BioMates

Public Summary of Deliverable D4.4

Environmental Assessment of Bio-based Refinery Intermediates

Version 02

Grant Agreement number:	727463
Project Acronym:	BioMates
Project title:	Reliable Bio-based Refinery Intermediates — BioMates
Start date of the project:	01.10.2016
Duration of the project:	31.03.2022
Deliverable N°.:	D46
Relative Deliverable N°.:	D4.4
Work Package N°. Task N°.:	WP4 (Integrated sustainability assessment), T4.3
Deliverable title	Report on environmental assessment
Scheduled date of submission	31/12/2021
Date of submission of Version 01:	28/01/2022
Version:	02
Date of submission of this version:	29/03/2022
Dissemination Level:	Public (full originally confidential report released as public summary)
Project website address:	www.biomates.eu
The deliverable is elaborated on the basis of	Amendment – AMD-727463-25
Submitting party:	IFEU – Institute for Energy and Environmental Research Heidelberg
Responsible author:	Heiko Keller
Co- author(s):	Nils Rettenmaier, Claudius Grehl
Reviewer:	-
Verification:	Report with public summary

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727463.

Editorial remark

The BioMates consortium has decided to publish the full confidential deliverable report. Therefore, the content of this public summary is identical to that of the main report.

Contact

Dr Heiko Keller
IFEU - Institute for Energy and Environmental Research Heidelberg
Wilckensstr. 3, 69120 Heidelberg, Germany
Phone: +49-6221-4767-777, fax -19
heiko.keller@ifeu.de, www.ifeu.de

Suggested citation

Keller, Heiko; Rettenmaier, Nils; Grehl, Claudius (2022): Environmental Assessment of Bio-based Refinery Intermediates. In: *BioMates project reports*, supported by the EU's Horizon 2020 programme under GA No. 727463. IFEU – Institute for Energy and Environmental Research Heidelberg, Heidelberg, Germany. https://www.ifeu.de/en/publication/Environmental-Assessment-of-Bio-based-Refinery-Intermediates/.

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Executive summary

The defossilisation of the transport sector is one of the major challenges in meeting the climate targets of the Paris Agreement. In contrast to other sectors, greenhouse gas (GHG) emissions from the transport sector in Europe continuously increased from 1990 to 2007 and, after a decline between 2008 and 2013, are on the rise again since 2014. They are projected to remain at a high level of around 1,100 Mt CO_2eq until 2035 if no additional measures were implemented [EEA 2021]. Over those three decades, extensive research was conducted on renewable fuels for transport. Biofuels have experienced a rollercoaster development and are currently considered as not fully environmentally sustainable due to land use-induced impacts. Therefore, innovative renewable transport fuels that ideally are independent of agricultural or forestry land use, have gained growing attention.

Against this background, the EU-funded BioMates project ('Reliable Bio-based Refinery Intermediates – BioMates', GA ID 727463) aims to effectively convert lignocellulosic biomass (biomass residues and non-food crops) into high-quality bio-based intermediates (BioMates), of compatible characteristics with conventional refinery conversion units, allowing their direct and low-risk integration to any refinery towards the production of hybrid fuels. However, a novel concept for advanced biofuel production does not automatically imply that the overall sustainability performance is better. Therefore, the R&D work in BioMates included an integrated sustainability assessment (ILCSA). One essential element of this is the environmental assessment that is presented here.

The aim of this study is to assess the potential environmental impacts associated with the implementation of the BioMates concept in the future. The main objective is to determine whether or under which conditions the BioMates concept is more environmentally sustainable than conventional (fossil) fuel provision. Another important goal of the study is to identify optimisation potentials from an environmental point of view to determine focal areas for the further development of the BioMates concept.

A number of key conclusions are drawn from the results of the environmental assessment and concern both the above main questions but also alternative uses of biomass as well as eligibility according to the recast Renewable Energy Directive (RED II):

- As a main result, it can be summarised that BioMates fuels show the same pattern of ***environmental advantages and disadvantages*** that can already be observed for decades for many other biofuels and bioenergy sources: In most variants of potential design, benefits in terms of greenhouse gas emission savings and non-renewable energy use are opposed by disadvantages in most other environmental impact categories. Thus, while climate benefits can be achieved, BioMates fuels are not automatically more environmentally friendly overall than fossil fuels just because renewable resources (biomass, green hydrogen and renewable electricity) are used in their production. For the BioMates concept to actually save greenhouse gas emissions, ***the following conditions must be met***:

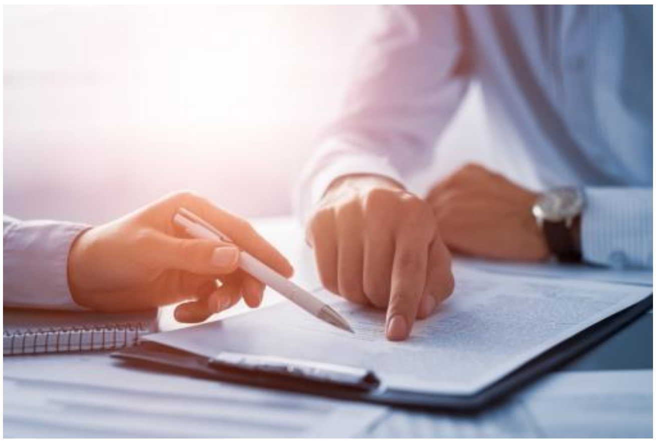
- *No competition for biomass use or land use*: The biomass residues used (straw and forest residues) must not be taken away from any existing environmentally friendly use, as otherwise indirect effects (indirect residue use competition, iRUC) mean that greenhouse gas savings cannot be achieved through other uses, which can lead to additional greenhouse gas emissions overall. This also applies in particular to the material use of these residues, which has not been considered in detail here. The same holds for the use of dedicated energy crops such as Miscanthus: here, the corresponding cultivation areas must be available without indirect effects (indirect land use change, iLUC).
- *Ample availability of renewable electricity*: Renewable electricity would have to be available on a large scale, both for the electrolytic production of the hydrogen needed for mild hydrogenation and for all other electricity requirements along the process chain. This renewable electricity would have to be available in addition to the increasing demand due to the energy transition (even with the phase-out of power generation from coal and natural gas) and in addition to the increasing demand due to the electrification of road transport. Only from an emission factor of less than about 250 g CO_2eq / kWh does the BioMates system pay off in terms of greenhouse gas emission savings.

- In the BioMates concept, the ***processes or inputs that are mainly responsible for resource use and emissions*** differ only to a small extent depending on the environmental impact category considered. Across all environmental impact categories, ***pyrolysis*** (here: electricity and partly heat demand) ***and hydrogen provision*** are particularly relevant for the environmental impacts.
- The greatest ***potential for optimisation*** in BioMates, which can be influenced by technology development, lies in pyrolysis. Here, it is particularly important to achieve maximum efficiencies.
- With regard to climate change, the investigated biomass residues straw and forest residues perform similarly, provided that forest residues can be air-dried to a water content of less than 20%. Although similar greenhouse gas emission savings can be reached using the energy crop Miscanthus, ***residue use is more environmentally friendly overall*** because Miscanthus cultivation requires cropland and thus leads to significantly higher land use-related impacts.
- The comparison of BioMates fuels with ***other biofuels produced either from the same feedstock*** (biomass residues) or by using the same land (dedicated energy crops) shows that the result ranges of various possible future industrial implementations of each technology overlap and that it depends on the exact design of the respective process chain. However, BioMates fuels could still have advantages in terms of greenhouse gas emission savings even under such conditions, especially if biomass residues are used for BioMates; advantages are achieved here unless the competing technologies (2G ethanol or BtL) would be implemented in the best possible technical way.
- With regard to cultivated biomass, on the other hand, Miscanthus considered here is in competition with many other land uses/crops, against which it has no clear advantages in terms of climate change mitigation. If the BioMates concept were to be implemented on the basis of Miscanthus, there would have to be strong economic or social reasons for doing so.

- The ***greenhouse gas balances calculated in this study according to the RED II*** are only exemplary calculations because two delegated acts that are required for the calculation were not yet adopted by the European Commission at the time of finalising this report. The results obtained show that the minimum savings required by the RED II can be achieved but also missed. Whether the required 65% threshold can be achieved depends essentially on the greenhouse gas intensity of the electricity used. In particular, the results look very promising if the entire electricity demand, including the electricity required for hydrogen production, can be met from eligible wind or solar electricity, as envisaged in the BioMates concept. In that case, savings of around 85% for straw, 80% for Miscanthus and 75% for forest residues are conceivable. Under optimal conditions, savings could be higher. If renewable electricity cannot be used or counted, achieving the minimum savings can only be achieved through multifactorial optimisation and possibly only at certain locations.

Based on these key conclusions, the following ***recommendations*** were derived for various stakeholders:

- Process developers and potential future operators of the BioMates concept should (i) further optimise pyrolysis in order to achieve maximum efficiencies, (ii) reduce the energy demand (both electricity and heat demand) and (iii) take into account a number of optimisations that have been investigated in the context of this project and that have been shown to be environmentally beneficial.
- Refinery operators should not make a final ruling on the BioMates concept before the official calculation rules under the RED II become available but only after a corresponding re-calculation has been carried out. If BioMates fuels will then comply with the 65% greenhouse gas emission savings threshold, production capacities for green hydrogen and additional renewable electricity should be actively built up.
- Policy makers should (i) adopt the pending delegated acts as soon as possible, (ii) underpin existing strategies, such as bioeconomy strategies at EU, member state and regional level with a holistic biomass use concept that takes into account not only biomass use for energy, but also the possible alternative material use of biomass (not examined in this study) and (iii) make a clear commitment to green hydrogen and create a supportive investment climate.



1. Preface

The EU-funded BioMates project (‘Reliable Bio-based Refinery Intermediates – BioMates’, GA ID 727463) aims to effectively convert lignocellulosic biomass (biomass residues and non-food crops) into high-quality bio-based intermediates (BioMates), of compatible characteristics with conventional refinery conversion units, allowing their direct and low-risk integration to any refinery towards the production of hybrid fuels. However, a novel concept for advanced biofuel production does not automatically imply that the overall sustainability performance is better. Therefore, the R&D work in BioMates included an integrated sustainability assessment to assess potential sustainability impacts associated with the implementation of the BioMates concept in the future. The sustainability assessment in BioMates is based on a life cycle approach, taking into account the entire life cycle ‘from cradle to grave’, including all co-products.

This ‘Report on environmental assessment’ (Deliverable D 4.4) covers the assessment of environmental impacts along this life cycle. The aim of this study is to assess the potential environmental impacts associated with the implementation of the BioMates concept in the future. The main objective is to determine whether or under which conditions the BioMates concept is more environmentally sustainable than conventional (fossil) fuel provision. Another important goal of the study is to identify optimisation potentials from an environmental point of view to determine focal areas for the further development of the BioMates concept. In order to cover the spectrum of all potential environmental impacts as completely as possible, the environmental assessment was carried out using a combination of two methods: screening Life Cycle Assessment (LCA) and Life Cycle Environmental Impact Assessment (LC-EIA).

The environmental assessment is embedded into an integrated sustainability assessment which is presented in chapter 3. Methodological details regarding the environmental assessment are summarised in chapter 4, followed by a description of the analysed systems in chapter 5. Results are presented in chapter 6. The report closes with conclusions and recommendations in chapter 7.

2. Introducing BioMates

2.1. The BioMates Project

The BioMates project aspires in combining innovative 2nd generation biomass conversion technologies for the cost-effective production of *bio*-based inter*mediates* (BioMates) that can be further upgraded in existing oil refineries as renewable and reliable co-feedstocks. The resulting approach allows minimisation of fossil energy requirements and therefore operating expense, minimization of capital expense as it partially relies on underlying refinery conversion capacity, and increased bio-content of final transportation fuels.

The BioMates approach encompasses innovative non-food/non-feed biomass conversion technologies, including **ablative fast pyrolysis (AFP)** and single-stage **mild catalytic hydroprocessing (mild-HDT)** as main processes. Fast pyrolysis in-line-catalysis and fine-tuning of BioMates-properties are additional innovative steps that improve the conversion efficiency and cost of BioMates technology, as well as its quality, reliability and competitiveness. Incorporating **electrochemical H_2-compression** and the state-of-the-art **renewable H_2-production** technology as well as **optimal energy integration** completes the sustainable technical approach leading to improved sustainability and decreased fossil energy dependency. The overall BioMates-Concept is illustrated in Figure 1.

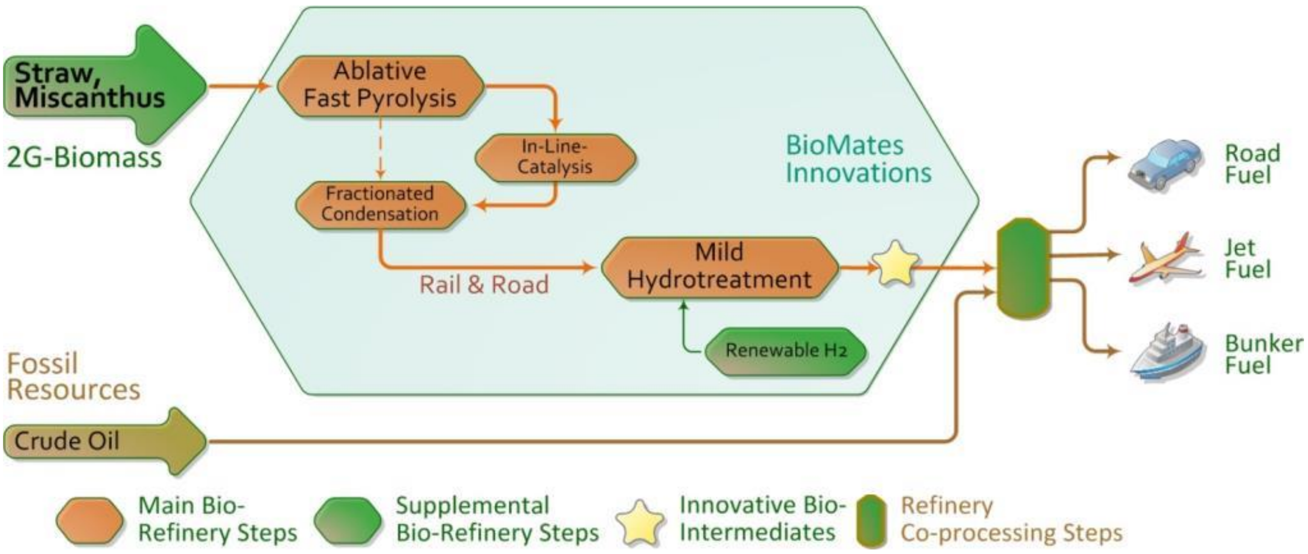


Figure 1: The BioMates-concept

The proposed technology aims to effectively convert residues and non-food/feed plants or commonly referred to as 2nd generation (straw and short rotating coppice like Miscanthus) biomass into high-quality bio-based intermediates (BioMates), of compatible characteristics with conventional refinery conversion units, allowing their direct and low-risk integration to any refinery towards the production of hybrid fuels.

2.2. European Commission support

The current framework strategy for a Resilient Energy European Union demands energy security and solidarity, a decarbonized economy and a fully integrated and competitive pan-European energy market, intending to meet the ambitious 2020 and 2030 energy and climate targets " [European Commission 2014a; b]. Towards this goal, the European Commission is supporting the BioMates project for validating the proposed innovative technological pathway, in line with the objectives of the LCE-08-2016-2017 call [European Commission 2015]. This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727463.

2.3. The BioMates team

The BioMates team comprises nine partners from industry, academia and research centres:

- Centre for Research & Technology Hellas / CERTH - Chemical Process & Energy Resources Institute / CPERI, Greece (Project Coordination) - http://www.cperi.certh.gr
- Fraunhofer Institute for Environmental, Safety, and Energy Technology UMSICHT, Germany - www.umsicht.fraunhofer.de
- University of Chemistry and Technology Prague UCTP, Czech Republic - http://www.vscht.cz
- Imperial College London ICL, United Kingdom - www.imperial.ac.uk
- ifeu - Institut für Energie und Umweltforschung Heidelberg gGmbH / IFEU, Germany - www.ifeu.de
- HyET Hydrogen B.V. / HyET, Netherlands - www.hyethydrogen.com
- RANIDO, s.r.o., Czech Republic - http://www.ranido.cz
- BP Europa SE, Germany - www.bp.com/en/bp-europa-se.html
- RISE Energy Technology Center / RISE- www.ri.se

For additional information and contact details, please visit www.biomates.eu.

3. The sustainability assessment in BioMates

3.1. Motivation for sustainability assessment within this project

The main motivation for this project is to provide renewable fuels in order to reduce dependency on fossil fuels and to mitigate global warming caused by their consumption. However, a novel approach for biofuel production doesn't automatically imply better sustainability performance. Therefore, it needs to be assessed for its sustainability, too. Furthermore, it has to be compared to other options of providing equivalent fuels and other options to use the required biomass or land to establish whether or under which conditions the approach followed in BioMates is more sustainable.

3.2. The pillars of sustainability

The most well-known definition of sustainability can be found in the report of the Brundtland Commission: 'sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs' [UN 1987]. At the 2005 World Summit it was noted that this requires the reconciliation of environmental, social and economic demands – the 'three pillars' of sustainability. This view has been expressed as a scheme using three overlapping ellipses indicating that the three pillars of sustainability are not mutually exclusive and can be mutually reinforcing (Figure 2).

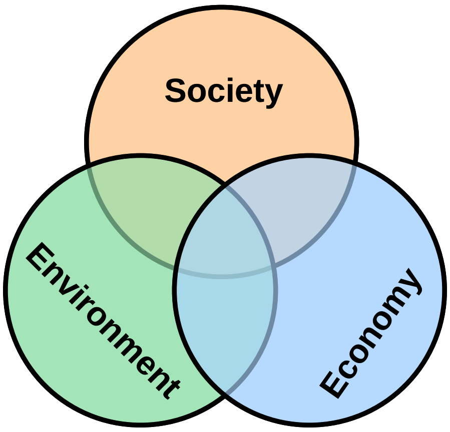


Figure 2: **Scheme of sustainable development: at the confluence of three constituent parts.**

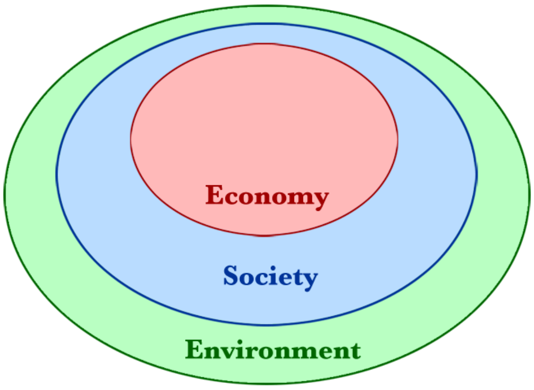


Figure 3: **Scheme indicating the relationship between the three pillars of sustainability [Scott-Cato 2008].**

The UN definition has evolved and undergone various interpretations. For example, many environmentalists think that the idea of sustainable development is an oxymoron as development seems to entail environmental degradation. From their perspective, the economy is a subsystem of human society, which is itself a subsystem of the ecosphere, and a gain in one sector is a loss from another. This can be illustrated as three concentric circles (Figure 3). Nevertheless, other interpretations exist as well.

As a result of the growing pressure on the environment and increased scarcity of natural resources, the sustainability discussion is often focussed on the environment, as both society and economy are constrained by environmental limits. There is abundant scientific evidence that humankind is currently living unsustainably and jeopardising the living conditions of future generations, e.g. by excessive use of resources and excessive use of the environment as a sink, e.g. for greenhouse gas emissions etc. Hence, strong efforts are needed to identify and develop sustainable technologies which are able to reconcile economic, social and environmental demands.

3.3. Implementation of sustainability assessment within BioMates

The sustainability assessment within BioMates is carried out by WP 4 (Sustainability). The main objective of WP 4 is to assess the sustainability of the BioMates value chains in a streamlined and comprehensive manner, covering the main aspects of sustainability: environment, economy, and society. The final integrated sustainability assessment will reveal the advantages, disadvantages and trade-offs of the BioMates value chains. A secondary aim of this WP is to provide an iterative feedback to the process developers in the form of preliminary life cycle assessment (LCA) and life cycle costing (LCC) results, which is used to further optimise the processes in the course of the project.

In order to achieve reliable and robust sustainability assessment results, it is inevitable that the principles of comprehensiveness and life cycle thinking (LCT) are applied. Life cycle thinking means that all life cycle stages for products are considered, i.e. the complete supply or value chains, from agricultural production of Miscanthus, through harvesting, pre-treatment, processing of the obtained fractions, to product use and - if applicable - end-of-life treatment and final disposal (see Figure 4). Through such a systematic overview and perspective, the unintentional shifting of environmental burdens, economic benefits and social well-being between life cycle stages or individual processes can be identified and possibly avoided or at least minimised.

The performance of each product and co-product is compared to alternative reference products. All three pillars of sustainability are analysed using techniques that are based on life cycle thinking (environmental life cycle assessment, social life cycle assessment and life cycle costing).

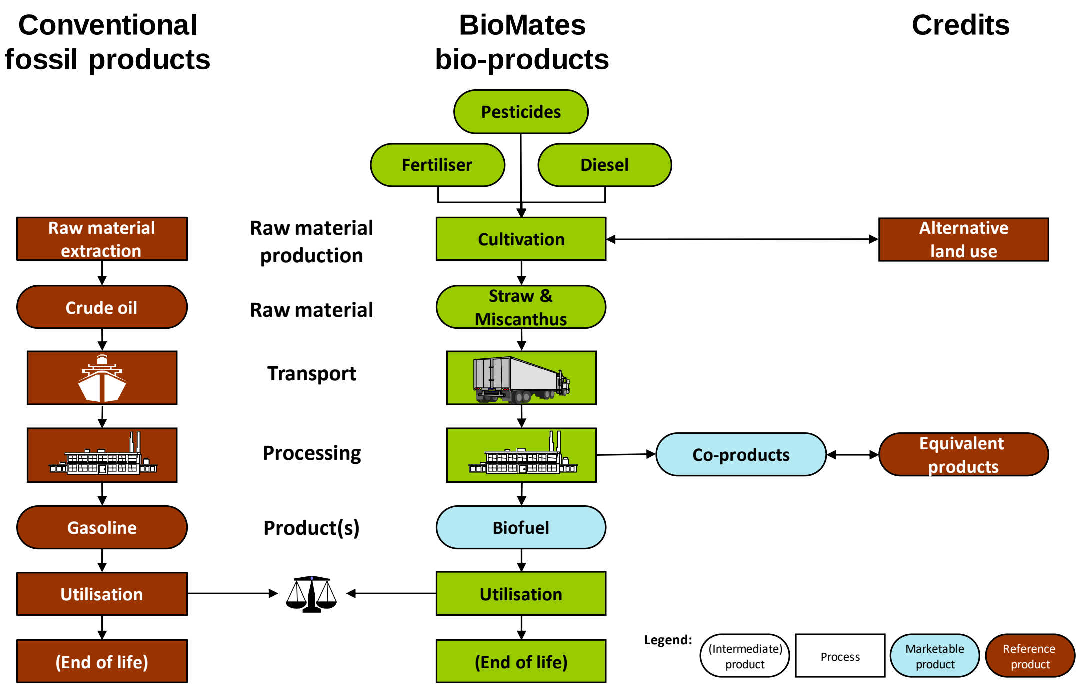


Figure 4: **Sustainability assessment in BioMates: The concept of life cycle sustainability assessment, which compares the whole life cycles of all involved products.**

This assessment is based on the methodology of Integrated Life Cycle Sustainability Assessment (ILCSA) [Keller et al. 2015]. WP 4 delivers:

- Analyses of technological, environmental, economic, societal, political implications using a variety of methods for the different tasks. The different aspects of the BioMates pathways are defined and evaluated and, where appropriate, compared to reference systems. A complementary SWOT (strengths, weaknesses, opportunities, threats) analysis identifies the key internal and external factors for the success of the BioMates pathways.
- Identification of the most sustainable pathways among the BioMates systems compared to all reference systems via a final integrated assessment based on a multi-criteria evaluation software tool. This is done by a screening using different variants and sensitivity analyses that reveal potential ways towards optimisation.

The structure of WP 4 is depicted in Figure 5.

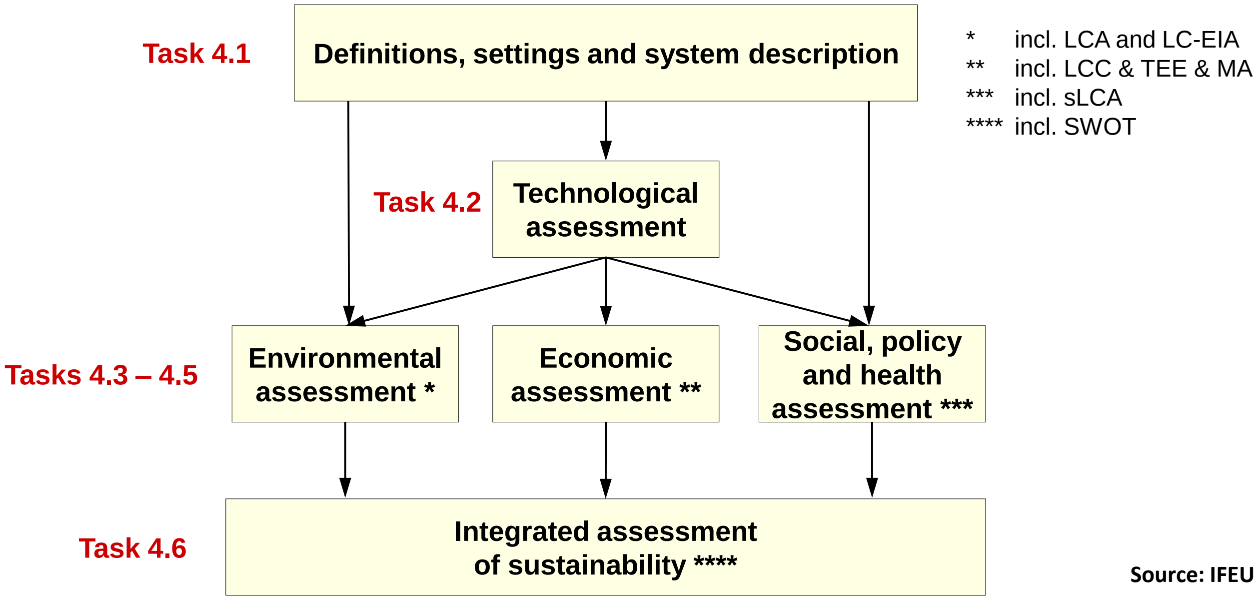


Figure 5: **Structure of BioMates WP 4 „Sustainability“.**
LC-EIA: Life cycle environmental impact assessment, TEE: Techno-economic evaluation, MA = Market analysis, sLCA = Social Life-Cycle Assessment.

Individual aspects of sustainability (technological, environmental, economic, social and political) are studied in separate Tasks within WP 4 and joined into an overall picture in Task 4.6 (Figure 5). This report presents the environmental assessment results of the BioMates value chains in comparison to their reference systems. It combines results of two sets of methodologies: life cycle assessment (LCA) and life cycle environmental impact assessment (LC-EIA). LCA evaluates the potential environmental impacts in terms of emissions and use of resources related to a product from cradle to grave. The screening LCA is taking into account the guidelines of ISO 14040/14044 [ISO 2006a; b] on product life cycle assessment. In a separate calculation, the rules for calculating greenhouse gas emission savings according to Annex V of the Renewable Energy Directive (RED II) [European Parliament & Council of the European Union 2018] are applied. Furthermore, the LC-EIA shows site-specific environmental impacts on fauna, flora, soil and water with a generic (life-cycle) approach [Keller et al. 2014; Kretschmer et al. 2012]. This methodology is applied to the production phase of crops in order to evaluate the impact of cultivation on biotic and abiotic resources. To produce comparable results, the common settings and definitions as explained in the following chapter 4 are indispensable.

4. Definitions & settings

The general definitions and settings (section 4.1) set the frame for the whole integrated sustainability assessment in BioMates but require further specification for each individual methodology applied within this framework. Therefore, the following sections specify which methodologies and specific settings are used for the assessment of global and regional environmental impacts via life cycle assessment (section 4.2) and the assessment of local environmental impacts via life cycle environmental impact assessment (section 4.3). Finally, section 4.4 contains the settings for the greenhouse gas balances according to the RED II.

4.1. General definitions and settings

The general definitions and settings set the frame for the whole integrated sustainability assessment in BioMates to ensure compatible assessments of technological, environmental, economic, social, policy and health aspects of sustainability. They are identical for all the latter assessments and are complemented by further specific settings for each methodology which are presented in sections 4.2, 4.3 and 4.4.

4.1.1. Goal & scope questions

The purpose of the so-called goal and scope questions is to guide the sustainability assessment. The comprehensiveness and depth of the sustainability assessment can differ considerably depending on its goal. This is similar to LCA studies, in which the scope of the study, including the system boundary and level of detail, depends on the subject and the intended use of the study. The integrated assessment of sustainability in this project aims at answering the following questions, which have been agreed upon by the BioMates consortium and updated during the project according to its progress.

Main question:

How and under which conditions can the feed-in of lignocellulose-based intermediates (BioMates) into a standard petrochemical refinery increase the sustainability of transportation fuels?

This main question leads to the following sub-questions:

- Which production and use concept of lignocellulose-based intermediates is best from a sustainability point of view?
  - Which input biomass shows the highest sustainability?
  - Which harvesting, logistics and conversion processes should be applied?
  - How do the specific results for the different perspectives on sustainability (such as environmental, economic, social) differ from each other?
  - Which unit processes determine the results significantly and what are the optimisation potentials?
- How does the BioMates concept perform compared to alternative uses of the same feedstock (biomass) for the provision of transportation fuels?
- Which technological, political or other barriers may hinder the large-scale implementation or continuous operation of plants according to the BioMates concept? Is there a risk that such barriers require changes to the concept that affect sustainability?

The answers to these questions are targeted at the following recipients:

- Decision makers in research and industry (including the consortium)
- Decision makers in policy
- General public (at least for the main question)

4.1.2. Settings and definitions

The analysis of the life cycles within BioMates is based on international standards such as [ISO 2006a; b], the International Reference Life Cycle Data System (ILCD) guidelines [JRC-IES 2012], the SETAC code of practice for life cycle costing [Swarr et al. 2011] and the UNEP / SETAC guidelines for social life cycle assessment [Andrews et al. 2009].

System boundaries

System boundaries specify which unit processes are part of the product system and thus included into the assessment. The sustainability assessment of the BioMates system takes into account the entire value chain (life cycle) from cradle to grave, i.e. from biomass cultivation or collection of residues, respectively, to the distribution and use of final products including land use change effects. The focus is on the provision of transportation fuels. All further products are considered as co-products. This aims at preventing a piece-meal approach. Life cycle approaches avoid problem shifting from one life cycle stage to another, from one geographic area to another and from one environmental medium or protection target to another.

For the economic assessment, input provision (e.g. biomass cultivation) may be taken into account by using market prices instead of explicit modelling if realistic prices are available for all scenarios under the chosen boundary conditions.

Technical reference

The technical reference describes the technology to be assessed in terms of plant capacity and development status / maturity.

To answer the goal and scope questions, it is essential to know how future production according to this concept performs as compared to established alternatives, which are operating at industrial scale. Therefore, the systems studied in this project are assessed as mature, industrial-scale technology (often termed “nth plant”). According to current insights, this scale corresponds to:

- About 150,000-300,000 tonnes of biomass input
- Ablative fast pyrolysis (AFP) units sized so that 4 stationary AFP units can feed 1 hydrotreatment (HDT) unit (about 10t biomass/h @ about 8000h/year)
- HDT unit: 50,000 tonnes annual production of BioMates

Timeframe

The BioMates system must be described not only in space but also in time. The timeframe of the assessment determines e.g. the development status of used technology. Likewise, the environmental impact associated with conventional products changes over time (hopefully decreasing), e.g. greenhouse gas emissions associated with electricity generation.

It seems realistic that a mature, industrial-scale plant could become operational around 2030. Therefore, this year is set as a reference.

Geographical coverage

Geography can play a crucial role in many sustainability assessments, determining e.g. productivity of crop cultivation, transport systems and electricity generation. The BioMates project focuses on the EU as a geographical region. If needed for some assessments, more concrete prototypical regions within the EU such as Southern Europe (GR), Central Europe (CZ), Western Europe (DE) may be used as a basis for calculations.

Infrastructure

Infrastructure is taken into account. However, only those infrastructure elements that may lead to relevant differences between BioMates scenarios and reference systems are assessed explicitly. This is determined in an overview analysis separately for each sustainability assessment methodology (e.g. LCA, LC-EIA, LCC) once all systems and reference systems are fixed. The environmental impacts of e.g. required roads may be less relevant and comparable between alternatives but infrastructure for e.g. photovoltaics installations may be important. For economic impacts, investment costs may be relevant in many cases in which the environmental impacts of the same installation is irrelevant.

Functional unit

The functional unit is a key element of the sustainability assessment. It is a reference to which the environmental, social and economic effects of the studied system are related, and is typically a measure for the function of the studied system. Consequently, it is the basis for the comparison of different systems.

The main goal of this project is to provide transportation fuels. Therefore, the functional unit needs to quantify the transportation capacity achieved with this fuel. This unit depends on the market, e.g. "1 km driven in a standard car" for passenger cars, "transportation of 1 tonne of cargo for 1 km" for trucks, cargo ships and cargo planes. To allow for comparisons, the energy content of the fuel serves as common reference unit. "1 MJ of fossil fuel equivalent" is chosen to account for potential differences in motor efficiency when using bio-based and standard fuels derived from fossil crude oil.

Independent of the choice of a functional unit, results may be displayed using various other reference units if necessary to support the conclusions. These may relate to biomass input (reference unit e.g. 1 tonne dry biomass input) and/or area basis (reference unit e.g. 1 ha of land).

Co-product handling

The sustainability assessment can follow a consequential or attributional approach, which has implications for co-product handling, especially in LCA. Consequential modelling is more extensive and "aims at identifying the consequences that a decision in the foreground system has for other processes and systems of the economy" according to ILCD Handbook [JRC-IES 2010]. The identification of the most appropriate LCA approach is closely linked to the decision-context. Based on guidelines in the ILCD handbook, consequential modelling is applied in this assessment.

The main focus of this project is on the provision of transportation fuels. Impacts of multi-output processes are therefore assigned to these main products. Co-products are assessed by so-called system expansion (substitution approach) that should preferentially be applied in consequential modelling according to ILCD Handbook: the impacts of a multi-output system are balanced with the avoided impacts of the reference products that are replaced by the products of the multi-output system. For example, if residues from biomass processing are used for bioenergy generation in a biogas plant, the avoided burdens of the fossil energy, which is replaced by this bioenergy, are deduced from or credited to the environmental burdens of the main products.

In case system expansion is not possible because reference products cannot be determined, the impacts are assigned to different outputs by means of allocation. In this case, the expenditures for a process chain are assigned to the different co-products by a defined allocation factor. The allocation factor can be derived from either physical properties (dry matter, energy content etc.) or economic properties (market value).

4.2. Settings and methodology for the assessment of global and regional impacts

Global and regional environmental impacts are assessed via a screening life cycle assessment (LCA). The LCA is based on international standards such as [ISO 2006a; b] and the International Reference Life Cycle Data System (ILCD) guidelines [JRC-IES 2012]. In the following, specific settings and methodological choices are detailed.

4.2.1. Settings for Life Cycle Inventory (LCI)

Data sources

The assessment requires a multitude of data for calculating the different scenarios.

Primary data:

Data and information on processes researched and developed within this project (primary data) is provided by project partners [Chrysikou et al. 2021].

Secondary data:

Environmental data on background processes (inputs to the BioMates system and conventional reference products) are compiled by IFEU based on several public and confidential sources. Selected data on biomass feedstocks are provided in Table 18 in the annex.

Attributional vs. consequential modelling

The sustainability assessment can follow a consequential or attributional approach, which has implications for co-product handling, especially in LCA. Consequential modelling is more extensive and “aims at identifying the consequences that a decision in the foreground system has for other processes and systems of the economy” according to ILCD Handbook [JRC-IES 2010]. The identification of the most appropriate LCA approach is closely linked to the decision-context. Based on guidelines in the ILCD handbook, consequential modelling is applied in this assessment. This has consequences for the assessment of co-products and indirect effects:

Co-products handling

See sub-section on Co-product handling in section 4.1.1 (p. 11).

Indirect effects such as indirect land use change

New systems using biomass can indirectly affect the environmental by withdrawing resources from other (former) uses. This can result in appropriation of biomass or land formerly not extracted or used by man, respectively. This can lead to indirect land use changes (iLUC): Biomass formerly used for other purposes (e.g. as food or feed) has to be produced elsewhere (e.g. outside of Europe) if it is now used for new products. This can indirectly cause a clearing of (semi-)natural ecosystems and hence changes in organic carbon stocks, damages to biodiversity etc. There is an ongoing international debate about these effects, mainly focussing on organic carbon stocks. Since the estimates on so called iLUC factors regarding carbon stocks are less certain and less is known about the influence of iLUC on other environmental impact categories, quantitative iLUC effects are only reported separately and only for the impact category global warming. Additionally, they are discussed qualitatively in the LC-EIA part.

Biogenic carbon

There are two possible sources for carbon dioxide (CO_2) emissions: (recent) mostly biogenic or fossil carbon stocks. For the carbon contained in the assessed bio-based (fraction of) products, the amount of CO_2 released into the atmosphere throughout the whole life cycle equals the amount of CO_2 that has been taken up by plants during biomass growth recently (short carbon cycle). Therefore, the life cycle of CO_2 taken up by plants and later on released to the atmosphere is carbon neutral, i.e. it does not affect global warming. This carbon is accounted for but for clarity its uptake and emissions are not displayed in the result graphs. Fossil carbon contained in largely bio-based products is nevertheless accounted for and displayed explicitly.

4.2.2. Settings for Life Cycle Impact Assessment (LCIA)

According to ISO standard 14040 [ISO 2006a], life cycle impact assessment (LCIA) includes the mandatory steps of classification and characterisation as well as the optional steps of normalisation and weighting. Classification and characterisation depend on the chosen impact categories and LCIA methods. Regarding the optional elements, only the normalisation step is applied within the BioMates project. The corresponding specifications of these LCIA elements are described in the following sections including

- Impact categories and LCIA methods
- Normalisation
- Weighting.

Impact categories and LCIA methods

All main environmental issues related to the BioMates value chains should be covered within the impact categories of the screening life cycle assessment in a comprehensive way. Furthermore, the impact categories must be consistent with the goal of the study and the intended applications of the results. Potential environmental impacts can be analysed at midpoint or at endpoint level. For environmental assessments within technology development projects such as BioMates, the midpoint level is considered as more suitable than the endpoint level because the impacts are analysed in a more differentiated way and the results are more accurate. This project assesses the midpoint indicators listed in Table 1. The LCIA methods follow the recommendations in [Detzel et al. 2016].

Table 1: **Overview of included midpoint impact categories and LCIA methods**

Midpoint impact category	LCIA method
Non-renewable energy use	[Borken et al. 1999; VDI (Association of German Engineers) 2012]
Climate change	[IPCC 2021]
Acidification	[CML 2016]
Eutrophication, terrestrial	[CML 2016]
Eutrophication, freshwater	[CML 2016]
Ozone depletion	[Ravishankara et al. 2009; WMO (World Meteorological Organization) 2010]
Particulate matter	[de Leeuw 2002]
Phosphate rock use	[Reinhardt et al. 2019]
Land use	[Fehrenbach et al. 2019]

This set of methods also includes two long-neglected impact categories covering environmental issues: phosphate rock footprint and land use footprint:

- The phosphate rock demand is dominated by phosphorus requirements of agricultural processes or fermentation processes and but other life cycle stages may also play an important role. The associated impacts on phosphorus resources are covered by the impact category 'phosphate rock footprint' [Reinhardt et al. 2019].
- Impacts on natural land use are addressed by the hemeroby approach according to [Fehrenbach et al. 2019]. This approach includes both the degree of human influence on a natural area and the distance of that area to the undisturbed state.

Impact categories that are irrelevant for the BioMates value chains are excluded from this study. This is the case for ionising radiation, for example. Emissions in the impact category summer smog (photochemical oxidant formation potential) were calculated and found not to be relevant because all scenarios showed only minor emissions on the side of the system under investigation and of the reference system. Furthermore, impact categories are excluded (i) that are still under methodological development or (ii) that cannot ensure sufficient LCI data quality for the reference year 2030 (i.e. impact categories on toxicity). Specific issues on human health are nevertheless covered by the category particulate matter formation.

Normalisation

Normalisation helps to better understand the relative magnitude of the results for the different environmental impact categories. To this end, the category indicator results are compared to reference information. Normalisation transforms an indicator result by dividing it by a selected reference value, e.g. a certain emission caused by the system is divided by this emission per capita in a selected country.

Within the BioMates project, Europe was chosen as geographical area. Therefore, the resource demand and emissions per capita in the European region, the so-called inhabitant equivalent (IE), are chosen as reference for normalisation. Last available data from [Sala et al. 2015] are taken. These values refer to the year 2010 and the EU 28 countries.

Weighting

Weighting is not applied. Weighting uses numerical factors based on value-choices to compare and sometimes also aggregate indicator results, which are not comparable on a physical basis.

4.3. Settings and methodology for the assessment of local impacts

There are a number of environmental management tools that differ both in terms of subject of study (product, production site or project) and in their potential to address environmental impacts occurring at different spatial levels. Environmental life cycle assessment (LCA), for example, addresses potential environmental impacts of a product system (see section 4.2). However, for a comprehensive picture of environmental impacts, also local/site-specific impacts on environmental factors like e.g. biodiversity, water and soil have to be considered. Although methodological developments are under way, these local/site-specific impacts are not yet covered in standard LCA studies. Thus, for the time being, LCA has to be supplemented by elements borrowed from other tools.

The methodology applied in this project borrows elements from environmental impact assessment (EIA) [and partly from strategic environmental assessment (SEA)] and is therefore called life cycle environmental impact assessment (LC-EIA) [Keller et al. 2014; Kretschmer et al. 2012].

4.3.1. Introduction to EIA methodology

Environmental impact assessment (EIA) is a standardised methodology for analysing proposed projects regarding their potential to affect the local environment. It is based on the identification, description and estimation of the project's environmental impacts and is usually applied at an early planning stage, i.e. before the project is carried out. EIA primarily serves as a decision support for project management and authorities which have to decide on approval. Moreover, it helps decision makers to identify more environmentally friendly alternatives as well as to minimise negative impacts on the environment by applying mitigation and compensation measures.

The environmental impacts of a planned project depend on both the nature/specifications of the project (e.g. a biorefinery plant housing a specific production process and requiring specific raw materials which have to be delivered) and on the specific quality of the environment at a certain geographic location (e.g. occurrence of rare or endangered species, air and water quality etc.). Thus, the same project probably entails different environmental impacts at two different locations. EIA is therefore usually conducted at a site-specific/local level. These environmental impacts are compared to a situation without the project being implemented ("no-action alternative").

Regulatory frameworks related to EIA

Within the European Union, it is mandatory to carry out an environmental impact assessment (EIA) for projects according to the Council Directive 85/337 EEC "on the assessment of the effects of certain public and private projects on the environment" [CEC 1985]. This Directive has been substantially amended several times. In the interests of clarity and rationality the original EIA Directive has been codified (put together as a code or system, i.e. in an orderly form) through Directive 2011/92/EU [European Parliament & Council of the European Union 2011]. The latter has once again been amended in 2014 through Directive 2014/52/EU [European Parliament & Council of the European Union 2014].

EIA methodology

An EIA covers direct and indirect effects of a project on certain environmental factors. The list of factors has been substantially altered with the 2014 amendment (addition and deletion of factors) [European Parliament & Council of the European Union 2014] and currently covers the following ones:

- population and human health
- biodiversity (previously: fauna and flora)
- land (new), soil, water, air and climate
- material assets, cultural heritage and the landscape
- the interaction between these factors

Please note: the relatively new factor "land" is indirectly addressed in the conflict matrices (via the factors "soil" and "landscape") since implementing rules for the new factor "land" are lacking or under development. Moreover, we continue to address the two factors "fauna" and "flora" separately, since we think that "biodiversity" alone wouldn't cover all aspects that were previously addressed under "fauna" and "flora" (e.g. the conservation/Red List status of species). This way, more specific recommendations can be derived.

An EIA generally includes the following steps:

- Screening
- Scoping
- EIA report
  - Project description and consideration of alternatives
  - Description of environmental factors
  - Prediction and evaluation of impacts
  - Mitigation measures
- Monitoring and auditing measures

Screening

Usually an EIA starts with a screening process to find out whether a project requires an EIA or not. According to Article 4 (1) and Annex 1 (6) of the EIA Directive, an EIA is mandatory for "Integrated chemical installations, i.e. those installations for the manufacture on an industrial scale of substances using chemical conversion processes, in which several units are juxtaposed and functionally linked to one another and which are"

- "for the production of basic plant health products and of biocides" (6d) or
- "for the production of basic pharmaceutical products using a chemical or biological process" (6e).

Referring to Annex 1 (6) of the EIA Directive, an EIA would be required if one of the studied facilities was implemented.

Scoping

Scoping is to determine what should be the coverage or scope of the EIA study for a project as having potentially significant environmental impacts. It helps in developing and selecting alternatives to the proposed action and in identifying the issues to be considered in an EIA. The main objectives of the scoping are:

- Identify concerns and issues for consideration in an EIA.
- Identify the environmental impacts that are relevant for decision-makers.
- Enable those responsible for an EIA study to properly brief the study team on the alternatives and on impacts to be considered at different levels of analysis.
- Determine the assessment methods to be used.
- Provide an opportunity for public involvement in determining the factors to be assessed, and facilitate early agreement on contentious issues.

EIA report

An EIA report consists of a project description, a description of the status and trends of relevant environmental factors and a consideration of alternatives including against which predicted changes can be compared and evaluated in terms of importance.

- Impact prediction: a description of the likely significant effects of the proposed project on the environment resulting from:
    - The construction/installation of the project; temporary impacts expected, e.g. by noise from construction sites.
    - The existence of the project, i.e. project-related installations and buildings; durable impacts expected e.g. by loss of soil on the plant site.
    - The operation phase of the project; durable impacts expected, e.g. by emission of gases.

Prediction should be based on the available environmental project data. Such predictions are described in quantitative or qualitative terms considering e.g.:

- Quality of impact
- Magnitude of impact
- Extent of impact
- Duration of impact

Mitigation measures are recommended actions to reduce, avoid or offset the potential adverse environmental consequences of development activities. The objective of mitigation measures is to maximise project benefits and minimise undesirable impacts.

Monitoring and auditing measures

Monitoring and auditing measures are post-EIA procedures that can contribute to an improvement of the EIA procedure.

Monitoring is used to compare the predicted and actual impacts of a project, so that action can be taken to minimise environmental impacts. Usually, monitoring is constrained to either potentially very harmful impacts or to impacts that cannot be predicted very accurately due to lack of baseline data or methodological problems.

Auditing is aimed at the improvement of EIA in general. It involves the analysis of the quality and adequacy of baseline studies and EIA methodology, the quality and precision of predictions as well as the implementation and efficiency of proposed mitigation measures. Furthermore, the audit may involve an analysis of public participation during the EIA process or the implementation of EIA recommendations in the planning process.

4.3.2. The LC-EIA approach in this project

Within this project, a set of different technological concepts for provision of transportation fuels from lignocellulosic biomass such as straw via co-processing in a petrochemical refinery is analysed. Each concept is defined by its inputs, the conversion, the downstream processes and the final products. This is also reflected in the objectives and settings of the sustainability assessment (chapter 4): the aim is to qualitatively assess the impacts associated with each of the potential future investigated concepts (in the sense of technological concepts) at a generic level. The assessment is not meant to be performed for a planned facility at a certain geographic location.

Environmental impact assessment (EIA), however, is usually conducted specifically for a planned (actual) project (see previous section 4.3.1). For the purpose of this project, which neither encompasses the construction of an actual industrial scale facility, it is therefore not appropriate to perform a full-scale EIA according to the regulatory frameworks. Monitoring and auditing measures, for example, become redundant if a project is not implemented, as they are post-project procedures. Consequently, monitoring and auditing measures are omitted within this project. Nevertheless, elements of environmental impact assessment (EIA) are used to characterise the environmental impacts associated with the systems investigated in this project at a generic level.

The elements of EIA used in this project are shown in Figure 6.

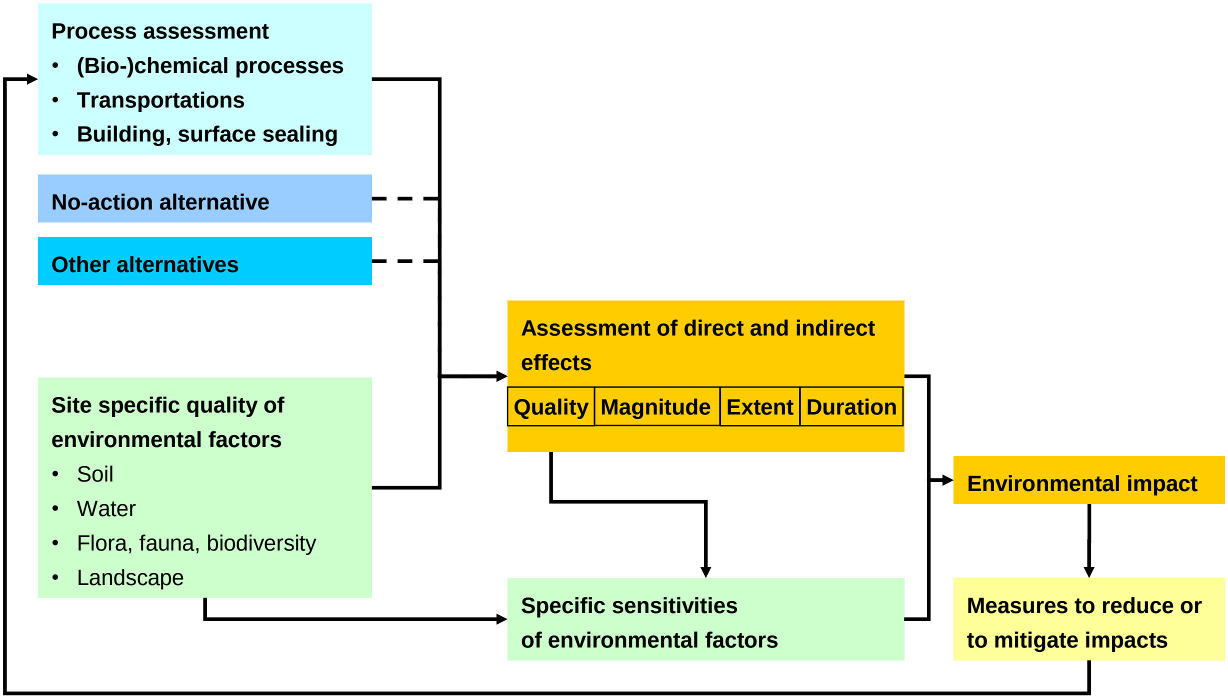


Figure 6: Structure of an LC-EIA.

Reference systems

Generally, an EIA compares a planned project to a so-called "no-action alternative" (a situation without the project being implemented) in terms of environmental impacts. This assessment is restricted to one specific project or site such as a processing facility. Production sites for raw material inputs (e.g. biomass) and/or the impacts associated with the end use of the manufactured products are usually not considered.

Within this life cycle based sustainability assessment, the scope, and therefore also the reference system, of the LC-EIA was chosen to encompass all life cycle stages from raw material provision through conversion up to the use of the final products. This corresponds to a life cycle perspective and goes beyond the regulatory frameworks for EIA.

Impact assessment

The assessment of local environmental impacts along the life cycle is carried out as a qualitative benefit and risk assessment. This is useful if no certainty exists regarding the possible future location of biomass production sites and conversion facilities.

For this qualitative impact assessment, so-called conflict matrices are used. These present in an aggregated manner the types of risk associated with each of the scenarios including a ranking of the impacts into five categories from A (low risk) to E (high risk). An example is given in the following Table 2.

Table 2: Comparison of scenarios regarding the risks associated with their implementation.

Type of risk	Scenario 1	Scenario 2	Scenario 3	Scenario 4	...
Soil erosion					
Soil compaction					
Eutrophication					
Accumulation of pesticides					
Depletion of groundwater					
Pollution of groundwater					
Pollution of surface water					
Loss of landscape elements					
Loss of habitat/biodiversity					

Categories (A = low risk, E = high risk): A B C D E

For biofuels from dedicated crops, which are cultivated to provide the reference products of the BioMates system, crop-specific conflict matrices are used. An example is provided in the following Table 3.

In these crop-specific conflict matrices, the environmental impacts of biomass cultivation are compared to a reference system (relative evaluation) and evaluated as follows:

- "positive": compared to the reference system, biomass cultivation is more favourable
- "neutral": biomass cultivation shows approximately the same impacts as the reference system
- "negative": compared to the reference system, biomass cultivation is less favourable.

Finally, mitigation measures could be deducted from these conflict matrices. However, since the sustainability assessment within this project is not targeting a specific location, mitigation measures are omitted.

Table 3: Risks associated with the cultivation of a specific annual/perennial crop.

Type of risk	Affected environmental factors								
	Ground water	Surface water	Soil	Plants/Biotopes	Animals	Climate/Air	Landscape	Human health/ recreation	Biodiversity
Soil erosion									
Soil compaction									
Eutrophication									
Accumulation of pesticides									
Pollution of groundwater									
Pollution of surface water									
Loss of landscape elements									
Loss of habitat/biodiversity									

Categories: positive - neutral – negative

4.4. Settings and methodology for the greenhouse gas balances according to the RED II

In the light of a controversial discussion on the net benefit of biofuels and bioenergy and the share of renewable energy in the transport sector, the European Renewable Energy Directive (2009/28/EC, RED) on the promotion of the use of energy from renewable sources [European Parliament & Council of the European Union 2009] set out a mandatory share of 10% by the year 2020 and a number of sustainability criteria. These criteria had to be met by biofuels and bioliquids to be able to be counted towards this target of 10%.

The RED has been substantially amended several times and recast in 2018 [European Parliament & Council of the European Union 2018]. The sustainability criteria defined in the RED II are partly the same as in the original RED and partly new or reformulated. In particular, the RED II introduces sustainability criteria for forestry feedstocks as well as greenhouse gas saving criteria for solid and gaseous biomass fuels. These requirements influence the marketing opportunities of biofuels within Europe. Biofuels that comply with the defined criteria have better chances on the market. Therefore, biofuel producers are interested if their biofuels fulfil the criteria or not.

Within the BioMates project, the climate change-related criteria of the RED II are most important: the greenhouse gas (GHG) emission savings from the use of biomass fuels. In the transport sector, the emission saving shall be at least 60% (after October 2015), increasing to 65% after January 2021 – including emissions from direct land-use changes (dLUC) – compared to the defined emissions of the fossil fuel comparator. For electricity, heating and cooling, the emission saving shall be at least 70% after January 2021.

The rules for calculating the GHG impact are defined in two annexes to the RED II: Annex V for biofuels and bioliquids and Annex VI for biomass fuels, respectively. The calculations rules under the RED II follow a considerably different approach than the ISO standards 14040 and 14044 (see section 4.2) since the RED II calculation rules were made for verifying compliance of each individual consignment of transport fuel with the greenhouse gas emissions saving criteria. For this purpose, the so-called energy allocation method was considered the most appropriate method for co-product accounting. However, as stated in Recital 116 of the RED II, the so-called substitution method (which is more in line with the ISO standard) should be used for the purposes of policy analysis.

However, several methodological issues were left open at the time the RED II was published and the European Commission was mandated to adopt a series of delegated acts, most of which by 31 December 2021. One of these delegated acts, deriving from Article 28(5), should target co-processed oil (processed in a refinery simultaneously with fossil fuel) of biomass or pyrolysed biomass origin. At the time of finalising this report, this delegated act is still pending and expected for the first quarter of 2022 instead [European Commission 2021a]. A second delegated act on requirements for renewable electricity deriving from Article 27 of the RED II, which is also relevant for BioMates, is also still pending and Commission adoption is planned for the fourth quarter 2021 [European Commission 2021b]. Nevertheless, exemplary calculations have been conducted in which the authors tried to anticipate the pending calculation rules to the best of their abilities.

Data for GHG intensities for input materials and energy was taken as far as possible from lists of standard values provided along with the GHG calculation tool BioGrace, which is approved by the European Commission to verify compliance with the emission saving requirements of the EU (www.biograce.net). For all inputs not contained in the respective lists, data from the LCA was taken (see section 4.2.1). Please note that it is expected that in particular GHG intensities of electricity provision can improve substantially depending on ongoing decarbonisation processes until a biofuel from a potential new BioMates installation could be certified.

5. The BioMates systems: qualitative descriptions

The following systems are assessed according to an agreement of all partners. These were originally defined in D4.1 of the BioMates project [Keller et al. 2018] and have been updated based on new insights gained in the further course of the project.

The base case scenario, shown in Figure 7, is defined as follows: Cereal straw (50% wheat and 50% barley) is air dried and baled on the field for transportation and storage. The biomass is technically dried to very low water content and converted to pyrolysis oil at the pyrolysis units by ablative fast pyrolysis (AFP) with staged condensation and hot gas filter. The pyrolysis oil is converted further in a mild hydrotreatment unit (HDT). The co-product pyrolysis char is primarily used internally for heat provision and excess pyrolysis char is sold for heat and energy production in a CHP. The aqueous fraction resulting from the pyrolysis process is used for energy recovery in a biogas digester. In this scenario, one pyrolysis unit is co-located with the mild hydrotreatment unit (HDT) and the refinery while three more pyrolysis units located elsewhere are delivering pyrolysis oil. The pyrolysis oil is converted at the mild hydrotreatment unit (HDT) with sulfided catalyst and electrochemical H_2 compression to the BioMates intermediate product. Off-gas from electro-chemical hydrogen recovery is used internally as far as needed to cover the heat demand. The rest sold to the adjacent petrochemical refinery for energy recovery and thus reduces the refinery's natural gas demand. The hydrogen is provided by electrolysis from renewable power and the oxygen-rich stream from electrolysis is vented. The BioMates product is transferred to an oil refinery, which is nearby the HDT in the base case, and mixed and co-processed with a suitable intermediate such as light cycle oil.

All other scenarios are modifications of this base case. Selected exemplary life cycle schemes of them can be found in the annex (Figure 23 and Figure 24).

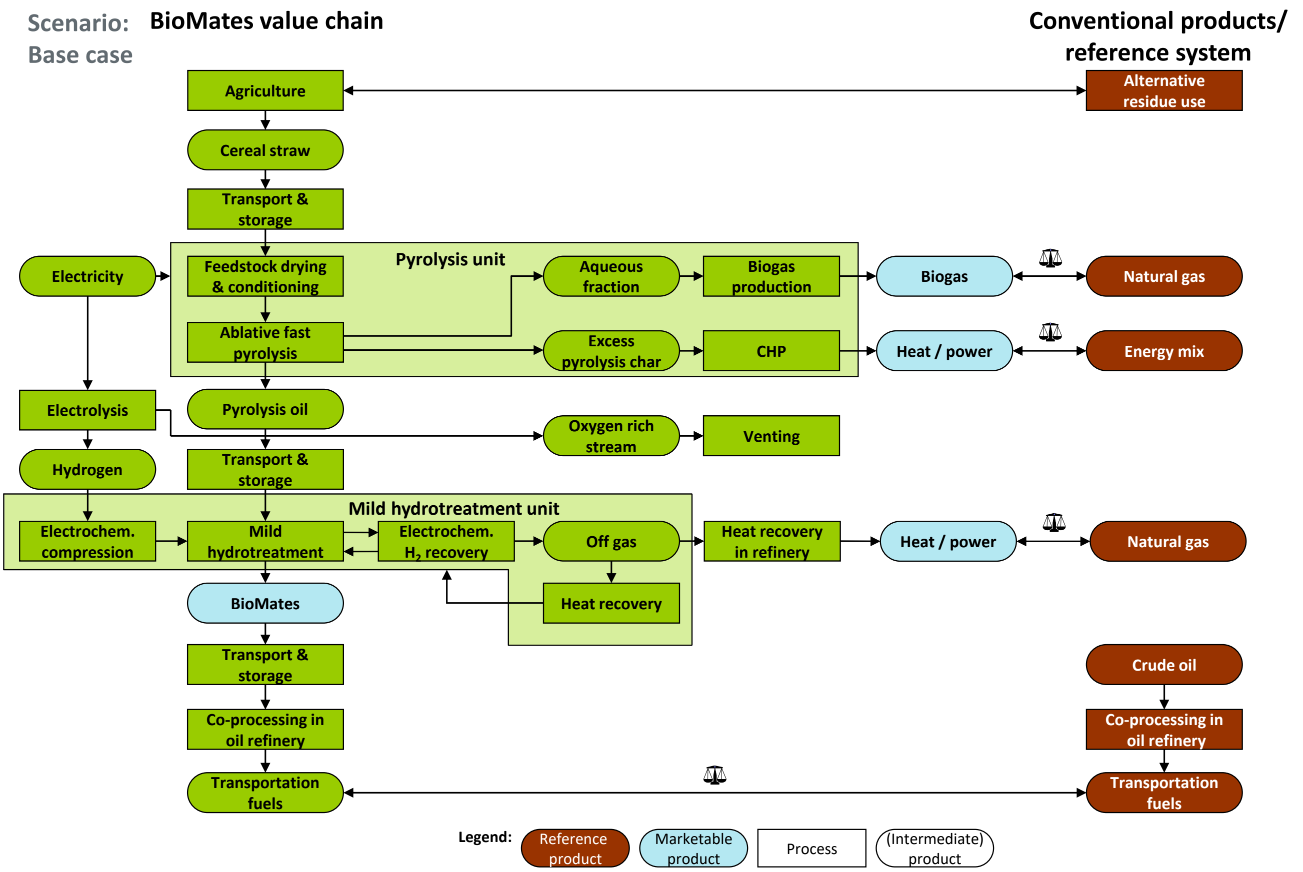


Figure 7: Life cycle scheme of the base case scenario

The following overall logistics concepts have been identified as promising options (see Figure 8):

- 1 HDT unit located at refinery, 1 AFP unit located at HDT, 3 AFP units distributed (base case)
- 1 HDT unit located at refinery, 4 AFP units distributed
- 1 HDT unit located close to biomass resources (=decentralised hydrotreatment), 1 AFP unit located at HDT unit, 3 additional AFP units distributed

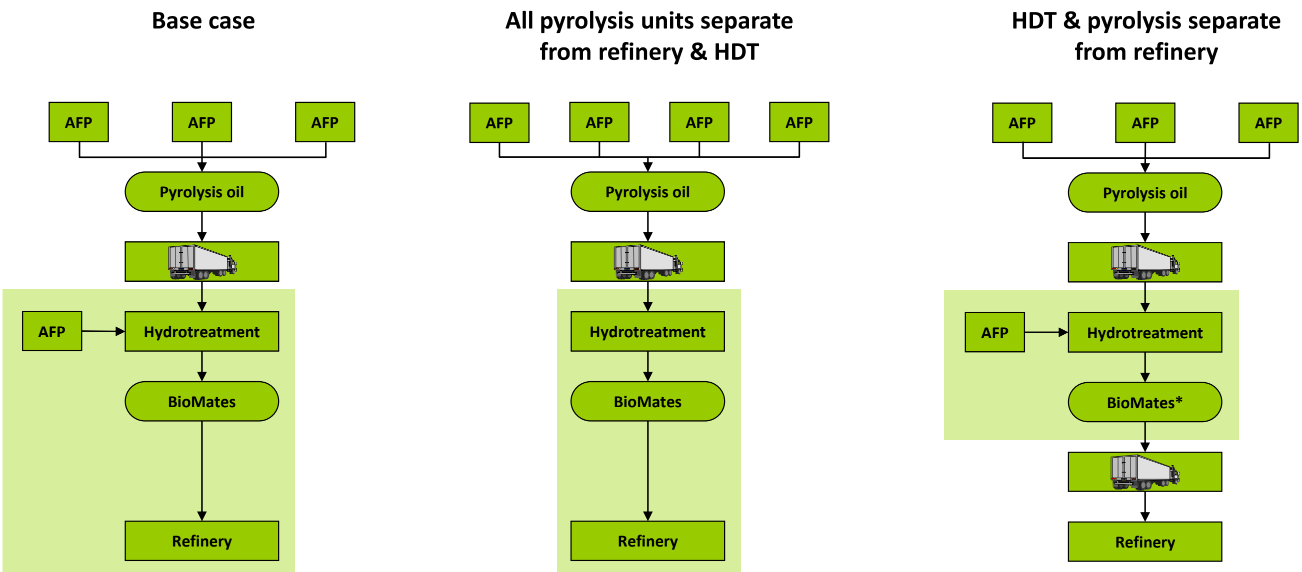


Figure 8: **Schemes of the three most promising logistics concepts. Light green boxes indicate co-located and, where applicable, integrated processes.**

5.1. Summary of scenarios

Many variants of processes are considered for each step of the value chain. This results in a very large number of possible scenarios. However, the big possible number of scenarios does not provide additional insight. Therefore, a base case scenario is chosen and all other process options are analysed by varying one process at a time based on the base case scenario (Table 4).

Table 4: **Overview of BioMates scenarios**

Scenario	Modification from base case
Base case	-
Miscanthus	Miscanthus replaces straw as biomass
Forest residues	Forest residues replace straw as biomass, no baling is required
All pyrolysis units separate from refinery & HDT	HDT and refinery are co-located, all pyrolysis units are separate, transportation from four pyrolysis units is required
HDT & pyrolysis separate from refinery	HDT and one pyrolysis units are co-located but separate from the refinery, transportation to refinery is required; off-gas from hydrogen recovery can only be used for energy recovery at HDT, the rest is flared
Disposal of aqueous phase	Aqueous phase from AFP is disposed and not used for biogas production
Pyrolysis char replaces coal/coke	Pyrolysis char is sold to replace hard coal on the market
H_2 from natural gas	Hydrogen is produced through steam reforming of natural gas instead of electrolysis, no oxygen is produced (see annex, Figure 23)
H_2 electrolysis using grid power mix	Hydrogen is produced through electrolysis from grid power mix instead of own renewable power
Mechanical H_2 compression	Hydrogen is compressed mechanically instead of electrochemically at the HDT
Mechanical H_2 recovery	Hydrogen is recovered mechanically instead of electrochemically at the HDT
O_2 use	Oxygen is purified and sold to replace oxygen on the market instead of venting (see annex, Figure 24)

5.2. Reference systems

Product reference systems

Only combustion engine fuels are considered as reference systems for detailed calculations because the project mainly aims at replacing fossil fuels.

The reference is the fossil reference system. This is the conventional process from crude petroleum coming from a well by different (consecutive) means of transport to a petroleum refinery, where it is processed to diesel, gasoline, jet and bunker fuel together with all other refinery products.

Electric mobility is not used as reference system because there will be many applications in which e-mobility will not be a solution for a long time such as aviation and marine transportation. Thus, a comparison to combustion engine fuels is much more helpful for the decision-makers addressed by our study.

Co-product reference systems

For co-products, the reference systems presented in Table 5 are considered.

Table 5: Co-product reference systems to be assessed. Bold print: base case to be considered first.

Process/product	Variants	Reference product
Excess PyCoke	**1. Energy use elsewhere** 2. Material use elsewhere	1. Energy mix 2. Coal/coke
Excess off-gas from the hydrogen recovery	**1. Energy recovery in adjacent refinery (if possible)** 2. Flaring	1. Natural gas 2. -
Oxygen from electrolysis	**1. Venting (base case)** 2. Sales after purification	1. - 2. O_2 from air (Linde process)

Resource use reference systems

If the amount of a certain resource that is available in any given year is limited, the use of this resource necessarily causes changes elsewhere in the economy or environment. Land use and biomass use are examples of such resource use that are relevant for BioMates. All land and biomass on the globe are used – if not by technical processes then by nature. Therefore, the consequences of land and biomass use have to be assessed.

In a first analysis (see section 6.1.2), besides the production of BioMates a competing use of the feedstock are taken into account. It is a typical use system for the feedstocks under consideration, **stationary heat and power production**:

- Combined heat and power (CHP) generation from lignocellulosic biomass

When used in this competing system, the feedstocks are dried to the extent necessary for combustion, transported to a steam turbine CHP plant and burned there.

Another assessment (section 6.1.8) compares BioMates to the production of other **biofuels** made from the lignocellulosic biomass residues under investigation or from crops grown on the fields otherwise cultivated for BioMates feedstock (here Miscanthus).

The following systems are investigated as alternatives for lignocellulosic biomass residue use:

- 2nd generation bioethanol
- 2nd generation BtL (Fischer-Tropsch diesel)

The following systems are assessed as alternatives for land use needed to produce cultivated biomass such as Miscanthus:

- 1st generation biodiesel (fatty acid methyl ester, FAME) from rapeseed
- 1st generation bioethanol from wheat grain
- 1st generation bioethanol from sugar beet

The first two systems produce liquid fuels (bioethanol and Fischer-Tropsch diesel, respectively) from the same agricultural residue straw. Therefore they are directly competing for the feedstock. As in the BioMates process straw is collected in the field and transported to a storage location, from where it is transported to a bioethanol units operating year-round. There it is hydrolysed using enzymes and the released sugars (only C6 sugars from cellulose or also C5 sugars from hemicellulose, depending on yeast strain) are further fermented to ethanol, which after distillation can be blended to the gasoline pool.

The next three systems produce 1st generation biofuels that compete like Miscanthus for agricultural land potentially used for food production. Rapeseed, wheat grain and sugar beet are harvested and stored temporarily. Whereas sugar beet is elaborated within a campaign lasting at maximum 3 months, wheat and rapeseed are processed all year long. Rapeseed is pressed in an oil mill, the oil is extracted from the rapeseed meal. The latter is used as animal feed, whereas the former is processed in a transesterification plant to fatty acid methyl ester. Wheat is treated in an ethanol plant by liquefaction, saccharification, fermenting and finally distillation to yield bio-ethanol. Sugar beet undergoes a similar process.

6. Results

The results of the environmental assessment are divided into three parts. The first section (6.1) related to the screening life cycle assessment, followed by the life cycle environmental impact assessment in section 6.2. Finally, exemplary greenhouse gas balance according to RED II are presented in section 6.3.

6.1. Life cycle assessment

A screening life cycle assessment (LCA) was carried out for the selected BioMates scenarios described in chapter 5. In the following, the results are presented (for details on the methods see sections 4.1 / 4.2). The results of the base case scenario are presented in section 6.1.1. After that, the influence of selected scenario parameter variations is evaluated in sections 6.1.2 to 6.1.6, followed by and an overview of all investigated scenarios in section 6.1.7. Finally, the base case scenario is compared to other biofuels (section 6.1.8).

6.1.1. Base case scenario

In this section, the results of the screening LCA for the base case scenario are presented in Figure 9.

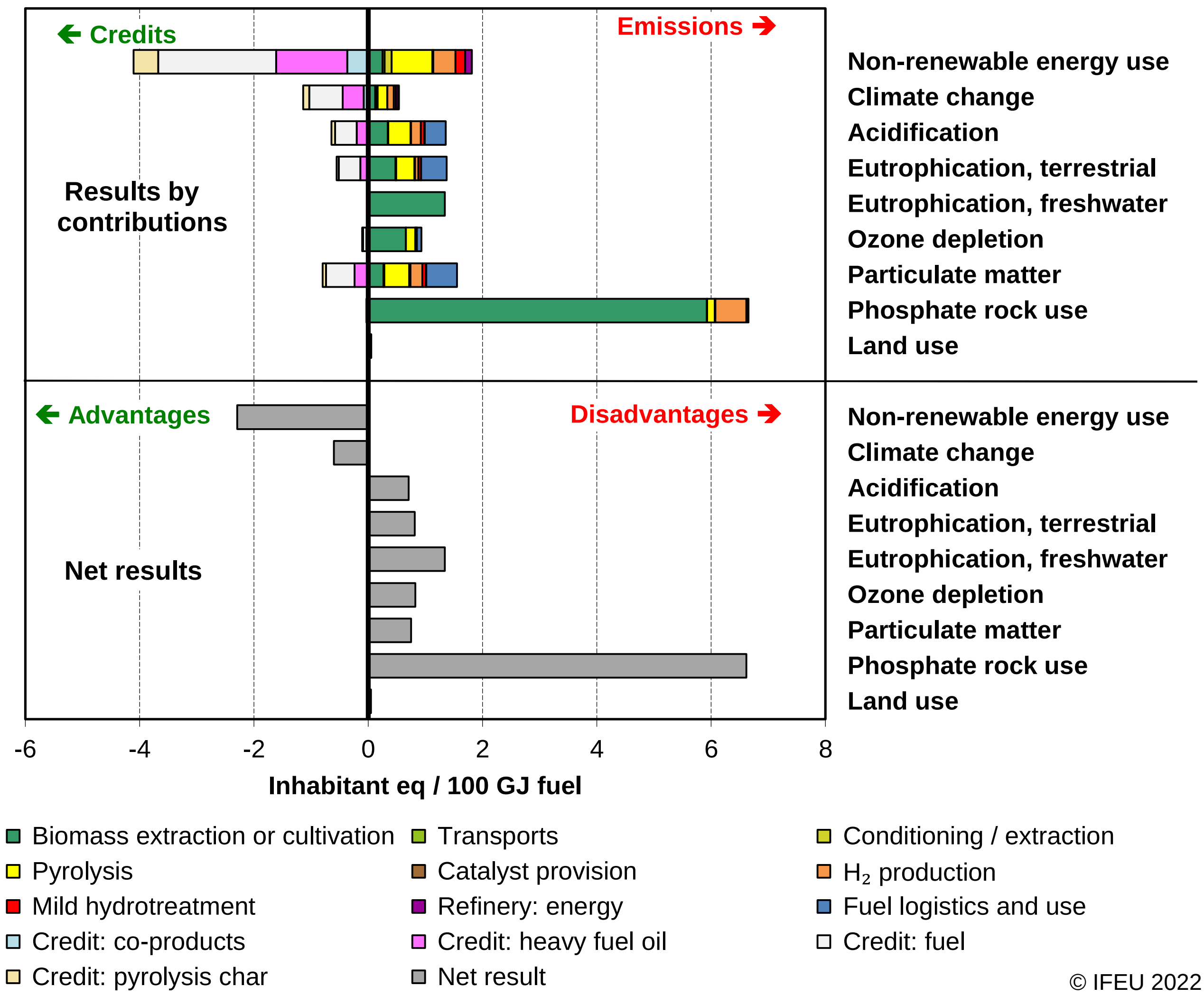


Figure 9: Normalised LCA results (given in inhabitant equivalents) for all impact categories for the BioMates base case scenario compared to those of conventional refinery products. Upper panel: results by contributions of individual life cycle steps. Lower panel: net results.
How to read the figure: The 2nd bar in the lower panel illustrates that replacing 100 GJ conventional fuels by the same amount of BioMates in the base case saves GHG emissions equal to the average annual GHG emissions of about 0.6 EU inhabitants (around 5.5 t CO_2 eq).

Results

- The production and use of BioMates (base case scenario) instead of conventional fuels shows environmental advantages and disadvantages within the scope of the environmental impact categories considered.
- Different life stage phases have different levels of influence on the various environmental impact categories.
- Net advantages of the BioMates fuel over conventional fuels could be expected for the BioMates base case in terms of non-renewable energy use and climate change (GHG emissions). Net disadvantages can be expected for instance in terms of phosphate rock use.

The processes developed within the BioMates project feature immature technology readiness levels (TRL), mainly TRL 4 and TRL 5. However, the LCA is conducted for scenarios representing mature technology on industrial scale (‘n^{th} plant’), as explained in section 4.1.2. To accommodate the inherent uncertainty regarding possible future technology developments, value ranges from ‘optimistic’ via ‘typical’ to ‘conservative’ are used. While in Figure 9, the LCA results are displayed for the ‘typical’ technology development scenario and *all* environmental impact categories, Figure 10 illustrates the results for all three technology developments for *one* impact category: ‘climate change’.

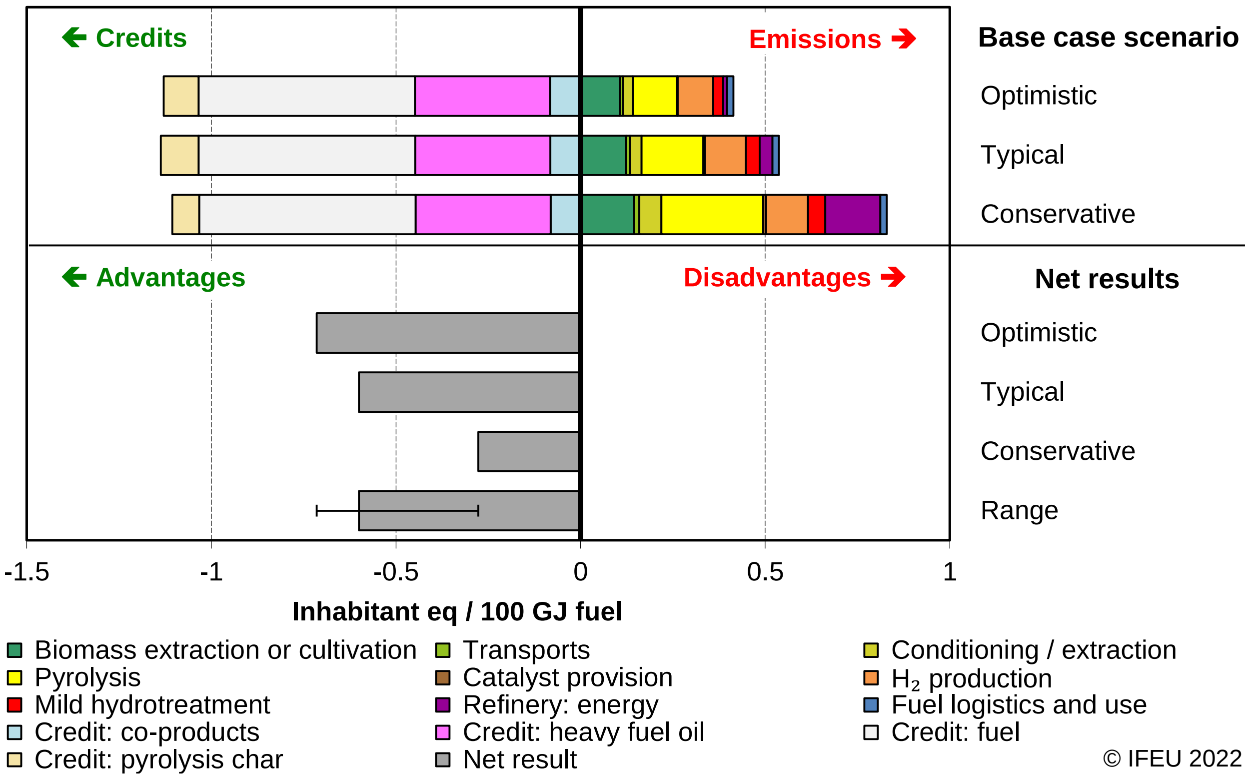


Figure 10: **Life cycle GHG emissions (given in inhabitant equivalents) for the BioMates base case scenario compared to conventional refinery products for three technology developments. Upper panel: results by contributions of individual life cycle steps. Lower panel: net results.**
How to read the figure: The 2^{nd} bar in the lower panel illustrates that replacing 100 GJ conventional fuels by the same amount of BioMates in the base case (typical technology development) saves GHG emission equal to the average annual emissions of about 0.6 EU inhabitants (around 5.5 t CO_2 eq).

Results

- The bars indicate result ranges based on sub-scenarios under conservative, typical and optimistic boundary conditions.

- Differences mainly originate from a range of possible process efficiencies that could result from future technology development and upscaling. This affects the amount of GHG emissions in several life cycle phases, as well as the net results.
- The differences between conservative and optimistic technology development are the greatest for the pyrolysis process.

Taking up the result ranges (due to unpredictable future technology developments) introduced in Figure 10, Figure 11 shows the corresponding result ranges for *all* investigated environmental impact categories.

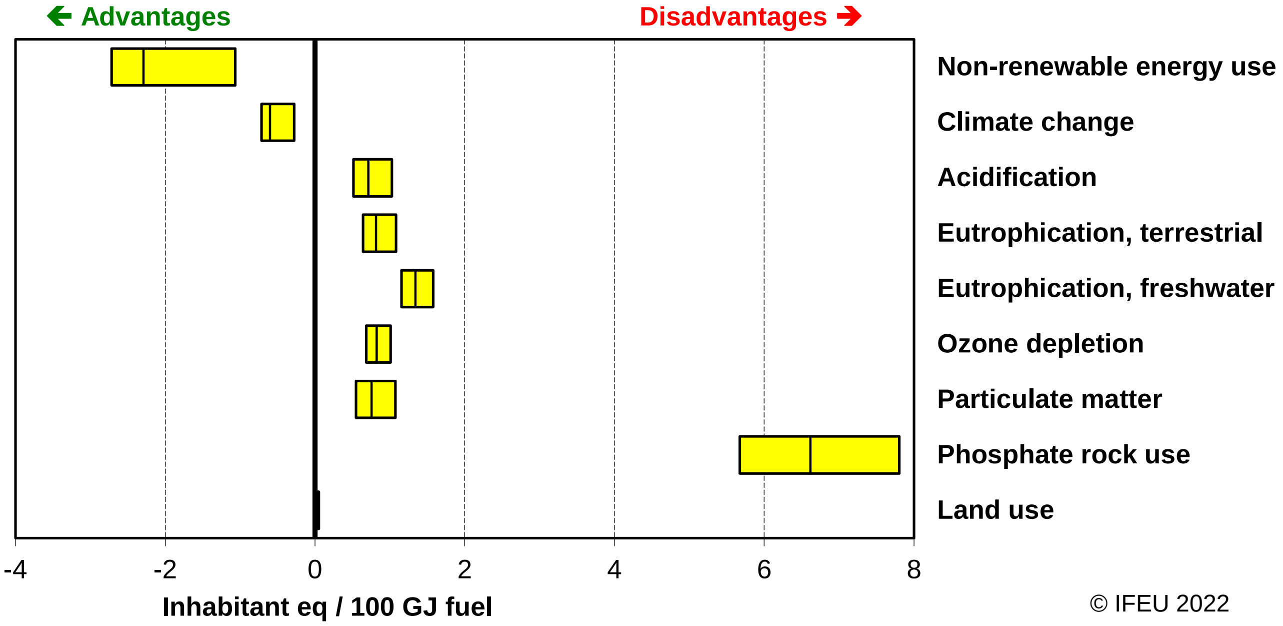


Figure 11: **Ranges of LCA results (given in inhabitant equivalents) for all impact categories for the BioMates base case scenario compared to those of conventional fuels. The bars show the results for three possible technology developments.**
How to read the figure: The 3rd bar illustrates that replacing 100 GJ conventional fuels by the same amount of BioMates in the base case leads to additional acidification in the range of the average annual emissions of 0.5 to one EU inhabitant (around 18 to 36 kg SO_2 eq).

Results

- The environmental impact categories show different ranges for the possible technological developments. This range is particularly wide for non-renewable energy use and phosphate rock use. These also show the greatest advantages and disadvantages in absolute terms.

Key findings

- The BioMates base case scenario shows environmental advantages and disadvantages compared to conventional fuels. Whereas in this scenario, the use of BioMates instead of fossil fuels certainly saves non-renewable energies and greenhouse gas emissions, other environmental impacts are worse with respect to fossil fuels.
- Life cycle stages contribute to the results of each impact category to different degrees.
- The inherent uncertainty regarding the future technology development of the pyrolysis process is responsible for most of the range of results. The pyrolysis process has the greatest potential to improve LCA results.

6.1.2. Biomass input

Screening LCA results for different biomass inputs to the BioMates production are presented in Figure 12. These are straw (base case), Miscanthus and forest residues, as described in chapter 5 (for details on the methods see sections 4.1 / 4.2).

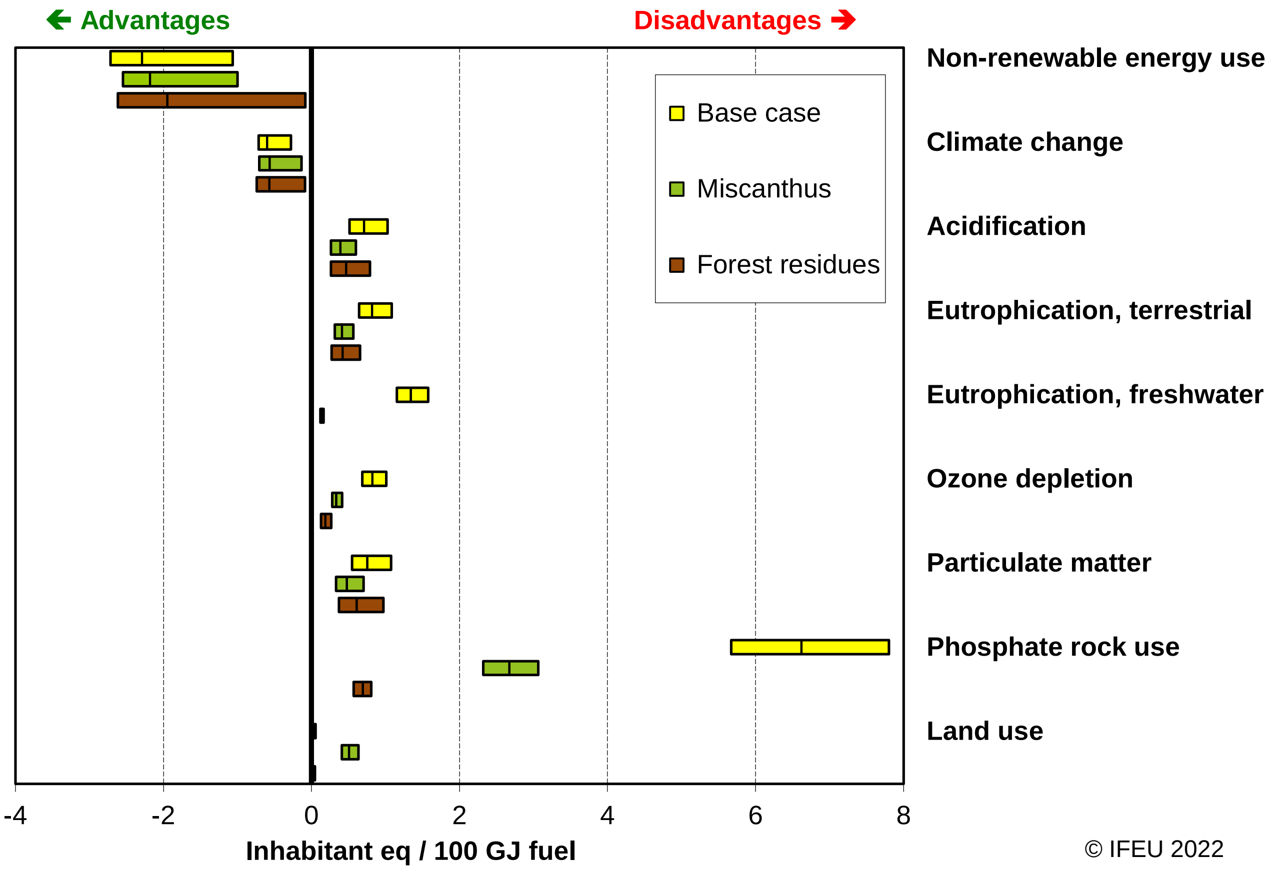


Figure 12: **Ranges of LCA results for the base case with straw, Miscanthus and forest residues as biomass input for all environmental impact categories from conservative to optimistic.**
How to read the figure: The 2nd bar from the top illustrates that replacing 100 GJ conventional fuels by the same amount of BioMates made from Miscanthus saves non-renewable energy equal to the average annual non-renewable energy demand of about 1.0 to 2.5 EU inhabitants (around 34 to 88 GJ).

Results

- In many environmental impact categories, the use of forest residues for BioMates fuels performs best in comparison of the three biomass feedstocks (exceptions: non-renewable energy use, acidification and particulate matter). On the other hand, the use of straw has more disadvantages than the other biomasses (except for land use, climate change and non-renewable energy use).
- The different biomasses show partly similar, partly strongly different result ranges in the future technological development.

Figure 12 above considers that all the biomass is provided only for BioMates – otherwise it would remain on the field (straw), in the forest (residues) or would not be produced at all (Miscanthus). Figure 13 gives answers to the question what happens if the BioMates production and another energy production (combined heat/power, CHP) compete for the same biomass. It shows screening LCA results for the case of different biomass inputs to the BioMates production as before and in case the biomass would otherwise be used for CHP production.

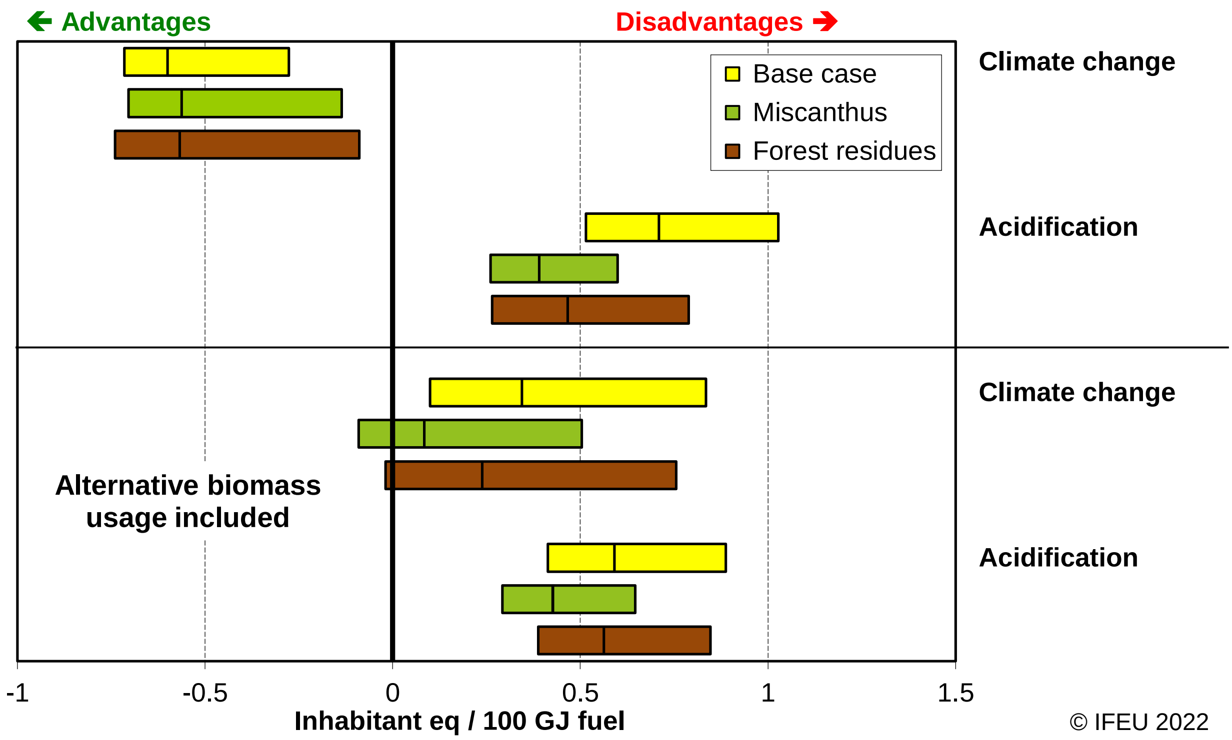


Figure 13: **Ranges of LCA results for the base case (straw), Miscanthus and forest residues as biomass input for selected environmental impact categories from conservative to optimistic. Upper/lower panel: without/with competition for biomass feedstocks. Assessed indirect effects of competition include forgone emission savings by withdrawal of biomass from CHPs.**
How to read the figure: The 2nd bar from the lower panel illustrates that replacing 100 GJ conventional fuels by the same amount of BioMates made from Miscanthus may lead to saved or additional GHG emissions equal to the average annual GHG emissions of up to 0.1 EU inhabitants (saved; around 0.8 t CO_2 eq) or up to 0.5 EU inhabitants (additional; around 4.6 t CO_2 eq)– if alternative biomass use is included and depending on the boundary conditions.

Results

- If alternative biomass use is taken into account, advantages of environmental impact categories might turn into disadvantages (e.g. in terms of climate change impact). In terms of acidification, a slight increase of disadvantages can be spotted.

Key findings

- BioMates fuel production from different feedstocks shows small differences for non-renewable energy use and climate change and significant differences for many other impact categories.
- The use of biomass for BioMates fuels to replace fossil fuels is similarly advantageous for the environment as combusting the same biomass instead for heat and power generation.
- Depending on the technology development, the replaced energy carriers and other boundary conditions, the results can be slightly in favour of BioMates or of the alternative biomass use.
- Most other impact categories (not displayed here) are (slightly) less disadvantageous if compared to CHP production.
- As long as biomass CHPs are still needed to replace fossil electricity and heat provision, any competing use of combustible biomass to be implemented on a large scale needs to achieve very high emission reductions to be environmentally more competitive. This cannot be achieved by BioMates. Therefore, only unused biomass residues and land should be used for BioMates.

6.1.3. Logistic scenarios

Screening LCA results for different logistics scenarios as described in chapter 5 are presented Figure 14 (for details on the methods see sections 4.1 / 4.2).

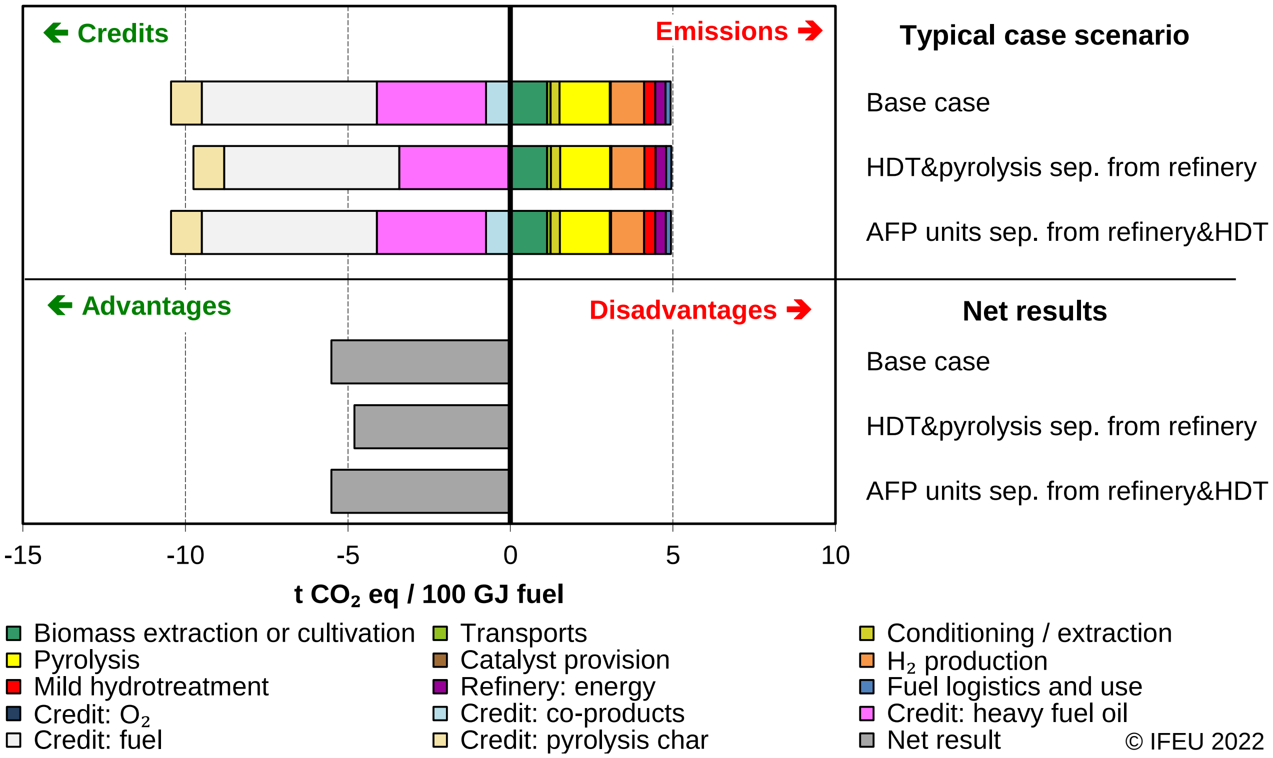


Figure 14: **LCA results (given in t CO_2 eq) for impact category: climate change. The base case scenario is compared to the scenarios HDT & pyrolysis separate from refinery and pyrolysis units (AFP) separate from refinery & HDT, which contain different logistics. Upper panel: results by contributions of individual life cycle steps. Lower panel: net results.**
How to read the figure: The 2nd bar in the lower panel illustrates that replacing 100 GJ conventional fuels by the same amount of BioMates, which is produced spatially separated from a refinery, saves GHG emissions of around 4.8 t CO_2 eq.

Results

- The second scenario with HDT and pyrolysis units separated from the refinery shows slightly less advantages. This is due to the lacking energy consumer (refinery) for the off-gases and waste heat from the pyrolysis process.

Key findings

- In environmental terms, there are only small differences between the different logistics options.
- If the pyrolysis units (AFP units) are all separate from the hydrogenation unit (HDT) and refinery, the differences to the base case are marginal.
- If the HDT and pyrolysis units are all separate from the refinery, this is clearly but only to a minor extent disadvantageous regarding all environmental impact categories. This is due to the fact that the off-gas from the hydrogenation cannot be used completely when away from large consumers of gas or heat energy.
- In order to optimize the process, the hydrogenation unit of a BioMates system should be near a refinery or another large consumer of gas or heat energy. However, optimizing the pyrolysis process has more potential for GHG gas savings than placing the hydrogenation unit near the refinery.

6.1.4. Hydrogen and electricity provision

Screening LCA results for different hydrogen (H_2) and electricity provision scenarios as described in chapter 5 are presented in Figure 15 (for details on the methods see sections 4.1 / 4.2).

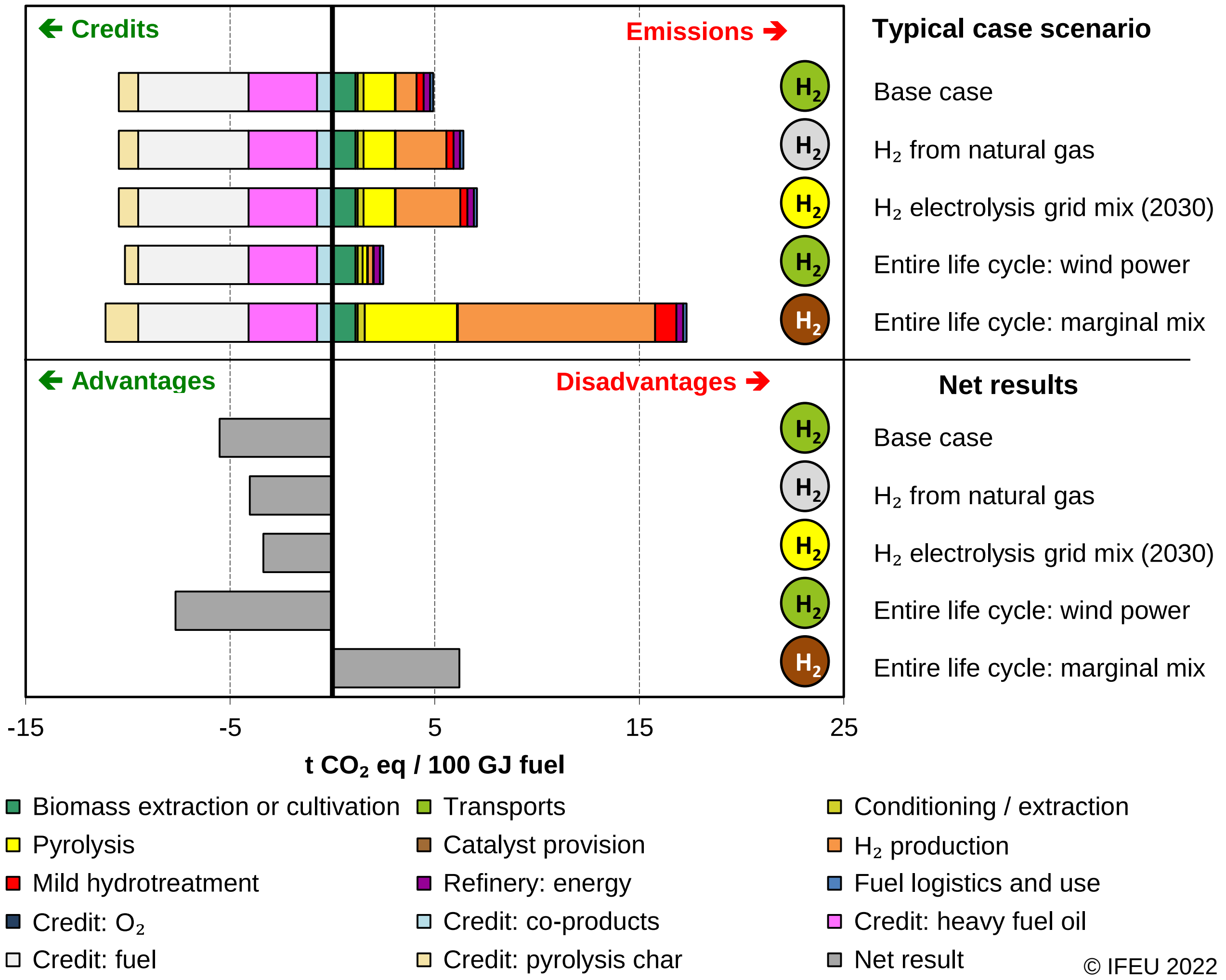


Figure 15: **Climate change (given in t CO_2 eq) for the scenarios base case (H_2 from PV power, rest from EU mix), H_2 from natural gas, H_2 electrolysis using grid mix power, wind power or a marginal mix in the entire life cycle. Upper panel: results by contributions of individual life cycle steps. Lower panel: net results.** How to read the figure: The 2nd bar in the lower panel shows that replacing 100 GJ conventional fuels by the same amount of BioMates produced with H_2 from natural gas, saves around 4 t CO_2 eq GHG emissions.

Key findings

- The source of the hydrogen used for producing BioMates fuels has a decisive impact on the environmental performance. This determines whether the net results show advantages or disadvantages.
- Using "green hydrogen" (produced in electrolysis using electricity from renewable sources) saves the highest amounts of greenhouse gases. Possible sources can be additional photovoltaics or wind power. Wind power is to be preferred in terms of the environmental impacts investigated here.
- If the production of BioMates fuel is not combined with an additional production of electricity from renewable energies, but leads only to an increased consumption of fossil energies in power production (also for other uses than BioMates), this causes overall additional emissions of greenhouse gases.

6.1.5. Hydrogen compression and recovery

In Figure 16 the screening LCA results are depicted for a comparison between the base case (electrochemical compression and recovery), mechanical H_2 compression and mechanical H_2 recovery – electrochemical in the respective other process. For details on the scenarios and methods, see chapter 5 and sections 4.1 / 4.2, respectively.

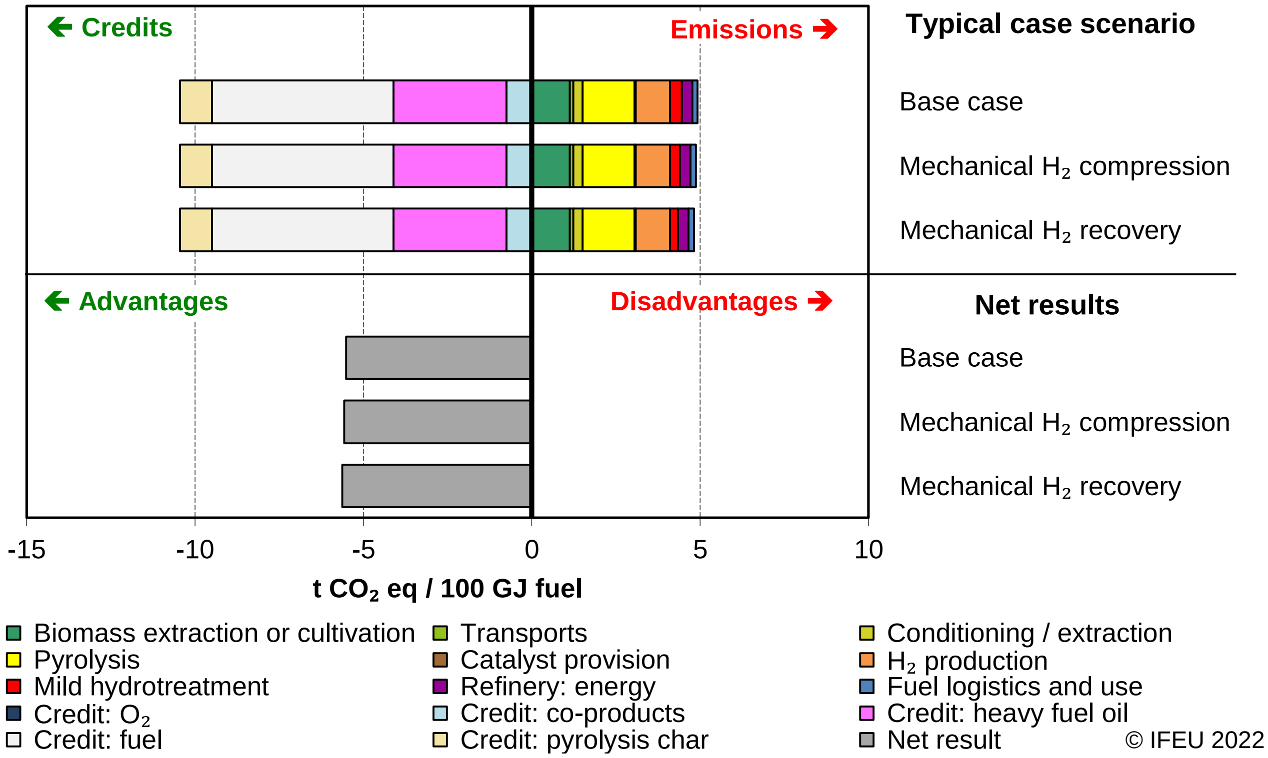


Figure 16: **LCA results (given in t CO_2 eq) for the scenarios base case, mechanical H_2 compression and mechanical H_2 recovery for impact category climate change. Upper panel: results by contributions of individual life cycle steps. Lower panel: net results.**
How to read the figure: The 2nd bar in the lower panel illustrates that replacing 100 GJ conventional fuels by the same amount of BioMates produced with mechanical H_2 compression, saves GHG emissions of around 5.6 t CO_2 eq.

Results

- There are nearly no differences in the results for the environmental impact category climate change when comparing the different options for H_2 compression and recovery. The type of compression and recovery technology does not change significantly the GHG balance of the BioMates process.

Key findings

- The different options of hydrogen compression and recovery in the hydrotreatment unit hardly show any differences in their environmental outcome. This holds true also for environmental impact categories other than climate change (not displayed in the figure).
- Which kind of hydrogen compression and recovery is used does not play a role in the BioMates life cycle. However, the focus of development should be on the optimisation of the pyrolysis process and the hydrogen production.

6.1.6. Co-product use

Screening LCA results for different co-product use scenarios as described in chapter 5 are presented in Figure 17 (for details on the methods see sections 4.1 / 4.2).

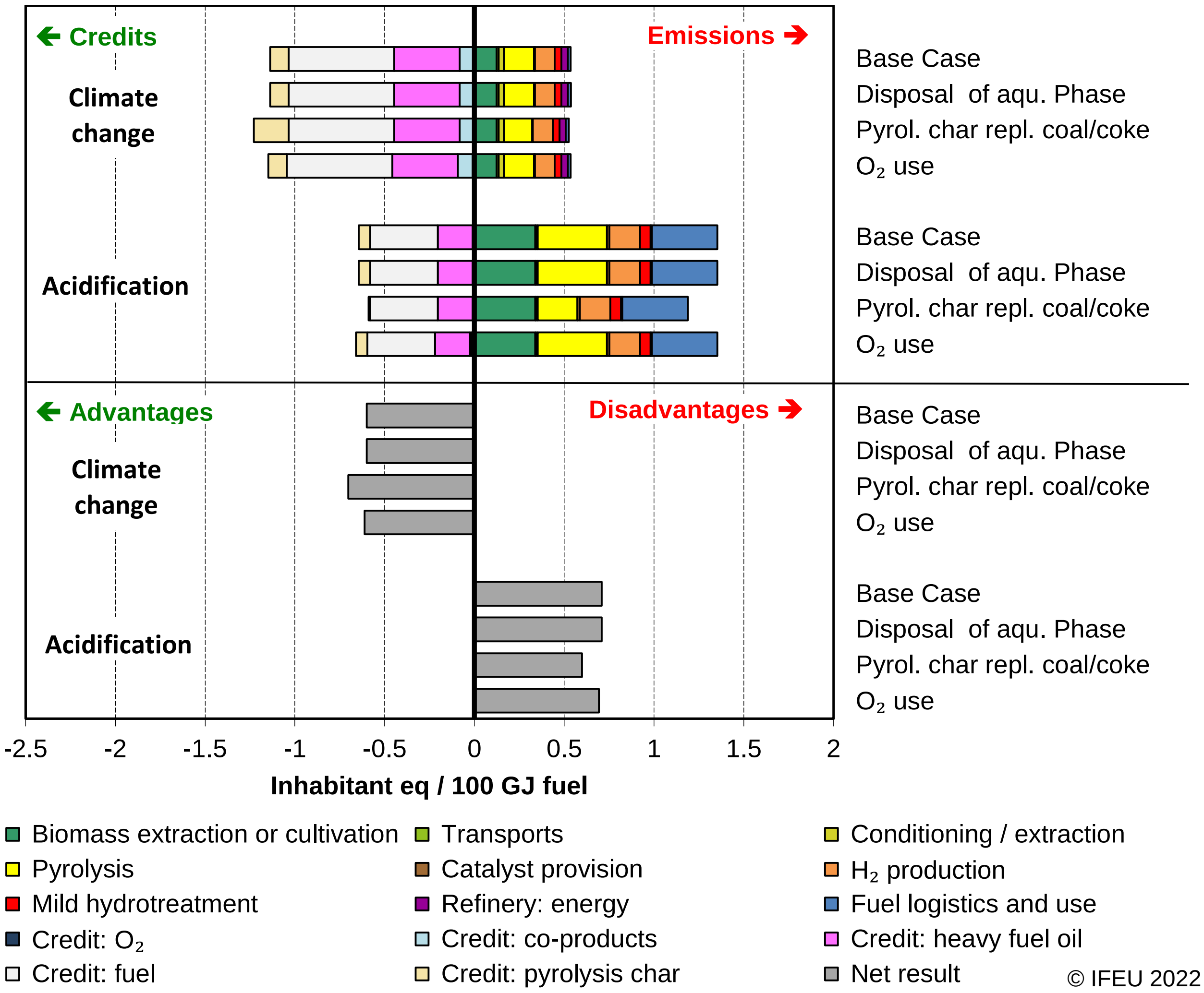


Figure 17: **LCA results (given in inhabitant equivalents) for scenarios with different uses of co-products from the BioMates production for selected impact categories (climate change and acidification). The base case scenario is compared to the scenarios: disposal of aqueous phase, pyrolysis char replaces coal/coke and O_2 use. Upper panel: results by contributions of individual life cycle steps. Lower panel: net results.** How to read the figure: The 2nd bar in the lower panel illustrates that replacing 100 GJ conventional fuels by the same amount of BioMates, including the disposal of aqueous phase, saves GHG emissions equal to the average annual GHG emissions of about 0.6 EU inhabitants (around 5.2 t CO_2 eq).

Key findings

- In many cases, using the co-products of the BioMates processes in one way or another does not change the environmental outcome significantly. This is the case for the fate of the aqueous phase from pyrolysis and for the use of oxygen from electrolysis.
- Regarding the pyrolysis char, the replacement of coal or coke is advantageous with respect to the replacement of electricity from the grid and heat from fossil fuels. This is the case also for other environmental impact categories.
- The use of pyrolysis char replacing directly a carbon-rich fossil fuel can enhance the environmental impact significantly with respect to electricity and/or heat production replacing grid/fossil fuel mix.

6.1.7. Overview of scenarios

Figure 18 shows the results of the screening LCAs for all BioMates scenarios described in chapter 5 for selected environmental impact categories. Ranges are spanned by conservative to optimistic variations of the scenarios' technology developments. The vertical black line inside the bars marks the scenario that is considered typical.

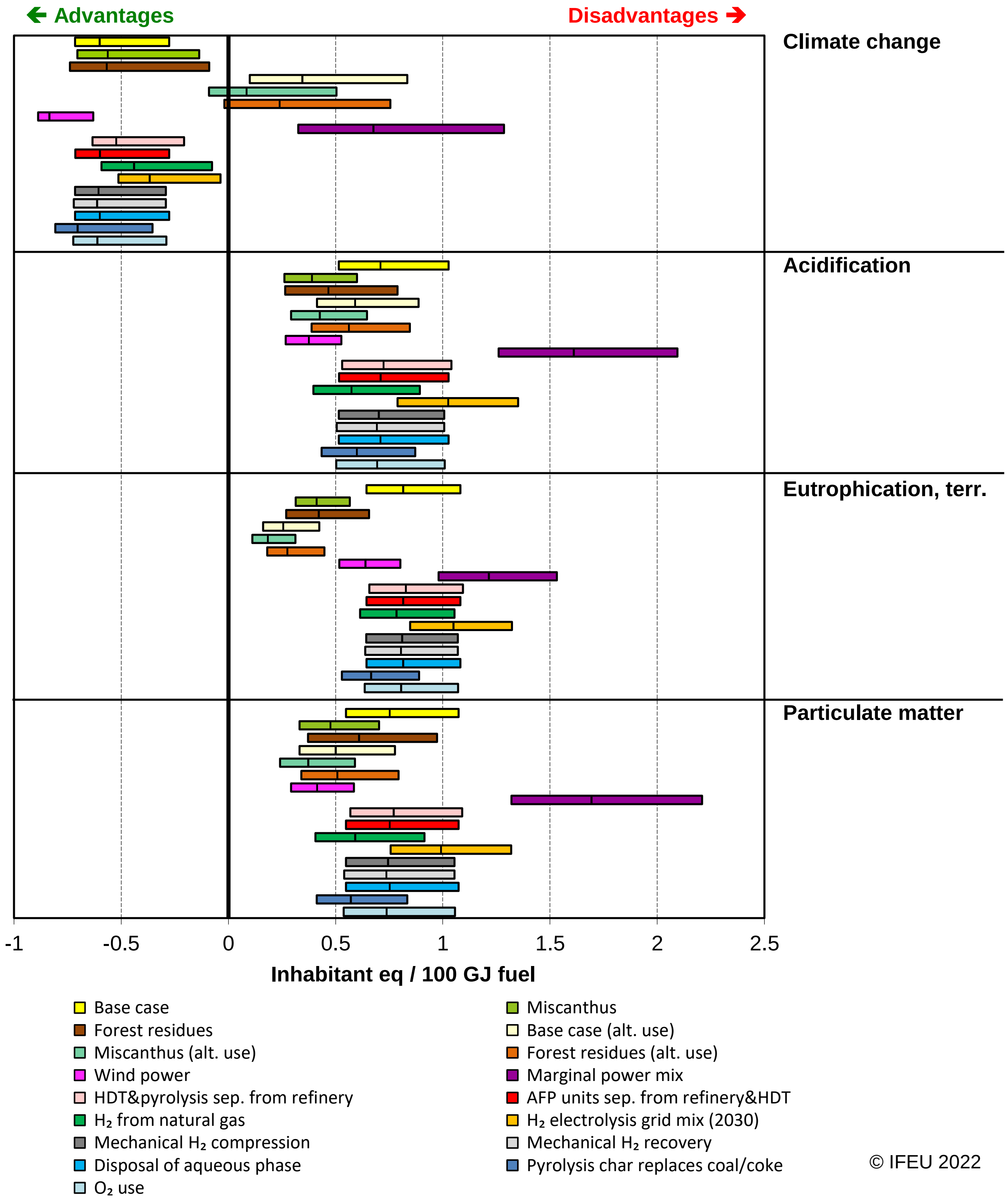


Figure 18: Ranges of LCA results (given in inhabitant equivalents) for all scenarios and selected environmental impact categories from conservative to optimistic.
How to read the figure: The 3rd bar from the top illustrates that replacing 100 GJ conventional fuels by the same amount of BioMates made from forest residues saves GHG emissions equal to the average annual GHG emissions of about 0.1 to 0.7 EU inhabitants (around 2.5 to 6.6 t CO_2 eq).

Results

- For all scenarios, the typical technology development is closer to the optimistic case than to the conservative one.

Key findings

- There are several factors influencing strongly the environmental performance of the BioMates system: which biomass input, hydrogen production and electricity source is used and how the pyrolysis char is used. Forest residues, hydrogen and electricity production from renewable sources and pyrolysis char replacing coal/coke perform best.
- Regarding the biomass input, it is important whether the biomass would (or could) otherwise be used for another form of energy provision or in such case would not be harvested/cultivated. The latter performs best with respect to climate change and non-renewable energy use.
- It is not possible to establish a BioMates system without some environmental impacts turning worse than before. However, to achieve savings at least in some environmental impacts, a BioMates system should consume biomass that otherwise would not be in use and utilise (at least to a certain extent) electricity from renewable sources that without BioMates would not be accessed.

6.1.8. Comparison with biofuels

Screening LCA results for the base case of the BioMates value chain compared to five biofuels are presented in Figure 19 and Figure 20 (for details on the methods see sections 4.1 / 4.2).

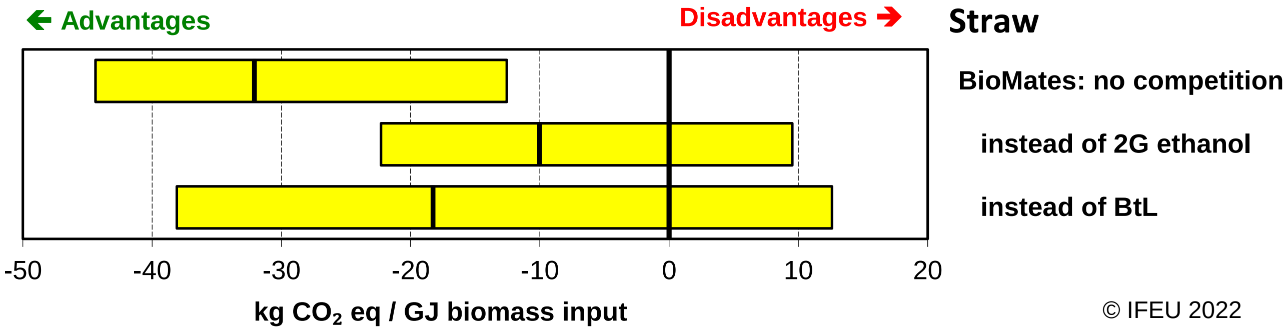


Figure 19: **LCA results (given in kg CO_2 eq) for the base case scenario using straw as biomass feedstock (without competition) and scenarios comparing the base case scenario to other biofuels (2G ethanol and BtL).**
How to read the figure: The 2nd bar from the top illustrates that replacing 2G ethanol from 1 GJ of biomass input by BioMates fuel from the same biomass amount may lead to either saved or additional GHG emissions of around 22 (saved) to 9.5 kg CO_2 eq (additional).

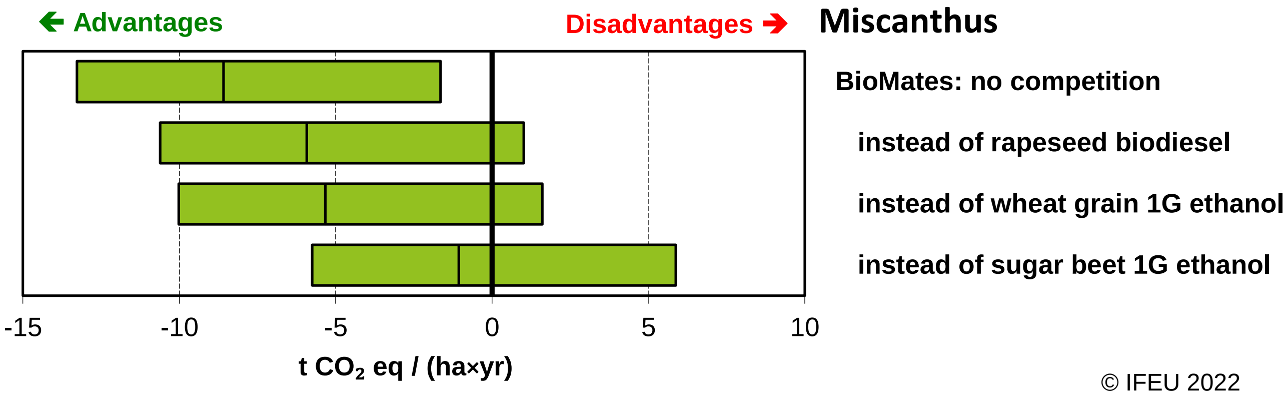


Figure 20: **LCA results (given in t CO_2 eq) for the base case scenario using miscanthus as biomass feedstock (without competition) and scenarios comparing the base case scenario to other biofuels (rapeseed biodiesel, wheat grain 1G ethanol, sugar beet 1G ethanol).**
How to read the figure: The 2nd bar from the top illustrates that replacing rapeseed biodiesel with BioMates fuel produced on 1 ha in one year each, may lead to either saved or additional GHG emissions of around 11 (saved) to 1 t CO_2 eq (additional).

Key findings

- A BioMates system saves greenhouse gas emissions not only with respect to fossil fuels, but generally also with respect to other biofuels. However, the savings are much lower.
- This is valid at least for the scenarios where a significant part of the electricity demand for the BioMates production stems from dedicated renewable sources and where the technology development is at least "typical".
- In other environmental impacts (not displayed here) BioMates fuel has disadvantages with respect to other biofuels, however these are lower than the disadvantages versus fossil fuels.

6.2. Life cycle environmental impact assessment

Local environmental impacts associated with the BioMates systems and conventional reference systems were studied following the life cycle environmental impact assessment (LC-EIA) methodology (see section 4.3). Section 6.2.1 focusses on the impacts of the BioMates systems whereas section 6.2.2 presents the impacts associated with the (conventional) reference systems. A comparison of all investigated systems is shown in section 6.2.3.

6.2.1. Local environmental impacts of the BioMates systems

Following the descriptions of the systems in chapter 5, the BioMates systems are divided into several life cycle stages. For the purpose of the LC-EIA, the following stages are evaluated:

- Biomass feedstock provision
- Biomass feedstock conversion

Biomass provision takes place in one location and biomass conversion is partly, spatially separated. Thus, intermediate transport and logistics steps are required.

Biomass feedstock provision

The production of BioMates can be based on lignocellulose biomass from residues and / or cultivated biomass. In the case of BioMates, residue feedstock mainly originates from agriculture, e.g. straw or other harvest co-products. Cultivated biomass is based on the energy crop Miscanthus from agriculture dedicated to energy production.

Provision of wheat / barley straw

Wheat / barley is grown on deep, heavy and nutrient-rich high quality soils and needs good drainage. Intensive agricultural use primarily leads to impacts on soil. Weed and pest control is obligatory, increasing the risk of soil compaction which is usually linked to negative aspects on the diversity of arable flora and epigeous fauna. Especially the young plants require application(s) of nitrogen fertiliser (app. 150 kg / ha) which increases the risk of nutrient leaching and eutrophication. Intensive cereal cultures are grown as monocultures and this generally leads to impacts on soil, water, plants / biotopes, animals and biodiversity.

Following the scenario of a potential use as BioMates product in a refinery it is assumed, that approx. 67% of the straw yield is left on the field as residues. This approach is sustainable as [Panoutsou et al. 2012] estimate that an export of 40% of straw in case of wheat and barley will maintain the carbon cycle.

In the reference system of conventional use it is assumed that 100% of the straw is left on the field and ploughed in the soil to maintain the soil organic carbon stock. Since both systems are sustainable, differences in impacts on the environmental factors between a conventional system (100% residues left on field) and the sustainable use of straw (approx. 33%, i.e. once every three years) in context with a use as BioMates product in a refinery are low. In case of intensified use of straw in the BioMates systems based on sustainable production conditions, the use of long-stalked cereal varieties might be increased thus leading to slightly positive effects for arable plants, since long-stalked varieties reduce the amount of pesticides necessary for weed control due to higher competitiveness. This might result in an increased number of animals linked to arable land (arthropods) and an increased biodiversity. Table 6 summarises the risks associated with the use of wheat / barley straw in the BioMates systems compared to no use of straw.

Table 6: Risks associated with the sustainable provision of straw from wheat / barley compared to the reference system of "straw left on field" (ploughing in)

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants / Biotopes	Animals	Climate / Air	Landscape	Human health & recreation	Bio-diversity
Soil erosion	neutral		neutral						
Soil compaction	neutral	neutral		neutral	neutral				neutral
Loss of soil organic matter	neutral			neutral	neutral				neutral
Soil chemistry / fertiliser	neutral	neutral							
Eutrophication	neutral	neutral	neutral	neutral	neutral				neutral
Nutrient leaching		neutral							
Water demand		neutral		neutral	neutral				neutral
Weed control / pesticides		neutral	neutral	neutral	neutral				neutral
Loss of landscape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				neutral / positive[1]	neutral / positive[1]				neutral / positive[1]
Loss of species				neutral / positive[1]	neutral / positive[1]				neutral / positive[1]

1: Positive in case of long-stalked varieties since less weed control is necessary

Provision of Miscanthus

As a fast growing culture Miscanthus is a promising energy crop. It can reach a high up to four meters in Central Europe and due to a high efficiency in photosynthesis (C4 metabolism) it is highly productive resulting in harvestable yields of 10-15 t DM / ha / year (on good soils up to 25 t, [Hartmann et al. 2011]). These yields represent about 65% of the total Miscanthus biomass production, as roots, stubbles and loss of leaves and other harvest residues stay on the field. Soil requirements are similar to maize preferring loose and deep soils. The plants are perennial with a life time of about 20 years and are quite robust. Reproduction occurs by means of vegetative propagation as no seeds are produced. High yield in root biomass result in net production of humus in the topsoil layer thus requiring very low needs of fertiliser and weed or pest control within the growth period. Due to low maintenance, Miscanthus can have positive effects on soil compaction compared to annual crops, e.g. maize.

Cultivation of Miscanthus is limited by the availability of groundwater. The huge water demand of Miscanthus may have local effects on groundwater levels. The impacts on plants / biotopes are expected to be negative as arable herbs might lose habitats due to perennial cultivation. Due to its high water demand, possible areas of cultivation include alluvial plains. Therefore and due to its vegetative propagation, Miscanthus might become invasive in alluvial areas.

The impacts of a Miscanthus plantation on landscape in comparison to non-rotational fallow land could be both negative and positive, depending on the local environmental conditions. A Miscanthus plantation in a flat arable area could be considered as a disturbance of the landscape, because the character of an open and wide landscape could change to a landscape segmented by stripes or patches of 4 m high plantations, which have visually a wall-like effect. But it can also increase the structural variety of a monotonous landscape, if the cultivation takes place in hedge like structures.

Miscanthus can increase the habitat diversity in intensively used regions, offering additional habitats for special types of plants and animals like epigeous arthropods (e.g. carabide beetles), especially as a refuge during winter time. Due to high water consumption and transpiration rates, Miscanthus plantations might slightly increase the local humidity thus offering special habitats for mosquitoes, slightly affecting climate and human health. Table 7 summarises the risks associated with cultivation of Miscanthus in comparison with non-rotational fallow land.

Table 7: **Risks associated with the cultivation of Miscanthus compared to the reference system non-rotational fallow land**

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants / Biotopes	Animals	Climate / Air	Landscape	Human health & recreation	Biodiversity
Soil erosion	neutral[1]		neutral[1]						
Soil compaction	positive[1]	neutral[1]		neutral[1]	neutral[1]				negative[2] / positive
Loss of soil organic matter	neutral[1]			neutral[1]	neutral[1]				neutral[1]
Soil chemistry / fertiliser	neutral[1]	neutral[1]	neutral[1]						
Eutrophication	neutral	neutral	neutral	neutral	neutral				neutral
Nutrient leaching	neutral[1]	neutral[1]							
Water demand		negative	neutral	negative					negative / positive
Weed control / pesticides		neutral[1]	neutral[1]	neutral[1]	neutral[1]				neutral
Loss of landscape elements				negative / positive	negative / positive	negative / positive	negative / positive	negative / positive	negative / positive
Loss of habitat types				neutral	neutral	neutral	neutral	neutral	Neutral
Loss of species				negative[2]	negative / positive				negative / positive

1: Regarding the total cultivation period of the crop; slightly negative in the first year

2: Negative due to risk of permanent impact on arable plants

Provision of forest residues

Forest productivity depends on soil quality and the availability of water resulting in regionally specific production rates. Since any use of wood is correlated with a loss of the ecosystem's nutrients, the intensity of forestry therefore has an effect on the sustainability issues. The main objective of forestry in central Europe is to keep the balance between growth and use of the system. Examples from literature indicate that an intensified use of the biomass can result in considerable losses in growth rates [Meiwes 2009].

Wood residues originate from harvesting (sawdust, break-of branches), the provision of stem wood (removal of tops and branches) and thinning. Amounts of available residues can vary quite a lot depending on the harvesting practice (use of harvester < motor-manual felling), physical relief of the woodland (the higher the slope the bigger the amount of residues) and the processing procedure (on site processing > processing on a centralised processing site).

Thinning is a process to remove especially younger trees allowing the remaining trees to maintain higher growth rates. Thinning material as well as wood residues usually is removed and sold, as there is a growing market (e.g. paper industry, firewood in case of the reference system). The demand for forestry residues is increasing and is expected to increase further in the future because of various decarbonisation strategies building on forestry residues.

As wood residues left on site (woody debris) are crucial for nature conservation and biodiversity an intensified use of wood residues is expected to affect the environmental factors of soil (decrease in soil organic matter) and biodiversity on the long term. Therefore, a no action scenario for a maximum of sustainability in forestry is leaving 100% of wood residues on site is positive for the environment. Compared to the reference system the use of wood residues is expected to have impacts on soil organic matter. In addition a lack of habitats especially for saproxylic animals (e.g. beetles) and other animals living on woody debris (e.g. wood bird like the Black woodpecker or bats) is expected on the long term. Table 8 summarises the risks associated with the use of forest residues in the BioMates systems compared to leaving them unused in the forest.

Table 8: **Risks associated with the provision of wood residues (forestry residues) compared to the reference system of leaving 100% of the biomass on-site.**

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants / Biotopes	Animals	Climate / Air	Landscape	Human health & recreation	Biodiversity
Soil erosion	neutral		neutral						
Soil compaction	neutral	neutral		neutral	neutral				neutral
Loss of soil organic matter	negative			neutral	negative				negative
Soil chemistry / fertiliser	negative	neutral	neutral		neutral				neutral
Eutrophication	neutral	neutral	neutral	neutral	neutral				neutral
Nutrient leaching	neutral	neutral							
Water demand		neutral	neutral	neutral					neutral
Weed control / pesticides		neutral	neutral	neutral	neutral				neutral
Loss of landscape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				negative	negative				negative
Loss of species				neutral	neutral				neutral

Subsequently, these risks were aggregated and categorised from A (low risk) to E (high risk), allowing a comparison of the BioMates feedstocks. The results are depicted in Table 9. Regarding straw there might be an increase in habitat diversity in case of a development towards the use of long-stalked varieties. Due to higher competition the amount of pesticides is expected to be less resulting in lower pressure on biodiversity. As Miscanthus is a perennial crop, cultivation is positive regarding soil compaction and availability of soil organic matter. Negative is an increased loss of habitat types and species. Uncontrolled propagation of Miscanthus (through rhizomes) could pose a risk, especially near nature conservation areas. An issue for both feedstocks could be the availability of water. Especially in areas with water scarcity during the dry season the need of irrigation could cause long term impacts on the environment [Doublet et al. 2012].

Table 9: Risks associated with the use of wheat / barley straw, forest residues and cultivation of Miscanthus compared to the respective reference system

How to read the table: Impacts are ranked into five comparative categories (A, B, C, D, E); "A" is assigned to the best options concerning the factor, "E" is assigned to unfavourable options concerning the factor.

<table>
<tr><th rowspan="2">Type of risk</th><th colspan="4">Feedstock</th></tr>
<tr><th colspan="2">Wheat / barley straw
Reference system: straw left on field (ploughing in)</th><th>Miscanthus
Reference system: non-rotational fallow land</th><th>Forest residues
Reference system: 100% left on site</th></tr>
<tr><td>Soil erosion</td><td colspan="2">C</td><td>B</td><td>C</td></tr>
<tr><td>Soil compaction</td><td colspan="2">C</td><td>B</td><td>C</td></tr>
<tr><td>Loss of soil organic matter</td><td colspan="2">C</td><td>B</td><td>D</td></tr>
<tr><td>Soil chemistry / fertiliser</td><td colspan="2">C</td><td>B</td><td>D</td></tr>
<tr><td>Eutrophication</td><td colspan="2">C</td><td>B</td><td>C</td></tr>
<tr><td>Nutrient leaching</td><td colspan="2">C</td><td>B</td><td>C</td></tr>
<tr><td>Water demand</td><td colspan="2">C</td><td>D</td><td>C</td></tr>
<tr><td>Weed control / pesticides</td><td colspan="2">C</td><td>B</td><td>C</td></tr>
<tr><td>Loss of landscape elements</td><td colspan="2">C</td><td>C</td><td>C</td></tr>
<tr><td>Loss of habitat types</td><td>B[1]</td><td>C</td><td>C</td><td>D</td></tr>
<tr><td>Loss of species</td><td>B[1]</td><td>C</td><td>C</td><td>D</td></tr>
</table>

1 In case of long-stalked varieties since less weed control is necessary

Key findings

- When comparing the two investigated biomass residues, the use of surplus cereal straw is rated largely neutral, meaning that low risks are associated with this feedstock. Using woody biomass, however, is connected with considerable risks in terms of soil nutrient and soil carbon balance and the forests' ability to act as a carbon sink and as a habitat for species.
- Miscanthus as a dedicated energy crop requires cropland for its cultivation which leads to land use-related impacts. These impacts can be neutral / positive (except impacts on water), if unused or abandoned land (non-rotational fallow land) is cultivated. However, if Miscanthus cultivation displaces an existing food or feed crop cultivation, this may - despite potential positive impacts of replacing an annual with a perennial crop - lead to negative impacts on the bottom line, due to the impacts of growing the displaced crop.
- Biomass feedstock provision from biomass residues and dedicated (perennial) crops must not be directly compared to each other since the respective reference systems are fundamentally different.

Transport and logistics

Transportation and distribution of biomass are mainly based on trucks and railway / ships with need of roads and tracks / channels. Depending on the location of the biomass conversion facility, there might be impacts resulting from the implementation of additional **transportation infrastructure**. In order to minimise transportation, it makes sense from an economic and ecological point of view to build the facility close to biomass production. Three different logistic designs in terms of distances from conversion facilities to biomass production and refinery are therefore considered in the BioMates scenarios. The biomass feedstock conversion is a two-step process with four AFP units and one HDT unit (for details see chapter 5, p. 20). If the AFP units and the HDT unit are separated from the refinery location, additional transportation is needed. As far as it is necessary to build additional roads, environmental impacts are expected on soil (due to sealing effects), water (reduced infiltration), plants, animals and biodiversity (loss of habitats, individuals and species, disturbance by moving vehicles).

Storage facilities for biomass can either be constructed at the site of biomass provision (decentralised storage on the field margin) and / or at the site of biomass conversion (at the site of the AFP unit). In any case, additional buildings cause sealing and compaction of soil, loss of habitats (plants, animals) and biodiversity as well as reduced groundwater infiltration.

Overall, the impacts associated with transportation and logistics are not expected to be significant.

Biomass feedstock conversion

Biomass conversion and provision is done in biomass conversion facilities. In the case of the BioMates systems four AFP units and one HDT unit are necessary to be built for production of lignocellulosic-based intermediates. Hence the lignocellulosic-based intermediates are co-processed in an existing refinery, no additional area is sealed for refining, only facilities of the HDT and the AFP are built. The local environmental impacts from implementation of the BioMates systems are considered to be smaller than putting a full new (bio-) refinery into operation.

Impacts are expected from:

- the construction of the facilities,
- the facilities themselves: buildings, infrastructure and installations and
- the operation of the facilities.

Impacts related to the **construction of the facility** are temporary and not considered to be significant.

Biomass conversion facilities need **buildings, infrastructure and installations**, which are usually associated with soil sealing. In most of the scenarios (with one exception) the HDT is built on the refinery area and no additional soil needs to be sealed. Differences are expected regarding the AFP facility's location, depending on whether the project is developed on a greenfield site or on a brownfield site:

- A greenfield site is land currently used for agriculture or (semi)natural ecosystems left to evolve naturally.
- A brownfield site is land that was previously used for industrial, commercial or military purposes (often with known or suspected contamination) and is not currently used. Most of the area is expected to be already sealed and traffic infrastructure might (at least partly) be available.

The HDT unit and partly the AFP units are very likely built on a brownfield site (dependent on the respective transportation scenario, see chapter 5, p. 20). A greenfield-scenario for some AFPs cannot be excluded entirely on rural sites.

Other impacts might vary in quantity but not in quality, which in case of a generic approach on potential environmental impacts of technologies is negligible. Significant impacts are expected on water, soil, plants, animals and landscape and are highly dependent on local conditions.

Impacts from the **operation of the facility** are expected from:

- emission of noise
- emissions of gases and particulate matter
- drain of water resources for production
- waste water production and treatment
- traffic (collision risks, emissions)
- electromagnetic emissions
- risk of accidents (explosion, fire in the facility or storage areas)

Significance of impacts might vary with the type of technology and the location of a potential facility. This variability cannot be taken into account by this generic LC-EIA. Moreover, this LC-EIA cannot replace a full-scale EIA according to Directive 2014/52/EU [European Parliament & Council of the European Union 2014].

Key finding

- Local environmental impacts of biomass feedstock conversion can be reduced substantially if BioMates facilities are built on (disused) industrial areas (“brownfield site”) instead of on agricultural land (“greenfield site”).

6.2.2. Local environmental impacts of the reference systems

Following a life cycle-oriented approach, the objective of the environmental assessment is to compare potential impacts of the BioMates systems with other (conventional) reference systems. Reference systems, which are compared to the BioMates system, include:

- Crude oil / gas refinery
- Biodiesel from rapeseed
- 1G Ethanol from sugar beet
- 2G BtL from straw
- 2G ethanol from straw

Alike the BioMates systems, also the reference systems are divided into several life cycle stages. For the purpose of the LC-EIA, mainly feedstock provision and feedstock conversion are distinguished. Transport and logistics are considered separately.

Feedstock provision

Beside processing of fossil crude oil and gas, also biofuels are examined as reference systems. Each is related with different types of risks causing potential impacts on the environment.

Provision of crude oil / gas

Oil refineries process crude oils into useful products e.g. naphtha, diesel or kerosene. The crude oil comes from oil production platforms (via pipelines or tankers) and is separated into fractions by fractional distillation. The fractions at the top of the fractionating column have lower boiling points than the fractions at the bottom. The heavy bottom fractions are often cracked into lighter, more useful products. All of the fractions are processed further in other refining units. Most of the products are used for energy purposes.

Impacts of crude oil / gas provision are expected to affect all environmental factors. The impacts are classified as unfavourable for the environment. Drilling processes especially in combination with the production of oil and water based mud and the huge demand of water [Ziegler 2011] bear significant risks for the environment. Further significant impacts are expected from transportation especially the implementation of pipelines.

Both value chains (crude oil / gas provision) include high risks of environmental impacts due to accidental and operational discharges from provision, transport and use [GPA 2014]. Basically the environmental factors soil, water, plants / biotopes, animals and biodiversity are affected. Table 10 summarises potential impacts on environmental factors on the value chains for both crude oil provision and gas provision (as exploitation and refining are very often done simultaneously) compared to the reference scenario: no use. An overview is further shown in Table 11.

Table 10: **Impacts on environmental factors related with the value chains of crude oil / gas provision; potentially significant impacts are marked with thick frames; reference scenario: no use**

Technological factor	Affected environmental factors								
	Soil	Ground water	Surface water	Plants / Biotopes	Animals	Climate / Air	Land-scape	Human health & recreation	Bio-diversity
Prospection	negative			negative	negative				negative
Drilling/mining	negative	negative	negative	negative	negative		negative		negative
Waste (oil- and water-based mud)	negative	negative	negative	negative	negative				negative
Demand of water (process water)		negative	negative	negative	negative		negative		negative
Emissions (exhaust fumes, water, metal)		negative	negative	negative	negative	negative		negative	
Land requirements	negative	negative	negative	negative	negative	negative	negative		negative
Demands of steel (tubes, equipment)	negative			negative	negative		negative		
Transportation (carriers, pipelines)	negative	negative	negative	negative	negative	negative	negative	negative	negative
Refining / processing	negative	negative	negative	negative	negative		negative	negative	negative
Accidents (traffic, pipeline leakage)	negative	negative	negative	negative	negative		negative	negative	negative

Likely significant impacts

Table 11: Potential impacts on the environment related to crude oil / gas provision compared to the reference system "no use"
How to read the table: Impacts are ranked in five comparative categories (A, B, C, D, E); "A" and "B" are assigned to the best options concerning the factor, but are not used in this case; "E" is assigned to unfavourable options concerning the factor; reference scenario: "no action"-alternative

Technological factor	Crude oil / gas
Prospection	C
Drilling / mining	E
Waste (oil- and water-based mud)	D
Demand of water (process water)	C / D[2]
Emissions (exhaust fumes, dust, water, metal)	C / D[2]
Land requirements	C / D[1]
Demands of steel (tubes, equipment)	D
Transportation (carriers, pipelines)	D
Refining / processing / enrichment	D
Accidents (traffic, pipeline leakage)	E

1: Increased land requirements in on-shore production

2: Increased impact in crude oil provision

Key finding

- Crude oil / gas provision is generally associated with heavy local environmental impacts.

Provision of rapeseed (ploughing of straw)

Rapeseed is generally grown on deep loamy grounds and requires adequate lime content and constant water supply. On heavy soils the production requires good nutrient supply with homogeneous precipitation. Both shallow and sandy soils lead to minor yields as rapeseed needs a high rooting depth. High efforts in weed / pest control is necessary as rapeseed is sensitive against diseases (e.g. fungi) and certain vermin beetles (e.g. cabbage stem flea beetle *Psylliodes chrysocephala* and cabbage stem weevil *Ceutorhynchus napi*). Furthermore rapeseed needs high doses of nitrogen (110-220 kg / ha) with an increased danger of nutrient leaching and eutrophication especially on groundwater. With a fruit : straw ratio of about 1 : 2,9 [Kaltschmitt et al. 2009] ploughing of straw after harvesting e.g. in case of biodiesel production can contribute to soil balance although the residues provide high nitrogen doses in the soil thus enhancing the risk of nutrient leaching.

Potential impacts on soil fertility can be minimised with rotational cropping e.g. using rapeseed as a winter crop. Due to its intensive rooting and a dense coverage it is often used as a starter crop for early wheat seeds. Although rapeseed is cultivated in monocultures thus affecting the biodiversity of epigeous fauna the blossoms attract flower-visiting insects with a promoting effect on animals and biodiversity. Table 12 summarises the risks associated with cultivation of rapeseed in comparison with non-rotational fallow land.

Table 12: Risks associated with the cultivation of rapeseed compared to the reference system of rotational fallow land

Type of risk	Affected environmental factors								
	Soil	**Ground water**	**Surface water**	**Plants / Biotopes**	**Animals**	**Climate / Air**	**Landscape**	**Human health & recreation**	**Bio-diversity**
Soil erosion	neutral / negative[1]		negative						
Soil compaction	negative	negative		negative	negative				negative
Loss of soil organic matter	neutral / negative[1,2]			neutral / negative[1,2]	neutral / negative[1,2]				neutral / negative[1]
Soil chemistry / fertiliser	negative	negative							
Eutrophication	negative	negative	negative	negative	negative				negative
Nutrient leaching		negative	negative						
Water demand		negative		negative	negative				neutral
Weed control / pesticides		negative	negative	negative	negative				negative
Loss of landsc. elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				neutral / negative	negative / positive[2]				negative / positive[2]
Loss of species				neutral / negative	negative / positive[2]				negative / positive[2]

1: Negative impact can be minimised in case of double cropping, if used as a starter crop

2: Negative because of low biodiversity due to monoculture but increased number of blossom visiting insects during flowering period

Provision of sugar beet

The cultivation of sugar beet e.g. for bioethanol production requires a high soil quality. Highest yields are achieved on deep soils with homogenous structure. As the young plants are endangered by overgrowth from the surrounding arable flora an intensive weed control is required. Due to a high number maintenance cycles and heavy vehicles (e.g. high applications of fertiliser [120-160 kg N / ha], need of weed and pest controls) there is a high risk of soil compaction. A consequence is an increased risk of nutrient leaching, affecting both groundwater and superficial water, especially by runoff during heavy precipitations. Ploughing of leaves after harvesting in fall will not compensate the loss of nutrients in total (fruit : leave ratio ≈ 1,2 : 0,8 [Schlegel et al. 2005]), so additional supply of organic fertiliser is necessary for soil balance. Intensive processing, use of heavy machines for the application of fertiliser and weed control in combination with the risk of erosion due to late soil coverage can affect plant and animal diversity. Thus succeeding crops (e.g. legumes, winter wheat) are recommended and help to minimise erosion. Potential impacts on landscape are comparable to the reference system of non-rotational fallow land.

Loss of habitat types and species might cause impacts if there is a change in habitat quality e.g. woodland is converted to arable land. The cultivation of sugar beet on arable land is not expected to cause a loss of habitats. Table 13 summarises the risks associated with cultivation of sugar beet in comparison with non-rotational fallow land.

Table 13: **Risks associated with the cultivation of sugar beet (ploughing of leaves) compared to the reference system of non-cropping (rotational fallow land)**

Type of risk	Affected environmental factors								
	Soil	Ground water	Surface water	Plants / Biotopes	Animals	Climate / Air	Land-scape	Human health & recreation	Bio-diversity
Soil erosion	negative[1]		negative						
Soil compaction	negative	negative		negative	negative				negative
Loss of soil organic matter	neutral / negative[1,2]			neutral / negative[1,2]	neutral / negative[1,2]				neutral / negative[1,2]
Soil chemistry/ fertiliser	negative	negative							
Eutrophication	negative	negative	negative	negative	negative				negative
Nutrient leaching		negative	negative						
Water demand		negative		negative	negative				neutral
Weed control / pesticides'		negative	negative	negative	negative				negative
Loss of landscape elements				neutral	neutral	neutral	neutral	neutral	neutral
Loss of habitat types				neutral / negative[1]	neutral / negative[1]				neutral / negative[1]
Loss of species				neutral / negative[1]	neutral / negative[1]				neutral / negative[1]

1: Negative impact can be minimised in case of crop rotation (succeeding crop), e.g. winter wheat;

2: Ploughing of leaves is usually not enough to compensate loss of nutrients)

Provision of straw

Straw can be used for 2G ethanol as well as for BtL production and has already been covered in detail in section 6.2.1 (p. 38).

Comparison of biogenic feedstocks

The risks associated with the biogenic feedstocks were aggregated and categorised from A (low risk) to E (high risk), allowing a (partial) comparison of the BioMates feedstocks. The results are depicted in Table 14. It must be noted that straw as a biomass residue cannot directly be compared to dedicated crops since the reference systems are fundamentally different.

Table 14: Risks associated with the provision of wheat / barley straw, rapeseed and sugar beet compared to the respective reference system

How to read the table: Impacts are ranked into five comparative categories (A, B, C, D, E); "A" is assigned to the best options concerning the factor, "E" is assigned to unfavourable options concerning the factor.

Type of risk	Feedstock			
	Wheat / barley straw Reference system: straw left on field (ploughing in)		Rapeseed (ploughing in of straw) Reference system: rotational fallow land	Sugar beet (ploughing in of leaves) Reference system: rotational fallow land
Soil erosion	C		D	E
Soil compaction	C		D	E
Loss of soil organic matter	C		C	E
Soil chemistry / fertiliser	C		D	E
Eutrophication	C		E	E
Nutrient leaching	C		D	D
Water demand	C		D	E
Weed control / pesticides	C		E	E
Loss of landscape elements	C		C	C
Loss of habitat types	B[1]	C	D	D
Loss of species	B[1]	C	D	D

1 In case of long-stalked varieties since less weed control is necessary

Key finding

- Biomass feedstock provision from dedicated (annual) crops is associated with high risks. A direct comparison to the relatively low-risk provision of residual straw, however, is not meaningful.

Transport and logistics

Crude oil is usually shipped to Europe. Long-distance transportation increases exhaust gases (cargo ships, lorries) with potential impacts on water (ocean), related organisms (plants, animals, biodiversity), air quality and landscape. Natural gas is supplied via pipelines with additional impacts on the environment. The distribution within Europe is basically done via pipelines and vessels.

Transportation and distribution of biomass are mainly based on trucks and railway / ships with need of roads and tracks/channels. Depending on the location of the biomass conversion facility, there might be impacts resulting from the implementation of additional **transportation infrastructure**. **Storage facilities** for biomass can either be constructed at the site of biomass provision (decentralised storage on the field margin) and/or at the site of biomass conversion. As far as it is necessary to build additional roads or buildings, environmental impacts are expected on soil (due to sealing effects), water (reduced infiltration), plants, animals and biodiversity (loss of habitats, individuals and species, disturbance by moving vehicles).

Overall, the impacts associated with transportation and logistics are not expected to be significant.

Feedstock conversion

Impacts from implementing a refinery for conversion and use of feedstock are expected from

- the construction of the plant
- buildings, infrastructure and installations on-site as well as to the
- operation of a prospective plant.

Impacts related to the **construction of the facility** are temporary and not considered to be significant.

Refineries and conversion facilities need **buildings, infrastructure and installations**, e.g. facilities for processing and energy generation, administration buildings, waste water treatment etc., which are usually associated with soil sealing. Other impacts might vary in quantity but not in quality, which in case of a generic approach on potential environmental impacts of technologies is negligible. Scaling up plants from different technologies to comparable outputs and yields might further minimise the differences in land consumption. Significant impacts are expected on water, soil, plants, animals and landscape and are highly dependent on local conditions.

Impacts from **operation of the facility** are expected from:

- emission of noise (refinery)
- emissions of gases and particulate matter
- emission of light (refinery)
- drain of water resources for production (refinery)
- waste water production and treatment (refinery)
- traffic (collision risks, emissions)
- electromagnetic emissions
- risk of accidents (explosion, fire in the facility or storage areas)

Significance of impacts might vary with the type of technology and the location of a potential facility. This variability cannot be taken into account by this generic LC-EIA. Moreover, this LC-EIA cannot replace a full-scale EIA according to Directive 2014/52/EU.

Key finding

- Local environmental impacts from the conversion of crude oil / natural gas as well as biogenic feedstocks into fuels are mostly expected from the operation phase of the respective facilities.

6.2.3. Comparison: BioMates systems vs. reference systems

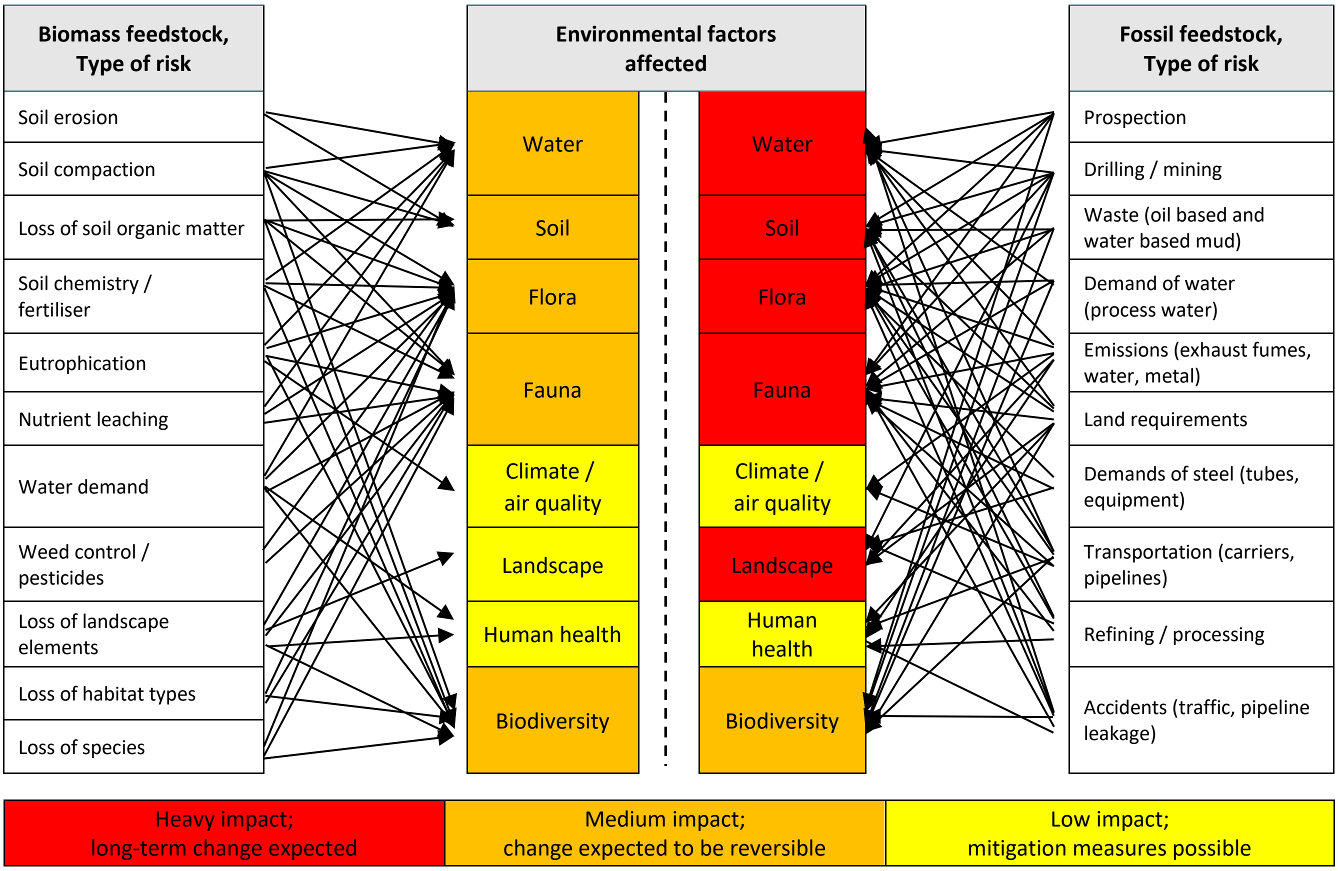
In this section, the local environmental impacts associated with the BioMates systems are compared to those associated with the reference systems.

Feedstock provision

The supply of feedstock is linked to local environmental impacts that vary depending on the type of feedstock and technology. Biomass feedstocks and fossil (non-renewable) feedstocks, can be used for energy production as well as for sources for further processing (e.g. chemical industry). However, there are fundamental differences in the provision technologies which in case of biomass feedstock are linked to different soil management and cultivation methods (agricultural practices).

Since the type of risks associated with these technologies are completely different in quality and quantity, a direct comparison is not possible. Nevertheless, Table 15 shows a comparison of impacts on environmental factors (in both cases, the reference system is 'no use'). Impacts are classified using three different impact levels: heavy, medium and low.

Table 15: **Comparison of impact on environmental factors due to provision of bio-based and conventional feedstock regarding impact sustainability in three different categories; reference system: no use**



The types of risks expected from provision of fossil (non-renewable) feedstock are based on extraction technologies focussing on components below the surface. Regeneration is usually not possible. Risks related to the provision of biomass feedstock are expected to be mostly reversible. For instance, soil erosion due to agricultural activities, depletion of water due to use of fertiliser and pesticides or loss of habitats and species due to changes in land use can be compensated over a certain period of time, if the responsible risk factor no longer prevails. However, most of the impacts associated with fossil feedstock provision, especially those on water, soil, flora, fauna and landscape, are expected to be long-term and non-reversible.

Key finding

- Biomass feedstock provision for prospective BioMates facilities is expected to cause overall less severe and less permanent local environmental impacts than feedstock provision for the conventional reference system.

Feedstock conversion

The conversion of feedstock causes local environmental impacts. The comparison of BioMates feedstock conversion and reference feedstock conversion leads to the following results, which are summarised in Table 16.

No significant differences are expected regarding the impacts related to the **construction of the facilities**. In both cases, the impacts are temporary and not considered to be significant.

Regarding the impacts related to **buildings, infrastructure and installations**, slight differences are expected between BioMates and all other types of feedstock conversion. In all cases, significant impacts are expected due to soil sealing, if the conversion facility is developed on a greenfield site. On a brownfield site, in contrast, impacts are not expected to be significant. As AFP and HDT for BioMates are built nearby existing refineries in most scenarios, location on a brownfield site is more likely. Other impacts might vary in quantity but not in quality, which in case of a generic approach on potential environmental impacts of technologies is negligible.

Some impacts from the **operation of the facilities** are expected to be comparable, e.g. regarding noise, light and electromagnetic emissions. The same holds for water demand and wastewater production. However, differences are expected in terms of:

- emission of gases and particulate matter: coal-fired and biomass-fired conversion facilities emit higher levels of particulate matter than the other conversion technologies. Crude oil refineries are more likely to be linked to emissions of harmful gases. As the heat is recovered in the HDT and hydrogen is produced via electrolysis through renewable energy, the BioMates system emits lower levels of gases and particulate matter than the other conversion technologies.
- traffic (emissions, collision risk): Emissions related to biomass supply are concentrated around the facility, resulting basically in an increase of vehicle movements (delivery of feedstock and products) in combination with an increase in emissions and the risk of accidents. Impacts are expected to be local. The supply of fossil feedstocks to facilities for conversion and use is usually linked to long distance transportation by ship / railway and / or pipelines with little impacts on local traffic.
- disposal of waste materials / residues: Residues from biomass conversion are often biodegradable (potential use as fertiliser) or combustible with potentially lower impacts on the environment. Considerable risks are expected from wastes originating from crude oil refineries.
- risk of accidents (explosion, fire in the facility or storage areas, release of GMO): Biomass conversion is generally associated with a lower risk of accidents. In case of ethanol production, genetically modified organisms (GMO) could potentially be released.

Key finding

- Local environmental impacts of prospective BioMates facilities do not differ significantly from those of conventional crude oil / gas refineries or 1G & 2G biofuel facilities.

Table 16: Potential impacts on the environment related to different technologies regarding feedstock conversion and transport

How to read the table: Impacts are ranked in five comparative categories; "A" is assigned to the best options concerning the factor (does not occur in a Greenfield scenario), "E" is assigned to unfavourable options concerning the factor; reference scenarios: "no action"-alternative

Technology / Product Technology related factor	BioMates systems	Reference systems				
	BioMates	Crude oil / refinery	Biodiesel production (transesterification)	1G Fermentation	Biorefinery	Biorefinery
	Fuels	Fuels	Biodiesel (rapeseed)	1G Ethanol (sugar beet)	BtL (straw)	2G ethanol (straw)
Impacts resulting from construction phase						
Construction works	C	C	C	C	C	C
Impacts related to buildings, infrastructure and installations						
Buildings, infrastructure and installations (size and height)	A[1] / E[2]	A[1] / E[2]	A[1] / E[2]	A[1] / E[2]	A[1] / E[2]	A[1] / E[2]
Impacts resulting from operation phase						
Emission of noise (refinery)	D	D	D	D	D	D
Emission of gases and particulate matter (refinery)	C	D	C	C	C	C
Emission of light (refinery)	C	C	C	C	C	C
Drain of water resources for production (refinery)	D	D	D	D	D	D
Waste water production and treatment (refinery)	D	D	D	D	D	D
Traffic (collision risk, emissions)	D	C[3]	D	D	C / D[7]	D / E
Electromagnetic emissions from high-voltage transmission lines	C	C	C	C	C	C
Disposal of wastes / residues	B / C	D[4]	C	B	C	B
Risk of accidents (explosion, fire in the facility or storage areas, release of GMO)	C / D[5]	E[3,4,5]	D[4,5]	C / D[6]	C / D[5]	C / D[6]

1 No significant impacts expected in a Brownfield scenario

2 Significant impacts expected in a Greenfield scenario

3 Less local impact due to transportation by import of feedstock from overseas

4 Increased impact potential expected due to potentially hazardous substances

5 Increased potential of accidents due to potentially hazardous production conditions

6 Increased impact potential expected due to operating with GMO (risk of release)

7 Increased emissions and traffic load in centralised plant

6.3. Greenhouse gas balances according to the RED II

The recast Renewable Energy Directive (RED II) [European Parliament & Council of the European Union 2018] requires at least 65% greenhouse gas savings for biofuels compared to a fossil fuel comparator from 1 January 2021. The RED II rules that need to be applied in case of BioMates are however not complete because article 28(5) refers to a delegated act that applies to co-processing of bio-based intermediates with fossil fuels and article 27 refers to a delegated act that specifies under which conditions imported renewable electricity may be counted. Both delegated acts were not available at the time of finalising this report. Therefore, the below GHG balances calculated according to the RED II are only exemplary.

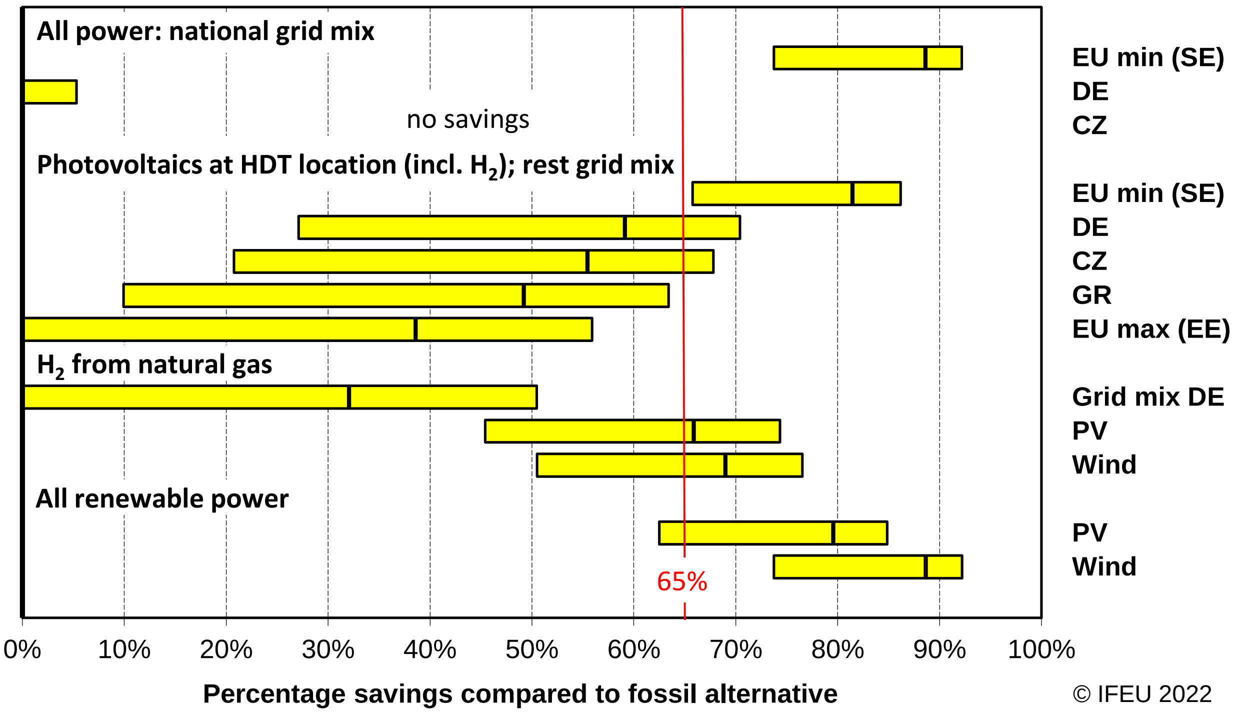


Figure 21: Relative GHG emission savings compared to fossil alternative according to REDII for the base case scenario with straw as feedstock using different electricity and hydrogen sources. Bars cover the result range from conservative (leftmost) via typical to optimistic (rightmost) boundary conditions. Abbreviations: HDT: hydroprocessing, EU min (SE): national electricity grid mix with lowest GHG emissions in the EU from Sweden, DE: Germany, CZ: Czech Republic, GR: Greece, EU max (EE): national electricity grid mix with highest GHG emissions in the mainland EU from Estonia, PV: electricity from photovoltaics

How to read the figure: The 1st bar from the top shows that the BioMates scenario using the Swedish electricity mix and using straw as input feedstock could fulfil the 65% goal for the conservative, typical and optimistic sub-scenarios according to the exemplary calculations made before relevant provisions in pending delegated acts were available.

Figure 21 shows that the result range only for the base case scenario using straw as feedstock can be enormous ranging from no savings at all to over 90% of savings compared to the fossil fuel comparator. These very large differences result from different boundary conditions mainly covering different process efficiencies reached during further technology development and upscaling (range covered by each bar) and different possible greenhouse gas intensities of used electricity and hydrogen (differences between bars).

- The results look very promising if the entire electricity demand incl. that for hydrogen production can be covered from wind or PV electricity (bars “all renewable power” in Figure 21), which is eligible to be counted according to RED II, as envisaged in the BioMates concept. The eligibility criteria are however still unclear and are expected to be part of a pending delegated act.

- If national grid mixes have to be counted for all parts of the process chain (bars "all power: national grid mix" in Figure 21), only few countries with very low carbon intensities in the national grid qualify as locations for BioMates facilities.
- If at least the main location, where hydrogen electrolysis, HDT unit and one of four AFP units are co-located according to analysed scenarios can receive eligible renewable power, then minimum savings can only be achieved through multifactorial optimisation of processes and not in all countries. If grey hydrogen from natural gas steam reforming is used, meeting minimum GHG savings requires a combination of typical to optimistic process efficiencies and renewable electricity.

For a final assessment of the BioMates concept, it is therefore necessary to wait until all official rules (especially the delegated acts) are available, because only then the corresponding calculations can be carried out with higher confidence.

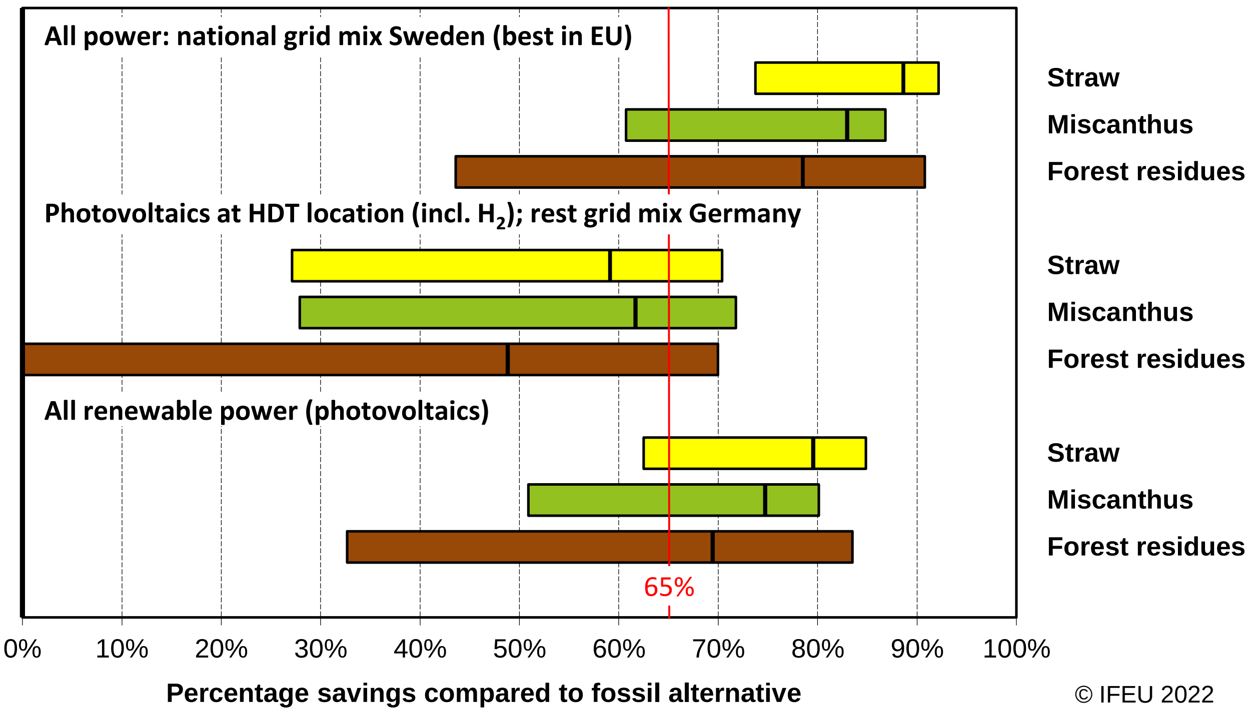


Figure 22: **Percentage savings of GHG emissions compared to fossil alternative according to REDII for different scenarios, comparison of different feedstocks.**
How to read the figure: The 2nd bar from the top shows that if Miscanthus is used for BioMates production with the Swedish power mix, the REDII limit can be met in the conservative, typical and optimistic scenario.

The overall picture looks very similar for the feedstocks Miscanthus and forest residues (Figure 22). If technology development and upscaling succeeds as expected or better (right hand segment of bars in Figure 22) and renewable power can be used and counted according to pending calculation rules, minimum savings requirements are expected to be met. Whenever this is not the case, all parameters have to be optimised thoroughly in order to achieve minimum savings with different outcomes for each biomass and potentially also location. In particular, it is important that biomass is air dried to a water content of below 20% to minimise technical biomass drying, which contributes substantially to the low GHG savings in the conservative sub-scenario of rather moist forest residues.

The ongoing decarbonisation is expected to lead to substantially lower GHG intensities of power generation at least in many European countries until a potential BioMates plant could become operational. Table 17 lists approximate thresholds until which 65% savings are expected to be reached in several scenarios.

Table 17: Maximum GHG emission factors of the used electricity grid mixes that could still achieve compliance with minimum GHG savings criteria of the RED II for the scenarios under typical conditions.

Biomass feedstock	All electricity national grid mix [g CO_2eq/kWh]	PV power at HDT location (including H_2 electrolysis), rest grid mix [g CO_2eq/kWh]
Straw	150	460
Miscanthus	130	480
Forest residues	100	190

Summarising the above results, it depends on many parameters whether the 65% savings stipulated in the RED II can be reached with a particular influence of the following ones:

- Technical availability of green hydrogen (from solar or wind power) that furthermore complies to clauses expected to be part of the pending delegated acts allowing the hydrogen to be counted as additional or otherwise eligible for the calculations of the greenhouse gas balance of the fuel.
- Ability to fulfil clauses expected to be part of the pending delegated acts allowing renewable electricity to be used in processes besides hydrogen electrolysis and to be counted as additional or otherwise eligible for the calculations of the greenhouse gas balance of the fuel.
- If neither green hydrogen nor renewable electricity can be counted, BioMates is expected to reach the minimum savings threshold only in countries such as Sweden, Switzerland, Norway, France, Albania and Iceland in which the national electricity grid mix is associated with low CO_2 emissions. Additionally, it must be ensured that ambitious process efficiencies can be reached as modelled in the scenarios and that the biomass feedstock is air-dried as far as possible.
- If green hydrogen but not renewable electricity for remaining processes can be counted, a series of optimisations has to be considered depending on the applicable national grid mix at the location of the plant at the time of certification. The following parameters will be particularly important at high greenhouse gas intensities of national grid mixes: (i) Process optimization to approach or even exceed the process parameters in the optimistic sub-scenarios, (ii) Feedstock selection depending on the strengths of the optimised process and (iii) Optimal air-drying of biomass.

  In countries that are phasing out coal power, the above mentioned optimisation measures could be sufficient to reach the minimum savings criteria. In countries with high shares of coal power, such as several Eastern European countries, this is however hard to reach.

Key findings

- Since delegated acts further defining calculation rules on renewable electricity and co-processing are still pending, only exemplary calculations could be done resulting in large ranges of results.
- Whether minimum GHG emission savings according to the RED II can be met, depends heavily on the GHG intensity of the used electricity and therefore on the exact content of a pending delegated act.
- If renewable electricity can be used and is eligible for calculations according to pending rules, the results of the exemplary calculations look promising for BioMates to fulfil the RED II requirements.

7. Conclusions and recommendations

7.1. Conclusions

The following conclusions are drawn from the results of the environmental assessment presented in chapter 6 and concern both the main question addressed in the report *'How and under which conditions can the co-processing of bio-based intermediates (BioMates) in a conventional petrochemical refinery increase the sustainability of transportation fuels?'*, but also alternative uses of biomass and eligibility according to the recast Renewable Energy Directive (RED II):

BioMates versus fossil fuels

- As a main result, it can be summarised that BioMates fuels show the same pattern of environmental advantages and disadvantages that can already be observed for decades for many other biofuels and bioenergy sources: In most facets of potential design, benefits in terms of greenhouse gas emission savings and non-renewable energy are opposed by disadvantages in most other environmental impact categories. Thus, while climate benefits can be achieved, BioMates fuels are not automatically more environmentally friendly overall than fossil fuels just because renewable resources (biomass, green hydrogen and renewable electricity) are used in their production. For the BioMates concept to actually save greenhouse gas emissions, ***the following conditions must be met***:
  - *No competition for biomass use or land use*: The biomass residues used (straw and forest residues) must not be taken away from any existing environmentally friendly use, as otherwise indirect effects (indirect residue use competition, iRUC) mean that greenhouse gas savings cannot be achieved through other uses, which can lead to additional greenhouse gas emissions overall. This also applies in particular to the material use of these residues, which has not been considered in detail here. The same holds for the use of dedicated energy crops such as Miscanthus: here, the corresponding cultivation areas must be available without indirect effects (indirect land use change, iLUC).

  - *Ample availability of renewable electricity*: Renewable electricity would have to be available on a large scale, both for the electrolytic production of the hydrogen needed for mild hydrogenation and for all other electricity requirements along the process chain. This renewable electricity would have to be available in addition to the increasing demand due to the energy transition (even with the phase-out of power generation from coal and natural gas) and in addition to the increasing demand due to the electrification of road transport (battery-electric cars, fuel cell electric trucks or overhead-catenary trucks/electric road systems). Only from an emission factor of less than about 250 g CO_2eq / kWh does the BioMates system pay off in terms of greenhouse gas emission savings. If conventional hydrogen from natural gas steam reforming (grey or blue hydrogen) and an electricity mix with a significantly higher emission factor were still used instead of green hydrogen, the greenhouse gas emission savings would decrease or even turn into additional emissions.

- In the BioMates concept, the ***processes or inputs that are mainly responsible for resource use and emissions*** differ only to a small extent depending on the environmental impact category considered. Across all environmental impact categories, ***pyrolysis*** (here: electricity and possibly heat demand) ***and hydrogen provision*** are particularly relevant for the environmental impacts.
- The greatest ***potential for optimisation*** in BioMates, which can be influenced by technology development, lies in pyrolysis. Here, it is particularly important to achieve maximum efficiencies. Other investigated variants for logistics, hydrogen compression and recovery or different uses of the co-products aqueous phase, pyrolysis char or oxygen (from electrolysis) show no major influence of these parameters on the results.
- With regard to climate change, the investigated biomass residues straw and forest residues perform similarly, provided that forest residues can be air-dried to a water content of less than 20%. Although similar greenhouse gas emission savings can be reached using the energy crop Miscanthus, residue use is overall more environmentally friendly because Miscanthus cultivation requires cropland and thus leads to significantly higher land use-related impacts.

BioMates vs. alternative uses of the same biomass residues or agricultural land

- The comparison of BioMates fuels with other biofuels produced either from the same feedstock (biomass residues) or by using the same land (dedicated energy crops) shows that the result ranges of various possible future industrial implementations of each technology overlap and that it depends on the exact design of the respective process chain. However, BioMates fuels could still have advantages in terms of greenhouse gas emission savings even under such conditions, especially if biomass residues are used for BioMates; advantages are achieved here unless the competing technologies (2G ethanol or BtL) would be implemented in the best possible technical way.
- With regard to cultivated biomass, on the other hand, Miscanthus considered here is in competition with many other land uses/crops, against which it has no clear advantages in terms of climate change mitigation. If the BioMates concept were to be implemented on the basis of Miscanthus, there would have to be strong economic or social reasons for doing so.

Greenhouse gas balances according to the RED II

As with the greenhouse gas balances according to the ISO standard discussed above, the results of the calculation according to the RED II is primarily determined by the electricity used for electrolytic hydrogen production and the rest of the process chain. Whether the required 65% reduction according to the RED II can be achieved thus depends essentially on the greenhouse gas intensity of the electricity used. The greenhouse gas balances calculated in this study according to the RED II are only exemplary calculations, as the delegated acts with the official calculation rules for co-processing according to Article 28(5) and another one according to Article 27, which regulates under which conditions renewable electricity may be eligible, were not yet adopted when finalising this report. The results obtained show that the minimum savings required by the RED II can be achieved but also missed. In particular, the results look very promising if the entire electricity demand, including the electricity required for hydrogen production, can be met from eligible wind or solar electricity, as envisaged in the BioMates concept. If this is not the case, achieving the minimum savings can only be achieved through multifactorial optimisation and possibly only at certain locations. For a final ruling on the BioMates concept, it therefore remains to be seen until all official rules are available, because then the corresponding calculations can be carried out in a serious manner.

7.2. Recommendations

Based on the conclusions drawn in the previous section, the following recommendations were derived for various stakeholders:

To process developers and potential future operators of the BioMates concept

- Apart from hydrogen production, pyrolysis causes the highest environmental impact in the production of BioMates fuels. It should be further optimised in order to achieve maximum efficiencies.
- The energy demand should be reduced by adequate measures, both the electricity demand (e.g. for comminution) and the heat demand for the process, which depends, among others, on the water content of the biomass used. The latter can be reduced through optimal air drying of the biomass.
- Furthermore, the concrete design of a possible future Bio-Mates plant should take into account a number of optimisations that have been investigated in the context of this project and that have been shown to be environmentally beneficial. Even if individual optimisations do not necessarily have a decisive effect, they can significantly improve the process altogether. These are:
  - Installation of a hot gas filter
  - Maximisation of external use of pyrolysis char by reducing the heat demand of the AFP process.
  - Co-location of refinery, HDT plant and, if possible, also a pyrolysis unit
  - Efficient use of waste heat from pyrolysis and offgas from hydrogen recovery not used internally
  - Use of the oxygen produced during electrolysis
  - At least low value use of the aqueous fraction from pyrolysis to avoid disposal
- In the case of electrochemical hydrogen compression and recovery, the progress made within the framework of BioMates is not yet sufficient to be able to achieve environmental advantages compared to the mechanical variant. Further efficiency improvements should be attempted here.

To refinery operators

- As explained above, the GHG balances according to RED II are exemplary calculations that are only of limited use to support investment decisions. Due to the lack of official calculation rules for co-processed bio-oil and requirements for the additionality of renewable electricity, corresponding calculations should be made after the publication of these rules.
- Production capacities for green hydrogen and additional renewable electricity (solar and wind parks as well as electrolysers) should be actively built up so that the environmental benefits of the BioMates concept can be fully exploited and the 65% GHG emission reduction required by RED II can be achieved as reliably as possible, depending on the regulations in force at the time. From an environmental point of view, such an investment would be a good idea anyway to cover the refinery's existing hydrogen demand. Such plants should be designed to be extendable in order to be able to integrate biofuels according to the BioMates concept with a shorter preparation time, among others.

To policy makers and research funding agencies

The current legal uncertainty, which is due to an absence of legislation in the context of the Renewable Energy Directive (RED II) acts as a significant barrier to the further development and potential implementation of the BioMates concept. Therefore, the open issues related to Articles 27 and 28(5) of the RED II should be resolved with high priority and the pending delegated acts should be adopted as soon as possible.

Political decision-makers should underpin existing strategies, such as bioeconomy strategies at EU, member state and regional level, with a ***holistic biomass use concept*** that takes into account not only biomass use for energy, but also the possible alternative material use of biomass (not examined in this study). This is urgently needed in view of (i) the foreseeable intensification of competition for biogenic residues and arable land (among other things, due to the strong incentives in RED II that encourage their use for energy purposes) with simultaneously limited potentials [Rettenmaier et al. 2022], (ii) the lack of alternatives for renewable/green carbon in the chemical sector, and (iii) the risk of potentially stranded investments in new technologies. When developing such a concept on the different spatial levels, it must be ensured that the respective subordinate level is taken into account, i.e. the EU level must take into account the member state level which in turn must take into account the regional level, in analogy to the development of a supra-regional biotope network. Such plans can help to address and resolve trade-offs between nature conservation objectives, dedicated crops cultivation and other alternative uses.

In addition, a clear commitment to green hydrogen and a supportive investment climate are needed on the part of policymakers. Green hydrogen is a fundamental prerequisite for many future technologies, not only for the BioMates concept.

Outlook

From an environmental point of view, the possibility of processing biomass decentrally in relatively small-scale pyrolysis plants to produce an intermediate with a higher energy density offers advantages over other advanced biofuels such as 2G ethanol or Fischer-Tropsch fuel (BtL) from lignocellulosic biomass, which are dependent on large-scale plants in the order of 200,000 t/a biomass input and above due to the economy of scale. This cannot be directly deduced from the LCA results, but after adding the local environmental impacts (traffic volume, affected radius of a plant) and looking at the biomass potentials [Rettenmaier et al. 2022], certain advantages for the BioMates concept are becoming apparent, which is further explored in the Integrated Sustainability Assessment [Keller et al. 2022].

In view of limited biomass potentials, the BioMates concept could leverage its advantages especially in the marine and aviation fuel sector, where liquid fuels for combustion engines will be needed for the foreseeable future. In road transport, on the other hand, use is only conceivable in niche applications in view of the advancing electrification. In addition, the use of partial streams with corresponding properties as bio-based naphtha for the chemical industry is also strategically promising. Corresponding systemic comparisons were not planned within the framework of BioMates, but are an important prerequisite for the creation of the above-mentioned biomass utilisation concepts.

8. Disclaimer

This Deliverable report reflects only the authors' view; the European Commission and its responsible executive agency CINEA are not responsible for any use that may be made of the information it contains. Furthermore, IFEU does not accept any liability for any use that may be made of the exemplary results presented in section 6.3. Due to the fact that the official calculation rules for co-processed bio-oil as well as the requirements regarding the additionality of renewable electricity applying under the RED II are still pending at the time of writing finalising this report, the presented results must be regarded as exemplary and subject to change.

9. Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727463.

The authors would like to thank all BioMates project partners sincerely for the provision of information and data, which forms the basis of this life cycle assessment, notably the mass and energy flow data provided to Task 4.2. Furthermore, we are grateful to Loukia Chrysikou, Ivan Souček, Yara Evans and Rocio Diaz-Chavez for the close interaction and continuous valuable discussions within WP4. Moreover, we would like to thank our IFEU colleagues Sven Gärtner, Guido Reinhardt and Julian Senn for valuable discussions, comments and support in preparing the report.

10.Abbreviations

1G	First generation (biofuels), produced from food and feed crops, e.g. rapeseed
2G	Second generation (biofuels), produced from biomass residues and waste, e.g. straw
AFP	Ablative fast pyrolysis
BtL	Biomass-to-liquid (Fischer-Tropsch fuel)
CHP	Combined heat and power (plant)
CINEA	European Climate, Infrastructure and Environment Executive Agency
CO_2	Carbon dioxide
CZ	Czech Republic
DE	Germany
dLUC	Direct land-use change
DM	Dry matter
EE	Estonia
EEC	European Economic Community
EIA	Environmental impact assessment
EtOH	Ethanol
EU	European Union
eq	Equivalent (e.g. in the context of CO_2 equivalents or inhabitant equivalents)
FAME	Fatty acid methyl ester
FM	Fresh matter
g	Gram
GA	Grant Agreement
GHG	Greenhouse gas
GJ	Giga joule
GMO	Genetically modified organism
GO	Gas oil
GR	Greece
h	Hour
H_2	Hydrogen
ha	Hectare (1 ha = 10,000 m^2)
HDT	(Mild) hydrotreatment
IE	Inhabitant equivalent
ILCD	International Reference Life Cycle Data System

ILCSA	Integrated life cycle sustainability assessment
iLUC	Indirect land-use change
ISO	International Organization for Standardization
kg	Kilogram
km	Kilometre
kWh	Kilowatt-hour
LCA	(environmental) Life cycle assessment, in this project a screening life cycle assessment
LCC	Life Cycle Costing
LCI	Life cycle inventory
LC-EIA	Life cycle environmental assessment
LCIA	Life cycle impact assessment
LCO	Light cycle oil
LCSA	Life Cycle Sustainability Assessment
LCT	Life cycle thinking: Principle behind LCA, LCC, ILCSA and related methodologies
m	Metre
MA	Market Analysis
MJ	Mega joule
N.A.	Not applicable
O_2	Oxygen
PV	Photovoltaics
RED	Renewable energy directive (EU directive about the renewable energy use)
SE	Sweden
sLCA	Social life cycle assessment
SWOT	Analysis of strengths, weaknesses, opportunities and threats
SETAC	Society of Environmental Toxicology and Chemistry
t	Tonne (metric)
TEE	Techno-economic evaluation
TRL	Technology readiness levels
UN	United Nations
UNEP	United Nations Environment Programme
WP	Work Package
yr	Year

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12. Annex

Table 18 provides an overview of some important publicly available technical parameters in relation to the upstream processes of input feedstocks. For other parameters, please refer to [Chrysikou et al. 2021].

Table 18: Overview of technical base data concerning feedstock parameters and upstream processes per unit t DM biomass. FM: fresh matter, DM: dry matter, N.A. not applicable

Reference unit:	Wheat straw			Miscanthus			Forest residues		
t DM biomass	conser-vative	typical	opti-mistic	conser-vative	typical	opti-mistic	conser-vative	typical	opti-mistic
Land use [$m^2 \times yr$]	0	0	0	800	727	667	0	0	0
Specific nutrient content relevant for fertilisation:									
N [kg]	5.2	5.2	5.2	3	3	3	N.A.	N.A.	N.A.
P_2O_5 [kg]	3.6	3.6	3.6	1.5	1.5	1.5	N.A.	N.A.	N.A.
K_2O [kg]	17.0	17.0	17.0	7.3	7.3	7.3	N.A.	N.A.	N.A.
Pesticides [kg]	N.A.	N.A.	N.A.	0.06	0.06	0.05	0	0	0
Fuel [kg]	1.99	1.99	1.99	4.21	4.05	3.91	17.26	11.50	5.75
Transport distance [km]	120	107	99	84	72	65	196	175	162
Water content at technical drying:									
prior [% FM]	14%	14%	14%	25%	20%	20%	25%	20%	17%
after [% FM]	5.4%	5.4%	5.4%	5.4%	5.4%	5.4%	5.4%	5.4%	5.4%
Drying: demand for									
Heat [MJ_{th}]	651	372	372	1,408	599	599	3,416	1,358	438
Electricity [kWh]	7.8	7.8	7.8	27.6	27.6	27.6	55.1	33.6	18.0

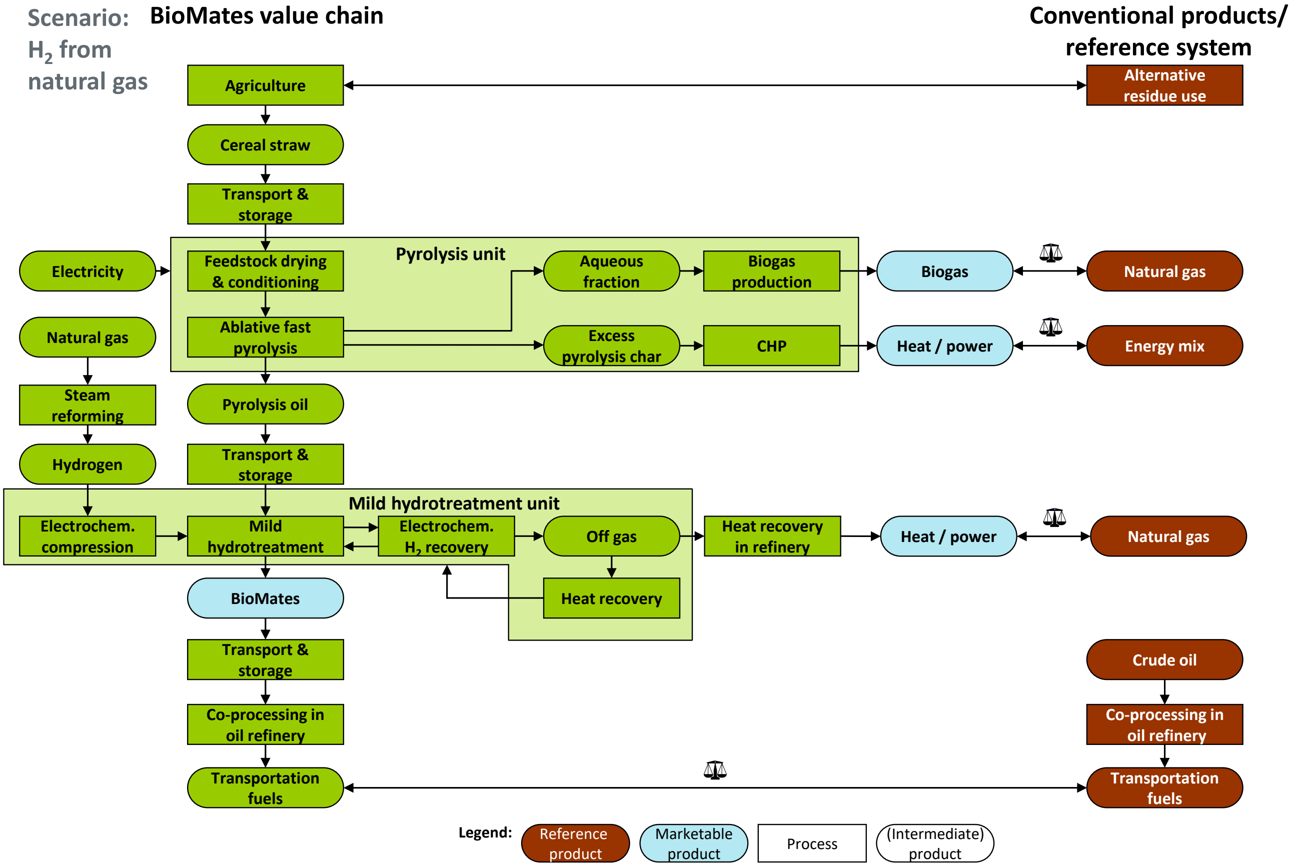

Figure 23: Life cycle scheme of the scenario: H_2 from natural gas

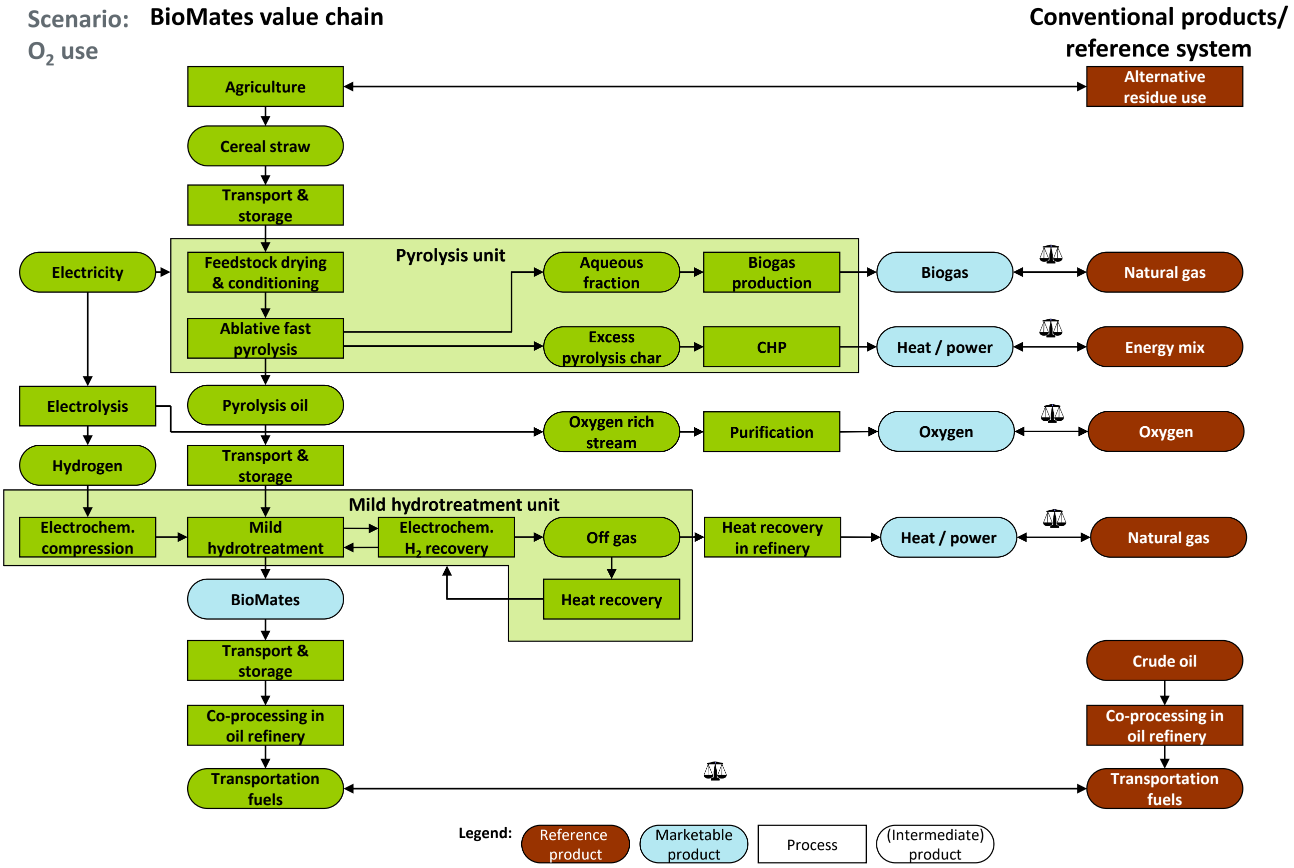

Figure 24: Life cycle scheme of the scenario: O_2 use