# BioMates

Public Summary of Deliverable D4.8

**Integrated Assessment of Sustainability of Bio-based Refinery Intermediates**

*Version 01*

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| Submitting party: | IFEU – Institute for Energy and Environmental Research Heidelberg |
| Responsible author: | Heiko Keller |
| Co- author(s): | Nils Rettenmaier, Claudius Grehl, Guido Reinhardt |
| Contributions by: | Stella Bezergianni, Jiri Celar, Loukia Chrysikou, Rocio Diaz-Chavez, Yara Evans, Petr Kubal, David Kubička, Ivan Souček, Vladimir Zemanek |
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## 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

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# 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 integrated assessment of sustainability' (Deliverable D 4.8) joins the previous specific assessment of technological, environmental, economic as well as social, policy and health aspects /Kubička-2021, Keller-2022, Souček-2021, Diaz-Chavez-2021/ into an overall picture and analyses them collectively to give an integrated view on the implications for sustainability associated with the BioMates concept. The main objective is to determine whether or under which conditions the co-processing of bio-based intermediates (BioMates) in a conventional petrochemical refinery can increase the sustainability of transportation fuels. Another important goal of the study is to identify optimisation potentials to determine focal areas for the further development of the BioMates concept. Furthermore, the integration of results offers the possibility to value and compare the different scenarios including all aspects of sustainability. The integrated sustainability assessment in BioMates, briefly introduced in chapter 2, is based on the integrated life cycle sustainability assessment (ILCSA) methodology /Keller-2015/.

# 2. Introducing BioMates

## 2.1. The BioMates Project

The BioMates project aspires in combining innovative 2$^{nd}$ generation biomass conversion technologies for the cost-effective production of *bio*-based inter*m*edi*ates* (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.

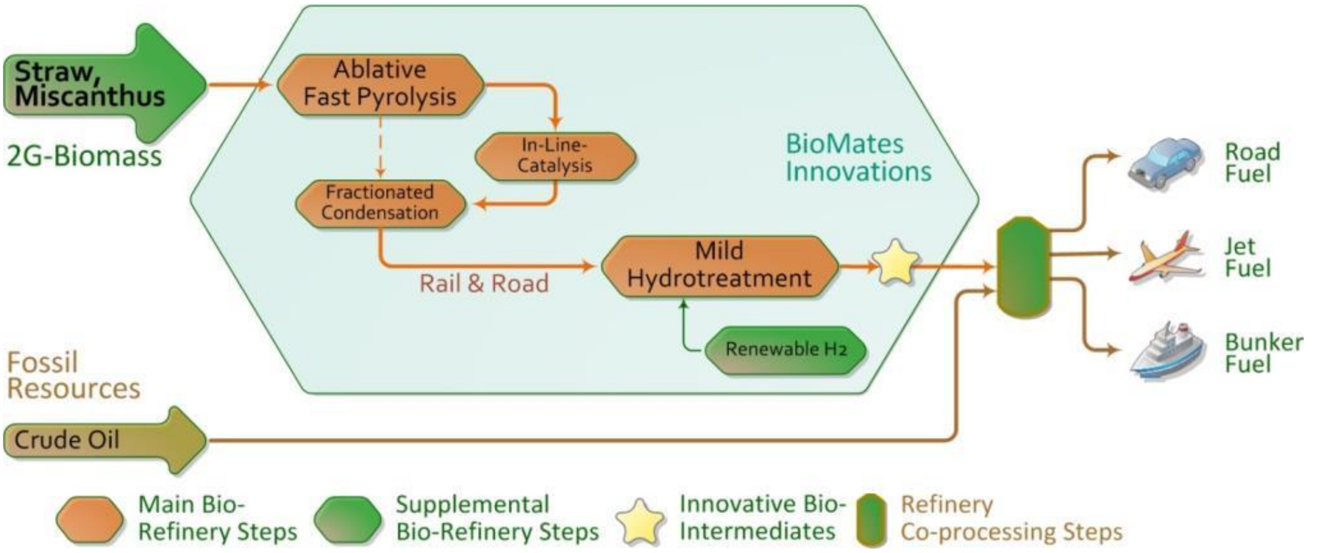


Figure 1: The BioMates-concept

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 " /EC-2014a, EC-2014b/. 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 /EC-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. Public 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 $CO_2$eq 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 life cycle sustainability assessment (ILCSA), which is based on the previous technological, environmental, economic as well as social, policy and health assessments /Kubička-2021, Keller-2022, Souček-2021, Diaz-Chavez-2021/. The ***conclusions*** of the ILCSA are summarised in the following, supplemented with selected results.

### General sustainability performance

Fuels from co-processing hydrotreated bio-based pyrolysis oil in petrochemical refineries according to the BioMates concept are not automatically more sustainable than conventional fuels just because renewable resources (biomass, green hydrogen and renewable electricity) are used in their production. As with almost any complex system, ***all scenarios analysed in this study are associated with sustainability advantages and disadvantages*** (Table 1). The following general picture can be drawn of the BioMates concept:

- The BioMates scenarios are generally ***rated positively from a social and policy perspective***, when compared to fossil fuels. However, risks of occupational hazards need to be and can be mitigated.
- The economic assessment has shown that ***economic viability is only given under certain conditions***. Economics are dominated by operational costs (OPEX), notably for biomass feedstock (17-35%), hydrogen (15-29%) and utilities (14-35%), and are very sensitive to the price of the BioMates intermediate sold to the refinery. This results in ***economically viable BioMates scenarios in Eastern Europe***, especially if optimistic process efficiencies can be reached. ***Geographic location is thus crucial*** because Western European costs represent a challenge that requires optimal boundary conditions including reaching optimistic process efficiencies.
- Substantial savings of greenhouse gas emissions and non-renewable energy resources compared to fossil fuels can be achieved under the condition that (i) ***additional renewable electricity*** is used for hydrogen provision from water electrolysis and for pyrolysis (ii) ***unused biomass residues are processed respecting their extraction limits***. If high or optimistic process efficiencies are reached, ***climate benefits can also be achieved compared to other biofuels*** produced from the same biomass residues or from the same arable land because the use of renewable electricity for reduction/deoxy-genation of carbohydrates to hydrocarbons increases carbon use efficiency. Renewable electricity is

also very important for achieving the minimum GHG emission savings stipulated by the RED II (65%): The results look very promising if the entire electricity demand, including the electricity required for hydrogen provision, can be met from eligible wind or solar electricity[i]. These advantages come at the cost of ***disadvantages regarding all other assessed environmental impacts*** compared to fossil fuels such as acidification and depletion of phosphate resources like for almost all other biofuels.

- ***Technological development is advanced*** but further steps e.g. towards maturity and availability of infrastructure still need to be taken and operational risks need to be managed.

Table 1: **Overview of results for integrated life cycle comparisons of BioMates scenarios to their alternatives for typical scenarios. N/A: not applicable, N/D: not determined/no data; Scenario descriptions and indicator descriptions can be found in the annex in Table 3 and Table 4, respectively.**

| | | | Typical performance | | | | |
|---|---|---|---|---|---|---|---|
| | | | BioMates scenarios | | | | |
| | | **Scenario name in report** | Base case | Miscanthus* | Forest residues | HDT&pyrolysis separate from refinery | All pyrolysis units separate from refinery&HDT |
| | Indicator | Unit | | | | | |
| **Technology** | Technical maturity | - | + | + | ++ | + | + |
| | Availability of logistics infrastructure | - | + | + | + | o | + |
| | Availability of main technological infrastructure | - | + | + | + | + | + |
| | Operational risks | - | o | – | o | – | – |
| | Complexity | - | o | – | o | – | o |
| | Hazardous substances | - | + | + | + | + | + |
| | Biomass feedstock flexibility | - | + | – | o | ++ | ++ |
| | Scale-up technological challenges | - | + | o | + | + | + |
| **Environment** | Climate change | t $CO_2$ eq / t BioMates | -2.0 | -1.9 | -1.9 | -1.8 | -2.0 |
| | Non-renewable energy use | GJ / t BioMates | -29 | -28 | -25 | -25 | -29 |
| | Acidification | kg $SO_2$ eq / t BioMates | 9.3 | 5.1 | 6.1 | 9.5 | 9.3 |
| | Eutrophication, terrestrial | kg $PO_4$ eq / t BioMates | 1.7 | 0.8 | 0.9 | 1.7 | 1.7 |
| | Ozone depletion | g CFC-11 eq / t BioMates | 17 | 7 | 4 | 17 | 17 |
| | Eutrophication, freshwater | kg $PO_4$ eq / t BioMates | 3.4 | 0.3 | 0.0 | 3.4 | 3.4 |
| | Particulate matter | kg PM2.5 eq / t BioMates | 7.8 | 5.0 | 6.3 | 8.0 | 7.8 |
| | Land use | $m^2$ artificial land × yr / t BioMates | 42 | 448 | 37 | 42 | 42 |
| | Phosphate rock use | kg phosphate rock eq / t BioMates | 57 | 23 | 6 | 57 | 57 |
| | $CO_2$ savings acc. RED II ** | % | 80 | 75 | 69 | 79 | 79 |
| | Soil | - | o | o | – | o | o |
| | Water | - | o | – | o | o | o |
| | Biodiversity | - | o | o | – | o | o |
| **Economy** | CAPEX | Million € | 79.1 | 79.1 | 79.1 | 79.1 | 79.1 |
| | **Western Europe** | | | | | | |
| | OPEX | € / t BioMates | 1,558 | 1,149 | 1,245 | 1,563 | 1,561 |
| | Break-even sales price (at IRR=10%) | € / t BioMates | 1,750 | 1,346 | 1,440 | 1,753 | 1,752 |
| | NPV | Million € | -155.7 | -9.8 | -39.6 | -157.7 | -156.9 |
| | IRR | % | N/A | N/A | N/A | N/A | N/A |
| | **Eastern Europe** | | | | | | |
| | OPEX | € / t BioMates | 1,196 | 1,041 | 1,137 | 1,201 | 1,199 |
| | Break-even sales price (at IRR=10%) | € / t BioMates | 1,377 | 1,236 | 1,328 | 1,382 | 1,379 |
| | NPV | Million € | -18.8 | 23.8 | -4.4 | -20.4 | -19.8 |
| | IRR | % | N/A | 8.9 | N/A | N/A | N/A |
| **Society & Policy** | Risk of lack of adequate labour laws | - | + | o | o | + | + |
| | Risk of occupational hazards | - | – | – | – | – | – |
| | Overall risk of gender inequality | - | + | + | + | + | + |
| | Overall risk of corruption | - | + | + | + | + | + |
| | Risk that children are out of school | - | + | + | + | + | + |
| **Composite indicators** | **Western Europe** | | | | | | |
| | $CO_2$ abatement costs | € / t $CO_2$ eq | 539 | 364 | 410 | 621 | 541 |
| | Fossil energy resource savings costs | € / GJ | 38 | 25 | 32 | 44 | 38 |
| | **Eastern Europe** | | | | | | |
| | $CO_2$ abatement costs | € / t $CO_2$ eq | 356 | 306 | 352 | 412 | 358 |
| | Fossil energy resource savings costs | € / GJ | 25 | 21 | 27 | 29 | 25 |

* cultivation on marginal land

** negative values = additional emissions

Taken together, the BioMates concept can improve many and important aspects of sustainability including climate change provided that critical limitations regarding availability of additional renewable electricity, unused biomass residues and economic viability can be overcome. A challenge could be that costs are much more favourable in Eastern Europe while availability of additional renewable electricity is generally higher in Western Europe. Furthermore, battery-electric cars (and in some years also trucks) that can use renewable electricity very efficiently, compete for additional renewable electricity.

**Table 1:** **(continued)**

| Typical performance | | | | | | | |
|---|---|---|---|---|---|---|---|
| **BioMates scenarios** | | | | | | | |
| Disposal of aqueous phase | Pyrolysis char replaces coal/coke | $O_2$ use | Mechanical $H_2$ compression | Mechanical $H_2$ recovery | $H_2$ electrolysis using grid mix power | $H_2$ from natural gas | $H_2$ from natural gas (no recycle) |
| | | | | | | | |
| | | | | | | | |
| + | + | + | ++ | ++ | + | ++ | N/D |
| + | + | + | + | + | + | + | N/D |
| + | + | + | ++ | ++ | + | ++ | N/D |
| ○ | ○ | ○ | + | + | ○ | + | N/D |
| + | ○ | – | + | + | + | + | N/D |
| + | + | + | + | + | + | + | N/D |
| + | + | + | + | + | + | + | N/D |
| + | + | + | + | + | + | + | N/D |
| | | | | | | | |
| -2.0 | -2.4 | -2.1 | -2.1 | -2.1 | -1.2 | -1.5 | -1.2 |
| -29 | -30 | -30 | -30 | -30 | -14 | -24 | -22 |
| 9.3 | 7.8 | 9.1 | 9.2 | 9.1 | 13.4 | 7.5 | 7.6 |
| 1.7 | 1.3 | 1.6 | 1.6 | 1.6 | 2.1 | 1.6 | 1.6 |
| 17 | 15 | 17 | 17 | 17 | 19 | 17 | 17 |
| 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 | 3.4 |
| 7.8 | 5.9 | 7.7 | 7.8 | 7.7 | 10.3 | 6.2 | 6.2 |
| 42 | 42 | 42 | 42 | 42 | 8 | 8 | 8 |
| 57 | 57 | 56 | 57 | 56 | 54 | 52 | 52 |
| 80 | 80 | 80 | 80 | 80 | -19 | 66 | 56 |
| ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| ○ | ○ | ○ | ○ | ○ | ○ | ○ | ○ |
| | | | | | | | |
| 79.1 | 79.1 | 79.1 | 79.1 | 79.1 | 79.1 | 79.1 | 72.8 |
| | | | | | | | |
| 1,558 | 1,558 | 1,558 | 1,548 | 1,537 | 1,974 | 1,407 | 1,480 |
| 1,758 | 1,750 | 1,440 | 1,739 | 1,728 | 2,177 | 1,482 | 1,655 |
| -159.0 | -155.7 | -39.7 | -151.8 | -147.6 | -316.5 | -97.3 | -123.6 |
| N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| | | | | | | | |
| 1,196 | 1,196 | 1,196 | 1,186 | 1,175 | 1,612 | 1,045 | 1,118 |
| 1,385 | 1,377 | 1,067 | 1,366 | 1,355 | 1,806 | 1,220 | 1,282 |
| -21.5 | -18.8 | 74.2 | -15.6 | -12.4 | -176.6 | 28.3 | 7.4 |
| N/A | N/A | 17.8 | N/A | N/A | N/A | 9.7 | 5.7 |
| | | | | | | | |
| + | + | + | + | + | + | + | + |
| – | – | – | – | – | – | – | – |
| + | + | + | + | + | + | + | + |
| + | + | + | + | + | + | + | + |
| + | + | + | + | + | + | + | + |
| | | | | | | | |
| | | | | | | | |
| 544 | 460 | 380 | 529 | 518 | 1,224 | 557 | 858 |
| 38 | 36 | 26 | 37 | 36 | 108 | 35 | 46 |
| | | | | | | | |
| 361 | 304 | 201 | 348 | 339 | 926 | 381 | 540 |
| 25 | 24 | 14 | 24 | 24 | 82 | 24 | 29 |

## Implementation conditions that improve sustainability

The BioMates concept can be implemented in many different ways. For the integrated sustainability assessment, 40 different variants are analysed and compared in a benchmarking process in order to identify those parameter settings that lead to a maximisation of sustainability benefits (Table 2).

Table 2: **Comparison of all other scenarios to the benchmark scenario 'base case'. N/D: not determined/no data; Scenario descriptions and indicator descriptions can be found in the annex in Table 3 and Table 4, respectively.**

| | | Benchmarking | | | | |
|---|---|---|---|---|---|---|
| | | BioMates scenarios | | | | |
| | **Scenario name in report** | Base case | Miscanthus* | Forest residues | HDT&pyrolysis separate from refinery | All pyrolysis units separate from refinery&HDT |
| | Indicator | | | | | |
| **Technology** | Technical maturity | | o | + | o | o |
| | Availability of logistics infrastructure | | o | o | – | o |
| | Availability of main technological infrastructure | | o | o | o | o |
| | Operational risks | | – | o | – | – |
| | Complexity | | – | o | – | o |
| | Hazardous substances | | o | o | o | o |
| | Biomass feedstock flexibility | | – – | – | + | + |
| | Scale-up technological challenges | | – | o | o | o |
| **Environment** | Climate change | | – | o | – | o |
| | Non-renewable energy use | | o | – | – | o |
| | Acidification | | + | + | o | o |
| | Eutrophication, terrestrial | | + | + | o | o |
| | Ozone depletion | | ++ | ++ | o | o |
| | Eutrophication, freshwater | | ++ | ++ | o | o |
| | Particulate matter | | + | + | o | o |
| | Land use | | – – | o | o | o |
| | Phosphate rock use | | ++ | ++ | o | o |
| | $CO_2$ savings acc. RED II ** | | o | – | o | o |
| | Soil | | o | – | o | o |
| | Water | | – | o | o | o |
| | Biodiversity | | o | – | o | o |
| **Economy** | CAPEX | | o | o | o | o |
| | **Western Europe** | | | | | |
| | OPEX | | + | + | o | o |
| | Break-even sales price (at IRR=10%) | | + | + | o | o |
| | NPV | | + | + | o | o |
| | IRR | | + | + | o | o |
| | **Eastern Europe** | | | | | |
| | OPEX | | + | + | o | o |
| | Break-even sales price (at IRR=10%) | | + | + | o | o |
| | NPV | | + | + | o | o |
| | IRR | | ++ | o | o | o |
| **Society & Policy** | Risk of lack of adequate labour laws | | – | – | o | o |
| | Risk of occupational hazards | | o | o | o | o |
| | Overall risk of gender inequality | | o | o | o | o |
| | Overall risk of corruption | | o | o | o | o |
| | Risk that children are out of school | | o | o | o | o |
| **Composite indicators** | **Western Europe** | | | | | |
| | $CO_2$ abatement costs | | + | + | – | o |
| | Fossil energy resource savings costs | | + | + | – | o |
| | **Eastern Europe** | | | | | |
| | $CO_2$ abatement costs | | + | o | – | o |
| | Fossil energy resource savings costs | | + | o | – | o |

* cultivation on marginal land

** negative values = additional emissions

**Table 2: (continued)**

| Benchmarking | | | | | | | |
|---|---|---|---|---|---|---|---|
| **BioMates scenarios** | | | | | | | |
| Disposal of aqueous phase | Pyrolysis char replaces coal/coke | $O_2$ use | Mechanical $H_2$ compression | Mechanical $H_2$ recovery | $H_2$ electrolysis using grid mix power | $H_2$ from natural gas | $H_2$ from natural gas (no recycle) |
| | | | | | | | |
| | | | | | | | |
| o | o | o | + | + | o | + | N/D |
| o | o | o | o | o | o | o | N/D |
| o | o | o | + | + | o | + | N/D |
| o | o | o | + | + | o | + | N/D |
| + | o | – | + | + | + | + | N/D |
| o | o | o | o | o | o | o | N/D |
| o | o | o | o | o | o | o | N/D |
| o | o | o | o | o | o | o | N/D |
| | | | | | | | |
| o | + | o | o | o | – | – | – |
| o | o | o | o | o | – | – | – |
| o | + | o | o | o | – | + | + |
| o | + | o | o | o | – | o | o |
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| o | o | + | o | o | – – | o | – |
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| o | + | + | o | o | – – | o | – |
| o | o | + | o | o | – – | o | – |

The two most important parameters influencing sustainability are biomass feedstock and hydrogen provision:

**Biomass feedstock:**

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- A ***biorefinery designed for cereal straw*** as a feedstock does not pose critical technological challenges. It has the big advantage of being rather flexible in feedstock choice because it is expected be able to process forest residues and similar feedstocks, too, so that economic opportunities can be seized and unsustainable excessive extraction of biomass residues in times of short supply can be avoided.

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- Both ***cereal straw and forest residues are comparable in terms of climate change mitigation*** although calculation rules according to the RED II result in artificially higher savings for straw because its withdrawal of nutrients from cropland and required compensatory fertilisation is not accounted for. If the ***higher risks of forest residue extraction to cause unacceptable local environmental impacts on soils and biodiversity*** can be mitigated through continuous location-specific management respecting ecological limits, then ***advantages of forest residues such as reduced other environmental disadvantages and higher economic viability*** can be exploited.

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- ***Miscanthus entails two severe disadvantages:*** its use is technologically more challenging and its cultivation occupies arable land. The latter could lead to indirect land use change (iLUC) which could jeopardise its future eligibility for regulatory advantages, e.g. as a so-called 'low iLUC-risk biofuel' under the RED. Despite cost benefits, this feedstock should not be targeted unless challenges can be overcome and substantial amounts of cropland are set free, for example by a substantial shift towards a more plant-based diet in Europe.

**Hydrogen provision:**

- The BioMates concept foresees provision of hydrogen from water electrolysis using renewable electricity ('green hydrogen'). A low emission factor for electricity is of utmost importance, since only in this case, the minimum GHG emission savings according to the RED II can be achieved. If green hydrogen is available at a price of 4 EUR/kg without investments by the biorefinery operator[ii], economic viability is challenging but can be achieved under certain conditions.
- From an economic point of view and supported by high technical maturity, the use of hydrogen from natural gas (steam methane reforming, 'grey hydrogen') would be more attractive than green hydrogen. However, this non-renewable hydrogen leads to significantly lower GHG emission savings, and the minimum threshold set by the RED II can only be achieved through multifactorial optimisation and possibly only at certain geographical locations.
- Higher costs and higher greenhouse gas savings when using green hydrogen lead to similar or slightly lower $CO_2$ abatement costs for the green solution. If these costs are considered politically acceptable then investments in green hydrogen should be made immediately instead of investing in temporary grey hydrogen provision.

Other parameter variations regarding logistics, co-product use and hydrogen handling helped to reveal further optimisation potentials:

- Because of benefits from integration (mainly sharing of infrastructure and hydrogen stream inter-linkages), the co-location of refinery and HDT plant performs best. If additionally biomass availability allows for the co-location of one (of four) pyrolysis units, advantages would further increase slightly.
- Regarding co-product use, a low-value use of the aqueous phase can only achieve minor advantages compared to adequate disposal, whereas the use of pyrolysis char to replace fossil coal or coke in material applications considerably improves the environmental performance compared to energy recovery. The capture, sale and use of oxygen, which is co-produced during water electrolysis, prove very beneficial in particular from an economic point of view. However, the price for oxygen could drop significantly in the future if the EU hydrogen strategy /EC-2020/ achieves a massive expansion of water electrolysis. Thus, the economics cannot rely on revenues from oxygen.
- Regarding hydrogen management, the progress made on electrochemical hydrogen compression and recovery within the BioMates project is substantial but not yet sufficient to outperform the conventional mechanical variant in this large-scale application. Hydrogen recovery positively contributes to the economics as well as to the environmental performance.

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

### Recommendations to process developers

- The integrated sustainability assessment clearly underlines that increased process efficiencies would be highly beneficial. Since both operational costs (OPEX) and environmental impacts are mainly determined by the same processes or inputs, synergies in that respect could and should be exploited. This holds particularly for the pyrolysis step, which causes particularly high sustainability impacts in the production of BioMates.
- 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 at least 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.

### Recommendations to potential future operators of biorefineries and linked petrochemical refineries

- Local stakeholders should be engaged to identify all key issues on biorefinery supply / value chains, particularly about local dynamics (e.g. community involvement, gender equity, health and safety and working conditions, and adequate remuneration.
- Biorefinery operators should demand that biomass suppliers adopt sustainable principles relating to land use, workforce, working conditions and wages, equality of opportunity, and health and safety.
- BioMates producers and investors should prioritise recruitment of local pools of labour, giving men and women equality of opportunity to access, progress and upskill on jobs and income-generating activities.
- Confirm the GHG balances according to RED II once official calculation rules for co-processed bio-oil and requirements for the additionality of renewable electricity are available. The values presented in this report are exemplary calculations made before the rules were decided on and thus are only of limited use to support investment decisions.
- 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 savings required by RED II can be achieved as reliably as possible, depending on the regulations in force at the time. Whether the economically attractive use of non-renewable hydrogen from natural gas (steam methane reforming, 'grey hydrogen') can be accommodated without missing the 65% threshold remains to be seen. Using this type of hydrogen could be conceivable in first facilities implementing the BioMates concept for a transitional period until electrolyser (and renewable electricity generation) capacities are significantly expanded. From an environmental point of view, investments into green hydrogen should anyway be pursued to cover the petrochemical 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.




### Recommendations 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-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.



- A clear commitment by policymakers to green hydrogen and a supportive investment climate are needed. Green hydrogen is a fundamental prerequisite for many future technologies, not only for the BioMates concept. A fast implementation could prevent stranded investments in fossil infrastructure.
- The development of knowledge-sharing platforms should be encouraged to link up investors (who may lack knowledge of the biofuels sector) with bioindustry promoters (who may lack knowledge about public funding and financial mechanisms) for leveraging private funding to scale up biorefinery concepts (e.g. BioMates).

## Outlook

Any replacement of crude oil by bio-based and/or synthetic, electricity- and $CO_2$-based fuels or hydrocarbon feedstocks for the chemical industry will (i) face considerable limitations in the availability of biomass and/or renewable electricity and (ii) be more expensive than fossil fuels – at least as long as the consumer does not pay the true environmental costs. The BioMates concept represents an interesting hybrid solution to provide hydrocarbons for applications that cannot (yet) be decarbonised, comprising the use of biomass as renewable carbon source and the use of renewable electricity for reduction and efficient conversion. Therefore, the future development of BioMates should concentrate on the defossilisation of such applications. Furthermore, the decentralised processing of biomass in relatively small-scale pyrolysis plants to produce an intermediate with a higher energy density leads to advantages of the BioMates concept over other advanced biofuels such as cellulosic ethanol or Fischer-Tropsch fuel (BtL) from lignocellulosic biomass, both of which are dependent on much larger central biomass processing facilities.

In view of limited sustainable biomass availability /Rettenmaier-2022/, the BioMates concept could leverage its advantages in the marine and especially in the aviation fuel sector, where attainable prices are much more attractive, but also by providing bio-based naphtha to the chemical industry. This could significantly improve the economic performance compared to the assessed scenarios, already under the regulatory and market conditions of the near future.

Advantages or disadvantages regarding sustainability and feasibility compared to competing renewable fuel options such as cellulosic ethanol and synthetic fuels but also material use of the same biomass, will be determined by uncertain future developments regarding technology improvements/upscaling and the political and regulatory framework that affect economic viability and access to biomass and renewable electricity. Since none of the competing renewable options is fully developed and optimised yet and has specific advantages for different applications and locations, it is impossible to identify the most promising option.

For these reasons, the further development and, if successful, first industrial-scale implementations of promising and suitable defossilisation technologies (such as the BioMates concept) for applications that cannot be decarbonised should be publicly supported, taking into account the above mentioned recommendations. Apart from financial incentives, this requires the rapid adoption of the pending delegated acts related to the RED II required for definitive greenhouse gas calculations to provide security of investment. Furthermore, an 'ecosystem' for the reliable provision of green hydrogen should be established as soon as possible. Based on these prerequisites, the BioMates concept can contribute to a sustainable defossilisation of the European mobility and industry.

## 4. 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.

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# 7. Annex

## Overview of the BioMates scenarios investigated in this study

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 3).

The base case scenario, shown in Figure 2, 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.

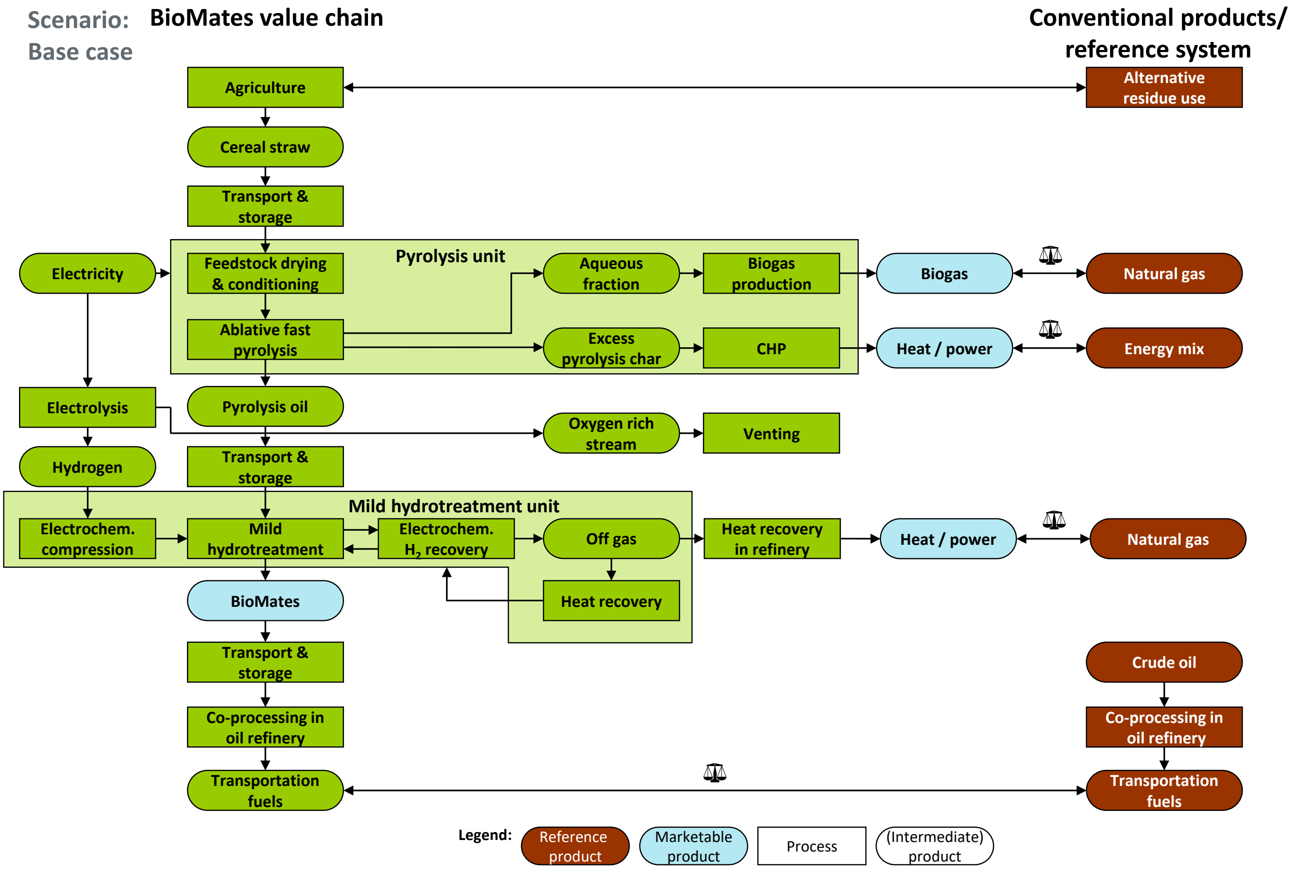


Figure 2: **Life cycle scheme of the base case scenario**

Table 3: **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 |
| **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 |
| **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 |
| **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 |
| **$O_2$ use** | Oxygen is purified and sold to replace oxygen on the market instead of venting |
| **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 |
| **$H_2$ electrolysis using grid power mix** | Hydrogen is produced through electrolysis from grid power mix instead of own renewable power |
| **$H_2$ from natural gas** | Hydrogen is produced through steam reforming of natural gas instead of electrolysis, no oxygen is produced |
| **$H_2$ from natural gas (no recycle)** | No recycling of hydrogen in HDT. Hydrogen is burned instead. Otherwise same scenario settings like for $H_2$ from natural gas. |

The 13 main scenarios are assessed under the assumption of three different future developments. In addition to a typical trajectory, conservative and optimistic trajectories are covered in order to cover a range of future developments.

## Overview of the sustainability indicators used in this study

**Table 4: Overview of sustainability indicators selected for the integrated assessment.**

| Impact category | Short description |
|---|---|
| **Technology** | |
| Technical maturity | Technical maturity of involved processes on EC's technology readiness level (TRL) scale from 1: basic principles observed to 9: actual system proven in operational environment /EC-2014c/ (potential barrier). |
| Availability of logistics infrastructure | Logistics and seasonal storage limitations (time, humidity) of biomass, intermediates and final products. |
| Availability of main technological infrastructure | Availability of required plants, installations and facilities, as well as potential new systems that need to be integrated at commercial scale (potential barrier). |
| Operational risks | Risk of explosions, gas leaks, and fires within industrial facilities (such as pyrolysis and hydro-treating units). |
| Complexity | Potential performance limitations of commercial-scale systems, automation challenges, integration challenges with other technologies. |
| Hazardous substances | Health risks due to poor handling of feeds, intermediates, by-products and emissions. |
| Feedstock flexibility | The capability of the core process to use several different feedstocks interchangeably or in a mixture. |
| Scale-up technological challenges | Further challenges that have to be resolved for up-scaling of the BioMates process. |
| **Environment: global/regional impacts** | |
| Climate change | Global warming/climate change as a consequence of the anthropogenic release of greenhouse gases. |
| Non-renewable energy use | Depletion of non-renewable energy resources, i.e. fossil fuels such as mineral oil, natural gas, coal and uranium ore. |
| Acidification | Shift of the acid/base equilibrium in soils by acidifying gases like sulphur dioxide, nitrogen oxides and ammonia (keyword "acid rain"). |
| Eutrophication, terrestrial | Input of excess nutrients into terrestrial ecosystems directly or indirect via gaseous emissions and erosion (e.g. nitrogen species such as ammonia and nitrogen oxides). |
| Ozone depletion | Loss of the protective ozone layer in the stratosphere by certain gases such as CFCs or nitrous oxide (keyword 'ozone hole'). |
| Eutrophication, freshwater | Input of excess nutrients into freshwater ecosystems directly or indirectly via input into soils and erosion or gaseous emissions (e.g. phosphorous, keyword "algal bloom"). |
| Particulate matter | Damage to human health due to air pollutants, such as fine, primary particles and secondary particles (mainly from $NO_X$, $NH_3$ and $SO_2$, key-word 'London smog'). |
| Land use | Occupation of land at varying degrees of human influence on a natural area /Fehrenbach-2015, Fehrenbach-2019/. |
| Phosphate rock use | Depletion of the limited phosphate resources and contribution to increasing scarcity /Reinhardt-2019/. |
| $CO_2$ savings acc. RED II | Savings of greenhouse gas emissions compared to fossil alternative calculated according to RED II; at least 65% savings are required. |

| Impact category | Short description |
|---|---|
| **Environment: local impacts** | |
| Soil | Soil quality is affected e.g. by erosion, compaction or loss of organic matter. |
| Water | Local water availability and quality for ecosystems. |
| Biodiversity | Local biodiversity among animals and plants. |
| **Economy** | |
| Capital expenditures (CAPEX) | Sum of capital to be invested for new BioMates facilities (excluding hydrogen production). |
| Operating expenditures (OPEX) | Ongoing costs for BioMates production (sum of variable costs, fixed costs and depreciation). |
| Break-even sales price | Sales price at which all costs for provision and a certain profit after tax (IRR = 10%) are covered. |
| Net Present Value (NPV) | The value of all future cash flows (positive and negative) over the entire life of an investment discounted to the present. |
| Internal Rate of Return (IRR) | Measure of profitability. Discount rate that makes NPV of the project zero. |
| **Society & Policy** | |
| Risk of lack of adequate labour laws | Risk of unfair conditions of work or labour accords violations in the value chain; such as child labour, low wages, forced labour, excessive working time or suppression of workers association. |
| Risk of occupational hazards | Risk along the value chain of high prevalence of occupational injuries and deaths, as well as high exposure to workplace hazards. |
| Overall risk of gender inequality | Risk of inequality in terms of rights, payment, opportunities due to gender |
| Overall risk of corruption | Risk of manufacturing processes located in countries or regions with weak legal systems, with high risk of corruption. |
| Risk that children are out of school | Risk of negative impacts along the value chain to the local community, especially in terms of children who do not attend school. |
| **Additional/Composite indicators** | |
| $CO_2$ abatement costs | Additional costs compared to fossil alternative per tonne of greenhouse gas emissions (in $CO_2$ equivalents) saved. |
| Fossil energy resource savings costs | Additional costs compared to fossil alternative per GJ of non-renewable primary energy resources saved. |

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[i] The greenhouse gas balances calculated in this study according to the RED II are only exemplary calculations, since two delegated acts (related to Articles 27 and 28(5) of the RED II) containing the official calculation and eligibility rules were not yet adopted at the time of finalising this report.

[ii] In the economic assessment the CAPEX of a dedicated photovoltaics-based renewable hydrogen facility has deliberately not been taken into account since it was considered a separate project.