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Biomass based energy intermediates boosting biofuel production

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D6.4 Energy Carrier Chain LCA

Sustainability assessment of energy carriers

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Nomenclature

CC	Global Warming Potential
CHP	Combined Heat and Power Plant
CML	Institute of Environmental Sciences of the Faculty of Science of Leiden University
CP	Catalytic Pyrolysis
DM	Dry Material
EIBI	European Industrial Bioenergy Initiative
FCI	Fixed Capital Investment
FD	Fossil Depletion Potential
FE	Freshwater Eutrophication potential
FET	Freshwater EcoToxicity potential
FP	Fast Pyrolysis
FT	Fischer Tropsch
FTE	Full Time Equivalent
GBEP	Global BioEnergy Partnership
GHG	GreenHouse Gases
HT	Human Toxicity potential
HTC	Hydrothermal Conversion
HTC	Hydrothermal Carbonization
IEA	International Energy Agency
IR	Ionizing Radiation potential
KPI	Key Performance Indicators
LCA	Life Cycle Assessment
ME	Marine Eutrophication potential
MET	Marine EcoToxicity potential
MRD	Metal Resource Depletion potential
MSP	Minimum Selling Price
NIBE	Dutch Institute for Building Biology and Ecology
OD	Ozone Depletion potential
OPEX	Operational Expenditure
PMF	Particulate Matter Formation potential
POF	Photochemical Oxidant Formation potential
RED	Renewable Energy Directive
TA	Terrestrial Acidification potential
TCI	Total Capital Investment
TET	Terrestrial EcoToxicity potential
Transport fuel	Gasoline and/or diesel

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1 Introduction

This report is a public deliverable from the EU-FP7 Bioboost project. The project addresses the complete value chain from feedstock potential, the investigation of pyrolysis and hydrothermal carbonisation conversion technologies, the optimization of transport and logistics to the exploitation of the energy carrier and its by-products. Part of the BioBoost project is a study on techno/economic and environmental assessments on the complete supply chain. This report describes results of complete sustainability assessment of the BioBoost energy carriers.

Increasing the share of biomass for renewable energy in Europe demands conversion pathways which are economic, flexible in feedstock and energy efficient. The BioBoost project concentrates on dry and wet residual biomass and wastes as feedstock for de-central conversion by fast pyrolysis, catalytic pyrolysis and hydrothermal carbonization to the intermediate energy carriers oil, coal or slurry.

Major activities in the project, include the analysis of economic efficiency of the complete production pathways, the optimization of logistic chains and the investigation of environmental compatibility. BioBoost aims at making a substantial improvement towards increasing the efficiency of the use of biomass and residues in the future.

This report describes a complete techno economic, and environmental assessment. It starts with a description of the methodology in chapter 2 and a full description of the reference pathways in chapter 3. In chapter 4 the results of the complete sustainability assessment is presented. The sustainability assessment in chapter 4 starts with a total costs calculation per pathway followed by a breakdown of the direct (techno economic) and indirect (environmental) costs into the consecutive steps of the pathway. A sensitivity analysis shows the impacts from the variation of relevant parameters as feedstock type and price, plant capacities and transport distances. The conclusions are presented in chapter 5.

2 Sustainability assessment methodology

This chapter describes the methodology of the techno-economic and environmental assessment. Section 2.1 presents the general approach of the sustainability assessment, Section 2.2 lists the key performance indicators (KPI) for the economic, environmental and social impacts. Section 2.3 shows the inventory process followed by this assessment.

The sustainability assessment methodology was previously published in the restricted BioBoost deliverable "D6.1 BioBoost Assessment Methodology Report". The methodology described in this report is a summary of the methodology report and includes some updates. In ANNEX A and ANNEX B additional information can be found concerning the shadow price and techno-economic assessment methodologies.

2.1 Sustainability assessment methodology

The backbone for the BioBoost methodology and assessments is the GBEP framework. The Global Bioenergy Partnership (GBEP) developed a set of indicators for policymakers and stakeholders to guide the development of the bioenergy sector and to meet international goals on sustainable development. These sustainability indicators are science-based and refer to environmental, social, and economic aspects as shown in Figure 2-1[1]. They were based on earlier roadmaps on biofuels by the International Energy Agency (IEA)[2]. For these reasons, GBEP framework was used as a guiding framework for BioBoost assessment. Practically, the themes from GBEP were used to identify and evaluate the Key Performance Indicators (KPI) which are used to express BioBoost's assessment results.

For the more specific techno-economic Key Performance Indicators, guidelines from the European Industrial Bioenergy Initiative (EIBI)[3] were also used in addition to the GBEP framework.

The specific environmental indicators were also based on Life Cycle Analyses (LCA) and ISO standards 14040 and 14044 (ISO, 2009a,b)[4,5] according to ReCiPe methodology[6]. Renewable Energy Directive (RED)[7] methodology was used as a starting point for the assessment of greenhouse gas emissions.

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[1] GBEP (2011) The global bioenergy partnership sustainability indicators for bioenergy.
[2] IEA (2011) Technology Roadmap - Biofuels for transport.
[3] EC (2011) Key Performance Indicators for the EIBI
[4] ISO (2006b) Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006)
[5] ISO (2006a) Environmental management - Life cycle assessment – Principles and framework (ISO 14040:2006)
[6] Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J., & Zelm, R. v. (2009) ReCiPe 2008 - A life cycle impact assessment methodology which comprises harmonised category indicators at the midpoint and endpoint level.
[7] (EC, 2009) DIRECTIVE 2009/28/EC on the promotion of the use of energy from renewable sources

PILLARS GBEP's work on sustainability indicators was developed under the following three pillars, note the interlinkages between them:		
Environmental	**Social**	**Economic**
THEMES GBEP considers the following themes, these themes form the basis for the relevant Key Performance Indicators (KPI's) for BioBoost assessments:		
Greenhouse gas emissions, Productive capacity of the land and ecosystems, Air quality, Water availability, use efficiency and quality, Biological diversity, Land-use change, including indirect effects.	Price and supply of a national food basket, Access to land, water and other natural resources, Labor conditions, Rural and social development, Access to energy, Human health and safety.	Resource availability and use efficiency in bioenergy production, conversion, distribution and end-use, Economic development, Economic viability and competiveness of bioenergy, Access to technology and technological capabilities, Energy security/Diversification of sources and supply, Energy security/Infrastructure and logistics for distribution and use.

Figure 2-1 An overview of the GBEP themes organized in three sustainability pillars which form the basis for the identification and evaluation of BioBoost's relevant Key Performance Indicators.

Figure 2-2 shows a graphical representation and the flow of information through this framework. Data from the partners was gathered via questionnaires and organized in a data inventory. The models extracted the required data from the inventory and calculate the selected KPI in the assessment, which are defined based on the GBEP and EIBI frameworks as previously mentioned.

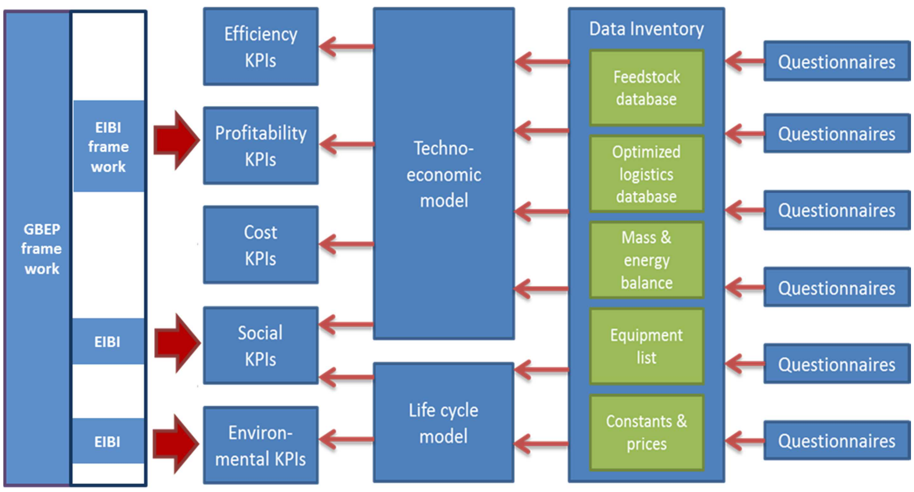


Figure 2-2 Graphical depiction of the framework used to calculate the key performance indicators

The aim of the assessments is to identify strengths and weaknesses of the final energy products and pathways on techno-economic, environmental and social impacts. For comparison reasons, both the final energy products as well as their intermediate products (the bioenergy carriers) were benchmarked with their fossil equivalents. Figure 2-3 shows how the intermediate products and the final energy products were benchmarked. This report is focused on the entire value chain, including the fossil benchmarks of the final products.

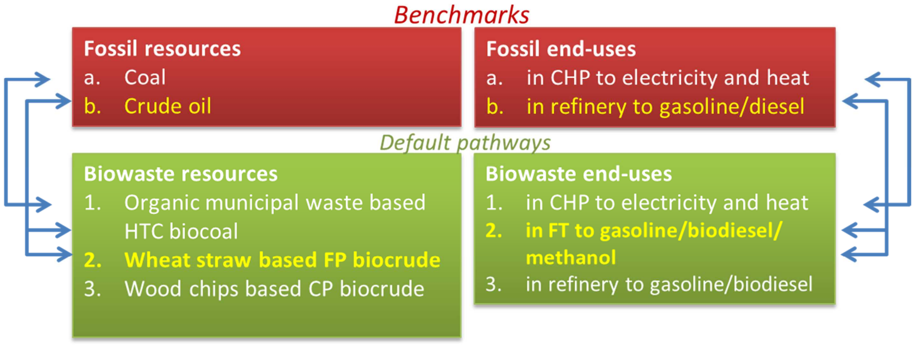


Figure 2-3 Overview of the fossil benchmark products and processes versus the reference (or default) pathways

2.2 Key performance indicators

2.2.1 Economic

The economic performance of each pathway is evaluated referring to the main pathway sections as shown in Table 2.1. Each section indicator includes all related costs, such as operational and capital if applicable. In this way, all pathway costs are converted to the same units and their sum gives the total production costs, or the minimum selling price, of the energy carriers and the final energy products. The units of the two-step approach are listed in Table 2.1. In terms of benchmarking, as stated in Section 2.1, the minimum selling price of the energy carriers and final energy products are compared to their fossil equivalents.

Table 2.1 Economic performance indicators

Pathway section	***Description***	***Units – step 1***	***Units – step 2***
Feedstock	Feedstock cost	EUR/MWh of energy carrier	EUR/MWh of final energy product
Logistics local	Handling and transport to local plant cost	EUR/MWh of energy carrier	EUR/MWh of final energy product
Local processing	Local processing plant cost	EUR/MWh of energy carrier	EUR/MWh of final energy product
Logistics central	Handling and transport to central plant cost	n.a.	EUR/MWh of final energy product
Central processing	Central processing plant cost	n.a.	EUR/MWh of final energy product

Additionally, the cost breakdown was also reported as the Key Performance Indicators listed in Table 2.2.

Table 2.2 Economic Key Performance Indicators

Key Performance Indicator	***Unit***
Cost of biomass at exit gates of the fields	EUR/kg of biomass
Cost to deliver biomass at local plant	EUR/kg of biomass
Cost for logistics to the local plant	EUR/kg of biomass
Cost for logistics to the central plant	EUR/kg of energy carrier
Total capital investment of local processing plant	EUR
Cost of operating local processing plant (incl. depreciation)	EUR/yr
Total capital investment of central processing plant	EUR
Cost of operating central processing plant (incl. depreciation)	EUR/yr
Cost to deliver energy carrier at central plant (minimum selling price)	EUR/MWh of energy carrier
Cost to produce a unit of the final energy product (minimum selling price)	EUR/MWh of final product

2.2.2 Environmental

The environmental assessment follows a three step approach to enable the comparison of the results with existing studies (see Table 2.3). In the first step only the greenhouse gas (GHG) footprint is assessed according to the Renewable Energy Directive (RED)[7]. In the second step, the environmental impacts from conventional Life Cycle Assessment (LCA) are taken into account to broaden the scope to other environmental impacts besides GHG. And in the third step, the -new- bio-related impacts; which are relevant to biomass but not yet included in a conventional LCA; are assessed. The uncertainties increase per step due to a lack of data and of existing methodologies for the -new- bio-related environmental impacts. Nevertheless, all steps are needed to assess the overall impacts of the production and use of bio-based energy carriers.

Table 2.3 Three step approach for the environmental assessment

	Assessment step	***Goal***
1	Assess **GHG footprint** according to RED	Benchmark the GHG performance with existing **RED** standards
2	Assess **additional conventional environmental impacts** according to ISO	Identify contributions of different processes to environmental impacts along the life cycle
3	Assess **-new- bio-related environmental** impacts: water, soil quality and land use	Explore -new- environmental risks with respect to biomass, not yet included in standard LCA

2.2.2.1 Step 1: GHG footprint according to RED

The first step in the assessment is the calculation of the GHG footprint according to the RED. The GHG emissions are calculated by summing up the emissions of the separate steps in the product chain or pathways by:

$$E = E_{ec} + E_l + E_p + E_{td} + E_u - E_{sca} - E_{ccs} - E_{ccr} - E_{eec} \qquad (2\text{-}1)$$

$\boldsymbol{E}$	**-**	**Total emissions from the use of the fuel**
E_{ec}	-	Emissions from the extraction and cultivation
E_l	-	Annualized emissions from carbon stock changes caused by land-use change
$\boldsymbol{E_p}$	**-**	**Emissions from processing**
$\boldsymbol{E_{td}}$	**-**	**Emissions from transport and distribution**
E_u	-	Emissions from the fuel in use
E_{sca}	-	Emission savings from soil carbon accumulation via improved agricultural management
E_{ccs}	-	Emission savings from carbon capture and storage
E_{ccr}	-	Emission savings from carbon capture and replacement
E_{eec}	-	Emission savings from excess electricity generation

The steps that are relevant in this assessment are the emissions from processing (E_p) and from transport and distribution (E_{td}). The other steps are not relevant for the product chains analyzed in this project because of the system boundaries of the pathways, the type of processes and the definitions in RED methodology.

In this assessment, the processing step also contains the emissions from the production of chemicals and products used in the process. The emissions from the manufacturing of machinery and equipment were excluded. The emissions from extraction and cultivation were set at zero because the studied pathways have waste and residues as feedstock. The use phase of the product and related emissions were excluded because of the system boundaries of the pathways. The pathways boundaries are after the production of the final energy products (fuel or electricity) and do not include the use of the fuel for transportation. However there is one exception. The CO_2 emissions in the use phase of the transport fuels are taken into account. These are making the positive difference between the biobased and the fossil fuels. The produced electricity was considered as a co-product and the related emissions will be divided on an energy base between the product (e.g. fuel) and the produced electricity.

2.2.2.2 Step 2: conventional impacts according ISO

The second step assesses the conventional environmental LCA impacts. It broadens the scope to other environmental themes than only climate change, which are include in standard LCAs according the ISO standards. The KPI related to these conventional impacts are given in Table 2.4. The KPI's are based on the impact categories from the ReCiPe methodology and are calculated using SimaPro software[8]. Shadow price methodology is used to aggregate the results to one indicator for the environmental impacts because all KPI have different units and cannot be compared directly. In this study they were aggregated as external or indirect costs. The shadow price for the theme of Marine Eutrophication has been changed due to advancing insight. It is set at 1.14 instead of 12.5 EUR/kg N-eq. See Annex L for a detailed motivation.

The metal and fossil depletion potential have a shadow price of zero EUR/kg. It is assumed that the scarcity of these resources will be internalized in the market price. Therefore, these impacts were excluded from this assessment when using the external costs as environmental impacts.

[8] Pré Consultants, SimaPro software version 7.3

Table 2.4 Overview of conventional KPI for the environmental assessment

	KPI	*Unit*
CC	global warming potential	kg (CO_2 to air)
TET	terrestrial ecotoxicity potential	kg (14-DCB to industrial soil)
OD	ozone depletion potential	kg (CFC-11 to air)
IR	ionizing radiation potential	kg (U^{235} to air)
TA	terrestrial acidification potential	kg (SO_2 to air)
HT	human toxicity potential	kg (14DCB to urban air)
POF	photochemical oxidant formation potential	kg (NMVOC to air)
PMF	particulate matter formation potential	kg (PM_{10} to air)
FE	freshwater eutrophication potential	kg (P to freshwater)
ME	marine eutrophication potential	kg (N to freshwater)
FET	freshwater ecotoxicity potential	kg (14-DCB to freshwater)
MET	marine ecotoxicity potential	kg (14-DCB to marine water)
MRD	metal depletion potential	kg (Fe)
FD	fossil depletion potential	kg (oil)

2.2.2.3 Step 3: New bio-related environmental impacts

The third step assesses the new bio related impacts which are relevant for bio-based processes but are not -yet- taken into account in conventional LCA. The results from this step have more uncertainty than the conventional LCA and the GHG footprint analysis due to a lack of data and existing LCA methodologies. The KPI for the new bio related impacts are listed in Table 2.5 and were fully explained in the methodology report (Deliverable D6.1).

The approach for Soil Quality Loss (SQL) is slightly modified. The soil quality is covered by the indicators of land occupation and transformation in the ReCiPe methodology. Nevertheless, GBEP explicitly mentions SQL as a relevant indicator. Within our framework we assume that on average 5% of value of the land is related to the soil quality. As a result the shadow price for land use is reduced by 5% and this value is allocated to the SQL.

Table 2.5 Overview of – new- bio related KPI for the environmental assessment

	KPI	*Unit**
SQL	soil quality lost	m^2·yr (agricultural land)
WD	non-renewable water depletion potential	m^3 (non-renewable water)
ALO	agricultural land occupation potential	m^2·yr (agricultural land)
ULO	urban land occupation potential	m^2·yr (urban land)
NLT	natural land transformation potential	m^2 (natural land)

* The unit of the impact category here is the unit of the indicator result, thus expressed relative to a reference intervention in a concrete LCA study.

2.2.3 Monetization of environmental impacts

The impacts referred to by the indicators are not directly interchangeable, e.g. climate change emissions cannot directly compared with toxic emissions, let alone exchanged with each other. This is why the ISO14040 Life Cycle Assessment Framework not allows weighing of different indicators into one overall indicator when comparing in public alternative production routes. Hence, product pathways can only be compared on the level of impact categories according to ISO. In some cases, with uniformly distributed results, this approach yields clear conclusions, however, in many cases the results in different impact categories take opposite directions leading to ambiguous conclusions.

The lack of comparability of environmental impacts poses a problem to investors, designers and not least to environmental policy-makers. To avoid a transfer of these interpretation problems to stakeholders, we choose to provide additional guidance with respect to the weighing of different impacts in order to be able to draw overall conclusions for different fossil or biobased pathways on the order of impacts. The environmental impacts are monetized by the shadow price methodology. In Annex A the methodology is explained in detail. In this section is summarized how emission data are processed to calculate impacts and finally to calculate valuation of the impact.

Figure 2-4   Two step approach to calculate the impact valuation from the inventory data

The environmental results as we showed in the result, are based on two main steps:

Step 1
1) From the inventory data to an environmental impact, e.g from CO2, CH4 emissions to the impacts of global warming (in CO2 equivalents). The inventory data are based on the partners questionnaires and/or databases like EcoInvent[9]. This step is fully in line with the ISO standards.

Step 2
2) From an environmental impact to external costs (in EUROS) using a shadow price. The shadow prices are in general based on damage costs of the impacts, e.g. the damage to human health and ecosystems by emitting 1 kg of CO2. Valuation of impacts is not in line with ISO as it contains subjective values for e.g. shadow prices.

Uncertainties will be there in every factor of the equation: inventory, characterization factor and shadow price. These uncertainties were not quantified in this study.

The shadow price approach values the environmental impacts from the perspective of present policy or present collective preferences and not for long-term sustainable solutions, because the shadow price of these long-term objectives is difficult to establish. The present collective preferences can differ per country. This implies that the use of shadow costs is meaningful at national or European level, where environmental pressure and environmental objectives and needs are more or less of a comparable order. Hence, although most of the prices used in this report are assessed for the Dutch situation, these prices are more or less representative for the European situation. This is confirmed by other European studies having assessed prices in the same order of magnitude. Nevertheless it is sensible to view the weighing with shadow prices as a what-if scenario ('what is the result if we assume this value'). See also Annex A for a more detailed explanation.

[9] EcoInvent database v2.2 (2010), Swis Centre for Life Cycle Inventories, Dübendorf

2.3 Data inventory process

The data inventory process is schematically shown in Figure 2-5. It started with the presentation and explanation on methodology followed by instructions for filling out the questionnaire. After a first collection of data and bilateral interaction with all partners a draft sustainability assessment was presented at the BioBoost consortium meeting in Delft 2013. Based on the presentation of these results and the discussions during the pathway workshops, improved questionnaires were generated, leading to the intermediate sustainability assessment presented in this intermediate report.

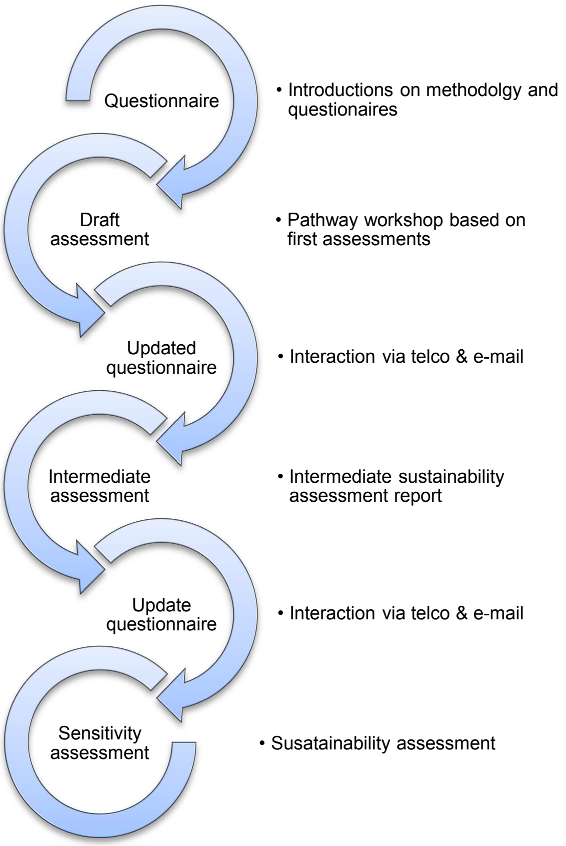


Figure 2-5 Process of gathering data via questionnaires, an intermediate assessment

3 Reference pathways for bioenergy carriers

3.1 Overall description of reference pathways and benchmarks

Three reference pathways were defined to build base scenarios for the sustainability assessment of biofuels production from waste biomass. These pathways relay on producing intermediate energy carriers in local plants which are then transported to central plants that convert them into biofuels. The project partners investigate the feasibility of producing energy carriers from fast pyrolysis, catalytic pyrolysis and hydrothermal carbonization. Table 3.1 lists the general description of the three pathways, studied in this project, including the type of biomass that each technology employs, their energy output capacities, main final energy product, and fossil benchmarks. Table 3.2 also lists the input and output capacities of each pathway. A complete description of each pathway is explained in the following sections.

Table 3.1 Reference pathways general description

	Fast Pyrolysis		*Catalytic Pyrolysis*	*Hydrothermal carbonization*
Biomass	Wheat straw		Beechwood	Clean organic municipal waste
Biomass capacity	219 ktonne/yr		187 ktonne/yr	80 ktonne/yr
Bioenergy carrier	Biosyncrude		Bio-oil	Biocoal
Bio energy carrier energy content [MJ/kg]	17,04		29,5	21
Bioenergy carrier benchmark	Fossil crude oil			Fossil coal
Local processing technology capacity	100 MW		50 MW	12 MW
Central processing technology	Gasification		Refinery	Combined Heat and Power
Biofuel	Gasoline and Diesel	Methanol	Gasoline and Diesel	Heat and Power
Biofuel fossil benchmark	Fossil gasoline and diesel	Methanol from natural gas	Fossil gasoline and diesel	Heat and Power
Biofuel energy content [MJ/kg]	43,00	19,95	43,00	NA
Central processing technology capacity	404 MW	550 MW	260 MW	*20MW*

Table 3.2 Reference pathways input and output capacities

Pathway	*design capacity (input)*	*operating hours*	*design capacity (input)*	*design capacity (output)*	*design capacity (output)*
	t/yr	hr/a	MW	t/yr	MW
FP-pyrolysis (wheat straw)	219123	7008	117	148056	100
FP-gasification (biosyncrude)	1479454	7008	999	237092	404
CP-pyrolysis (beechwood)	186864	8000	104	46716	47.9
CP-refinery (bio-oil)	249690	7901	259	172200	260
HTC (biowaste)	79968	8000	47	16800	12.2 *MWe*
CHP (bio-coal)	100800	8000	74		20

As it was mentioned before, biomass is the raw material for the production of bioenergy carriers and each technology can handle different types of biomass depending on their specifications. Table 3.3 shows a lists of feedstock specifications that each technology employs as a reference. A logistics and transportation study was carried out by FHOÖ investigating the appropriate transport media depending on the bioenergy carriers and final energy products. This study also considers the storage and handling of the biomass, bioenergy carriers, and final energy products.

Table 3.3 Feedstock specifications

Parameter	***Fast Pyrolysis***	***Catalytic Pyrolysis***	***Hydrothermal carbonization***
Biomass type	Wheat straw	Beechwood	Clean organic municipal waste
Biomass size range [mm]	3 x 10	5	5 - 50
Moisture content [%wt]	15	8	70
Ash content [% wt]	6	0,54	15
Biomass density [DM kg/m3]	150	250	150-200
Energy content - LHV [MJ/kg]	13,44	16	16,9

3.1.1 Sensitivity analysis description

The aim of the sensitivity analysis is to vary each parameter independently to analyze how does each parameter influence the economic and environmental Key Performance Indicators (KPI). Therefore, each parameter will be treated independently to define a window of operation and a realistic and optimistic scenario(s).

Parameters assessed in the sensitivity analysis

- *Feedstock* - The choice of different feedstocks influences the overall process performance as well as in the economic and environmental impacts. Therefore, the sensitivity analysis aims to integrate the implications of using different feedstocks for each pathway. At the beginning of the project, several feestocks were selected for each technology and TNO requested information to the technology partners to assess the performance of the processes and compare them with the reference feedstock. The feestocks selected for each technology are as the following: wheat straw, scrap wood, miscanthus for Fast Pyrolysis, beechwood, wheat straw, miscanthus or cardoon for Catalytic pyrolysis, and organic municipal waste and brewing residues for HTC.

- *Feedstock cost* - As well as the feedstock influence the overall performance of the processes, the cost of each feedstock will influence the economic profile of each technology. The sensitivity analysis aims to consider a minimum and maximum feedstock cost to define an cost window for the main cost driver.
- *Transport distances* - In order to assess the influence of the transport distances and logistics cost, minimum and maximum distances from the feedstock source to decentral plants and to central plants were defined. This values should also be compared or get from the optimization model in order to consider the feedstock availability and possible distances to decentral and central plants.
- *Capacities* - In order to analyze the economies of scale, possible and feasible minimum and maximum plant capacities for both, decentral and central plants were defined. This information will also be used to compare with the optimization done by FHOÖ and to evaluate technically feasible scenarios.

The following sections include more specific values for the sensitivity parameters.

3.2 Description and assumptions of reference pathway using fast pyrolysis

3.2.1 Description of pathway

As described in Section 3.1, fast pyrolysis reference pathway converts wheat straw into biosyncrude in the local processing plant. Later, biosyncrude is converted either into gasoline and diesel or methanol in a central gasification plant designed for both products. The capacity for the local processing plant was designed for 100 MW of biosyncrude with a biomass capacity of 219 ktonne/yr. Figure 3-1 illustrates the value chain for the fast pyrolysis reference pathway including the truck transportation (50 km) of wheat straw to the local fast pyrolysis plant and rail transport (250 km) of biosyncrude to the central gasification plant. It was assumed that the agricultural fields are 50 km away from the fast pyrolysis plant and the central gasification plan is in a distance of 250 km from the local plant.

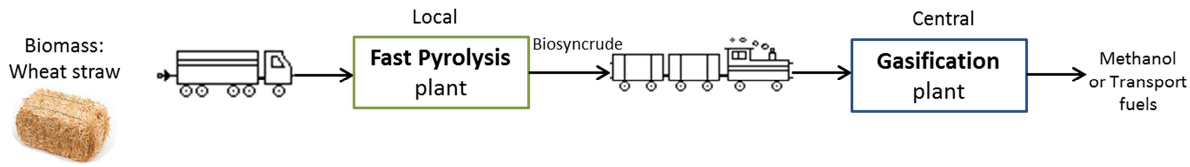


Figure 3-1 Fast pyrolysis reference pathway diagram

The conversion of the biomass by fast pyrolysis consists in three major steps: biomass preparation, fast pyrolysis reaction, and product recovery. In the biomass preparation step, the biomass is cut, milled, and dried. Then, it is send to the fast pyrolysis reaction which takes few seconds before the pyrolysis products are recovered. The recovery steps consists in a first solid separation, where the char is recovered and the gas products are sent to two condensation steps where the organic and aqueous phase are separated. The remaining gas phase is then transferred to a gas burner to use it as process energy. Finally, the char, the organic and aqueous phases are mixed to form the biosyncrude[10].

In terms of the central gasification process, two options were considered. The first one consists in feeding the biosyncrude to a gasifier to produce syngas, which is then converted to gasoline and

[10] KIT – Fast pyrolysis process diagram

diesel via Fischer-Tropsch synthesis. The second option consists on converting the syngas from the biosyncrude into methanol[11].

3.2.2 Sensitivity parameters

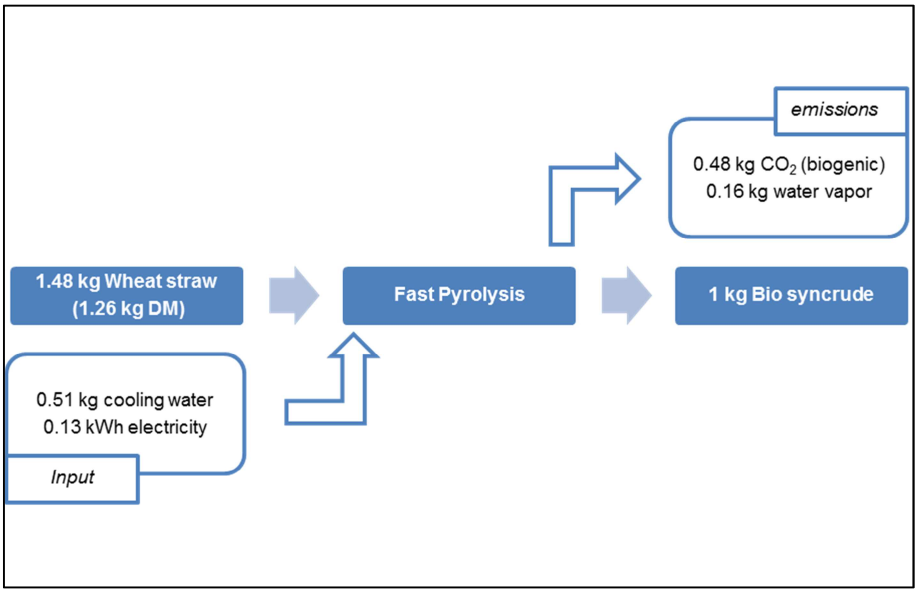
The following parameters and values were used in the sensitivity analysis of the fast pyrolysis pathway to produce a transport fuel (gasoline and diesel). The parameters and consequential values were defined in close cooperation with the partners.

Table 3.4 Sensitivity parameters and values of the fast pyrolysis process

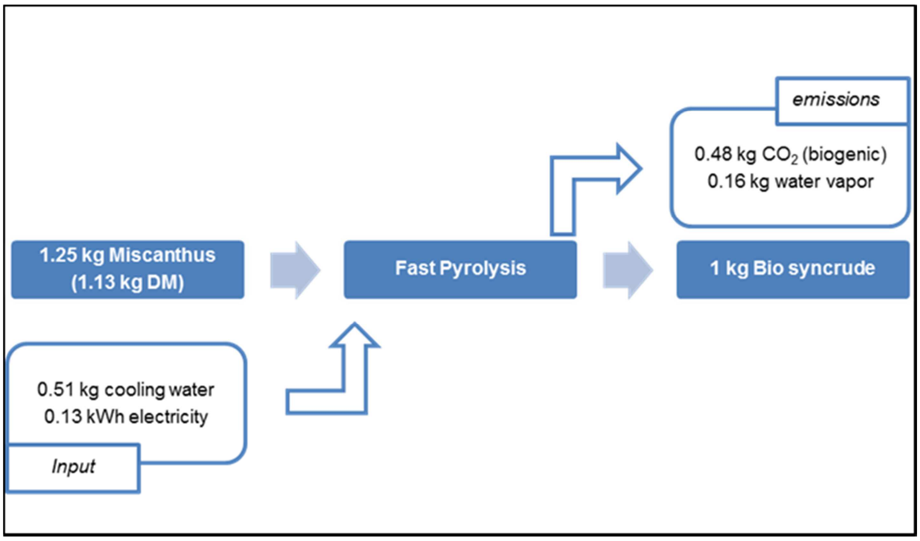
Parameter	*Values*
Feedstock	wheat straw, miscanthus and scrap wood
Feedstock cost	wheat straw 32, 60 and 140 euro/tonne
Local transport distance	25, 50, 100 and 250 km
Central transport distance	150, 250, 500 and 750 km
Local output capacity	50, 100, 300 and 900 MW
Central output capacity	150, 300, 404 and 1000 MW

3.2.3 Overall input and output diagram

Figure 3-2 shows the physical inputs and outputs of the fast pyrolysis process to produce 1 kg of biosyncrude from wheat straw, miscanthus and scrap wood[12]. The inputs for the fast pyrolysis process are electricity[13] and cooling water[14]. Biogenic CO_2 and water vapor are the reported emissions of the process. There are no by-products and no waste stream identified in the process. The environmental impacts from wheat straw production and miscanthus are based on data from Renew project[15]. The scrapwood is based on EcoInvent process for industrial wood chips[16].



[11] KIT – FT and Methanol process diagrams
[12] KIT, Questionnaire version 2012.08.24, updated July 2014 by KIT for other feedstock
[13] EcoInvent process - Electricity, low voltage, at grid/DE U, adjusted for year 2020
[14] EcoInvent process - Water, cooling, surface
[15] Jungbluth N. (2007) LCA of BTL-fuel production: Inventory Analysis – process: wheat straw, bales, at field/kg/RER
[16] EcoInvent process - Wood chips, mixed, from industry, u=40%, at plant/RER U



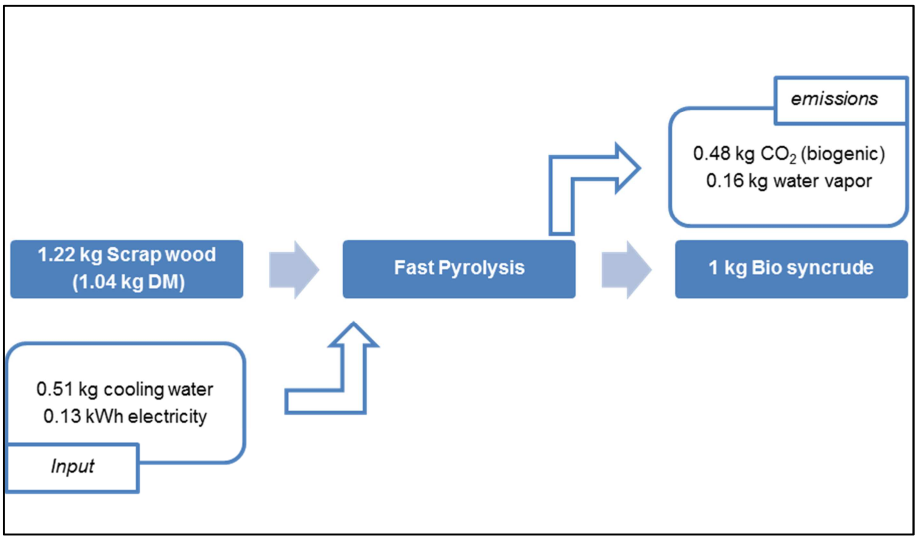


Figure 3-2 Input/output diagram of 1 kg of biosyncrude production via the fast pyrolysis process, with wheat straw, miscanthus and scrap wood as feedstock

Figure 3-3 show the physical inputs and outputs of the production of respectively and 1 kg of transport fuel[17] from biosyncrude and 1 kg of methanol[18] via the gasification process. Electricity is generated as by-product. The inputs are natural gas, to start up the process, and air. Biogenic CO_2 and water vapor are the only reported emissions. The waste streams are water and slag but no stream composition were given. For that reason, several assumptions were made. For instance, an average incineration residue was selected from the EcoInvent database[19] for the slag stream and an average waste water treatment plant was assumed[20].

[17] KIT, Questionnaire version 2013.04.10
[18] KIT, Questionnaire version 2013.04.10
[19] EcoInvent process - Disposal, average incineration residue, 0% water, to residual material landfill/CH U
[20] EcoInvent process - Treatment, sewage, to wastewater treatment, class 3/m^3/CH

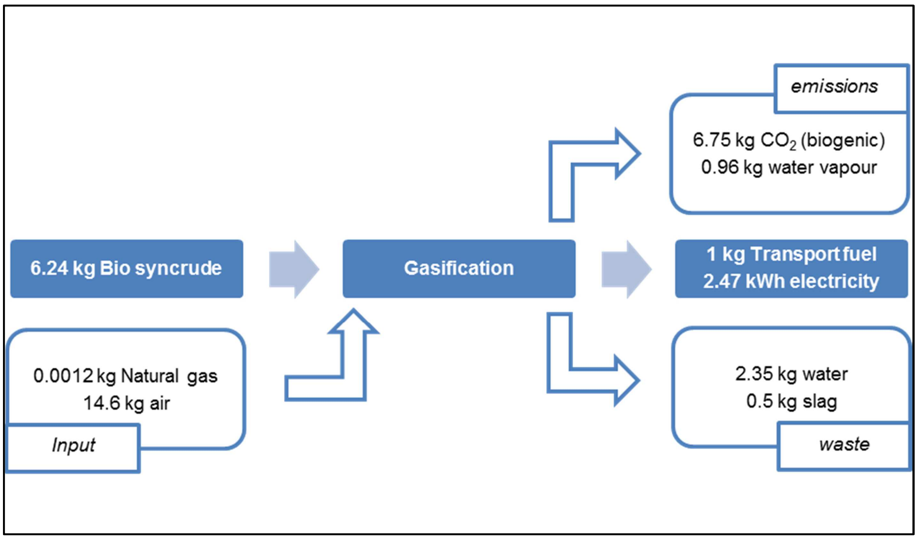


Figure 3-3 Input/output diagram of the production of 1 kg of transport fuel production via the gasification process

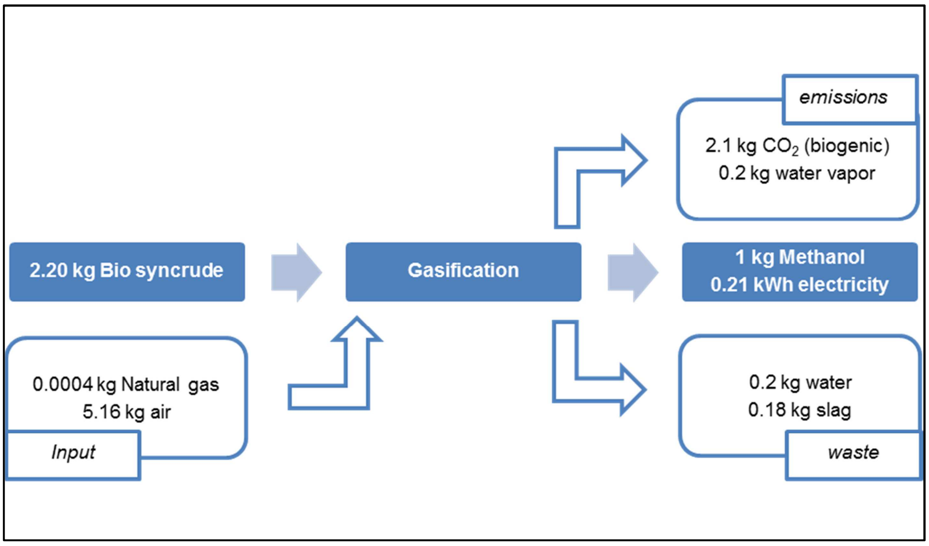


Figure 3-4 Input/output diagram of the production of 1 kg of methanol via the gasification process

3.3 Description and assumptions of reference pathway using catalytic pyrolysis

3.3.1 Description of pathway

Catalytic pyrolysis reference pathway converts beechwood into bio-oil in the local processing plant as also described in Section 3.1. Later, bio-oil is converted into gasoline and diesel in a refinery plant. The capacity for the local processing plant was designed for 50 MW of bio-oil with a biomass capacity of 187 ktonne/yr. Figure 3-5 illustrates the value chain for the catalytic pyrolysis reference pathway including the truck transportation (50 km) of beechwood to the local pyrolysis plant and rail transport (250 km) of bio-oil to the central refinery plant. It was assumed that the forestry fields are 50 km away from the catalytic pyrolysis plant and the refinery plan is in a distance of 250 km from the local plant.

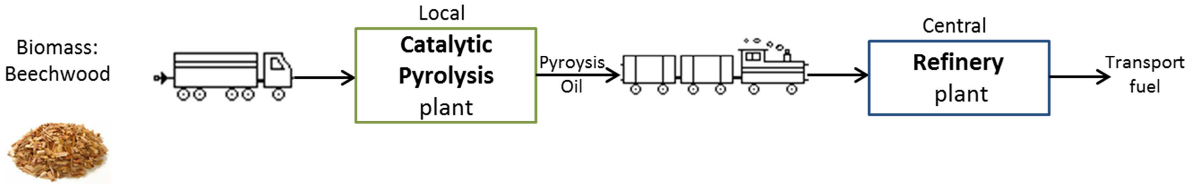


Figure 3-5 Catalytic pyrolysis reference pathway diagram

This pathway consists in milling and drying the beechwood before it enters the catalytic reactor. The vapor produced in the reaction is separated from the catalyst and char to enter the fractionation system. Coke and char are burned in the regenerator vessel an provide the energy required for the pyrolysis process. Later, the organic vapors from the reactor are cooled down in several steps to form a partially condensed liquid, from which a light gas fraction is separated and the organic liquid is the bio-oil[21]. The bio-oil is then upgraded in a refinery plant which consists on mixing the bio-oil with hydrogen before it enters the hydrotreater. The product from the hydrotreater is heated before entering the hydrocracker from which the upgraded bio-oil is produced with a reduced oxygen content. Later, the upgraded bio-oil goes to a heat recovery steam generator before entering the cracking unit which separates the long chain hydrocarbons, from C6 to C20 as final products[22]. ANNEX E describes the upgrading concept used on this study.

3.3.2 Sensitivity parameters

The following parameters and values were used in the sensitivity analysis of the fast pyrolysis pathway to produce a transport fuel. The parameters and consequential values were defined in close cooperation with the partners.

Table 3.5 Sensitivity parameters and values of the catalytic pyrolysis process

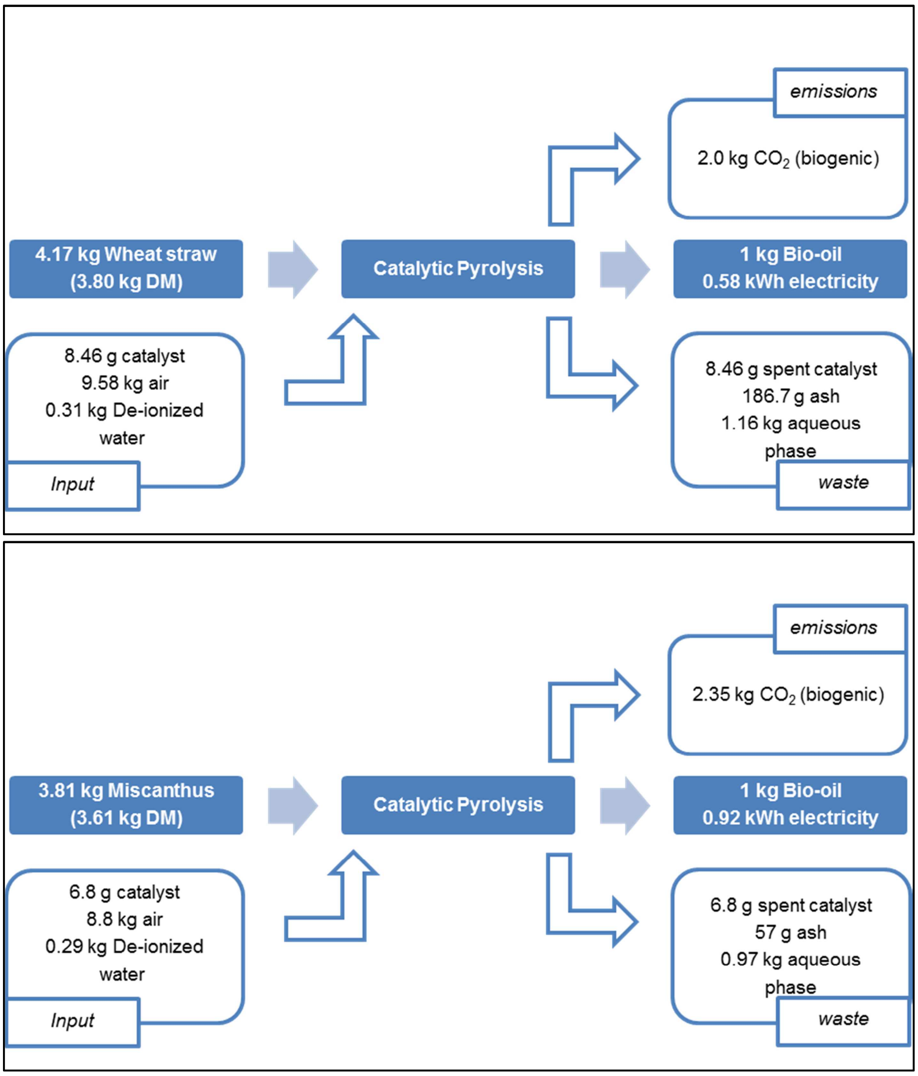
Parameter	*value*
Feedstock	wheat straw, miscanthus and beech wood
Feedstock cost	beech wood 30, 40 and 80 euro/tonne
Local transport distance	25, 50, 100 and 250 km
Central transport distance	150, 250, 500 and 750 km
Local output capacity	25, 50, 200 and 500 MW
Central output capacity	130, 260, 520 and 780 MW

[21] Vasalos, I, et al. CERTH progress report: Biomass catalytic pyrolysis investment and utility cost, 2013.04.02

[22] Gust, S. CPO upgrading options report, 2013.08.14

3.3.3 Overall input and output diagram

Figure 3-6 shows the physical inputs and outputs of the catalytic pyrolysis process to produce 1 kg of bio-oil[23] from beechwood. Additional inputs are the catalyst, air, and de-ionized water. The environmental impacts for the biomass production (e.g energy needed for harvesting, land used) were assumed similar as for residual hard wood from the EcoInvent database[24]. The residual hard wood is a by-product in the multi output process of thinning/final cutting hardwood similar as the beechwood. For the catalyst, an Al_2O_3/SiO_2 based catalyst was taken as a reference[25] For the waste streams of catalyst, ash and water three processes from the EcoInvent database were selected in absence of real data[26][27][28].



[23] CERTH, questionnaire 2013.05.20

[24] EcoInvent - residual wood, hardwood, under bark, air dried, u=20%, at forest road/m3/RER, The residual hard wood is a by-product in the multi output process of thinning/final cutting hardwood, with round wood as the main product. The allocation of impacts is based on the overall proceeds of the site,

[25] EcoInvent - zeoliteZeolite, powder, at plant/kg/RER

[26] EcoInvent - Disposal, zeolite, 5% water, to inert material landfill/CH U

[27] EcoInvent - Disposal, wood ash mixture, pure, 0% water, to municipal incineration/CH U

[28] EcoInvent - Treatment, sewage, to wastewater treatment, class 3/CH U

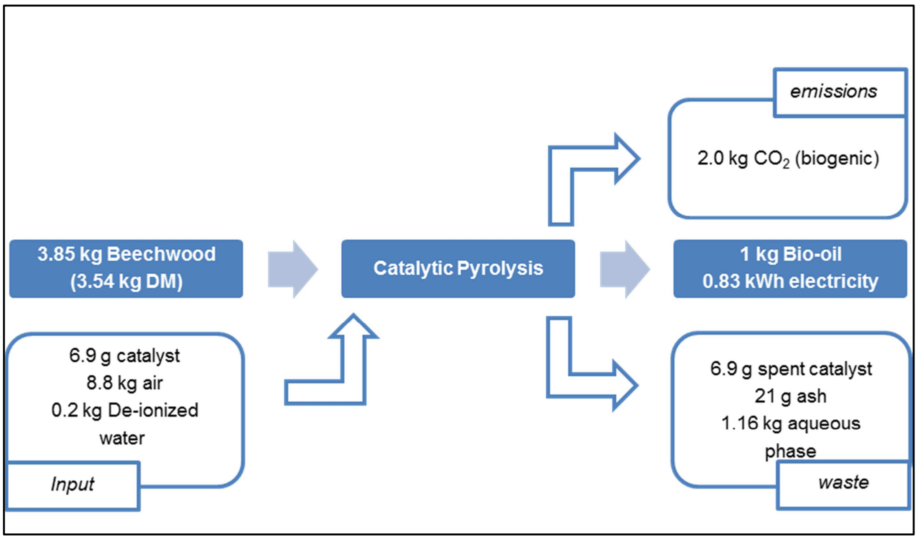


Figure 3-6 Input/output diagram of the catalytic pyrolysis process to produce 1 kg of bio oil, with wheat straw, miscanthus and beech wood as feedstock

Figure 3-7 shows the physical inputs and outputs of the catalytic pyrolysis process to produce 1 kg of transport fuel[29]. For electricity, hydrogen and steam production, processes from the EcoInvent database were selected[30][31]

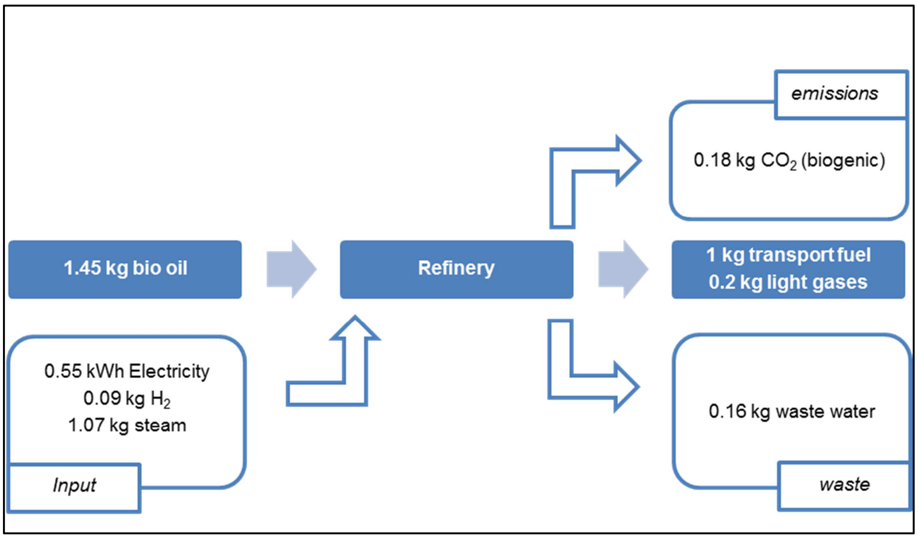


Figure 3-7 Input/output diagram of the refinery process to produce of 1 kg of transport fuel

[29] Nesté/TNO, discussion 2013.08.13
[30] EcoInvent - Steam, for chemical processesprocess - Electricity, low voltage, at plant/RERgrid/DE U, adjusted for year 2020
[31] EcoInvent - Hydrogen, cracking, APMESteam, for chemical processes, at plant/RER U

3.4 Description and assumptions of reference pathway using hydrothermal carbonization

3.4.1 Description of pathway

Hydrothermal carbonization (HTC) reference pathway converts clean organic municipal waste into biocoal in the local processing plant as it is also described in Section 3.1. For this reference pathway it is assumed that biocoal is converted into electricity and heat in a combined heat and power plant (CHP). The capacity for the local processing plant was designed for 12 MW of biocoal with a biomass capacity of 80 ktonne/yr. Figure 3-8 illustrates the value chain for the HTC reference pathway including only the transport by truck (100 km) of biocoal to the central CHP plant. In this case, it was assumed that the HTC plant is next to the collection site of municipal waste.

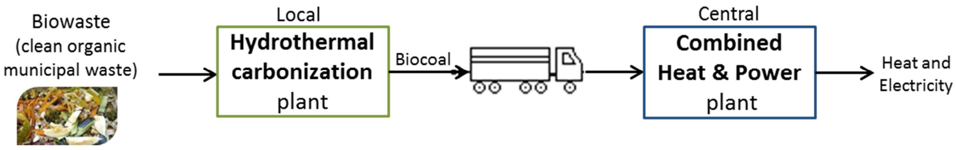


Figure 3-8 Hydrothermal carbonization reference pathway diagram

The hydrothermal carbonization process is a multi-batch process that enables a continuous processing of biomass. In the process, the biomass is mixed with hot water before it enters the reactors, where the carbonization reaction takes place and runs for several hours. After the reaction is completed, the produced slurry is sent to a high and low pressure flash tanks where the water is removed as steam. In this way, the biocoal is recovered at the bottom of the tanks. Later, the biocoal is dried and filtered to ensure the right properties for a safe transport and combustion in a CHP plant where heat and power are produced.

3.4.2 Sensitivity parameters

The following parameters and values were used in the sensitivity analysis of the fast pyrolysis pathway to produce a transport fuel. The parameters and consequential values were defined in close cooperation with the partners.

Table 3.6 Sensitivity parameters and values of the hydrothermal conversion process

Parameter	*Value*
Feedstock	Organic municipal waste, brewery spent grains
Feedstock cost	Organic municipal waste -60, -15 and 0 euro/tonne
Central transport distance	25, 50, 100 and 250 km
Local output capacity	6, 12, 36 and 72 MW
Central output capacity	10, 20, 60 and 120 MW

3.4.3 Overall input and output diagram

Figure 3-9 shows the physical inputs and outputs of hydrothermal conversion (HTC) process to produce 1 kg of biocoal[32]. Organic municipal waste and brewery spent grains[33] are the selected feedstock for the process. The organic municipal waste is a waste stream and no impacts are

[32] AVACO, questionnaire 2013.05.15, updated august 2014

[33] LCA data brewery spent grain derived from Novozymer, 2009, Comparative life cycle assessment of malt-based beer and 100% barley beer

allocated to the waste itself. The only impacts are from the collection of the waste by a waste collection van[34]. The brewery spent grains are a by-product from the beer brewing process. A small part of the impacts up to the wort process are allocated to the spent grains, based on an economic allocation. Electricity and steam are other inputs of the process, and the environmental impact of the processes are taken from the EcoInvent database[35,36]. For the waste water an average waste water treatment plant is selected[37].

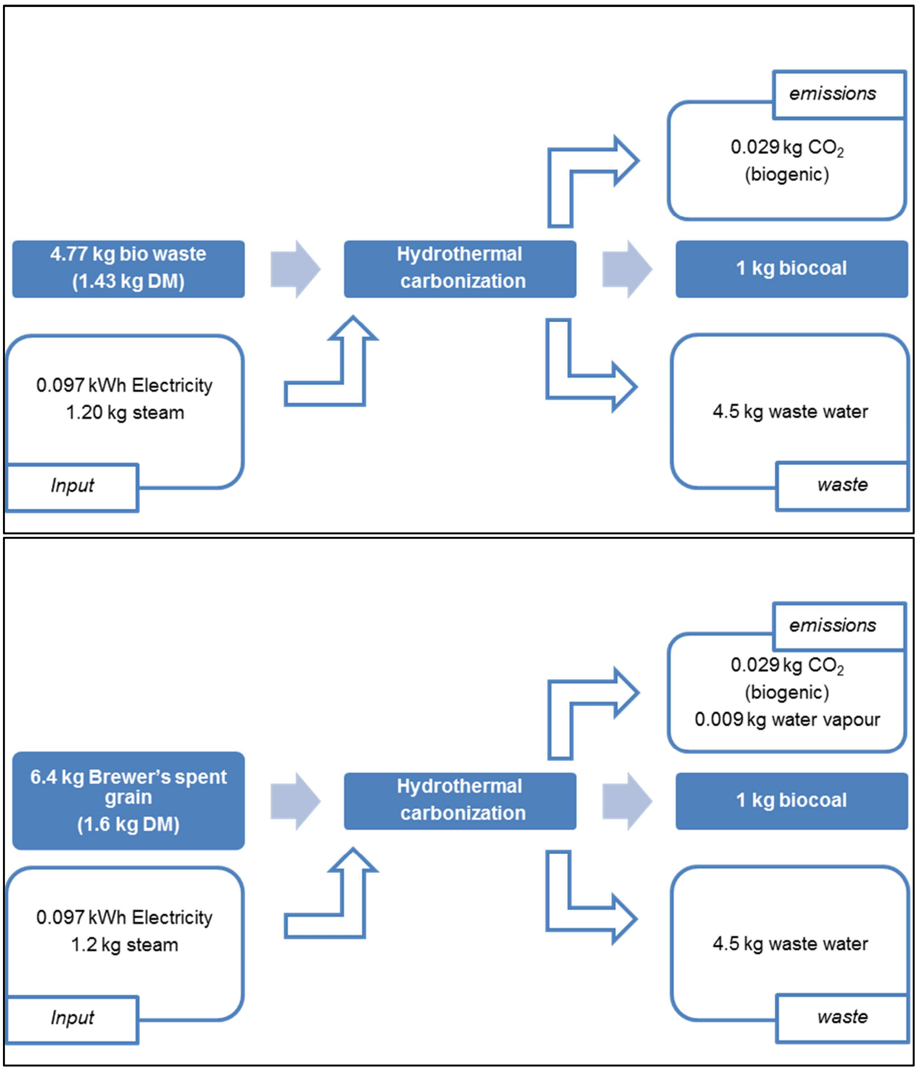


Figure 3-9 Input/output diagram of bio-coal production via the HTC process with organic municipal waste and brewery spent grain as feedstock.

The biocoal is fed into the CHP to produce heat and power. The output ratio is 1/3 electricity and 2/3 heat. The overall efficiency of the plant is approximately 83%. A large amount of ash is generated, approximately 18% of the biocoal input remains as ash.

[34] Collection of waste based on EcoInvent0 process Transport, municipal waste collection, lorry 21t/CH U
[35] EcoInvent process - Electricity, low voltage, at grid/DE U, adjusted for year 2020
[36] EcoInvent process - Steam, for chemical processes, at plant/RER U
[37] EcoInvent - Treatment, sewage, to wastewater treatment, class 3/CH U

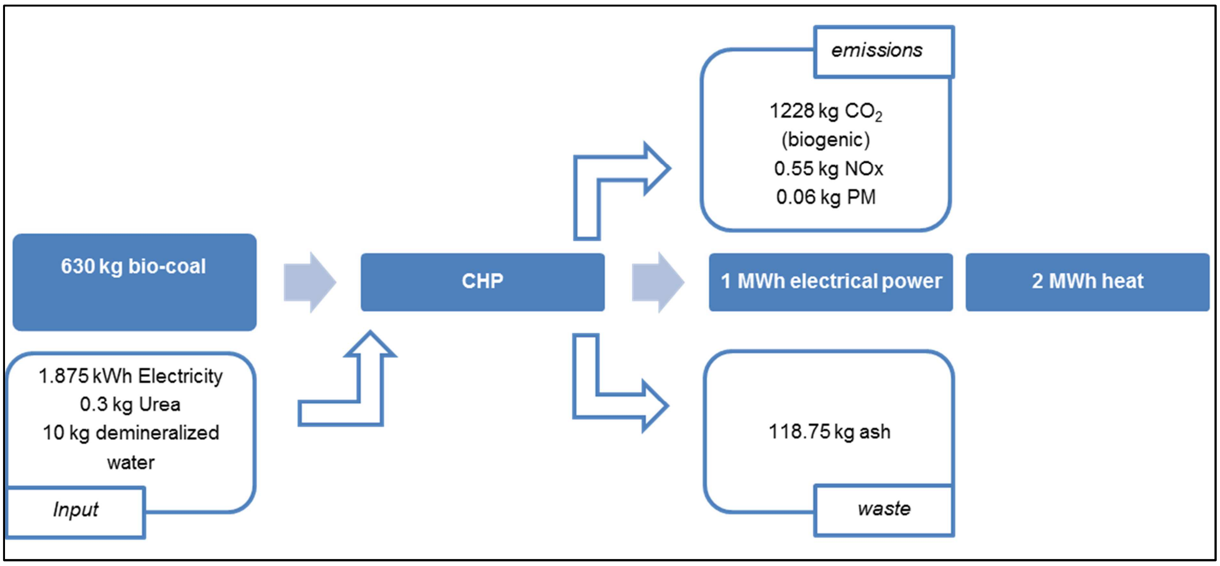


Figure 3-10 Input/output diagram of power production via the CHP

4 Sustainability assessment & sensitivity results

In this chapter, the results of the sustainability assessment are presented for the three reference pathways. First the environmental assessment is presented in three steps covering an increasingly broad and uncertain scope of environmental impacts, as described in the methodology in chapter 2. It concerns CO_2 emissions according to the Renewable Energy Directive (RED), conventional impacts according standard LCA and new biorelated impacts (on land-use and water depletion).
Next, the results of the integrated sustainability assessment and the sensitivity analysis are discussed. The results will be discussed starting at a high level, which means comparison of the direct and indirect costs, where the latter are the monetized environmental impacts from the environmental assessment. Thereafter the direct and indirect costs will be discussed in more detail by breaking them down into the various process steps and environmental themes. In the sensitivity analysis the effects of the input parameters are assessed.

All integrated results are expressed in euro/MWh. The direct costs were calculated according to the methodology described in paragraph 2.2.1 and the indirect costs or environmental costs were calculated using the shadow price methodology, paragraph 2.2.2.

The results are based on a cradle to gate assessment. This means the costs include the extraction of resources, transport (local and central) and processing (local and central) costs. Section 4.1 describes the assessment and sensitivity analysis of the transport fuels production via FP and CP pathways and section 4.3 the electricity and heat production via the HTC pathway.

4.1 Environmental assessment of the production of transport fuels

Transport fuel can be produced via the fast (FP) and catalytic pyrolysis (CP) pathways. Both pathways are analyzed with respect to their environmental impacts in three steps, viz. CO_2 emissions according to the Renewable Energy Directive (RED), conventional impacts according standard LCA and new biorelated impacts (on land-use and water depletion).

4.1.1 RED CO_2 emissions

The first step of the three step environmental assessment is the evaluation of Green House Gas emissions of the pathways. For the assessment RED guidelines will be used. Results will be benchmarked against a fossil based processes.

Figure 4-1 shows the RED CO_2 emissions for transport fuels produced from the various feedstock by the fast and catalytic pyrolysis pathway. The reference emission factor for the fossil benchmark is 83.8 g CO_2 /MJ. The FP/miscanthus pathway leads to a 61% reduction in CO_2, for the other feedstock types, the reduction is 80%. The CP/miscanthus pathway has a 68% reduction in CO_2, the other feedstock types show a reduction of 81%. Miscanthus is an energy crop, emissions from cultivation are taken into account, whereas the emissions from byproducts are set zero (according RED guidelines).

Typical greenhouse gas emission values from Annex V from the RED are for biodiesel: 35 g CO_2 /MJ (sunflower), 46 g CO_2 /MJ (rape seed) and 50 g CO_2 /MJ (soy bean). CP and FP using miscanthus is in the same order of CO_2 emissions of sunflower, CP and FP using waste streams with approximately 15 g CO_2 /MJ has considerably lower CO_2 emissions. In Annex V from the RED, waste wood Fisher-Tropsch diesel has a lower greenhouse gas emission estimated at 4 g CO_2 /MJ.

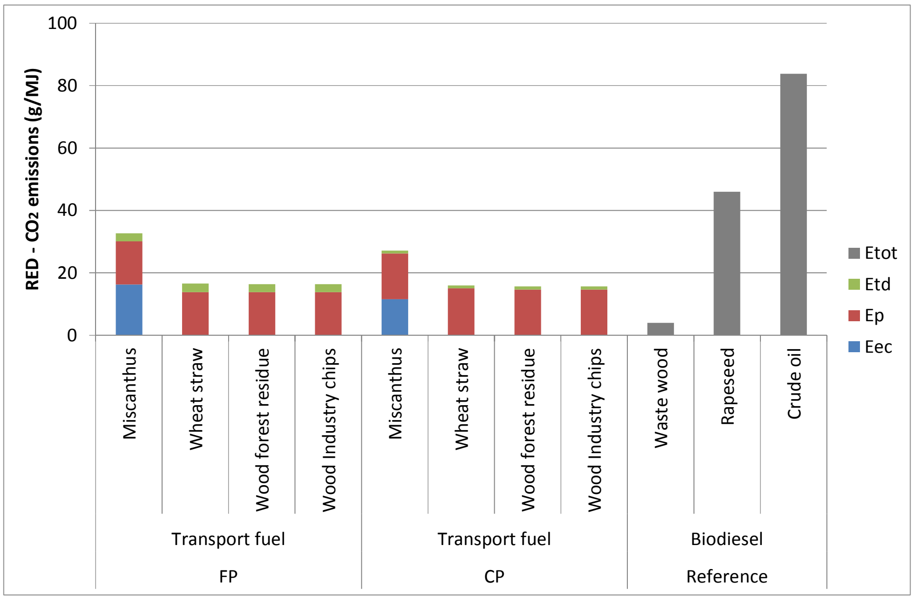


Figure 4-1 RED CO_2 emissions for the various feedstock and technologies to produce a transport fuel. CO_2 emissions from extraction & cultivation (Eec), processes (Ep) transport & distribution (Etd) and total emissions for the references (Etot).

Figure 4-2 shows the RED CO_2 emissions for the fast pyrolysis pathway to produce transport fuel and methanol from the various feedstock. Typical greenhouse gas emission values from Annex V from the RED are estimated at 4 g CO_2 /MJ for waste wood methanol.

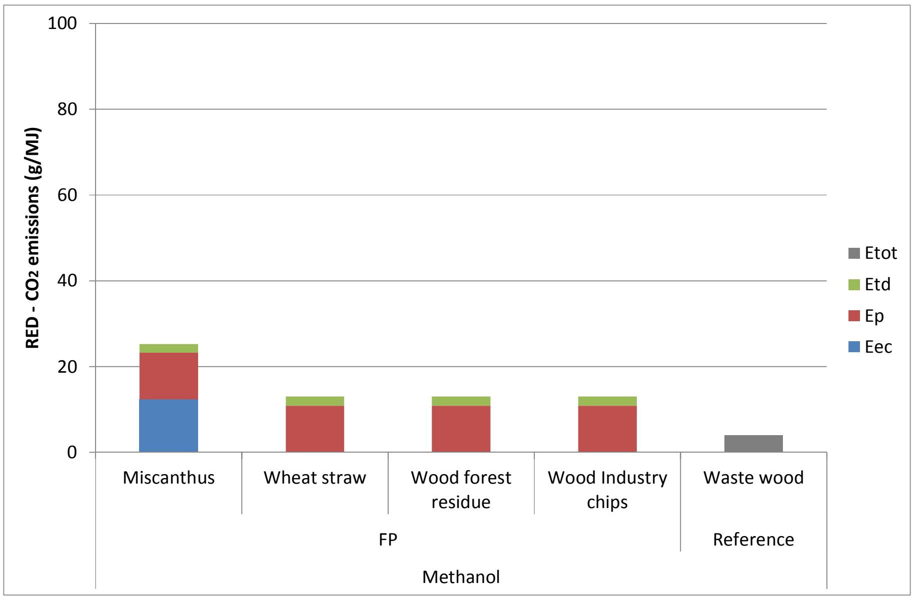


Figure 4-2 RED CO_2 emissions for the fast pyrolysis pathway to produce transport fuel and methanol. CO_2 emissions from extraction & cultivation (Eec), processes (Ep) and transport & distribution (Etd).

Summarized results

- The fast pyrolysis and catalytic pyrolysis pathway lead to a CO_2 reduction up to respectively 80 and 81% compared to fossil reference when waste streams are used as a feedstock. Using energy crops the reduction is lower, because emissions from cultivation have to be taken into account.
- The pathways perform better than biodiesel produced from first generation feedstock as sunflower, rape seed and soya bean. They do not yet meet the emissions as given in the RED directive, e.g. for biodiesel from waste wood via gasification.
- The current CO_2 emissions from the methanol pathway are higher than the emissions given in the RED directive.

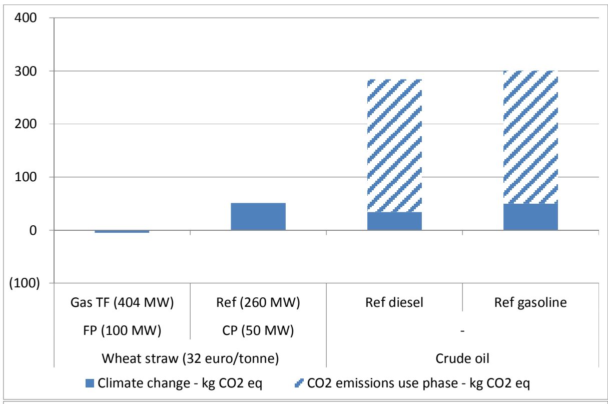
4.1.2 Conventional impacts

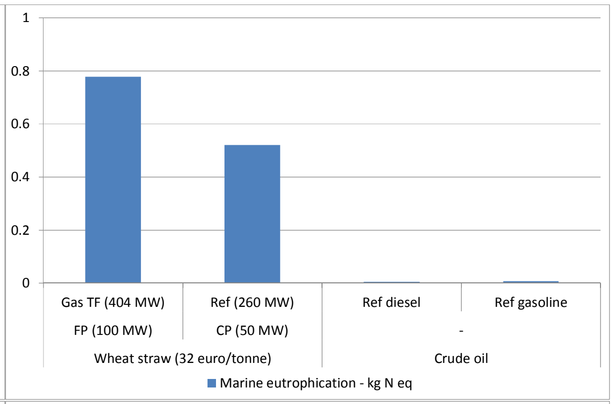
Second step in the environmental assessment is evaluation of the individual conventional impacts. For the assessment LCA according ISO will be used. As ISO prescribes, individual indicators will be presented and cannot be weighed in a comparative assessment of different products. This means that different impacts cannot be compared either. In addition to the biobased pathways, a fossil equivalent is presented as a benchmark.

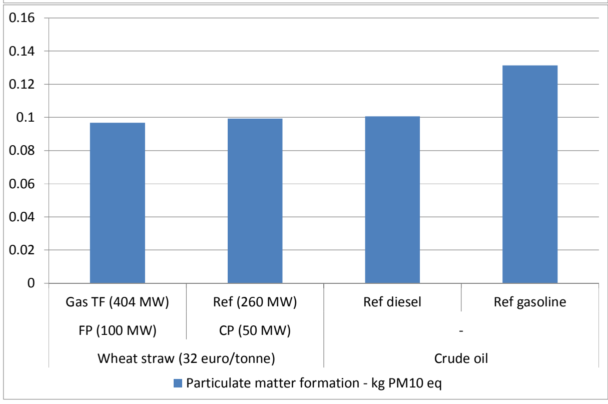
In Figure 4-3 the individual conventional environmental impacts of the fast and catalytic pyrolysis pathways are given versus the fossil references. It is also presented in the form of a table, see Table 4.1.

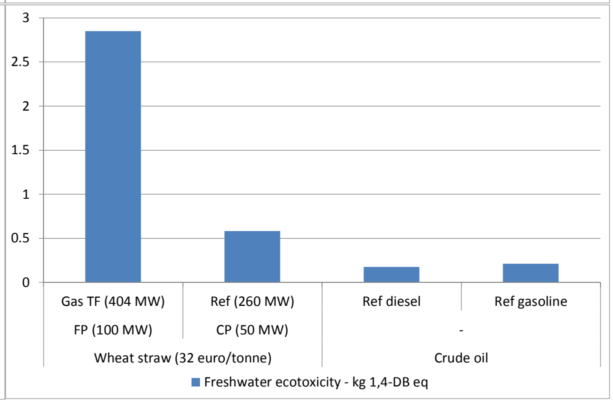
The figure shows the impacts to climate change for the production of the transport fuel and the use phase. This calculation uses the ISO LCA methodology which is different from the RED method. Particularly, the coproduction of electricity is valued in terms of avoided CO_2 emissions, which is not the case in the RED methodology. For reasons of completeness, we present the complete set of environmental impacts, including climate change.

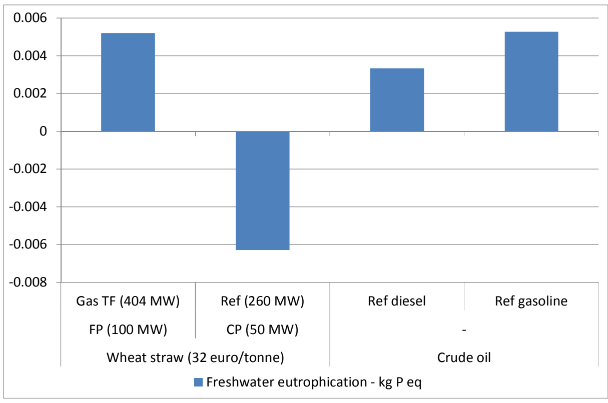
The CO_2 emissions from fossil fuels are dominated by the use phase where fossil fuels are combusted. The main contributors to climate change due to the biobased pathways are the CO_2 and N_2O emissions from the biomass cultivation and the CO_2 emissions from the electricity, steam and hydrogen production for the processing steps. In the gasification step (central conversion in FP pathway) and the catalytic pyrolysis step, electricity is co-produced. This leads to an environmental benefit equal to the prevented emissions from the current electricity from the grid. Therefore, the CO_2 emissions of the biobased pathways are even lower than according to RED. As the electricity from the grid is expected to be more sustainable in the future, these benefits will decrease and the overall impacts will increase in the future.

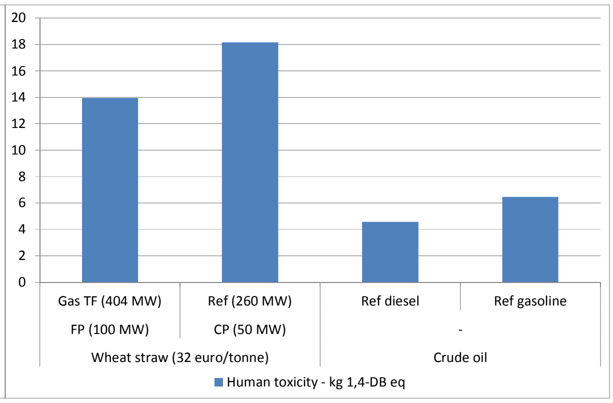

400
300
200
100
0
(100)
Gas TF (404 MW)
FP (100 MW)
Ref (260 MW)
CP (50 MW)
Wheat straw (32 euro/tonne)
Ref diesel
Ref gasoline
-
Crude oil
Climate change - kg CO2 eq
CO2 emissions use phase - kg CO2 eq

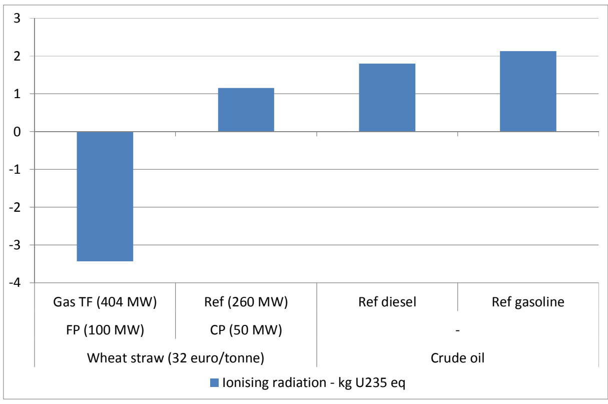

1
0.8
0.6
0.4
0.2
0
Gas TF (404 MW)
FP (100 MW)
Ref (260 MW)
CP (50 MW)
Wheat straw (32 euro/tonne)
Ref diesel
Ref gasoline
-
Crude oil
Marine eutrophication - kg N eq

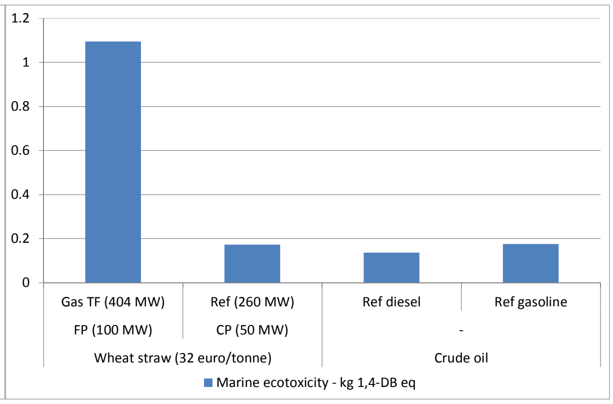

0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Gas TF (404 MW)
FP (100 MW)
Ref (260 MW)
CP (50 MW)
Wheat straw (32 euro/tonne)
Ref diesel
Ref gasoline
-
Crude oil
Particulate matter formation - kg PM10 eq


3
2.5
2
1.5
1
0.5
0
Gas TF (404 MW)
FP (100 MW)
Ref (260 MW)
CP (50 MW)
Wheat straw (32 euro/tonne)
Ref diesel
Ref gasoline
-
Crude oil
Freshwater ecotoxicity - kg 1,4-DB eq


0.006
0.004
0.002
0
-0.002
-0.004
-0.006
-0.008
Gas TF (404 MW)
FP (100 MW)
Ref (260 MW)
CP (50 MW)
Wheat straw (32 euro/tonne)
Ref diesel
Ref gasoline
-
Crude oil
Freshwater eutrophication - kg P eq


20
18
16
14
12
10
8
6
4
2
0
Gas TF (404 MW)
FP (100 MW)
Ref (260 MW)
CP (50 MW)
Wheat straw (32 euro/tonne)
Ref diesel
Ref gasoline
-
Crude oil
Human toxicity - kg 1,4-DB eq


3
2
1
0
-1
-2
-3
-4
Gas TF (404 MW)
FP (100 MW)
Ref (260 MW)
CP (50 MW)
Wheat straw (32 euro/tonne)
Ref diesel
Ref gasoline
-
Crude oil
Ionising radiation - kg U235 eq


1.2
1
0.8
0.6
0.4
0.2
0
Gas TF (404 MW)
FP (100 MW)
Ref (260 MW)
CP (50 MW)
Wheat straw (32 euro/tonne)
Ref diesel
Ref gasoline
-
Crude oil
Marine ecotoxicity - kg 1,4-DB eq

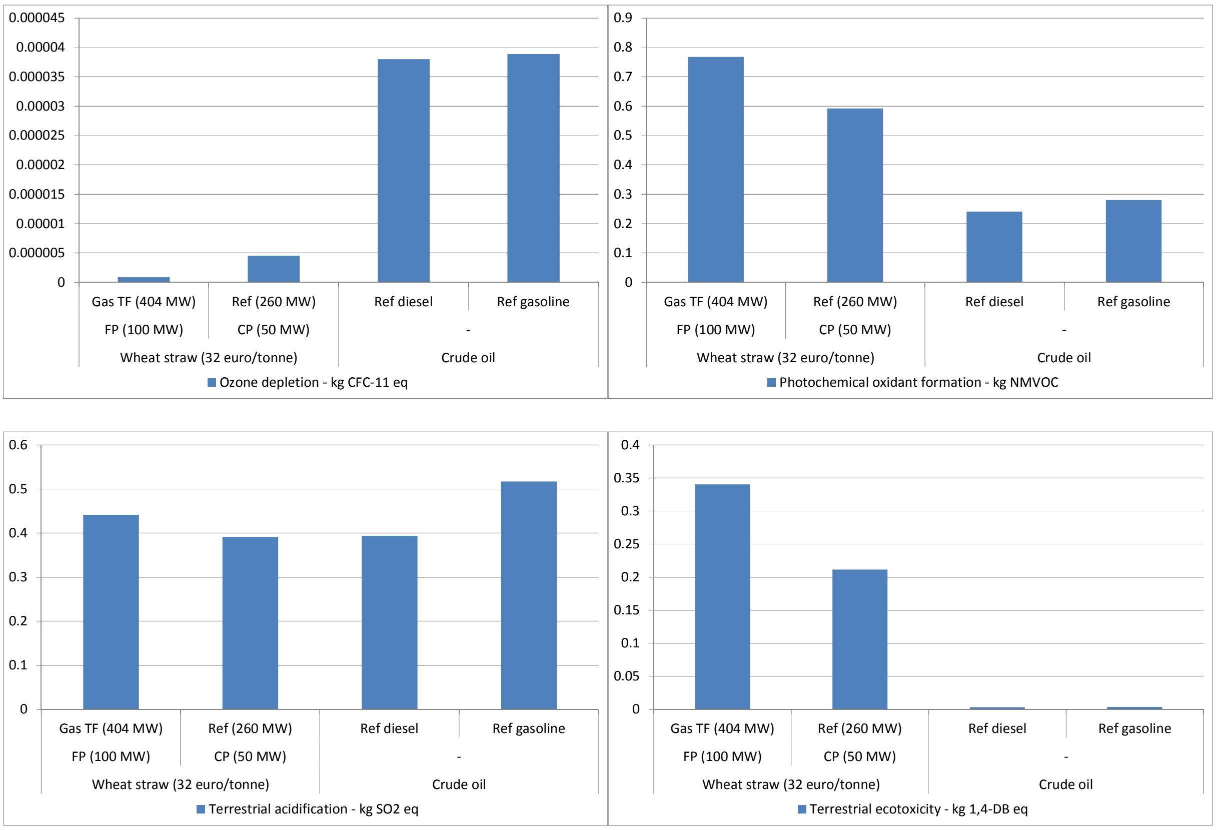


Figure 4-3 Comparison of conventional environmental themes for the biobased pathways versus the fossil references (impacts per MWh of product)

Table 4.1 Conventional environmental impacts per MWh of transport fuel via fast and catalytic pyrolysis pathway (wheat straw, 50 km local and 250 km central transport) and the fossil references

Impact category	**unit**	**FP straw**	**CP straw**	**Diesel**	**Gasoline**
Climate change	kg CO_2 eq	-4.97E+00	8.38E+01	3.42E+01	5.02E+01
Fossil depletion	kg oil eq	-1.15E+01	2.66E+01	9.94E+01	1.04E+02
Freshwater ecotoxicity	kg 1,4-DB eq	2.85E+00	1.03E+00	1.77E-01	2.12E-01
Freshwater eutrophication	kg P eq	5.21E-03	2.86E-02	3.34E-03	5.27E-03
Human toxicity	kg 1,4-DB eq	1.39E+01	5.26E+01	4.58E+00	6.47E+00
Ionising radiation	kg U235 eq	-3.43E+00	4.40E+00	1.80E+00	2.13E+00
Marine ecotoxicity	kg 1,4-DB eq	1.09E+00	6.04E-01	1.37E-01	1.76E-01
Marine eutrophication	kg N eq	7.78E-01	5.30E-01	5.41E-03	7.02E-03
Metal depletion	kg Fe eq	2.42E-02	4.91E-01	9.81E-03	8.86E-02
Ozone depletion	kg CFC-11 eq	8.87E-07	6.01E-06	3.80E-05	3.89E-05
Particulate matter formation	kg PM10 eq	9.67E-02	1.11E-01	1.01E-01	1.31E-01
Photochemical oxidant formation	kg NMVOC	7.68E-01	6.22E-01	2.41E-01	2.80E-01
Terrestrial acidification	kg SO2 eq	4.42E-01	4.28E-01	3.93E-01	5.17E-01
Terrestrial ecotoxicity	kg 1,4-DB eq	3.40E-01	2.13E-01	3.15E-03	3.89E-03

The figure and table show with respect to the conventional environmental impacts that sometimes impacts are larger for fossil fuels (climate change, fossil depletion, particulate matter formation and ozone depletion) and in other cases smaller (mainly human and ecotoxicity as well as eutrofication). In general, the higher fossil fuel emissions are related to higher fossil fuel combustion (since the pyrolysis pathways co-produce heat and power). The higher toxicity emissions from the biopathways are stemming from plant protection products related to the wheat cultivation and partly allocated to the straw. The higher eutrofying emissions from straw based pathways are due to the leaching of nitrates from fertilizers applied in the biomass production. In cases of wood, both types of emissions do not occur. This is illustrated in Figure 4-4.

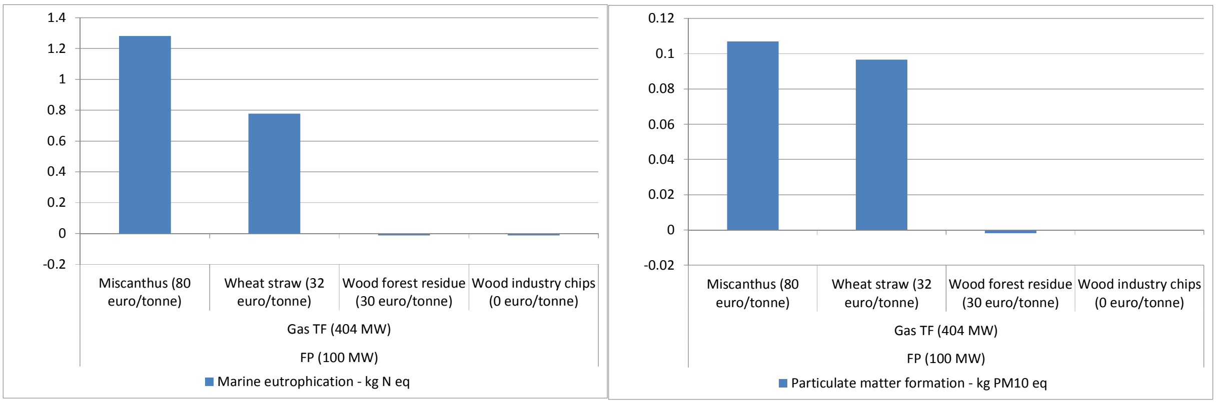


Figure 4-4 Comparison of main conventional environmental themes for the various feedstock in the biobased pathways (impacts per MWh of product)

Summarized results

– Conventional life cycle environmental impacts are sometimes larger for fossil fuels (climate change, fossil depletion, particulate matter formation and ozone depletion) and in other cases larger for biobased pathways (mainly human and ecotoxicity as well as eutrofication).
– The higher eutrofication and toxicity emissions from the biopathways are related to straw cultivation and do not occur in case of wood.

4.1.3 New bio-related impacts

The third step in environmental assessment is the assessment of new bio related impacts. The agricultural nature of processes differs from its equivalent fossil value chains. For this reason, new bio-related indicators are relevant for the environmental assessment of biobased pathways. It should be realized, however, that the assessment of these impacts is relatively new in terms of data inventory and impact methodology. Hence, uncertainties are large. Nevertheless, these indicators should not be ignored but should be viewed rather as a potential risk instead of an impact.

Figure 4-5 presents the new bio-related impacts in comparison to the fossil reference fuels (see Table 4.2 for the numbers). It concerns relatively new impacts on land-use and water depletion, which are defined not yet so precise and data are surrounded with larger uncertainties than those of the conventional impacts. Obviously, these bio-related impacts are generally higher for biobased than for fossil pathways. Exception is the water depletion of FP, which is lower than that of CP and fossil pathways. The negative value for water depletion is due to the large amount of electricity produced, and the prevented impacts from the production of fossil energy, i.e. water use in the mining process. For the reason of prevented conventional electricity production, and more specific the renaturalisation of landfill and mining areas, the land transformation numbers are negative for especially the FP pathway. For the land-use related impacts, it is clear that the FP has larger impacts than the CP. This is due to the lower chain efficiency of FP compared to CP.

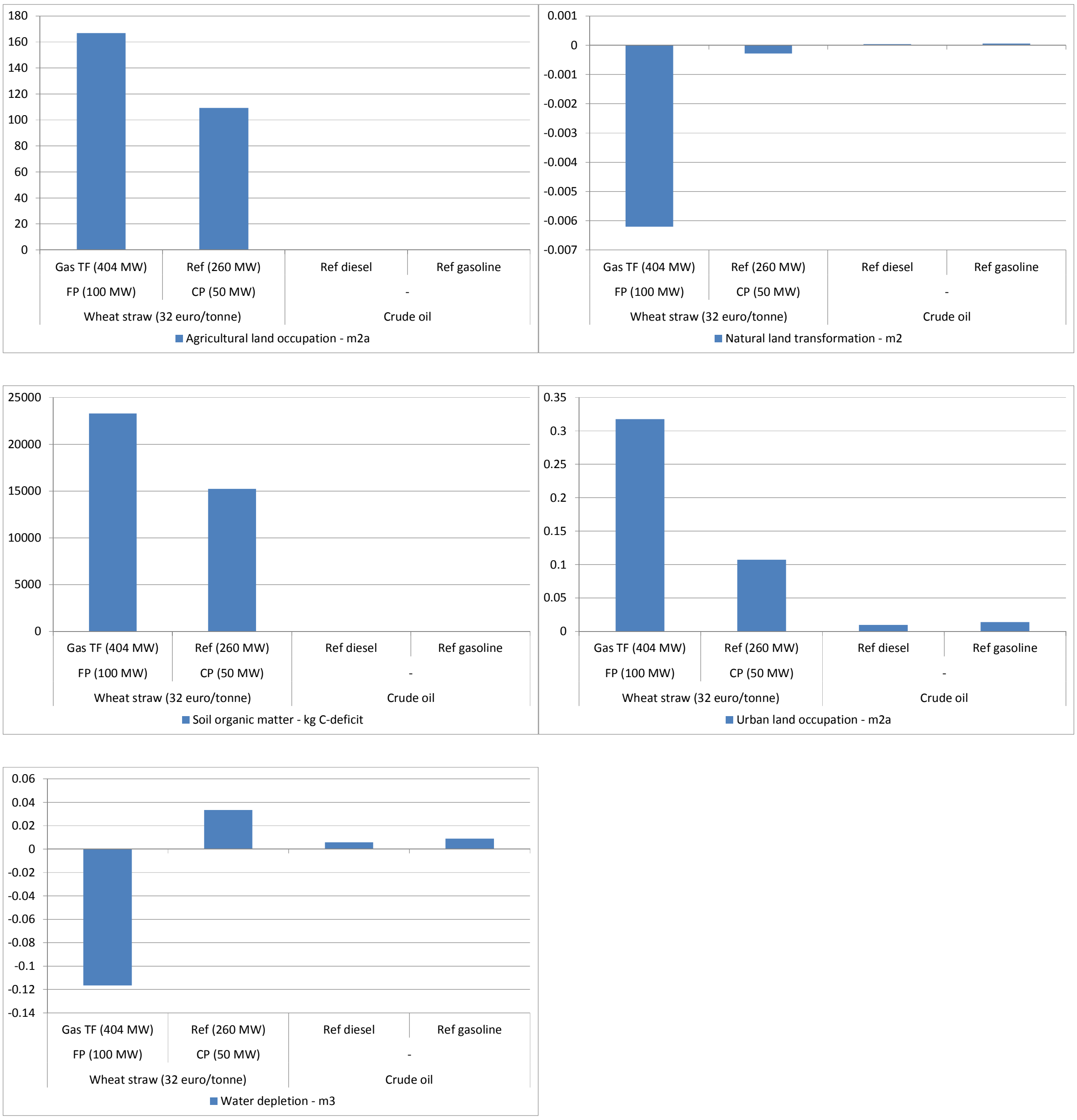


Figure 4-5 Comparison of new biorelated themes for the various biobased and fossil fuel pathways (impacts per MWh of product)

The agricultural land occupation impacts differ largely between different feedstocks, see Figure 4-6. For example, wood residue and wheat straw have low impacts, due to low allocations of impacts to the low value byproduct. Miscanthus has a high allocation, but is as an energy crop efficient with respect to the land-use. Wood forest residue has a low allocation, but at the same time a very low land-use efficiency. That explains the relatively high agricultural land occupation. It just refers to the amount of square meter needed to “cultivate” the biomass. However, it should be noted that the intensity of the land occupation is not included in this factor.

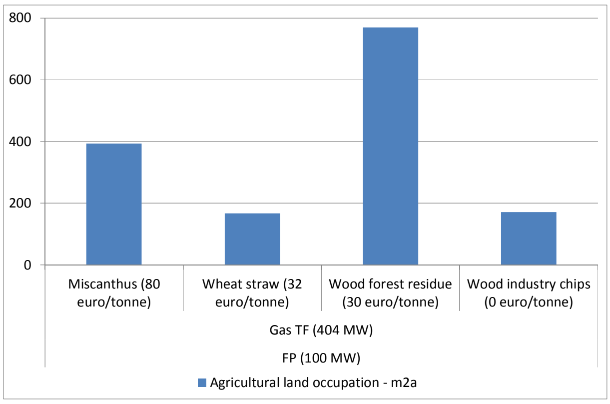


Figure 4-6 Comparison of agricultural land occupation for the various feedstock in the biobased pathways (impacts per MWh of product)

Table 4.2 New bio-related environmental impacts per MWh of transport fuel via fast and catalytic pyrolysis pathway (wheat straw, 50 km local and 250 km central transport) and the fossil references

Impact category	unit	FP straw	CP straw	Diesel	Gasoline
Agricultural land occupation	m2a	1.67E+02	1.09E+02	1.24E-02	1.82E-02
Natural land transformation	m2	-6.20E-03	7.51E-04	3.71E-05	5.37E-05
Soil organic matter	kg C-deficit	2.33E+04	1.52E+04	1.77E-01	2.68E-01
Urban land occupation	m2a	3.18E-01	1.47E-01	9.79E-03	1.40E-02
Water depletion	m3	-1.16E-01	9.09E-02	5.76E-03	8.92E-03

Summarized results

– The new bio-related impacts are generally higher for biobased than for fossil pathways but are surrounded with large uncertainty.

4.2 Integrated sustainability assessment of the production of transport fuels

As has become clear in the previous paragraphs, environmental profiles of different pathways can have both positive and negative differences. If an option avoids CO_2 but emits more toxic emissions, does it provide an improvement for the environment or not? In order to be able to determine which option is the most environmentally friendly, it is often necessary to weigh the different impacts. Moreover, if we value the impacts in terms of environmental damage, it is possible to make an integrated assessment for decision making.
The integrated sustainability assessment presented in this chapter consists of an overview of both benefits and costs. These consist of both direct (techno-economic) costs and indirect (environmental) effects. This approach indicates strengths and weaknesses relative to one another and supports decision making on different options and pathways.

The assessment of the direct and indirect costs of these pathways will be the starting point for the conclusion and recommendations chapter. Breakdowns of the direct and indirect costs will be shown to identify which steps in the pathway contribute the most to respectively the minimum selling price and the environmental impact. Feedstock type and prices, transport distances and plant sizes are varied to assess the effect on the overall direct and indirect costs.

4.2.1 Direct versus indirect cost

As previously described, the methodology of this assessment is based on the monetization of the environmental impacts with the main objective to be able to compare among technologies, feedstock, and logistics. Therefore, this section describes the comparison of two different technologies by means of direct and indirect costs. As an example, Figure 4-7 shows the direct and indirect costs of the production of transport fuels from wheat straw via the fast and catalytic pyrolysis pathways. The production costs of the biofuels are benchmarked with fossil diesel and gasoline. In this example the indirect costs only result from conventional environmental impacts. The new bio-related impacts are separately assessed in section 4.2.3.

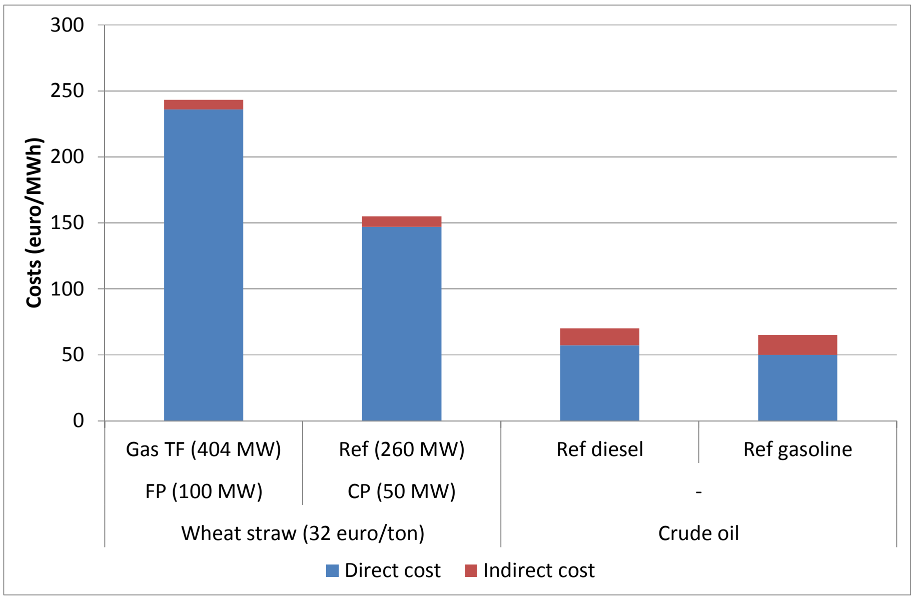


Figure 4-7 Direct versus indirect (conventional) cost to produce transport fuels via the fast pyrolysis (FP) and catalytic pyrolysis (CP) pathways based on wheat straw and the fossil benchmarks, in euro/MWh

It is clear that the overall costs of the biobased pathways are higher than those of the fossil benchmarks due to the higher direct (or production) costs. The direct costs are in the range of 147-236 euro/MWh for the bio-based pathways and 50-57 euro/MWh for the fossil benchmarks. A breakdown of the direct cost is explained in section 4.2.2 in order to understand the large difference between the biobased and fossil routes.

The system boundaries of the pathways is cradle to gate. This means the assessment ends at the plant gate and the use phase of the fuel is excluded. The use phase of the fossil and bio fuels can be assumed to be similar, with one major exception: CO_2. The CO_2 emissions from biofuels are biogenic and not contributing to climate change as they is un uptake of CO_2 by the biomass during its growth. The net CO_2 emissions for biomass is assumed to be zero within this study. To show the benefits of using biofuels the CO_2 emissions from the benchmark are added.

The indirect costs of the biobased pathways (7-8 euro/MWh) are lower than for the fossil reference (13-15 euro/MWh). Proportionally, the indirect cost are relatively small. They represent approximately 5% of the overall costs for the biobased routes and approximately 20% for the fossil benchmarks.

The indirect costs (from conventional impacts) of the FP pathway are similar than those of the CP pathway (7-8 euro/MWh), using wheat straw as feedstock. The breakdown of the impacts will show which steps in the pathway are most contributing to the various environmental impact categories. The sensitivity analysis will show the effects on various impacts (for e.g. the different types of feedstock). See sections 4.1.4 – 4.1.8.

In addition, Figure 4-7 shows that the overall costs of the fast pyrolysis pathway are higher than those of the catalytic pyrolysis pathway since the overall efficiency for the FP pathway is 40% versus 50%

for the CP pathway (see ANNEX B). In the following paragraphs a breakdown of direct and indirect costs will be given and discussed.

Summarized results

- Overall costs (direct and indirect) are higher for the biobased pathways than for the fossil benchmarks;
- The fossil benchmarks have a relatively higher fraction of indirect costs (20%) than the biobased pathways (5%) when the new bio related impacts are not taken into account. Also in absolute values the indirect cost of the fossil benchmark (13-15 euro/MWh) are higher than for the biobased pathway (7-8 euro/MWh);
- The production costs of transport fuels from wheat straw via Fast Pyrolysis pathway are higher than those of the Catalytic Pyrolysis pathway. The overall efficiency for the FP pathway is 40% versus 50% for the CP pathway.
- The indirect costs (from conventional impacts) of the FP pathway are similar than those of the CP pathway (7-8 euro/MWh), using wheat straw as a feedstock.

4.2.2 Breakdown of the direct costs

A breakdown of the direct costs for the production of transport fuels is given in Figure 4-8. They are allocated to the various steps in the fast and catalytic pyrolysis pathways. In case of the fossil benchmarks direct costs are represented by the market prices of gasoline and diesel (excluding taxes) in 2014[38].

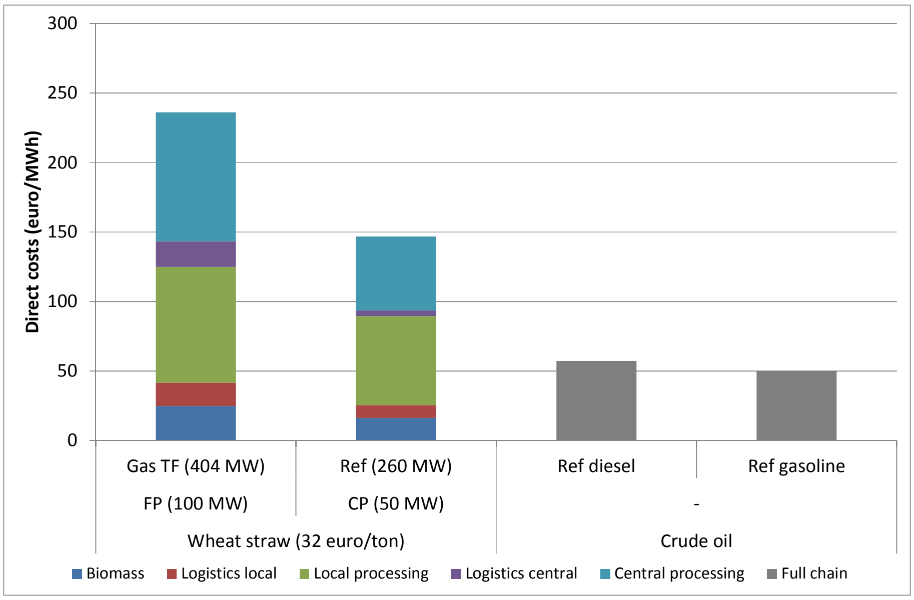


Figure 4-8 Breakdown of the direct costs into the various steps of the biobased pathways for the production of a transport fuel from wheat straw via fast pyrolysis (FP) and catalytic pyrolysis (CP). For the fossil benchmark no cost breakdown was available and therefore direct costs are represented by the market prices in 2014.

The direct costs of the biobased pathways are 3 to 4 times higher than those of the fossil benchmarks. The local and central processing steps give the largest contribution to the total direct costs of the fast and catalytic pyrolysis pathway, as indicated by the green and light blue bars. Logistics give the smallest contribution to the total direct costs, ranging from 10 to 15%. Biomass contributes for approximately 12% to the overall direct costs.

[38] Retrieved from https://www.energy.eu/, on January 7th 2015, 89 €/MWhr

In addition, Figure 4-8 shows that the production cost of transport fuels are lower via the CP pathway. This is because the CP pathway has a higher energy conversion efficiency from biomass towards the intermediate energy carrier and the final transport fuel. For instance, wheat straw has a LHV of 13.44 MJ/kg, conversion via CP results in bio-oil with an LHV of 29.5 MJ/kg, conversion via FP results in biosyncrude with a significantly lower LHV of 17.04 MJ/kg. The energy content of the intermediate energy carrier determines the energy conversion towards gasoline or diesel with a LHV of 43 MJ/kg. Therefore the economic success of both routes rely on the energy concentration of the intermediate, favoring logistics cost and overall production costs.

As stated in the methodology in section 2.2.1, the direct costs for the local and central plants represent the minimum selling price which considers the production costs and a discounted rate of 5% over 20 years. These production costs include operating costs like utilities, labor, maintenance, other fixed costs that relates to the capital investment such as financing and depreciation and other general expenses. The production costs per kg of transport fuels produced from the FP and CP pathways are illustrated in Figure 4-9 and Figure 4-10, respectively. It is clear that the major cost contributor are the biosyncrude and bio-oil costs. This result can be correlated to Figure 4-8, where production costs of biosyncrude and bio-oil of approximately 125 and 90 euro per MWh of transport fuel are presented, which is approximately 50-60% of the total cost.

Figure 4-9 and Figure 4-10 also illustrate the effect of other cost components per kg of product produced. The majority of these components are multiplication factors and are described in the methodology report. Nevertheless, factors such as depreciation, labor (including supervision and overhead) and utilities are technology dependent. In both cases, the energy carrier, biosyncrude and bio-oil, are the major cost contributors. This reflect the production costs for the biosyncrude and the bio-oil per kg of transport fuel.

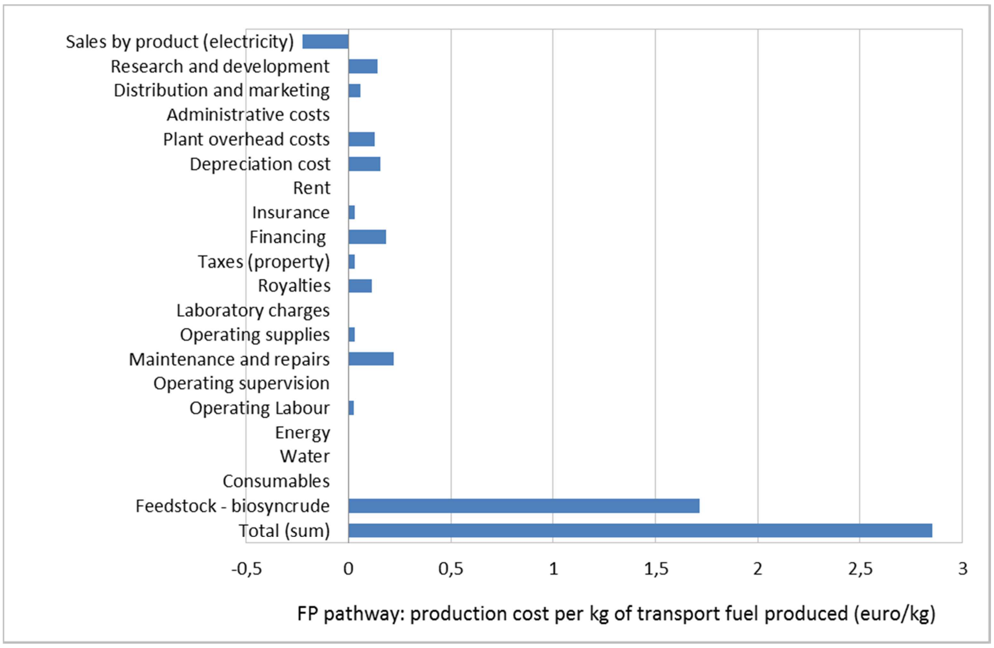


Figure 4-9 Production cost of transport fuels produced via FP reference pathway.

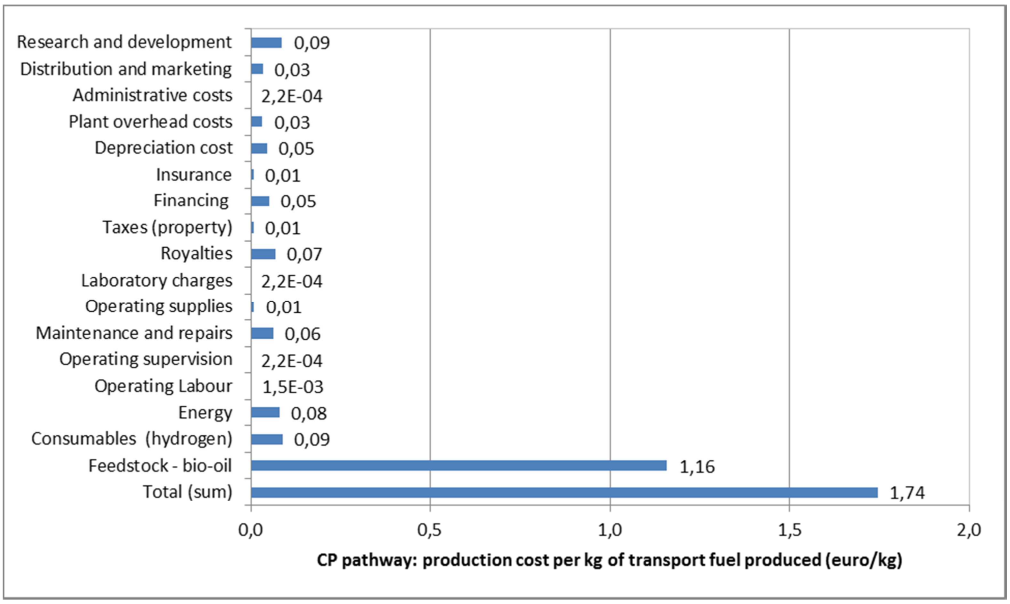


Figure 4-10 Production cost of transport fuels produced via CP reference pathway

Summarized results

– For both pathways, CP and FP, the larger part of direct costs are processing costs.
– Comparison of the fast (FP) with the catalytic pyrolysis (CP) pathway shows that CP has lower direct costs due to a higher overall conversion yield, 53% vs 35%, for:
  - Biomass: because of a higher overall yield (53% vs 35%), less feedstock is needed to produce the transport fuel.
  - Transportation: as the overall yield of CP is higher, transportation costs for feedstock and for intermediate energy carrier (per energy unit) are lower.
  - Central processing: because of the higher quality (higher energy density) product from the CP (bio-oil, 29.5 MJ/kg) than from FP (biosyncrude, 17 MJ/kg), less costs have to be made per energy unit of transport fuel.

4.2.3 Breakdown of the indirect costs

Figure 4-11 shows a breakdown of the indirect costs of the biobased pathways for the production of a transport fuel from wheat straw via fast pyrolysis (FP) and catalytic pyrolysis (CP). The indirect costs are allocated to the various steps in the pathways. The indirect cost of the fossil benchmark are given for the full chain.

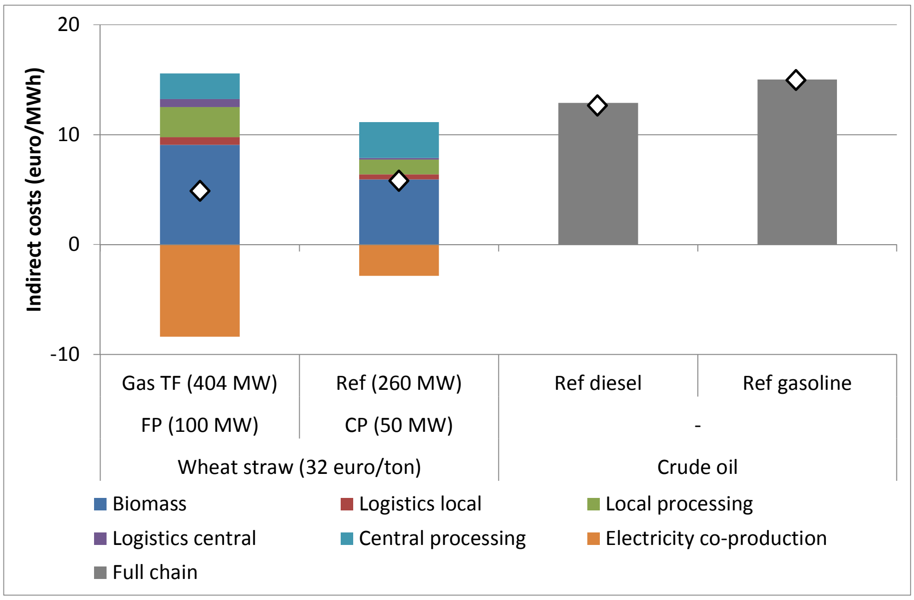


Figure 4-11 Breakdown of the conventional indirect costs into the various steps of the biobased pathways for the production of a transport fuel from wheat straw via fast pyrolysis (FP) and catalytic pyrolysis (CP). For the fossil benchmark no break down was available and the indirect costs of the full chain are displayed. The marker show the total indirect cost of the pathway.

The indirect costs of the FP pathway (7 euro/MWh) and CP pathway (8 euro/MWh) are similar. The indirect costs of the fossil benchmark are 13-15 euro/MWh. Main contribution in the biobased pathways comes from the biomass. The cultivation of wheat causes impacts due to the use of fertilizers and tractors, which are partially allocated to the by-product, i.e. wheat straw. The local and central transport have low indirect costs.

The fast pyrolysis pathway shows a large benefit (negative costs) for the co-production of electricity in the central plant. These benefits are based on the prevented emissions from electricity generation. These emissions are based on the German electricity mix in 2020. As the electricity mix is expected to get more sustainable over time, i.e. lower environmental impacts, the benefits will also decrease in the coming years. The catalytic pyrolysis pathway co-produces electricity in the local process. The co-produced electricity is explicitly represented in the graphs via the orange bars. It is not included in the bars for the local and central processes.

The fast pyrolysis pathway shows higher indirect costs for local processing. This is mainly due to the use of electricity in the FP process. The catalytic pyrolysis pathway shows higher costs for the central process, the refinery. The impacts from that process step are mainly due the consumption of hydrogen and steam.

Figure 4-12 shows again the indirect costs, in this plot the contribution of the various conventional environmental impact categories are given (left graph). The most relevant impact categories will be discussed below.

Climate change: The main contributors to climate change are the CO_2 and N_2O emissions from the biomass cultivation and the CO_2 emissions from the electricity, steam and hydrogen production for the processing steps.

Marine Eutrophication: The main source is the leaching of nitrates from fertilizers applied in the biomass production.

Particulate matter formation: emissions of ammonia and nitrogen oxides are contributing to the particulate matter formation during biomass production. In the central processing step of the CP pathway sulfur dioxides and nitrogen dioxides for electricity, steam and hydrogen production are contributing to the particulate matter formation.

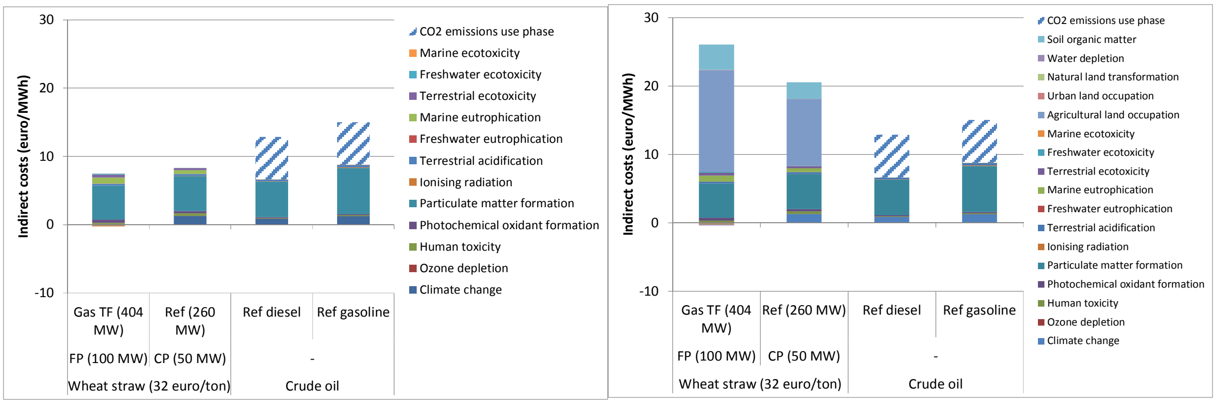


Figure 4-12 Breakdown of the indirect costs into the various impact categories of the biobased pathways for the production of a transport fuel from wheat straw via fast pyrolysis (FP) and catalytic pyrolysis (CP) and the fossil references. Conventional impacts in the left and including new in the right plot.

The right plot in Figure 4-12 shows a breakdown of the indirect costs into the various impact categories, including the new bio related impacts. It clearly shows the high impacts from the new bio-related themes as agricultural land occupation and soil organic matter. These impacts occur during the biomass production by the occupation of land and loss of carbon from the soil. The indirect costs increase up to 26 euro/MWh for the FP and to 21 euro/MWh for the CP pathway. The CP process has a higher overall yield (53% versus 35%) which reduces the use of feedstock, and the consequential environmental impacts.

Summarized results

– The indirect costs of the FP pathway (7 euro/MWh) and the CP pathway (8 euro/MWh), when using wheat straw as a feedstock and taking into account the conventional impacts, are lower than for the fossil benchmark (13-15 euro/MWh). Especially due to the CO_2 emissions of the fossil fuels in the use phase.
– The new, bio-related impacts have a large contribution to the overall impact of the biobased pathways. The new bio-related impacts show an increase of the indirect costs up to 26 euro/MWh (FP) and 21 euro/MWh (CP).
– The FP pathway shows large benefits from the co-generation of electricity in the central process.
– The local and central logistics have a small impact on the overall environmental impact.

4.2.4 Sensitivity for feedstock type

Figure 4-13 shows the influence of different feedstock on the direct and indirect costs, respectively. The feedstock considered in this analysis are wheat straw, miscanthus, forestry residues and industrial chips for the FP and CP pathways.

The feedstock type influences the overall costs as a result of different prices and yields. These differences result in a variation in the overall costs for the FP pathway from 195 euro/MWh (wood industry chips) to 261 euro/MWh (miscanthus). For example, the miscanthus price is 80 euro/ton while the wood industry chips price is 0 euro/ton. Also, in order to produce 1 kg of biosyncrude,1.26 kg of DM wheat straw or 1.04 kg of DM of wood industry chips or 1.03 kg of DM miscanthus is needed.

Therefore, the lowest production costs for transport fuels via the FP pathway are obtained by utilizing wood industry chips, which have the highest yield and the lowest price.

Furthermore, for the CP pathway the lowest direct cost are obtained by utilizing wheat straw and forest residue (146 euro/MWh and 150 euro/MWh, respectively) and the highest by utilizing miscanthus (167 euro/MWh). These results also consider the differences in yield. In order to produce 1 kg of bio-oil the CP pathway requires 3.54 kg of DM forest residue, 3.43 kg of DM miscanthus or 3.80 kg DM wheat straw. Therefore, even though miscanthus has the highest yield, its high price makes it a more expensive route than utilizing forest residues or wheat straw.

Overall, for the FP pathway, the average use of different feedstock (miscanthus, wheat straw and wood chips) is 1.15 kg DM of feedstock per 1 kg of biosyncrude produced with +/- 10% of variation. And for the CP pathway, the use of different feedstock (miscanthus, wheat straw, and wood forest residue) gives an average yield of 3.6 kg of DM of feedstock per 1 kg of bio-oil with +/- 5% of variation.

Figure 4-7 also shows that the costs of local processing are also slightly dependent on the feedstock, however, this is caused by the model structure, where the operating cost factors such as research and development and distribution and marketing are dependent on the operating costs itself. Therefore, the results from the processing plants show a small difference that could be neglected since the overall costs for the production of transport fuel are mainly influenced by the feedstock yield on the final product and their price. Section 4.2.5 describes the effect of feedstock price as an isolated parameter.

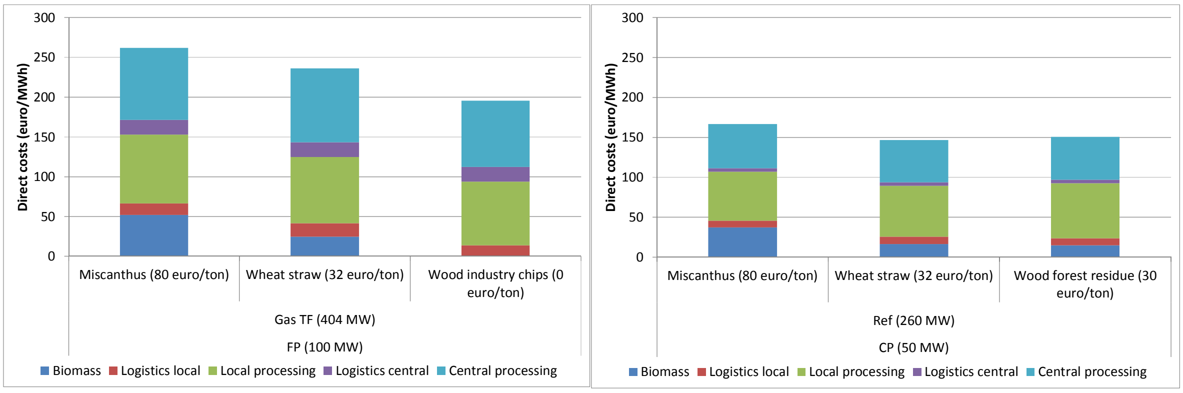


Figure 4-13 Breakdown of the direct costs into the various steps of the biobased pathways for the production of a transport fuel from wheat straw, miscanthus and wood via fast pyrolysis (FP) and catalytic pyrolysis (CP).

Figure 4-14 and Figure 4-15 show the sensitivity for the feedstocks in the FP and CP pathway for respectively the conventional and the conventional including the new, bio-related impacts.

The feedstocks with their characteristics are:

– *Miscanthus* is an energy crop, not a byproduct. All impacts from the cultivation are allocated to the miscanthus. The energy density of miscanthus is rather high (MJ/m^2);
– *Wheat straw* is a byproduct from the wheat cultivation. The impacts are distributed over both outputs, not based on a mass or energy, but based on the price;
– *Wood* has a high value for land occupation, because of a low energy yield per m^2 per year. The feedstock doesn't consist of high quality wood, but of by residues from forest and industry. Allocation of land occupation impacts is not based on mass/energy, but on the price (see ANNEX E for details).

Using wheat straw and miscanthus in the FP and CP pathways result in the highest contribution to the conventional impacts. These are cultivated crops (miscanthus) or by-products from food production (wheat). The impacts are originating from fertilizer production, leaching of fertilizer in the soil and diesel emissions from tractors.

The feedstock has a large impact on the amount of ash produced in the CP process. The disposal of ashes can have a serious contribution to the (human) toxicity, depending on the composition. Especially specific trace metals as manganese are dominating these in the given disposal process for wood ash. Wheat straw generates even a 10 times higher amount of ash than wood in the CP process. But literature showed that the ash has a much lower fraction of manganese and a higher silica fraction than wood. For an improved assessment a detailed analysis of the ash fraction is needed. This will also influence the way the ash will be handled after implementation of the technology. Does it need to be handled as a waste stream or can it be used as a fertilizer. This affects the economic and environmental assessment.

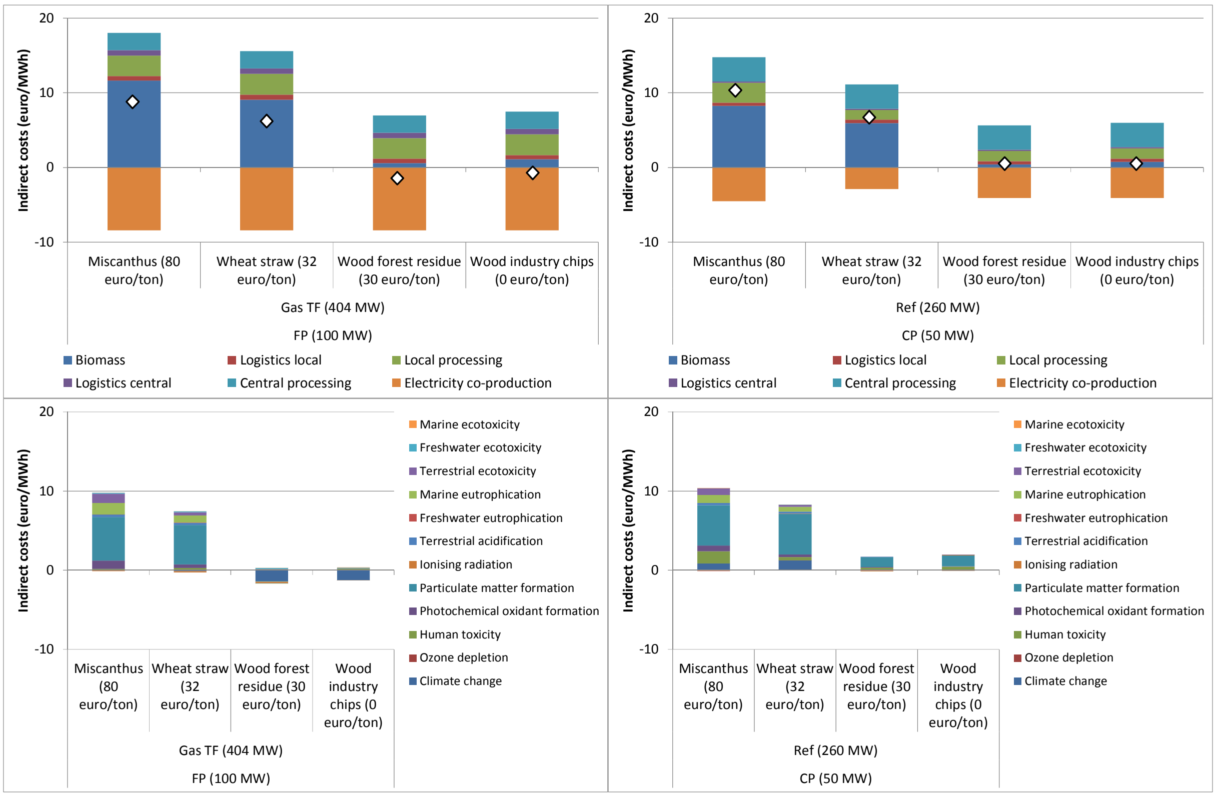


Figure 4-14 Breakdown of the conventional indirect costs into the various impact categories of the biobased pathways for the production of a transport fuel from wheat straw, miscanthus and wood via fast pyrolysis (FP) and catalytic pyrolysis (CP).

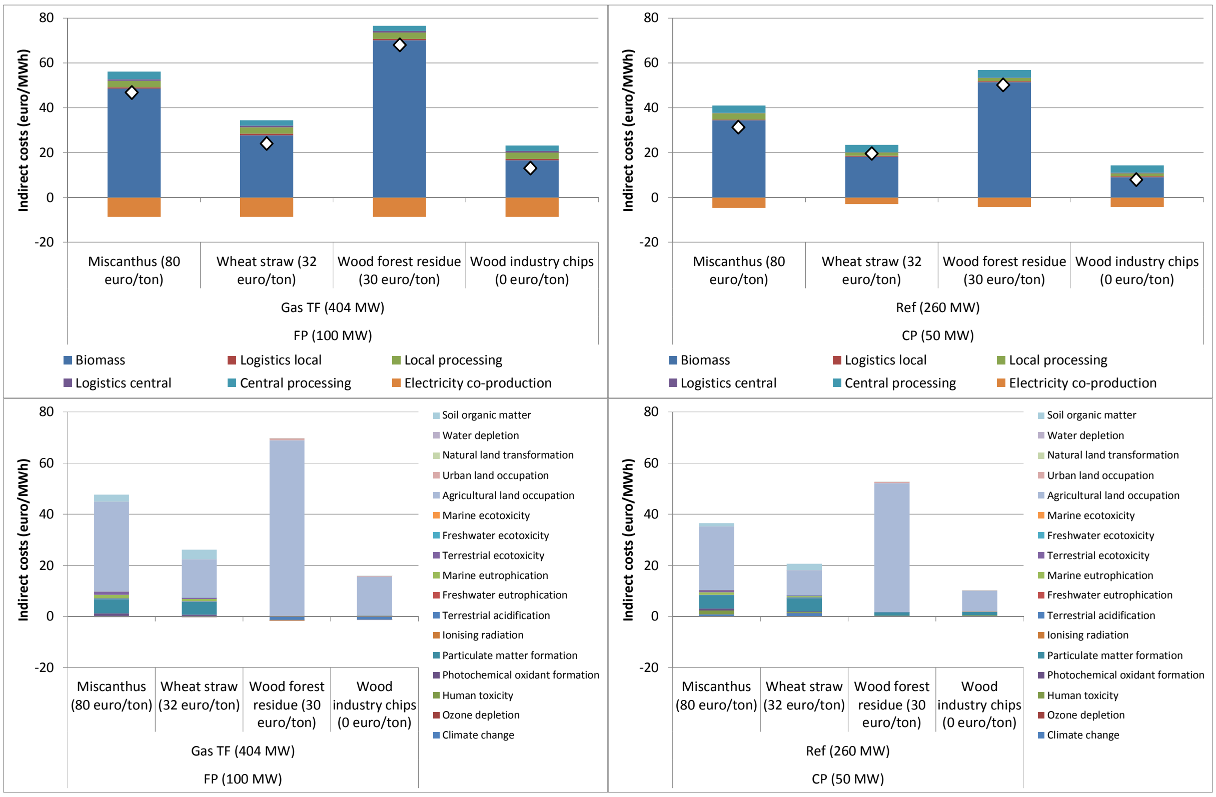


Figure 4-15 Breakdown of the indirect costs into the various impact categories of the biobased pathways for the production of a transport fuel from wheat straw, miscanthus and wood via fast pyrolysis (FP) and catalytic pyrolysis (CP).

The choice of feedstock has high impact on the overall indirect costs when taking into account the new, bio-related impacts. The indirect costs vary from 14 to 67 euro/MWh for the FP pathways, and from 10 to 52 euro/MWh for the CP pathway. For both pathways the order from low to high costs is: wood industry chips, wheat straw, miscanthus and wood forest residue. The impact from wood as a feedstock is mainly land occupation. The land area and time to grow 1 m^3 of wood (land occupation) is divided over the various products (as e.g. round wood and residual wood). The preferred option from ISO is to allocate impacts based on a physical parameter, like mass or energy. As there is a difference in main (round wood) and by-products (residual wood) an allocation on price will a better reflection. The price ration used in EcoInvent is 4:1 for round wood versus residual wood. The wood chips from industrial residual wood has an even lower value, and as a consequence lower impacts from land occupation are allocated.

The valuation determines how heavy the land occupation related impacts such as biodiversity are weighted compared to the other environmental impact categories (e.g. climate change, human toxicity etc.). The approach is based on the value on average global ecosystem services (Constanza, 1997), 0,094 EUR/m^2.yr (A factor 7 lower than the default of 0,6 euro/m^2.yr in ReCiPe based on potentially disappeared species). Nevertheless, this value is still based upon the assumption that a complete loss of the eco system services occurs. It does not differentiate between a forest or a paved area with asphalt. This is a remaining weakness in the method, but in current literature no other values are available. In Annex E the impacts from land occupation are explained in more detail. In case of complete preservation of biodiversity, a damage price of 0 would be more realistic.

Given all uncertainties on the inventory as well as the valuation of impacts of new biobased related impacts, the results on new biobased impacts should be viewed as a worst case scenario, presented to indicate the potential maximum risks of using certain types of biobased resources.

Summarized results

- Feedstock price and yield towards the final product have a significant influence on the total production costs.
- The lowest production costs for transport fuels via the FP pathway are obtained by utilizing wood industry chips which have the highest yield (1.04 kg DM/1 kg biosyncrude) and the lowest price (0 euro/tonne).
- For the CP pathway, the lowest overall costs are obtained by utilizing wheat straw and forest residue (146 euro/MWh and 150 euro/MWh, respectively).
- The choice of a feedstock has a significant impact on the environmental performance of the pathway.
- Cultivated crops (miscanthus, wheat straw) have higher conventional impacts than wood as a feedstock due to climate change and particulate matter formation. The price ratio of the by-product versus the main product is used to allocate the impacts from the cultivation over the main and by-product.
- Assuming a worst case scenario of a total loss of eco system services due to feedstock harvesting, the new, bio-related impacts give a higher contribution to the overall impacts than the conventional impacts in the biobased pathways. The largest bio-related impact comes from the factor agricultural land occupation. Especially in case of wood forest residue this factor has a strong effect due to the large land areas being used per MJ of feedstock. In case of complete preservation of biodiversity, the biodiversity impacts would become 0.
- Results on new biobased impacts are presented to indicate maximum potential risks of using certain types of biobased resources. The current valuation of land use needs further discussion.

4.2.5 *Sensitivity for the feedstock price*

In the previous section the effect of feedstock type and price was explained, however, this section illustrates the effect of feedstock price as an independent parameter to understand the impact on the overall pathway.

Figure 4-16 shows the sensitivity of wheat straw and forest residue prices for the FP and CP pathway, respectively. It is clear that the direct costs have a linear relationship with the feedstock price (blue bars) for both pathways. In practice, the feedstock price will rise as soon as the utilization or demand grows. Therefore, pathway optimization is required to lower feedstock utilization per region and to centralized conversion plants, where logistics and utilization are optimized in order to keep low feedstock prices.

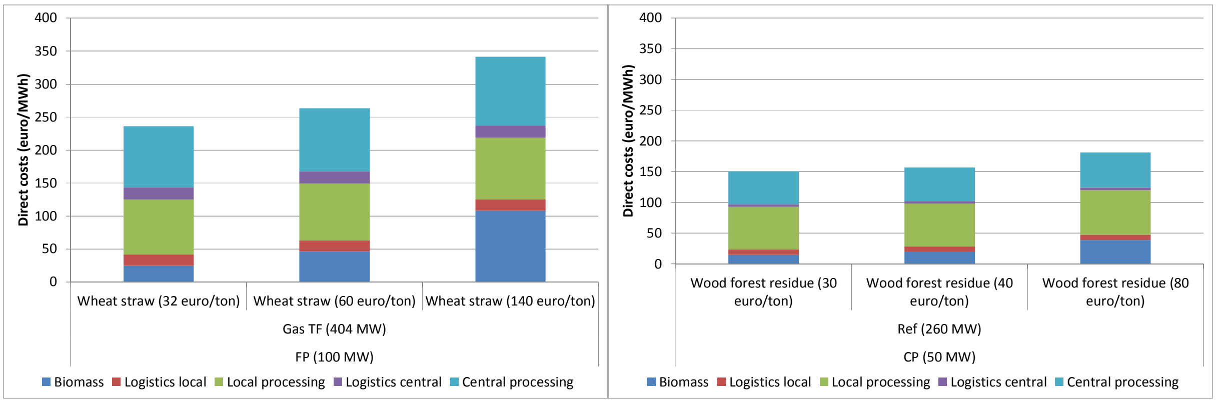


Figure 4-16 Sensitivity of the direct costs (euro/MWh) for the price of the feedstock. Variation in price of wheat straw for the FP pathway and wood for the CP pathway.

The price of the feedstock has no direct impact on the environmental impacts. When the feedstock is a by-product, the price ratio of main product versus the by-product changes could change. This could influence the allocation of the impacts. This has not been assessed within this section.

Summarized results

- Overall direct costs are directly proportional to the feedstock prices.
- Feedstock prices are affected by economic factors such as feedstock utilization, which could be controlled by means of optimization of logistics.
- Feedstock prices are not directly correlated to environmental impacts. When the price ratio of main and by-product also changes, this could influence the economic allocation of environmental impacts.

4.2.6 Sensitivity for the local and central transport distance

A sensitivity analysis was performed in order to determine the impact of the transport distance on the overall costs. A similar approach was followed as for the feedstock price. Figure 4-17 shows the sensitivity of the direct costs for the local transport distance. Transport distances are varied from 25 to 200 km in the FP and CP pathway. Figure 4-18 shows the sensitivity of the direct costs for the central transport distance. Transport distances are varied from 150 to 750 km in the FP and CP pathway.
In both cases, the logistics cost (red and purple bars) increases almost linearly as the distance increases. The only factor that makes the logistic cost not directly proportional is the handling costs, which depends on the amount of feedstock but not on the transported distance.

The conclusion of this analysis could be straightforward, however, longer transport distance should be seen as a consequence of larger plants, where more feedstock has to be brought from farther away regions to keep feedstock utilization per region below a certain level with the aim of maintaining a low feedstock price, which in the end has a larger effect on the overall costs.

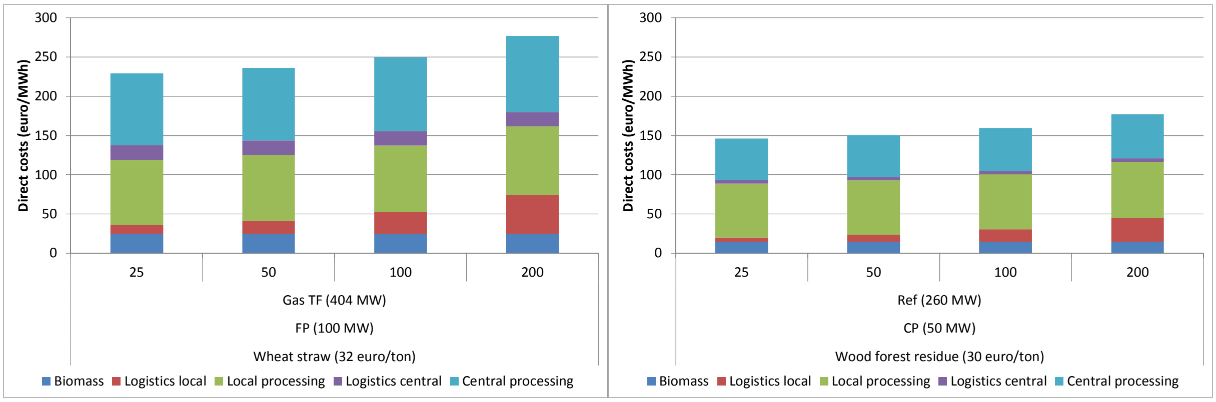


Figure 4-17 Sensitivity of the direct costs (euro/MWh) for the local transport distance. Variation in distance for the wheat straw/FP pathway and wood/CP pathway.

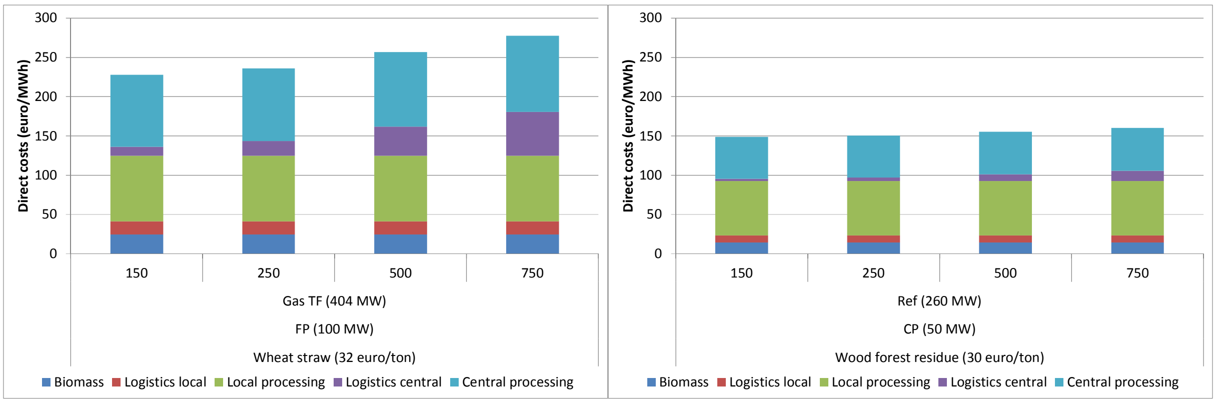


Figure 4-18 Sensitivity of the direct costs (euro/MWh) for the central transport distance. Variation in distance for the wheat straw/FP pathway and wood/CP pathway.

Figure 4-19 shows the sensitivity of the indirect costs for the local transport distance for the conventional and for the combination with the new, bio-related themes. There is a linear relation between the transport distance and the environmental impact. With an increasing transport distance the relative contribution to the overall impact increases. Taking into account the conventional impact the relative contribution in the FP pathway varies from 10 to 30% and in the CP pathway from 15 to 60%. Taken also into account the new, bio-related impacts (Figure 4-20), the contribution of the local logistics varies from 2 to 9% (FP) and from 1 to 3 % (CP).

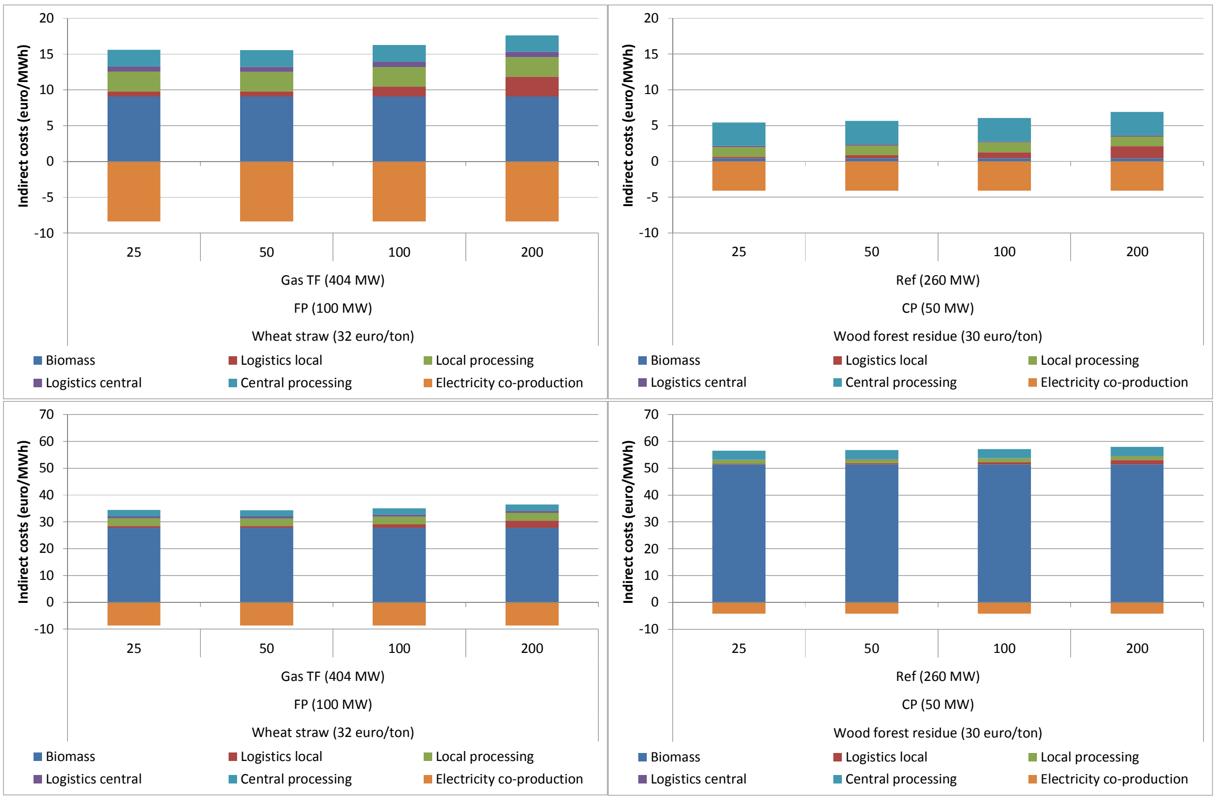


Figure 4-19 Sensitivity of the indirect costs (euro/MWh) for the local transport distance (in red). Variation in distance for the wheat straw/FP pathway and wood/CP pathway (conventional impacts upper, including new lower graphs).

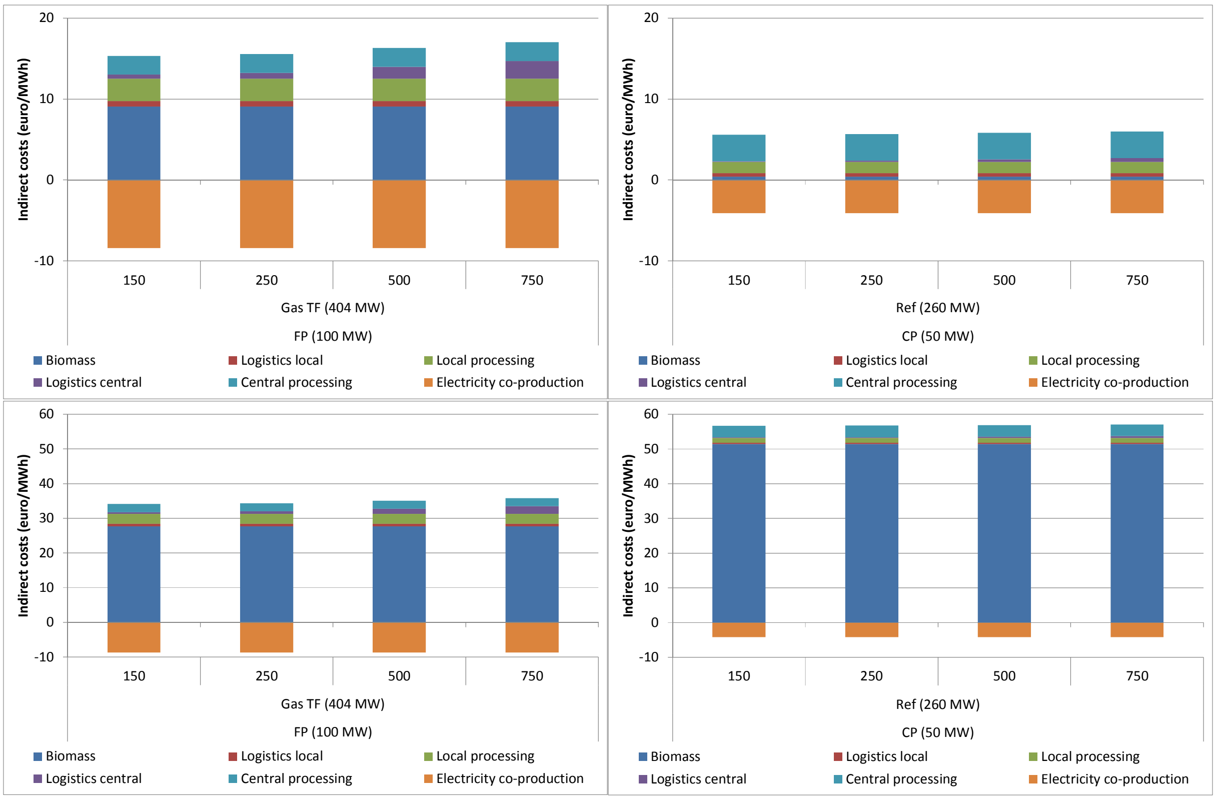


Figure 4-20 Sensitivity of the indirect costs (euro/MWh) for the central transport distance (in purple). Variation in distance for the wheat straw/FP pathway and wood/CP pathway (conventional impacts in upper graphs, including new bio related impacts in lower graphs).

The local and central transport are respectively truck and train (diesel/electric) based. Figure 4-21 shows the relative contribution. The fuel based processes mainly contribute to climate change and particulate matter formation. The electricity related processes also contribute to human and eco toxicity, as the electricity is generated in fossil and nuclear power plants.

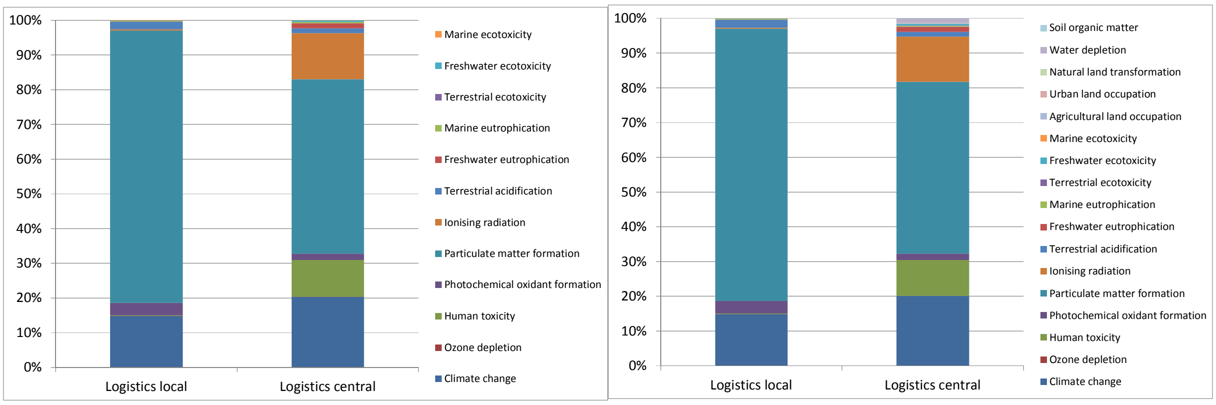


Figure 4-21 Relative contribution of environmental impact categories to the indirect costs (euro/MWh) for the local (truck) and central (train) transport for the conventional (left) and including the new impacts (right).

Summarized results

– Transport distance has a small effect on the overall costs. However, the transported distance is a key element in optimizing regional feedstock utilization and prices together with the processing capacities.
– Both direct and indirect transport costs for the FP pathway are higher than that for the CP pathway because of a lower overall conversion efficiency.
– Environmental impacts are directly proportional related to the transport distance. The contribution to the overall impact is small, but increases with increasing transport distance.
– Impacts due to transport are from conventional themes. Local transport (truck) mainly contributes to climate change and particulate matter, because of the fossil transport fuel emissions. Central transport (train) also contributes to human and eco-toxicity, because of the electricity use.

4.2.7 Sensitivity for plant capacity

Figure 4-22 and Figure 4-23 show the sensitivities for the local and central plant capacity for the direct costs, respectively. In both cases the economies of scale effect is visible, the bigger the scale the lower the direct costs. However, Figure 4-22 and Figure 4-23 show the direct costs, which comprise capital and operating costs, minimizing the effect of the economies of scale in the overall costs. The scaling factors used for scaling up and scaling down the reference capacities are listed in Table 4.3 and **Error! Reference source not found.** When available, the scaling factors per equipment were considered .

The objective of this analysis is to identify and determine the capacity limits towards a realistic implementation. For example, large capacity implies longer transport distances or higher feedstock utilization resulting in higher feedstock prices at the plant gate. However, the effect of the economies of scale will always lead to larger plants in order to reduce costs.

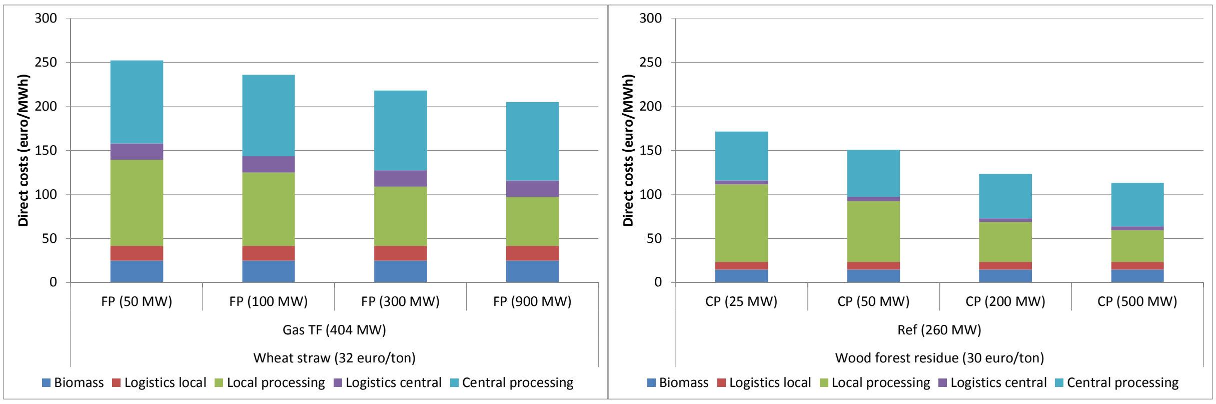


Figure 4-22 Sensitivity of the direct costs (euro/MWh) for the local plant capacity. Variation in capacity for the wheat straw/FP pathway and wood/CP pathway.

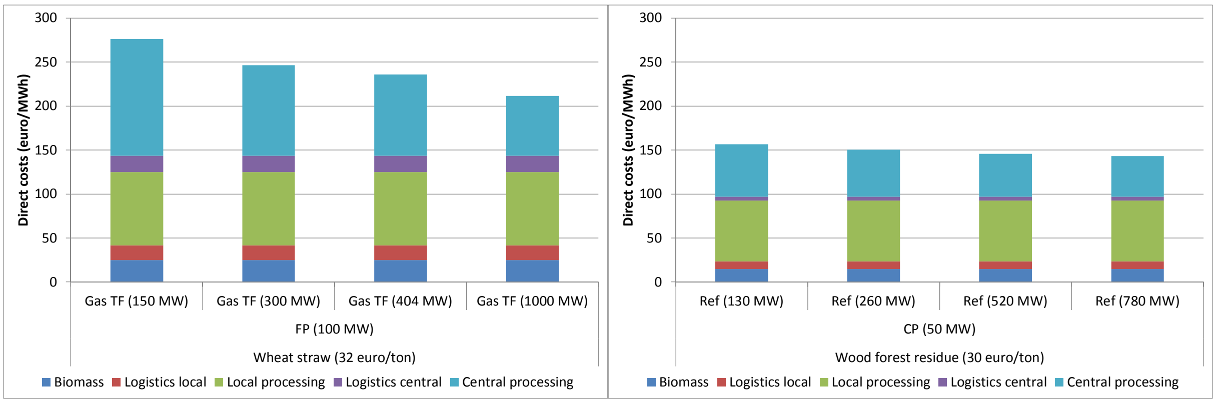


Figure 4-23 Sensitivity of the direct costs (euro/MWh) for the central plant capacity. Variation in capacity for the wheat straw/FP pathway and wood/CP pathway.

Table 4.3 Scaling factors per equipment and operating time for FP pathway

Scaling factors for FP pathway			
	FP		**Gasification**
Storage	0.80	Slurry mixing	0.60
Pre-treatment	0.80	Air separation unit	0.70
Heat carrier loop	0.80	Cooling and quench water system	0.60
Product recovery	0.80	Gasifier and auxiliaries	0.75
Biosyncrude mixing	0.80	Raw syngas treatment	0.70
Other	0.80	Syngas cleaning	0.65
		Slag recovery and handling	0.70
		Fiscer-Tropsch synthesis	0.65
		Product recovery and upgrading	0.70
		Power island	0.75
Processing time	7008 hrs		7008 hrs

Table 4.4 Scaling factors per equipment and operating time for the CP pathway

Scaling factors for CP pathway			
	CP		**Upgrading**
Air compressor	0.74	Catalytic Pyrolisis Oil Upgrader (see ANNEX E)	0.70
Regenerator	0.74		
Reactor	0.70		
Biomass crusher/grinder, metal separation, silo	0.90		
Main fractionator	0.75		
Biomass dryer	0.85		
Light gases furnace	0.70		
Precipitator	0.70		
Expander turbine and steam turbine	0.70		
Processing time	8000 hrs		7901 hrs

The plant capacity has no impact on the environmental performance. All relevant parameters influencing the environmental performance are expressed in units per MWh of product, independent of the plant size.

Summarized results

– Scaling factors have a large impact while scaling up and down.
– Large plant capacities will have lower processing costs and are therefore favorable for implementation. The larger the capacity, the lower the overall costs.
– In case of large processing plants the anticipated increase in local feedstock prices due to increased feedstock utilization has to be limited by means of optimization of logistics
– Similarly, small plant capacities will require optimized logistics and feedstock prices in order to compete with large scale plants.
– The plant capacity has no impact on the environmental performance. All relevant inputs influencing the environmental performance are expressed in units per MWh of product, independent of the plant size.

4.2.8 Sensitivity for product

Figure 4-24 shows the various products produced from the FP and CP pathways considering wheat straw as a reference feedstock. The comparison shows that the production of methanol has lower costs than the production of transport fuel via the FP pathway because it has a higher efficiency towards the production of methanol than the production of transport fuels (45.7% versus 39.8%). However the transport fuel produced via the CP pathway results in the lowest production costs.

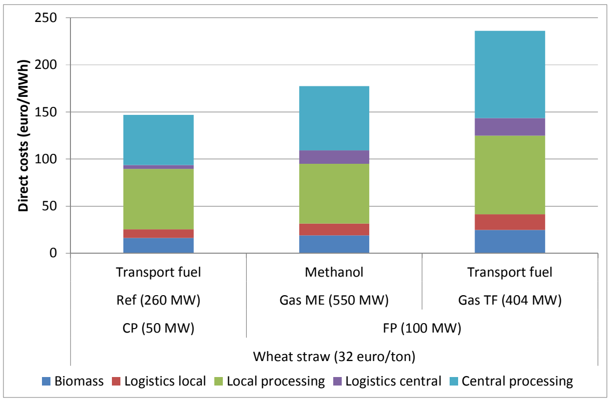


Figure 4-24 Sensitivity of the direct costs (euro/MWh) for final product. Variation in final product with wheat straw as a feedstock in the FP and CP pathway

Figure 4-25 shows the indirect costs of the production of transport fuel and methanol from wheat straw. Taking into account the conventional impacts, the environmental impacts are all in the same order of magnitude. Production of transport fuel via the FP pathway has a slightly lower indirect costs than production of methanol, because of the larger benefits from electricity co-generation.

Including the new, bio related environmental impacts, CP has the lowest indirect costs. Potentially, the FP pathway for transport fuel might see an increase of indirect costs, since benefits from electricity co-production will reduce over time.

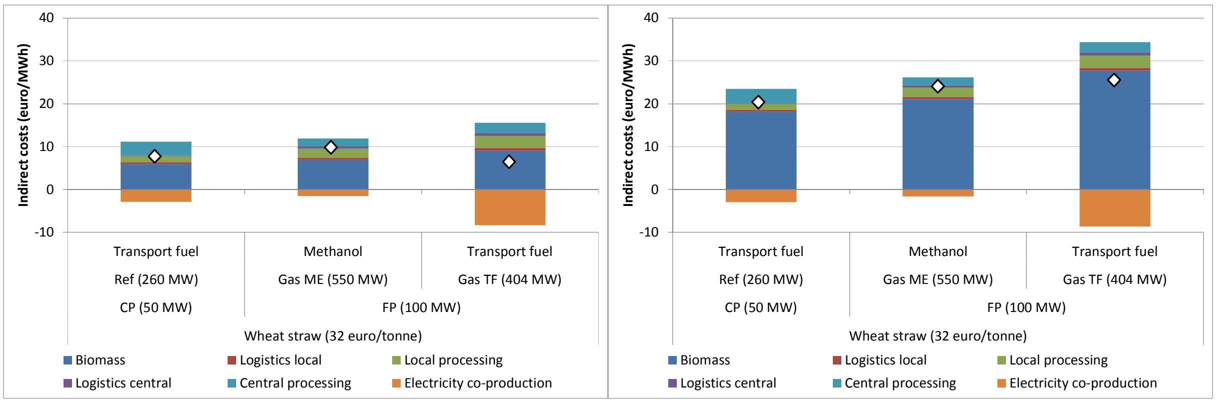


Figure 4-25 Sensitivity of the indirect costs (euro/MWh) for final product. Variation in final product with wheat straw as feedstock in the FP and CP pathway. Conventional impacts left an including new on right.

Summarized results

- Methanol is a more competitive product from the FP pathway when wheat straw is used as a feedstock.
- When starting from wheat straw and considering direct costs, biofuel produced via CP is the most competitive product.
- The conventional environmental impacts of all products is in the same order of magnitude. Methanol has a slightly higher impact as the benefits from the electricity co-generation is smaller than for the transport fuel production.
- Taking into account all costs, including the new bio-related costs, transport fuels from wheat straw via CP is the most competitive route.

4.3 Environmental assessment of the production of electricity via hydrothermal conversion and combined heat and power

4.3.1 RED CO_2 emissions

The first step of the three step environmental assessment is the evaluation of Green House Gas emissions of the pathways. For the assessment RED guidelines will be used. Results will be benchmarked against a fossil based processes.

Figure 4-27 shows the RED CO_2 emissions for the HTC pathway to produce electricity from the organic municipal waste and brewery spent grain. It is clear that CO_2 emissions stem from energy consumption in the HTC process to produce the biocoal. The life cycle emissions from fossil coal are approximately 111 g CO_2/MJ. The GHG emissions from the fossil benchmark, i.e. the hard coal mix in Germany, are 13 g CO_2-eq/MJ up to the production while the use phase will add another 98 g CO_2-eq/MJ. The bio-coal will have no CO_2 emissions in the use phase.
This means that over the life cycle, biocoal reduces greenhouse gas emissions with almost 60%.

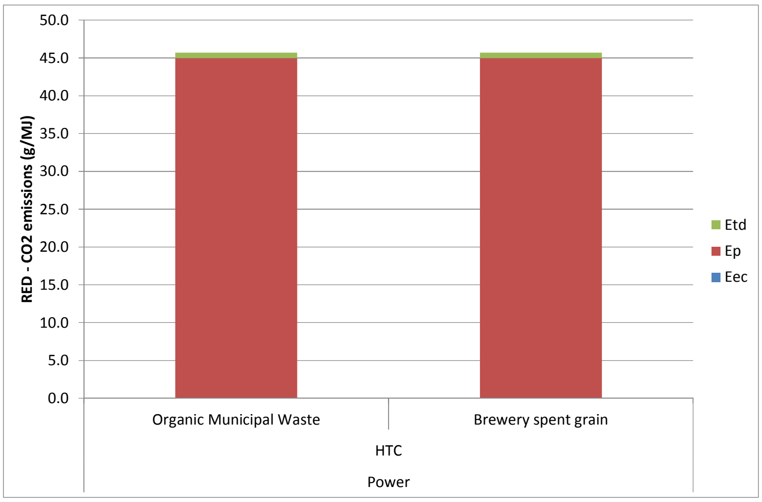


Figure 4-26 RED CO_2 emissions for the HTC pathway. CO_2 emissions from extraction & cultivation (Eec), processes (Ep) and transport & distribution (Etd).

Summarized results

– Over the life cycle, HTC produced biocoal reduces greenhouse gas emissions with almost 60% compared to the fossil coal reference.

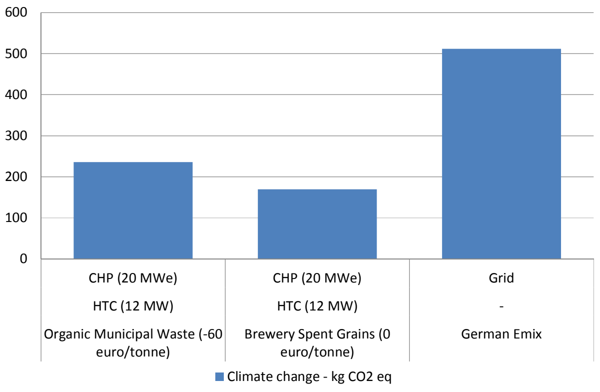
4.3.2 Conventional impacts

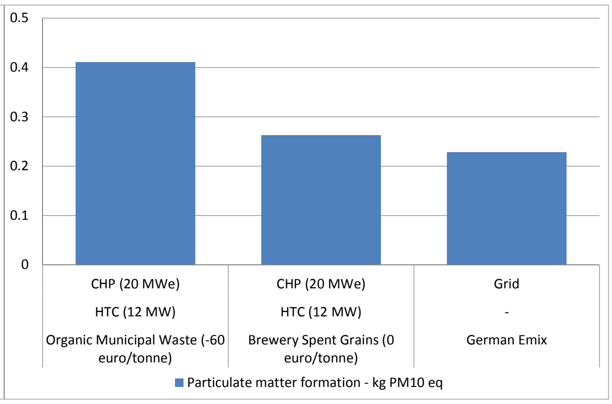
Second step in the environmental assessment is evaluation of the individual conventional impacts. For the assessment LCA according ISO will be used. As ISO prescribes, individual indicators will be presented and cannot be weighed in a comparative assessment of different products. This means that different impacts cannot be compared either. In addition to the biobased pathways, a fossil equivalent is presented as a benchmark.

Figure 4-27 presents conventional environmental impacts of combined heat and power production by the biobased HTC pathways on Organic Municipal Solid Waste (OMSW) and brewery spent grains (BSG) versus the fossil reference, ie electricity from the German grid (impacts per MWh of product).

The greenhouse gas emissions differ from the RED approach taken in the previous section, particularly due to the fact that the full life cycle including electricity production is taken into account.

If we compare HTC generated power to average electricity from the German grid, it is clear that the first avoids CO_2 emissions and eutrofying, human and eco-toxic emissions while the German grid has lower impacts on particulate matter and photochemical oxidant emissions. The biocoal fuelled CHP has relative high PM and photochemical oxidant emissions. These emissions are higher for the HTC variant on OMSW since these have higher transport emissions due to additional (house to house stop and go) collection of the OMSW.
Another difference of OMSW and BSG is the allocation of impacts of the cultivation of brewery grains, based upon the relative value. It leads to impacts in terrestrial ecotoxicity, particularly due to plant protection products.


600
500
400
300
200
100
0
CHP (20 MWe) HTC (12 MW) Organic Municipal Waste (-60 euro/tonne)
CHP (20 MWe) HTC (12 MW) Brewery Spent Grains (0 euro/tonne)
Grid - German Emix
Climate change - kg CO2 eq


0.5
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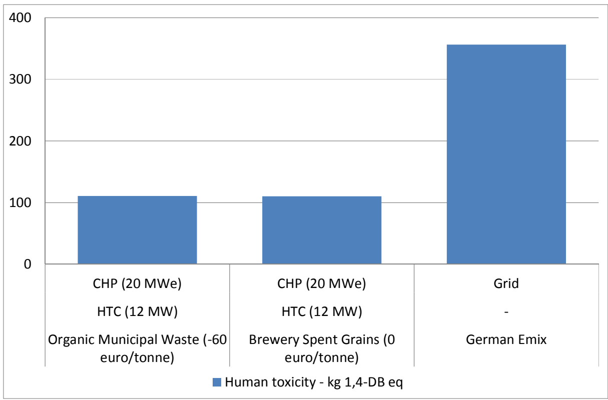
CHP (20 MWe) HTC (12 MW) Organic Municipal Waste (-60 euro/tonne)
CHP (20 MWe) HTC (12 MW) Brewery Spent Grains (0 euro/tonne)
Grid - German Emix
Particulate matter formation - kg PM10 eq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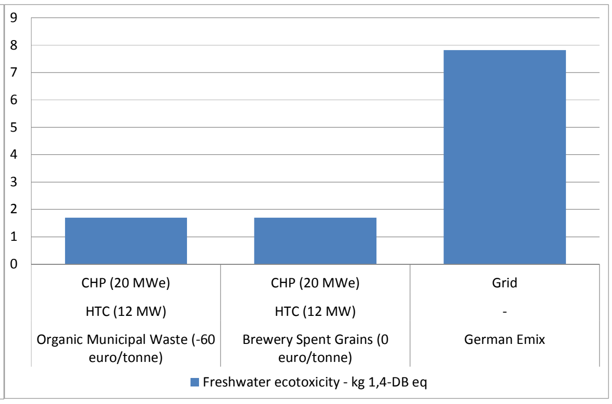
CHP (20 MWe) HTC (12 MW) Organic Municipal Waste (-60 euro/tonne)
CHP (20 MWe) HTC (12 MW) Brewery Spent Grains (0 euro/tonne)
Grid - German Emix
Human toxicity - kg 1,4-DB eq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2
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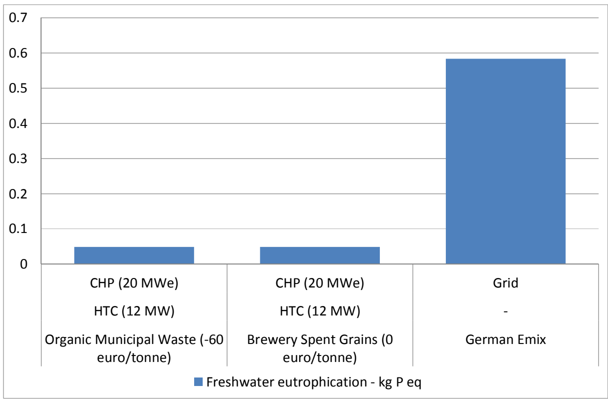
CHP (20 MWe) HTC (12 MW) Organic Municipal Waste (-60 euro/tonne)
CHP (20 MWe) HTC (12 MW) Brewery Spent Grains (0 euro/tonne)
Grid - German Emix
Freshwater ecotoxicity - kg 1,4-DB eq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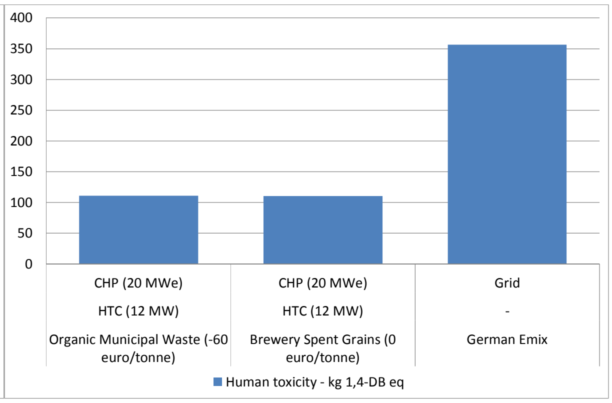
CHP (20 MWe) HTC (12 MW) Organic Municipal Waste (-60 euro/tonne)
CHP (20 MWe) HTC (12 MW) Brewery Spent Grains (0 euro/tonne)
Grid - German Emix
Freshwater eutrophication - kg P eq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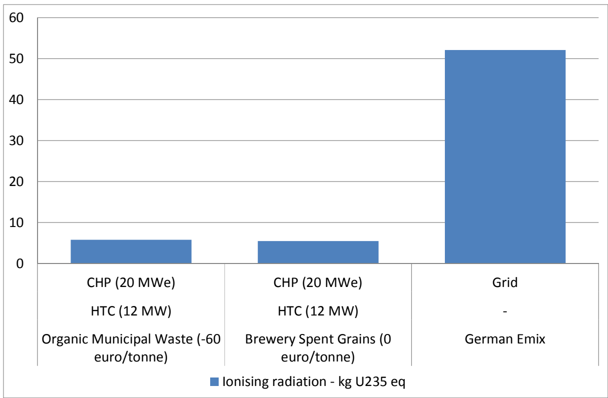
CHP (20 MWe) HTC (12 MW) Organic Municipal Waste (-60 euro/tonne)
CHP (20 MWe) HTC (12 MW) Brewery Spent Grains (0 euro/tonne)
Grid - German Emix
Human toxicity - kg 1,4-DB eq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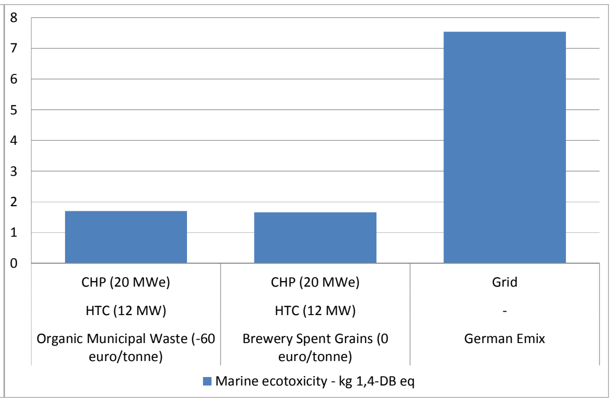
CHP (20 MWe) HTC (12 MW) Organic Municipal Waste (-60 euro/tonne)
CHP (20 MWe) HTC (12 MW) Brewery Spent Grains (0 euro/tonne)
Grid - German Emix
Ionising radiation - kg U235 eq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CHP (20 MWe) HTC (12 MW) Organic Municipal Waste (-60 euro/tonne)
CHP (20 MWe) HTC (12 MW) Brewery Spent Grains (0 euro/tonne)
Grid - German Emix
Marine ecotoxicity - kg 1,4-DB eq

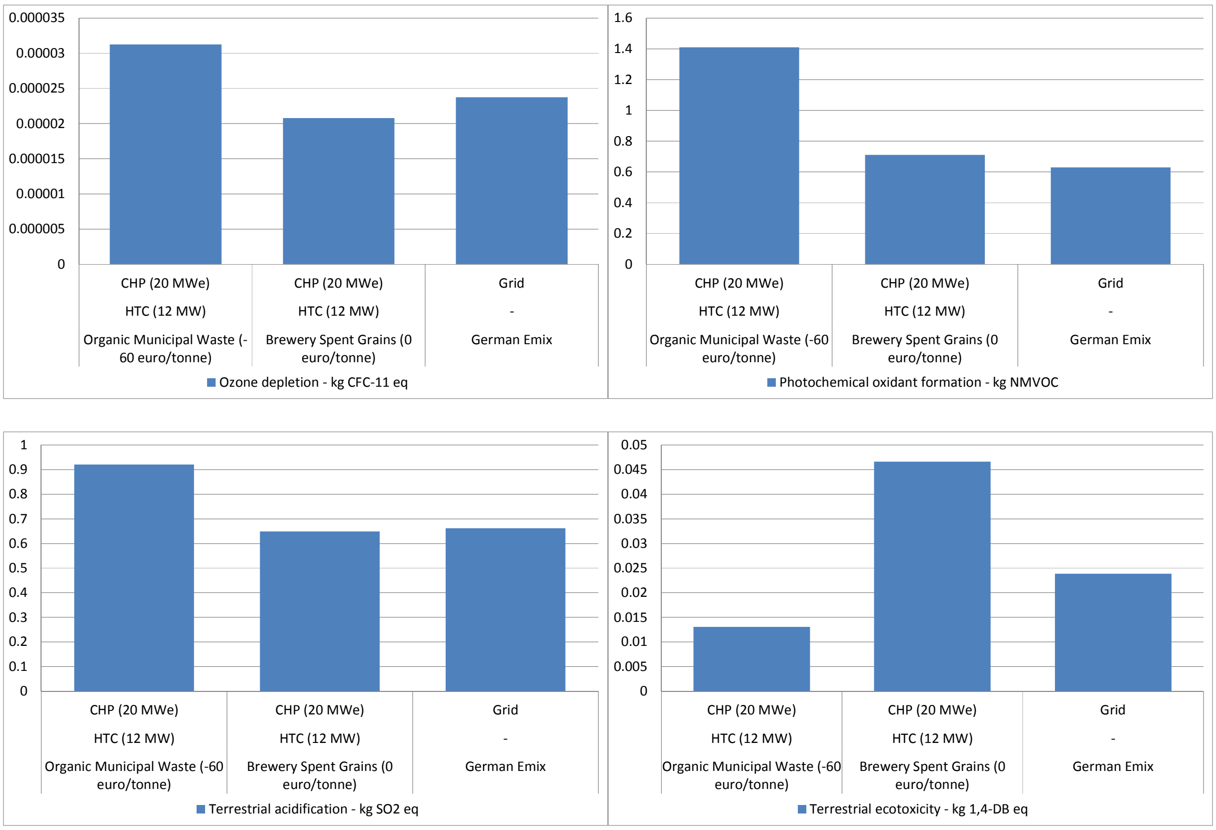


Figure 4-27 Comparison of conventional environmental impacts for the biobased HTC pathways versus the fossil references (impacts per MWh of product)

Table 4.5 Conventional environmental impacts per MWh of electricity via HTC pathway (organic municipal waste, 12 MW HTC and 20 MW CHP plant, 0 km local and 50 km central transport) and electricity from the grid as fossil reference

Impact category	unit	HTC OMW	Electricity grid
Climate change	kg CO2 eq	2.35E+02	5.12E+02
Fossil depletion	kg oil eq	8.03E+01	1.42E+02
Freshwater ecotoxicity	kg 1,4-DB eq	1.69E+00	7.82E+00
Freshwater eutrophication	kg P eq	4.82E-02	5.84E-01
Human toxicity	kg 1,4-DB eq	1.11E+02	3.57E+02
Ionising radiation	kg U235 eq	5.78E+00	5.21E+01
Marine ecotoxicity	kg 1,4-DB eq	1.70E+00	7.54E+00
Marine eutrophication	kg N eq	9.37E-02	1.51E-01
Metal depletion	kg Fe eq	2.09E-02	1.77E-01
Ozone depletion	kg CFC-11 eq	3.10E-05	2.38E-05
Particulate matter formation	kg PM10 eq	4.07E-01	2.29E-01
Photochemical oxidant formation	kg NMVOC	1.40E+00	6.29E-01
Terrestrial acidification	kg SO2 eq	9.14E-01	6.62E-01
Terrestrial ecotoxicity	kg 1,4-DB eq	1.29E-02	2.39E-02

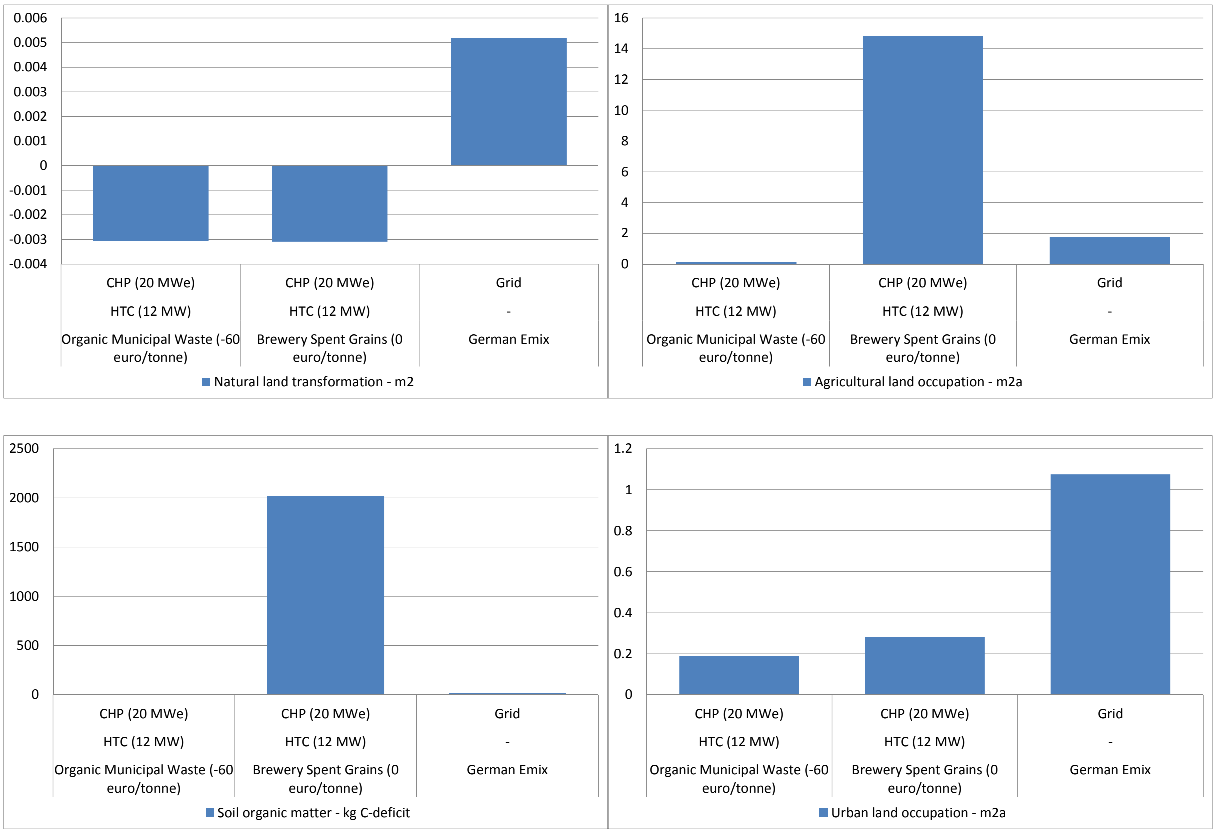
Summarized results

- Compared to average electricity from the German grid, HTC generated power, avoids CO_2 emissions and eutrofying, human and eco-toxic emissions while the German grid has lower impacts on particulate matter and photochemical oxidant emissions. The biocoal fuelled CHP has relative high PM and photochemical oxidant emissions due to transport for waste collection, which is particularly true for the collection of Organic Municipal Solid Waste.
- The use of brewery spent grains (BSG) has the disadvantage compared to Organic Municipal Solid Waste that it has impacts in terrestrial ecotoxicity due to the allocation of impacts of the cultivation of brewery grains based upon the relative value.

4.3.3 New bio-related impacts

The third step in environmental assessment is the assessment of new bio related impacts. The agricultural nature of processes differs from its equivalent fossil value chains. For this reason, new biorelated indicators are relevant for the environmental assessment of biobased pathways. It should be realized, however, that the assessment of these impacts is relatively new in terms of data inventory and impact methodology. Hence, uncertainties are large. Nevertheless, these indicators should not be ignored but should be viewed rather as a potential risk instead of an impact.

Obviously, the land-use impacts of HTC fuelled by OMSW are limited. Due to avoidance of electricity generation on the grid, natural land transformation (in fossil energy extraction) is avoided. A limited impact on urban land occupation occurs due to plant facilities but this is lower than for public power generation. There is no impact on agricultural land occupation and soil organic matter. The latter is the case for the use of BSG, also higher than for power generation from the grid.
Water depletion is lower for HTC than for power generation, due to the avoided water demand in fuel extraction.



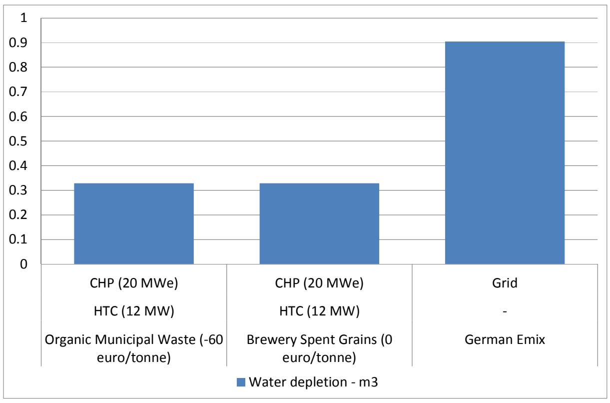


Figure 4-28 Comparison of new bio-related environmental impacts for the biobased HTC pathways versus the fossil references (impacts per MWh of product)

Table 4.6 New bio-related environmental impacts per MWh of electricity via HTC pathway (organic municipal waste, 12 MW HTC and 20 MW CHP plant, 0 km local and 50 km central transport) and electricity from the grid as fossil reference

Impact category	**unit**	**HTC OMW**	**Electricity grid**
Agricultural land occupation	m2a	1.35E-01	1.75E+00
Natural land transformation	m2	-3.06E-03	5.19E-03
Soil organic matter	kg C-deficit	2.59E+00	1.84E+01
Urban land occupation	m2a	1.88E-01	1.07E+00
Water depletion	m3	3.29E-01	9.04E-01

Summarized results

- Power produced with HTC on OMW has lower biobased related impacts on land-use and water depletion than average German power production.
- This also applies for power produced with HTC on BSG, except for the impact on agricultural land-use, which is higher than for average German power production.

4.4 Integrated sustainability assessment of the production of electricity via hydrothermal conversion and combined heat and power

As has become clear in the previous paragraphs, environmental profiles of different pathways can have both positive and negative differences. If an option avoids CO_2 but emits more toxic emissions, does it provide an improvement for the environment or not? In order to be able to determine which option is the most environmentally friendly, it is often necessary to weigh the different impacts. Moreover, if we value the impacts in terms of environmental damage, it is possible to make an integrated assessment for decision making.
The integrated sustainability assessment presented in this chapter consists of an overview of both benefits and costs. These consist of both direct (techno-economic) costs and indirect (environmental) effects. This approach indicates strengths and weaknesses relative to one another and supports decision making on different options and pathways.

The products of the HTC pathway, electricity and heat, cannot directly be compared with the products from the previous pathways (transport fuels and methanol), which are energy carriers. Heat and power are energy products. Therefore, this pathway is assessed in a separate section based on the same approach, starting from the overall direct and indirect costs and their cost breakdown, followed by the sensitivity analysis of feedstock, feedstock price and capacity.

The products of the HTC pathway, electricity and heat, cannot directly be compared with the products from the previous pathways (transport fuels and methanol), which are energy carriers. Heat and power are energy products. Therefore, this pathway is assessed in a separate section based on the same approach, starting from the overall direct and indirect costs and their cost breakdown, followed by the sensitivity analysis of feedstock, feedstock price and capacity.

4.4.1 Direct versus indirect cost

Figure 4-29 illustrates the direct and indirect (conventional) costs of the HTC pathway, using organic municipal waste as a feedstock. As a benchmark the market price of electricity from the German grid is plotted. The overall costs of the HTC pathway are similar to those of the fossil benchmark. To be more specific, the direct costs of the HTC pathway are 102 euro/MWh versus 100 euro/MWh for electricity from the grid. Revenues from selling the produced heat are not included in the production costs, which would result in lower production costs and minimum selling price. The indirect costs are 31 euro/MWh for the HTC pathway versus 36 euro/MWh for the benchmark. Compared with the pathways in section 4.1, the contribution of the indirect costs is higher in the HTC pathway. In the next sections the breakdown of direct and indirect costs will give more insight in how the costs are built-up.

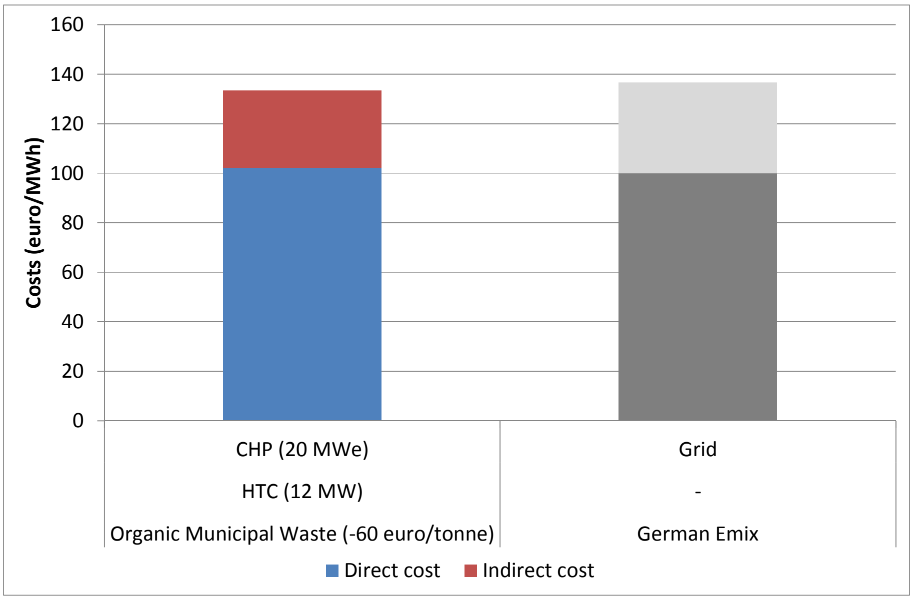


Figure 4-29 Direct versus indirect (conventional) cost to produce electricity via the Hydrothermal conversion (HTC) and Combined Heat and Power (CHP) based on Organic Municipal Waste and electricity from the German grid, in euro/MWh

Summarized results

- The production costs of electricity from organic municipal waste for the HTC and CHP pathway are similar to the market price of electricity from the grid.
- The indirect costs are in the same order of magnitude. The HTC pathway has (conventional) indirect costs of 31 euro/MWh versus 36 euro/MWh. for the benchmark.
- With a feedstock price of -60 euro/ton electricity production from organic municipal waste is competitive with electricity from the German grid.

4.4.2 Breakdown of the direct costs

The direct costs breakdown for the HTC pathway is more complex than for the FP and CP pathways. This pathway considers a negative value of the feedstock which leads to a more complicated analysis of the resulting plots. Figure 4-30 shows two different plots. On the left side a comparison of the direct costs of the energy carrier of HTC, bio-coal, with the costs for producing electricity and heat. The right side plot compares the production of electricity and heat with the benchmark electricity price.

The plot on the left side shows that the production costs of bio-coal in terms of euro per MWh have an overall negative value of approximately 40 euro/MWh. As a result, negative feedstock costs are considered in the direct costs calculation for the CHP plant. The overall direct costs are the sum of the negative feedstock costs and the positive processing costs, resulting in 102 euro/MWh.
Figure 4-31 shows the operating cost breakdown of operating costs, which sum up to a total of 127 euro/MWh heat and power produced. Thus, the production cost (or minimum selling price) of 102 euro/MWh considers the revenues from the electricity and the heat produced. In this case, the heat sales price was assumed to be 20 euro/MWh. This way, revenues from produced heat result in a competitive cost price for electricity via the HTC pathway.

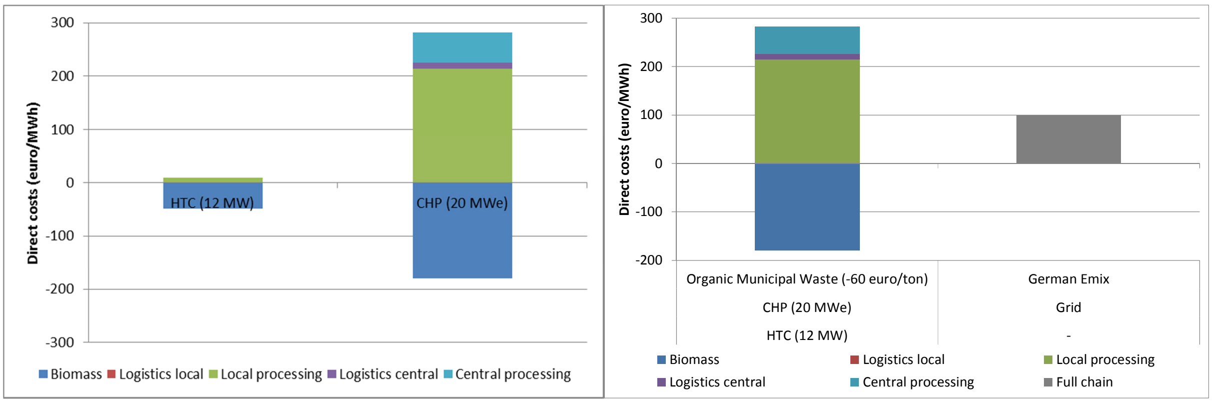


Figure 4-30 Breakdown of the direct costs into the various steps of the biobased pathways for the production of electricity from organic municipal waste via hydrothermal conversion (HTC) and CHP and electricity from the German grid. For electricity no break down was available and the direct costs of the full chain are displayed.

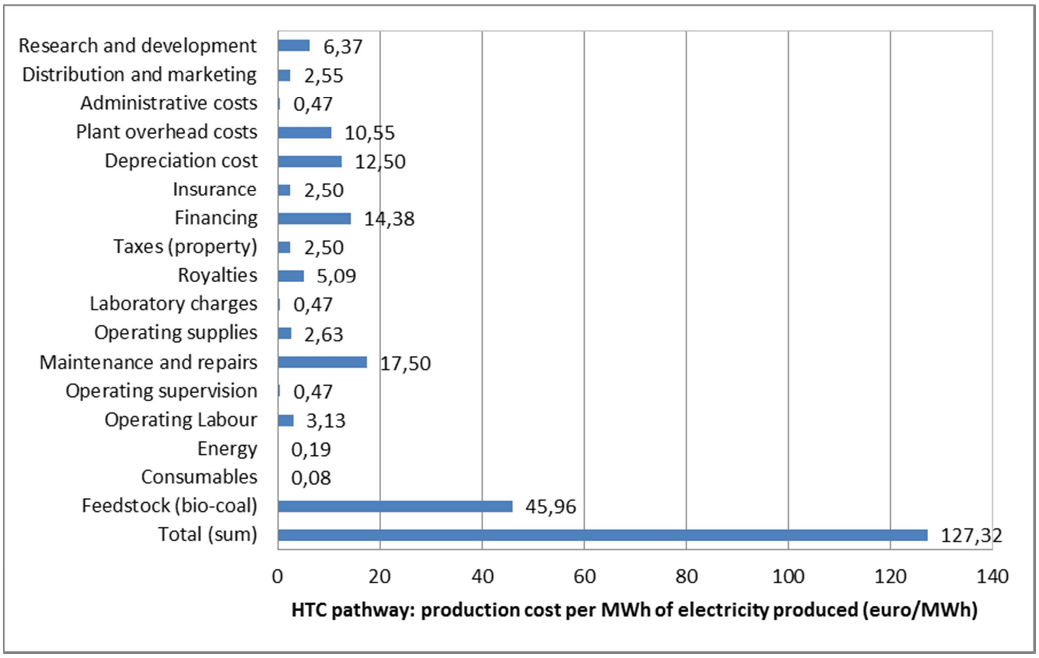


Figure 4-31 Production cost of electricity produced via HTC pathway

Summarized results

- Due to the negative feedstock price for organic municipal waste, electricity can be produced via the HTC pathway at competitive cost price with regard to the benchmark.
- The major cost contributor in the production of electricity via hydrothermal combustion is the conversion of organic municipal waste into bio-coal.
- The sales revenues from the heat produced are essential to produce electricity at a competitive price.

4.4.3 Breakdown of the indirect costs

The indirect costs of the HTC pathway for organic municipal waste and the benchmark, electricity from the German grid, are in the same order of magnitude. Figure 4-32 shows the breakdown of the indirect costs into the various steps in the pathway. The contribution of logistics in negligible. The shares of feedstock, local and central processing are similar in size. No impacts are allocated to waste, only collection and transport by truck are taken into account. The emissions from waste collection contribute to climate change and particulate matter formation. Local processing contributes to climate change as well, because of the use of steam which is generated by the use of natural gas burners. Overall, the CHP process contributes mainly to human toxicity, because of the large amount of ash produced during the combustion of coal. See Figure 4-33 for the break down into the impact categories.

Comparison of the conventional and new environmental impacts in Figure 4-33 shows that the new impacts do not contribute to the indirect costs. Conventional impacts from waste collection, natural gas combustion (steam) and waste (ashes from coal combustion) are dominating the overall impact.

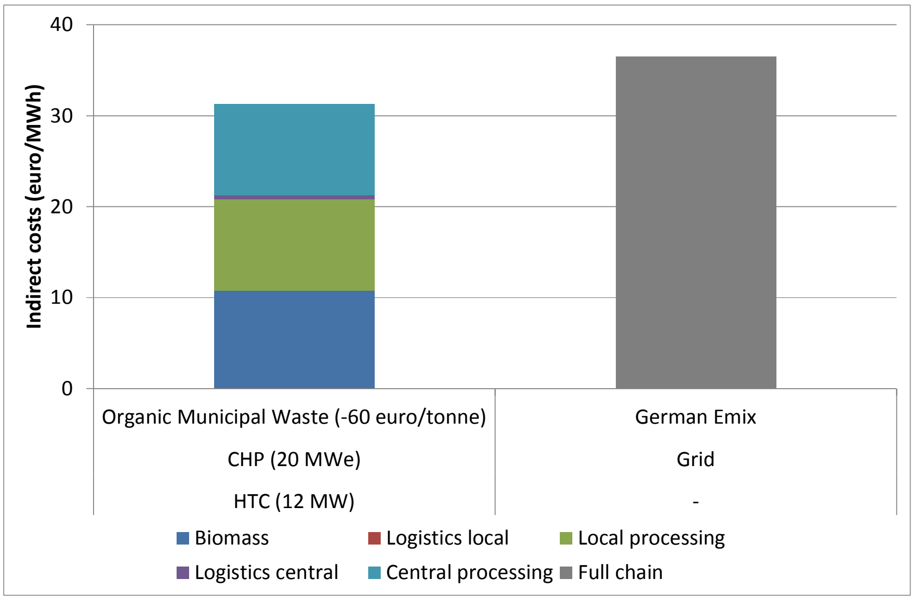


Figure 4-32 Breakdown of the indirect costs into the various steps of the biobased pathway for the production of electricity from organic municipal waste via hydrothermal conversion (HTC) and CHP, and total indirect costs for electricity from the German grid. For electricity from the grid no breakdown was available and therefore the indirect costs of the full chain are displayed.

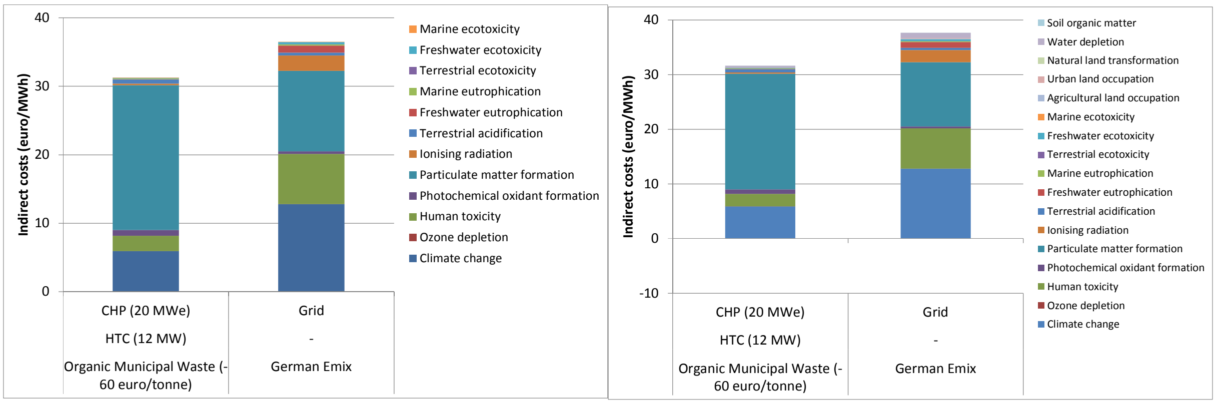


Figure 4-33 Breakdown of the indirect costs into the various impact categories of the biobased pathways for the production of electricity from municipal organic waste via hydrothermal conversion (HTC) and CHP and electricity from the grid. Conventional impacts are displayed in the graph on the left and the new impacts are included in the graph on the right.

The HTC pathway has a potential for improvement on the environmental impacts. The current assessment assumes an average waste collection truck, collecting waste from door to door over a distance of 25 km. The repeated stops and starts of the truck cause relatively large emissions of CO_2 and particulate matter. By cleaner transport mode and/or a more efficient collection system, the impacts allocated to the feedstock could be reduced.
The steam used in the local process is generated by burning natural gas. The CO_2 emissions resulting from this contribute the most to the impacts of the local process. When steam could be generated via a non-fossil route, CO_2 emission could be limited and the environmental impacts reduced.
The CHP process generates a large amount of ash. Disposal of these ashes can have a serious impact on human toxicity, depending on the composition. For the market implementation of the technology, it is needed to investigate the disposal possibilities, or even look for options to use it as a fertilizer.

Summarized results

- Environmental impacts from logistics are negligible. Feedstock, local and central processing have equal shares in the overall indirect costs. Conventional impacts, mostly resulting from waste collection, steam generation and CHP, contribute to the most to the total environmental impacts, while the new, biorelated impacts only play a minor role in the HTC pathway.
- The HTC pathway contains uncertainties and has a potential for improvement. A cleaner and/or more efficient waste collection can reduce impacts allocated to the feedstock. An alternative way of producing steam for the local proces, e.g. using non-fossil energy, could reduce CO_2 emissions. The CHP process produces a large amount of ash and its disposal can have a serious impact on toxicity.

4.4.4 Sensitivity for feedstock

Figure 4-34 shows the comparison between the production of electricity and heat from organic municipal waste (OMW) and brewery spent grains (BSG). The total direct costs are approximately 102 euro/MWh for OMW and 329 euro/MWh for BSG. This difference is the result of the different biomass feedstock costs, which is -60 euro/tonne for OMW and 0 euro/tonne for BSG. As stated in the previous section, the negative biomass costs for OMW resulted in negative intermediate (bio-coal) costs. When biomass costs per unit of energy are zero or positive, as for BSG, this has an impact on the overall costs as shown in Figure 4-34. Also, the HTC process requires 1.6 kg DM of BSG per kg of bio-coal compared to 1.43 kg DM of OMW.

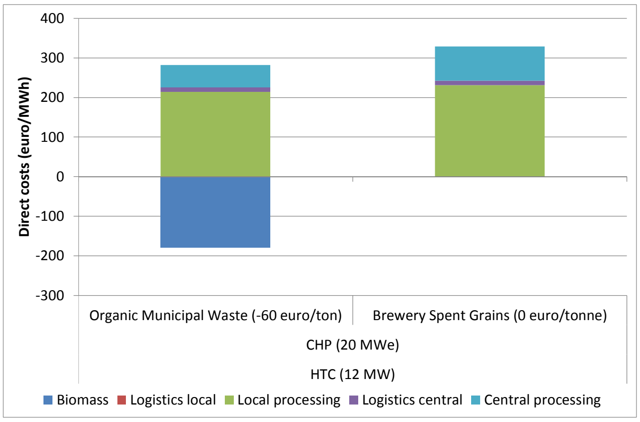


Figure 4-34 Breakdown of the direct costs into the various steps of the biobased pathways for the production of electricity via Hydrothermal Conversion (HTC) and Combined Heat and Power (CHP).

Figure 4-35 and Figure 4-36 show the breakdown of the environmental impacts for OMW and BSG as feedstock for the HTC process. When considering environmental impact categorized by pathway steps (Figure 4-35), the impacts from the local and central process are similar for both feedstocks. The main effect comes from biomass step. When considering the environmental impact categorized by impact category (Figure 4-36), the main difference in impact comes from particulate matter formation and climate change. As mentioned before, the impacts from organic municipal waste are larger, because of the required collection of the waste from door to door. The brewery spent grains are a by-product from the beer brewery. A part of the impacts from the beer brewing process, up to the wort process are allocated to the brewery spent grains.

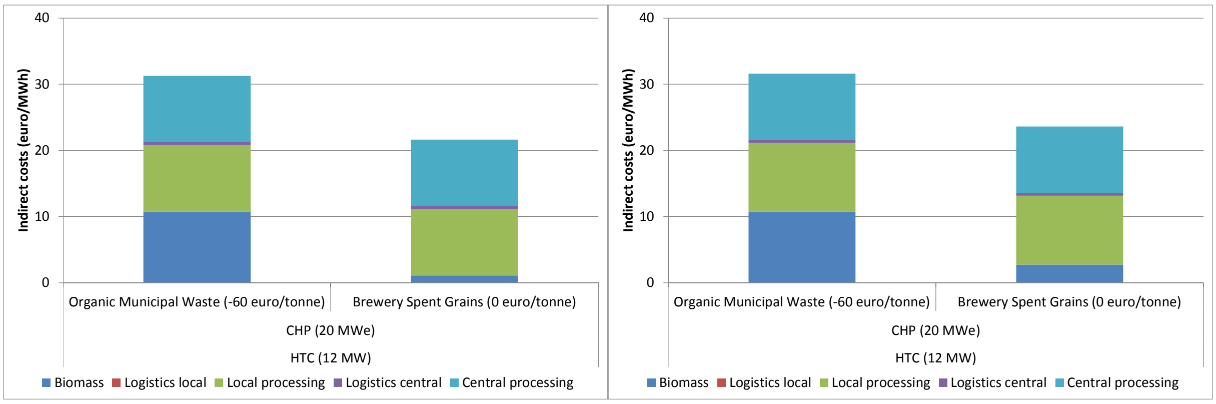


Figure 4-35 Breakdown of the indirect costs into the various steps of the biobased pathways for the production of electricity via Hydrothermal Conversion (HTC) and CHP (left conventional and right including new impacts).

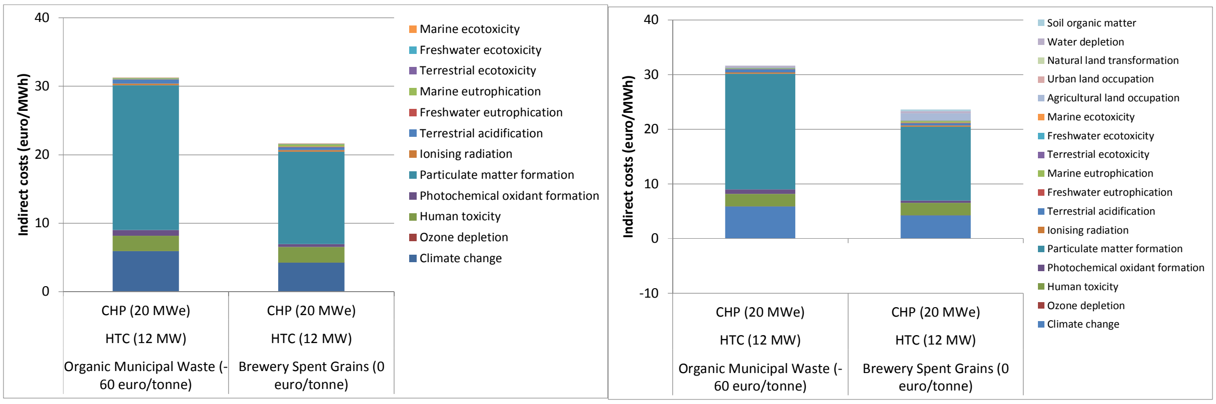


Figure 4-36 Breakdown of the indirect costs into the various environmental impacts of the biobased pathways for the production of electricity via Hydrothermal Conversion (HTC) and CHP(left conventional and right including new impacts).

Summarized results

- When comparing the effect of using BSG or OMW as feedstock on the direct costs of the HTC pathway, feedstock costs have a larger influence on the overall costs than the difference in conversion yield.
- When considering indirect costs per process step, the type of feedstock only has an impact on the biomass step. The impacts from local and central processing are the same. Organic municipal waste has an higher impact due to the waste collection.
- When considering indirect costs per impact category, the impacts resulting from organic municipal waste are relatively large due to particulate matter formation and climate change, which is assumed to be generated during waste collection. In this respect, the impacts from the brewery spent grains are small.

4.4.5 Sensitivity for the price of the feedstock

From the comparison between OWM and BSG in the previous section it became clear that biomass costs have a large influence on the overall costs. In this analysis, the OMW price was varied in order to decouple the effect of different yields. Figure 4-37 shows the effect on the overall pathway of feedstock prices of -60, -15, and 0 euro/ton. As stated earlier, the final costs are the sum of the negative and positive values per column. This means that the final direct costs for the production of electricity add up to 102, 273, and 329 euro/MWh for feedstock prices of -60, -15, and 0 euro/ton respectively. This results shows that the feasibility of the HTC pathway is greatly dependent on the feedstock costs.

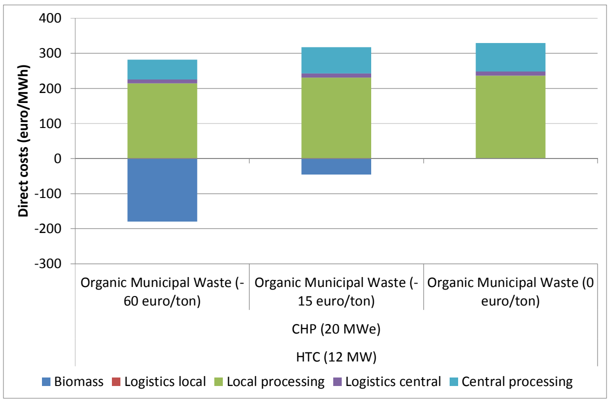


Figure 4-37 Sensitivity of the direct costs (euro/MWh) for the feedstock price. Variation in the feedstock price of organic municipal waste in the hydrothermal conversion (HTC) pathway.

The price of the feedstock has no direct impact on the environmental impacts. When the feedstock is a by-product, the price ratio of main product versus the by-product changes could change. This could influence the allocation of the impacts. This has not been assessed within this section.

Summarized results

– The feasibility of the electricity generation via the HTC pathway heavily depends on the feedstock price. Therefore, residual biomass is preferred as feedstock.
– Feedstock prices are not directly correlated to environmental impacts. When the price ratio of main and by-product also changes, this could influence the economic allocation of environmental impacts.

4.4.6 Sensitivity for central transport distance

Figure 4-38 illustrates the effect of transport distance on direct costs. It shows that the contribution of transport distance to the overall costs does not have a large effect below 250 km. Nevertheless, the logistics costs linearly increases as the distance becomes larger. This means that when the transport distance exceeds 250 km it starts to become a relevant cost contributor. Since bio-coal will most likely be produced near municipal waste collection centers it will have to be transported over longer distances to existing CHP plants.

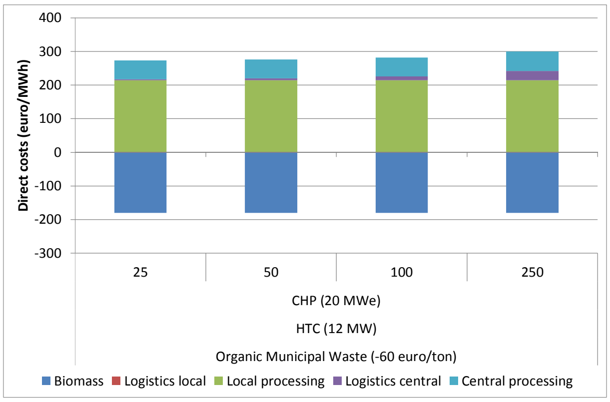


Figure 4-38 Sensitivity of the direct costs (euro/MWh) for the central transport distance. Variation in the central transport distance from 25 to 250 km in the hydrothermal conversion pathway.

The environmental impacts from the central transport are small compared to the overall impact of the pathway. The impacts are proportionally related to the transport distance.

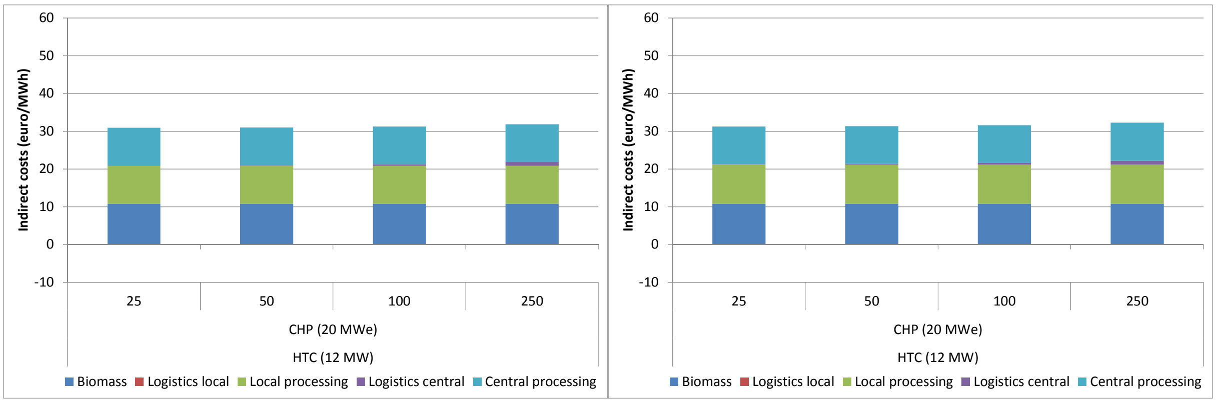


Figure 4-39 Sensitivity of the indirect costs (euro/MWh) for the central transport distance. Variation in the central transport distance from 25 to 250 km in the Hydrothermal conversion pathway. (left conventional and right including new environmental impacts.

Summarized results

- Transport costs to central plants does not play an important role when the distance is below 250 km. However, if bio-coal has to be transported to existing CHP plants, distances can become larger making the logistics cost a relevant factor.
- The environmental impacts from central transport are proportionally related to the distance, but nevertheless small compared to the overall impact of the pathway.

4.4.7 *Sensitivity for plant capacity*

The HTC plant design has a minimum of 6 MW capacity, which is equivalent to 6 reactors. Therefore scaling up and down from the reference capacity (12 MW) was done by using a scaling factor of 1. Figure 4-40 shows that the local processing costs decrease as the local capacity increases. The processing costs for the local processing plant go down from 250 euro/MWh on a 6 MW HTC plant to 186 euro/MWh on a 72 MW HTC plant.

Figure 4-41 shows the effect of capacity on central processing costs. The scaling factor used for the CHP plants was 0.8. Central processing costs decrease from 75 euro/MWh for a 10 MWe CHP plant to 25 euro/MWh for a 120 MWe CHP plant. The overall costs (summing up negative and positive) correspond to 122, 102, 81, and 71 euro/MWh for 10, 20, 60, and 120 MW, respectively.

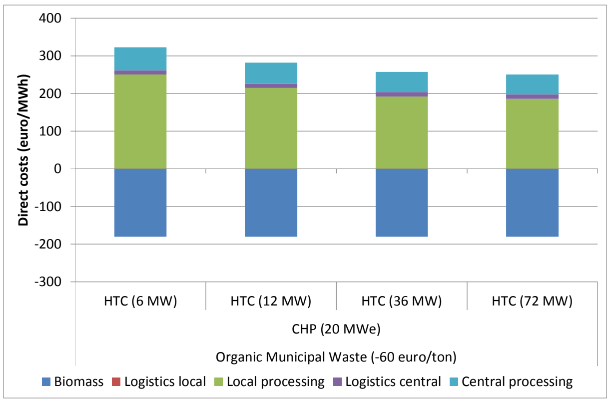


Figure 4-40 Sensitivity of the direct costs (euro/MWh) for the local plant capacity. Variation in capacity from 6 to 72 MW in the HTC pathway.

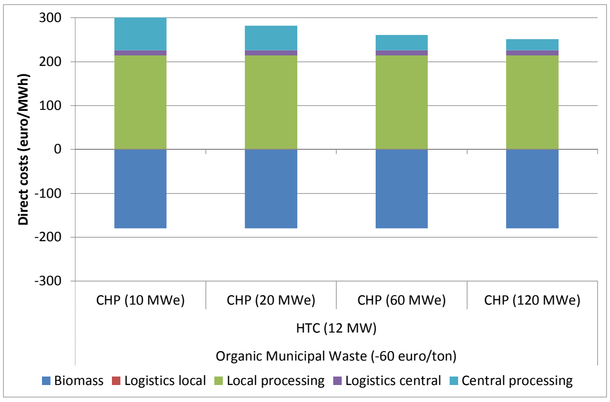


Figure 4-41 Sensitivity of the direct costs (euro/MWh) for the central plant capacity. Variation in capacity from 10 to 120 MW in the HTC pathway.

The plant capacity has no impact on the environmental performance. All relevant parameters influencing the environmental performance are expressed in units per MWh of product, independent of the plant size.

Summarized results

- Even though the scaling factor of the HTC plant is 1 and of the CHP plant is 0.8, a higher capacity results in both cases in lower processing costs.
- By increasing HTC plant capacity six times from 12 to 72 MW, the processing costs decrease from 9.4 to 1.7 euro/MWh.
- By increasing CHP plant capacity six times, from 20 to 120 MWe, the processing costs decrease from 56 to 25 euro/MWh.
- The plant capacity has no impact on the environmental performance. All relevant parameters influencing the environmental performance are expressed in units per MWh of product, independent of the plant size.

5 Conclusions and recommendations

The conclusions based on the results of the integrated assessment including sensitivity analysis will be given per sensitivity parameter below.

5.1 Fossil versus bio-based routes

Techno economic

Production of transport fuels via the bio-based routes (FP and CP pathways) is not yet competitive with the fossil routes. The minimum selling prices for transport fuel produced via the FP and CP reference pathways are 236 and 150 euro/MWh respectively. These prices are higher than the current market prices for fossil transport fuels, which are in the order of 50 euro/MWh. This difference makes implementation of the bio-based routes challenging.

From the results it is observed that feedstock price and logistics costs together can already take up 50-100% of the fossil fuel prices. This observation stresses the importance of scenario optimization for the competitiveness of biofuels via the FP and CP pathways.

It has also been observed that the overall yield for feedstock to biofuel has a strong effect on direct production costs. The difference in direct costs for biofuel produced via FP and CP is strongly related to the respective yields of 35% and 53%. It is also related to the assumptions for the plant design and costs. For instance, this study considers 7008 operating hours for FP pathway and 8000 for CP. Also, the CP refinery costs consist on an additional units for upgrading the bio-oil, assuming that it will be processed in existing refineries. On the contrary, FP pathway considers a full gasification plant. Therefore, besides the different yield, assumptions on the plant costs also have a strong effect on the direct costs.

The results from this study showed that electricity production from biomass is competitive with electricity generated from fossil feedstock. The electricity cost price from bio-coal produced via the HTC pathway are in the same range as the current market prices. This is partly due to suitable feedstock for this process. This allows the choice for economically attractive feedstock such as organic municipal waste, which has a negative feedstock price. Any improvement in the HTC technology will benefit the profit margin for this pathway.

Environmental

The environmental assessment consisted of three steps covering an increasingly broad and uncertain scope of environmental impacts, viz. CO_2 emissions according to the Renewable Energy Directive (RED), conventional impacts according standard LCA and new biorelated impacts (on land-use and water depletion).

The bio-based pathways have substantial CO_2 reductions. The other environmental effects give a more differentiated picture.

The fast pyrolysis and catalytic pyrolysis pathway lead to a CO_2 reduction of about 80% compared to fossil transport fuel pathways.

Conventional life cycle environmental impacts are sometimes larger for fossil fuels (climate change, fossil depletion, particulate matter formation and ozone depletion) and in other cases larger for biobased pathways (mainly human and ecotoxicity as well as eutrofication). The higher eutrofication and toxicity emissions from the biopathways are related to straw cultivation and do not occur in case of wood.

The production of transport fuels via the bio-based routes (FP and CP pathways) have a total lower environmental impact than the fossil benchmarks when only the conventional impacts are taken into account. The indirect costs are 7-8 euro/MWh versus 13-15 euro/MWh for the fossil routes.

The environmental performance of the CP and especially the FP pathway strongly benefits from the co-generation of electricity. The environmental benefits are based on prevented emissions from the electricity production. As the production will be cleaner in the future, the benefits will become smaller in future. Some countries already have a cleaner energy mix because of e.g. high contribution of hydropower. In these locations the benefits of electricity co production are already smaller.

The new bio-related impacts are generally higher for biobased than for fossil pathways but are surrounded with large uncertainty. Assuming a worst case scenario of a total loss of eco system services due to feedstock harvesting, the new, bio-related impacts give a higher contribution to the overall impacts than the conventional impacts in the biobased pathways. The largest bio-related impact comes from the factor agricultural land occupation. Especially in case of wood forest residue this factor has a strong effect due to the large land areas being used per MJ of feedstock. In case of complete preservation of biodiversity, the biodiversity impacts would become 0.
Results on new biobased impacts are presented to indicate maximum potential risks of using certain types of biobased resources. The current valuation of land use needs further discussion.

HTC produced biocoal reduces greenhouse gas emissions with almost 60% compared to the fossil coal reference. –Compared to average electricity from the German grid, HTC generated power, avoids CO_2 emissions and eutrofying, human and eco-toxic emissions while the German grid has lower impacts on particulate matter and photochemical oxidant emissions. The biocoal fuelled CHP has relative high PM and photochemical oxidant emissions due to transport for waste collection, which is particularly true for the collection of Organic Municipal Solid Waste. In total, the environmental impacts from electricity generation via the HTC pathway are lower than via benchmark, the German electricity mix in 2020. For the HTC route the new bio related impacts are of minor importance.

5.2 Feedstock

Techno economic
Feedstock price has an obvious, direct effect on the overall production costs. But also feedstock type has a significant, though indirect, effect on overall production costs. Each type of feedstock has a different energy and water content. These two properties affect the overall yield in the production of the energy carriers and the final products. Therefore, the economic feasibility of the FP and CP pathways depends on the combination of both feedstock type and price.
The influence of the feedstock type and price is even greater for the HTC pathway. This pathway benefits from the broad scope of suitable feedstock. This allows the choice for economically attractive feedstock, such as organic municipal waste, which even has a negative feedstock price as a reward for its disposal.

Environmental
The choice of feedstock has a large impact on the overall environmental performance of the pathway.
Considering conventional environmental impacts, the use of cultivated crops such as miscanthus and wheat straw as feedstock has a large impact as a result of particular matter formation due to the use and production of fertilizers and the operation of tractors. Leaching of nitrate from fertilizers leads to marine eutrophication. Additionally, taking into account the new, biorelated environmental impacts, the use of cultivated crops can have an impact due to agricultural land occupation. As has been said, these new impacts are surrounded with uncertainties, nevertheless, results on new biobased impacts indicate a maximum potential risks of using certain types of biobased resources.

Miscanthus is an energy crop, all impacts are allocated to the product. Wheat straw is a byproduct from wheat production, with an economic value. The same applies for forest residues as a by-product from the round wood production. An allocation of impacts on a mass or energy base would not reflect reality, as the main product has a higher value. An economic allocation is regarded as the most suitable option to divide the impacts over the main and by products.

Wood is the most environmentally friendly feedstock (taking into account the conventional impacts) above wheat straw and miscanthus. Land occupation is the main environmental impact for wood, as the yield per m^2.year is relatively low. However, an uncertainty exists on the valuation of land occupation, which could have a major impact. It is recommended to be sure that low value wood is used, from industry or forest.

Disposal of waste can have a serious impacts on the environmental performance. In the CP process the amount of ash strongly depends on the kind of feedstock. The combination with the composition determines the environmental impact. For the market implementation of a process a strategy is needed how to deal with the waste. According to waste and recycling regulations mixed organic waste streams may not be returned to the life cycle, source separated streams if quality standards are met. Transferred to ash this would mean that it could only be an input to a fertilizer production plant, direct recycling is prohibited.

Organic municipal waste has an higher environmental impact than the brewery spent grains. This is due to the emissions from the waste collection from house to house (stop and go gives relatively high emissions), contributing to climate change and particulate matter formation.
On the other hand, the use of brewery spent grains (BSG) has the disadvantage compared to Organic Municipal Solid Waste that it has impacts in terrestrial ecotoxicity due to the allocation of impacts of the cultivation of brewery grains based upon the relative value. In a weighed total, however, these impacts contribute less.

In the CHP process large amounts of ash are produced. Depending on its composition it can have a significant contribution to the environmental impacts due to toxicity.

5.3 Logistics

Techno economic

The logistics costs consist of handling, transportation and storage costs. However, the main contribution comes from transportation costs. Transportation costs are directly proportional to transport distance, where especially the reduction of local transport distance for ‘low-energy’ biomass leads to a reduction in transport costs per unit of energy produced. However, since transport distance does not only affect transport costs, an optimum has to be determined for each scenario, both local and central, between transport distance and processing plant capacity, taking into account maximum plant capacity and feedstock price, which depends on local feedstock utilization.

The logistics of the HTC pathway are dictated by the requirement of a high water content in the feedstock for successful application of the HTC process. To fulfill this requirement and simultaneously limit transportation of ‘low-energy’ biomass, the HTC plants need to be located next to their feedstock source, the municipal waste depots or industrial waste streams as it is the case for brewery spent grains. As a result the capacity of the HTC plant is dictated by the capacity of the municipal waste depot or industrial waste streams, which could reduce the beneficial effects from economies of scale.
Both direct and indirect transport costs per unit of energy produced could be substantially reduced upon optimization of the conversion yields of the different biobased processes.

Since the feedstock has a lower energy content, it is recommended to limit its transport distance to 100 km. The main reason for this is that at 100 km the feedstock costs and the logistic costs per MWh produced are similar, therefore the logistic cost does not exceed the feedstock costs in which case it would be more feasible to buy local feedstock.

On the other hand, since the energy carrier has a higher energy content, it can be transported over longer distances. From the results, it is recommended to limit transport distance for biosyncrude to 500 km and for bio-oil to 750 km. Since the bio-oil has a higher energy content than the biosyncrude longer transport distances are afforded.

A similar conclusion can be derived for the HTC pathway, the logistics costs for transporting the bio-coal does not play a role when considering transport distances up to 250 km.

Environmental

The contribution of impacts from transport is relatively small within the defined ranges. The impacts from transport are directly proportional related to the distance. Impacts due to transport originate from the conventional themes. Local transport (truck) mainly contributes to climate change and particulate matter, because of the fossil transport fuel emissions. Central transport (train) also contributes to human and eco-toxicity, because of the electricity use.

5.4 Economies of scale

Techno economic

From a production cost perspective, the larger the plant the lower the cost per unit produced. The economies of scale principle is valid for all technologies studied in this project. However, the benefit of the economies of scale depends greatly on the scaling factor used for scaling up. Therefore, the scaling factor used has to consider not the first commercial plant, but the n^{th} plant. Therefore, it is recommended to review and define the most realistic scaling factors for each technology.

It has to be taken into account, but it has to be considered, that an increase in processing plant capacity in the FP and CP pathway will lead to increased local feedstock prices when local feedstock utilization is not optimize through logistics.

Furthermore, the HTC technology has already been optimized and the feasibility is proven for a 6-reactor plant and the scaling factor for this technology is 1. This implies that in order to increase the plant throughput, an additional 6-reactor plant has to be built.

Environmental

The plant capacity has no impact on the efficiency of the pathway. Hence, it has no significant impact on the environmental performance. All relevant inputs influencing the environmental performance are expressed in units per MWh of product, independent of the plant size.

5.5 CO_2 price

Environmental

The CO_2 price does not influence the environmental performance of the processes. The CO_2 price is not an input in the life cycle assessment. Of course it can be a (economic) driver for lower CO_2 emissions, and e.g. the use of renewable electricity. This will have an effect on the environmental performance of the “new” process.

5.6 Recommendations for scenario analysis and market implementation plan

Techno economic

Based on the results and conclusions of this study, there are several routes to improve the economic feasibility of the biobased pathways towards the production of transport fuels and electricity. These routes comprise the optimization of feedstock price, scale and transport distance. These are the more relevant factors that can enable the implementation of the biobased pathways. For instance, in order to lower the transport fuel and electricity prices, it is essential to lower the feedstock price by optimizing the regional utilization and their logistics cost. Another important factor relies on the optimized transport of feedstock and energy carriers. For example, the optimization should lead to shorter transport distances for the feedstock, enabling local or decentral plants and longer distances for the energy carriers, enabling central plants. Since the economies of scale will always benefit larger plants, the optimized scenario will then look for regions with high feedstock potential where large plants can be built, reducing the processing and logistics costs. The high interdependency of these factors makes a complex solution. Therefore, several scenarios were defined in order to find the conditions for the market implementation plan. These scenarios are listed in ANNEX G.

Environmental

The feedstock type contributes significantly to the overall environmental performance of a pathway and a sound choice should be made. As the main impacts are from cultivation (fertilizers) and the occupation of land, it is recommended to abandon dedicated energy crops (e.g. miscanthus) and go for real waste or low value byproducts.

New impacts can have a potential large impact on the environmental performance. Results on new biobased impacts have been presented to indicate potential risks of using certain types of biobased resources. However the valuation of the impacts needs more nuance to reflect the actual loss of ecosystem services. New standards and methodologies need to be developed and adopted to create the requested nuance in e.g. occupational land use.

The above study is based on limited information on emissions (other than CO_2) from the technology providers. Detailed information on the composition of waste/ ashes is needed for a proper assessment.

ANNEX A Shadow price methodology

Environmental costs are external costs

Economic activities are almost without exception accompanied by a certain stress on human being or the environment. For human being , this means an encroachment on health and safety, for the environment, the dislocation of ecosystems, often quantified by a reduction in stocks of clean air, water, soil and biotic and abiotic material [2]. The cost of stress on the environment and human being are not discounted in the product price through the market. That is why they are called external charges, compared with internal production costs.

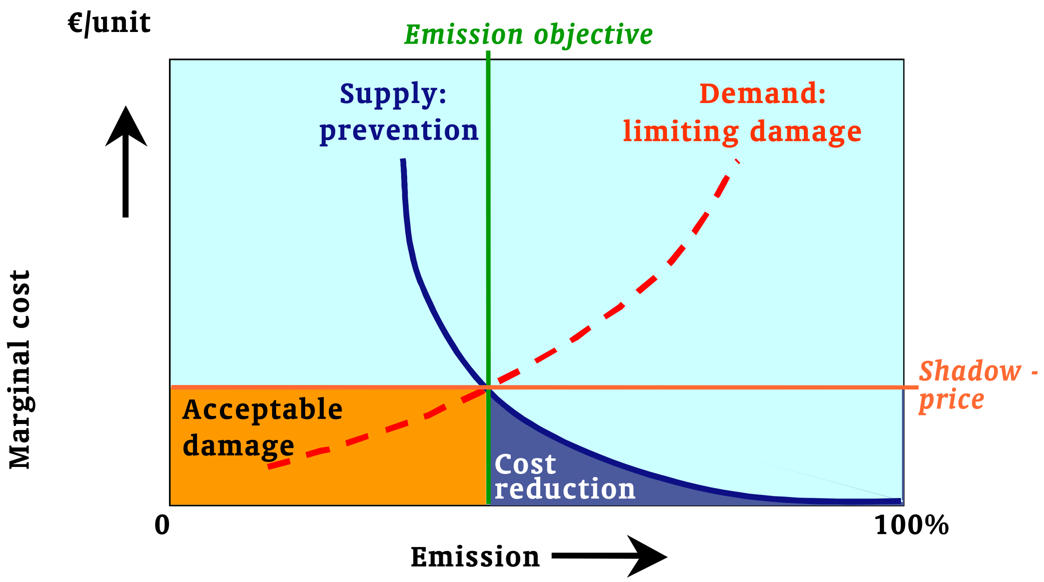


Figure A1 Demand for limitation and supply of emission prevention on the virtual environmental market form an equilibrium price. If a government objective crosses the equilibrium point of demand and supply, the shadow price will under this objective be the same as the equilibrium price.

The cost of the environmental burden depends on the price that society is willing to pay for a clean environment and is related to the situation and moment. Generally speaking, the heavier the environmental burden, the greater the willingness to pay a higher price to limit environmental damage. In this way, a demand curve is created towards limiting environmental damage (see Figure A1).

A virtual environmental market

In addition to demand for emission restriction, there is a supply of emission prevention opportunities which also has a particular price for each level of prevention. Generally speaking, the price increases the greater the reduction demanded. If there were to be a market for the environment, demand and supply would form an equilibrium price at the intersection of the curves of marginal damage limitation and marginal prevention cost.

Government restrictions on external effects provide a shadow price

Because external charges are not remunerated through the market, an authority will have to determine to what extent the damage must be limited. This can be done by formulating an emission objective. The point where this objective intersects the marginal damage curve is called the shadow price. This is the extent to which the total cost and benefit change as a result of a change in a limiting factor, in this case the emission limitation. In the present environmental example, the shadow price is in fact the highest permissible environmental cost level per unit of environmental damage that the government is still prepared to bear.

A cost-effective shadow price approximates the equilibrium price

A government that wishes to work cost-effectively positions its emission objective in such a way that it appears at the intersection so that demand and supply are in equilibrium. These total charges concern the cost of the preventive measures in question (the surface beneath the marginal prevention curve to the right of the emission objective) plus the environmental damage sustained as a result of unprevented emissions, the surface beneath the shadow price to the left of the objective. If the government discharges its task as a representative of society properly and works cost-effectively, it will ensure that the shadow price of its environmental objective coincides with the equilibrium price adopted in society. If this is in fact not the case, the perceived environmental damage will increase more strongly in relation to the market equilibrium than the prevention costs will reduce (if the reduction objective is positioned too low) or the prevention expenses will increase more sharply than the environmental damage avoided (if the reduction objective is excessive).

Charging through the shadow price creates an environmental market

However, because the damage is collective, benefits in the form of damage avoided often do not directly profit the investor in prevention costs. In fact, the equilibrium price is virtual. If, on the other hand, the external charges resulting from environmental damage are charged through to the polluter, investment in prevention will certainly result in benefits for the polluter. The damage can, for example, be internalised in the product price. This substantiates an essential criterion of present environmental policy, the "polluter pays" principle. This implies that every individual and every organisation is in principle responsible for the damage caused by him or her to the environment. Moreover, this is done in this manner in an economically cost-effective way. A price has thereby been set for the environment that plays a role in economic dealings. A polluter can decide for himself whether it is advantageous to pay the levy or to reduce his emissions himself and thereby incur additional cost for the reduction measures to be adopted. In either case, the environmentally polluting products will become more expensive and the environmentally friendly less so. This approach with the aid of market-conforming instruments has been the centre of attention in recent years. NO_x equalisation in heavy industry and the negotiable CO_2 emission rights are well-known examples of this.

Application of the shadow price

In addition to the actual charging through of the shadow price by means of e.g. an environmental levy, the shadow price, like the market price, is an easily interpreted signal of economic scarcity. In studies with such varying subjects as life cycle assessment, technological development, sustainability strategies or environmentally friendly designs, in which environmental effects of different kinds must be compared with each other, the shadow price can be easily used to calculate the environmental damage. This is done by multiplying the emissions by the shadow price. The environmental damage calculated in this way, also known as environmental cost or shadow cost, provides an indication of the environmental losses pertaining to present or future emission objectives [5][6][7][8] and [10]. Some studies use the environmental burden calculated in this way in micro-economic cost-benefit analyses, while others do so in micro-economic studies to correct GNP in order thereby to calculate a green GNP [5].

Advantages of the shadow price method

The shadow price has a neutral unit with which various environmental effects can be gathered under a single denominator. Using the shadow price method, different environmental effect categories can be easily weighed up. The shadow price also has the advantage that it dovetails with the use of market-conforming instruments. It also matches the present economic reality in the business world since external charges are rendered visible. It supports integral analyses in order to provide transparent results wherein policy and business can recognise their own activities and the relationship with environmental topics.

Conditions for applying the shadow price method

The shadow price approach is especially suitable for calculating through the present policy or present collective preferences and not for long-term sustainable solutions, because the shadow price of these long-term objectives is difficult to establish. The present collective preferences differ per country [4]. This implies that the use of shadow costs is meaningful at national or European level, where environmental pressure and environmental desires are more or less of a comparable order. This is not the case on a world scale.

Two possible routes for determining the shadow price

The shadow price can be determined firstly by estimating the environmental damage associated with the established emission objectives. Secondly, assuming that the government works cost-effectively, the shadow price can also be derived by combining the prevention cost with the emission objectives adopted.

Environmental damage is difficult to establish

The value (monetary) of environmental damage is difficult to establish. An approach for this is the "willingness-to-pay" principle, whereby the amount is established that society (or groups in society) can pay to avoid particular environmental damage. This can be done directly ("stated preferences") by enquiries (contingent valuation method) or by inferring the revealed influence of the environmental burden on market prices ("revealed preferences"). The disadvantage of these methods of willingness to pay is that they are very moment-related and must be implemented simultaneously for all environmental effect categories if comparable results are to be obtained. One wonders in particular whether, for the alleged preferences, obstruction is correctly estimated, in other words in the right relationship with real investment decisions [11].

Emission prevention costs can be established more accurately

The emission prevention costs or combating costs can be established more accurately. The highest permissible cost for preventing certain environmental effects, the so-called marginal cost that society must incur if the emission objective desired by government is to be achieved, can be used as a basis. An alternative method is to resort to price elasticities, but these are available only to a limited extent. It is assumed that the government or society is sufficiently rational to position its objective at the point of the equilibrium price *and* that the location of this point is known. In other words, that the marginal environmental damage has been quantified. This is not in fact the case, so that the shadow price derived from the present policy objective and marginal prevention curve must be interpreted more as a yardstick of present policy preferences. The shadow price is above all an estimate of the equilibrium price by present policy. Since policy-makers wish to set to work cost effectively, the consequence of the present objective is that the marginal damage is evidently estimated at the shadow price level. The actual environmental damage as perceived in society may lie at a completely different level.

CE has established the shadow prices within the Netherlands [11] for the environmental effect categories of the CML-2 method, except for six categories in the area of human toxicity, ecotoxicity and abiotic raw material depletion. It should be mentioned here that CE in fact establishes the shadow price for emission objectives for the year 2010. This can be done because the environmental effect categories that CE deals with are properly worked out and documented in policy plans and measures. This is not the case with the other topics, where objectives, insofar as they are set, often influence more than one environmental effect category. An analysis of the present situation is therefore more opportune, so the shadow price of present policy can be derived from it on the basis of the steps taken.

Overview of steps taken

The shadow prices to be used in the weighing up method for the environmental effect categories of abiotic raw materials depletion and toxicity are worked out by five stages:

1. determining present policy for the various environmental effect categories;
2. selecting relevant guide substances, sectors and firms for the policy to be implemented;
3. collecting cost data for measures by means of literature research and telephone interviews of firms, licensors and experts;
4. calculating the shadow price on the basis of the cost estimates of the measures;

Table A1 shows the shadow prices for the various impact categories as used in the assessment.

Table A1 Overview of shadow prices

Impact category abbreviation	Characterization factor name	Shadow price	Unit	Reference
CC	global warming potential	0,025	kg (CO_2-eq)	[39]
TET	terrestrial ecotoxicity potential	1,28	kg (1,4-DCB-eql)	[40]
SQL	soil quality lost	to be developed	m^2·yr (agricultural land)	-
OD	ozone depletion potential	39,1	kg (CFC-11-eq)	[39]
IR	ionizing radiation potential	0,0425	kg (U^{235}-eq)	[39]
TA	terrestrial acidification potential	0,638	kg (SO_2-eq)	[39]
HT	human toxicity potential	0,0206	kg (1,4-DCB-eq)	[39]
POF	photochemical oxidant formation potential	0,585	kg (NMVOC-eq)	[39]
PMF	particulate matter formation potential	51,5	kg (PM_{10}-eq)	[39]
WD	non-renewable water depletion potential	1.0	m^3 (non-renewable water)	[41]
FE	freshwater eutrophication potential	1,78	kg (P from STP-eq)	[39]
ME	marine eutrophication potential	12,5	kg (N-eq)	[39]
FET	freshwater ecotoxicity potential	0,04	kg (1,4-DCB-eq)	[40]
MET	marine ecotoxicity potential	0,0001	kg (1,4-DCB-eq)	[40]
ALO	agricultural land occupation potential	0,094	m^2·yr	[41]
ULO	urban land occupation potential	0,094	m^2·yr	[41]
NLT	natural land transformation potential	0,0019	m^2	[41]
MRD	mineral depletion potential	0	kg (Fe)	[39]
FD	fossil depletion potential	0	kg (oil)	[39]

References from ANNEX A

[1] EmissieMonitor/ Loketvraag, see Annex B.

[2] Guinée, J.B. et al, Life cycle assessment - an operational guide to the ISO standard, vol. I, II and III, Institute of Environmental Sciences - Universiteit Leiden, May 2001.

[3] Huijbregts, M.A.J., Priority Assessment of Toxic Substances in the frame of LCA – draft, Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, March 2000.

[39] CE, Guidebook Shadow prices – weighting and valuation of emissions and environmental impacts (in Dutch: Handboek schaduwprijzen – waardering en weging van emissies en milieueffecten). CE, Delft, the Netherlands, 2010, CE № 10.7788.25a

[40] Harmelen, drs. A.K. van, drs. ing. R.H.J. Korenromp, dr. T.N. Ligthart, ir. S.M.H. van Leeuwen, ing. R.N. van Gijlswijk (2007), The price of toxicity, Methodology for the assessment of shadow prices for (eco-)toxicity and abiotic depletion, pp 105-125, Eco-Efficiency in Industry and Science, Quantified Eco-Efficiency, ISBN 978-1-4020-5398-6, Springer 2007

[41] TNO report, to be published

[4] Huppes, G., M.D. Davidson, J. Kuyper, L. van Oers, H.A. Udo de Haes and G. Warringa, Eco-efficient environmental policy in oil and gas production in the Netherlands, Project for NOGEPA, The Hague, 2002/2003

[5] Jantzen, J., Duurzame groei in Nederland? Het duurzaam Nationaal Inkomen onder Paars (1990-2000), Institute for Applied Environmental Economics (TME), June 2002.

[6] KPMG Sustainability en CE. Duurzame winst! De milieuwinst van de Groenregeling inzichtelijk gemaakt. September 2002. http://www.kpmg.nl/docs/bas_sustainability_advisory_services/rapport%20duurzame%20winst%20kpmg%20en%20ce.pdf

[7] Kroon, P., et al, Weegfactoren voor luchtverontreiniging, Systeem voor de integrale evaluatie van de uitworp van luchtverontreiniging, ECN, ECN-R--94-006, June 1994

[8] NIBE Research, Duurzaam & Gezond Bouwen, July 2002

[9] RIVM, Milieubalans 2000

[10] RIVM/EFTEC, Valueing the benefits of environmental policy: The Netherlands, RIVM report No. 481505024, Bilthoven, July 2001

[11] Soest, Jan Paul van, Hein Sas, Gerrit de Wit. Appels, peren en milieumaatregelen. Afweging van milieumaatregelen op basis van kosteneffectiviteit. CE, Delft. October 1997.

ANNEX B Techno-economic assessment methodology

A techno-economic model will be used to calculate the total capital investments (TCI_{local}, $TCI_{central}$) and variable operation costs ($OPEX_{local}$, $OPEX_{central}$) at the local and central processing plants. The total energy carrier production cost ($C_{energy\ carrier}$) described below and the final energy product cost (C_{final}) for each pathway are calculated by adding the fixed costs (including depreciation) and general expenses to the variable operation costs. Figure depict the cost components for TCI and OPEX models.

Total Capital Investment (TCI or CAPEX)

Figure illustrates the relation between the different cost components needed to calculate the Total Capital Investment (TCI). Total Capital Investment (TCI) consists of the capital needed to build the processing installations, called Fixed-Capital Investment (FCI), and capital needed for operation of the plant, called Working Capital (WC) as shown in Equation 8.

$$TCI = FCI + WC \tag{1}$$

Working capital refers to the capital necessary for the operation of the plant; such as raw materials and finished product in stock, accounts and cash. It is typically between 10% and 20% of the fixed capital costs. In Bioboost an average value of 15% is assumed.

In Bioboost, the method of the delivered-equipment cost will be employed to estimate the TCI. It consists of determining the capital cost components based on the equipment cost. Therefore, the Bioboost TEA requires an inventory of the major equipment of each processing plant. Also, it will require cost acquisition data and methods from each partner to overcome discrepancies on estimating equipment costs. Furthermore, the purchased equipment method uses predefined averages to determine the direct and indirect capital costs illustrated in Table .

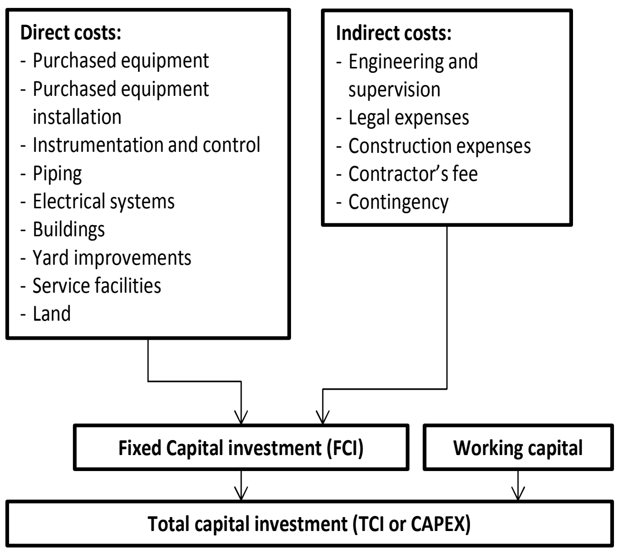


Figure B-1 In the following section the factors to estimate the indirect and direct costs are described

Fixed Capital Investment (FCI)

The estimation of the fixed capital investment (FCI) is calculated according to the delivered-equipment method as described by Equation 9. According to Equation 9, the FCI is the result of the multiplication of the delivered equipment cost by the total sum of direct and indirect factors.

$$FCI = E\sum(1 + f_1 + f_2 + \cdots + f_n) \qquad 2$$

Table B-1 Description of parameters to estimate total capital investment for local or central plants

Parameter	*Unit*	*Description*
FCI	€	Fixed capital investment
E	€	Total cost of delivered equipment
$f_1 + f_2 + \cdots + f_n$	-	Factors for the different components of direct and indirect costs

Averaged factors are allocated depending on the type of the plant (i.e. solid, solid-fluid, fluid, processing plants). Therefore, Bioboost methodology uses the factors allocated for solid-fluid processing plants to take into account the use of solid feedstock. According to Peters[42] the direct and indirect costs for typical chemical solid-fluid processing plants had been reported and are listed in Table and the ones provided by the partners are listed in Table . In Bioboost, the processing technologies vary from low to high maturity level of development. Therefore, some assumptions have to be made in collaboration with the partners since limited data might be available for some cases. Nevertheless, this methodology ensures an adequate estimate for preliminary studies and benchmarking. The expected accuracy of this method is ±20 to 30 percent[42].

[42] Peters, M., Timmerhaus, K., West, R. Plant Design and Economics for Chemical Engineers. McGraw-Hill, Boston (2004).

Table B-2 Purchased equipment factors for FCI estimation and working capital factor

	Fraction of delivered-equipment for a solid-liquid processing plant
Direct costs	
Purchased equipment installation	0.39
Instrumentation and controls	0.26
Piping	0.31
Electrical systems	0.10
Buildings	0.29
Yard improvements	0.12
Service facilities	0.55
Indirect costs	
Engineering and supervision	0.32
Construction expenses	0.34
Legal expenses	0.04
Contractor's fee	0.19
Contingency	0.37
Working capital	15% FCI

Table B-3 Purchased equipment factors for FCI estimation per pathway

	FP-pyrolysis (wheat straw)	**FP-gasification (biosyncrude)**	**CP-pyrolysis (beechwood)***	**CP-refinery (bio-oil)**	**HTC (biowaste)**	**CHP (bio-coal)****
Direct cost description	**Fraction of delivered equipment, fi**					
Purchased equipment	1	1	1	1	1	1
Purchased equipment installation	0.47	0.47	0.00	0.39	0.39	
Instrumentation and controls	0.36	0.36	0.00	0.26	0.26	
Piping	0.68	0.68	0.00	0.31	0.31	
Electrical systems	0.11	0.11	0.00	0.10	0.10	
Buildings	0.18	0.18	0.18	0.29	0.29	
Yard improvements	0.10	0.10	0.07	0.12	0.12	
Service facilities	0.70	0.70	0.34	0.55	0.55	
Indirect costs description						
Engineering and supervision	0.33	0.33	0.14	0.32	0.32	
Construction expenses	0.41	0.41	0.21	0.34	0.34	
Legal expenses	0.04	0.04	0.02	0.04	0.04	
Contractor's fee	0.22	0.22	0.12	0.19	0.19	
Contingency	0.44	0.44	0.06	0.37	0.37	
Fixed capital investment (FCI) - Lang factor	5.04	5.04	2.15	4.28	4.28	

*Equipment costs provided included installation, instrumentation and controls, piping, and electrical systems, therefore factors are zero.
** CHP cost data was available as Fixed Capital Investment, therefore the factorial method was not used in this case.

Annual production costs (OPEX)

The total annual production costs include various costs components like the feedstock cost, labor, utilities, capital expenses, overhead etc. The relation between the various cost components that should be taken into account can be seen in Figure .

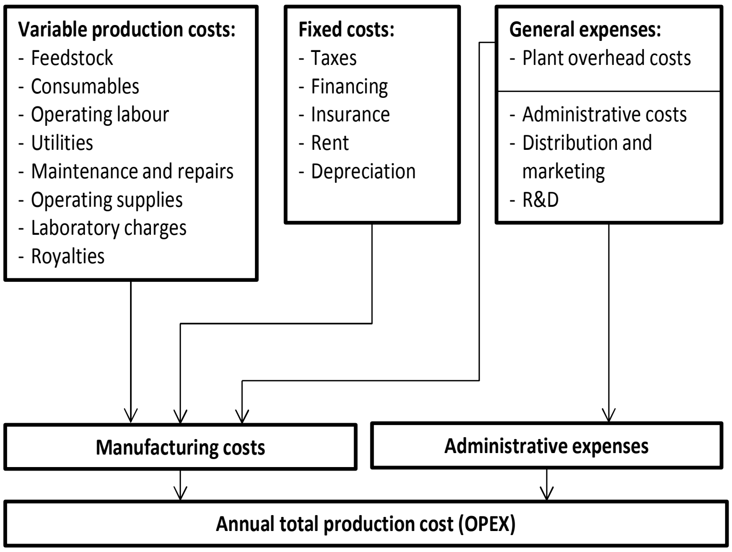


Figure B-2 Total annual production cost components (OPEX)

The annual production costs are divided into two main categories: manufacturing costs and administrative expenses (See Figure). The manufacturing costs refer to all expenses related to the operation of the plant. The administrative costs refer to all expenses related to the operation of the company. All costs associated with the manufacturing of the products are classified in three main categories: variable, fixed and general expenses. Table illustrates the breakdown of components and factors used to calculate the production cost (OPEX).

Table B-4 OPEX parameter values and factors

OPEX Parameter	*Factor or value*
Variable production costs	
Operating labor	50,000 €/person.year
Operating supervision	0.15 of operating labor
Maintenance and repairs	0.07 of FCI
Operating supplies	0.15 of maintenance and repairs
Laboratory charges	0.15 of operating labor
Royalties	0.04 of production cost
General expenses	
Plant overhead costs	0.5 of total expenses of labor and maintenance
Administrative costs	0.15 of operating labor
Distribution and marketing	0.02 of production cost
Research and development	0.05 of production cost

Depreciation, Taxes and Financing

Depreciation and taxes are part of the operating costs, however, they vary depending on the depreciation method. A linear depreciation is recommended by the EIBI for the economic evaluations. However, the length of time over which depreciation takes places depends highly on government policy. In this case to make it consistent with the EIBI evaluation method, the depreciation time will be considered as the same as the evaluation time and this study will consider a scenario with no governmental subsidies. Table lists the reference parameters that will be used in the profitability assessment.

Table B-5 Economic parameters: depreciation, interest rate, and taxes

Economic parameter	*Bioboost value*
Project life time (after investment)	20 years
Depreciation	Linear for 20 years
Inflation for capital costs	0 %
Interest rate (discount rate)	5 %
Investment plan	1st year 70% FCI, 2nd year 30% FCI
Plant start-up	At the end of year 2
Taxes	30 %
Insurance	1 % of FCI

ANNEX C Energy efficiencies and conversion yields

Table C1 and C2 show respectively the energy efficiency and yield of the various pathways. The values are based on the flow diagrams as given in Chapter 3.

Table C-1 Energy efficiencies

	Feedstock	Local	Central	Overall
FP Methanol	Wheat straw	83.7	55.0	45.7
	Miscanthus	83.7	55.0	45.7
	Forrest residue	83.7	55.0	45.7
FP transport fuel	Wheat straw	83.7	47.6	39.8
	Miscanthus	83.7	47.6	39.8
	Forrest residue	83.7	47.6	39.8
CP transport fuel	Wheat straw	56.4	88.9	50.1
	Miscanthus	53.8	88.9	47.8
	Forrest residue	52.7	88.9	46.9
HTC	Organic municipal waste	75.4	81.6	61.5
	Brewery spent grain	61.6	81.6	50.3

Table C-2 Yield

	Feedstock	Local	Central	Overall
FP Methanol	Wheat straw	85.7	53.2	45.6
	Miscanthus	85.7	53.2	45.6
	Forrest residue	85.7	53.2	45.6
FP transport fuel	Wheat straw	85.7	40.4	34.6
	Miscanthus	85.7	40.4	34.6
	Forrest residue	85.7	40.4	34.6
CP transport fuel	Wheat straw	52.6	100.5	52.9
	Miscanthus	48.4	100.5	48.6
	Forrest residue	47.9	100.5	48.1
HTC	Organic municipal waste	86.9	27.2	23.6
	Brewery spent grain	69.1	27.2	18.8

ANNEX D RED CO_2 emissions

The GHG emissions are calculated by summing up the emissions of the separate steps in the product chain or pathways by:

$$E = E_{ec} + E_l + E_p + E_{td} + E_u - E_{sca} - E_{ccs} - E_{ccr} - E_{eec} \qquad \text{(D-1)}$$

$\boldsymbol{E}$	-	**Total emissions from the use of the fuel**
$\boldsymbol{E_{ec}}$	-	**Emissions from the extraction and cultivation**
E_l	-	Annualized emissions from carbon stock changes caused by land-use change
$\boldsymbol{E_p}$	-	**Emissions from processing**
$\boldsymbol{E_{td}}$	-	**Emissions from transport and distribution**
E_u	-	Emissions from the fuel in use
E_{sca}	-	Emission savings from soil carbon accumulation via improved agricultural management
E_{ccs}	-	Emission savings from carbon capture and storage
E_{ccr}	-	Emission savings from carbon capture and replacement
E_{eec}	-	Emission savings from excess electricity generation

The steps that are relevant in this assessment are the emissions from extraction and cultivation (Eec), processing (Ep) and from transport and distribution (Etd). The other steps are not relevant for the product chains analyzed in this project because of the system boundaries of the pathways, the type of processes and the definitions in RED methodology.

In this assessment, the processing step also contains the emissions from the production of chemicals and products used in the process. The emissions from the manufacturing of machinery and equipment were excluded. The emissions from extraction and cultivation were set at zero for the waste and residues as feedstock. The use phase of the product and related emissions were excluded because of the system boundaries of the pathways. The pathways end after the production of e.g. a fuel and do not include the use of the fuel for transportation. The produced electricity was considered as a co-product and the related emissions will be divided on an energy base between the product (e.g. fuel) and the produced electricity.

Figure D-1 shows the RED CO_2 emissions for transport fuels produced from the various feedstock by the fast and catalytic pyrolysis pathway. The reference emission factor for the fossil benchmark is 83.8 g CO_2 /MJ. The FP/miscanthus pathway leads to a 61% reduction in CO_2, for the other feedstock the reduction is 80%. The CP/miscanthus pathway has a 68% reduction in CO_2, the other feedstock show a reduction of 81%. Miscanthus is an energy crop, emissions from cultivation are taken into account, whereas the emissions from by products are set zero.

Typical greenhouse gas emission values from Annex V from the RED are for biodiesel: 35 gCO_2/MJ (sunflower), 46 gCO_2/MJ (rape seed) and 50 gCO_2/MJ (soy bean). For waste wood Fisher-Tropsch diesel the typical greenhouse gas emission is estimated at 4 gCO_2/MJ.

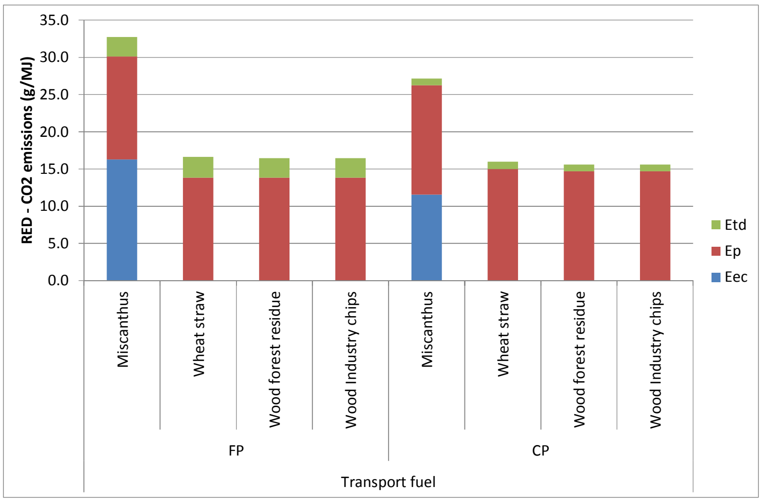


Figure D-1 RED CO_2 emissions for the various feedstock and technologies to produce a transport fuel. CO_2 emissions from extraction & cultivation (Eec), processes (Ep) and transport & distribution (Etd).

Figure D-2 shows the RED CO_2 emissions for the fast pyrolysis pathway to produce transport fuel and methanol from the various feedstock. Typical greenhouse gas emission values from Annex V from the RED are estimated at 4 gCO_2/MJ for waste wood methanol.

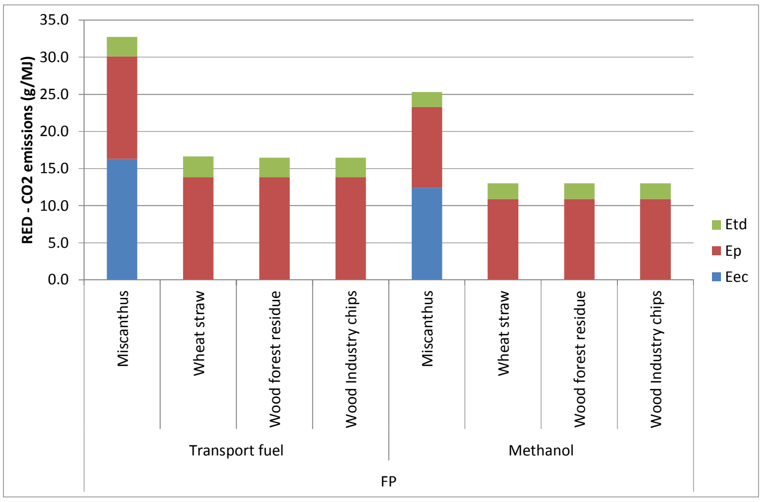


Figure D-2 RED CO_2 emissions for the fast pyrolysis pathway to produce transport fuel and methanol. CO_2 emissions from extraction & cultivation (Eec), processes (Ep) and transport & distribution (Etd).

Figure D-3 shows the RED CO_2 emissions for the HTC pathway to produce electricity from the organic municipal waste and brewery spent grain.

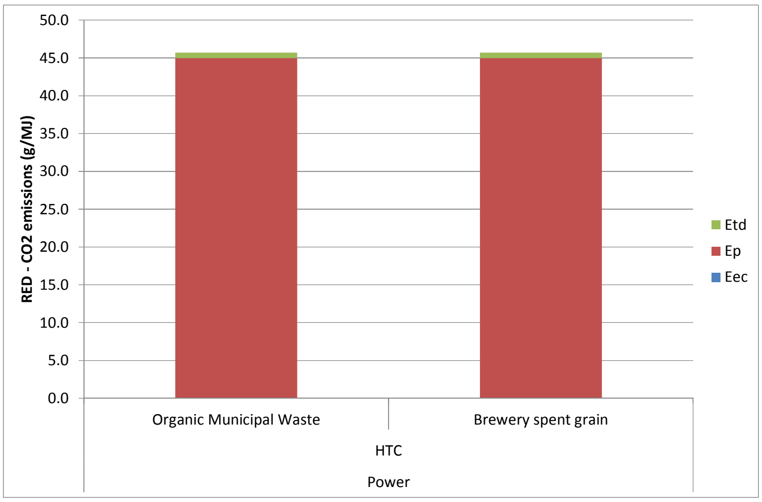


Figure D-3 RED CO_2 emissions for the HTC pathway. CO_2 emissions from extraction & cultivation (Eec), processes (Ep) and transport & distribution (Etd).

ANNEX E Catalytic Pyrolysis Oil Upgrade Concept

CPO Upgrader Block Diagram and Energy Balance (Reference: NESTE)

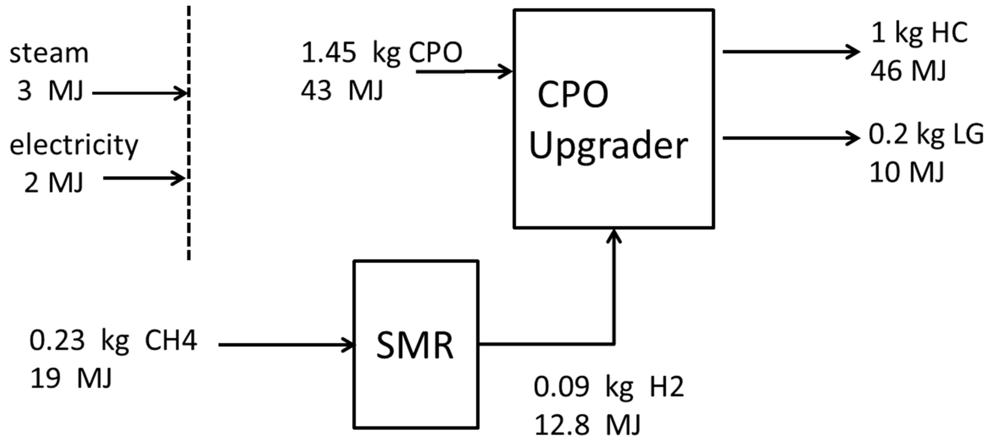


Figure E-1 Catalytic Pyrolysis Oil Upgrader Concept (ref: Steven Gust)

The mass and energy balance from this concept was used to define the block diagram for the refinery concept described in Section 3 Figure 3-7. Additionally, some literature values were used in order to define the investment for this concept. *Brown, et al*[43]. reported the installed equipment costs for a fast pyrolysis and hydroprocessing study as it is illustrated in Figure . The reference capacity of this study is 172200 tonne gasoline/year (57.4 Mgal/year) and the equipment costs only for hydrotreating are about 45 M$, equivalent to 33.8 M€.

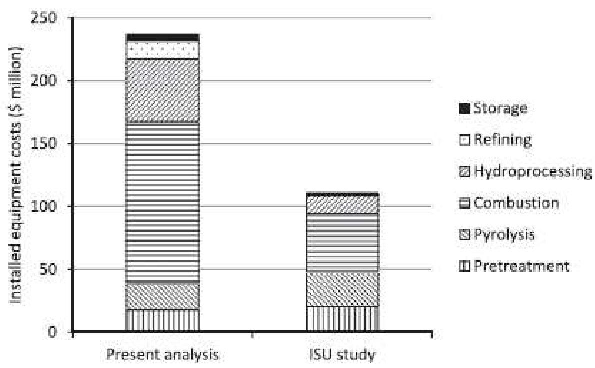


Fig. 2. Installed equipment costs for the present analysis and the 2010 ISU study (indirect costs, working capital, and land costs are excluded) [8].

Figure E-2 Installed equipment costs from *Brown et al*.

Another study from *Jones et al*[44]. designed another hydrotreating unit for a plant capacity of about 60 Mgal of fuel per year, equivalent to approximately 172 600 tonne/year. The cost reported from this study are shown in Figure . In this study, they reported the fixed capital investment for the

[43] Brown et al. Techno-economic analysis of biomass to transportation fuels and electricity via fast pyrolysis and hydroprocessing. Fuel (2013), 463-469.
[44] Jones et al. Process design and economics for the conversion of lignocellulosic biomass to hydrocarbon fuels. 2013. PNNL-23053.

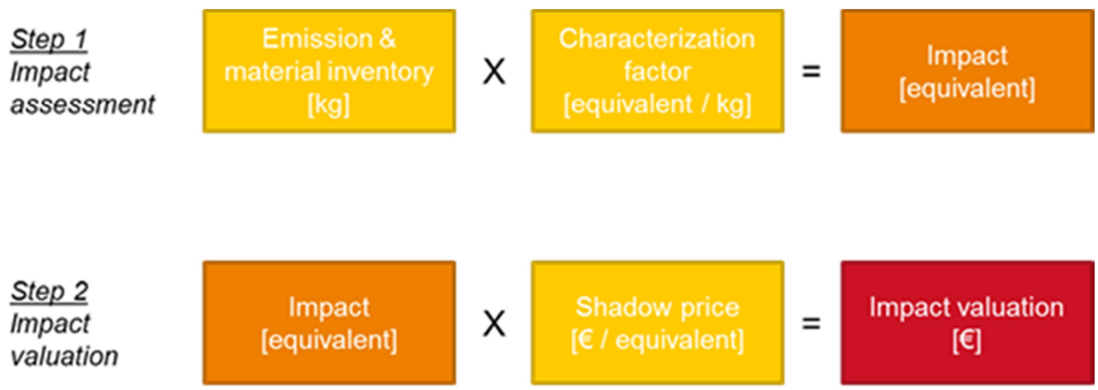
hydrotreating process area of 198 M$ and considering a Lang factor of 4.4 the total equipment cost is about 45 M$, equivalent to 33.8 M€. The Lang factor is not reported in this study, but based on the previous reference we can consider that the range of the hydrotreating equipment cost is about 30-40 M€ for a capacity of 172 Mtonne of fuel/year. Considering the previous references, BioBoost study used a hydrotreating equipment cost of 33.8 M€ for a capacity of 172200 tonne of fuel per year for the year of 2010.

Table 16. Total Project Investment

Process Area	Total Capital	Fixed Capital Investment (2011 MM$)
100	Fast pyrolysis	279
100	Heat recovery & filtration	22
200	Hydrotreating	198
300-500	Product Finishing	32
600	Hydrogen generation	119
700	Balance of Plant	16
Total		**665**

Figure E-3 Total Project Investment from *Jones et al* study.

ANNEX F Environmental impacts from wood as a feedstock



1. From the inventory data to an environmental impact, e.g from CO2, CH4 emissions to the impacts of global warming (in CO2 equivalents). The inventory data are based on the partners questionnaires and/or databases like EcoInvent.

2. From an environmental impact to external costs (in euros) using a shadow price. The shadow prices are in general based on damage costs of the impacts, e.g. the damage to human health and ecosystems by emitting 1 kg of CO_2.

Uncertainties will be there in every factor of the equation: inventory, characterization factor and shadow price. But why are the high environmental impacts for the use of wood, forest residues that high?

Inventory data: based on statistics for average German/middle European forests. Expected to be reliable, could argued about the definition of residue. But even assuming the production yield of the forest doubles, it would not really change the figures, i.e. a dominating contribution from land use. However, there is one sensitive issue. At system boundaries, sometimes allocation is needed. This is the case with the use of forest residues. Which part of the environmental burden is allocated to the residues and which part to the other products from the forest? EcoInvent has a default allocation, usually physical (based on volume). That would mean that all different streams, including residues, receive an equal share relative to the volumes. That also means that the amount of m^2 per ton wood and its environmental burden is equal for residual wood, round wood etc.

This is not doing justice to the fact that the quality of residual wood is different. That is why an economic allocation is favored, where the m^2 and environmental burden is relative to the economic value of different coproducts. In the table below you can see that a different, much smaller share of burdens are allocated to residual wood.
Here is really the discussion, because in peoples mind, residual wood or waste wood implies that the wood has no value. If this is really the case, the allocation of environmental burdens would be 0. For free, free of burdens. However, if this was really the case, it was adopted in the economic system very quickly, and would get a value and a price. So, this is a not very realistic scenario, but a most optimistic benchmark.

Table E1 External costs of wood using physical and economic allocation in euro/m^3

			Physical allocation (based on volume)	*Economic allocation (based on price)*
1	m^3	Residual wood, hardwood, under bark, u = 80%, at forrest road	189	72
1	m^3	Industrial wood, hardwood, under bark, u = 80%, at forrest road	189	68
1	m^3	Round wood, hardwood, under bark, u = 70%, at forrest road	189	304

Characterization factor, every occupation of land (forest, crop, etc) (expressed in m2.yr) is directly translated by a factor of 1 to agricultural land occupation (m2.yr). based on the ReCiPe methodology. This is standard.

Shadow price: this valuation determines how heavy the land use related impacts such as biodiversity are weighted compared to the other environmental impact categories (eg climate change, human toxicity etc). The existing approach in ReCiPe is based upon potentially disappeared fraction of species. This gives the marginal value of highly biodiverse areas, which does to our opinion not apply for Western European countries. Hence, the approach was adapted and based on the value of average global ecosystem services (Constanza, 1997), 0,094 EUR/m^2.yr (a factor 7 lower than the default of 0,6 euro/m^2.yr). Nevertheless, this value is still based upon the assumption that a complete loss of the eco system services occurs. It does not matter whether it concerns a forest or a paved area with asphalt.

Table E-2 Land use data based on EcoInvent

Nr.		Hardwood	Softwood	Source	refers to	comment
1	Yield [m^3 / ha]	7.84E+02	1.34E+03	Schweinle 2001	total area including forest roads	including bark (hardwood 12%; softwood 10% (v/v) bark in total yield)
2	Time from planting trees to final harvesting [a]	1.50E+02	1.20E+02	Schweinle 2001		
3	Forest road (length) [m / ha]	5.40E+01	5.40E+01	Schweinle 2001	total area including forest roads	
4	Forest road width [m]	2.00E+00	2.00E+00	estimate		
5	Forest road area [m^2/m^2]	1.08E-02	1.08E-02	calculated (3, 4)	total area including forest roads	
6	Yield [m^3/m^2]	7.84E-02	1.34E-01	calculated (1)	total area including forest roads	
7	Yield [m^3/m^2]	7.92E-02	1.35E-01	calculated (5, 6)	forest area excluding forest roads	
8	Land use forest [m^2/m^3]	1.26E+01	7.40E+00	calculated (7)	total yield (including bark)	without forest roads
9	Land use forest roads [m^2/m^3]	1.38E-01	8.08E-02	calculated (5,1)	total yield (including bark)	
10	Time for which land is used as forest (after transformation to forest) [a]	1.00E+03	1.00E+03	estimate		
11	Land transformation forest [m^2/m^3]	1.89E+00	8.88E-01	calculated (10, 12)	total yield (including bark)	
12	Land occupation forest [m^2a/m^3]	1.89E+03	8.88E+02	calculated (2, 8)	total yield (including bark)	
13	Land transformation forest road [m^2/m^3]	2.07E-02	9.70E-03	calculated (10, 14)	total yield (including bark)	
14	Land occupation forest road [m^2a/m^3]	2.07E+01	9.70E+00	calculated (2, 9)	total yield (including bark)	

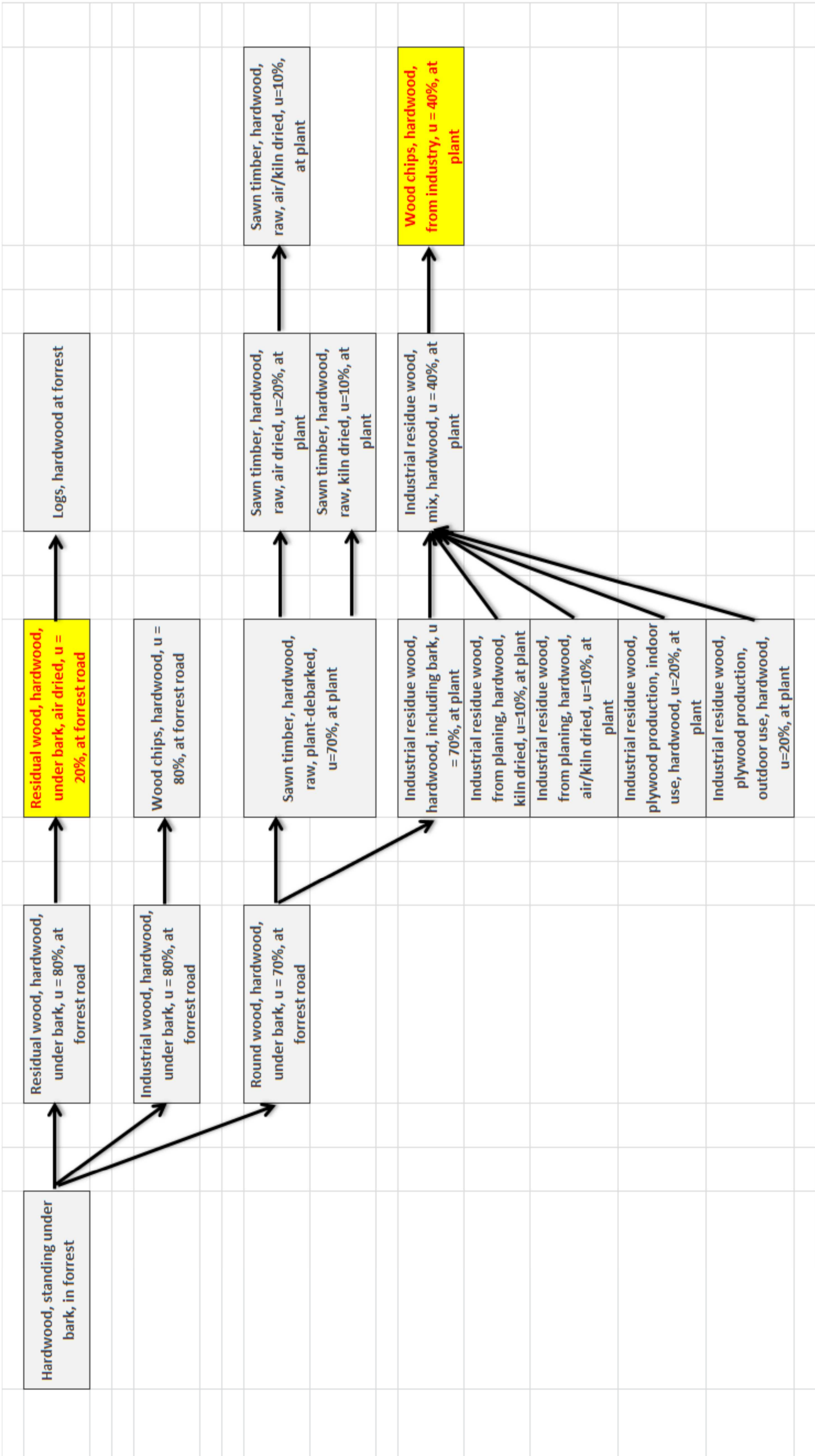


Figure E-1 EcoInvent multi output processes from hardwood

	IN		OUT				price CHF/m3	EUR (2000) /m3
Hardwood, standing under bark, in forrest	1.00		0.16	**Residual wood, hardwood, under bark, u = 80%, at forrest road**			32	20.8
			0.33	**Industrial wood, hardwood, under bark, u = 80%, at forrest road**			44	28.6
			0.51	**Round wood, hardwood, under bark, u = 70%, at forrest road**			133	86.45
			1.00					

Figure E-2 EcoInvent multi output processes from hardwood, with fractions and prices

ANNEX G Scenarios for optimization and market implementation plan

Rank	Scenario	Sub-scenario	Affected parameters	Implementation	Results to be analyzed
1	Scenario B.1 – Energy Prices	Increase in (fossil) energy prices (expected prices 2020/2050, low oil price 2015)	Logistic costs: Fuel price Prices following report EU for 2015, 2020 and 2050: Fuel: 100, 104, 126% Gas: 100, 114, 116% Electricity: 100, 106, 90%	- Comparison 3 scenarios (TNO defines prices) - For two regions - 1. AT+ - 2. FR+ - For FP and CP - 20 runs each	- Return on investment (TransportFuel costs) - Plant location and capacities of decentral and central plants (maps and numbers) - Utilization of biomass (type and quantity) - CO_2 emission and environmental impact - GHG savings from most profitable plants
2	Scenario D – Feedstock	Feedstock price goes up due to competing biomass applications Non-reference feedstock	Feedstock price of biomass sources (both, initial and at 100%) ➔ Tbd by syncom	Increase following the scenario Double threshold and maximum. What makes sense? - For two regions - 1. AT+ - 2. FR+ - For FP and CP - 20 runs each	
3	Scenario A – Implementatio n	National implementation Joint European implementation	Transport distance, feedstock sourcing areas	- Select regions 1. AT 2. AT+ 3. EU - For FP and CP - 20 runs each?	
4	Scenario G – Ramp-Up	Ramping up production	- Best regions to start - Medium implementation - Broad implementation	- Based on EU results of scenario A. - Look into most profitable plants (from previous runs, run for Europe) and define best, medium and broad.	
5	Scenario F – Central vs Decentral	Central/decentral comparison	Transport distance Decentral to central: 0 km Decentral capacity (output) = central capacity (input)	TNO makes calculation for central (incl CO2) for FP and CP	

6	Scenario B.2 – Energy Prices	Tax on CO_2	Product: CO_2 price (disposal costs)	Increase following scenario - 5, 10, 100 €/t for respectively 2015, 2020, 2050. - For two regions - 1. AT+ - 2. FR+ - For FP and CP - 20 runs each	
7	Scenario E – Seasonality	Year-round feedstock, seasonality	Storage time (safety stock days) ➔ Tdb by syncom		
8	Scenario C - GHG saving mandate	Saving mandate from 2% to 6% GHG Volume mandate 2^{nd} gen.	Look for most profitable plants and compare how much GHG savings and the cost	This will be an outcome of models ran before.	

AT+: AT, HU, Bavaria, CZ, northern Italy
FR+: FR, ES, PT

ANNEX H Environmental impacts reference pathways

Table H.1 Environmental impacts per MWh of transport fuel via fast pyrolysis pathway (wheat straw, 100MW FP and 404 MW gasification plant, 50 km local and 250 km central transport)

Impact category	unit	Biomass	Logistics local	Local processing	Logistics central	Central processing	Electricity co-production	Grand Total
Agricultural land occupation	m2a	1.67E+02	2.01E-04	1.32E-01	1.59E-02	2.82E-02	-4.02E-01	1.67E+02
Climate change	kg CO2 eq	5.12E+01	4.08E+00	3.88E+01	5.97E+00	1.31E+01	-1.18E+02	-4.97E+00
Fossil depletion	kg oil eq	6.27E+00	1.31E+00	1.07E+01	1.60E+00	1.27E+00	-3.27E+01	-1.15E+01
Freshwater ecotoxicity	kg 1,4-DB eq	7.27E-01	2.62E-03	5.90E-01	8.26E-02	3.24E+00	-1.80E+00	2.85E+00
Freshwater eutrophication	kg P eq	1.21E-02	5.00E-05	4.40E-02	6.15E-03	7.69E-02	-1.34E-01	5.21E-03
Human toxicity	kg 1,4-DB eq	8.47E+00	7.38E-02	2.69E+01	3.75E+00	5.66E+01	-8.18E+01	1.39E+01
Ionising radiation	kg U235 eq	1.09E+00	4.85E-02	3.93E+00	2.27E+00	1.19E+00	-1.20E+01	-3.43E+00
Marine ecotoxicity	kg 1,4-DB eq	9.00E-02	4.20E-03	5.68E-01	8.00E-02	2.08E+00	-1.73E+00	1.09E+00
Marine eutrophication	kg N eq	7.92E-01	1.50E-03	1.14E-02	2.08E-03	5.04E-03	-3.47E-02	7.78E-01
Metal depletion	kg Fe eq	2.50E-02	1.75E-04	1.33E-02	7.11E-03	1.92E-02	-4.05E-02	2.42E-02
Natural land transformation	m2	-2.57E-04	7.55E-07	3.91E-04	8.22E-05	-5.23E-03	-1.19E-03	-6.20E-03
Ozone depletion	kg CFC-11 eq	3.13E-06	6.14E-07	1.79E-06	3.35E-07	4.74E-07	-5.45E-06	8.87E-07
Particulate matter formation	kg PM10 eq	1.06E-01	1.05E-02	1.72E-02	7.14E-03	8.58E-03	-5.24E-02	9.67E-02
Photochemical oxidant formation	kg NMVOC	7.74E-01	4.17E-02	4.74E-02	2.25E-02	2.65E-02	-1.44E-01	7.68E-01
Soil organic matter	kg C-deficit	2.33E+04	2.70E-03	1.39E+00	2.08E-01	2.27E+00	-4.22E+00	2.33E+04
Terrestrial acidification	kg SO2 eq	4.82E-01	2.46E-02	4.99E-02	1.61E-02	2.12E-02	-1.52E-01	4.42E-01
Terrestrial ecotoxicity	kg 1,4-DB eq	3.21E-01	4.60E-04	1.80E-03	2.38E-04	2.21E-02	-5.48E-03	3.40E-01
Urban land occupation	m2a	5.62E-02	1.48E-04	2.57E-01	1.23E-02	2.38E-01	-2.47E-01	3.18E-01
Water depletion	m3	9.44E-03	8.53E-05	6.81E-02	9.70E-03	3.72E-03	-2.07E-01	-1.16E-01

Table H..2 Environmental impacts per MWh of transport fuel via fast catalytic pyrolysis pathway (forest residue, 50 MW CP and 260 MW refinery plant, 50 km local and 250 km central transport)

Impact category	unit	Biomass	Logistics local	Local processing	Logistics central	Central processing	Electricity co-production	Grand Total
Agricultural land occupation	m2a	5.65E+02	1.22E-04	9.07E-02	2.24E-03	7.70E-02	-1.96E-01	5.65E+02
Climate change	kg CO2 eq	1.91E+00	2.48E+00	3.58E+00	8.64E-01	4.96E+01	-5.76E+01	8.44E-01
Fossil depletion	kg oil eq	6.85E-01	7.97E-01	1.11E+00	2.49E-01	2.21E+01	-1.59E+01	9.01E+00
Freshwater ecotoxicity	kg 1,4-DB eq	2.77E-03	1.60E-03	3.31E-01	8.68E-03	3.40E-01	-8.75E-01	-1.90E-01
Freshwater eutrophication	kg P eq	7.74E-05	3.04E-05	2.55E-03	6.14E-04	2.51E-02	-6.53E-02	-3.69E-02
Human toxicity	kg 1,4-DB eq	2.03E-01	4.49E-02	3.86E+01	3.95E-01	1.60E+01	-3.99E+01	1.53E+01
Ionising radiation	kg U235 eq	2.53E-01	2.95E-02	1.29E+00	4.94E-01	2.41E+00	-5.83E+00	-1.36E+00
Marine ecotoxicity	kg 1,4-DB eq	2.56E-03	2.56E-03	3.13E-01	8.53E-03	3.38E-01	-8.43E-01	-1.78E-01
Marine eutrophication	kg N eq	1.54E-03	9.15E-04	3.96E-03	3.24E-04	7.81E-03	-1.69E-02	-2.37E-03
Metal depletion	kg Fe eq	1.51E-02	1.06E-04	4.10E-01	1.27E-03	1.27E-02	-1.98E-02	4.19E-01
Natural land transformation	m2	3.72E-02	4.59E-07	6.51E-04	1.00E-05	2.21E-04	-5.81E-04	3.75E-02
Ozone depletion	kg CFC-11 eq	2.72E-07	3.73E-07	3.64E-07	6.13E-08	3.41E-06	-2.66E-06	1.83E-06
Particulate matter formation	kg PM10 eq	6.41E-03	6.37E-03	7.59E-03	2.01E-03	2.77E-02	-2.56E-02	2.45E-02
Photochemical oxidant formation	kg NMVOC	5.47E-02	2.54E-02	1.16E-02	5.60E-03	7.76E-02	-7.04E-02	1.05E-01
Soil organic matter	kg C-deficit	1.35E+02	1.64E-03	4.06E+00	2.85E-02	7.93E-01	-2.06E+00	1.38E+02
Terrestrial acidification	kg SO2 eq	1.36E-02	1.50E-02	1.48E-02	5.02E-03	8.37E-02	-7.41E-02	5.81E-02
Terrestrial ecotoxicity	kg 1,4-DB eq	5.64E-04	2.80E-04	5.27E-04	4.47E-05	2.14E-03	-2.67E-03	8.89E-04
Urban land occupation	m2a	5.53E+00	8.99E-05	7.34E-02	1.45E-03	4.64E-02	-1.20E-01	5.53E+00
Water depletion	m3	3.21E-04	5.19E-05	1.54E-02	9.32E-04	7.44E-02	-1.01E-01	-9.95E-03

Table H.3 Environmental impacts per MWh of methanol via fast pyrolysis pathway (wheat straw, 100MW FP and 550 MW gasification plant, 50 km local and 250 km central transport)

Impact category	unit	Biomass	Logistics local	Local processing	Logistics central	Central processing	Electricity co-production	Grand Total
Agricultural land occupation	m2a	1.27E+02	1.51E-04	1.00E-01	1.21E-02	2.18E-02	-7.36E-02	1.27E+02
Climate change	kg CO2 eq	3.90E+01	3.06E+00	2.95E+01	4.54E+00	1.02E+01	-2.17E+01	6.46E+01
Fossil depletion	kg oil eq	4.77E+00	9.82E-01	8.15E+00	1.21E+00	9.83E-01	-5.98E+00	1.01E+01
Freshwater ecotoxicity	kg 1,4-DB eq	5.53E-01	1.97E-03	4.48E-01	6.28E-02	2.52E+00	-3.29E-01	3.25E+00
Freshwater eutrophication	kg P eq	9.20E-03	3.75E-05	3.34E-02	4.67E-03	5.95E-02	-2.45E-02	8.23E-02
Human toxicity	kg 1,4-DB eq	6.44E+00	5.53E-02	2.04E+01	2.85E+00	4.39E+01	-1.50E+01	5.87E+01
Ionising radiation	kg U235 eq	8.30E-01	3.64E-02	2.98E+00	1.73E+00	9.05E-01	-2.19E+00	4.29E+00
Marine ecotoxicity	kg 1,4-DB eq	6.84E-02	3.15E-03	4.32E-01	6.08E-02	1.62E+00	-3.17E-01	1.86E+00
Marine eutrophication	kg N eq	6.03E-01	1.13E-03	8.67E-03	1.58E-03	1.52E-03	-6.36E-03	6.09E-01
Metal depletion	kg Fe eq	1.90E-02	1.31E-04	1.01E-02	5.41E-03	1.48E-02	-7.43E-03	4.20E-02
Natural land transformation	m2	-1.95E-04	5.66E-07	2.97E-04	6.25E-05	-4.06E-03	-2.18E-04	-4.11E-03
Ozone depletion	kg CFC-11 eq	2.38E-06	4.60E-07	1.36E-06	2.54E-07	3.63E-07	-9.99E-07	3.82E-06
Particulate matter formation	kg PM10 eq	8.04E-02	7.85E-03	1.31E-02	5.43E-03	6.59E-03	-9.61E-03	1.04E-01
Photochemical oxidant formation	kg NMVOC	5.89E-01	3.13E-02	3.60E-02	1.71E-02	2.05E-02	-2.65E-02	6.67E-01
Soil organic matter	kg C-deficit	1.77E+04	2.02E-03	1.05E+00	1.58E-01	1.76E+00	-7.74E-01	1.77E+04
Terrestrial acidification	kg SO2 eq	3.67E-01	1.84E-02	3.79E-02	1.22E-02	1.62E-02	-2.79E-02	4.23E-01
Terrestrial ecotoxicity	kg 1,4-DB eq	2.44E-01	3.45E-04	1.37E-03	1.81E-04	1.71E-02	-1.00E-03	2.62E-01
Urban land occupation	m2a	4.27E-02	1.11E-04	1.96E-01	9.34E-03	1.84E-01	-4.52E-02	3.87E-01
Water depletion	m3	7.18E-03	6.39E-05	5.18E-02	7.37E-03	2.88E-03	-3.80E-02	3.13E-02

Table H.4 Environmental impacts per MWh of electricity via HTC pathway (organic municipal waste, 12 MW HTC and 20 MW CHP plant, 0 km local and 50 km central transport)

Impact category	unit	Biomass	Local processing	Logistics central	Central processing	Grand Total
Agricultural land occupation	m2a	3.50E-03	1.11E-01	6.23E-05	2.03E-02	1.35E-01
Climate change	kg CO2 eq	7.14E+01	1.59E+02	1.26E+00	2.76E+00	2.35E+02
Fossil depletion	kg oil eq	2.30E+01	5.56E+01	8.11E-01	8.51E-01	8.03E+01
Freshwater ecotoxicity	kg 1,4-DB eq	4.23E-02	4.51E-01	8.12E-04	1.20E+00	1.69E+00
Freshwater eutrophication	kg P eq	8.70E-04	3.39E-02	1.55E-05	1.34E-02	4.82E-02
Human toxicity	kg 1,4-DB eq	1.22E+00	2.46E+01	2.29E-02	8.48E+01	1.11E+02
Ionising radiation	kg U235 eq	8.43E-01	4.54E+00	1.50E-02	3.87E-01	5.78E+00
Marine ecotoxicity	kg 1,4-DB eq	4.23E-02	5.20E-01	1.30E-03	1.13E+00	1.70E+00
Marine eutrophication	kg N eq	1.86E-02	5.64E-02	4.66E-04	1.82E-02	9.37E-02
Metal depletion	kg Fe eq	3.04E-03	1.47E-02	1.08E-04	3.11E-03	2.09E-02
Natural land transformation	m2	1.31E-05	3.02E-04	2.34E-07	-3.38E-03	-3.06E-03
Ozone depletion	kg CFC-11 eq	1.08E-05	1.98E-05	1.90E-07	2.48E-07	3.10E-05
Particulate matter formation	kg PM10 eq	1.60E-01	9.55E-02	3.24E-03	1.49E-01	4.07E-01
Photochemical oxidant formation	kg NMVOC	7.20E-01	2.01E-01	1.29E-02	4.64E-01	1.40E+00
Soil organic matter	kg C-deficit	4.70E-02	1.03E+00	8.36E-04	1.52E+00	2.59E+00
Terrestrial acidification	kg SO2 eq	3.30E-01	3.13E-01	7.62E-03	2.63E-01	9.14E-01
Terrestrial ecotoxicity	kg 1,4-DB eq	2.48E-03	1.01E-02	1.43E-04	1.49E-04	1.29E-02
Urban land occupation	m2a	2.58E-03	6.32E-02	4.57E-05	1.22E-01	1.88E-01
Water depletion	m3	1.49E-03	3.24E-01	2.64E-05	2.72E-03	3.29E-01

Table H.4 Environmental impacts per MWh ofdiesel and gasoline

Impact category	unit	Diesel	Gasoline
Agricultural land occupation	m2a	1.24E-02	1.82E-02
Climate change	kg CO2 eq	3.42E+01	5.02E+01
Fossil depletion	kg oil eq	9.94E+01	1.04E+02
Freshwater ecotoxicity	kg 1,4-DB eq	1.77E-01	2.12E-01
Freshwater eutrophication	kg P eq	3.34E-03	5.27E-03
Human toxicity	kg 1,4-DB eq	4.58E+00	6.47E+00
Ionising radiation	kg U235 eq	1.80E+00	2.13E+00
Marine ecotoxicity	kg 1,4-DB eq	1.37E-01	1.76E-01
Marine eutrophication	kg N eq	5.41E-03	7.02E-03
Metal depletion	kg Fe eq	9.81E-03	8.86E-02
Natural land transformation	m2	3.71E-05	5.37E-05
Ozone depletion	kg CFC-11 eq	3.80E-05	3.89E-05
Particulate matter formation	kg PM10 eq	1.01E-01	1.31E-01
Photochemical oxidant formation	kg NMVOC	2.41E-01	2.80E-01
Soil organic matter	kg C-deficit	1.77E-01	2.68E-01
Terrestrial acidification	kg SO2 eq	3.93E-01	5.17E-01
Terrestrial ecotoxicity	kg 1,4-DB eq	3.15E-03	3.89E-03
Urban land occupation	m2a	9.79E-03	1.40E-02
Water depletion	m3	5.76E-03	8.92E-03

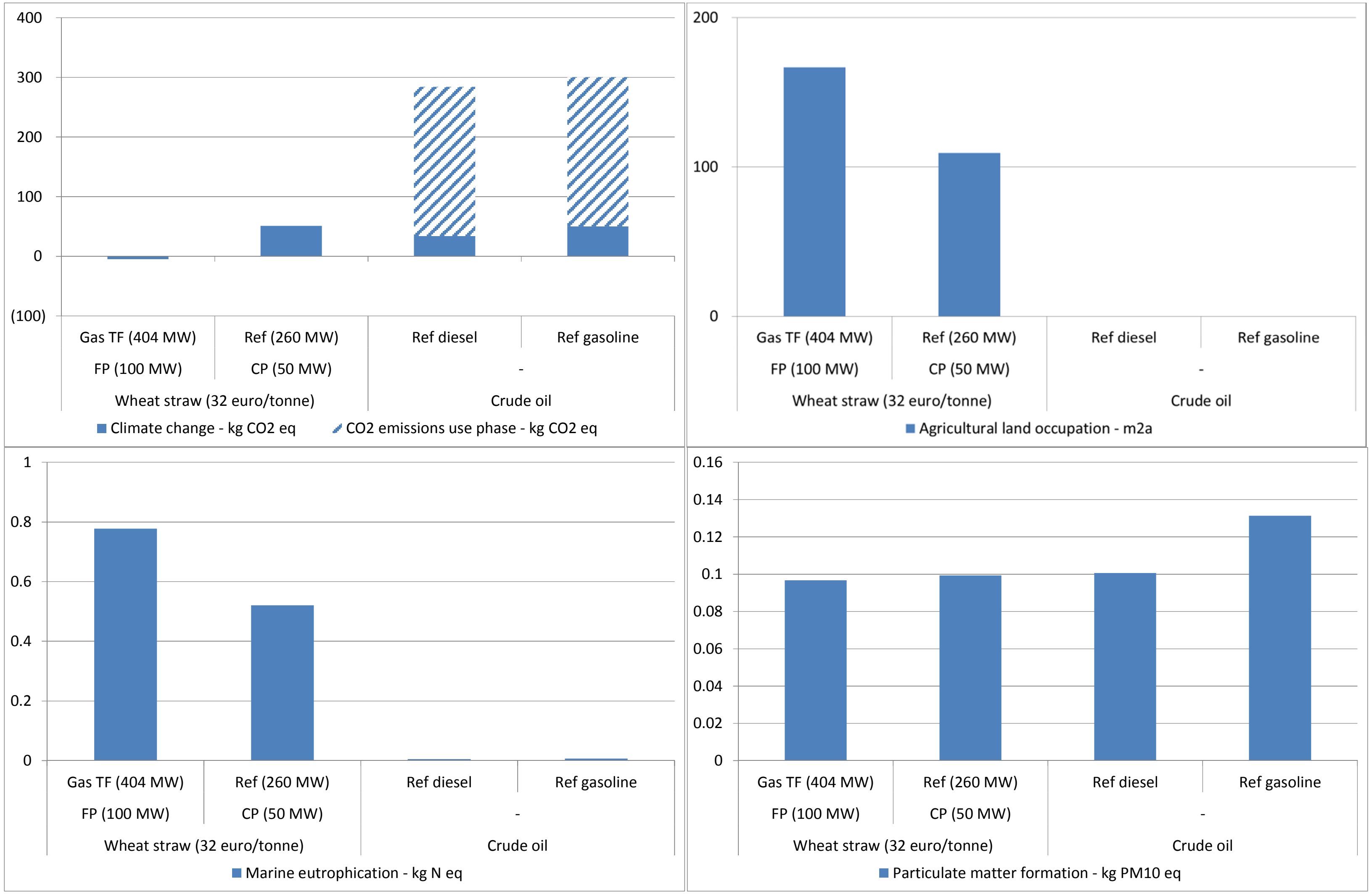


Figure H-1 Comparison of main environmental themes for the biobased pathways versus the fossil references (impacts per MWh of product)

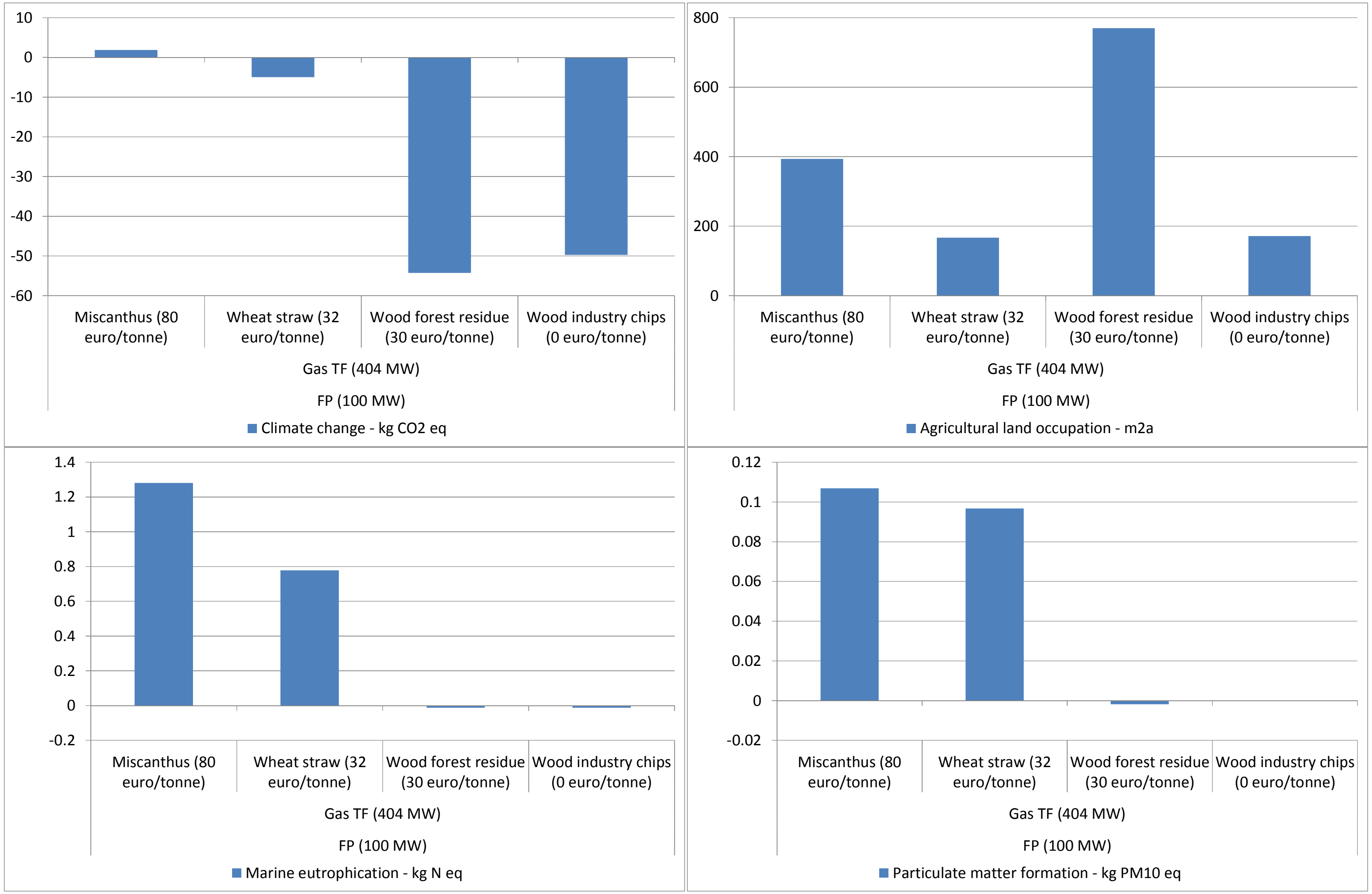


Figure H-2 Comparison of main environmental themes for the various feedstock in the biobased pathways (impacts per MWh of product)

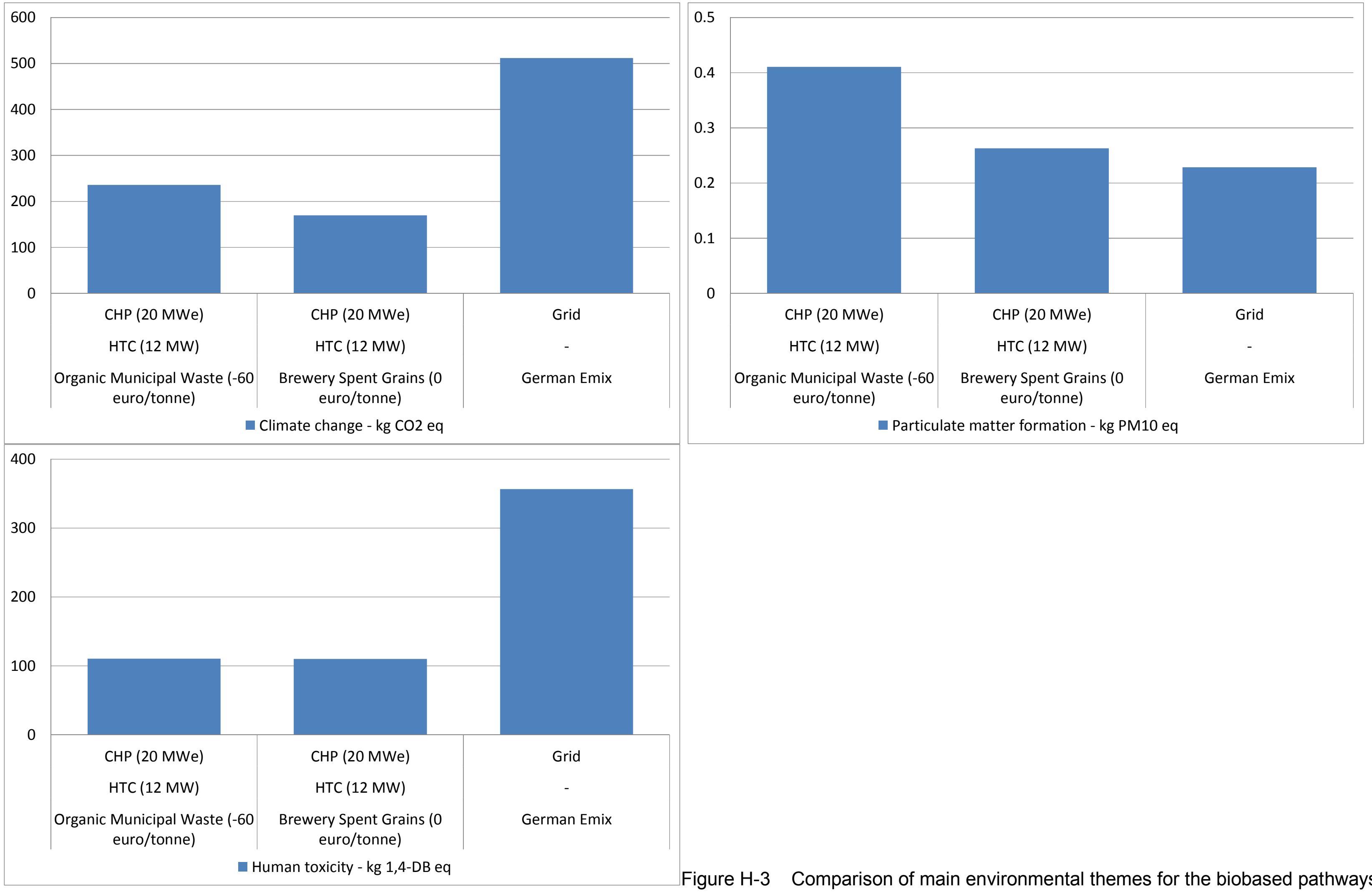


Figure H-3 Comparison of main environmental themes for the biobased pathways versus the fossil references (impacts per MWh of product)

ANNEX I Indirect costs reference pathways

Table I-1 Indirect costs transport fuel via fast pyrolysis pathway (wheat straw, 100MW FP and 404 MW gasification plant, 50 km local and 250 km central transport)

Impact category	Unit	Biomass	Logistics local	Local processing	Logistics central	Central processing	Electricity co-production	Grand Total
Agricultural land occupation	EUR/MWh	1.49E+01	1.80E-05	1.18E-02	1.42E-03	2.52E-03	-3.59E-02	1.49E+01
Climate change	EUR/MWh	1.28E+00	1.02E-01	9.71E-01	1.49E-01	3.29E-01	-2.96E+00	-1.24E-01
Fossil depletion	EUR/MWh	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Freshwater ecotoxicity	EUR/MWh	2.91E-02	1.05E-04	2.36E-02	3.30E-03	1.30E-01	-7.18E-02	1.14E-01
Freshwater eutrophication	EUR/MWh	2.15E-02	8.90E-05	7.83E-02	1.09E-02	1.37E-01	-2.38E-01	9.27E-03
Human toxicity	EUR/MWh	1.74E-01	1.52E-03	5.53E-01	7.73E-02	1.17E+00	-1.69E+00	2.87E-01
Ionising radiation	EUR/MWh	4.64E-02	2.06E-03	1.67E-01	9.65E-02	5.06E-02	-5.08E-01	-1.46E-01
Marine ecotoxicity	EUR/MWh	9.00E-06	4.20E-07	5.68E-05	8.00E-06	2.08E-04	-1.73E-04	1.09E-04
Marine eutrophication	EUR/MWh	9.03E-01	1.71E-03	1.30E-02	2.37E-03	5.74E-03	-3.96E-02	8.87E-01
Metal depletion	EUR/MWh	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Natural land transformation	EUR/MWh	-4.63E-07	1.36E-09	7.07E-07	1.48E-07	-9.44E-06	-2.15E-06	-1.12E-05
Ozone depletion	EUR/MWh	1.22E-04	2.40E-05	7.00E-05	1.31E-05	1.85E-05	-2.13E-04	3.47E-05
Particulate matter formation	EUR/MWh	5.45E+00	5.39E-01	8.87E-01	3.68E-01	4.42E-01	-2.70E+00	4.98E+00
Photochemical oxidant formation	EUR/MWh	4.53E-01	2.44E-02	2.77E-02	1.32E-02	1.55E-02	-8.45E-02	4.49E-01
Soil organic matter	EUR/MWh	3.73E+00	4.32E-07	2.22E-04	3.33E-05	3.62E-04	-6.76E-04	3.73E+00
Terrestrial acidification	EUR/MWh	3.08E-01	1.57E-02	3.18E-02	1.03E-02	1.35E-02	-9.70E-02	2.82E-01
Terrestrial ecotoxicity	EUR/MWh	4.11E-01	5.89E-04	2.30E-03	3.05E-04	2.83E-02	-7.01E-03	4.36E-01
Urban land occupation	EUR/MWh	5.01E-03	1.32E-05	2.30E-02	1.10E-03	2.13E-02	-2.20E-02	2.84E-02
Water depletion	EUR/MWh	9.44E-03	8.53E-05	6.81E-02	9.70E-03	3.72E-03	-2.07E-01	-1.16E-01
Grand Total		**2.77E+01**	**6.87E-01**	**2.86E+00**	**7.44E-01**	**2.34E+00**	**-8.66E+00**	**2.57E+01**

Table I-2 Indirect costs transport fuel via fast catalytic pathway (forest residue, 50 CP and 250 MW refinery plant, 50 km local and 250 km central transport)

Impact category	Unit	Biomass	Logistics local	Local processing	Logistics central	Central processing	Electricity co-production	Grand Total
Agricultural land occupation	EUR/MWh	5.05E+01	1.09E-05	8.10E-03	2.00E-04	6.88E-03	-1.75E-02	5.05E+01
Climate change	EUR/MWh	4.77E-02	6.20E-02	8.95E-02	2.16E-02	1.24E+00	-1.44E+00	2.11E-02
Fossil depletion	EUR/MWh	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Freshwater ecotoxicity	EUR/MWh	1.11E-04	6.38E-05	1.32E-02	3.47E-04	1.36E-02	-3.50E-02	-7.61E-03
Freshwater eutrophication	EUR/MWh	1.38E-04	5.42E-05	4.53E-03	1.09E-03	4.46E-02	-1.16E-01	-6.57E-02
Human toxicity	EUR/MWh	4.19E-03	9.25E-04	7.95E-01	8.14E-03	3.29E-01	-8.21E-01	3.16E-01
Ionising radiation	EUR/MWh	1.07E-02	1.25E-03	5.46E-02	2.10E-02	1.02E-01	-2.48E-01	-5.77E-02
Marine ecotoxicity	EUR/MWh	2.56E-07	2.56E-07	3.13E-05	8.53E-07	3.38E-05	-8.43E-05	-1.78E-05
Marine eutrophication	EUR/MWh	1.76E-03	1.04E-03	4.51E-03	3.69E-04	8.90E-03	-1.93E-02	-2.70E-03
Metal depletion	EUR/MWh	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Natural land transformation	EUR/MWh	6.72E-05	8.29E-10	1.18E-06	1.81E-08	3.99E-07	-1.05E-06	6.78E-05
Ozone depletion	EUR/MWh	1.06E-05	1.46E-05	1.42E-05	2.40E-06	1.33E-04	-1.04E-04	7.14E-05
Particulate matter formation	EUR/MWh	3.30E-01	3.28E-01	3.91E-01	1.03E-01	1.43E+00	-1.32E+00	1.26E+00
Photochemical oxidant formation	EUR/MWh	3.20E-02	1.49E-02	6.81E-03	3.28E-03	4.54E-02	-4.12E-02	6.12E-02
Soil organic matter	EUR/MWh	2.15E-02	2.63E-07	6.50E-04	4.56E-06	1.27E-04	-3.29E-04	2.20E-02
Terrestrial acidification	EUR/MWh	8.69E-03	9.55E-03	9.46E-03	3.21E-03	5.34E-02	-4.73E-02	3.70E-02
Terrestrial ecotoxicity	EUR/MWh	7.22E-04	3.59E-04	6.74E-04	5.73E-05	2.74E-03	-3.42E-03	1.14E-03
Urban land occupation	EUR/MWh	4.94E-01	8.03E-06	6.56E-03	1.29E-04	4.14E-03	-1.07E-02	4.94E-01
Water depletion	EUR/MWh	3.21E-04	5.19E-05	1.54E-02	9.32E-04	7.44E-02	-1.01E-01	-9.95E-03
Grand Total		**5.14E+01**	**4.18E-01**	**1.40E+00**	**1.64E-01**	**3.35E+00**	**-4.22E+00**	**5.25E+01**

TableI-3 Indirect costs methanol via fast pyrolysis pathway (wheat straw, 100MW FP and 550 MW gasification plant, 50 km local and 250 km central transport)

Impact category	Unit	Biomass	Logistics local	Local processing	Logistics central	Central processing	Electricity co-production	Grand Total
Agricultural land occupation	EUR/MWh	1.13E+01	1.35E-05	8.96E-03	1.08E-03	1.95E-03	-6.58E-03	1.13E+01
Climate change	EUR/MWh	9.74E-01	7.64E-02	7.38E-01	1.13E-01	2.55E-01	-5.42E-01	1.61E+00
Fossil depletion	EUR/MWh	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Freshwater ecotoxicity	EUR/MWh	2.21E-02	7.86E-05	1.79E-02	2.51E-03	1.01E-01	-1.32E-02	1.30E-01
Freshwater eutrophication	EUR/MWh	1.64E-02	6.67E-05	5.95E-02	8.32E-03	1.06E-01	-4.37E-02	1.47E-01
Human toxicity	EUR/MWh	1.33E-01	1.14E-03	4.21E-01	5.87E-02	9.04E-01	-3.09E-01	1.21E+00
Ionising radiation	EUR/MWh	3.53E-02	1.55E-03	1.27E-01	7.34E-02	3.84E-02	-9.32E-02	1.82E-01
Marine ecotoxicity	EUR/MWh	6.84E-06	3.15E-07	4.32E-05	6.08E-06	1.62E-04	-3.17E-05	1.86E-04
Marine eutrophication	EUR/MWh	6.87E-01	1.28E-03	9.88E-03	1.80E-03	1.73E-03	-7.25E-03	6.94E-01
Metal depletion	EUR/MWh	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Natural land transformation	EUR/MWh	-3.52E-07	1.02E-09	5.37E-07	1.13E-07	-7.32E-06	-3.94E-07	-7.42E-06
Ozone depletion	EUR/MWh	9.30E-05	1.80E-05	5.32E-05	9.95E-06	1.42E-05	-3.91E-05	1.49E-04
Particulate matter formation	EUR/MWh	4.14E+00	4.04E-01	6.74E-01	2.80E-01	3.39E-01	-4.95E-01	5.34E+00
Photochemical oxidant formation	EUR/MWh	3.44E-01	1.83E-02	2.11E-02	1.00E-02	1.20E-02	-1.55E-02	3.90E-01
Soil organic matter	EUR/MWh	2.83E+00	3.24E-07	1.69E-04	2.53E-05	2.81E-04	-1.24E-04	2.83E+00
Terrestrial acidification	EUR/MWh	2.34E-01	1.18E-02	2.42E-02	7.80E-03	1.03E-02	-1.78E-02	2.70E-01
Terrestrial ecotoxicity	EUR/MWh	3.13E-01	4.42E-04	1.75E-03	2.32E-04	2.19E-02	-1.28E-03	3.36E-01
Urban land occupation	EUR/MWh	3.81E-03	9.89E-06	1.75E-02	8.34E-04	1.64E-02	-4.03E-03	3.45E-02
Water depletion	EUR/MWh	7.18E-03	6.39E-05	5.18E-02	7.37E-03	2.88E-03	-3.80E-02	3.13E-02
Grand Total		**2.11E+01**	**5.15E-01**	**2.17E+00**	**5.65E-01**	**1.81E+00**	**-1.59E+00**	**2.46E+01**

Table I4 Indirect costs electricity via HTC pathway (organic municipal waste, 12 MW HTC and 20 MW CHP plant, 0 km local and 50 km central transport)

Impact category	Unit	Biomass	Logistics local	Local processing	Logistics central	Central processing	Grand Total
Agricultural land occupation	EUR/MWh	3.13E-04	0.00E+00	9.94E-03	5.57E-06	1.81E-03	1.21E-02
Climate change	EUR/MWh	1.79E+00	0.00E+00	3.98E+00	3.16E-02	6.90E-02	5.87E+00
Fossil depletion	EUR/MWh	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Freshwater ecotoxicity	EUR/MWh	1.69E-03	0.00E+00	1.80E-02	3.25E-05	4.80E-02	6.78E-02
Freshwater eutrophication	EUR/MWh	1.55E-03	0.00E+00	6.04E-02	2.76E-05	2.38E-02	8.58E-02
Human toxicity	EUR/MWh	2.52E-02	0.00E+00	5.07E-01	4.71E-04	1.75E+00	2.28E+00
Ionising radiation	EUR/MWh	3.58E-02	0.00E+00	1.93E-01	6.39E-04	1.65E-02	2.46E-01
Marine ecotoxicity	EUR/MWh	4.23E-06	0.00E+00	5.20E-05	1.30E-07	1.13E-04	1.70E-04
Marine eutrophication	EUR/MWh	2.12E-02	0.00E+00	6.43E-02	5.31E-04	2.08E-02	1.07E-01
Metal depletion	EUR/MWh	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Natural land transformation	EUR/MWh	2.37E-08	0.00E+00	5.44E-07	4.22E-10	-6.10E-06	-5.53E-06
Ozone depletion	EUR/MWh	4.22E-04	0.00E+00	7.75E-04	7.43E-06	9.69E-06	1.21E-03
Particulate matter formation	EUR/MWh	8.24E+00	0.00E+00	4.92E+00	1.67E-01	7.65E+00	2.10E+01
Photochemical oxidant formation	EUR/MWh	4.21E-01	0.00E+00	1.17E-01	7.56E-03	2.71E-01	8.17E-01
Soil organic matter	EUR/MWh	7.53E-06	0.00E+00	1.64E-04	1.34E-07	2.43E-04	4.15E-04
Terrestrial acidification	EUR/MWh	2.10E-01	0.00E+00	2.00E-01	4.86E-03	1.68E-01	5.83E-01
Terrestrial ecotoxicity	EUR/MWh	3.18E-03	0.00E+00	1.30E-02	1.83E-04	1.90E-04	1.65E-02
Urban land occupation	EUR/MWh	2.30E-04	0.00E+00	5.64E-03	4.09E-06	1.09E-02	1.68E-02
Water depletion	EUR/MWh	1.49E-03	0.00E+00	3.24E-01	2.64E-05	2.72E-03	3.29E-01
Grand Total		**1.08E+01**	**0.00E+00**	**1.04E+01**	**2.13E-01**	**1.00E+01**	**3.14E+01**

ANNEX J Cost calculation for fast pyrolysis and gasification pathway

Calculation of Total Capital Investment (TCI) for local (fast pyrolysis) processing plant

KPI description	Model parameter	Value	Unit
Total capital investment of local processing plant	TCIlocal	64,072,268.23	EUR
Working capital of local processing plant	WClocal	8,357,252.38	EUR
Fixed capital investment of local processing plant	FCIlocal	55,715,015.85	EUR
Calculation of Fixed Capital Investment (FCI) for local processing plant			
Direct costs			
Cost description	**Fraction of delivered equipment, fi**	**Value**	**Unit**
Purchased equipment	1	11,054,566.64	EUR
Purchased equipment installation	0.47	5,195,646.32	EUR
Instrumentation and controls	0.36	3,979,643.99	EUR
Piping	0.68	7,517,105.31	EUR
Electrical systems	0.11	1,216,002.33	EUR
Buildings	0.18	1,989,821.99	EUR
Yard improvements	0.1	1,105,456.66	EUR
Service facilities	0.7	7,738,196.65	EUR
Indirect costs			
Cost description	**Fraction of delivered equipment, fi**	**Value**	**Unit**
Engineering and supervision	0.33	3,648,006.99	EUR
Construction expenses	0.41	4,532,372.32	EUR
Legal expenses	0.04	442,182.67	EUR
Contractor's fee	0.22	2,432,004.66	EUR
Contingency	0.44	4,864,009.32	EUR
Fixed capital investment (FCI) of local processing plant	5.04	55,715,015.85	EUR

Calculation of equipment cost for local processing plant			
Relevant parameters (description)	**Model parameter**	**Value**	**Unit**
Capacity of equipment for local processing plant	Capacity_local	148,056,338	kg/year
Energy capacity of equipment for local processing plant	Energy_capacity_local	100	MW
Capacity of reference equipment for local processing plant	Capacity_ref_l	118,676,275.20	kg/year
Energy capacity of reference equipment for local processing plant	Energy_capacity_ref_l	80.15	MW
Cost reference year for equipment purchase cost	Year_implementation	2012	-
Description	**Equipment part**	**Cost of delivered equipment (in EUR)**	**Scaling factor**
Cost of delivered equipment part (1) for local processing plant	Storage	1,406,217.49	0.8
Cost of delivered equipment part (2) for local processing plant	Pre-treatment	1,586,843.70	0.8
Cost of delivered equipment part (3) for local processing plant	Heat carrier loop	5,085,415.84	0.8
Cost of delivered equipment part (4) for local processing plant	Product recovery	1,658,366.83	0.8
Cost of delivered equipment part (5) for local processing plant	Biosyncrude mixing	921,314.91	0.8
Cost of delivered equipment part (6) for local processing plant	Other	396,407.86	0.8
Total cost of delivered equipment for local processing plant	**Elocal**	**11,054,566.64**	-

Calculation of Operational Expenditure (OPEX) for local (fast pyrolysis) processing plant

KPI description	Variable name	Value	Unit
Cost of operating local processing plant	OPEXlocal	**32,076,448.79**	EUR/year

Relevant parameters (description)	Value	Unit
Annual production capacity of the local processing plant	**148,056,338.03**	kg/year
Annual energy production capacity of the local processing plant	**100.00**	MW
Energy density of feedstock (biomass)	**0.0037**	MWh/kg
Energy density of end product (energy carrier)	**0.0047**	MWh/kg
Operating time of the local processing plant	**7008**	hr/yr

Cost description	Factor or annual quantity	Rate or quantity unit	Annual cost (EUR)
Variable costs			
Raw materials	-	-	11,764,734.29
- Feedstock (biomass)	219,123,380.28	kg	11,764,734.29
- Consumables	-	-	0.00
Utilities	-	-	2,029,556.28
- Water	75,508,732.39	kg	151,017.46
- Energy	19,247.32	MWh	1,878,538.82
Operating Labour	12.00	person(s)	600,000.00
Operating supervision	0.15	of operating labour	90,000.00
Maintenance and repairs	0.07	of FCIlocal	3,900,051.11
Operating supplies	0.15	of maintenance and repairs	585,007.67
Laboratory charges	0.15	of operating labour	90,000.00
Royalties	0.04	of production cost (OPEXlocal)	1,283,057.95
Fixed costs			
Taxes (property)	0.01	of FCIlocal	557,150.16
Financing (interest paid because of loan / loan=TCI)	0.05	of TCIlocal	3,203,613.41
Insurance	0.01	of FCIlocal	557,150.16
Rent	0.10	of value of rented land and buildings	
Depreciation cost			2,785,750.79
General expenses			
Plant overhead costs	0.50	of total expenses of labour and maintenance	2,295,025.55
Administrative costs	0.15	of operating labour	90,000.00
Distribution and marketing	0.02	of production cost (OPEXlocal)	641,528.98
Research and development	0.05	of production cost (OPEXlocal)	1,603,822.44

Calculation of Total Capital Investment (TCI) for central (gasification) processing plant - methanol

KPI description	**Model parameter**	**Value**	**Unit**
Total capital investment of central processing plant	TCIcentral	721,162,159.62	EUR
Working capital of central processing plant	WCcentral	94,064,629.52	EUR
Fixed capital investment of central processing plant	FCIcentral	627,097,530.11	EUR
Calculation of Fixed Capital Investment (FCI) for central processing plant			
Direct costs			
Cost description	**Fraction of delivered equipment, fi**	**Value**	**Unit**
Purchased equipment	1	124,424,113.12	EUR
Purchased equipment installation	0.47	58,479,333.16	EUR
Instrumentation and controls	0.36	44,792,680.72	EUR
Piping	0.68	84,608,396.92	EUR
Electrical systems	0.11	13,686,652.44	EUR
Buildings	0.18	22,396,340.36	EUR
Yard improvements	0.1	12,442,411.31	EUR
Service facilities	0.7	87,096,879.18	EUR
Indirect costs			
Cost description	**Fraction of delivered equipment, fi**	**Value**	**Unit**
Engineering and supervision	0.33	41,059,957.33	EUR
Construction expenses	0.41	51,013,886.38	EUR
Legal expenses	0.04	4,976,964.52	EUR
Contractor's fee	0.22	27,373,304.89	EUR
Contingency	0.44	54,746,609.77	EUR
Fixed capital investment (FCI) of central processing plant	5.04	627,097,530.11	EUR

Calculation of equipment cost for central processing plant			
Relevant parameters (description)	**Model parameter**	**Value**	**Unit**
Capacity of equipment for central processing plant	Capacity_c	695,024,986.5	kg/year
Energy capacity of equipment for central processing plant	Energy_capacity_c	549.6	MW
Capacity of reference equipment for central processing plant	Capacity_ref_c	610,775,000	kg/year
Energy capacity of reference equipment for central processing plant	Energy_capacity_ref_c	549.6	MW
Cost reference year for equipment purchase cost	Ref_year	2012	-
Description	**Equipment part**	**Cost of delivered equipment (in EUR)**	**Scaling factor**
Cost of delivered equipment part (1) for central processing plant	Slurry handling	6,745,405.84	0.6
Cost of delivered equipment part (2) for central processing plant	Air separation unit	19,803,416.95	0.7
Cost of delivered equipment part (3) for central processing plant	Cooling and quench water system	2,024,938.79	0.6
Cost of delivered equipment part (4) for central processing plant	Gasifier and auxiliaries	23,636,817.51	0.75
Cost of delivered equipment part (5) for central processing plant	Raw syngas treatment	8,518,626.81	0.7
Cost of delivered equipment part (6) for central processing plant	Syngas cleaning	29,423,239.91	0.65
Cost of delivered equipment part (7) for central processing plant	Slag recovery and handling	4,213,729.52	0.7
Cost of delivered equipment part (8) for central processing plant	Methanol synthesis	12,464,778.46	0.65
Cost of delivered equipment part (9) for central processing plant	Methanol recovery	5,507,867.03	0.7
Cost of delivered equipment part (10) for central processing plant	Power island	12,085,292.29	0.75
Total cost of delivered equipment for central processing plant	**Ecentral**	124,424,113.12	-

Calculation of Operational Expenditure (OPEX) for central (gasification) processing plant - methanol

KPI description	Variable name	Value	Unit
Cost of operating central processing plant	OPEXcentral	658,561,590.08	EUR/year

Relevant parameters (description)	Value	Unit
Annual production capacity of the central processing plant (if applicable)	695,024,986.47	kg/year
Annual energy production capacity of the central processing plant	549,60	MW
Energy density of feedstock (energy carrier)	0,0047	MWh/kg
Energy density of end product (if applicable)	0,0055	MWh/kg
Operating time of the central processing plant	7008	hr/yr

Cost description	Factor or annual quantity	Rate or quantity unit	Annual cost (EUR)
<u>**Variable costs**</u>			
Raw materials	-	-	420,471,238.32
- Feedstock (energy carrier)	1,531,140,045.18	kg	420,471,238.32
- Consumables	-	-	0.00
Utilities	-	-	127.04
- Water	0.00	-	0.00
- Energy	278,009.99	kg	127.04
Operating Labour	131.00	person(s)	6,550,000.00
Operating supervision	0.15	of operating labour	982,500.00
Maintenance and repairs	0.07	of FCIcentral	43,896,827.11
Operating supplies	0.15	of maintenance and repairs	6,584,524.07
Laboratory charges	0.15	of operating labour	982,500.00
Royalties	0.04	of production cost (OPEXcentral)	26,342,463.60
<u>**Fixed costs**</u>			
Taxes (property)	0.01	of FCIcentral	6,270,975.30
Financing (interest paid because of loan / loan=TCI)	0.05	of TCIcentral	36,058,107.98
Insurance	0.01	of FCIcentral	6,270,975.30
Rent	0.10	of value of rented land and buildings	
Depreciation cost			31,354,876.51
<u>**General expenses**</u>			
Plant overhead costs	0.50	of total expenses of labour and maintenance	25,714,663.55
Administrative costs	0.15	of operating labour	982,500.00
Distribution and marketing	0.02	of production cost (OPEXcentral)	13,171,231.80
Research and development	0.05	of production cost (OPEXcentral)	32,928,079.50

Calculation of Total Capital Investment (TCI) for central (gasification) processing plant – transport fuels

KPI description	**Model parameter**	**Value**	**Unit**
Total capital investment of central processing plant	TCIcentral	864,733,567.98	EUR
Working capital of central processing plant	WCcentral	112,791,334.95	EUR
Fixed capital investment of central processing plant	FCIcentral	751,942,233.02	EUR
Calculation of Fixed Capital Investment (FCI) for central processing plant			
<u>Direct costs</u>			
Cost description	**Fraction of delivered equipment, fi**	**Value**	**Unit**
Purchased equipment	1	149,194,887.50	EUR
Purchased equipment installation	0.47	70,121,597.13	EUR
Instrumentation and controls	0.36	53,710,159.50	EUR
Piping	0.68	101,452,523.50	EUR
Electrical systems	0.11	16,411,437.63	EUR
Buildings	0.18	26,855,079.75	EUR
Yard improvements	0.1	14,919,488.75	EUR
Service facilities	0.7	104,436,421.25	EUR
<u>Indirect costs</u>			
Cost description	**Fraction of delivered equipment, fi**	**Value**	**Unit**
Engineering and supervision	0.33	49,234,312.88	EUR
Construction expenses	0.41	61,169,903.88	EUR
Legal expenses	0.04	5,967,795.50	EUR
Contractor's fee	0.22	32,822,875.25	EUR
Contingency	0.44	65,645,750.50	EUR
Fixed capital investment (FCI) of central processing plant	5.04	751,942,233.02	EUR

Calculation of equipment cost for central processing plant			
Relevant parameters (description)	**Model parameter**	**Value**	**Unit**
Capacity of equipment for central processing plant	Capacity_c	237,092,048	kg/year
Energy capacity of equipment for central processing plant	Energy_capacity_c	404.1	MW
Capacity of reference equipment for central processing plant	Capacity_ref_c	215,629,401	kg/year
Energy capacity of reference equipment for central processing plant	Energy_capacity_ref_c	404.1	MW
Cost reference year for equipment purchase cost	Ref_year	2012	-
Chemical Engineering Plant Cost Index at year of implementation			-
Description	**Equipment part**	**Cost of delivered equipment (in EUR)**	**Scaling factor**
Cost of delivered equipment part (1) for central processing plant	Slurry handling	6,607,877.64	0.6
Cost of delivered equipment part (2) for central processing plant	Air separation unit	19,333,167.97	0.7
Cost of delivered equipment part (3) for central processing plant	Cooling and quench water system	1,983,653.47	0.6
Cost of delivered equipment part (4) for central processing plant	Gasifier and auxiliaries	23,035,963.80	0.75
Cost of delivered equipment part (5) for central processing plant	Raw syngas treatment	8,316,344.77	0.7
Cost of delivered equipment part (6) for central processing plant	Syngas cleaning	28,773,910.82	0.65
Cost of delivered equipment part (7) for central processing plant	Slag recovery and handling	4,113,670.93	0.7
Cost of delivered equipment part (8) for central processing plant	Fiscer-Tropsch synthesis	13,381,229.66	0.65
Cost of delivered equipment part (9) for central processing plant	Product recovery and upgrading	24,000,393.56	0.7
Cost of delivered equipment part (10) for central processing plant	Power island	19,648,674.89	0.75
Total cost of delivered equipment for central processing plant	**Ecentral**	149,194,887.50	-

Calculation of Operational Expenditure (OPEX) for central (gasification) processing plant – transport fuels

KPI description	Variable name	Value	Unit
Cost of operating central processing plant	OPEXcentral	676,701,979.39	EUR/year

Relevant parameters (description)	Value	Unit
Annual production capacity of the central processing plant (if applicable)	237,092,048.37	kg/year
Annual energy production capacity of the central processing plant	404.10	MW
Energy density of feedstock (energy carrier)	0.0047	MWh/kg
Energy density of end product (if applicable)	0.0119	MWh/kg
Operating time of the central processing plant	7008	hr/yr

Cost description	Factor or annual quantity	Rate or quantity unit	Annual cost (EUR)
<u>**Variable costs**</u>			
Raw materials	-	-	406,277,673.90
- Feedstock (energy carrier)	1,479,454,381.84	kg	406,277,673.90
- Consumables	-	-	0.00
Utilities	-	-	1,375.13
- Water	0.00	-	0.00
- Energy	275,026.78	kg	1,375.13
Operating Labour	131.00	person(s)	6,550,000.00
Operating supervision	0.15	of operating labour	982,500.00
Maintenance and repairs	0.07	of FCIcentral	52,635,956.31
Operating supplies	0.15	of maintenance and repairs	7,895,393.45
Laboratory charges	0.15	of operating labour	982,500.00
Royalties	0.04	of production cost (OPEXcentral)	27,068,079.18
<u>**Fixed costs**</u>			
Taxes (property)	0.01	of FCIcentral	7,519,422.33
Financing (interest paid because of loan / loan=TCI)	0.05	of TCIcentral	43,236,678.40
Insurance	0.01	of FCIcentral	7,519,422.33
Rent	0.10	of value of rented land and buildings	
Depreciation cost			37,597,111.65
<u>**General expenses**</u>			
Plant overhead costs	0.50	of total expenses of labour and maintenance	30,084,228.16
Administrative costs	0.15	of operating labour	982,500.00
Distribution and marketing	0.02	of production cost (OPEXcentral)	13,534,039.59
Research and development	0.05	of production cost (OPEXcentral)	33,835,098.97

ANNEX K Cost calculation for hydrothermal carbonization and heat and power pathway

Calculation of Total Capital Investment (TCI) for local (HTC) processing plant – bio-coal

KPI description	Model parameter	Value	Unit
Total capital investment of local processing plant	TCIlocal	16,094,940.00	EUR
Working capital of local processing plant	WClocal	2,099,340.00	EUR
Fixed capital investment of local processing plant	FCIlocal	13,995,600.00	EUR
Calculation of Fixed Capital Investment (FCI) for local processing plant			
Direct costs			
Cost description	**Fraction of delivered equipment, fi**	**Value**	**Unit**
Purchased equipment	1	3,270,000.00	EUR
Purchased equipment installation	0.39	1,275,300.00	EUR
Instrumentation and controls	0.26	850,200.00	EUR
Piping	0.31	1,013,700.00	EUR
Electrical systems	0.1	327,000.00	EUR
Buildings	0.29	948,300.00	EUR
Yard improvements	0.12	392,400.00	EUR
Service facilities	0.55	1,798,500.00	EUR
Indirect costs			
Cost description	**Fraction of delivered equipment, fi**	**Value**	**Unit**
Engineering and supervision	0.32	1,046,400.00	EUR
Construction expenses	0.34	1,111,800.00	EUR
Legal expenses	0.04	130,800.00	EUR
Contractor’s fee	0.19	621,300.00	EUR
Contingency	0.37	1,209,900.00	EUR
Fixed capital investment (FCI) of local processing plant	4.28	13,995,600.00	EUR

Calculation of equipment cost for local processing plant			
Relevant parameters (description)	**Model parameter**	**Value**	**Unit**
Capacity of equipment for local processing plant	Capacity_local	16,800,000	kg/year
Energy capacity of equipment for local processing plant	Energy_capacity_local	12.26	MW
Capacity of reference equipment for local processing plant	Capacity_ref_l	16,800,000	kg/year
Energy capacity of reference equipment for local processing plant	Energy_capacity_ref_l	12.26	MW
Cost reference year for equipment purchase cost	Year_implementation	2012	-
Chemical Engineering Plant Cost Index at year of implementation			-
Description	**Equipment part**	**Cost of delivered equipment (in EUR)**	**Scaling factor**
Cost of delivered equipment part (1) for local processing plant	Confidential description	**3,270,000.00**	1
Total cost of delivered equipment for local processing plant	**Elocal**	**3,270,000.00**	-

Calculation of Operational Expenditure (OPEX) for local processing plant

KPI description	Variable name	Value	Unit
Cost of operating local processing plant	OPEXlocal	85,280.63	EUR/year

Relevant parameters (description)	Value	Unit
Annual production capacity of the local processing plant	16,800,000.00	kg/year
Annual energy production capacity of the local processing plant	12.26	MW
Energy density of feedstock (biomass)	0.0047	MWh/kg
Energy density of end product (energy carrier)	0.0058	MWh/kg
Operating time of the local processing plant	8000	hr/yr

Cost description	Factor or annual quantity	Rate or quantity unit	Annual cost (EUR)
Variable costs			
Raw materials	-	-	-4,798,080.00
- Feedstock (biomass)	79,968,000.00	kg	-4,798,080.00
- Consumables	-	-	0.00
Utilities	-	-	663,048.96
- Water	0.00	-	0.00
- Energy	20,161,629.60	MWh	663,048.96
Operating Labour	8.00	person(s)	400,000.00
Operating supervision	0.15	of operating labour	60,000.00
Maintenance and repairs	0.07	of FCIlocal	979,692.00
Operating supplies	0.15	of maintenance and repairs	146,953.80
Laboratory charges	0.15	of operating labour	60,000.00
Royalties	0.04	of production cost (OPEXlocal)	3,411.23
Fixed costs			
Taxes (property)	0.01	of FCIlocal	139,956.00
Financing (interest paid because of loan / loan=TCI)	0.05	of TCIlocal	804,747.00
Insurance	0.01	of FCIlocal	139,956.00
Rent	0.10	of value of rented land and buildings	
Depreciation cost			699,780.00
General expenses			
Plant overhead costs	0.50	of total expenses of labour and maintenance	719,846.00
Administrative costs	0.15	of operating labour	60,000.00
Distribution and marketing	0.02	of production cost (OPEXlocal)	1,705.61
Research and development	79,968,000.00	of production cost (OPEXlocal)	4,264.03

Calculation of Total Capital Investment (TCI) for central (CHP) processing plant – heat and power

KPI description	**Model parameter**	**Value**	**Unit**
Total capital investment of central processing plant	TCIcentral	46,000,000.00	EUR
Working capital of central processing plant	WCcentral	6,000,000.00	EUR
Fixed capital investment of central processing plant	FCIcentral	40,000,000.00	EUR
Calculation of Fixed Capital Investment (FCI) for central processing plant			
<u>Direct costs</u>			
Cost description	**Fraction of delivered equipment, fi**	**Value**	**Unit**
Purchased equipment	1	40,000,000.00	EUR
Purchased equipment installation	0	0.00	EUR
Instrumentation and controls	0	0.00	EUR
Piping	0	0.00	EUR
Electrical systems	0	0.00	EUR
Buildings	0	0.00	EUR
Yard improvements	0	0.00	EUR
Service facilities	0	0.00	EUR
<u>Indirect costs</u>			
Cost description	**Fraction of delivered equipment, fi**	**Value**	**Unit**
Engineering and supervision	0	0.00	EUR
Construction expenses	0	0.00	EUR
Legal expenses	0	0.00	EUR
Contractor's fee	0	0.00	EUR
Contingency	0	0.00	EUR
Fixed capital investment (FCI) of central processing plant	1	40,000,000.00	EUR

Calculation of equipment cost for central processing plant			
Relevant parameters (description)	**Model parameter**	**Value**	**Unit**
Capacity of equipment for central processing plant	Capacity_c	160,000	MWh
Energy capacity of equipment for central processing plant	Energy_capacity_c	20	MW
Capacity of reference equipment for central processing plant	Capacity_ref_c	160,000	MWh
Energy capacity of reference equipment for central processing plant	Energy_capacity_ref_c	20	MW
Cost reference year for equipment purchase cost	Ref_year	2012	-
Chemical Engineering Plant Cost Index at year of implementation			-
Description	**Equipment part**	**Cost of delivered equipment (in EUR)**	**Scaling factor**
Cost of delivered equipment part (1) for central processing plant	Confidential description	40,000,000.00	0.8
Total cost of delivered equipment for central processing plant	**Ecentral**	**40,000,000.00**	-

Calculation of Operational Expenditure (OPEX) for central (CHP) processing plant – heat and power

KPI description	Variable name	Value	Unit
Cost of operating central processing plant	OPEXcentral	20,370,831.25	EUR/year

Relevant parameters (description)	Value	Unit
Annual production capacity of the central processing plant (if applicable)	160,000.00	MWh
Annual energy production capacity of the central processing plant	20.00	MW
Energy density of feedstock (energy carrier)	0.0058	MWh/kg
Energy density of end product (if applicable)	0.0000	MWh/kg
Operating time of the central processing plant	8000	hr/yr

Cost description	Factor or annual quantity	Rate or quantity unit	Annual cost (EUR)
<u>**Variable costs**</u>			
Raw materials	-	-	7,367,538.85
- Feedstock (energy carrier)	100,800,000.00	kg	7,354,338.85
- Consumables	-	-	13,200.00
Utilities	-	-	30,000.96
- Water	0.00	-	0.00
- Energy	300.01	kg	30,000.96
Operating Labour	10.00	person(s)	500,000.00
Operating supervision	0.15	of operating labour	75,000.00
Maintenance and repairs	0.07	of FCIcentral	2,800,000.00
Operating supplies	0.15	of maintenance and repairs	420,000.00
Laboratory charges	0.15	of operating labour	75,000.00
Royalties	0.04	of production cost (OPEXcentral)	814,833.25
<u>**Fixed costs**</u>			
Taxes (property)	0.01	of FCIcentral	400,000.00
Financing (interest paid because of loan / loan=TCI)	0.05	of TCIcentral	2,300,000.00
Insurance	0.01	of FCIcentral	400,000.00
Rent	0.10	of value of rented land and buildings	
Depreciation cost			2,000,000.00
<u>**General expenses**</u>			
Plant overhead costs	0.50	of total expenses of labour and maintenance	1,687,500.00
Administrative costs	0.15	of operating labour	75,000.00
Distribution and marketing	0.02	of production cost (OPEXcentral)	407,416.62
Research and development	0.05	of production cost (OPEXcentral)	1,018,541.56

ANNEX L Cost calculation for catalytic pyrolysis and refinery pathway

Calculation of Total Capital Investment (TCI) for local (catalytic pyrolysis) processing plant – bio-oil

KPI description	**Model parameter**	**Value**	**Unit**
Total capital investment of local processing plant	TCIlocal	71,293,811.81	EUR
Working capital of local processing plant	WClocal	9,299,192.84	EUR
Fixed capital investment of local processing plant	FCIlocal	61,994,618.96	EUR
Calculation of Fixed Capital Investment (FCI) for local processing plant			
Direct costs			
Cost description	**Fraction of delivered equipment, fi**	**Value**	**Unit**
Purchased equipment	1	28,859,564.00	EUR
Purchased equipment installation	0	0.00	EUR
Instrumentation and controls	0	0.00	EUR
Piping	0	0.00	EUR
Electrical systems	0	0.00	EUR
Buildings	0.18	5,166,218.25	EUR
Yard improvements	0.07	2,137,745.48	EUR
Service facilities	0.34	9,798,000.12	EUR
Indirect costs			
Cost description	**Fraction of delivered equipment, fi**	**Value**	**Unit**
Engineering and supervision	0.14	4,097,345.51	EUR
Construction expenses	0.21	6,056,945.53	EUR
Legal expenses	0.02	712,581.83	EUR
Contractor's fee	0.12	3,384,763.68	EUR
Contingency	0.06	1,781,454.57	EUR
Fixed capital investment (FCI) of local processing plant	2.15	61,994,618.96	EUR

Calculation of equipment cost for local processing plant			
Relevant parameters (description)	**Model parameter**	**Value**	**Unit**
Capacity of equipment for local processing plant	Capacity_local	46,716,000	kg/year
Energy capacity of equipment for local processing plant	Energy_capacity_local	47.85	MW
Capacity of reference equipment for local processing plant	Capacity_ref_l	46,716,000	kg/year
Energy capacity of reference equipment for local processing plant	Energy_capacity_ref_l	47.85	MW
Cost reference year for equipment purchase cost	Year_implementation	2012	-
Chemical Engineering Plant Cost Index at year of implementation			-
Description	**Equipment part**	**Cost of delivered equipment (in EUR)**	**Scaling factor**
Cost of delivered equipment part (1) for local processing plant	Air compressor	4,221,508.00	0.74
Cost of delivered equipment part (2) for local processing plant	Regenerator	9,731,240.00	0.74
Cost of delivered equipment part (3) for local processing plant	Reactor	5,830,927.00	0.7
Cost of delivered equipment part (4) for local processing plant	Biomass crusher/grinder, metal sep, silo	1,108,000.00	0.9
Cost of delivered equipment part (5) for local processing plant	Main fractionator	2,405,260.00	0.75
Cost of delivered equipment part (6) for local processing plant	Biomass dryer	816,000.00	0.85
Cost of delivered equipment part (7) for local processing plant	Light gases furnance	950,000.00	0.7
Cost of delivered equipment part (8) for local processing plant	Precipitator	2,440,266.00	0.7
Cost of delivered equipment part (9) for local processing plant	Expander turbine and steam turbine	1,356,363.00	0.7
Cost of delivered equipment part (10) for local processing plant	0	0.00	0
Total cost of delivered equipment for local processing plant	**Elocal**	28,859,564.00	-

Calculation of Operational Expenditure (OPEX) for local processing plant

KPI description	Variable name	Value	Unit
Cost of operating local processing plant	OPEXlocal	31,683,703.96	EUR/year

Relevant parameters (description)	Value	Unit
Annual production capacity of the local processing plant	46,716,000.00	kg/year
Annual energy production capacity of the local processing plant	47.85	MW
Energy density of feedstock (biomass)	0.0044	MWh/kg
Energy density of end product (energy carrier)	0.0082	MWh/kg
Operating time of the local processing plant	8000	hr/yr

Cost description	Factor or annual quantity	Rate or quantity unit	Annual cost (EUR)
<u>**Variable costs**</u>			
Raw materials	-	-	9.859.056,76
- Feedstock (biomass)	186.864.000,00	kg	9.018.056,64
- Consumables	-	-	841.000,12
Utilities	-	-	704.944,44
- Water	14.014.800,00	kg	704.944,44
- Energy	0,00	-	0,00
Operating Labour	32,00	person(s)	1.600.000,00
Operating supervision	0,15	of operating labour	240.000,00
Maintenance and repairs	0,07	of FCIlocal	4.339.623,33
Operating supplies	0,15	of maintenance and repairs	650.943,50
Laboratory charges	0,15	of operating labour	240.000,00
Royalties	0,04	of production cost (OPEXlocal)	1.297.469,38
<u>**Fixed costs**</u>			
Taxes (property)	0.01	of FCIlocal	619,946.19
Financing (interest paid because of loan / loan=TCI)	0.05	of TCIlocal	3,564,690.59
Insurance	0.01	of FCIlocal	619,946.19
Rent	0.10	of value of rented land and buildings	
Depreciation cost			3,099,730.95
<u>**General expenses**</u>			
Plant overhead costs	0.50	of total expenses of labour and maintenance	3,089,811.66
Administrative costs	0.15	of operating labour	240,000.00
Distribution and marketing	0.02	of production cost (OPEXlocal)	648.734,69
Research and development	0.05	of production cost (OPEXlocal)	1.621.836,72

Calculation of Total Capital Investment (TCI) for central (refinery) processing plant – transport fuels

KPI description	Model parameter	Value	Unit
Total capital investment of central processing plant	TCIcentral	179,680,842.96	EUR
Working capital of central processing plant	WCcentral	23,436,631.69	EUR
Fixed capital investment of central processing plant	FCIcentral	156,244,211.27	EUR
Calculation of Fixed Capital Investment (FCI) for central processing plant			
Direct costs			
Cost description	**Fraction of delivered equipment, fi**	**Value**	**Unit**
Purchased equipment	1	36,505,656.84	EUR
Purchased equipment installation	0.39	14,237,206.17	EUR
Instrumentation and controls	0.26	9,491,470.78	EUR
Piping	0.31	11,316,753.62	EUR
Electrical systems	0.1	3,650,565.68	EUR
Buildings	0.29	10,586,640.48	EUR
Yard improvements	0.12	4,380,678.82	EUR
Service facilities	0.55	20,078,111.26	EUR
Indirect costs			
Cost description	**Fraction of delivered equipment, fi**	**Value**	**Unit**
Engineering and supervision	0.32	11,681,810.19	EUR
Construction expenses	0.34	12,411,923.32	EUR
Legal expenses	0.04	1,460,226.27	EUR
Contractor’s fee	0.19	6,936,074.80	EUR
Contingency	0.37	13,507,093.03	EUR
Fixed capital investment (FCI) of central processing plant	4.28	156,244,211.27	EUR
Calculation of equipment cost for central processing plant			
Relevant parameters (description)	**Model parameter**	**Value**	**Unit**
Capacity of equipment for central processing plant	Capacity_c	172,200,000	kg/year
Energy capacity of equipment for central processing plant	Energy_capacity_c	260.32	MW
Capacity of reference equipment for central processing plant	Capacity_ref_c	172,200,000	kg/year
Energy capacity of reference equipment for central processing plant	Energy_capacity_ref_c	260.32	MW
Cost reference year for equipment purchase cost	Ref_year	2012	-
Chemical Engineering Plant Cost Index at year of implementation			-
Description	**Equipment part**	**Cost of delivered equipment (in EUR)**	**Scaling factor**
Cost of delivered equipment part (1) for central processing plant	See Annex E	**36,505,656.84**	0.7
Total cost of delivered equipment for central processing plant	**Ecentral**	**36,505,656.84**	-

Calculation of Operational Expenditure (OPEX) for central (refinery) processing plant

KPI description	Variable name	Value	Unit
Cost of operating central processing plant	OPEXcentral	278,908,154.69	EUR/year

Relevant parameters (description)	Value	Unit
Annual production capacity of the central processing plant (if applicable)	172,200,000.00	kg/year
Annual energy production capacity of the central processing plant	260.33	MW
Energy density of feedstock (energy carrier)	0.0082	MWh/kg
Energy density of end product (if applicable)	0.0119	MWh/kg
Operating time of the central processing plant	7901	hr/yr

Cost description	Factor or annual quantity	Rate or quantity unit	Annual cost (EUR)
<u>**Variable costs**</u>			
Raw materials	-	-	214.975.115,67
- Feedstock (energy carrier)	249.690.000,00	kg	199.515.860,67
- Consumables (Hydrogen)	-	-	15.459.255,00
Utilities	-	-	13.850.046,00
- Water	0,00	-	0,00
- Energy	184.348.710,00	MWh	13.850.046,00
Operating Labour	5,00	person(s)	250.000,00
Operating supervision	0,15	of operating labour	37.500,00
Maintenance and repairs	0,07	of FCIcentral	10.937.094,79
Operating supplies	0,15	of maintenance and repairs	1.640.564,22
Laboratory charges	0,15	of operating labour	37.500,00
Royalties	0,04	of production cost (OPEXcentral)	12.013.427,19
<u>**Fixed costs**</u>			
Taxes (property)	0.01	of FCIcentral	1,562,442.11
Financing (interest paid because of loan / loan=TCI)	0.05	of TCIcentral	8,984,042.15
Insurance	0.01	of FCIcentral	1,562,442.11
Rent	0.10	of value of rented land and buildings	
Depreciation cost			7,812,210.56
<u>**General expenses**</u>			
Plant overhead costs	0.50	of total expenses of labour and maintenance	5.612.297,39
Administrative costs	0.15	of operating labour	37.500,00
Distribution and marketing	0.02	of production cost (OPEXcentral)	6.006.713,60
Research and development	0.05	of production cost (OPEXcentral)	15.016.783,99

ANNEX M Land occupation in comparative studies

One of the conclusion in the underlying reports is that the new bio-related impacts are surrounded with large uncertainty. Assuming a worst case scenario of a total loss of eco system services due to feedstock harvesting, the new, bio-related impacts give a higher contribution to the overall impacts than the conventional impacts in the biobased pathways. The largest bio-related impact comes from the factor agricultural land occupation.

How is the topic dealt with in other studies? Based on the renew study, Jungbluth et al.45 assessed the land occupation for various technologies and pathways. The results are given in Figure I.1. As a general remark, the study assesses other technologies and has a broader scope, i.e. well to wheel. The impacts are weighed using Eco-Indicator points.

The study shows that land occupation can have a large contribution to the overall impacts, especially for cultivated products as miscanthus and round wood. Straw has a lower impacts, as only part of the impacts (10%) are allocated to the straw and the remaining impacts to the wheat. This is in line with the approach and results of the BioBoost project.

The Eco-Indicator methodology differentiates between various types of land occupation, occupation by forest has a 10 times lower weighing factor than occupation by crops. This leads to a lower impact by the use of forest wood versus cultivated products. This differentiation was not available within the ReCiPe methodology and the shadow price approach used in BioBoost. However it was concluded that this valuation needs discussion and that differentiation is needed for various types of land occupation. The assessment of the new bio-related indicators within BioBoost show a maximum potential risk, rather than an impact.

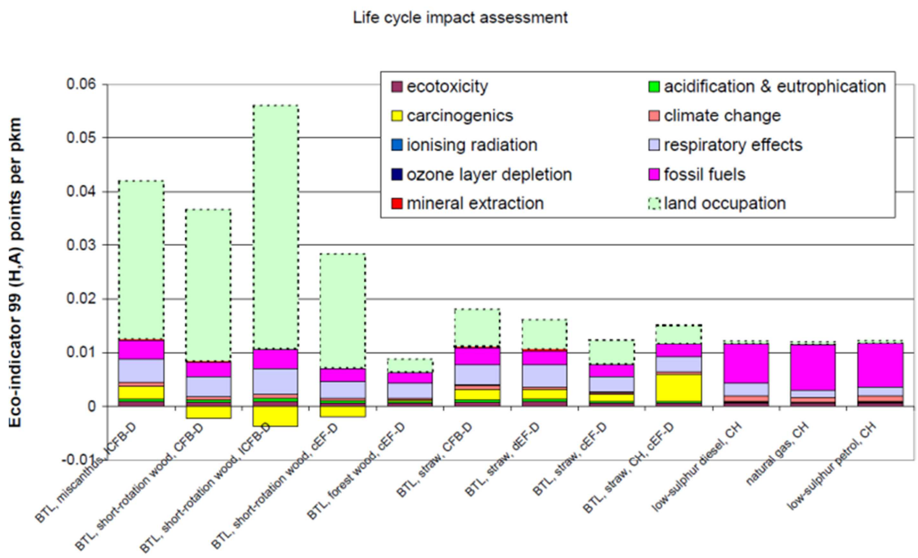


Figure M.1 Eco-indicator score of transport service (points/pkm)[1]

45 Jungbluth, N. et al., Life Cycle Assessment of Biomass-to-Liquid fuels

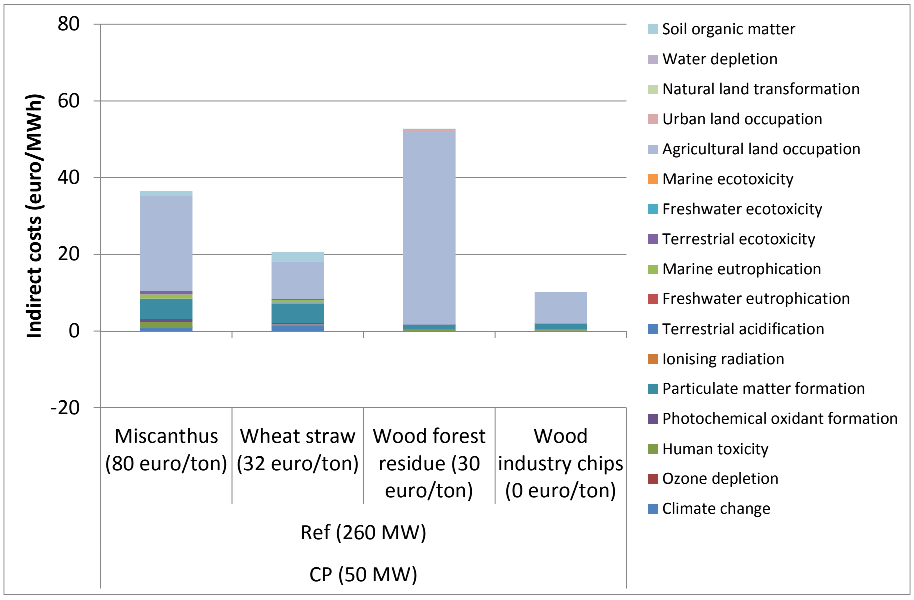


Figure M.2 Breakdown of the indirect costs (in euro/MWh) into the various impact categories of the biobased pathways for the production of a transport fuel from wheat straw, miscanthus and wood via catalytic pyrolysis (CP).