–	–	–	–	–	–
	Risk of country not passing laws to protect indegenous		++	++	++	++	++	–	–	–	++	++
	Risk of not having access to improved sanitation - rural		+	+	+	+	+	+	+	+	+	+
SWOT + comp.	Direct add. land use		○	○	–	○	○	○	○	○	○	–
	Risk of indirect land use change		○	○	–	○	○	○	○	○	○	–
	Availability of infrastructure		–	–	–	–	–	–	–	–	–	–
	Acceptance and experience among farmers / forest own.		○	○	–	○	○	+	+	+	○	–
	Use of GMOs		–	–	–	–	–	○	○	○	○	○
	Risk of explos. / fires		○	○	○	○	○	–	–	–	–	–
Calc. results	**CO_2 avoidance cost**	**€ / t CO_2 eq**	1,133.14	160.78	222.98	N/A	N/A	742.05	452.23	402.12	433.79	585.42
	Energy resource saving costs	**€ / GJ**	86.45	10.63	14.14	N/A	N/A	48.01	30.53	31.60	23.43	37.95

6.3 Benchmarking: SUPRABIO optimisation scenarios vs. main scenarios

6.3.1 Alternative settings for thermochemical conversion

In this section, the advantages and disadvantages of different optimisation options for the thermochemical pathway are discussed based on the main “Forest residues to FT fuels (2025)” scenario (II):

- Use of natural gas for internal steam generation in CHP instead of steam import (VI)
- Centralised pyrolysis (enhanced process integration) (VII)
- High pressure gasification (VIII)
- High pressure gasification and high quenching temperature (IX)

All indicators selected for integrated assessment (Table 3-1) are shown except technological indicators. Technological indicators were not assessed for the thermochemical sensitivity scenario. Indicators are calculated as described in subchapter 3.4.

The results of the comparison are shown in Table 6-3 (thermochemical conversion of forest residues to FT fuels, mature SUPRABIO plant, 2025):

- The use of natural gas for internal steam generation in CHP causes higher costs but leads to a better environmental performance. Even though the greenhouse gas savings are not marked as significantly better and the costs are higher, CO_2 avoidance costs are lower. This is due to the fact that the bandwidth of GHG emissions between the scenarios is very big and 10 % of the bandwidth are defined as threshold. But also GHG savings lower than 10 % of the bandwidth can decrease the CO_2 avoidance costs by more than 10 % of the bandwidth.
- Centralised pyrolysis leads to lower CO_2 avoidance costs and energy resource savings costs. The GHG emissions are also slightly lower and the costs are more or less equal.
- High pressure gasification – with or without higher quenching temperature – is the best optimisation option and shows environmental as well as economic advantages while being neutral regarding all other indicators.

In conclusion, high pressure gasification is the most recommendable optimisation options regarding the assessed indicators. Whether higher pressures potentially lead to higher risks for process security could not be assessed in detail in this study.

Table 6-3 Optimisation scenarios for the thermochemical pathway. Benchmark: Forest residues to FT fuels, 2025 (Scenario II).

			SUPRABIO Scenarios			
			VI	VII	VIII	IX
Area	**Indicator**	**Unit**	Natural gas	Centralized pyrolysis	High pressure gasification	High pressure gasification and high quenching temperature
Environment: LCA	CED (non-renewable)	MJ / t biomass (dry)	+	○	+	+
	Global warming	kg CO_2 eq / t biomass (dry)	○	○	○	○
	Terrestrial acidification	g SO_2 eq / t biomass (dry)	+	○	○	○
	Marine eutrophication	g N eq / t biomass (dry)	○	○	○	○
	Freshwater eutrophication	g P eq / t biomass (dry)	○	○	○	○
	Photochem. oxidant formation	g C_2H_4 eq / t biomass (dry)	+	○	+	+
	Ozone depletion	g F11 eq / t biomass (dry)	○	○	○	○
	Particulate matter formation	g PM10 eq / t biomass (dry)	○	○	○	○
Envi: EIA	Water		○	○	○	○
	Soil		○	○	○	○
	Fauna		○	○	○	○
	Flora		○	○	○	○
	Landscape		○	○	○	○
Proc. econ. - quantitativ	NPV [M€]	M€ / plant	– –	○	+	++
	CAPEX	€ / t biomass (dry)	– –	○	○	○
	OPEX	€ / t biomass (dry)	○	○	○	○
	Production costs	€ / t biomass (dry)	–	○	+	○
	Break-even price	€ / t biomass (dry)	–	○	+	+
	PI	%	+	○	+	+
Society	Risk of child labor		○	○	○	○
	Risk of forced labor		○	○	○	○
	Risk of country not passing laws to protect indegenous		○	○	○	○
	Risk of not having access to improved sanitation - rural		○	○	○	○
SWOT + comp.	Direct additional land use		○	○	○	○
	Risk of indir. land use change		○	○	○	○
	Availability of infrastructure		○	○	○	○
	Acceptance and experience among farmers / forest own.		○	○	○	○
	Use of GMOs		○	○	○	○
	Risk of explosion and fires		○	○	○	○
Calc. results	**CO_2 avoidance cost**	**€ / t CO_2 eq**	++	++	++	++
	Energy resource saving costs	**€ / GJ**	++	++	++	++

6.3.2 Process energy generation in biochemical biorefineries

In this section, the advantages and disadvantages of different process energy generation scenarios in SUPRABIO biochemical biorefineries are discussed. The main “Straw to Ethanol (2025)” scenario (II-1-A) foresees process energy generation via a gas turbine without early solids separation. Four sensitivity scenarios have been assessed:

- Gas engine (II-1-B) without early solids separation
- Gas turbine with early solids separation (II-2-A)
- Gas engine with early solids separation (II-2-B)
- Boiler and early solids separation (II-2-C)

All indicators selected for integrated assessment (Table 3-1) are shown. Indicators are calculated as described in subchapter 3.4.

Table 6-4 shows the relative performance of the different process energy generation scenarios for straw processing to ethanol in a mature SUPRABIO biorefinery (year 2025). The comparison shows:

- Process energy generation highly affects the economics of the processing plant, while environmental and social impacts are only slightly affected.
- Compared to main (sub-)scenario (II-1-A), all alternative process energy generation scenarios (sub-scenarios II-1-B, II-2-B and II-2-C) enhance economic performance except the gas turbine with early solids separation (sub-scenario II-2-A). The latter furthermore increases CO_2 avoidance costs and energy resource saving costs.
- In case of poplar processing (see Table 6-5), boiler technology shows some environmental disadvantages regarding energy and greenhouse gas balance leading to higher CO_2 avoidance costs (sub-scenario III-2-C). In poplar processing chains, the gas turbine technology in combination with early solids separation (sub-scenario III-2-A) shows significant economic and environmental disadvantages compared to sub-scenario III-1-A (gas turbine without early solids separation).

In conclusion, the use of gas engines, if possible in combination with early solids separation, increases the sustainability of the conversion chain.

Table 6-4 Process energy generation scenarios for the biochemical route (Straw to Ethanol, 2025). Benchmark: gas turbine without early solids separation (II-1-A).

			SUPRABIO Scenarios			
			II-1-B	II-2-A	II-2-B	II-2-C
Area	Indicator	Unit	Gas engine	Gas trubine + ESS	Gas engine + ESS	Boiler + ESS
Tech-nology	Net efficiency		o	o	o	–
	Maturity		o	o	o	+
	Complexity		o	o	o	+
Environment: LCA	CED (non-renewable)	MJ / t biomass (dry)	o	o	o	o
	Global warming	kg CO_2 eq / t biomass (dry)	o	o	o	o
	Terrestrial acidification	g SO_2 eq / t biomass (dry)	o	o	o	o
	Marine eutrophication	g N eq / t biomass (dry)	o	o	+	o
	Freshwater eutrophication	g P eq / t biomass (dry)	o	o	o	o
	Photochem. oxidant formation	g C_2H_4 eq / t biomass (dry)	o	o	o	o
	Ozone depletion	g F11 eq / t biomass (dry)	o	o	o	o
	Particulate matter formation	g PM10 eq / t biomass (dry)	o	o	o	o
Envi: EIA	Water		o	o	o	o
	Soil		o	o	o	o
	Fauna		o	o	o	o
	Flora		o	o	o	o
	Landscape		o	o	o	o
Proc. econ. - quantitative	NPV [M€]	M€ / plant	++	o	++	++
	CAPEX	€ / t biomass (dry)	++	o	++	++
	OPEX	€ / t biomass (dry)	+	o	+	o
	Production costs	€ / t biomass (dry)	++	o	++	++
	Break-even price	€ / t biomass (dry)	++	o	++	++
	PI	%	++	o	++	++
Market	Market volume		o	o	o	o
	Market maturity		o	o	o	o
	Product value		o	o	o	o
Society	Risk of child labor		o	o	o	o
	Risk of forced labor		o	o	o	o
	Risk of country not passing laws to protect indegenous		o	o	o	o
	Risk of not having access to improved sanitation - rural		o	o	o	o
SWOT + comp.	Direct additional land use		o	o	o	o
	Risk of indir. land use change		o	o	o	o
	Availability of infrastructure		o	o	o	o
	Acceptance and experience among farmers / forest own.		o	o	o	o
	Use of GMOs		o	o	o	o
	Risk of explosion and fires		o	o	o	o
Calc. results	**CO_2 avoidance costs**	**€ / t CO_2 eq**	++	– –	++	++
	Energy resource saving costs	**€ / GJ**	++	– –	++	++

Table 6-5 Process energy generation scenarios for the biochemical route (poplar to ethanol, 2025). Benchmark: gas turbine without early solids separation (III-1-A).

Area	Indicator	Unit	SUPRABIO Scenarios			
			III-1-B Gas engine	III-2-A Gas trubine + ESS	III-2-B Gas engine + ESS	III-2-C Boiler + ESS
Tech-nology	Net efficiency		○	–	○	– –
	Maturity		○	○	○	+
	Complexity		○	○	○	+
Environment: LCA	CED (non-renewable)	MJ / t biomass (dry)	○	–	○	– –
	Global warming	kg CO_2 eq / t biomass (dry)	○	○	○	–
	Terrestrial acidification	g SO_2 eq / t biomass (dry)	○	○	○	○
	Marine eutrophication	g N eq / t biomass (dry)	○	○	+	+
	Freshwater eutrophication	g P eq / t biomass (dry)	○	○	○	○
	Photochem. oxidant formation	g C_2H_4 eq / t biomass (dry)	+	–	○	○
	Ozone depletion	g F11 eq / t biomass (dry)	○	○	○	○
	Particulate matter formation	g PM10 eq / t biomass (dry)	○	○	○	○
Envi: EIA	Water		○	○	○	○
	Soil		○	○	○	○
	Fauna		○	○	○	○
	Flora		○	○	○	○
	Landscape		○	○	○	○
Proc. econ. - quantitative	NPV [M€]	M€ / plant	++	– –	++	++
	CAPEX	€ / t biomass (dry)	++	–	++	++
	OPEX	€ / t biomass (dry)	+	–	+	○
	Production costs	€ / t biomass (dry)	++	– –	++	++
	Break-even price	€ / t biomass (dry)	++	–	++	++
	PI	%	++	–	++	++
Market	Market volume		○	○	○	○
	Market maturity		○	○	○	○
	Product value		○	○	○	○
Society	Risk of child labor		○	○	○	○
	Risk of forced labor		○	○	○	○
	Risk of country not passing laws to protect indegenous		○	○	○	○
	Risk of not having access to improved sanitation - rural		○	○	○	○
SWOT + comp.	Direct additional land use		○	○	○	○
	Risk of indir. land use change		○	○	○	○
	Availability of infrastructure		○	○	○	○
	Acceptance and experience among farmers / forest own.		○	○	○	○
	Use of GMOs		○	○	○	○
	Risk of explosion and fires		○	○	○	○
Calc. results	**CO_2 avoidance cost**	**€ / t CO_2 eq**	++	– –	++	– –
	Energy resource saving costs	**€ / GJ**	++	– –	++	++

6.4 Comparison of feedstock use options

The following table (Table 6-6) shows the relative performance of alternative use options for straw. As benchmark scenario, the SUPRABIO main scenario “Straw to Ethanol, 2025” was chosen. The table includes all assessed straw use options, including the optimised energy generation scenarios for the biochemical conversion (see subchapter 6.3.1) and the alternative final products of the biochemical conversion process (organic acids, see subchapters 6.1 and 6.2). The relative performance of the optimised energy generation scenarios and the alternative final products of SUPRABIO biochemical conversion have already been discussed in the chapters mentioned before. The relative performance of biochemical and thermochemical conversion of straw was also already discussed (see subchapters 6.1 and 6.2).

The interesting outcome of this subchapter is the comparison of all those scenarios with the direct combustion of straw. It becomes obvious that from an environmental point of view, direct combustion of straw is more sustainable in all LCA categories and shows no disadvantages in EIA, social or SWOT categories.

Economic performance of direct combustion was not assessed. But since the profitability of SUPRABIO biorefineries is very low, it is likely that direct combustion is not less economic.

Technological constraints for direct combustion of straw could not be assessed this project.

The same results are found for “Forest residues to FT fuels” (Table 6-7) and “Poplar to Ethanol” (Table 6-8), even though the advantages of direct combustion of forest residues or poplar wood are not as significant as the advantages of direct combustion of straw.

Table 6-6 Comparison of straw use options. Benchmark: Straw to Ethanol, 2025 (Scenario II-1-A).

			SUPRABIO Scenarios							Alt.
			II-1-B	II-2-A	II-2-B	II-2-C	IVa	IVb	IV	
			Straw EtOH 1-B	Straw EtOH 2-A	Straw EtOH 2-B	Straw EtOH 2-C	Straw Butyric 2-C	Straw Propionic 2-C	Straw FT diesel	Wheat straw Direct combustion
Area	**Indicator**	**Unit**								
Tech-nology	Net efficiency		o	o	o	–	– –	– –	– –	
	Maturity		o	o	o	+	–	–	o	
	Complexity		o	o	o	+	–	–	o	
Environment: LCA	CED (non-renewable)	MJ / t biomass (dry)	o	o	o	o	– –	– –	–	++
	Global warming	kg CO_2 eq / t biomass (dry)	o	o	o	o	– –	– –	o	+
	Terrestrial acidification	g SO_2 eq / t biomass (dry)	o	o	o	o	– –	– –	++	++
	Marine eutrophication	g N eq / t biomass (dry)	o	o	+	o	– –	– –	++	++
	Freshwater eutrophication	g P eq / t biomass (dry)	o	o	o	o	– –	– –	+	++
	Photochem. oxidant formation	g C_2H_4 eq / t biomass (dry)	o	o	o	o	– –	– –	++	++
	Ozone depletion	g F11 eq / t biomass (dry)	o	o	o	o	o	o	o	+
	Particulate matter formation	g PM10 eq / t biomass (dry)	o	o	o	o	o	– –	++	+
Envi: EIA	Water		o	o	o	o	o	o	o	o
	Soil		o	o	o	o	o	o	o	o
	Fauna		o	o	o	o	o	o	o	o
	Flora		o	o	o	o	o	o	o	o
	Landscape		o	o	o	o	o	o	o	o
Proc. econ. - quantitativ	NPV [M€]	M€ / plant	++	o	++	++	– –	– –	– –	
	CAPEX	€ / t biomass (dry)	++	o	++	++	+	o	++	
	OPEX	€ / t biomass (dry)	+	o	+	o	– –	– –	++	
	Production costs	€ / t biomass (dry)	++	o	++	++	– –	– –	++	
	Break-even price	€ / t biomass (dry)	++	o	++	++	– –	– –	++	
	PI	%	++	o	++	++	– –	– –	– –	
Market	Market volume		o	o	o	o	o	o	o	o
	Market maturity		o	o	o	o	o	o	+	+
	Product value		o	o	o	o	o	o	o	o
Society	Risk of child labor		o	o	o	o	o	o	o	o
	Risk of forced labor		o	o	o	o	o	o	o	o
	Risk of country not passing laws to protect indegenous		o	o	o	o	o	o	o	o
	Risk of not having access to improved sanitation - rural		o	o	o	o	o	o	o	o
SWOT + comp.	Direct additional land use		o	o	o	o	o	o	o	o
	Risk of indir. land use change		o	o	o	o	o	o	o	o
	Availability of infrastructure		o	o	o	o	o	o	o	o
	Acceptance and experience among farmers / forest own.		o	o	o	o	o	o	o	o
	Use of GMOs		o	o	o	o	o	o	+	+
	Risk of explosion and fires		o	o	o	o	o	o	–	o
Re-sults	**CO_2 avoidance cost**	**€ / t CO_2 eq**	++	– –	++	++	N/A	N/A	– –	
	Energy resource saving costs	**€ / GJ**	++	– –	++	++	N/A	N/A	– –	

Table 6-7 Comparison of forest residues use options. Benchmark: Forest residues to FT fuels, 2025 (Scenario II).

Area	Indicator	Unit	SUPRABIO Scenarios III For. res. DME	VI For. res. FTD: NG	VII For. res. FTD: Centr.	VIII For. res. FTD: HP	IX For. res. FTD: HP&HT	Alt. Forest residues Direct combustion
Tech-nology	Net efficiency		○					
	Maturity		○					
	Complexity		○					
Environment: LCA	CED (non-renewable)	MJ / t biomass (dry)	○	+	○	+	+	++
	Global warming	kg CO_2 eq / t biomass (dry)	○	○	○	○	○	+
	Terrestrial acidification	g SO_2 eq / t biomass (dry)	○	+	○	○	○	○
	Marine eutrophication	g N eq / t biomass (dry)	○	○	○	○	○	○
	Freshwater eutrophication	g P eq / t biomass (dry)	○	○	○	○	○	++
	Photochem. oxidant formation	g C_2H_4 eq / t biomass (dry)	–	+	○	+	+	+
	Ozone depletion	g F11 eq / t biomass (dry)	○	○	○	○	○	++
	Particulate matter formation	g PM10 eq / t biomass (dry)	○	○	○	○	○	○
Envi: EIA	Water		○	○	○	○	○	○
	Soil		○	○	○	○	○	○
	Fauna		○	○	○	○	○	○
	Flora		○	○	○	○	○	○
	Landscape		○	○	○	○	○	○
Proc. econ. - quantitativ	NPV [M€]	M€ / plant	++	– –	○	+	++	
	CAPEX	€ / t biomass (dry)	○	– –	○	○	○	
	OPEX	€ / t biomass (dry)	○	○	○	○	○	
	Production costs	€ / t biomass (dry)	○	–	○	+	○	
	Break-even price	€ / t biomass (dry)	○	–	○	+	+	
	PI	%	++	+	○	+	+	
Market	Market volume		○					○
	Market maturity		–					○
	Product value		○					○
Society	Risk of child labor		○	○	○	○	○	○
	Risk of forced labor		○	○	○	○	○	○
	Risk of country not passing laws to protect indegenous		○	○	○	○	○	++
	Risk of not having access to improved sanitation - rural		○	○	○	○	○	○
SWOT + comp.	Direct additional land use		○	○	○	○	○	○
	Risk of indir. land use change		○	○	○	○	○	○
	Availability of infrastructure		○	○	○	○	○	+
	Acceptance and experience among farmers / forest own.		○	○	○	○	○	○
	Use of GMOs		○	○	○	○	○	○
	Risk of explosion and fires		○	○	○	○	○	+
Calc. results	**CO_2 avoidance cost**	**€ / t CO_2 eq**	++	++	++	++	++	
	Energy resource saving costs	**€ / GJ**	– –	++	++	++	++	

Table 6-8 Comparison of poplar use options. Benchmark: Poplar to Ethanol, 2025 (Scenario III-1-A).

Area	Indicator	Unit	SUPRABIO Scenarios III-1-B Poplar EtOH 1-B	III-2-A Poplar EtOH 2-A	III-2-B Poplar EtOH 2-B	III-2-C Poplar EtOH 2-C	V Poplar FT diesel	Alt. Poplar Direct combustion
Tech-nology	Net efficiency		○	–	○	– –	– –	
	Maturity		○	○	○	+	○	
	Complexity		○	○	○	+	○	
Environment: LCA	CED (non-renewable)	MJ / t biomass (dry)	○	–	○	– –	– –	++
	Global warming	kg CO_2 eq / t biomass (dry)	○	○	○	–	–	○
	Terrestrial acidification	g SO_2 eq / t biomass (dry)	○	○	○	○	++	++
	Marine eutrophication	g N eq / t biomass (dry)	○	○	+	+	++	++
	Freshwater eutrophication	g P eq / t biomass (dry)	○	○	○	○	○	++
	Photochem. oxidant format.	g C_2H_4 eq / t biomass (dry)	+	–	○	○	+	++
	Ozone depletion	g F11 eq / t biomass (dry)	○	○	○	○	○	++
	Particulate matter formation	g PM10 eq / t biomass (dry)	○	○	○	○	+	○
Envi: EIA	Water		○	○	○	○	○	○
	Soil		○	○	○	○	○	○
	Fauna		○	○	○	○	○	○
	Flora		○	○	○	○	○	○
	Landscape		○	○	○	○	○	○
Proc. econ. - quantitativ	NPV [M€]	M€ / plant	++	– –	++	++	– –	
	CAPEX	€ / t biomass (dry)	++	–	++	++	++	
	OPEX	€ / t biomass (dry)	+	–	+	○	○	
	Production costs	€ / t biomass (dry)	++	– –	++	++	++	
	Break-even price	€ / t biomass (dry)	++	–	++	++	++	
	PI	%	++	–	++	++	– –	
Market	Market volume		○	○	○	○	○	○
	Market maturity		○	○	○	○	+	+
	Product value		○	○	○	○	○	○
Society	Risk of child labor		○	○	○	○	○	○
	Risk of forced labor		○	○	○	○	○	○
	Risk of country not passing laws to protect indegenous		○	○	○	○	○	○
	Risk of not having access to improved sanitation - rural		○	○	○	○	○	○
SWOT + comp.	Direct additional land use		○	○	○	○	○	○
	Risk of indir. land use change		○	○	○	○	○	○
	Availability of infrastructure		○	○	○	○	○	+
	Acceptance and experience among farmers / forest own.		○	○	○	○	○	○
	Use of GMOs		○	○	○	○	+	+
	Risk of explosion and fires		○	○	○	○	–	○
Re-sults	**CO_2 avoidance cost**	**€ / t CO_2 eq**	++	– –	++	– –	– –	
	Energy resource saving costs	**€ / GJ**	++	– –	++	++	– –	

6.5 Comparison of land use options

The production of biofuels and biochemicals from cultivated biomass requires arable land. Arable land is a limited resource and should be used in the most sustainable way. This sub-chapter compares different land use options for bioenergy generation: SUPRABIO biochemical and thermochemical fuel production from SRC wood (poplar), HVO production from seed oils (=SUPRABIO alternative routes), 1st generation ethanol production from wheat grain, sugar beet and maize, heat and electricity generation by direct combustion of poplar or triticale, heat and energy generation via biogas production from maize silage and finally biodiesel production from rape seed oil.

The following table (Table 6-9) shows the advantages and disadvantages of the different land use options (functional unit: 1 ha of land). The comparison is limited to technological, environmental, social and SWOT indicators and market analysis. An economic assessment of the alternative use options could not be provided in SUPRABIO.

The comparison shows:

- Lignocellulosic crop cultivation for 2nd generation biofuels (SUPRABIO) is not necessarily more sustainable compared to 1st generation (cereals, sugar beet or oil crop cultivation). Higher energy and greenhouse gas savings are achieved only in case of high conversion efficiency. SUPRABIO ethanol value chains achieve similar CO_2 and primary energy savings as 1st generation ethanol from wheat. But perennial lignocellulosic crops in most cases show a better performance regarding most local environmental aspects compared to 1st generation annual crops.
- The import of biomass from tropical and subtropical regions (soy, palm oil, Jatropha) is associated with higher risk of negative social impacts because of higher vulnerability of local populations and weaker governance.
- First generation bioenergy systems are more mature systems.

Table 6-9 Comparison of land use options. Colours: deviation from average > 10 %.

Area	Indicator	Unit	SUPRABIO Scenarios					
			III-1-A Poplar EtOH 1-A	III-1-B Poplar EtOH 1-B	III-2-A Poplar EtOH 2-A	III-2-B Poplar EtOH 2-B	III-2-C Poplar EtOH 2-C	V Poplar FT diesel
Tech-nology	Net efficiency		++	++	+	++	○	– –
	Maturity		–	–	–	–	○	–
	Complexity		–	–	–	–	○	–
Environment: LCA	CED (non-renewable)	MJ / (ha×yr)	-139,600	-135,260	-113,405	-125,615	-93,206	-48,310
	Global warming	kg CO_2 eq / (ha×yr)	-8,855	-7,810	-7,367	-7,348	-3,408	-3,132
	Terrestrial acidification	g SO_2 eq / (ha×yr)	27,272	24,981	28,206	24,007	30,037	-1,884
	Marine eutrophication	g N eq / (ha×yr)	6,993	6,921	6,100	5,977	6,042	1,818
	Freshwater eutrophication	g P eq / (ha×yr)	1,155	1,118	1,135	1,079	1,178	571
	Photochem. oxidant formation	g C_2H_4 eq / (ha×yr)	4,285	2,611	6,276	3,141	5,008	1,880
	Ozone depletion	g F11 eq / (ha×yr)	35	32	37	33	200	8
	Particulate matter formation	g PM10 eq / (ha×yr)	4,016	3,242	4,723	3,361	5,074	-291
Envi: EIA	Water		○	○	○	○	○	○
	Soil		+	+	+	+	+	+
	Fauna		+	+	+	+	+	+
	Flora		+	+	+	+	+	+
	Landscape		○	○	○	○	○	○
Proc. econ. - quantitativ	NPV [M€]	M€ / plant	-499.00	-27.00	-669.00	-145.00	-83	-746.00
	CAPEX	€ / (ha×yr)	1,598.50	954.50	1,748.00	1,069.50	851	1,012.00
	OPEX	€ / (ha×yr)	1,345.50	1,023.50	1,598.50	1,173.00	1,334.00	1,230.50
	Production costs	€ / (ha×yr)	2,955.50	1,966.50	3,346.50	2,231.00	2,173.50	2,242.50
	Break-even price	€ / (ha×yr)	3,760.50	2,449.50	4,220.50	2,771.50	2,599.00	2,748.50
	PI	%	-57.5%	-5.3%	-70.5%	-25.0%	-18.1%	-136.0%
Market	Market volume		++	++	++	++	++	++
	Market maturity		+	+	+	+	+	++
	Product value		○	○	○	○	○	○
Society	Risk of child labor		++	++	++	++	++	++
	Risk of forced labor		–	–	–	–	–	–
	Percent of pop. living on <$2/day		N/A	N/A	N/A	N/A	N/A	N/A
	Risk of country not passing laws to protect indegenous		++	++	++	++	++	++
	Risk of not having access to improved sanitation - rural		+	+	+	+	+	+
SWOT + comp.	Direct add. land use		–	–	–	–	–	–
	Risk of indir. land use change		–	–	–	–	–	–
	Availability of infrastructure		–	–	–	–	–	–
	Acceptance and experience among farmers / forest own.		–	–	–	–	–	–
	Use of GMOs		–	–	–	–	–	○
	Risk of expl. and fires		○	○	○	○	○	–
Calc. results	**CO_2 avoidance cost**	**€ / t CO_2 eq**	222.98	84.94	330.43	134.12	238.50	585.42
	Energy resource saving costs	**€ / GJ**	14.14	4.90	21.47	7.84	8.72	37.95

Table 6-9 (continued).

Alternative Scenarios										
Rapeseed HVO	1) Oil palm HVO	2) Soybean HVO	3) Jatropha HVO	Wheat (grain) ethanol	Sugar beet ethanol	Maize ethanol	Poplar Direct combustion	Triticale Direct combustion	Maize biogas	Rape seed biodiesel
-31,176	-146,905	-15,017		-53,319	-88,041	-31,320	-201,072	-79,221	-174,729	-41,428
-764	9,152	16,684		-3,326	-7,784	-1,579	-11,421	-3,500	-6,452	-1,203
25,357	19,239	1,157		5,196	-1,945	17,624	761	37,058	20,361	23,850
4,771	3,548	218		1,404	1,052	3,271	-225	4,113	6,793	4,634
641	954	594		-2,510	-7,612	-2,803	-3,158	-1,626	-1,283	382
105	77	25		18	-47	66	37	105	111	104
16,123	17,160	1,451		371	-1,585	7,752	-7,794	22,728	-4,771	14,564
13,791	29,530	4,136		11,262	43,932	13,831	2,056	5,691	12,343	14,006
–	–	– –	– –	○	–	–	○	○	–	–
– –	–	–	–	○	– –	– –	+	–	– –	– –
–	–	– –	N/A	○	–	–	+	–	–	–
–	–	– –	N/A	○	– –	– –	+	–	– –	–
○	○	–	N/A	○	○	○	○	○	○	○
N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
				++	++	++	++	++	++	++
				+	+	+	++	++	+	+
				○	○	○	○	○	○	○
++	–	–	–	++	++	++	++	++	++	++
–	–	–	–	–	–	–	–	–	–	–
N/A	– –	–	– –	N/A	N/A	N/A	N/A	N/A	N/A	N/A
++	–	–	–	++	++	++	++	++	++	++
+	– –	– –	– –	+	+	+	+	+	+	+
– –	–	– –	–	– –	– –	– –	–	– –	– –	– –
– –	– –	– –	– –	–	–	–	–	–	–	–
○	○	○	○	○	○	○	○	○	○	○
+	+	+	+	+	+	+	–	+	+	+
○	○	○	○	○	○	○	○	○	○	○
○	○	○	○	○	○	○	○	○	○	○

7 Conclusions, limitations and recommendations

The SUPRABIO project researches, develops and demonstrates a toolkit of novel generic processes that can be applied to a range of biorefinery concepts based on different types of sustainable biomass feedstock. A strict and overarching sustainability assessment is conducted to validate the benefits and risks of the investigated SUPRABIO biorefinery concepts and, ultimately, to provide a basis for the development of policy incentives.

This study assesses the environmental, economic and social sustainability of the proposed biorefinery concepts on the basis of scenarios, which reflect possible implementations of the concepts with mature technology in the year 2025. A thermochemical route for the production of Fischer-Tropsch fuels (FT fuels) or dimethyl ether (DME) from forest residues and a biochemical route for the production of 2nd generation (lignocellulosic) ethanol from straw are assessed as main scenarios. Several sensitivity scenarios and alternative use options are analysed and compared to the main scenarios. Furthermore, a number of so-called other routes or add-ons for enhancement of overall performance were considered. The entire life cycles of the biorefinery products are compared with those of equivalent conventional (reference) products and competing use options for biomass and agricultural land.

Key conclusions from the assessments of individual sustainability aspects as well as conclusions on the interplay of these dimensions are presented in subchapter 7.1. Subchapter 7.2 lists some limitations of the assessment while in subchapter 7.3, recommendations for policy makers, industries, biomass producers and researchers are given.

7.1 Summary and conclusions

This subchapter gives short answers to the questions posed in subchapter 2.2:

There is no such thing as a free lunch: Sustainability impacts of SUPRABIO systems

The integrated life cycle sustainability assessment applied to SUPRABIO biorefineries is a practical approach capable of revealing synergies, conflicts and trade-offs which would be associated with future implementation of the investigated biorefineries. Generally, it becomes clear that

- The SUPRABIO systems are not necessarily more sustainable than conventional (mostly petroleum-based) reference systems, just because biomass is a renewable resource.
- **All SUPRABIO systems are showing advantages and disadvantages** regarding the selected sustainability indicators. None of them is free of disadvantages.
- There is ample room for improvement: **optimisation of all processes and close-to-optimum technical implementation is needed** to obtain systems that are both environmentally friendly and economically profitable.

Significant issues of SUPRABIO systems

Sustainability impacts occur at all stages of the life cycle, however, the extent to which each life cycle stage contributes to the overall impacts varies both *between scenarios* and *between impact categories / sustainability indicators*.

- **Biomass conversion**, i.e. the core biorefinery processes (pre-treatment and main process), **is responsible for the majority of the global / regional environmental and economic impacts**. These are to a large extent under the direct management influence of the biorefinery, but future operators also need to take responsibility regarding upstream processes such as enzyme provision since optimisations are needed along the entire supply chain. This is especially the case within the biorefinery itself.
- **Biomass provision dominates local environmental and social impacts** of SUPRABIO systems. However, the impacts' extent and magnitude is largely dependent on the type of biomass feedstock. The provision of biomass residues (wheat straw or forest residues) and the provision of dedicated lignocellulosic crops (e.g. perennial crops like SRC poplar) are associated with comparatively low risks - provided that biomass residue extraction rates are sustainable and provided that no direct or indirect land use changes are induced (=main precondition underlying this assessment). Higher risks are associated with imported biomass, especially oil crops.

SUPRABIO vs. conventional systems

Apart from the expenditures / emissions associated with the bio-based product, the **environmental and social impacts as well as the costs associated with the substituted conventional reference product are decisive**.

- Since the environmental burden associated with the latter is avoided, the avoided expenditures / emissions are credited to the bio-based product in the LCA. Depending on the nature of the product, this credit varies a lot: highest credits are obtained for complex molecules that would require substantial inputs if produced synthetically from petroleum. From an LCA point of view, the **investigated biofuels typically** lead to advantages in terms of non-renewable energy use (dependency on fossil fuels is reduced) and global warming potential but due to disadvantages regarding other environmental impact categories, they **do not show a clear advantage over conventional fuels**. The **investigated mixed organic acids lead to clear additional environmental burdens** in all environmental impact categories.
- Since the type of risks associated with the biomass-based systems and conventional (mostly petroleum-based) systems are completely different in quality and quantity, a direct comparison is not possible. However, a comparison of impacts at the level of environmental factors is feasible. The **land use impact of biomass provision is orders of magnitude higher than the land use impact of conventional (fossil) feedstock provision** – provided that crude oil extraction from conventional petroleum deposits is considered. On the other hand, the environmental impacts related to the provision of biomass feedstock are expected to be mostly reversible – as long as the main precondition underlying this assessment (no land use changes) is fulfilled. In contrast to that, most of the impacts from conventional (fossil) feedstock provision are expected to be long-term and non-reversible. **In terms of water use, the drain of water resources by biorefineries likely exceeds the one by conventional refineries – at least in case of the bio-**

chemical route. This could cause negative impacts in water-scarce regions, especially during the hot season.

- The economic assessment revealed that unfortunately **most SUPRABIO scenarios are uneconomic** – except three out of five sub-scenarios for 2nd generation ethanol produced from wheat straw in 2025. The "Straw to Ethanol (2025)" scenario is most **sensitive to the reference product price**, followed by CAPEX and less sensitive to the biomass cost (NPV is still positive if the cost is increased by 50 %). The "Forest residues to FT liquids (2025)" scenario is less sensitive to product price and biomass cost but most sensitive to the investment cost: NPV values would still be negative even with a theoretical 50 % CAPEX cut. It becomes obvious that the **SUPRABIO systems need further technological improvement** to be sustainable options for biofuel production.
- Alike local environmental impacts, social impacts are mostly tied to biomass provision by which a higher number of people is affected compared to conventional (fossil) feedstock provision. The hotspot analysis has shown that **very high social risks are associated with biomass which is imported form emerging / developing countries**.

The sustainability impacts of the so-called add-ons, advanced technology options, plant capacity and time frame can be summarised as follows:

- Add-on technologies could not be taken into account due to lack of data (see chapter 4).
- Simultaneous saccharification and co-fermentation (SScF) as set for the mature technology configuration – in combination with larger processing units – has a positive impact on sustainability. Economic as well as environmental performance and efficiency is enhanced while social and SWOT aspects are not affected. But, mature technology alone is not sufficient to achieve a positive NPV.
- Big plants are often more profitable and hence contribute to value generation in rural areas. But on the other hand, large plants need large amount of biomass. There are few locations where large amounts of biomass can be provided regionally without negatively affecting local environmental sustainability and negatively affecting other local biomass users.
- SUPRABIO value chains are still immature, but under rapid development. For the 2025 timeframe, advanced technologies are assumed to be available which lower costs and increase primary energy and CO_2 savings. Economic performance will be better in 2025 but still no positive NPV and PI are expected (without subsidies).

Optimisation potentials

Optimisation of each process is crucial. Energy demand, consumption of nitrogen-containing inputs (for the biochemical route) and conversion efficiency are most important for the assessed processes. The highest energy demand is caused by product separation from the fermentation broth (biochemical route) or by the water gas shift reaction and acid gas removal (FT fuels production).

The following optimisation potentials could be identified:

- Co-product treatment (biochemical route):
  The use of gas engines and boilers – with or without early solids separation – lowers the

costs remarkably and makes the plants profitable (positive NPV) without leading to relevant environmental disadvantages (see Table 6-4 and Table 6-5).

- Enzymes and nitrogen-containing inputs (biochemical route):
  For ethanol production, concrete optimisation potentials from an environmental perspective were identified regarding enzyme provision and performance as well as reduction of nitrogen inputs into the fermentation process (see /Keller et al. 2014/).
- High-pressure gasification (thermochemical route):
  The use of natural gas for internal steam generation in CHP (instead of steam import) causes higher costs but leads to a better environmental performance of the thermochemical pathway. The CO_2 avoidance costs are reduced. Centralised pyrolysis also leads to lower CO_2 avoidance costs and energy resource saving costs. High pressure gasification – with or without higher quenching temperature – is the best optimisation option and shows environmental as well as economic advantages while being neutral regarding all other indicators (see Table 6-3).

Comparison of SUPRABIO systems: And the winner is...?

The aim of the integrated sustainability assessment was to identify those SUPRABIO systems which constitute the best possible compromise in having least environmental burdens and costs and best environmental, economic and social benefits.

The analysis has shown that none of the investigated systems is necessarily superior from a sustainability point of view. Since all scenarios show advantages and disadvantages, positive and negative aspects have to be balanced based on individual preferences and subjective value choices.

In SUPRABIO, two fundamentally different conversion routes have been investigated:

- The manufacture of bio-based products via the **thermochemical route** (syngas route) which involves the breakdown of biomass into C1 molecules. From an environmental perspective, the *specific* energy and greenhouse gas savings (per kg of product) are relatively small; however, the overall savings potential might be considerable due to the relatively large market volumes.
  - Products obtained via the thermochemical route in 2025 show a more advantageous environmental performance regarding eutrophication, acidification and photochemical oxidant formation. Moreover, production costs are lower and the products have a higher market maturity than products manufactured via the biochemical route. But because of low product prices, the net present value (NPV) of the thermochemical biorefineries is negative and the conversion units are not profitable without subsidies
  - Compared to the main product FT diesel, DME production shows a slightly better economic performance and similar environmental impacts, but has to overcome the hurdle of a lower market maturity.
- The manufacture of bio-based products via the **biochemical route** which tries to make use of nature's synthesis by trying to preserve the molecular mass and chemical functions of the biomass intermediates. From an environmental perspective, the *specific* energy and greenhouse gas savings (per kg of product) are relatively big, however, the overall savings potential might be less significant due to the relatively small market volumes.

- Ethanol production in 2025 shows highest primary energy and greenhouse gas savings and the lowest energy resource savings and greenhouse gas saving costs. The NPV of ethanol production chains with optimised process energy generation are the only SUPRABIO value chains achieving a positive NPV and hence can be considered economically feasible. However, ethanol as a fuel faces blending restrictions.
- Production of ethanol performs much better than organic acid production, both from an economic and an environmental point of view. Differences in social and SWOT indicators are low. This is due to the fact that social sustainability is more affected by biomass provision and region than by product portfolio.

Today, the best possible compromise from a sustainability point of view would be 2nd generation ethanol, but FT fuels show an interesting potential in the future.

SUPRABIO vs. other biomass-based systems

This comparison could only be performed from an environmental and social angle.

The availability of biomass or land for its production is the main limiting factor for the production of bio-based products. Thus, all SUPRABIO scenarios have to be compared to other use options of the same biomass or land to be able to answer the question if and under which conditions these scenarios should be established on large scale.

The comparison of SUPRABIO scenarios and **alternative uses of the same biomass** shows that under conditions expected for 2025, fuel production from lignocellulosic biomass cannot reach levels of climate change mitigation which could be achieved by direct combustion of the same biomass for heat and power generation in a CHP plant.

Comparing the SUPRABIO scenarios (e.g. for 2nd generation biofuels) to **alternative uses of the same land** (e.g. for 1st generation biofuels), it could be shown that:

- Lignocellulosic crop cultivation for 2nd generation biofuels is not necessarily more sustainable compared to starch, sugar or oil crop cultivation for 1st generation biofuels. Second generation biofuels are in most cases still less economically feasible. Higher energy and greenhouse gas savings are achieved only in case of high conversion efficiency. SUPRABIO ethanol value chains achieve similar GHG and primary energy savings as 1st generation ethanol from wheat. But perennial lignocellulosic crops show in most cases a better performance regarding most local environmental aspects compared to 1st generation annual crops. As far as the SUPRABIO thermochemical route is concerned, the results for FT fuels from poplar are considerably better than the results for other diesel-type biofuels such as FAME and HVO produced from rapeseed.
- The import of biomass from tropical and subtropical regions (soy, palm oil, Jatropha) is associated with higher risk of negative social impacts because of higher vulnerability of local populations and weaker governance.

We conclude that 2nd generation technology does not show the potential to significantly improve the land use efficiency of ethanol. Thus, 2nd generation ethanol production from dedicated crops (even if perennial) does not live up to the high expectations connected to it in terms of environmental benefits. The thermochemical route towards FT fuels offers higher (relative) improvements over 1st generation biodiesel, however, **2nd generation ethanol**

shows higher potentials for climate change mitigation per unit area than FT fuels from the same biomass feedstock. Yet, **FT fuels display advantages over lignocellulosic ethanol regarding other environmental impacts** (other than climate change). Moreover, FT fuels do not face any blending restrictions (in contrast to ethanol) and might be more desirable since the demand for diesel-type and kerosene-type renewable fuels in Europe will increase in the future, whereas gasoline demand (and thus the demand for ethanol) is projected to decrease.

Regarding other biomass-based systems, which compete for the same biomass or land, the fiercest competitor for SUPRABIO is direct combustion of biomass for combined heat and power generation. **As long as a significant share of power is produced from coal, the stationary use of biomass is expected to mostly outperform the biofuel use of biomass by far**. However, the quantitative results of the stationary use of biomass for energy depend on the composition of the substituted conventional electricity mix: the higher its specific non-renewable energy demand and specific emissions are, the better the results if it is substituted. Today, the share of coal in the electricity mix is still high. In the long run, however, the transition of the energy system is likely to reduce the share of coal in the electricity mix and at the same time to decrease the environmental burdens avoided by new biomass-fired CHP plants. In view of the latter and considering increasing environmental burdens of petroleum-based fuels, **2nd generation biofuels might become more attractive in the future**.

Moreover, renewable heat and power can also be provided from sources other than biomass whereas airplanes, ships and heavy trucks are unlikely to be electrified in the near future and will most probably depend on liquid or (compressed) gaseous hydrocarbons. The latter can be produced renewably either from biomass or via power-to-gas / power-to-liquid technology (as discussed for material use, see above). In other words: the choice of the most environmentally friendly biomass use option varies over time.

Sustainability is not just a question of resolving technological challenges

The sustainability of a biorefinery is not just a question of technology (especially important for global / regional environmental and economic impacts) but is also critically influenced by other aspects such as biomass availability (important for all impacts), biomass production by farmers / forest owners and their involvement as stakeholders (especially important for local environmental and social impacts) and political framework (important for all impacts).

In Europe, arable land is limited. Due to a small-scale agricultural landscape, the availability of large quantities of uniform feedstock (and thus the possibility of providing it to a future biorefinery) is limited as well. Moreover, in regions where suitable feedstock is available in relevant quantities, competing uses are being established. For example in case of forest residues, the use of log wood for domestic heating might even increase. In some regions, the use of forest products might negatively affect indigenous rights. Therefore, the implementation of large biorefineries (capacity of 400 kt DM/a in 2025) bears risks. However, it is a trade-off situation: **From the point of view of local environmental impacts, it makes sense to reduce plant capacities and to implement a configuration with distributed pre-treatment units.** This offers the chance to take different types of feedstock into account in order to react to market demands. On the other hand, **larger and centralised biorefiner-**

ies are often more profitable due to economies of scale **and also more advantageous as regards global / regional environmental impacts** due to higher process efficiencies.

The biomass competition analysis has shown that the availability of land and biomass is limited, i.e. that various land and biomass uses are competing with each other. Since the European biomass potential is significantly lower than the energy demand in the EU, Europe will be dependent on imported biomass, especially from tropical countries.

Methodological achievements and challenges

This study successfully demonstrates how established assessment methodologies such as environmental life cycle assessment (LCA) and cost-benefit analysis from a business perspective can be supplemented by innovative approaches to cover and integrate all sustainability-related aspects of future SUPRABIO biorefineries.

There are still challenges in the sustainability assessment of biorefineries especially if such a variety of products – mainly bio-based materials and chemicals – is assessed. Results are greatly influenced by the agreed methods used, boundary conditions, technology development depicted in the scenarios and data available for also assessed competing markets. Thus, comparisons are only valid within the same framework of setting, which are uniformly applied to all scenarios within this study. Comparisons to results from other studies are very difficult and require extensive adjustments in most cases. However, future sustainability-oriented politics requires reliable indicators as a basis for decisions. A first step towards increased comparability was done by harmonising settings of LCA and economic assessment between the FP 7 biorefinery projects BIOCORE, SUPRABIO and EUROBIOREF[1]. On a wider basis, this challenge is currently being addressed by a work group of the European Committee for Standardization (CEN/TC 411/WG 4). It adds specifications to existing environmental LCA standards for the purpose of a more comparable assessment of bio-based products. Ultimately, work should be continued towards uniform sustainability standards for all biomass uses including feed and food.

7.2 Limitations

The integrated sustainability assessment in SUPRABIO provides a broad overview on sustainability implications of SUPRABIO biorefining concepts and allows conclusions and recommendations on most promising options. Nevertheless, the assessment has some limitations that should be kept in mind when interpreting the outcomes:

- The economic assessment assessed only the economies of the processing plants. Life cycle costing was not applied. Hence, neither the economics for biomass providers nor for the downstream value chain or consumers were taken into account. In a strict sense, the economic indicators used in this assessment are more “feasibility indicators” than economic sustainability indicators. An economic sustainability assessment in a strict

[1] Despite these methodological harmonisation achievements, it has to be kept in mind for comparisons that very different pathways and products are studied in these projects and scenario definitions are inevitably subjective if such innovative technologies are studied, for which future performance is necessarily uncertain.

sense would require a macroeconomic approach considering welfare effects on national or regional level.

- Furthermore, neither economic nor social sustainability assessment did consider net job creation potentials. The bioeconomy is often considered a job creator, but job or income losses in competing reference product value chains have to be taken into account for a full sustainability assessment.

In conclusion, the sustainability assessment could not take into account all relevant aspects of sustainability but takes into account all available information and can be considered a step forward to an integrated picture on overall sustainability of biorefining value chains.

7.3 Recommendations

Recommendations to policy makers

Since biomass potentials are limited (not only land for dedicated crops but also residues and wastes), the scarce resource biomass needs to be used as efficiently as possible. The current political framework diverts huge amounts of biomass towards energy use. This practise is already creating unwanted and disadvantageous environmental and social effects elsewhere because former uses of this biomass are replaced. This applies to cultivated biomass (iLUC, indirect land use change) and increasingly also to residues (iRUC, indirect residue use change). It is apparent that lignocellulose-based biorefineries will not be able to compete with highly subsidised and regulated biomass and land use options (i.e. biofuel and bioenergy production) in the foreseeable future without considerable changes regarding the political and economic framework conditions. Therefore, policymakers have a special responsibility in the design and organisation of future options.

Competition about biomass or land use between bio-based materials, chemicals, fuels and energy, as well as foodstuffs, fodder and nature conservation represents one of our most important societal challenges around biorefineries. New technologies such as advanced biorefineries will increase the demand for biomass. This conflict must be actively managed with clear objectives. We specifically recommend the following measures:

- In the mid- to long-term, national and European **biomass and land use allocation plans** should be compiled[2]. Because environmental burdens and social impacts of resource scarcity in particular do not possess an adequate price, market mechanisms cannot replace these plans.
- **Regional planning**, which comprises project planning guidelines, should be based on this premise. This framework should also rule out the cultivation of cultures that are unsuited to the local conditions. For example, the quantity of agricultural or forest residues that can be extracted without impairing soil fertility, depends on the location. Moreover, regional planning is also important because market participants with individual high bio-

[2] Such plans need to include mandatory biomass and land use limits to avoid increasing imports, and prioritisation schemes to allocate these resources to the most sustainable use options. This is recommended by many experts and institutions including the UNEP /UNEP 2014/.

mass demand and large market power are created with the aid of public funding, and may be additionally created by establishing biorefineries. Distortions in the biomass market can and must be mitigated by appropriate planning. Additionally, we expect regional plans to be beneficial for future approval processes for biorefineries. A regional plan for land allocation has to include other aspects, e.g. nature conservation or soil conservation, and thereby helps to prevent conflicts, e.g. with species conservation issues. This helps to create a safer environment for future investments.

- As long as this is not the case, **mandatory area- and cultivation-specific sustainability criteria** should be uniformly defined **for all biomass uses**, i.e. for bio-based materials, chemicals, fuels and energy, and ideally also for food and feed. Furthermore, standardisation activities (by CEN) for bio-based products including labelling should be supported.
- Technologies that are flexible and less demanding regarding biomass input should be supported to reach industrial scale demonstration stage.

In addition to that, we recommend the following measures:

- Find ways to ensure a stable investment climate (political framework) so that new technologies with high investment requirements can be introduced in an environment of constantly adapted policies and regulations, which is unavoidable and required for a transition towards a more sustainable economy.
- Support of 2nd generation biofuels should be re-thought and differentiated as this technology can lead to environmental benefits but also to additional burdens (e.g. if iRUC is caused). Thus, policy support and/or funding should be awarded according to clear targets (sustainability criteria), e.g. on proven GHG emission savings.
- A project to provide a greenhouse gas calculation tool according to the RED should be initiated for 2nd generation biofuels ('BioGrace III'). This is urgently needed to clarify ambiguities and create a safe investment climate. For example, greenhouse gas emissions calculated for 2nd generation ethanol within the KACELLE project cannot be compared to results given here as long as detailed background information on the calculations is not published /Persson 2014/.

Recommendations to industrial decision makers

- Strategic decisions concerning **the selection of the product portfolio** in particular determine early on whether a SUPRABIO biorefinery has the potential to produce environmentally friendly products and to be economically viable. A multitude of factors and influences has to be considered for the selection of the product portfolio. Therefore, a rigorous specific analysis of the associated environmental impacts in the planning stage of a biorefinery project is as important as a thorough financial analysis. This especially applies if public and politics have to be convinced to provide support (e.g. subsidies) and secure access to biomass.
- The planning of a biorefinery should pay attention to very high **energy and material efficiency**. Reduction of energy demand through process integration, reduction of nitrogen-containing inputs (for the biochemical route) and high conversion efficiency are most important for the assessed processes.

- **Biomass potentials at the proposed biorefinery site** should exceed projected demands. In all likelihood, the demand for biomass from several sectors, including bioenergy production, will increase considerably in the near future.
- Particularly in cases where the supply of biomass from sustainable production is already scarce, bottlenecks due to poor harvests may put pressure on operators of biorefineries to switch to feedstocks from non-sustainable sources. This may be counteracted by a **flexible** biorefinery design that allows the processing of **several types of biomass** if necessary.
- **Underutilised lignocellulosic residues are to be preferred over cultivated biomass** because these residues do not pose a risk of competition with food production and thus potential indirect land use changes. The potential of using lignocellulosic residues for fuel production is a genuine advantage of 2nd generation technologies. This advantage should be used especially in the context of rising public awareness (e.g. food vs. fuel debate). Otherwise, the **choice of feedstock should be made according to local conditions** and suitability for the used technology.
- Consider making **local stakeholders** and especially biomass producers (farmers / forest owners) shareholders of the biorefinery to promote a long term stability of biomass supply and prices. This will need to consider new business models in the EU as well as in developing countries.
- Involve independent **third party auditors** to ensure health and occupational safety especially in plants outside of the EU.

Recommendations to academic and industrial researchers and developers

One of the main paradigms of SUPRABIO was that low volume, high value products would become an economic driver of integrated biorefineries by providing higher economic margins to support high volume, low value products such as fuels. Aiming at the substitution of imported petroleum with domestic raw materials, these economic margins would be required to build or retrofit facilities capable of utilising biomass as feedstock, to justify industrial use of biomass and to incorporate technology for its conversion. At the same time, they would lead to a profitable biorefinery operation.

This aim continues to promise environmental advantages although the approaches in SUPRABIO were no immediate success. The following lessons could be learned from this project for further research in this direction:

- A competition of high volume, low value and low volume, high value products for the same feedstock fraction, as it is the case for ethanol production and the production of mixed acids (all competing for the C6 and partly for the C5 stream), should be avoided.
- Synergies should be aimed at through production of high value products from complex molecules that are present in the feedstock. These products have a high potential to replace conventional products that would require complex and energy-intensive syntheses otherwise, which can lead to high environmental benefits. In the case of lignocellulosic biomass, this mainly applies to lignin-based products, which could replace phenol derivatives. Although this could be successfully demonstrated for lignin originating from the Organosolv pre-treatment /Rettenmaier et al. 2013/, SUPRABIO lignin from steam explosion turned out not to be suitable for material use as without further processing. Never-

theless, any promising option towards this direction should be investigated further. In contrast, the thermochemical approach is less suitable for the integration with low volume / high value products because all potentially valuable compounds within the biomass are broken down into small and rather simple molecules in the initial pyrolysis step.

The following SUPRABIO-specific recommendations could be identified:

- For bioethanol production, concrete recommendations are concerning enzyme provision and performance as well as reduction of nitrogen inputs into the fermentation process. Nitrogen inputs should be limited to the amount necessary for sustaining microbial growth or by recycling microbial cell material. Moreover, other bases than N-containing ammonia should be used for pH adjustment. Furthermore, gasification of solid process residues prior to combustion is advantageous.
- For FT fuel production, high gasification pressures and high syngas input temperatures to the gas cleaning process are recommended.

Apart from that, the following general recommendations are given:

- **Energy-efficient separation and purification** should be the subject of R&D. One option may be selective procedures via membranes or adsorption processes.
- **Developers** of conversion processes (e.g. fermentation specialists) and developers of downstream processes **should collaborate at an early stage** in order to minimise energy consumption during separation and purification. Value chains that combine particularly efficient conversion techniques with optimised purification measures have a distinct capacity for significant reduction of environmental burdens.
- Sustainability research should continue to work towards a **standardisation of established sustainability indicators**. This will improve the comparability of sustainability assessments and make them a more robust basis for political decisions.
- Sustainability assessments should always **aim at covering every relevant aspect of sustainability** to avoid shifting of burdens. If there is no established quantitative indicator available or data needed for producing reliable results using a particular indicator is lacking, a qualitative approach should be followed instead. Special attention should be paid on the development of assessment methods for social and macroeconomic impacts. The assessment methods for the “society” and “economy” pillar of sustainability are much less developed compared to environmental impact assessment and LCA.

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9 Abbreviations and glossary

Abbreviation	Explanation
ASP	Activated sludge process
β-glucan	Beta-glucan
CHP	Combined heat and power (plant)
CO_2	Carbon dioxide
DHA	Docosahexaenoic acid , an omega-3 fatty acid
DM	Dry matter, further specification for mass units; often used as tonne DM (→t)
DME	Dimethyl ether
DoW	Description of Work
EDBM	Electrodialysis using bipolar membranes
EIA	Environmental impact assessment
EPA	Eicosapentaenoic acid, an omega-3 fatty acid
eq.	Equivalent
FT (diesel)	Fischer-Tropsch (diesel)
GHG	Greenhouse gas(es)
GMO	Genetically modified organism
ha	Hectare (10^4 m^2)
HVO	Hydrogenated Vegetable Oil; liquid biofuel made by hydrotreatment of vegetable oil
IE	Inhabitant Equivalent, yearly environmental impact of an average European (EU27)
ILCD	International Reference Life Cycle Data System
iLUC	Indirect land use change
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kt	Kilotonne, 1000 tonnes (10^6 kg)
LCA	Life Cycle Assessment
LC-EIA	Life Cycle Environmental Impact Assessment
LCI	Life cycle inventory (phase 2 of LCA)
LCIA	Life cycle impact assessment (phase 3 of LCA)
odt	oven dry tonne
ReCiPe	A method for life cycle impact assessment (→LCIA)
RED	Renewable Energy Directive, EU directive 2009/28/EC
REED	Reversed electro-enhanced dialysis
RO	Reverse osmosis
SEA	Strategic environmental assessment
SHcF	Separate hydrolysis and co-fermentation
SOC/SOM	Soil organic carbon / soil organic matter
SRC	Short rotation coppice
SSF	Simultaneous saccharification and fermentation
t	(Metric) tonne (10^3 kg)
UF	Ultrafiltration
UNEP	United Nations Environment Programme
VFA	Volatile fatty acid
WP	Work package
WWT	Waste water treatment
yr	Year

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