Sustainable and integrated production of liquid biofuels, green chemicals and bioenergy from glycerol in biorefineries: Integrated assessment

Final report

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Executive summary

Due to an increased biodiesel production in recent years, large amounts of glycerol entered the world market and gradually saturated the demand for glycerol as a chemical. Therefore a search of alternative uses for glycerol seems to be worthwhile. For this, the European commission funded the project "Sustainable and integrated production of liquid biofuels, bioenergy and green chemicals from glycerol in biorefineries (GLYFINERY)". It ran from 2088 to 2012 and five research institutions from Denmark, Germany and Poland investigated several biotechnological conversions pathways for glycerol use (/GLYFINERY 2012a/. This project includes an integrated sustainability assessment covering technological, environmental and economic aspects, which is presented in this report.

The investigated use options for glycerol are:

- Direct material use of glycerol
- Generation of energy by combustion of glycerol or production of biogas out of glycerol
- Biotechnological conversion of glycerol into either ethanol, butanol or PDO (1,3-propanediol, a precursor for the production of bioplastics).

In summary, the conventional **direct material use** is the best of the assessed options from an environmental point of view. This scenario covers that glycerol as a final product functionally substitutes simpler chemicals as an additive to a wide range of products like cosmetics. This is currently the most common way to use glycerol, which can be realised with limited technological efforts and financial expenditures. However, the direct material use of glycerol is a limited market and may lose importance if the biodiesel market and thus the production of glycerol will expand further, especially, if no completely new material use options will be identified.

To the extent to which a direct material use cannot be realised anymore because of limited capacities, alternatives such as **biotechnological use options** and the **use for energy production** including biogas can play a bigger role in future. Of the investigated options, these are especially the production of PDO, butanol or biogas via cofermentation, which have different environmental potentials each. It will be essential to realise these individually. In contrast, the production of ethanol and the optional refining of biogas to biomethane are clearly disadvantageous compared to the other options. Under the underlying conditions of this study, the production of butanol stands out due to its high probability to be economically profitable, whereas the production of ethanol will likely lead to losses. The innovatively produced PDO involves the highest economic chances but also high risks.

Taken together, the **PDO process** is estimated to be the most likely **future winning technology** after a saturation of the direct material use options out of those that were assessed in this project from both an environmental and economical perspective. An important rationale for this is that the high energy inputs and lower yields of the innovative bioprocesses are likely to improve significantly with future efforts.

In particular, the **conversion of glycerol to ethanol, butanol or PDO** by means of innovative biotechnological processes is technically demanding and energy consuming, which causes high economic and environmental expenditures. Limited technical risks exist but they are controllable. For these reasons, the biotechnological conversions are mainly environmentally disadvantageous compared to the direct material use of glycerol but comparable to its use for energy generation. From an economic point of view, the higher expenditures for products of higher value can pay off although significant economic risks exist. Generally, the bandwidths of the results are high for these pathways because they are currently only established in a pilot scale. In contrast to the other conversions, the **production of ethanol** is unfavourable from an environmental and economic perspective. The **production of PDO** can lead to the highest possible profits and environmental benefits of the innovative pathways but can also result in significant losses, in part due to uncertain market perspectives, and additional environmental burdens under unfavourable conditions. The **production of butanol**, in which PDO is obtained as a by-product, shows profits under all assessed conditions and additionally offers nearly unlimited market capacities. Environmentally, it performs in tendency slightly worse than the sole production of PDO.

The option to produce heat and / or power from glycerol via **direct combustion** in stationary plants or via **biogas production** can be rated similarly sustainable from an environmental and economic point of view. Depending on the specific design, the assessed processes of energy generation show minor differences: the purification of biogas to biomethane for feeding into the natural gas grid results in environmental disadvantages but can result in economic advantages. Another example is the production of biogas from glycerol without mixing in other substances, which has in tendency less advantages from an environmental and economic perspective. Compared to the direct material use, the energy generation is disadvantageous under environmental and economic perspectives. Only potential synergy effects from a biogas fermentation, in which glycerol is mixed with other substrates, could substantially improve the performance. Nevertheless, the energy generation is not limited in capacity and can be realised with similarly low technological efforts and investments as the direct material use.

The most important **recommendations** for different groups of decision makers, especially from science, industry and politics, are the following ones (more recommendations are listed in the full report):

- From an environmental perspective, further development of the investigated biotechnological conversion processes are recommended, if at all, only for the production of PDO or butanol.
- The further development of the biotechnological conversion processes should focus especially on increasing yields and on a significant reduction of the energy input for product purification. This should also be taken into account for the development of sustainable biotechnological processes in other contexts.
- The further development and field testing of the biogas production from glycerol should focus on synergy effects in the cofermentation of mixed substrates and on the sustainable supplementation of nutrients in case of the separate fermentation of glycerol.
- Other use options for glycerol should be explored besides the ones assessed here. This could be other applications for glycerol without conversion e.g. as a product ingredient, a biotechnological conversion into other chemicals, and also catalytic chemical conversions.

As an **outlook**, other external factors should be considered, which will be important for the future development of the glycerol market and upcoming glycerol use options. Generally, the glycerol market will be influenced on the supply side by the development of the biodiesel production and on the side of the demand by the emergence of new use options. One example is the recent production start of a big chemical plant by Solvay to convert bio-glycerol into a precursor for epoxy resins. Therefore, fluctuations of the glycerol price seem more likely than a constant decline taking the current developments into account. The assessed use options can play an important role if the glycerol supply rises but they represent only a part of all possible alternatives. Furthermore, a politically relevant and comprehensive rating of glycerol use options also has to take other aspects into account like the security of the energy and food supply, social aspects or the progress of knowledge, which is especially important for industrialised countries in Europe. The results, conclusions and recommendations of this study can be of great value for defining the concept and specifications of such assessments.

1 Introduction, goal and scope

According to the EU directive 2009/28/EC of 23 April 2009 /EC 2009/, all member countries shall ensure by 2020 that the share of energy from renewable sources in transport is at least 10 % of the total fuel consumption. For achieving this goal, an increased production of biodiesel from biomass plays an important role. In biodiesel production, glycerol is produced as by-product. Due to an increased biodiesel production in recent years, high amounts of glycerol entered the market. This development led to a restructuring of the glycerol market over the last years with prices for crude glycerol fluctuating considerably.

The objective of the GLYFINERY project is to search for alternative uses for glycerol. Thereby, sustainable usage pathways for glycerol shall be determined and the biodiesel production as a whole shall be optimised. This is achieved by designing biorefinery production schemes for the production of biofuels, bioenergy and green chemicals from glycerol. This project includes the assessment of the technological, economic and environmental sustainability of the glycerol processing schemes and their influence on the sustainability of the biodiesel production (work package 7).

There are two core questions, for which the sustainability assessment will provide answers:

1. What is the most sustainable way to use glycerol resulting from biodiesel production?
2. How do the different usage pathways for glycerol from biodiesel production affect the sustainability of biodiesel production as a whole?

To address the core questions, the following issues will be assessed:

- What are the advantages and disadvantages of innovative glycerol usage pathways in comparison to the currently existing pathways?
- What is the best use of the chemicals derived from glycerol processing?
- How does the production of green energy from glycerol via biogas compare to the direct combustion or the conventional direct material use in the chemical industry?
- What is the influence of different usage pathways for the by-products on the overall results and which usage shall be preferred?
- What is the relative importance of various life cycle steps on the overall results?

This report was prepared as a fulfilment of work task 7.5: *Integrated assessment* as part of work package 7: *Integrated assessment*. It delivers results of an overall sustainability assessment. It compares the glycerol processing pathways based on sustainability indicators from previous assessments in tasks 7.1 – 7.4 and adds new integrating efficiency indicators.

2 Methodology, data and definitions

The sustainability assessment of the GLYFINERY project builds on three basic parts, the technological /GLYFINERY 2012b/, environmental /GLYFINERY 2012c/ and economic /GLYFINERY 2012d/ assessments. The integrated assessment combines these three assessments with a specific scope into a general sustainability assessment. Therefore, the essential parts of the methodologies are summarised below for all parts. Please refer to the original reports for more details.

2.1 Basic methodology, data and definitions

The basis for a sustainability assessment is the definition of the systems that will be assessed and their exact boundaries.

2.1.1 Systems to be studied

In chapter 1, two core objectives have been defined: the comparison of glycerol processing options as well as the assessment of their impacts on the biodiesel production as a whole. To analyse both issues, two different systems are considered: glycerol processing only and the biodiesel production as a whole including glycerol processing.

Glycerol processing

The analysis starts with crude glycerol as it leaves the biodiesel plant (80 % purity). Transports, processing as well as the use of main and by-products are examined. The aim is to deliver a detailed analysis of glycerol processing and usage as well as to identify best possible use options. A schematic overview of the assessed glycerol processing options is given in Fig. 2-1. The studied scenarios are described in chapter 3. The supply chain of glycerol, which is the biodiesel production, is not taken into account in the environmental assessment because it is not necessary for the aims mentioned above. The whole biodiesel life cycle is the scope of the system described in the next paragraph.

Whole biodiesel production

The whole life cycle of biodiesel production is examined, i. e. the production of oil crops, their processing to biodiesel as well as the processing and usage of all by-products including glycerol. Besides different pathways for glycerol usage, other parameters are varied as well, e. g. the raw materials. This analysis aims at depicting the impact of different glycerol usage pathways on the whole biodiesel production. A schematic overview of the whole biodiesel production system is shown in Fig. 2-2.

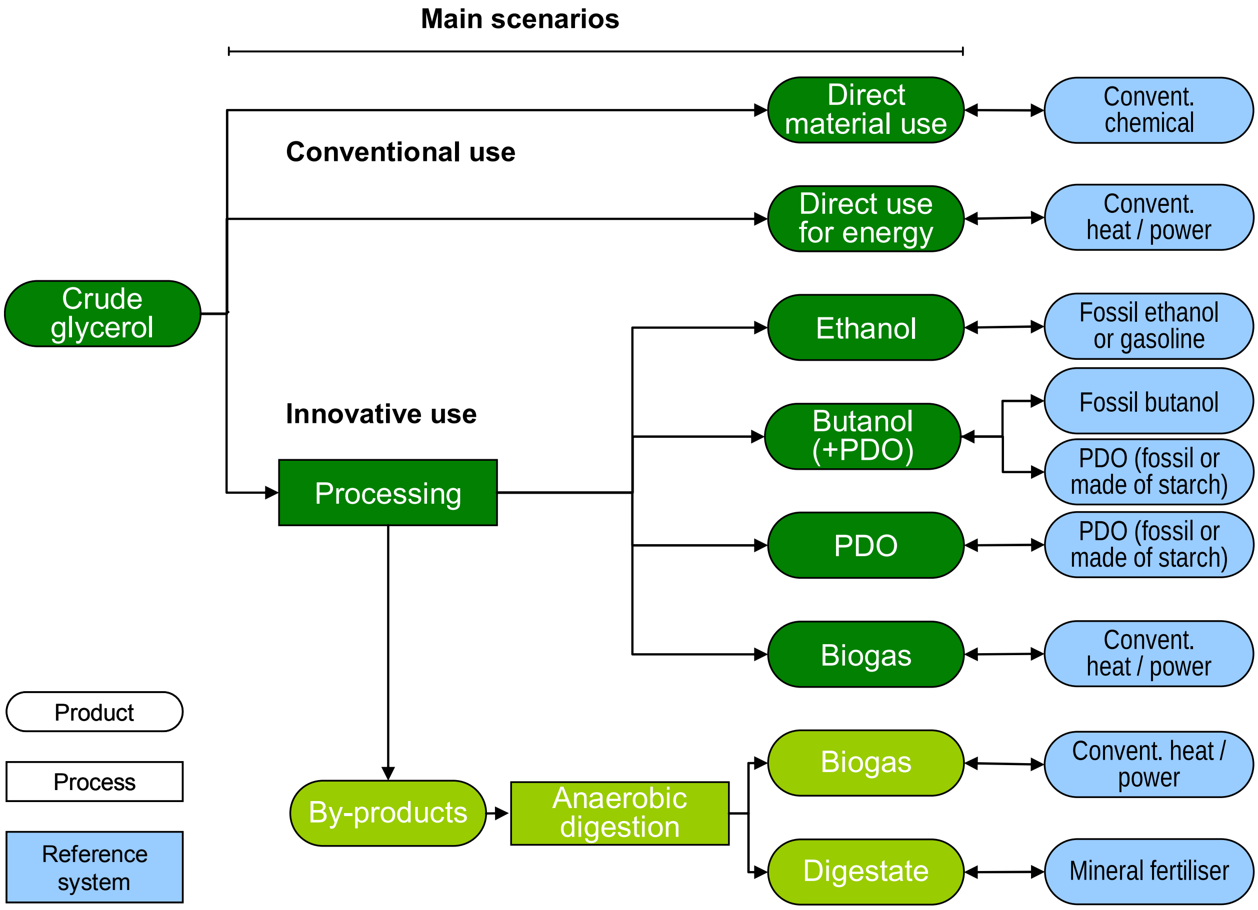

Fig. 2-1 Life cycle of glycerol processing with alternative glycerol use options, for details about the assessed scenarios see chapter 3. PDO: 1,3-propanediol

2.1.2 General settings

For the environmental and economic analysis of the GLYFINERY scenarios, general definitions and settings are necessary. They are used in all analyses and guarantee their consistency. The general definitions and settings have been described within the report for task 7.1 (Technological assessment) and are quoted below.

- **Technical reference (pilot or mature).** Mature technologies are used as basis for the environmental and economic assessment.
- **Time frame.** The analysed technologies are currently in development and not yet existent. First pilot plants might be available in 2015. As the objective of this project is to compare mature technologies (see 'Technical reference'), 2020 is set as reference year.
- **Functional unit.** The questions to be answered result in different functional units. As the main objective of the GLYFINERY project is to optimise glycerol processing, 1 ton of pure glycerol is set as functional unit.
  With regard to the second question – the optimisation of biodiesel production as a whole with an optimal use of glycerol playing an important role – the output of the biodiesel pro-

duction is used as functional unit, i. e. all results are related to 1 ton biodiesel (fatty acid methyl ester, FAME).

- **Geographical coverage.** Europe is the main producer of biodiesel in the world and therewith of glycerol. As glycerol is traded world wide and as critical amounts of glycerol are needed for a successful implementation of innovative technologies, Europe as a whole (and not a specific country within Europe) is set as geographical reference. This implies the use of EU27 average values for prices, yields, power mixes, etc..

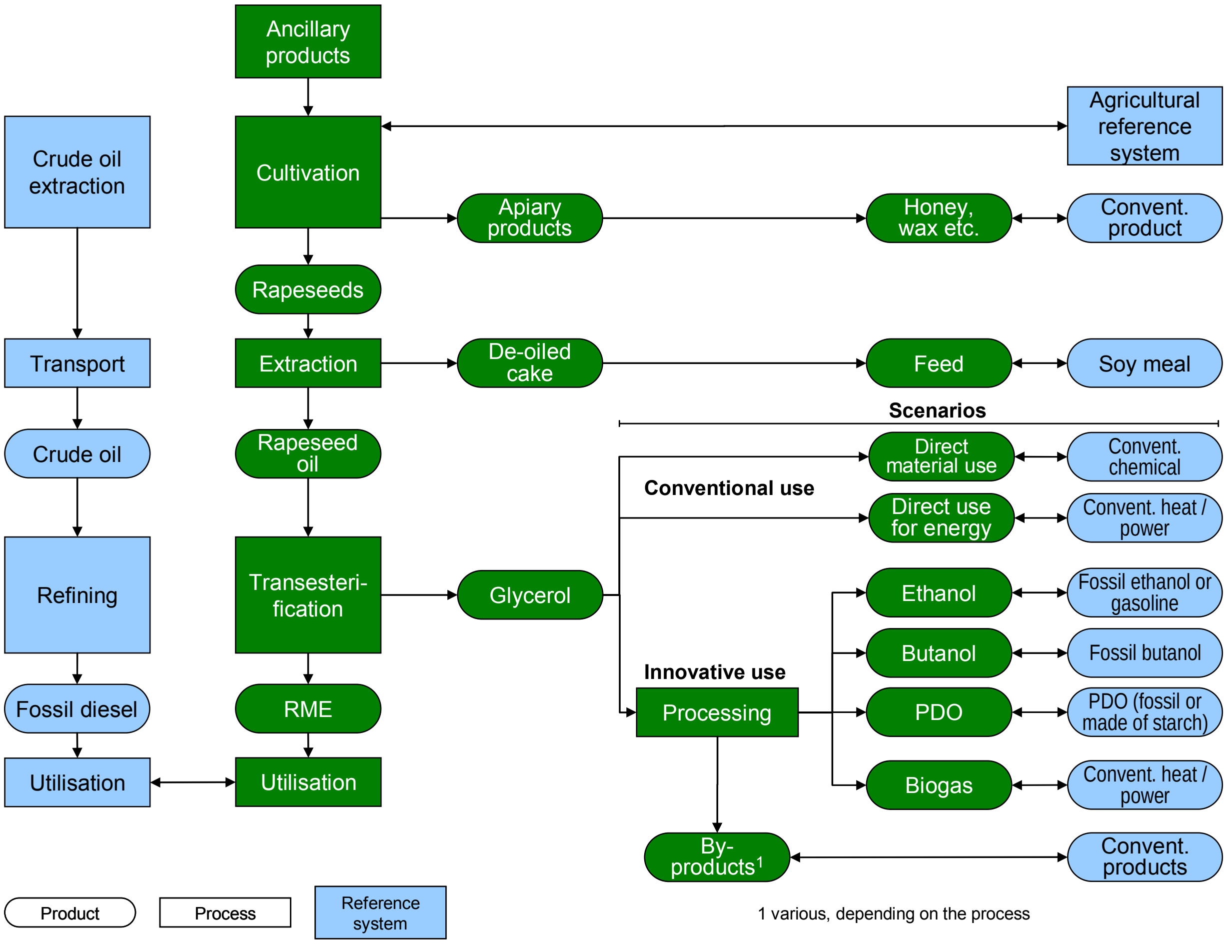

Fig. 2-2 Life cycle comparisons of biodiesel from rapeseed including alternative glycerol use options. RME: rapeseed methyl ester

2.2 Methodology for technological assessment

A processing technology is sustainable if it is technically feasible, shows a similar performance as competing technologies and does not impose unjustifiable risks or disturbances e.g. by unpleasant odours.

The technological assessment summarises the state of the art of the assessed glycerol use pathways as they are implemented today in laboratory or pilot scale. Furthermore, the technological novelty is assessed by comparisons with similar existing technologies. Based on this data, process flow charts are generated and provided as a basis for the economic and environmental assessment. Feasibility, performance, risks and possible disturbances for a future implementation in industrial scale are deduced from the available knowledge at the current stage of development. A special focus of the technological assessment are the biotechnological conversion processes. Therefore, many indicators are tailored for their evaluation although they do not apply to all glycerol use pathways and are thus omitted from the further integrated assessment.

The following indicators are used:

- Type of process

  Describes if the process is run in continuous, batch or fed-batch mode

- Current yield (crude glycerol)

  Relates the product yield to the feedstock mass

- Productivity

  This indicator describes how much product is produced within a specific fermenter volume per hour.

- Highest achievable titre

  This is the maximum product concentration in the fermentation broth.

- Yield on substrate basis

  Relates the maximum amount of product in the fermentation broth to the added amount of feedstock.

- Percentage of theoretical maximum

  The theoretical maximum is defined as the yield that could be reached if 100 % of the carbon of the feedstock would be converted to the product i.e. with no side or by-products formed except biomass. This measure is organism and strain specific.

- % Energy recovered from substrate

  The amount of energy recovered in the product on a purely thermodynamical basis based on the amount of energy present in the initial feedstock compared to what is captured in the final product.

- GLYFINERY Development stage

  This refers to the current stage of development of the processes within the GLYFINERY project.

- World Market development stage

  This refers to the current stage of development of related processes with different feedstocks outside of the GLYFINERY project.

- Production of effluents

  This indicates the liquid waste products.

- Risk associated with chemicals involved

  This indicator lists special risks associated with chemicals involved in the process.

- GMO technology

  This indicator states if genetically modified organisms (GMOs) are used according to the definitions discussed in chapter 4.1.2.

- Odour emissions

  This indicator covers potential or unavoidable emissions of odours outside of the production plant, which could disturb residents in the surrounding.

- Technological challenges/bottlenecks

  This indicator pinpoints further challenges that have to be resolved.

2.3 Methodology for environmental assessment

The environmental advantages and disadvantages of biomass based products cannot be evaluated and listed instantly, but have to be quantified exactly by considering the whole system. For the quantification of environmental implications, a life cycle assessment (LCA) is an adequate instrument.

Life cycle assessments analyse the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of emissions) of a product. They take into account the product's entire life cycle from raw material acquisition through production (including co-products), use, end-of-life treatment, recycling and final disposal ("cradle-to-grave approach"). All inputs from and outputs to the natural system, such as resource extraction and emissions, are taken into account. The whole life cycle of the product is compared to the use (and thus to the life cycle) of a conventional product that is replaced by the use of a biomass based product. In this case different use and production pathways of glycerol – a co-product of biodiesel production – will be taken into account and compared to respective conventional equivalent products.

It is outside the scope of the project to carry out a complete LCA. Nonetheless, this screening LCA closely follows the ISO norms 14040 and 14044 /ISO 2006/ and consists of four phases: (1) the goal and scope definition phase, (2) the inventory analysis phase, (3) the impact assessment phase and (4) the interpretation phase.

In Fig. 2-3, the basic principle of an LCA is shown.

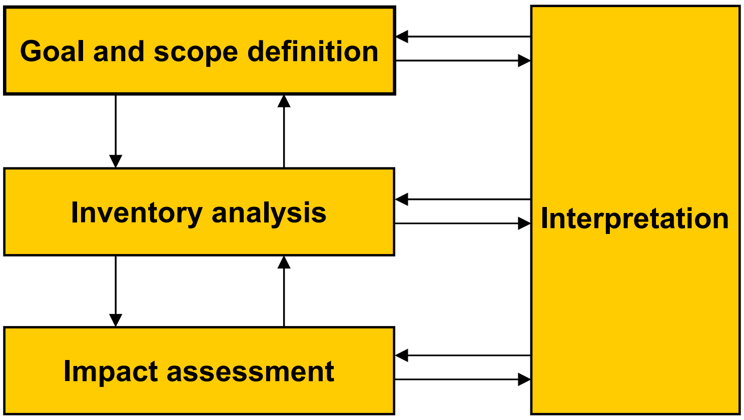

Fig. 2-3 Principle of an LCA according to ISO 14040 & 14044

Following the goal and scope definition an inventory analysis is carried out. Fig. 2-4 takes a chemical, which is produced from biomass as feedstock, as an example for such a life cycle inventory analysis. As it is shown, in this step all inputs and outputs to each process of the entire life cycle, from the extraction of raw materials to co-products and agricultural reference systems are considered. Based on the question, a number of parameters and system boundaries have to be defined such as the handling of co-products. These general settings, which are specific for the environmental assessment, are the following:

- **Co-product assessment.** All co-products are assessed with system expansion. They replace conventional products and the saved expenditures are credited to the process, from which the by-products originated. During glycerol processing, residues are produced by glycerol fermentation (in biogas pathways) and by secondary fermentation of extraction residues (in chemical pathways). They are used as fertilisers and replace mineral fertiliser, hence the expenditures for mineral fertiliser saved by the use of these products are credited to the glycerol processing. Agricultural by-products from FAME production are assessed likewise. Depending on the feedstock, by-products are for example used as animal feed or tensides and receive credits according to the replaced conventional product.
- **Agricultural reference system.** The agricultural reference system is an essential part of LCAs for agricultural products. It defines the alternative land use, i. e. what the cultivation area would be used for if the crop under investigation was not cultivated. The assessment of FAME production considers different land use change scenarios for soy and palm oil production:

  - o A standard scenario without any land use change.
  - o A medium land use change scenario assuming land use change of savannah to cropland (for soy beans) and tropical rain forest on mineral soils to plantation (for oil palm).
  - o A high land-use change scenario assuming deforestation of rainforests on mineral soils (for soy beans) or organic soils (for oil palm).

  The carbon release is calculated by assuming a linear depletion over 100 years.

- **Infrastructure.** Expenditures for infrastructure are not included into the assessment. Former studies showed that expenditures for infrastructure (buildings, machineries etc.) are not relevant for the results.

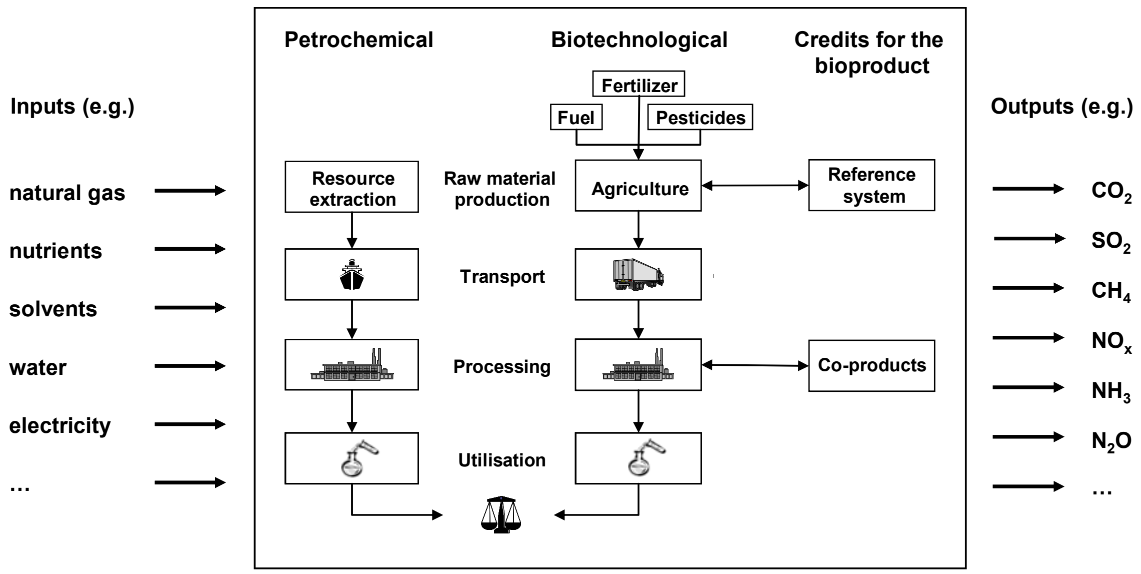

Fig. 2-4 Life cycle comparison between a chemical produced from biomass as a feedstock and a conventional chemical produced from fossil resources (simplified flow chart)

2.3.1 Environmental impact categories and their interpretation

In this LCA, the environmental impacts energy consumption, greenhouse effect, acidification, eutrophication, photosmog and ozone depletion are studied. They are described in detail in Table 2-1. Their derivation from the respective environmental parameters is shown in

Table 2-2.

These impact categories are commonly considered in life cycle assessments and described in the relevant literature.

To provide a realistic picture, the impact category “energy consumption” should be divided into renewable and non-renewable resources. Here, the results for the consumption of non-renewable energy is shown.

Table 2-1 Environmental impact categories and their description

Impact category	Description
Non-renewable energy demand	Depletion of non-renewable energy resources, i.e. fossil fuels such as mineral oil, natural gas and different types of coal as well as uranium ore. The procedures and general data for the calculation are documented in detail in /Borken et al. 1999/. This category is referred to in short as energy demand.
Climate change	Global warming as a consequence of the anthropogenic release of greenhouse gases. Besides carbon dioxide (CO_2) originating from the combustion of fossil energy carriers, a number of other greenhouse gases contribute to the climate change – among them methane (CH_4) and nitrous oxide (N_2O).
Acidification	Shift of the acid/base equilibrium in soils and water bodies by acid forming gases (keyword 'acid rain'). Air borne emissions such as sulphur dioxide, nitrogen oxides, ammonia, and hydrogen chloride contribute to the acidification.
Eutrophication	Input of nutrients into soils via air pollutants (terrestrial eutrophication). Substances such as nitrogen oxides and ammonia contribute to the eutrophication.
Photosmog (summer smog)	Formation of specific reactive substances such as ozone in the lower atmosphere due to gases such as hydrocarbons and nitrogen oxides in presence of solar radiation (keyword 'ozone alert').
Ozone depletion	Loss of the protective ozone layer in the stratosphere by certain gases like CFCs (chlorofluorocarbons) or nitrous oxide (keyword 'ozone hole').

Concerning greenhouse gas balances, carbon in biomass will be distinguished from fossil carbon. For instance, in the transesterification process for biodiesel production (fossil) methanol is used and thus fossil carbon becomes part of the biogenic biodiesel. Therefore the respective fractions of the fossil and biogenic carbon have to be assessed separately and taken into account in the calculations.

For photosmog, the suggested models aggregating the potentially ozone creating substances are still debated on among experts. Due to the complex chemical reactions involved in the troposphere ozone formation, modelling the interrelations between emissions of unsaturated hydrocarbons and nitrogen oxides is extremely difficult. As yet, the photochemical ozone creation potential (POCP), expressed in ethene equivalents, is applied in impact assessments. Within this study, POCP is used as an indicator for photosmog. The high uncertainty of this indicator has to be taken into account in the interpretation of the results.

Within this study, certain impact categories are not considered even tough they might be relevant because they are very difficult or impossible to assess. One example is the impact category "human- and ecotoxicity". It comprises different substances such as nitrogen oxides, diesel particles, dust, dioxines or other toxic chemicals. However, up to now there are no commonly accepted equivalent factors available to convert the different substances into one category indicator (see /JRC 2011/) and exposures to those substances are impossible to predict for processes that are not yet implemented.

Table 2-2 Indicators, LCI parameters and characterization factors for the respective impact categories (/CML 2004/, /IPCC 2007/, /Klöpffer & Renner 1995/, /Leeuw 2002/, /Ravishankara et al. 2009/, /IFEU 2011/ based on /IPCC 2007/)

Impact category	Category indicator	Life cycle inventory parameter	Formula	Character. factor
Energy demand	Cumulative energy demand from non-renewable sources	Crude oil Natural gas Hard coal Lignite Uranium ore	—	—
Climate change	CO_2 equivalent (carbon dioxide equivalent)	Carbon dioxide fossil Nitrous oxide Methane biogene* Methane fossil**	CO_2 N_2O CH_4 CH_4	1 298 25 27.75
Acidification	SO_2 equivalents (sulphur dioxide equivalent)	Sulphur dioxide Nitrogen oxides Ammonia Hydrochloric acid	SO_2 NO_X NH_3 HCl	1 0.7 1.88 0.88
Eutrophication	PO_4 equivalents (phosphate equivalent)	Nitrogen oxides Ammonia	NO_X NH_3	0.13 0.346
Photosmog (POCP)	C_2H_4 equivalents (ethene equivalents)	Non-methane hydrocarbons Methane	NMHC CH_4	0.5 0.007
Ozone depletion	CFC-11 equivalents	Nitrous oxide (Dinitrogen oxide)	N_2O	0.017

*without CO_2 effect; **with CO_2 effect after CH_4 oxidation in the atmosphere

Other possible parameters, which are also difficult to assess, are land occupation and biodiversity. According to an overview analysis, these categories are less affected by the processing of the by-product glycerol and were therefore excluded from analysis. Nevertheless, they are likely highly affected by biodiesel production as a whole and should be included in studies focussed on the biodiesel process chain.

2.3.2 Data origin and data quality

Since the different GLYFINERY systems are multi input / multi output systems, they require a multitude of data for calculating the different scenarios:

- All data for the biodiesel systems were deduced by IFEU /IFEU 2011/.
- Pilot scale data on the production process of chemicals, biofuel and bioenergy from glycerol (core GLYFINERY systems) were provided by the partners and extrapolated by IFEU in collaborations with the partners to a mature technology state expected for 2020. Data on projects that did not proceed beyond lab scale before the end of the data collection period were estimated by IFEU based on internal database or literature research (applies to separation processes of butanol and partially to that of PDO as well as to glycerol monofermentation pathways).
- Data on equivalent products of the outputs of the GLYFINERY system and their production chains were deduced by IFEU (/IFEU 2011/, /Ecoinvent 2010/, /GEMIS 2010/).
- Inhabitant equivalents were calculated based on the latest available set of statistical data from 2005 because prognoses for 2020 are highly uncertain if available at all (/Eurostat 2007/, /CML 2009/ and /Eurostat 2010/). See also Table 7-1.

2.4 Methodology for economic assessment

The following is a summary of the methods of the economic assessment. For a detailed description of the methodology and the techno-economic model please refer to economic assessment report /GLYFINERY 2012c/.

2.4.1 Assessment of innovative products

The economic assessment summarises work from 20 individual techno-economic models describing the different innovative and conventional usages of glycerol. The innovative pathways are compared with respect to key financial figures like earnings before interest and taxes (EBIT), internal rate of return (IRR), and simple payback period. The EBIT is determined from the revenue, direct cost, feed cost, indirect cost, and depreciation of equipment and buildings (CAPEX divided by life time of plant). The expression is:

$$EBIT = Revenue - feed\ cost - direct\ cost - indirect - depreciation$$

The revenue, feed cost, direct cost, indirect cost, and depreciation have been determined in the techno-economic models for all pathways and scenarios. The sum of feed cost, direct cost, indirect cost, and depreciation will in the following be referred to as production costs. The direct cost includes cost of additives, power etc. The indirect cost includes cost of staff, repairs maintenance, operating supplies, insurance etc. The feed cost includes all primary feeds and depreciation includes both the depreciation of equipment and the depreciation of buildings.

2.4.2 Comparing innovative products with reference products

To compare the innovative biochemical and biogas pathways with the reference products a, parameter called cost difference (dCost) is introduced. This parameter is defined as:

$$\text{dCost}\left[\frac{\text{Euro}}{\text{kWh or kg of product}}\right] = \text{EBIT}_{\text{Innovative product}} - \text{EBIT}_{\text{Reference product}}$$

To ensure compatibility between the economic and environmental assessment in the integrated assessment, the dCost is determined in relation to amount of glycerol.

The dCost in the reported unit $\left(\frac{\text{Euro}}{\text{t glycerol}}\right)$ is determined from the yield (Y) as:

$$\text{dCost}\left[\frac{\text{Euro}}{\text{t glycerol}}\right] = \text{dCost}\left[\frac{\text{Euro}}{\text{kWh or kg of product}}\right] * \text{Y}\left[\frac{\text{kWh or kg of product}}{\text{t glycerol}}\right]$$

The EBIT is defined as:

$$EBIT = Revenue - Production\ cost$$

Since, the revenue per kWh and kg of product is equal to the selling price, the above expression becomes

$$EBIT = Selling\ Price - Production\ Cost$$

This is used directly in the biogas scenario. In the biochemical pathways, the products are the same but the production route differs, hereby the selling price of the “reference product”and the products by the innovative pathways is assumed to be the same the expression can be reduced to:

$$dCost = Production\ cost_{reference\ product} - Production\ Cost_{innovative\ product}$$

This simplified expression is used in the comparison of products from the chemical pathways with the reference products.

The production cost of reference products for the chemical pathways is presented in Table 2-3.

Table 2-3 Production cost of chemical reference products

Reference Product	Cost of production [Euro/kg]	Reference
Ethanol from fossil sources	0.15	/Beta Analytic 2012/
Bio-Ethanol From Starch	0.71	/ClimateTechWiki 2012/
Butanol From Propylene	1	/SRI Consulting 1999/
PDO from Ethylene	1.3	Estimated from selling price of Propanediol
PDO from Glucose	1.77	/Shen et al. 2009/

The production cost of reference products for the biogas pathways is presented in Table 2-4.

Table 2-4 Production cost of biogas reference products

Reference Product	Cost of production [Euro/kWh]	Reference
Conventional electricity production (gas fired)	0.016	/PB Power 2004/
Conventional electricity production by CHP (gas fired)	0.021	
Gasoline	0.05	/California Energy Commission 2012/
Natural gas	0.24 (Euro/Nm3)	/Nelder 2009/

The cost production will be the basis of the comparison of product produced by the innovative pathway with the reference products.

2.4.3 Economics of whole biodiesel process

The overall biodiesel process economy is based on published data from the year 2007 in /Demirbas 2007/. In this work Demirbas determines the production cost of biodiesel from rape seed is 0.44 Euro/l and a biodiesel selling price of 0.15 – 0.2 Euro/l. Hereof, EBIT for rape seed produced biodiesel is between -0.29 and -0.24 Euro/l. In order to fit the three cases in this assessment, the lowest value is used as the worst case, the average is used as the typical, and the high value is used as the best case. Since EBIT from a typical biodiesel is negative it can be concluded, that biodiesel production is currently not feasible. This is confirmed in 2010 by the annual report of Neste oil (/Neste Oil 2011/), which states an operating profit of - 65 Mn Euro for their biodiesel production. To determine the dependency on the type of feed, prices for palm oil, rape seed, and soya has been collected and used in typical case /Demirbas 2007/. These are listed with the estimated values used in worst and best case in the table below.

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Table 2-5 Prices of feedstock for biodiesel

	Unit	Worst	Typical	Best
Palm oil	Euro/t	625	500	375
Rape seed	Euro/t	1000	800	600
Soya	Euro/t	750	600	400

Since the EBIT is known for a rape seed plant and the cost of feed is typically is 83% /Department of Agriculture and Food 2006/ of the total production cost based on this the EBIT for feedstock, *i* can be calculated from the prices in Table 2-5.

2.4.4 Data origin and selection philosophy

All mass balance related and process specific data has been obtained from the relevant partner. It was chosen to use the partners expert judgment for the matured technology in 2020.

- Ethanol fermentation: Technical University of Denmark (DTU)
- Butanol + PDO fermentation: Biogasol
- PDO fermentation: A&A Biotechnology
- Biogas: DTU
- Product Recovery processes: Prochimia

The size of plant has been defined in the deliverable 7.1 Technological assessment.

The parameters defining the feasibility of a process are the direct costs, price of feedstock, and revenue. These are determined based on the overall mass balance obtained from the relevant partner and multiplied with the prices. Assessment of prices is, therefore, crucial for the techno-economic model. The prices used in the techno-economic model, has been assessed by literature study and quotations from vendors. Germany was used as base cost reference for all costs and prices.

Market studies was performed for the most promising product pathways for key prices butanol (presented in the market perspective section), PDO (presented in the perspective section), ethanol (will not be presented in this work), and green electricity selling price including cost breakdown (will not be presented). Ethanol is omitted from the work since the economic assessment shows that this pathway unfeasible in all scenarios and ethanol has already been investigated extensively in the literature. The Biogas and green electricity products are omitted because the expected production from the glycerol plants is insignificant compared to the global production. Since all costs and prices fluctuate in time and the time reference of the assessment is 2020, it has been decided also to use the typical, best and worst case introduced in the balances for prices. Costs have been found for all components in the overall mass balances but only the key prices for feedstocks and products is presented in this work (see Table 2-6).

Table 2-6 Key market prices used in the techno-economic model

Chemical	Unit	Worst	Typical	Best
Glycerol	Euro/t	220	170	100
Corn Silage	Euro/t	60	45	30
PDO (Low market size scenario)	Euro/kg	2.0	2.2	2.4
PDO (High market size scenario)	Euro/kg	1	1.4	1.85
Butanol	Euro/kg	1.6	1.9	2.1
Ethanol	Euro/kg	1.0	1.2	1.3
Biomethane	Euro/kWh	0.08	0.1	0.12
Green Electricity	Euro/kWh	0.08	0.10	0.12
Selling price of conv. electricity	Euro/kWh		0.06	

Another important process cost constituent is the cost of plant (CAPEX). It was assumed that the costs of a plant scale related to the size with a scaling exponent of 0.7 as obtained from literature (/Timmerhaus et al. 2004/). The CAPEX for the plants in the chemical pathways was determined based on the cost of the Dupont Tate&Lyle starch PDO plant in Loudon, Tennessee. The cost of this has been reported to 75,000,000 Euro and has the capacity of 45,000 ton product/yr (/Timmerhaus et al. 2004/). In the butanol + PDO chemical pathway, the size was determined as the butanol produced plus the PDO produced in t/yr.

The CAPEX for the biogas pathways is based on a cost of 4,000,000 Euro of a biogas plant with a capacity of 1 $MW_{electricity}$ produced. The scaling exponent was assumed to be 0.6 for biogas plants, whereas, it was 0.7 when estimating the cost of plant in a biochemical pathway. The reason for this is that the main cost constituent in the biogas plants is large concrete tanks which have low scaling exponents compared to the steel components in a typical biochemical plant. Therefore, the overall scaling exponent for the entire biogas plants will also become lower than for a typical chemical plant. However, the co-fermentation corn silage biogas plants have been defined to be 700,000,000 Nm^3/yr and 100,000,000 Nm^3/yr in the best and typical case, respectively. The largest biogas plant in the world is in Konnern, Germany this plant has an annual capacity 15,000,000 Nm^3/yr. Based on this it has been decided to use a scaling exponent of 1 in the co fermentation scenarios. This is equivalent to building adjacent plants opposed to building the plant larger. Since there is some inherent uncertainty using this top-down method, the typical, worst and best case scenarios were also adapted to CAPEX. For the resulting CAPEX please refer to the result section.

The last cost constituent in the process economics is the indirect cost, which is mainly the cost of staff and repairs and maintenance. These costs are expert judgment based on experience.

2.4.5 Limitations of the model

The Techno Economic (TE) model and subsequent results is based on recognised fundamental financial calculations. The construction of the TE model and the chosen financial indicator follows the recommendations by National renewable energy lab in /Short et al. 1995/.

The main limitations in the TE model are related to the input and estimation of those. Especially, cost estimation, complete mass balance, and CAPEX are linked with high uncertainty. When extrapolating the prices to 2020 the uncertainty increases.

All prices are projected using a 2.5% rate of inflation, furthermore, several factors besides inflation affects the prices and costs. These factors are usually not identifiable, and correction can unfortunately not be done. The price of crude glycerol in EU has increased from 110 Euro/t to 210 Euro/t in the period from October 2009 to September 2010 (/Taylor et al. 2010/). Fluctuation in price, greater than 100 Euro/t was observed in USA from June to July 2010 (/Taylor et al. 2010/). Other prices and costs are used in the TE model these are also expected to fluctuate. Therefore was extrapolation of single prices not used, instead best, typical, and worst case scenarios was used for the price of glycerol and other key components (as well as in the mass balance). In recognition of the uncertainties and limitations outlined above it was decided to do a comprehensive sensitivity analysis on key-cost drivers, to investigate the impact of each cost driver on the overall process economy.

2.5 Methodology for integrated assessment

A mail goal of this sustainability assessment is to find the most sustainable of the assessed use options for glycerol from biodiesel production. Regarding the quantitative environmental and economic indicators, this comparison of processes has two aspects:

1. Which process can achieve the highest economic gains and causes the lowest environmental burdens?
2. Which the most economically efficient way of reducing environmental burdens?

The methodology of assessing these two aspects is addressed in the following paragraphs.

2.5.1 Benchmarking

The comparison of the glycerol use options has to take two very important aspect into account: Glycerol is a by-product, which is available only in certain amounts defined by the biodiesel production. At the same time, all glycerol from this biodiesel production has to be dealt with in some way because it cannot be deposited for example in land fills. Consequently, the question behind the sustainability assessment is not „Can product x be produced more sustainably from glycerol or from another feedstock?“ but rather as stated in the definition of goals „Which is the most sustainable way of using the produced glycerol?”.

In an analogy to hazardous waste, it might be most sustainable to burn it thereby generate energy although the energy could be generated much cheaper and with less environmental burdens otherwise. But an alternative option to detoxify and recycle the waste might be even more costly. Although glycerol is a valuable by-product, similar questions arise simply because the amount of glycerol can not be controlled. Therefore, a glycerol use pathway can never be evaluated by itself but has to be compared to all other available pathways.

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

For all quantitative indicators, the benchmarking process involves calculating the differences between the respective scenario and the benchmark. These comparisons should serve as a decision support to answer the question whether a pathway performs better than the benchmark regarding a certain indicator. Therefore, these indicators are categorised into positive (+), neutral (0), or negative (-). A minimum difference of 10 % was chosen as a cut off value for the category neutral. The certainty of this rating is evaluated by additionally taking the bandwidth of the data into account. If the comparisons based on the best case and worst case subscenarios come to a different conclusion the overall comparison is rated neutral.

For all qualitative indicators, a scenario is rated positive (+), neutral (0), or negative (-) if it performs better, equal, or worse than the benchmark, respectively.

2.5.2 Efficiency analysis

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

In analogy to CO_2 avoidance costs, similar indicators can be defined for other environmental impact categories like for example SO_2 avoidance costs or non-renewable energy savings costs. The same methodology applies for those indicators as discussed in the following for the example of CO_2 avoidance costs.

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

- the determination of a baseline, which is in this case the choice of the benchmark scenario as discussed in the previous chapter (2.5.1).
- the inclusion of different cost items (e.g. full costs vs. additional costs)
- the inclusion of temporal dynamics of systems under consideration (e.g. developments of investment costs of systems, of prices for energy carriers, etc.)
- the different perspectives – especially microeconomic and macroeconomic approaches

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

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

$$CO_2\ avoidance\ costs = \frac{EBIT - EBIT\ (benchmark)}{GHG\ emissions - GHG\ emissions\ (benchmark)}$$

CO_2 avoidance costs are expressed in Euro per ton of CO_2 equivalents, EBIT refers to earnings before interest and taxes as defined in chapter 2.4.1 and greenhouse gas emissions (GHG emissions) expressed in CO_2 equivalents are defined in chapter 2.3.1.

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

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

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

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

Fig. 2-5 shows that out of nine possible result options only two allow an interpretation of the avoidance costs. If negative avoidance costs occur it has to be reconsidered if this results from the lower total costs or from the possibly higher emissions. Differences approaching zero make a calculation of avoidance costs impossible. If two differences are compared to each other it can lead to over proportional influences of uncertainties. This is especially the case if either the emissions or the EBIT of the compared pathways are very similar. If for example the CO_2 emissions of the two pathways differ by 10 % then a 5 % error of estimating these emissions can lead to a deviation in CO_2 avoidance costs of 100 %. Furthermore, small emission savings mathematically lead to very high and at the same time very uncertain avoidance costs. Therefore, avoidance costs are only then a reliable indicator if the uncertainties of emissions and the EBIT are small compared to the respective differences between the pathways.

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

Fig. 2-5 Different result options for the calculation of CO_2 avoidance costs (modified from /Pehnt et al. 2010/).

The second limitation is that avoidance costs are very prone to changes in the course of time because they can generally be very sensitive to changes as discussed above and they depend on the technological developments as well as market changes for two different systems. Therefore, it is especially important only to compare avoidance costs if they are determined for the same time frame and under the same conditions. This makes it difficult to find comparable avoidance costs outside of this study although there is plenty of data on avoidance costs in literature.

Taken together, avoidance costs for environmental burdens such as greenhouse gas emissions can help to decide how mitigations of environmental burdens can be reached for the lowest price or even with profits. A possible outcome of the decision process could also be that none of the environmentally beneficial options under investigation is realised because they cause high costs per ton of emission savings compared to emission reductions elsewhere outside of the scope of this study. Therefore, it has to be assured that the avoidance costs have a sufficient certainty and are not misleading in comparison to avoidance costs published elsewhere.

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

2.5.3 Overall comparison

The integrated sustainability assessment of this project is based on five qualitative technological indicators, six quantitative environmental indicators as well as one quantitative and two qualitative economic indicators (see chapter 4.4.1 for an overview). These are a subset of all possible indicators, which were assessed and found to be relevant for decisions in the previous steps of the sustainability assessment. Of course, it is very unlikely that all indicators support the same decision for one of the glycerol use options. The challenge of such a multi-indicator assessment is to come to a conclusions while taking all indicators into account.

One strategy would be to first normalise and then weight these indicators to result in one aggregated score. As stated for life cycle assessments in international norms and guidelines /ISO 2006, JRC 2011/, all normalisation steps require the choice of a reference like the annual environmental burdens caused by an average citizen in a certain region like the EU (see also chapter 4.2.3). These normalisation factors are available for the chosen environmental impact categories but not for the other technological and economic indicators. There is especially no commonly recognised method to normalise qualitative indicators. A subsequent weighting steps has to be based on subjective norms and preferences. As this project affects multiple groups of stakeholders with presumably different preferences, it is in principle not possible to find such a common basis for weighting all indicators. Therefore, an aggregation of all indicators into one common score is not possible for this assessment. Instead, all indicators have to be compared and the pros and cons of each glycerol use option have to be weighed and discussed. This will result in recommendations specific for various groups of stakeholders. An outlook will place the discussed options in a broader context beyond the defined scope of this study to raise an awareness for possible external influences of for example political developments or competitors.

The following questions, which were defined as goals of this sustainability assessment (see chapter 1), serve as a guideline for the comparison glycerol use options and weighing their advantages and disadvantages:

- Core question 1: What is the most sustainable way to use glycerol resulting from biodiesel production?
  - Detailed question 1.1: What are the advantages and disadvantages of innovative glycerol usage pathways in comparison to the currently existing pathways?
  - Detailed question 1.2: What is the best use of the chemicals derived from glycerol processing?
  - Detailed question 1.3: How does the production of green energy from glycerol via biogas compare to the direct combustion or the conventional direct material use in the chemical industry?
  - Detailed question 1.4: What is the influence of different usage pathways for the by-products on the overall results and which usage shall be preferred?
  - Detailed question 1.5: What is the relative importance of various life cycle steps on the overall results?
- Core question 2: How do the different usage pathways for glycerol from biodiesel production affect the sustainability of biodiesel production as a whole?

In the course of the study, it has been found that the detailed questions 1.2 and 1.3 do not yield conclusive answers if they are discussed separately on a general level outside of the context of other aspects. Therefore, these questions are not listed and answered separately in the discussion in chapter 5.1.

3 Glycerol use scenarios under investigation

The GLYFINERY project investigates several innovative glycerol use options to determine the potential for adding value to the glycerol by-product (see also Fig. 2-1 and Fig. 2-2). The products under investigation are:

- Ethanol
- Butanol
- 1,3-Propanediol (PDO)
- Biogas / biomethane

These four innovative pathways will be compared to conventional glycerol use systems:

- Direct combustion
- Direct material use in the chemical, pharmaceutical or cosmetics industry

For each of these pathways, different scenarios can be defined. Table 3-1 lists the main GLYFINERY scenarios including the use of the main product, the plant design (centralised / decentralised) as well as the respective reference products. The scenarios are described in the following chapter. Further details can be found in the technological assessment (work task 7.1) /GLYFINERY 2012b/.

3.1 Conventional glycerol use pathways

3.1.1 Direct material use

This scenario describes the direct material use of glycerol as a component of chemicals and cosmetic products, for example. For these purposes, crude glycerol has to be refined to technical grade (98 % purity) or pharmaceutical grade (> 99,7 % purity). In general, most synthesised glycerol from petrochemical sources is already replaced by glycerol from biodiesel production (chemically identical replacement). Therefore, this scenario is only based on the replacement of lower value chemicals, which we consider a market that can realistically take up more glycerol from biodiesel processing. According to this scenario, glycerol is used instead of diols from petrochemical sources (functional replacement). Three sub-scenarios (typical, best and worst case) cover a bandwidth of functional equivalents with different expenditures for petrochemical synthesis and thus varying credits for bio-glycerol. However, this market may be limited, too, depending on the future increase of biodiesel processing. This may lead either to a saturation or to the replacement of chemicals with even lower expenses in synthesis and therefore lower credits.

Table 3-1 Summary of main GLYFINERY scenarios

Main product	Location	Use	Reference product
Ethanol	Centralised[1]	Chemical	Fossil ethanol via ethylene (crude oil)
		Transport fuel	Gasoline
Butanol	Centralised[1]	Chemical	Fossil butanol via propylene (crude oil)
PDO	Centralised[1]	Chemical	Fossil PDO via ethylene oxide (crude oil)
			PDO from glucose (corn starch)
Biogas from mono-fermentation	Local (at biodiesel plant)	Process energy for bio-diesel production	Conventional heat / electricity (average energy mix[2])
		Export of heat / electricity	*Conventional electricity*
			Conventional heat / electricity (co-generation)
Biogas from co-fermentation	Decentralised (in surrounding biogas plants)	Export of heat / electricity	Conventional heat / electricity (co-generation)
			Conventional electricity
Biomethane from mono-fermentation	Local (at biodiesel plant)	Biomethane as fuel	Natural gas
			Gasoline
		Biomethane for heat / electricity production	*Conventional electricity*
			Conventional heat / electricity (co-generation)
Biomethane from co-fermentation	Decentralised (distribution to surrounding biogas plants with bio-methane refining)	Biomethane as fuel	Natural gas
			Gasoline
		Biomethane for heat / electricity production	*Conventional electricity*
			Conventional heat / electricity (co-generation)

Italic type indicates sub-scenarios for biogas / biomethane pathways that are included as sensitivity analyses.

[1]: Glycerol from several biodiesel plants is collected and processed in a central biorefinery.

[2]: Energy provided for existing industrial plants replaces the average energy mix. In all other biogas and biomethane scenarios, additionally produced and exported energy reduces the need for building conventional power plants and / or heating plants and thus a marginal energy mix is replaced.

3.1.2 Direct combustion

In the conventional scenario direct combustion, crude glycerol is burned and used for power and heat generation in a steam turbine. This option is not limited in capacity and therefore represents the conventional alternative if the use as a material is not possible.

The following sub-scenarios for the produced power and heat are included:

a. Provision of energy to biodiesel plant: replacement of average electricity + average heat mix
b. Heat is not used, electric power is fed into the grid: replacement of the marginal electricity mix
c. Electrical power is fed into the grid (replacing marginal electricity mix); heat is externally used (replacing marginal heat mix)
d. No electric power is generated, heat is externally used (replacing marginal heat mix)

As the energy demand of the biodiesel plant is higher than the energy generated from thermal use for glycerol, internal use of energy is defined as standard scenario while the other three scenarios are included as sensitivity studies.

3.2 Innovative chemical pathways

These pathways represent innovative biotechnological conversions of glycerol into the chemicals ethanol, butanol and PDO.

3.2.1 Ethanol

Ethanol is currently produced in two different pathways: synthetic ethanol from ethylene and ethanol from the fermentation of renewable resources (cereals, sugar crops, lignocellulose). Most of the worlds ethanol production is used as fuel (72 %), 16 % is used in the chemical industries and 12 % of the whole ethanol production is used for beverages (ethanol from fermentation only). Ethanol from glycerol processing will replace synthetic ethanol if it is used as a chemical. Replacement of other bioethanol was not included. Alternatively, ethanol from glycerol can be used as bio-based transportation fuel replacing gasoline. The demand for bioethanol as fuel is still rising and politically supported. Hence, it is not likely that the amounts of ethanol that can be produced from glycerol will replace other bioethanol.

Within the GLYFINERY project, the following sub-scenarios for the ethanol from glycerol fermentation are analysed:

- Usage in the chemical industry as a substitute for ethanol from fossil sources (crude oil ➔ naphtha ➔ ethylene ➔ ethanol)
- Usage as fuel as a substitute for fossil gasoline

Various by-products are generated during ethanol production from glycerol. Carbon dioxide as main gaseous product is emitted to the atmosphere while organic compounds and biomass remain in the fermentation broth after the extraction of ethanol. The fermentation broth is used for biogas production without by-product extraction (see chapter 3.2.4).

Ethanol from glycerol fermentation can only be produced in large centralised plants. The overall average ethanol yield from glycerol fermentation is about 25 % (by mass) in the standard scenario. Glycerol from at least 16 biodiesel plants is needed to meet the minimum capacity of the bioethanol plant. Crude glycerol with a purity of 80 % is transported by lorry to the ethanol processing plant. Considering the biodiesel and glycerol fermentation plant sizes and the average distribution of biodiesel plants in Europe, the average transportation distance for glycerol is around 280 km.

3.2.2 Butanol

Butanol is mostly used in the chemical industry. It is an important platform chemical and can be used for various purposes. Almost all butanol used today is synthesised from fossil sources. This can be done in a variety of ways but the most prevalent is via propylene hydroformylation (oxo synthesis) from fossil propylene.

Within the GLYFINERY project the following pathway for butanol from glycerol fermentation is analysed:

- Usage of butanol in the chemical industry as substitute for butanol from fossil sources (crude oil ➔ naphtha ➔ propylene➔ butanol)

Various by-products are generated during butanol production from glycerol. The main organic by-product is PDO (see chapter 3.2.3). Because of its amount and value, PDO is extracted from the fermentation broth. Carbon dioxide as main gaseous product is emitted to the atmosphere while other organic compounds and biomass remain in the fermentation broth after the extraction of butanol and PDO. The fermentation broth is used for biogas production without by-product extraction (see chapter 3.2.4).

The overall average yields of butanol and PDO from glycerol fermentation are about 25 % and 20 % (by mass), respectively. As for ethanol production, crude glycerol is transported to a central facility for fermentation and separation of butanol and PDO. Around six biodiesel plants are needed to supply one central butanol processing unit, resulting in an average transport distance of 180 km.

3.2.3 PDO

1,3-Propanediol or trimethylene glycol (PDO) is a chemical mostly used for the production of the polymer polytrimethyleneterephthalate (PTT). PTT is a relatively new polymer, which is mainly used to produce textile fibres. In certain fields of applications, these have superior characteristics compared to fibres from chemically related PET or nylon. A strong growth is predicted for the PTT market – and thus for PDO. So far, the production of PDO stems mostly from petrochemical sources although some biological production has been implemented. The latter is applied since 2006 by DuPont that produces PDO from corn starch fermentation (capacity: 45 000 tonnes/yr).

The GLYFINERY project covers the following usages of PDO:

- Usage in chemical industries as substitute for PDO from fossil sources (crude oil ➔ naphtha ➔ ethylene oxide ➔ PDO)
- Usage in chemical industries as substitute for PDO from corn starch fermentation

It is possible, that an increasing availability of PDO from glycerol leads to an expansion of the PTT production, which then replaces other polymers like PET. In that case, not fossil PDO would be replaced but PET (or other polymers) from fossil resources, which can be produced very efficiently. This would probably result in smaller avoidances of environmental burdens. This scenario is very hard to predict because PTT cannot be compared directly to PET due to possible superior properties of PTT in processing and use /Kurian 2005/. However, these applications are largely still under development and information is mostly proprietary. Therefore, we included a substitution of PET by PTT from glycerol-derived PDO as a worst case into the scenario "PDO from glycerol replaces PDO from fossil resources". This is based on the assumption that PTT has no advantages from superior properties. Thus, this sub-scenario represents an estimate of the lowest possible avoidance of environmental burdens.

As for the ethanol process, carbon dioxide as main gaseous by-product is emitted to the atmosphere while organic compounds and biomass remain in the fermentation broth, which is used for biogas production (see chapter 3.2.4).

The overall average PDO yield from glycerol processing is about 55 % (by mass). The crude glycerol (with 80 % purity) produced in biodiesel plants is transported to PDO plants for further processing. Around 8 biodiesel plants are needed to supply one central PDO production plant. The average transport distance is about 200 km.

3.2.4 Use of by-products from chemical pathways

During the processing of glycerol into ethanol, butanol and PDO, various organic compounds and biomass are generated as by-products. They are removed by centrifugation or remain in the fermentation broth after extraction of the main product. Furthermore, residues from glycerol filters are obtained in the production of each of the three products. Both types of residues can be used as a feedstock for biogas production. This means that filter residues and fermentation broth are used in small biogas plants, which are directly attached to the glycerol processing facilities. The biogas is used for the production of process energy which is used for glycerol processing and replaces fossil energy carriers.

If the residues are fermented, digestate is obtained as a by-product. It is used as fertiliser and replaces mineral fertiliser. In case genetically modified organisms are used for glycerol processing, the use of the digestate as fertiliser needs to be clarified.

3.3 Innovative biogas and biomethane pathways

Besides scenarios described above, glycerol can also be fermented in a biogas plant to provide energy. Two options are considered for the biogas production: glycerol can be fermented alone (monofermentation) or be used as co-substrate (cofermentation). Biogas can either be directly used for power and heat generation or be refined to biomethane. These four pathways are divided into scenarios according to the use of biogas or biomethane (see Table 3-1).

3.3.1 Biogas and biomethane from monofermentation

Monofermentation of glycerol is still a subject of ongoing research and not put into practice at industrial scale. The direct production and use of biogas can be realised in a biogas plant built at the biodiesel facility. A typical biodiesel facility produces ca. 10 000 t of glycerol a year, which is equivalent to a plant performance of more than 5 MW. Hence, no transport is needed. Crude glycerol is a rich carbon source but does not contain sufficient other nutrients for sustaining bacterial growth. Thus, a medium containing mineral nutrients has to be added. As the required amount of additional nutrients is still under research our estimates based on lab scale experiments are very uncertain.

The biogas obtained from glycerol monofermentation can be used in different ways:

a. Internal use in biodiesel plant replacing average power and heat mix.

b. External use of heat and power replacing marginal power and heat mix.

c. External use of power replacing marginal power mix without heat use.

Biogas plants for glycerol monofermentation will be new plants, hence glycerol does not substitute another substrate. For internal and external use of heat, we set a heat use efficiency of 100 % and 50 %, respectively. As the energy demand of the biodiesel plant is higher than the energy generated from biogas, internal use of energy is defined as standard scenario.

Biogas can be refined to biomethane to be fed into the natural gas grid or used as transportation fuel. The processing of biogas into biomethane is economically viable only for big plants. But regarding the high biogas yields achievable from glycerol fermentation, the glycerol delivered by one biodiesel plant is considered to be sufficient for an efficient biogas refining. Hence biomethane can also be produced locally within the biodiesel facility.

Biomethane can be used

a. for combined heat and power production, replacing marginal heat and power mixes

b. for power production only, replacing marginal power mix

c. as fuel replacing natural gas

d. in a compressed form as fuel replacing conventional gasoline

For combined heat and power production, the heat use efficiency is set to 100 % because biomethane is available via the natural gas grid at places with sufficient heat demand.

As biomethane is chemically identical with natural gas, natural gas could be used in all cases, too. Hence the replacement of natural gas is used as standard scenario, while the other options are included as sensitivity scenarios.

All settings for fermentation (nutrient supply etc.) are set the same as for biogas without refining to biomethane.

3.3.2 Biogas and biomethane from cofermentation

The use of glycerol as a co-substrate is already practiced. The addition of glycerol can increase the biogas yields of a biogas plant considerably. Nevertheless, there is still a big potential for optimising the yields. In order to cover the whole bandwidth of glycerol cofermentation, two options are assessed:

- Cofermentation with manure (from cattle and pig)
- Cofermentation with corn

6 % glycerol (by weight) is added to both substrates. To this end, glycerol is distributed to biogas plants in the surrounding of the biodiesel plant as it would be a much bigger effort to transport the co-substrates to the biodiesel plant. If only 6 % of glycerol is added as co-substrate, several biogas plants of average size are needed to ferment the glycerol production of one biodiesel plant.

For glycerol cofermentation, no nutrient supply is needed because the co-substrates corn and manure already contain sufficient nutrients for bacterial fermentation. Reports vary considerably in their conclusion, if and under which conditions synergy effects occur during the cofermentation, i.e. that more biogas is produced compared to the separate fermentation of both substrates (/Kryvoruchko et al. 2004/, /Amon et al. 2006/, /Hutňan et al. 2009/). Synergy effects represent the biggest optimisation potential and at the same time the biggest uncertainty. We assumed 0 %, 10 %, and 100 % in worst, typical, and best case sub-scenarios, respectively.

The use of biogas and biomethane follows the same scenarios as described for biogas monofermentation above except for the omission of internal use at the biodiesel facility. Therefore, the standard use of biogas from cofermentation is considered to be cogeneration of heat and power replacing marginal heat and power mix. Decentralised plants often have difficulties to efficiently use heat energy. Thus, we set the heat use efficiency to 20 %.

3.3.3 Use of by-products

In biogas production, digestate (fermentation residue) is obtained as by-product. The digestate is applied to fields replacing mineral fertilisers. Technical standard is a closed storage of the digestate, so that no NH_3 and N_2O emissions occur during storage.

3.4 Sensitivity analyses

As specified in the general settings, this life cycle assessment analyses new technologies as they will probably be implemented in the year 2020. This requires a number of estimations and assumptions, which are necessarily uncertain. In a first step, it was assumed that the currently available technologies are scaled up to industrial scale with some improvements but without significant technological changes. For this main assessment, best case and worst case sub-scenarios have been additionally defined for all glycerol processing scenarios to cover a bandwidth of possible parameters.

Certain important aspects technological aspects, which can be actively influenced during this scale-up process, have been analysed separately in the work task 7.4 (*Optimisation*). Their environmental and economic performance was assessed via separate optimisation scenarios.

3.4.1 Best and worst case subscenarios

The **typical case sub-scenario** can be described as follows:

- Average process yields
- Average input of energy and materials, medium heat recovery in glycerol and FAME processing
- Medium transport distances between biodiesel and biogas plants for cofermentation scenarios (10 km)
- For monofermentation biogas plants: internal use of locally generated heat and power
- For direct material use: replacement of diols with medium environmental burdens
- For direct combustion: internal use of the generated heat and power

For the **worst case sub-scenario**, all variable parameters are set in the way that lowest possible expenditure savings are achieved:

- Low process yields
- High inputs of energy and materials, low heat recovery
- Long transport distances between biodiesel and biogas plants for cofermentation scenarios (30 km)
- For energy use from biogas, biomethane, and direct combustion: worst case of all sub-scenarios
- For direct material use: replacement of diols with low environmental burdens

For the **best case sub-scenario**, all variable parameters are set in the way that highest possible expenditure savings are achieves:

- Maximum process yields that are realistic to achieve with the current technology
- Low inputs of energy and materials, high heat recovery
- Short transport distances between biodiesel and biogas plants for cofermentation scenarios (2 km)
- For energy use from biogas, biomethane, and direct combustion: best case of all sub-scenarios
- For direct material use: replacement of diols with high environmental burdens

The definitions of the sub-scenarios result in additive deviations caused by the various changes of parameters although it is unlikely that all parameters turn out worst or best at the same time. Statistics on probable compensations of deviations were not included in favour of displaying uncertainties conservatively.

3.4.2 Optimisation scenarios

The following aspects were assessed in more detail in separate optimisation scenarios:

The **energy that is required for the separation** of the product from the fermentation broth is the biggest expenditure in all innovative scenarios on the conversion of glycerol into chemicals in the impact categories climate change and non-renewable energy demand. Additionally, energy is an important economic cost factor. The biggest share of this energy is consumed for heating in distillation processes.

The **product yield** influences both the economical and the environmental performance significantly because the product accounts for the biggest economic revenues and biggest credits in the environmental balances of almost all impact categories. The overall yields are influenced by the degree of feedstock conversion into products (fermentation yields) and by the recovery efficiency of the product from the fermentation broth. These steps can be affected by various measures such as strain development, optimisation of fermentation conditions and optimisation of recovery methods. As many of these factors can influence each other, the approach was chosen to combine their optimisation in one scenario.

Nitrogen-containing **nutrients**, which are added to the fermentation broth, are very important for the environmental impacts in the category ozone deletion. These environmental impacts can be influenced by choosing nutrients from certain sources. This optimisation scenario is only assessed qualitatively from the environmental perspective.

In the public view of industrial processes, **transports** are often seen as main causes for environmental damages. Consequently, they are often suggested as optimisation targets. This optimisation scenario is based on the assumption that no transports are necessary at all and the glycerol-based biorefinery is build next to an extremely big biodiesel plant providing enough glycerol as a feedstock. This clearly hypothetical scenario was chosen to emphasise the low importance of transports in this context.

The **energy supply** for the biorefinery plant in the basic scenarios is based on the average mixtures of energy sources that are expected to be used in the EU in the year 2020. The lowest environmental burdens would arise if the glycerol biorefinery would be powered entirely based on renewable energies. However, this is not realistic to be achieved by 2020. A realistic option is the provision of heat and power from cogeneration with natural gas as fuel, which was chosen as an optimisation scenario.

The environmental impact category photosmog generally shows relatively low burdens when compared to the emissions in this category, which are caused by an average EU citizen. However, pronounced environmental impacts are caused by the PDO and butanol scenarios. This is almost entirely due to solvents, which are used for product extraction from the fermentation broth. This scenario assesses the effect of an additional **solvent recovery** step.

4 Results

As the integrated assessment combines indicators from all basic assessments with specific scopes, their results are summarised in chapters 4.1 to 4.3. New comparative indicators are presented in chapter 4.4 and the GLYFINERY processes are subsequently compared based on all available indicators.

4.1 Technological assessment

The technological assessment describes the processes and assesses the technological performance and risks. Details can be found in the technological assessment report /GLYFINERY 2012b/. This excerpt of results focuses on the biotechnological conversion pathways to provide a basis for the integrated assessment.

4.1.1 Process flowcharts

Glycerol to ethanol

The flowchart for the production of ethanol can be seen in Fig. 4-1. The purification method is simple distillation. The purification of ethanol by liquid/liquid extraction or solid phase extraction (as specified in WT 5.2 and WT 5.6) was not investigated. Hence the purification is done by simple distillation.

All other by-products are left in the residual fermentation broth for use in the downstream anaerobic degradation step.

Glycerol to butanol

The flowchart for the production of butanol can be seen in Fig. 4-2. Besides the main product butanol, 1,3-propanediol is produced as a by-product and extracted from the fermentation broth. This extraction was omitted for clarity from Fig. 4-2. It is essentially the same purification process as described for the 1,3-propanediol process in Fig. 4-3 starting from the post fermentation broth. Any other residual products are left in the residual fermentation broth for use in the downstream anaerobic degradation.

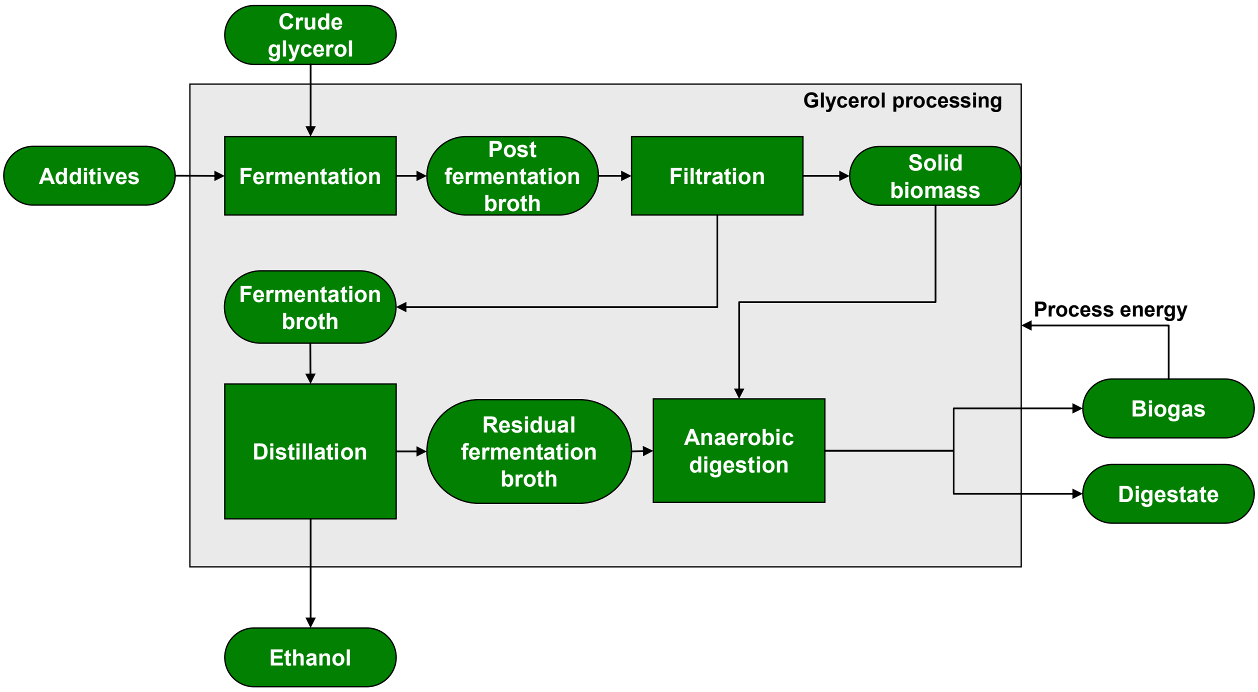


Fig. 4-1 Detailed flowchart depicting the glycerol processing to ethanol.

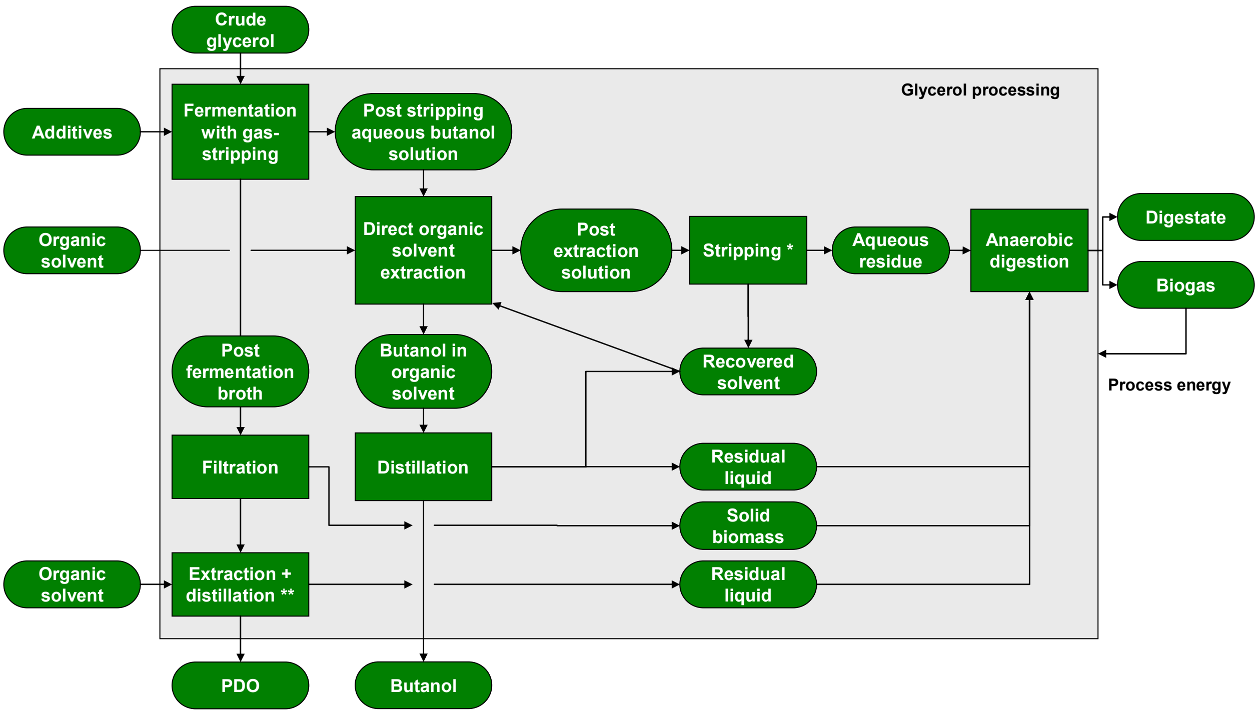


Fig. 4-2 Detailed flowchart depicting the glycerol processing to butanol. PDO: 1,3-propanediol, (*): The stripping for an additional solvent recovery was implemented after finishing the data collection for this report and is therefore not part of the environmental and economic assessment. (**): PDO is a by-product of this process, which is purified as shown in detail in Fig. 4-3.

Glycerol to 1,3-propanediol

The flowchart for the production of 1,3-propanediol can be seen in Fig. 4-3. The most promising purification method for 1,3-propanediol is continuous direct liquid/liquid extraction. As in the other processes the remaining products and residual glycerol and nutrients are left in the residual fermentation broth for use in anaerobic degradation.

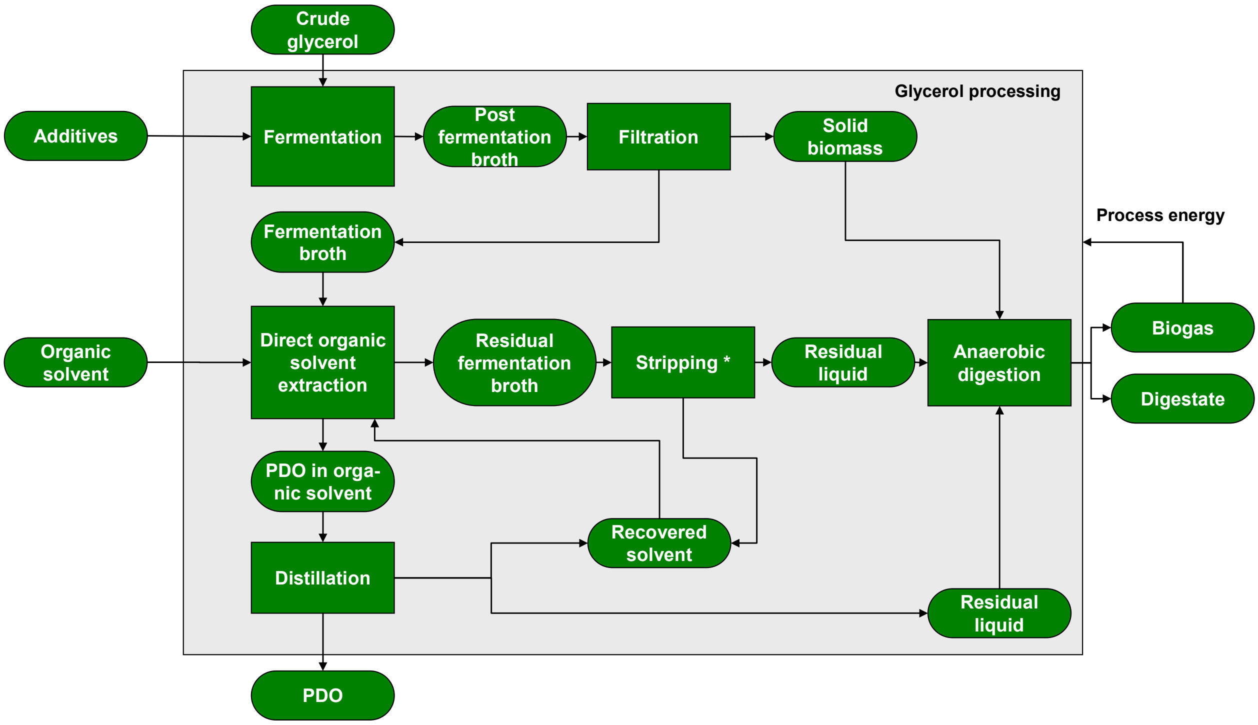


Fig. 4-3 Detailed flowchart depicting the glycerol processing to 1,3-propanediol (PDO). (*): The stripping for an additional solvent recovery was implemented after finishing the data collection for this report and is therefore not part of the environmental and economic assessment.

4.1.2 Biosafety

The term genetically modified organism (GMO) has many definitions. One definition is:

> "The term GMO means an organism in which the genetic material has been altered in a way that does not occur naturally through fertilisation and/or natural recombination. GMOs may be plants, animals or micro-organisms, such as bacteria, parasites and fungi." /EFSA 2012/

The operative word here is natural alteration. The strains used in the GLYFINERY project have all been isolated from the environment and are as such in their natural state. The improvements that have followed have all been by classical mutagenesis a process common in nature especially on a sunny day. The mutations have been caused by a naturally occurring process and strains with improved properties have been isolated and used for further development. In this iterative process no non natural manipulation of the genetic material has been applied. Hence none of the microorganisms are GMO.

The directive /EC 2000/ defines the risk associated with biological agents. Directives /EC 1990/ and /EC 2000/ provide the classification of biological agents into four infection risk groups on the basis of the following criteria:

Group 1: biological agent means one that is unlikely to cause human disease.

Group 2: biological agent means one that can cause human disease and might be a hazard to workers; it is unlikely to spread to the community; there is usually effective prophylaxis or treatment available.

Group 3: biological agent means one that can cause severe human disease and present a serious hazard to workers; it may present a risk of spreading to the community, but there is usually effective prophylaxis or treatment available.

Group 4: biological agent means one that causes severe human disease and is a serious hazard to workers; it may present a high risk of spreading to the community; there is usually no effective prophylaxis or treatment available.

Many species from *Clostridium* are class 2 but the inclusion of the general Clostridium spp. does not indicate that all are dangerous. It is under the assumption that those organisms that are generally non pathogenic are excluded from the list.

The organisms used in this project are *Clostridium pasteurianum* (butanol) and *Clostridium butyricum* (1,3-PDO)

The EC directive /EC 2000/ does not mention *C. pasteurianum* or *C. butyricum*. Bundesanstalt für Arbeitsschutz und Arbeitsmedizin (BAuA) in Germany classifies *C. pasteurianum* as class 1 (group 1) and *C. butyricum* as class 2 (group 2) /BAuA 2010/.

Further certain strains of *C. butyricum* are used as a probiotics in Asia /Seki et al. 2003/ . The American Type Culture Collection (ATCC) classifies C. butyricum as biosafety level 1 (group 1) in accordance with the recommended guidelines of Centers for Disease Control and Prevention (CDC) (/ATCC 2012/, /CDC 2012/). With this in mind the risks from the microorganisms used in the GLYFINERY project would be considered low.

4.1.3 Summary

This section summarises the key indicators from each technology described in more detail in the previous chapters and the technological assessment report /GLYFINERY 2012b/.

Glycerol is an attractive substrate for current and future bioconversion due to the increasing volumes available on the market concomitant with rising biodiesel production, particularly in Europe. Crude glycerol obtained from biodiesel producers varies in composition dependent on the oil feedstock used. Several microorganisms and the respective submerged cultivation processes, particularly bacterial, have been shown to be inhibited by components found in the crude biodiesel. One success of the GLYFINERY project has been to develop robust bioprocesses based on organisms, which are not sensitive (either naturally or through random mutagenesis) to variations in crude glycerol available from a typical biodiesel producer.

Table 4-1 Key technological indicators for the three main processes proposed for the GLYFINERY.

Indicator	**1,3-propanediol**	**Butanol**	**Ethanol**
Type of process	Two stage process: Continuous and batch	Fed Batch with gas stripping	Batch/fed-batch
Current yield (crude glycerol)	537 kg/ton	>225 kg/ton	260 kg/ton
Productivity	0.85 g/l/h	> 1.5g/l/h	Phase I 0.16 g/l/h Phase II 0.18 g/l/h Phase III 0.06 g/l/h
Highest achievable titre	30.2 g/L		28.1 g/L
Yield on substrate basis	0.56 g/g	>0.280 mol/mol	0.56 mol/mol
Percentage of theoretical maximum	-	>70%	56%
% Energy recovered from substrate	92%	72%	54%
GLYFINERY Development stage	Large-scale	Large-scale	Large-scale
World Market development stage	Commercial production based on plant sugars	Butanol from sugar has been commercialised	Ethanol from plant sugars commercialised at industrial scale
Production of effluents	Recycle water, biomass to biogas	Recycle water, biomass to biogas	Recycle water, biomass to biogas
Risk associated with chemicals involved	Solvents	Solvents	None
GMO technology	No	No	No
Odour emissions	No	No	No
Technological challenges/bottlenecks		*In situ* removal of butanol	Improve ethanol tolerance

Three main product streams have been investigated as being part of the proposed glycerol biorefinery: two anaerobic processes based on *Clostridium* species producing 1,3-PDO and butanol respectively, and a micro-aerobic process based on the yeast *P. tannophilus* producing ethanol. There are currently no commercial processes based on conversion of glycerol to these products.

The envisaged GLYFINERY scenario includes all the described processes, in a typical (bio)refinery concept with conversion of the feed substrate to several (bio)products. The spent biomass from the processes as well as some of the recovered liquid would be fed into biogas production on-site to generate energy for the biorefinery. Further water recycling to the bioprocesses is also envisaged. Based on the results obtained in the GLYFINERY project and summarised in Table 4-1, it is clear that on the basis of energy recovered from substrate, that 1,3-PDO is the most technologically favourable product. However, large amounts of solvent are required for recovery which are likely to cause problems concerning chemical recycling and waste effluent treatment. The butanol production process could also be technologically favourable if the challenge of in situ removal of butanol at pilot scale could be overcome. Further improvements in yield for the ethanol process would be required to ensure the technological viability. This process has a yield of ethanol at the required level for making distillation technically feasible; this should be improved upon for optimised recovery.

4.2 Environmental assessment

This chapter contains a summary of the results of the environmental assessment (work task 7.2). For details and additional data please refer to the report /GLYFINERY 2012c/.

In several environmental impact categories, the expenditures and credits for each glycerol processing scenario are compared. The analysis starts with crude glycerol as it leaves the biodiesel plant. The net results are used to compare the scenarios among each other. This allows for the identification of the best use option of glycerol.

It has to be noted that the comparison of a glycerol-based product to its reference product (e.g. glycerol based ethanol versus ethanol from fossil resources) is not within the scope of this study. This would require a convention for allocating parts of the environmental burdens that are caused by the biodiesel production to its by-product glycerol. Therefore, a positive (or negative) net result for a glycerol-based product does not mean that it causes bigger (or smaller) environmental impacts than the respective reference product.

4.2.1 Influence of life cycle stages

The processing of glycerol to chemicals needs several expenditures. The most important input from an environmental point of view is the energy input. But also material inputs as e.g. solvents or nutrients have to be considered. On the other hand, the processing of glycerol avoids environmental burdens by replacing fossil chemicals. These savings are credited to the glycerol processing. Fig. 4-4 shows the expenditures and savings in the categories climate change and photosmog for the five chemical glycerol processing pathways (typical scenarios only). The balances (difference between credits and expenditures) for all analysed impact categories are presented in chapter 4.2.2.

The most important processing step from an environmental point of view is the separation of the product from the fermentation broth: This requires the highest energy input. Depending on the technique used, the expenditures for separation contain energy for centrifugation and filtration, emissions from providing extraction solvents, and as the biggest single contribution the heat required for distillation. The energy demand for distillation is highest for ethanol because the whole fermentation broth is distilled. PDO and butanol are first extracted from the broth and then distilled at a later stage from a smaller volume. On the credits side, the expenditures for the supply of the fossil reference products are most important. Per ton of product, butanol an PDO synthesis from fossil resources cause most greenhouse gas emissions. Additionally, the yields of PDO and butanol are higher than that of ethanol. Therefore, they receive the biggest credits.

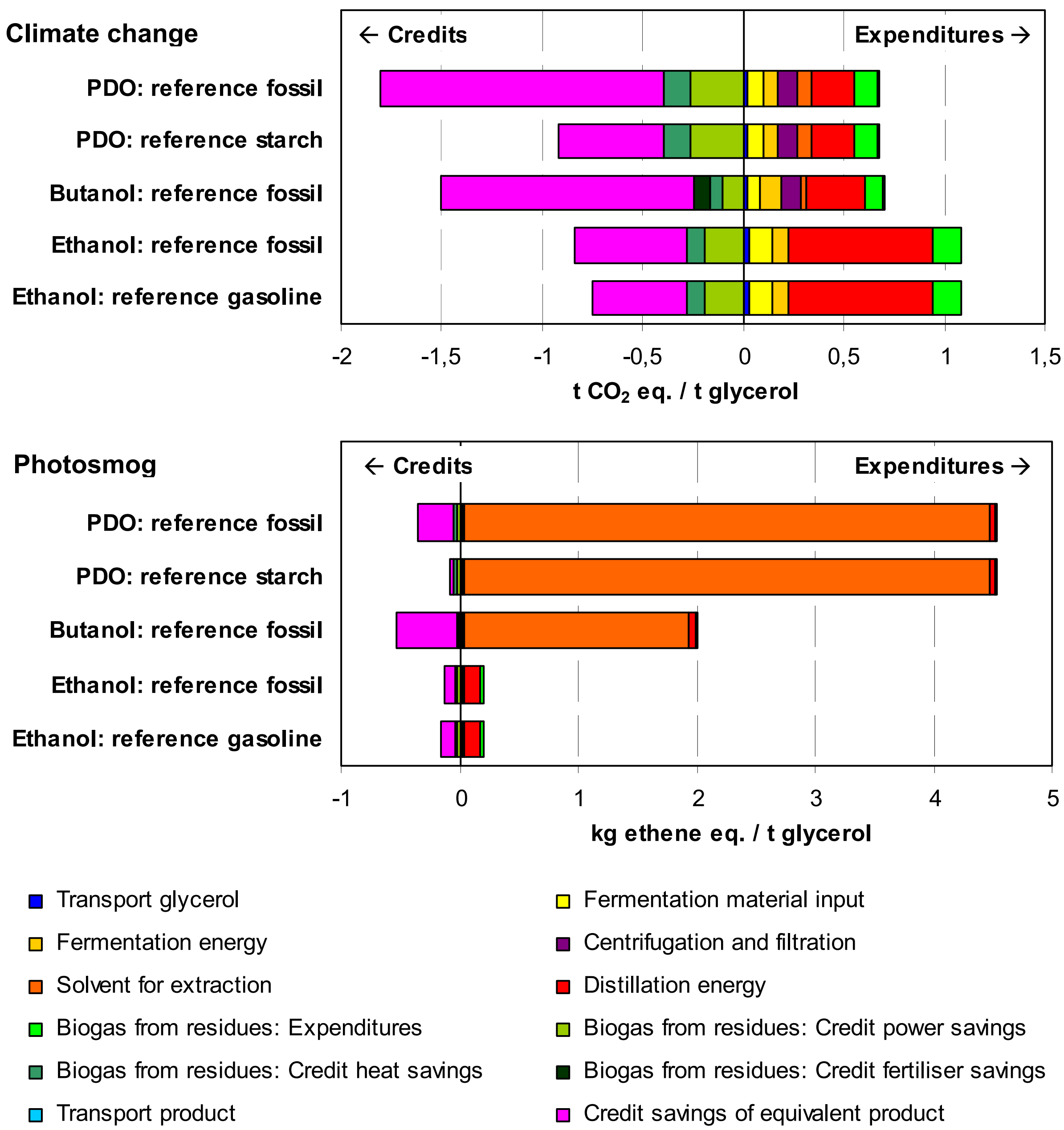


Fig. 4-4 Credits and expenditures for glycerol processing to PDO, butanol and ethanol. Impact categories climate change and photosmog, typical scenario.

How to read Fig. 4-4: Example PDO from glycerol (reference fossil PDO first bar)

The processing of glycerol to PDO causes the emission of about 0.7 tons of greenhouse gases (in CO_2 equivalents) per t of glycerol (expenditures). The biggest contribution is caused by the energy use for distillation (about 0.2 t CO_2 eq., red bar). On the other hand, about 1.8 t of greenhouse gases are saved (credits), mostly by saving fossil PDO (1.4 t CO_2 eq. per t of glycerol, pink bar).

Photosmog is almost entirely due to emissions of organic chemicals, which are used as extraction solvents for PDO and butanol and partially evaporate during the process (see Fig. 4-4). These solvent losses are based on the separation technology, which was implemented in a lab scale. As suggested in the optimisation report /GLYFINERY 2012e/, these burdens could be reduced in industrial plants by using additional solvent recovery steps. This technology has recently been implemented in the pilot reactor by the project partners but could not be completely assessed any more. Please see the technological assessment report for further details /GLYFINERY 2012b/.

The contributions of the individual life cycle stages to other environmental impact categories can be found in the annex (chapter 7.1.1). The contributions to the energy demand are similar to those of the greenhouse effect (see Fig. 7-1). Many life cycle steps contribute significantly to acidification and eutrophication without a clearly dominant single factor (see Fig. 7-2, Fig. 7-3). The ozone depletion is mainly caused by N_2O emissions, which are very hard to predict and influence (Fig. 7-4). Please see the optimisation report for a detailed discussion /GLYFINERY 2012e/.

Summary on influence of individual life cycle stages

The biggest influence on results in the categories climate change and energy demand have: the energy demand of product purification and the yields (via credits for fossil equivalents). There is no clearly dominating factor regarding the categories acidification and eutrophication. The results in categories photosmog and ozone depletion are critically influenced by contributions that may still change considerably due to minor modifications of the technology. Therefore, the environmental impact categories photosmog and ozone depletion should be interpreted conservatively.

4.2.2 Comparing ethanol, butanol, PDO and conventional scenarios

The impact categories climate change, non-renewable energy demand and acidification show very similar pictures (Fig. 4-5 and Fig. 7-5 in the annex): Direct material use of glycerol almost certainly is the best option. The scenarios PDO and butanol production with replacement of equivalents from fossil sources and direct combustion perform similarly as second best option considering the bandwidths of the sub-scenarios. Regarding acidification, also PDO production with replacement of PDO from starch is part of this group. Naturally, the uncertainties of the innovative options are much higher than those of the conventional options. Especially the scenario PDO (reference fossil PDO) has the potential to result in savings of environmental burdens compared to the direct combustion of glycerol or partially even direct material use.

Regarding eutrophication, direct material use and PDO (reference PDO from starch) show the best results (Fig. 7-6). The main reason for the good performance of PDO (reference PDO from starch) is that emissions from corn cultivation to produce starch are avoided. Butanol and PDO (reference fossil equivalents) and direct combustion form a group of scenarios following next.

The categories photosmog and ozone depletion are dominated by effects based on very uncertain data as discussed in the previous section (4.2.1). As mentioned, these uncertainties may well lead to results outside of the bandwidths displayed here. Therefore, no general ranking of scenarios in these categories is given.

All innovative pathways show a high difference between worst-case and best-case sub-scenarios. Hence, process optimisation is of high importance for an environmentally friendly glycerol processing. The bandwidth for the best ranking option direct material use is of a different nature: All sub-scenarios have only a limited capacity of glycerol usage. The more glycerol is available, the less valuable is the replaced product. As the economic values of the replaced products mainly depend on the complexity and energy consumption of their syntheses, a higher glycerol supply will lead to less environmental advantages for direct material use.

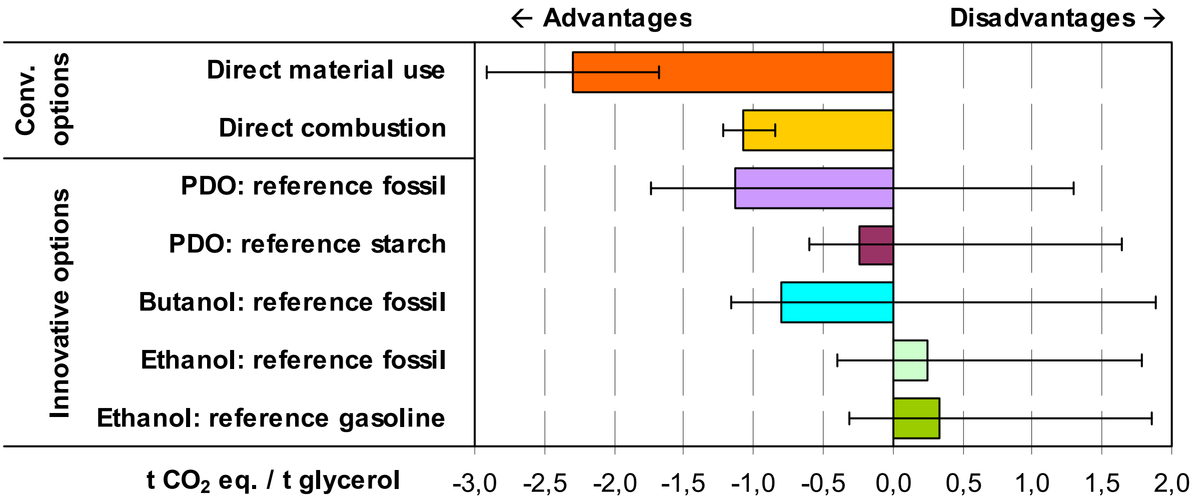


Fig. 4-5 Comparison of the environmental effects of innovative chemical and conventional scenarios for glycerol processing in the impact category climate change (in CO_2 equivalents). Coloured bars show results for the typical scenario. Thin lines describe results for worst case and best case sub-scenarios (i.e. bandwidth).

How to read the figure:

Direct material use scenario (first bar)

Direct material use of glycerol as replacement of diols from petrochemical sources saves about 2.3 t CO_2 eq. emissions per ton of glycerol. The bandwidth is about 2.9 t (best case) to 1.7 t (worst case) CO_2 eq. savings per ton of glycerol.

4.2.3 Normalisation of impact categories by inhabitant equivalents

In case one scenario performs well in some environmental impact categories but worse in others, the different categories have to be weighted to come to a final conclusion. This weighting depends on personal values and political goals and can not be provided by science. As a first less subjective step, impact categories can be normalised, which is to compare them to typically occurring environmental burdens. One indicator for the relevance of the different impacts of process or product is given by the normalisation via inhabitant equivalents (IE). The inhabitant equivalent of an environmental burden expresses how many average citizen of a region (in this case the European Union) cause the same environmental burden within one year as a certain amount of the assessed product. For example, the processing of 1000 tons of glycerol to PDO instead of the provision of PDO from fossil resources causes that much less of greenhouse gas emissions as about 100 EU citizens cause in one year (see Fig. 7-8 on inhabitant equivalents in the annex). This results in one possible ranking showing a high relevance for the environmental impact categories energy demand and climate change, a medium relevance for acidification and photosmog, and a low relevance for eutrophication and ozone depletion. If the emissions due to high solvent losses are not taken into account, the category photosmog is of low relevance, too.

4.2.4 Optimisation of glycerol conversion to chemicals

The optimisation potentials of the chemical pathways have been assessed previously /GLYFINERY 2012e/. In summary, a reduction in energy demand for separation, an increase in fermentation and extraction yields as well as a shift to combined heat and power production from natural gas as a more sustainable energy source are the most promising optimisation strategies. For each glycerol use pathway, the ranking of these three optimisation strategies is dependent on which improvements can already be reached by scaling up the process.

Based on the most likely results from upscaling the process (typical case of the basic scenarios), the best way to optimise PDO production is to increase the yields. An increase in yields has remarkable positive effects on all environmental impacts categories except for photosmog. Ozone depletion is mitigated only in comparison to PDO from starch, but not in comparison to PDO from fossil resources. An increase in yields is also the best way to optimise butanol production. Here it leads to a remarkable increase in environmental performance in all impact categories including photosmog and ozone depletion. For ethanol production, a shift in energy source is best, showing remarkable advantages in all categories except for photosmog.

The contribution of the analysed pathways to photosmog creation, which is not or only slightly reduced by the three mentioned optimisation strategies, can be reduced by solvent recovery. However, the energy demand for solvent recovery is unclear up to now. It should not exceed 1 GJ per ton of glycerol for PDO production and 0.5 per ton of glycerol for butanol production to avoid negative impacts in other categories. A reduction of transport distances did not lead to a remarkable improvement of the environmental performance compared to the base case.

4.2.5 Comparison of energy production scenarios

In the environmental impact category climate change, the direct combustion of glycerol performs better than the typical cases of biogas or biomethane production (Fig. 4-6). This also applies to most other environmental impact categories (see annex chapter 7.1.3). However, the innovative scenarios have a much higher bandwidth and the potential to perform better than the conventional direct combustion if the best case sub-scenarios can be realised in practise. This reflects the fact that the innovative biogas pathways are still under development.

Considering the bandwidth, the typical cases of biogas monofermentation and cofermentation show similar results in most categories. The deviating results for acidification are mainly caused by the replacement of conventional power from different sources (average mix for exported energy vs. marginal mix for internal use). In the best case sub-scenarios, cofermentation performs clearly better than monofermentation and direct combustion in the categories energy demand and climate change due to possible synergy effects between co-substrates.

Biogas can be refined to biomethane, which requires further energy and results in lower yields. Biogas refining to biomethane is mostly used in cases where an efficient heat or power use is not possible at the place of the biogas facility. As biodiesel plants have a high energy demand, all energy can be used internally, and hence refining is not necessary to achieve high heat use efficiencies. That is the case for monofermentation biogas plants at biodiesel facilities, which is reflected by the clearly worse results for biomethane from glycerol monofermentation compared to biogas from the same source. Also for cofermentation, biomethane refining is disadvantageous in the typical cases of all environmental impact categories although the differences are mostly less pronounced.

The normalisation of environmental impact categories by inhabitant equivalents (see chapter 4.2.3 for general remarks) shows a high variability between the pathways (typical case sub-scenarios) and thus importance for the category energy demand, medium variability for climate change and acidification and low variability for eutrophication, ozone depletion and photosmog (Fig. 7-8). The absolute values in inhabitant equivalents can be grouped and ranked similarly.

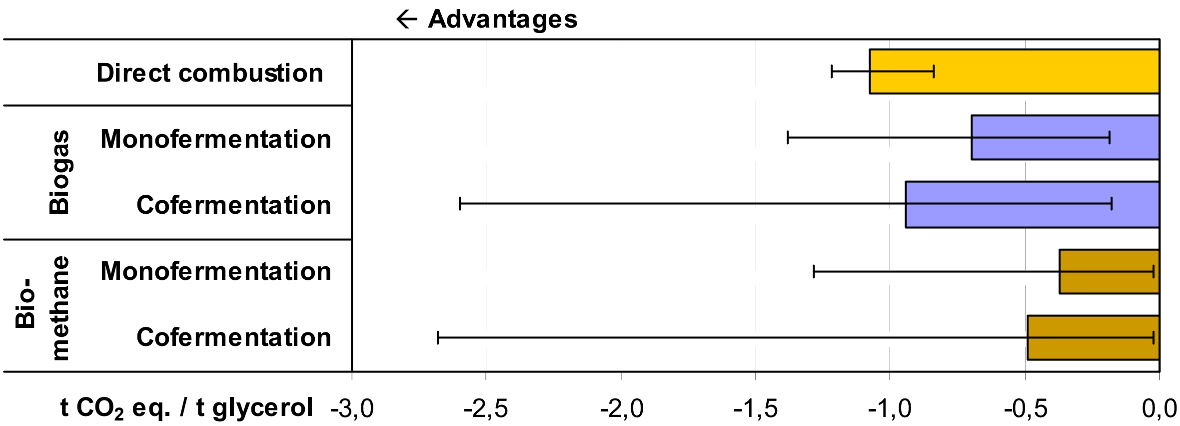


Fig. 4-6 Comparison of the environmental effects of energetic use of glycerol via conventional combustion and innovative biogas fermentation with and without refining to biomethane. For cofermentation, data for cofermentation with corn are shown. Data for manure cofermentation are almost identical. Coloured bars show the typical cases of the standard scenarios (as described in the scenario descriptions in chapter 3.3). Thin lines describe results for worst case and best case (i.e. bandwidth) over all scenarios. See Fig. 4-5 for an explanation how to read this type of figure.

Summary of results on biogas and biomethane pathways

For producing energy from glycerol, the conventional scenario of direct combustion is most likely the best option regarding the assessed environmental impacts. The results of the innovative biogas scenarios show high potentials but also risks because they are new technologies. Especially the glycerol cofermentation has the potential to perform clearly better than direct combustion in the important categories energy demand and climate change if presumed synergy effects between co-substrates can be realised in practise. For all these scenarios, the efficient use of heat from cogeneration of heat and power is very important. Refining of biogas to biomethane is not suitable from an environmental point of view.

4.2.6 Effect on biodiesel production

Bio-glycerol is an unavoidable co-product of the biodiesel production and thus an integral part of the biodiesel life cycle (see Fig. 4-5). In the following it is assessed, how the biodiesel production as a whole is affected by the different ways of using glycerol. Furthermore, the effects of this choice are compared to effects of the choice of feedstock and occurrence of land use changes.

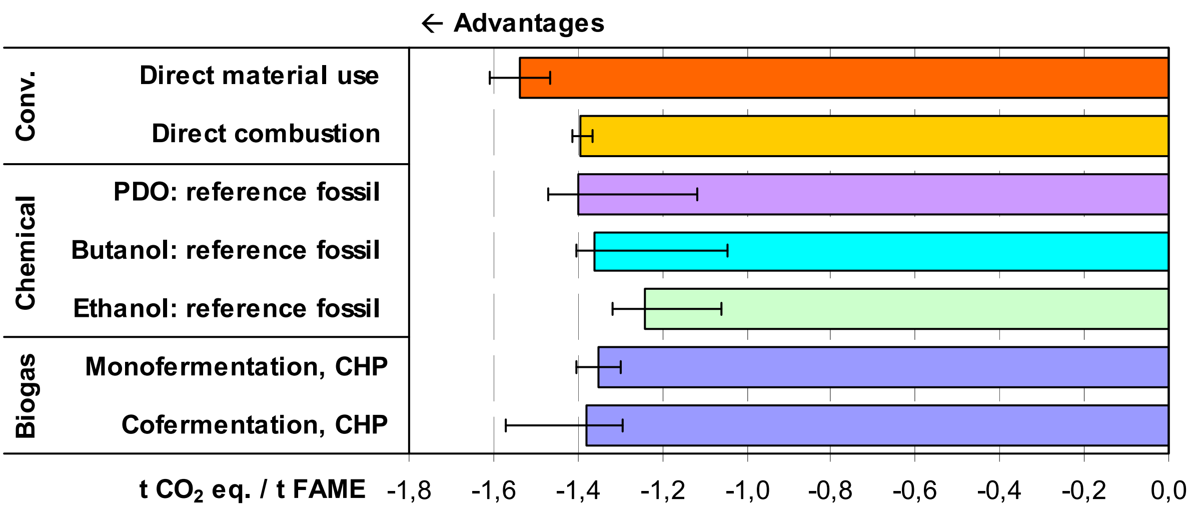


Fig. 4-7 Environmental impacts of the whole biodiesel life cycle including glycerol processing and use. Coloured bars represent the typical cases whereas the bandwidth includes the best and worst cases. Feedstock: rapeseed. See Fig. 4-5 for an explanation how to read this type of figure.

Fig. 4-7 shows how the different glycerol processing scenarios affect the greenhouse gas emissions of the whole biodiesel life cycle. It is apparent, that possible long-term improvements by innovative glycerol processing instead of using conventional options are small compared to the overall environmental impacts. In the typical cases, clear deviations are only seen towards higher burdens for ethanol production in the categories climate change and energy demand and in some cases for worst case sub-scenarios. Nevertheless, also small improvements can have a considerable impact in a growing market of this size. As possible disadvantages due to the use of innovative technologies are bigger than possible advantages, an implementation of the best technology is important.

The choice of the feedstock and possible land use changes have much bigger effects than the choice of the glycerol use option (Fig. 4-8). A land use change for production of energy crops such as the conversion of savannah or forests into agricultural crop land cannot be compensated by environmentally friendly glycerol processing under any circumstances. Hence, such land use changes have to be avoided with highest priority.

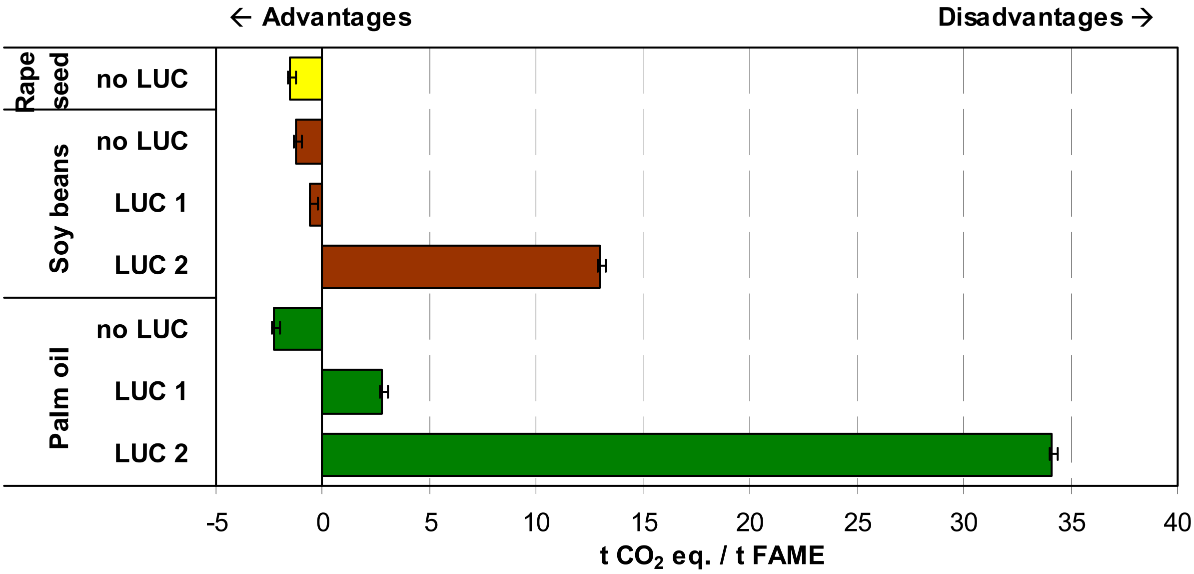


Fig. 4-8 Effects of land use change on climate change. Coloured bars represent the balance of the whole biodiesel life cycle including glycerol use for direct combustion. The displayed bandwidth covers the typical cases of all glycerol use scenarios. Worst case and best case scenarios are not shown. See Fig. 4-5 for an explanation how to read this type of figure. LUC: land use change, LUC 1: savannah (soy) or tropical forest on mineral soils (palm oil) to cropland, LUC 2: tropical forest on mineral soils (soy) or tropical forest on organic soils (peat swamp forest, palm oil) to cropland. There is no LUC for raoe seed from European production.

Summary of the results of the environmental assessment

Compared to the currently dominating direct material use of glycerol, the assessed innovative use options of glycerol via biochemical conversion generally show environmental disadvantages. The alternatives to use glycerol for energy production via direct combustion or biogas production are environmentally disadvantageous, too. To the extent to which a direct material use cannot be realised any more because of limited capacities, innovative use options and the use for energy production can play a bigger role. There is no clear winner amongst these options from an environmental perspective. However, the production of ethanol and the optional refining of biogas to biomethane are disadvantageous regarding almost all environmental aspects. All other processes each have different environmental potentials. It will be essential to realise these individually.

4.3 Economic assessment

In the following, the market perspectives for PDO and butanol are summarised (chapter 4.3.1). Subsequently, the potential plant process economics will be presented for the chemical and biogas ways in relation to revenue, production cost, and resulting earnings before interest and taxes (EBIT) (see chapter 4.3.2). The chemical and biogas pathways will be compared to the reference products in correspondence with the reference system defined in the technological assessment /GLYFINERY 2012b/. The impact of the innovative pathways on the overall biodiesel process economics is presented and sensitivity analysis on key parameters is presented. Finally, a macroeconomic analysis is presented to assess potential conflicts between a business-centred standpoint and a wider perspective on the society (chapter 4.3.3).

4.3.1 Market perspectives

The market perspectives of the most promising products were assessed. The promising pathways were found to be PDO and butanol + PDO (see chapter 4.3.2). Ethanol was omitted because the economic assessment gives a considerable deficit.

The market potential for PDO is considered to be 190,000,000 kg/yr with the existing bio-PDO capacity or 4 – 5 new plants with the capacity stated in the technological assessment. The selling price at this market size is assessed to be 2 – 2.4 Euro/kg. For PTT to access the Nylon market of 6600 Mn kg/yr, the PDO needs to be available at a selling price of 1 – 1.85 Euro/kg. Two scenarios are therefore made where 1) the PDO has a selling price of 2 – 2.4 Euro/kg and 2) where the PDO has a selling price of 1 – 1.85 Euro/kg. The low, average, and high value is used in the worst, typical and best case, respectively.

The market potential for butanol is very high even without considering the biofuel option and it is to be expected that more capacity is required if the current growth is maintained. The potential capacity 10,000 ton/yr of a butanol plant seems insignificant compared to the global production in 2006 of 2,100,000 ton/yr. Some uncertainty, however, exist to how the market will react to the new bio based products. Therefore, from a market perspective the potential number of butanol plants utilising glycerol seems only limited by the available glycerol. As a conservative estimate, the Oceanio enterprises quote at 1600 Euro/t is used as the worst case and the low spot price in EU is used in the best case.

Further detailed results can be found in the economic assessment report /GLYFINERY 2012d/.

4.3.2 Microeconomic analysis

The chemical and biomethane produced by the innovative pathways is compared with the EBIT if the crude glycerol is burned to generate energy or is sold to a glycerol refiner (direct material use). Only the most profitable biogas pathways, cofermentation of corn silage and manure to produce biomethane which is feed into the natural gas grid, are presented here.

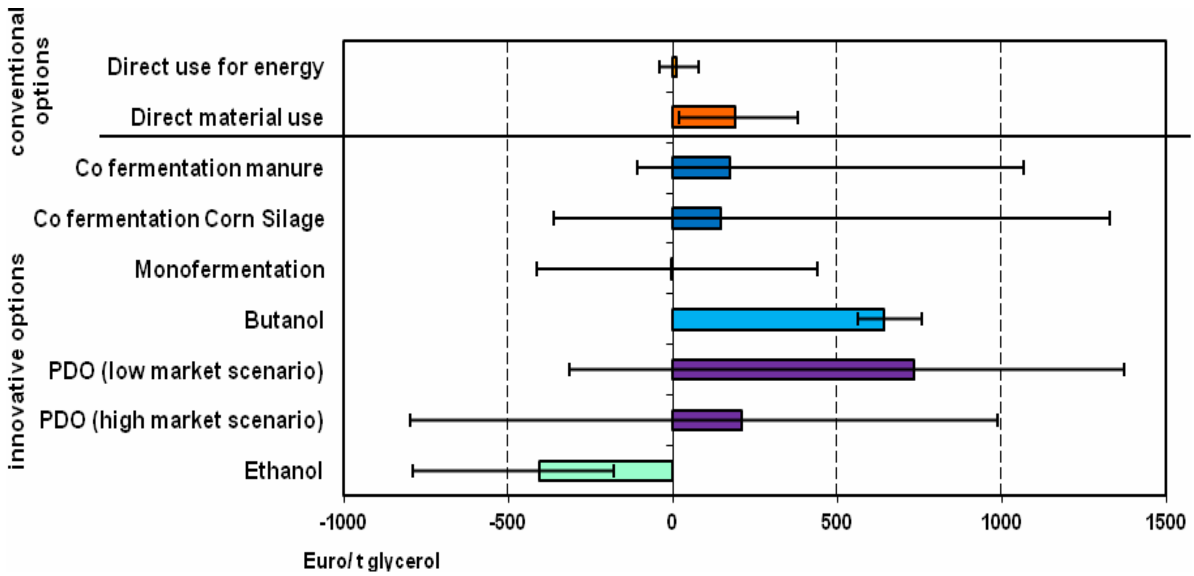


Fig. 4-9 Comparison of EBIT for classic usage and innovative use of glycerol. The error bars indicate the best and worst case.

It is seen in Fig. 4-9 that the processes which are more profitable than the direct use of material are:

- The butanol + PDO in all cases
- The PDO (low market size scenario) in typical and best case compared to all cases in direct material use
- The PDO (high market size scenario) in best case
- Co fermentation to produce biomethane which is feed into the natural gas grid or used in automobiles in the best case

In the typical case the highest EBIT is obtained in the PDO (low market size scenario) pathway with a profit of 730 Euro/t glycerol compared to the 600 Euro/t glycerol in the butanol + PDO pathway. However, the PDO (high market size scenario) is only in comparable to the direct material use in the typical scenario at an EBIT of approximately 200 Euro/t glycerol. In the best case scenario the most profitable pathway is also found to be the PDO pathway at an EBIT of 1400 Euro/t glycerol. In the best case the co fermentation is found to be of comparable profitability with the PDO process at 1300 Euro/t glycerol and 1100 Euro/t glycerol in corn silage and manure scenario. Furthermore the PDO (high market size scenario) is found to profitable in the best case at 1000 Euro/t. In the worst case the only process which is found to be profitable is the butanol + PDO.

Detailed results of the biotechnological conversion processes are discussed below. Further detailed results on conventional processes and processes to produce energy from glycerol can be found in the annex chapters 7.2.1 and 7.2.2, respectively.

Process economics – Ethanol

Table 4-2 Plant size and CAPEX for ethanol

Parameter	Unit	Best	Typical	Worst
Plant size	t glycerol/yr	175400	192000	213000
CAPEX	Mn Euro	60	80	120

The plant economics of the ethanol pathway where the ethanol is priced as chemical is shown in Fig. 4-10.

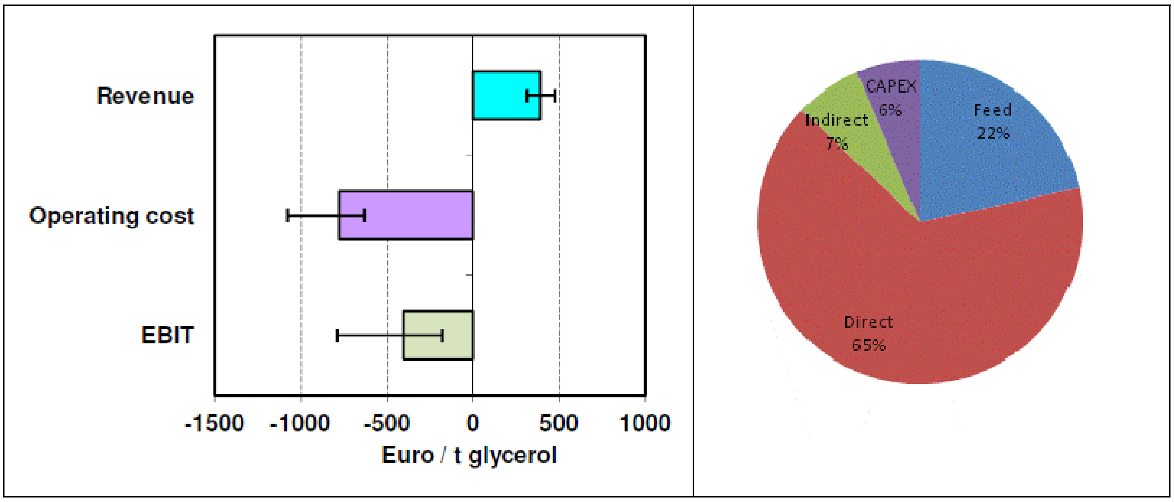


Fig. 4-10 Ethanol pathway plant economics when priced as a chemical (to the left) and distribution of total production cost in % of total production cost (to the right). The error bars indicate the best and worst case.

It is seen in Fig. 4-10 that the potential revenue in the typical case is only half the production cost and even in the best case there is a considerable deficit at -800 - -200 Euro/t glycerol from the worst to the best case. If the ethanol is sold for a reduced price as for gasoline, the EBIT decreases further (see annex chapter 7.2.3).

The IRR, NPV or simple payback period is not applicable, because the EBIT is negative. The maximum glycerol price is shown in the table below.

Table 4-3: Key financial figures for the ethanol pathway

Parameter	Unit	Best	Typical	Worst
Maximum glycerol price	Euro/t glycerol	-78	-235	-570

It is seen in the table above that the maximum glycerol price in even in the best case negative meaning that even if the glycerol was free the ethanol would still not be feasible. It can therefore be concluded that the nutrients are too expensive for the ethanol pathway to be economically viable.

Process economics – PDO

Table 4-4: Plant size and CAPEX for the PDO process.

Parameter	Unit	Best	Typical	Worst
Capacity	t glycerol /yr	70000	84000	100000
CAPEX	Mn Euro	53	75	113

The plant economics of the low market size scenario are presented in Fig. 4-16.

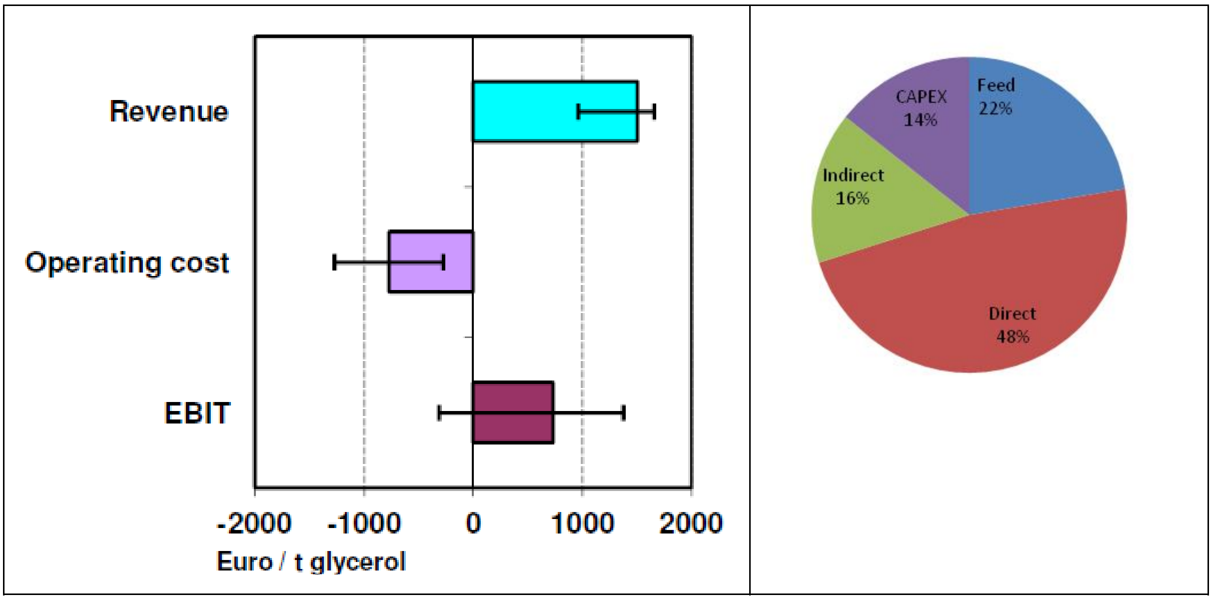


Fig. 4-11 PDO plant economics in the low market size scenarios (to the left) and distribution of production cost in % of total production cost (to the right) The error bars indicates the best and worst case.

The PDO pathway gives a considerable profit of 730 – 1400 Euro/t glycerol in the typical and best case, respectively. However, it is also seen in Fig. 4-16 that the EBIT is a significant deficit of approximately -300 Euro/t glycerol in the worst case scenario indicating that the PDO process is vulnerable to changes in prices. Furthermore, it is seen that the main cost driver in the PDO process is direct production cost which is mainly cost of nutrients (approx. 70%). This indicates that the PDO process is vulnerable to changes in nutrients cost. To avoid a comprehensive numbers of figures it has been decided only to show the typical case. The tendency has been found to be the same in all cases.

The plant economics of the high market size scenario are presented in Fig. 4-12.

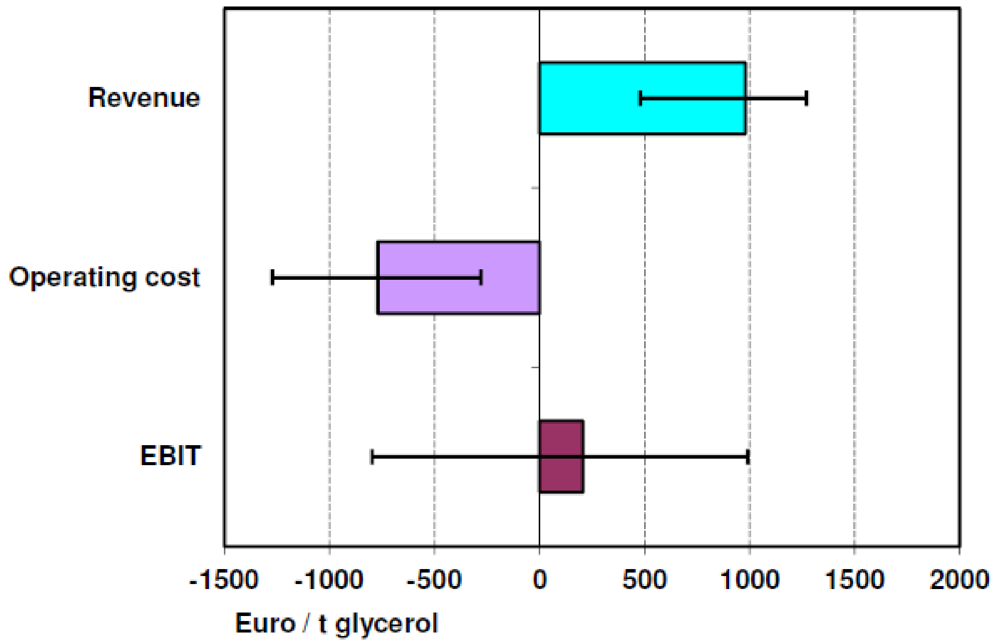


Fig. 4-12 PDO plant economics in the high market size scenarios

It is seen in Fig. 4-12 that the revenue and thereby the EBIT is reduced in all scenarios in the high market size scenario. Due to the reduced selling price of PDO enabling the high market the EBIT is reduced in the low market size scenario to -800, 200 and 1000 Euro/t glycerol in the worst, typical and best case, respectively.

The key financial indicators for the low market size scenario are shown in the table 4-5.

Table 4-5: Key financial figures for the PDO pathway

Parameter	Unit	Best	Typical	Worst
Simple payback period	yr	0,5	1,2	-
IRR	%	111	54	-
Maximum glycerol price	Euro/t glycerol	1700	900	-20

The financial indicator shows that the PDO pathway is a very feasible process in the best and typical scenarios.

Process economics – Butanol + PDO

The butanol pathway produces considerable amount of PDO as by-product. Therefore this will be accounted for in the following and the process will be referred to as the butanol + PDO pathway.

Table 4-6: Plant size and CAPEX for the butanol + PDO pathway

Parameter	Unit	Best	Typical	Worst
Capacity	t glycerol/yr	35875	40503	41740
CAPEX	Mn Euro	30	42.5	63.8

It is seen in the table above that the butanol plant sizes is significantly lower than both the ethanol and PDO plants. The capacity is approximately 20% and 50% of the ethanol and the PDO plant, respectively. This difference in scale is important to bear in mind when comparing the process economics, due to economy of scale. The cost is relatively higher (in Euro/t glycerol) at lower scale than higher scale, both in relation to CAPEX and production cost.

Because of the lower capacity, the CAPEX of the butanol plants is significantly lower than the ethanol and PDO plants, 50% and 40%, respectively. The investment intensity is important if a plant is financed by loans instead of being financed by equity.

The plant economics is presented in Fig. 4-13.

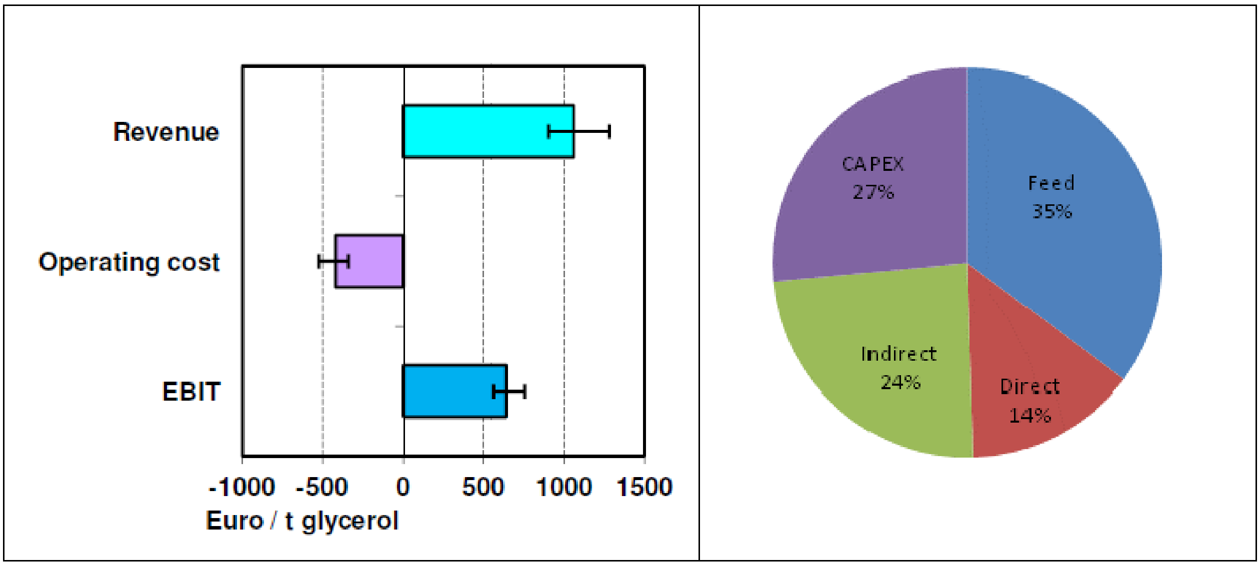


Fig. 4-13 Butanol + PDO plant economics (to the left) and distribution of production cost in % of total production cost (to the right). The error bars indicates the best and worst case.

The revenue consists of 55% butanol and 45% PDO. It is seen in Fig. 4-13 that the combined butanol and PDO plant gives a positive EBIT of approximately 640 and 760 Euro/t glycerol in the typcical and best case. Furthermore, it is seen that the positive EBIT is sustained in best, worst and typical all cases, and in the worst case with an EBIT of 560 Euro/t glycerol in the worst scenario. The butanol + PDO pathway is the only one which has a positive EBIT in all cases. Hereby, it can be derived that the butanol process is not as vulnerable to changes in prices of feedstock, production cost, and product selling price as the other processes. The main cost drivers in the butanol + PDO plant are identified in Fig. 4-13 to be the feed, CAPEX, and the indirect production cost in descending order. The direct production cost which is mainly nutrients is seen not to have as high an impact in the butanol + PDO pathway as in the other pathways. To avoid a comprehensive numbers of figures it has been decided only to show the typical case. The tendency has been found to be the same in all cases.

The key financial indicators for the butanol + PDO plant are shown in the table below.

Table 4-7: Key financial figures for the butanol + PDO pathway

Parameter	Unit	Best	Typical	Worst
Simple payback period	yr	1	1.7	4.3
IRR	%	69	44	23
Maximum glycerol price	Euro/t glycerol	1000	800	600

The financial indicator shows that the butanol + PDO pathway is a feasible process in all scenarios. The IRR and simple payback period of 23% and 4.3 years in the worst case shows that the butanol and PDO process is economical feasible even in the worst case.

Furthermore, it is expected that the butanol + PDO process can do better if it was considered at the same scale as the ethanol and PDO process.

Optimisation potentials

Optimisation potentials of the chemical conversion pathways were studied in the optimisation assessment /GLYFINERY 2012e/. The assessed scenarios are described in chapter 3.4.2. From an economic point of view, the most efficient way to optimise PDO production is to increase yields. The EBIT could be increased by abut 50 % if the yield optimisation can be realised. But other optimisation scenarios may lead to similar results in the best case. The highest optimisation potential for butanol production is achieved by a shift in energy source (from average heat and energy mix to natural gas based combined heat and power plants). This may even increase the EBIT by more than 50 %. For ethanol production, the negative EBIT of the base case does not become positive in any optimisation scenario. If the ethanol production is to become feasible, the nutrient input should be optimised further.

Influence on economics of biodiesel production

The economy of the chemical and biogas pathways is compared to the biodiesel plant as a whole. Only the most profitable biogas pathway to produce biomethane, which is feed into the natural gas grid, is presented here.

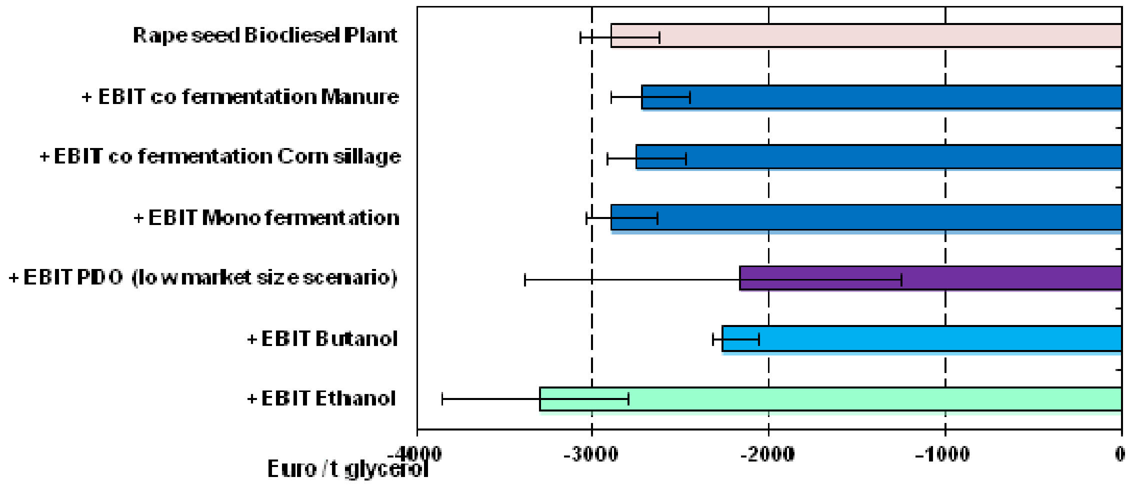


Fig. 4-14 Impact of innovative pathway on overall biodiesel plant economy for the feedstock rape seed. The error bars indicate the best and worst case.

It is seen in Fig. 4-14 that none of the pathways has the potential to change the current unfavorable economy of the biodiesel plants to give positive EBIT. The PDO and butanol processes have the highest impact, which is in line with the previous analysis, as these processes have the highest EBIT.

4.3.3 Macroeconomic analysis of ethanol, butanol and PDO production

The chemical pathways are compared in Fig. 4-15 to reference products according to the scenarios described in chapter 3. The butanol + PDO process is compared to butanol from fossil propylene. The PDO and ethanol process is compared to the products produced both from starch and fossil sources.

As derived in /GLYFINERY 2012d/, the differential cost (dCost) parameter is defined as the difference in production for the reference product and the production of product produced by the innovative pathway. Therefore, a positive dCost is an advantage for the product produced by the innovative pathway.

Fig. 4-15 shows that both the PDO and the butanol + PDO processes are advantageous compared to the reference products. The most advantageous process is the PDO process compared to PDO produced from starch, secondly the butanol process compared to butanol produced from sources. The PDO process is only advantageous compared to PDO from starch sources in the typical and best case scenario. In general, the macroeconomic analysis results in the same ranking of these pathways compared to the microeconomic analysis (chapter 4.3.2). Thus, this assessment does not see potential conflicts between the ambitions of businesses and the society regarding the economics of these processes. Further detailed results can be found in the economic assessment report /GLYFINERY 2012d/.

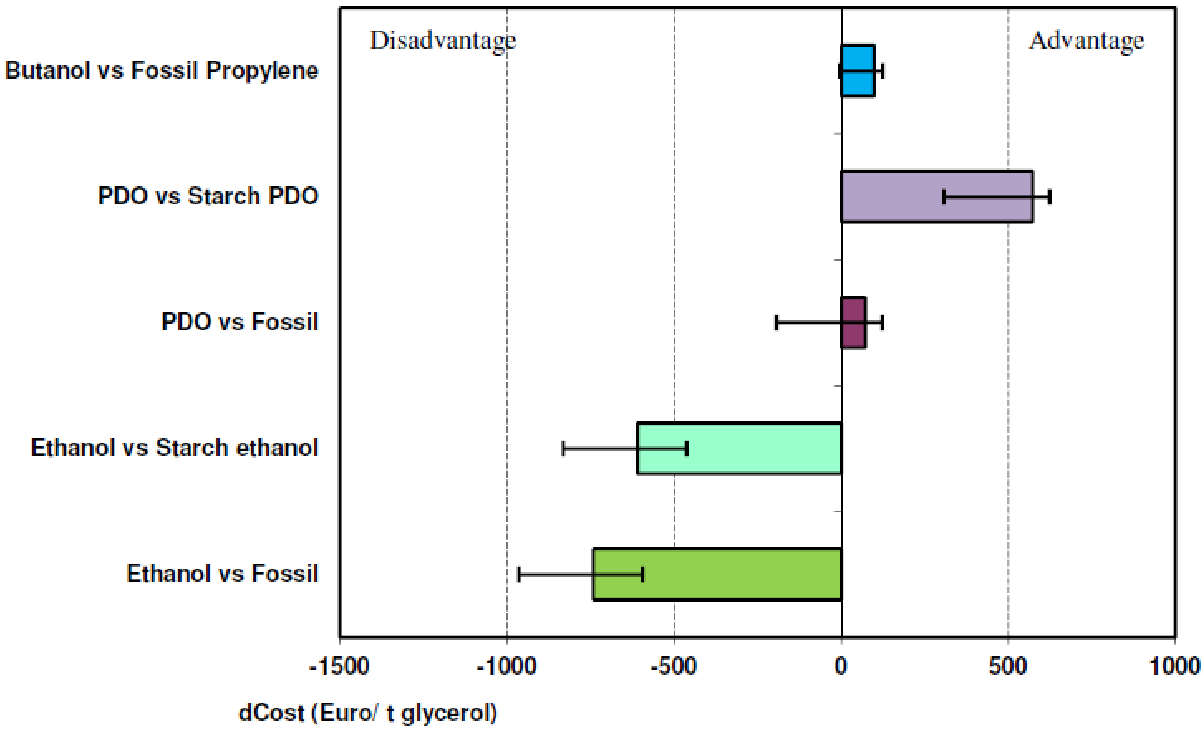


Fig. 4-15 Comparison of dCost for the chemical pathways with reference chemicals. The error bars indicate the best and worst case.

4.3.4 Economic assessment conclusion

The processes that are more profitable than the direct material use or the direct combustion are the production of butanol with PDO as a by-product in all cases, the production of PDO (small market size scenario) in the typical and best cases, the production of PDO (high market size scenario) in the best case and the cofermentation to produce biomethane, which is fed into the natural gas grid or used in automobiles, in the best case. An analysis from a macroeconomic perspective results in a similar ranking of the innovative scenarios. Thus, there are no conflicting goals of businesses and the society regarding the assessed economic aspects.

The PDO process has the most promising profits and financial indicators in the typical and best case scenario. However, it has also been proven vulnerable because it results in losses in the worst case along with a higher sensitivity to changes in product selling price and nutrient costs. The market potential was found to be limited to six new PDO plants in total. If the PDO process is to benefit from the large market volumes where PTT, a polymer made from PDO, is substituting nylon the profits from the process are significantly reduced and below those of the butanol + PDO scenario. The butanol + PDO process was found to give smaller profits compared to the PDO process under the assumption of a small market size. However, this process was as the only that was found to be feasible in the worst case scenario. In the sensitivity analysis, it was found to have to lowest sensitivity to changes in nutrient costs and main product selling price. Furthermore, the market for butanol was assessed to be secure and established. The annual growth, which has been sustained throughout the last 10 years, is sufficient for six new butanol + PDO plants per year.

4.4 Integrated assessment: Benchmarking and efficiency analysis

The purpose of the benchmarking and efficiency analysis is to condense the available data and provide a decision support regarding the questions phrased in chapter 1. The main question is to find the best use option for glycerol. As the data presented in the previous chapters does not support an unequivocal decision, the advantages and disadvantages of the glycerol use options will have to be discussed for several possible background situations in the year 2020 and several different perspectives of stakeholders. The benchmarking process will provide a condensed overview of advantages, disadvantages and uncertainties associated with possible decisions. The efficiency analysis evaluates how economically effective certain environmentally beneficial decisions are and show the limitations of this approach.

			Direct material use	Direct combustion	Ethanol reference fossil	Ethanol reference gasoline	Butanol reference fossil	PDO reference fossil	PDO reference starch	Biogas monofermentation	Biogas cofermentation	Biomethane monofermentation	Biomethane cofermentation
			typical										
technological	**Maturity**		+	+	0	0	0	0	0	+	+	+	+
	Biological risk: GMOs		+	+	0	0	0	0	0	0	0	0	0
	Biological risk: pathogenicity		+	+	0	0	0	0	0	0	0	0	0
	Risks through solvents		+	+	+	+	-	-	-	+	+	+	+
	Odours		+	+	0	0	0	0	0	-	-	-	-
environmental	**Climate change**	t CO2 eq. / t glycerol	-2.3	-1.1	0.2	0.3	-0.8	-1.1	-0.2	-0.7	-0.9	-0.4	-0.5
	Energy demand	GJ / t glycerol	-40.5	-20.7	2.7	5.5	-18.6	-22.9	-4.5	-16.2	-13.0	-7.6	-9.6
	Acidification	kg SO2 eq. / t glycerol	-3.9	-2.3	0.4	1.4	-1.7	-1.8	-1.1	-2.1	-0.6	0.4	0.0
	Eutrophication	kg PO4 eq. / t glycerol	-0.2	0.0	0.1	0.2	-0.1	0.0	-0.2	-0.1	0.0	0.0	0.0
	Photosmog	kg ethen eq. / t glycerol	-0.5	-0.1	0.1	0.0	1.5 *	4.2 *	4.5 *	-0.1	-0.1	-0.1	-0.1
	Ozone depletion	g CFC-11 eq. / t glycerol	-0.2	-0.1	3.2	3.1	-0.4	2.4	-1.0	0.2	-0.6	0.6	0.1
econom.	**Earnings (EBIT)**	€ / t glycerol	190	-30	-378	-428	640	733	733	-275	-9	-4	147
	Investments		+	+	-	-	-	-	-	+	+	0	0
	Market potential		0	+	-	+	+	0	0	+	+	+	+
			worst										
	Climate change	t CO2 eq. / t glycerol	-1.7	-0.8	1.8	1.9	1.9	1.3	1.6	-0.2	-0.2	0.0	0.0
	Energy demand	GJ / t glycerol	-27.1	-10.4	26.6	29.1	38.1	22.4	29.8	-7.8	-4.2	-2.6	-2.6
	Acidification	kg SO2 eq. / t glycerol	-2.4	-0.1	2.9	3.7	10.2	6.9	6.6	-0.6	0.4	0.7	0.7
	Eutrophication	kg PO4 eq. / t glycerol	-0.2	0.1	0.4	0.5	0.5	0.5	0.3	0.0	0.0	0.0	0.1
	Photosmog	kg ethen eq. / t glycerol	-0.3	-0.1	0.4	0.3	1.8 *	9.7 *	9.9 *	0.0	0.0	0.0	0.0
	Ozone depletion	g CFC-11 eq. / t glycerol	-0.2	0.0	6.4	6.4	1.0	6.5	3.7	3.9	3.8	4.2	4.2
	Earnings (EBIT)	€ / t glycerol	20	-80	-744	-806	377	-310	-310	-550	-475	-415	-362
			best										
	Climate change	t CO2 eq. / t glycerol	-2.9	-1.2	-0.4	-0.3	-1.2	-1.7	-0.6	-1.2	-2.6	-0.7	-1.4
	Energy demand	GJ / t glycerol	-54.0	-20.7	-7.5	-4.4	-25.4	-33.1	-9.4	-24.1	-33.3	-12.5	-26.4
	Acidification	kg SO2 eq. / t glycerol	-5.5	-2.3	-0.7	0.3	-2.5	-3.1	-2.3	-3.4	-1.6	0.0	-0.4
	Eutrophication	kg PO4 eq. / t glycerol	-0.3	0.0	0.0	0.1	-0.2	-0.2	-0.4	-0.1	-0.1	0.0	0.0
	Photosmog	kg ethen eq. / t glycerol	-0.8	-0.1	-0.1	-0.1	1.4 *	2.8 *	3.1 *	-0.1	-0.2	-0.1	-0.2
	Ozone depletion	g CFC-11 eq. / t glycerol	-0.2	-0.3	2.0	2.0	0.3	1.5	-2.9	-0.2	-1.6	0.3	0.1
	Earnings (EBIT)	€ / t glycerol	380	40	-178	-296	939	1397	1397	65	674	440	1329

Fig. 4-16 Available qualitative and quantitative indicators from the technological, environmental and economic assessments. For the quantitative indicators, the bandwidths are given by the “worst” and “best” case subscenarios. Green backgrounds indicate advantageous data, for example emission savings (negative numbers) or profits (positive numbers). Red and yellow are used likewise. Please note that the emission data does not include emissions due to the production of glycerol (see also chapter 2.1.1). (*): These emissions could still be reduced considerably after finishing the data collection for this report.

4.4.1 Benchmarking

The aim of the benchmarking process is to provide qualitative information whether a potential decision has positive, negative or neutral / uncertain effects. As glycerol is a by-product, one of the available use options has to be chosen because it is not possible to decide not to produce glycerol in the biodiesel production. Consequently, the question behind the sustainability assessment is not „Can product x be produced more sustainably from glycerol or from another feedstock?“ but instead as stated in the definition of goals „Which is the most sustainable way of using the produced glycerol?”. Therefore, the decisions have to be based on the comparison of pathways instead of absolute values for one glycerol use option. The comparisons are based on the qualitative and quantitative indicators that resulted from the technological, environmental and economic assessments (Fig. 4-16).

In a first step, the benchmark has to be chosen depending on the decision situation and the perspectives of the stakeholders. We decided to focus on three of all possible contexts, which are detailed in Table 4-8. Additionally, any other possible comparison can be made based on the data provided in Fig. 4-16.

Table 4-8 Decision contexts and related benchmarks

Decision context	Benchmark
Status quo: Any glycerol use option is compared to the direct material use, which is most commonly used option today and will be the most environmentally favourable option if the market situation does not change drastically until 2020. This context is relevant for most stakeholders.	Direct material use
High glycerol availability, no development of new options: If the glycerol production increases strikingly until 2020, the direct material use is not an option any more. In that case, the conventional option with unlimited capacity is the only alternative unless alternatives have been established until then. This context is especially relevant for decision makers who have to decide if investments into the further development of new technologies should be promoted e.g. by subsidies.	Direct combustion
Highest economic profit: All options are compared to the scenario with the probably highest economic profit for the businesses realising this option. This context shows advantages, disadvantages and risks associated with this decision, which is especially relevant for potential investors.	PDO reference fossil

There are two options how to take quantitative uncertainties into account. The question whether a scenario can perform better than the benchmark under optimal conditions can be based on two comparisons: first, the best case of this scenario versus the typical case of the benchmark or, second, comparison of both best cases. This translates into the question whether the parameter behind these best case scenarios are independent for each scenario or not. An example for an independent parameter would be the efficiency of a specific process. It is a valid option to compare the optimal performance to the typical performance of the benchmark to see whether specific investments into optimisation could change the performance of this scenario relative to the benchmark. An example of a common parameters is the glycerol price, which affects all scenarios in the same way. In this case, a comparison of the best case of one scenario to the typical case of the benchmark is not valid. In this assessment, the indicators are results of previous assessments, in which the bandwidths were based on both independent and common parameters with different importance for the results. The results of both ways of treating uncertainties are shown in the annex chapter 7.3.1. As the results of these two alternative ways are mostly in agreement, the local comparison of best, typical and worst subscenarios amongst each other is chosen for the further evaluation as methodologically safer alternative. Exemplary results of the benchmarking for quantitative indicators are shown in Fig. 4-17. The corresponding benchmarking results for the qualitative indicators are shown in Fig. 4-18. These comparative tables will be used as a basis for the overall comparison of glycerol use options in chapter 4.5.1.

Benchmark: Direct combustion	Direct material use	Direct combustion	Ethanol reference fossil	Ethanol reference gasoline	Butanol reference fossil	PDO reference fossil	PDO reference starch	Biogas monofermentation	Biogas cofermentation	Biomethane monofermentation	Biomethane cofermentation
Climate change	+		-	-	0	0	-	0	0	-	0
Energy demand	+		-	-	0	0	-	0	0	-	0
Acidification	+		-	-	0	0	0	0	-	-	-
Eutrophication	+		-	-	0	0	0	+	0	0	0
Photosmog	+		-	-	-	-	-	0	0	-	0
Ozone depletion	0		-	-	0	-	0	-	0	-	-
Earnings (EBIT)	+		-	-	+	0	0	0	0	0	0

Fig. 4-17 The benchmarking process for quantitative data converts these into categorised qualitative comparisons of scenarios. Exemplary results are shown for the scenario direct combustion as a benchmark. The results "+" or "-" indicate that the scenario performs better or worse, respectively, than the benchmark in any case (i.e. same performance of best, typical and worst case). "0" indicates that the comparisons are ambiguous or differ from the benchmark by less than 10 %.

Benchmark: Direct combustion	Direct material use	Direct combustion	Ethanol reference fossil	Ethanol reference gasoline	Butanol reference fossil	PDO reference fossil	PDO reference starch	Biogas monofermentation	Biogas cofermentation	Biomethane monofermentation	Biomethane cofermentation
Maturity	0		-	-	-	-	-	0	0	0	0
Biological risk: GMOs	0		-	-	-	-	-	-	-	-	-
Biological risk: pathogenicity	0		-	-	-	-	-	-	-	-	-
Risks through solvents	0		0	0	-	-	-	0	0	0	0
Odours	0		-	-	-	-	-	-	-	-	-
Investments	0		-	-	-	-	-	0	0	-	-
Market potential	-		-	0	0	-	-	0	0	0	0

Fig. 4-18 The benchmarking process for qualitative data simply compares qualitative ratings to those of a benchmark scenario. Exemplary results are shown for the scenario direct combustion as a benchmark. The results "+", "0", or "-" indicate that the scenario performs better, equal, or worse, respectively, than the benchmark.

4.4.2 Efficiency analysis

The economic and environmental performances of a pathway in comparison to the benchmark are not necessarily in agreement. Often, a conflict between economic and environmental goals occurs. One way to resolve this conflict is to define a primary goal, for example to achieve greenhouse gas savings, with the precondition to do this in the economically most efficient way. This means to achieve the highest possible environmental benefits with the lowest possible expenses. The quotient of the differential costs and the differential environmental burdens are termed avoidance costs.

Benchmark: Direct material use		Direct material use	Direct combustion	Ethanol reference fossil	Ethanol reference gasoline	Butanol reference fossil	PDO reference fossil	PDO reference starch	Biogas monofermentation	Biogas cofermentation	Biomethane monofermentation	Biomethane cofermentation
		typical										
Climate change	t CO2 eq. / t glycerol	0.0	1.2	2.5	2.6	1.5	1.2	2.1	1.6	1.4	1.9	1.8
Energy demand	GJ / t glycerol	0.0	19.9	43.2	46.0	22.0	17.6	36.1	24.3	27.6	32.9	31.0
Acidification	kg SO2 eq. / t glycerol	0.0	1.6	4.3	5.3	2.2	2.1	2.8	1.9	3.4	4.3	3.9
CO2 avoidance costs	€ / t CO2	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
Energy saving costs	€ / GJ	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
SO2 avoidance costs	€ / kg SO2	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
		worst										
Climate change	t CO2 eq. / t glycerol	0.0	0.8	3.5	3.5	3.6	3.0	3.3	1.4	1.5	1.7	1.7
Energy demand	GJ / t glycerol	0.0	16.7	53.8	56.2	65.2	49.5	56.9	19.3	22.9	24.5	24.6
Acidification	kg SO2 eq. / t glycerol	0.0	2.3	5.3	6.1	12.6	9.3	9.0	1.8	2.8	3.1	3.1
CO2 avoidance costs	€ / t CO2	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
Energy saving costs	€ / GJ	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
SO2 avoidance costs	€ / kg SO2	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
		best										
Climate change	t CO2 eq. / t glycerol	0.0	1.7	2.5	2.6	1.8	1.2	2.3	1.8	0.3	2.3	1.5
Energy demand	GJ / t glycerol	0.0	33.3	46.4	49.6	28.6	20.9	44.6	29.9	20.7	41.5	27.6
Acidification	kg SO2 eq. / t glycerol	0.0	3.2	4.8	5.8	2.9	2.3	3.2	2.1	3.9	5.5	5.1
CO2 avoidance costs	€ / t CO2	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
Energy saving costs	€ / GJ	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
SO2 avoidance costs	€ / kg SO2	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D

Fig. 4-19 Avoidance costs for selected environmental impact categories with the benchmark scenario direct material use. Avoidance costs are calculated based on the typical, worst and best case subscenarios. Advantageous or disadvantageous values are highlighted in green or red, respectively. "N/D" indicates that avoidance costs are not defined because there is no avoidance compared to the benchmark.

The environmental impact categories climate change, non-renewable energy demand and acidification are used as examples to evaluate the conclusiveness of avoidance costs in the context of this project. If the currently most common glycerol use pathway "direct material use" is chosen as a benchmark it becomes apparent that no pathway achieves avoidances in any of these impact categories (Fig. 4-19). As detailed in chapter 2.5.2, avoidance costs are not defined if there are no avoidances. Thus, an efficiency indicator cannot be used in this context. This is a special situation because the default situation rarely is the environmentally most beneficial one. However, a reverse comparison can be meaningful in other decision situations. A less environmentally advantageous glycerol use option could be preferred for example for economic reasons. Then the question would be, which environmental burdens can be avoided when abstaining from implementing this option. This then creates opportunity costs by not realising a profitable option. The avoidance costs can help to decide in this case, too, if the avoidance of environmental burdens is efficient in economic terms. The avoidance costs for this example are shown in Fig. 4-20 for the benchmark scenario PDO production with reference PDO from fossil resources. The only case where there are avoidances in the typical, worst and best case compared to the benchmark is the scenario “direct material use”. Only there, avoidance costs could serve as an indicator supporting decisions. However, the costs for saving one tonne of greenhouse gases (i.e. CO_2 equivalents) vary between about -100 € to almost 900 €. A similar picture can be observed for most of the possible comparisons. Therefore it has to be concluded that avoidance costs are not suitable as a decision support given the uncertainties of the data this study is based on.

Benchmark: PDO reference fossil		Direct material use	Direct combustion	Ethanol reference fossil	Ethanol reference gasoline	Butanol reference fossil	PDO reference fossil	PDO reference starch	Biogas monofermentation	Biogas cofermentation	Biomethane monofermentation	Biomethane cofermentation
		typical										
Climate change	t CO2 eq. / t glycerol	-1.2	N/S	1.4	1.5	0.3	0.0	0.9	0.4	0.2	0.8	0.6
Energy demand	GJ / t glycerol	-17.6	N/S	25.6	28.4	4.3	0.0	18.4	6.7	9.9	15.3	13.3
Acidification	kg SO2 eq. / t glycerol	-2.1	-0.5	2.2	3.2	N/S	0.0	0.7	-0.2	1.3	2.2	1.8
CO2 avoidance costs	€ / t CO2	464	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
Energy saving costs	€ / GJ	31	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
SO2 avoidance costs	€ / kg SO2	255	1582	N/D	N/D	N/D	N/D	N/D	4155	N/D	N/D	N/D
		worst										
Climate change	t CO2 eq. / t glycerol	-3.0	-2.1	0.5	0.6	0.6	0.0	0.3	-1.5	-1.5	-1.3	-1.3
Energy demand	GJ / t glycerol	-49.5	-32.8	4.2	6.7	15.7	0.0	7.3	-30.2	-26.6	-25.0	-25.0
Acidification	kg SO2 eq. / t glycerol	-9.3	-7.1	-4.0	-3.2	3.3	0.0	N/S	-7.5	-6.5	-6.3	-6.2
CO2 avoidance costs	€ / t CO2	-111	-108	N/D	N/D	N/D	N/D	N/D	156	109	80	40
Energy saving costs	€ / GJ	-7	-7	N/D	N/D	N/D	N/D	N/D	8	6	4	2
SO2 avoidance costs	€ / kg SO2	-35	-33	108	156	N/D	N/D	N/D	32	25	17	8
		best										
Climate change	t CO2 eq. / t glycerol	-1.2	0.5	1.3	1.4	0.6	0.0	1.1	0.6	-0.9	1.1	0.3
Energy demand	GJ / t glycerol	-20.9	12.4	25.6	28.7	7.7	0.0	23.7	9.0	N/S	20.6	6.7
Acidification	kg SO2 eq. / t glycerol	-2.3	0.8	2.4	3.5	0.6	0.0	0.9	N/S	1.5	3.2	2.8
CO2 avoidance costs	€ / t CO2	863	N/D	N/D	N/D	N/D	N/D	N/D	N/D	839	N/D	N/D
Energy saving costs	€ / GJ	49	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D
SO2 avoidance costs	€ / kg SO2	436	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D	N/D

Fig. 4-20 Avoidance costs for selected environmental impact categories with the benchmark scenario PDO with reference PDO from fossil resources. Avoidance costs are calculated based on the typical, worst and best case subscenarios. Advantageous or disadvantageous values are highlighted in green or red, respectively. “N/D” indicates that avoidance costs are not defined because there is no avoidance compared to the benchmark. Differences of less than 10 % are defined as not significant (“N/S”).

4.5 Integrated assessment: Overall comparison

An overall comparison of the glycerol use options requires careful weighing of various advantages and disadvantages. The comparisons are based on the benchmarking tables, which were introduced in chapter 4.4.1. Efficiency criteria are not taken into account because they were found to be too uncertain to support any later decisions (see chapter 4.4.2). First, the glycerol use options themselves are analysed and subsequently their influence on the whole biodiesel production process is discussed.

4.5.1 Glycerol use options

The glycerol use option, which is the currently most common way of using glycerol, is the direct material use. At the same time, this option is clearly outstanding for its environmental performance. Regarding any of the environmental indicators, all other assessed options perform worse or a clear preference cannot be stated (Fig. 4-21). The same applies to the technological indicators and the required investments.

	Benchmark: Direct material use	Direct material use	Direct combustion	Ethanol reference fossil	Ethanol reference gasoline	Butanol reference fossil	PDO reference fossil	PDO reference starch	Biogas monofermentation	Biogas cofermentation	Biomethane monofermentation	Biomethane cofermentation
technological	Maturity		0	-	-	-	-	-	0	0	0	0
	Biological risk: GMOs		0	-	-	-	-	-	-	-	-	-
	Biological risk: pathogenicity		0	-	-	-	-	-	-	-	-	-
	Risks through solvents		0	0	0	-	-	-	0	0	0	0
	Odours		0	-	-	-	-	-	-	-	-	-
environmental	Climate change		-	-	-	-	-	-	-	-	-	-
	Energy demand		-	-	-	-	-	-	-	-	-	-
	Acidification		-	-	-	-	-	-	-	-	-	-
	Eutrophication		-	-	-	-	-	0	-	-	-	-
	Photosmog		-	-	-	-	-	-	-	-	-	-
	Ozone depletion		0	-	-	0	-	0	-	0	-	-
econom.	Earnings (EBIT)		-	-	-	+	0	0	-	0	0	0
	Investments		0	-	-	-	-	-	0	0	-	-
	Market potential		+	-	+	+	0	0	+	+	+	+

Fig. 4-21 Qualitative comparison of all assessed main glycerol use pathways to the option of direct material use. The results "+" or "-" indicate that the scenario performs better or worse, respectively, than the benchmark in any case (i.e. same performance of best, typical and worst case subscenario). "0" indicates that the comparisons are ambiguous or differ from the benchmark by less than 10 %. Details about this type of benchmarking figure are discussed in chapter 4.4.1. GMO: genetically modified organism, EBIT: earnings before interest and taxes.

The main drawback of this option is the limited market potential. This scenario is already based on the assumption that lower value chemicals are replaced and not synthetic glycerol itself. Nevertheless, if the biodiesel production is increasing substantially and consequently the glycerol supply rises, the replaced chemicals will be of still lower value and eventually the capacities will be exceeded. Nevertheless, this scenario is probably still a realistic and the most environmentally friendly option in the year 2020 based on the market prognoses which we consider most likely. Besides the market potential, some other glycerol use options offer higher economic profits. According to our estimations, the production of butanol with PDO as a by-product ("Butanol reference fossil") will be more profitable in all cases, i.e. in the typical, best and worst case subscenarios. The production of PDO only shows higher profits than the direct material use for special applications associated with a limited market potential. However, in that case it is the most profitable of all options. Some ways of producing biogas or biomethane have the potential to be more profitable than the direct material use, too. But this requires reaching ambitions optimisation goal for the biogas production of which it is not clear yet if the can be reached.

The production of PDO is the most profitable option under certain market conditions (see chapter 4.3.2, Fig. 4-9). Therefore, the comparison of other glycerol use options to the production of PDO is especially informative (Fig. 4-22). All biotechnological conversions have in common that they require high investments, are less technologically mature than the conventional options or the production of biogas and could potentially bear certain risks. As detailed in chapter 4.1.2, these risks do not need to apply because for example genetically modified or potentially pathogenic organisms do not need to be used. The risks associated with the use of solvents can hardly be avoided for the production of PDO and butanol but they are manageable. Thus, big biotechnological plants of this kind are not inherently safe but do not impose major risks either.

The very important environmental impact categories climate change and energy demand show disadvantages for the other biotechnological conversion pathways compared to the production of PDO (see chapter 4.2.3 for details on possible normalisation methods for environmental impacts). In other categories, which are less important regarding the total amount of emissions, the other conversion methods mostly perform similar or better. This heterogeneous picture is analysed in detail in chapter 4.2.2. It comes to the conclusion that the production of PDO and the production of butanol with PDO as a by-product perform rather similar from an environmental perspective but the production of ethanol is clearly disadvantageous. The same applies to the economic assessment (see chapter 4.3.2). Therefore, a comparison of the most promising innovative conversion methods to PDO or butanol with PDO as a by-product is of special interest. As stated above, they are similar in their environmental performance. Individual optimisations of the efficiencies will be most important in this case. Although the environmental performance is worse than that of the direct material use under the most probable conditions in 2020, this picture may change if the glycerol supply grows faster than expected and the optimisation of the biotechnological processes increase the efficiencies. Higher profits can be expected for the production of PDO compared to the production of butanol under good conditions but it bears higher risks, too. Besides that, the market potentials for butanol are unlimited in respect to the possible glycerol supply. For PDO this is only the case if the prices sink significantly below the current level, which will make it less profitable than the production of butanol.

The possibilities to produce energy from glycerol are more or less equivalent to the production of PDO or butanol regarding their environmental performance. Again, the efficiency optimisations of the of individual processes are more important than the choice among these pathways. The direct combustion stands out because there is little optimisation potential and the predicted relatively good environmental performance can be realised for sure. Only the optional refining of biogas to biomethane with feeding into the natural gas grid causes environmental disadvantages. On the other hand, the energy production is less profitable than the conversion to PDO or butanol. Amongst the energy production scenarios, the biomethane production via cofermentation with other substrates is probably most profitable, the biogas production without refining to biomethane and the direct combustion is expected to cause about as big costs as revenues and the monofermentation is most likely not viable. Like the production of butanol, the energy production is not limited in its capacity. A disadvantage of the biogas production can be the emission of odours. This is more likely to occur in smaller plants, which are often not equipped with the technology to avoid these odours.

Benchmark: PDO reference fossil		Direct material use	Direct combustion	Ethanol reference fossil	Ethanol reference gasoline	Butanol reference fossil	PDO reference fossil	PDO reference starch	Biogas monofermentation	Biogas cofermentation	Biomethane monofermentation	Biomethane cofermentation
technological	Maturity	+	+	0	0	0		0	+	+	+	+
	Biological risk: GMOs	+	+	0	0	0		0	0	0	0	0
	Biological risk: pathogenicity	+	+	0	0	0		0	0	0	0	0
	Risks through solvents	+	+	+	+	0		0	+	+	+	+
	Odours	+	+	0	0	0		0	-	-	-	-
environmental	Climate change	+	0	-	-	-		-	0	0	0	0
	Energy demand	+	0	-	-	-		-	0	0	0	0
	Acidification	+	0	0	0	0		0	0	0	0	0
	Eutrophication	+	0	0	-	0		+	0	0	0	0
	Photosmog	+	+	+	+	+		0	+	+	+	+
	Ozone depletion	+	+	0	0	+		+	+	+	+	+
econom.	Earnings (EBIT)	0	0	-	-	0		0	-	-	-	0
	Investments	+	+	0	0	0		0	+	+	+	+
	Market potential	0	+	-	+	+		0	+	+	+	+

Fig. 4-22 Qualitative comparison of all assessed main glycerol use pathways to the option of PDO production with replacement of PDO from fossil resources. The results "+" or "-" indicate that the scenario performs better or worse, respectively, than the benchmark in any case (i.e. same performance of best, typical and worst case subscenario). "0" indicates that the comparisons are ambiguous or differ from the benchmark by less than 10 %. Details about this type of benchmarking figure are discussed in chapter 4.4.1. GMO: genetically modified organism, EBIT: earnings before interest and taxes.

The various advantages and disadvantages of the assessed glycerol use options can not lead to a scientifically unambiguous ranking of the pathways. Subjective preferences have to be taken into account for a weighting of the indicators and the resulting rating has to be placed in the context of the society.

With respect to defining a winning technology, the result is highly dependent on the future supply of glycerol from the biodiesel industry and therefore on the development of the biodiesel market. Direct material use is clearly the best option from both an environmental and economical point of view which is mainly a consequence of the energy input and lower yield of the innovative bioprocesses. However, a continuing increase in biodiesel production will lead to excess glycerol in the future and the market for material uses is then likely to become saturated. As this expected saturation can be delayed by new ways of using glycerol without conversion, these options should be investigated. After a saturation, the winning technology will be the biotechnological conversion of glycerol to either PDO or butanol (in combination with PDO). Since the high energy input and lower yield of the innovative bioprocesses are variables that are likely to be significantly improved with future efforts, the PDO process is estimated to be the future winning technology out of those that were assessed in this project from both an environmental and economical perspective. This will be discussed in more detail in chapter 5.1.

4.5.2 Whole biodiesel production

The choice of the glycerol use pathway does not affect the overall economic or environmental performance of the biodiesel production significantly unless very disadvantageous options are chosen and implemented with the worst plausible efficiency. From the environmental standpoint, other choices are much more important for the sustainability of the biodiesel production. The biggest influence has a possible land use change like deforestation for planting oil palms or soy beans. Also the choice of the feedstock, which is mostly soy beans, rape seed or palm oil, is more important than the glycerol use (Fig. 4-8). For details please see the results of the environmental assessment of the whole biodiesel process chain in chapter 4.2.6. Furthermore, none of the assessed pathways has the potential to change the currently unfavourable economy of the biodiesel production to result in profits without subsidies (see chapter 4.3.2).

5 Conclusions, recommendations and outlook

Various options to use glycerol were investigated under technological, environmental and economic aspects in the previous chapters. In this chapter, the individual results are joined into a general picture. The essential results are presented as answers to questions listed in chapter 1, which can be summarised in two central thematic complexes: first, which is the most sustainable way to use glycerol resulting from biodiesel production, and second, how do the different usage pathways affect the sustainability of the biodiesel production as a whole. All assessed usage pathways for glycerol are considered in this process:

1. The direct material use of glycerol
2. The generation of energy by direct combustion of glycerol or production of biogas out of glycerol
3. The biotechnological conversion of glycerol into ethanol, butanol or PDO (1,3-propanediol, a precursor for the production of bioplastics).

Based on the findings and the overall evaluation, recommendations for individual groups of decision makers are derived (chapter 5.2: Recommendations). Finally, the results of this study are placed in a broader context (chapter 5.3: Outlook).

Note: Generally, there are no explanations given for particular results mentioned in this chapter apart from a few exceptions. Detailed background information can be found in the respective chapters concerning the technological, environmental, economic and integrated assessment.

5.1 Conclusions

Core question 1:

What is the most sustainable way to use glycerol resulting from biodiesel production?

The assessment from technological, environmental and economic perspectives yielded the following results for the various use options of glycerol resulting from the biodiesel production:

- Direct material use (glycerol as final product):

  From an environmental point of view, the best option so far was the substitution of conventional, i.e. petrochemically produced glycerol by bio-glycerol. The increasing amount of glycerol resulting from biodiesel production meanwhile squeezed petrochemical synthesised glycerol out of the market, so that this pathway is no option for relevant amounts of glycerol in the future. Thus this option has no further potential and is excluded from further consideration.

  The second option for a direct use of bio-glycerol is a substitution of simpler chemicals, e.g. as additives to cosmetics or food. This is currently the most common way to use glycerol. This only requires a technological simple purification of the glycerol, which can be realised with limited financial investments. From an environmental perspective, this is the best option of those assessed in this study. In the future, increasing amounts of glycerol will be tendentially used in areas of minor value unless new applications for a direct material use will become accessible. This reduces the achievable profits. As in the lower-value application areas substances with tendentially lower environmental impacts will be replaced, the environmental advantages will generally be reduced.

- Energy generation

  From an environmental and economic point of view, the use option of direct combustion of glycerol in stationary plants for provision of power and / or heat and the option of biogas production can be rated similarly sustainable. In detail, i.e. depending on the specific design, the investigated processes of energy generation show small differences: the purification of biogas to biomethane for feeding into the natural gas grid for example result in environmental disadvantages and probably in economic advantages. Another example is the production of biogas via monofermentation of glycerol without mixing in other substrates, which in tendency has less advantages from an environmental and economic perspective.

  Compared to the option of direct material use mentioned above, the use options of glycerol for energy generation are disadvantageous under environmental and economic perspectives. Biogas production only leads to substantial economic and environmental advantages compared to the direct material use if synergies by cofermentation, i.e. a combined use of glycerol together with other substrates for biogas production, can be realised. On the other hand, the use of glycerol for energy generation has an unlimited uptake capacity, whereas the direct material use currently shows only limited potentials. From a technological perspective, an energetic use has similar advantages as the direct material use. Mature and relatively simple plants can be built with limited financial investments. However, an increase in the efficiency of the biogas production from glycerol is still possible by an optimisation of the fermentation conditions and an improved process control.

- Conversion of glycerol to ethanol, butanol or PDO

  The conversion of glycerol to ethanol, butanol or PDO by means of innovative biotechnological processes is technically demanding and energy consuming, which causes high economic and environmental expenditures. This is the main reason why these options perform environmentally disadvantageous compared to the direct material use of glycerol. From an economic point of view, the higher expenditures for products of higher value can pay off, although partially significant economic risks exist.

  Compared to each other, the production of PDO or butanol is equivalent from an environmental perspective, whereas the production of ethanol shows notable disadvantages. Regarding the comparison of the production of PDO and butanol and the use options for generating energy, no clear preference can be expressed, as the results overlap depending on the specific design. This is not affected by the fact that the production of butanol provides PDO as a by-product. Especially the investigated innovative biotechnological processes show relatively wide bandwidths in positive as well as negative directions. Clear advantages can only be expected for the production of PDO under optimal conditions.

  From an economic perspective, the production of butanol shows advantages under all assessed conditions compared to the direct material use of glycerol, and additionally offers nearly unlimited market capacities, as butanol already is a well established platform chemical. Under certain conditions, PDO production can in some cases achieve higher profits than butanol production. However, this comes along with higher risks, which are partially due to uncertain market potentials.

In summary, it can be said that the direct material use of glycerol will in tendency lose importance, depending on the expansion of the biodiesel market and thus the increase in the production of glycerol – at least if no completely new material use options will be identified. To the extent to which a direct material use cannot be realised anymore because of limited capacities, innovative use options and the use for energy production including biogas can play a bigger role in future. There is no clear winner amongst these options from an environmental perspective. However, the production of ethanol and the optional refining of biogas to biomethane are disadvantageous regarding almost all environmental aspects compared to the other usage options of glycerol. All other processes, especially the production of PDO, butanol or biogas via cofermentation, each have different environmental potentials. It will be essential to realise these individually. Under the assumed conditions, the production of butanol stands out due to its high probability to be economically profitable, whereas the production of ethanol will likely lead to losses. The highest potential profits can be expected for the production of PDO. The innovatively produced PDO involves high economic chances but high risks as well

Detailed question 1a:

What are the advantages and disadvantages of innovative glycerol usage pathways in comparison to the currently existing pathways?

Each pathway has specific technological, environmental and economic advantages and disadvantages, which are all discussed in detail in chapter 4. Besides these, the novelty of the innovative pathways itself naturally generates certain advantages and disadvantages compared to the currently existing pathways. All innovative technologies perform worse than the existing pathways with respect to their environmental implications and still require efforts in development. As discussed above, most innovative glycerol use options can be valuable alternatives to the currently preferred direct material use if its capacities as of today are exceeded. Besides efforts in development, all innovative pathways require investments in new facilities. These market entry barriers are lowest for the biogas production via cofermentation because it can be realised without further development in a small scale even in existing biogas plants although e. g. an optimisation of the substrate mixtures could substantially improve the results. A biotechnological conversion of glycerol to other chemicals requires dedicated expensive plants and most of the optimisations have to be completed before the construction can be started. Uncertainties may make it challenging to find investors for such projects although high profits are possible. The technological risks associated with the assessed new technologies are controllable. Potentially pathogenic organisms as well as genetically modified organisms do not need to be used.

Detailed question 1b:

What is the influence of different usage pathways for the by-products on the overall results and which usage shall be preferred?

In the case of biotechnological conversions, the refining of by-products accounts for a substantial part of all environmental and economic expenditures. Therefore, it is only worthwhile for PDO that is generated as a by-product of the butanol production. Besides this, only lower value compounds are produced as by-products in relatively low concentrations. The remaining extracted fermentation broth can only be utilised for a secondary biogas production, which improves the overall performance of the process. The same applies to the use of the digestate after biogas production as a fertiliser although regulatory restrictions may apply if genetically modified or potentially pathogenic organisms have been used in the prior processes.

Detailed question 1c:

What is the relative importance of individual life cycle steps on the overall results and which optimisation potentials can be identified?

Regarding the biotechnological conversions, the energy demand for product separation from the fermentation broth causes the biggest environmental burdens. Moreover, the overall yields and the used energy sources influence the environmental performance significantly while affecting most life cycle steps. Therefore, the improvement of these parameters is the most promising optimisation strategy from an environmental point of view. In many cases, energy savings and efficiency gains are win-win situations for economy and environment. Which parameter has the highest priority regarding environment and economy depends on the process and was assessed in /GLYFINERY 2012e/. The most significant optimisation potential for the biogas production is caused by potential synergy effects when glycerol is fermented together with other substrates.

Core question 2:

How do the different usage pathways for glycerol from biodiesel production affect the sustainability of the biodiesel production as a whole?

None of the assessed use options of glycerol critically affects the environmental or economic sustainability of the biodiesel production. From an environmental perspective, the conditions of cultivating oil-crops, in particular possible land use changes, are for example more important than the way of using glycerol. Maximising the profits from selling glycerol is of course desirable for the biodiesel producer from an economic point of view. On the other hand, the operation of existing biodiesel plants or the construction of new ones will in future depend only to a minor extent on the profits from glycerol but primarily on different, especially political, constraints.

5.2 Recommendations

Based on the single results of the technological, environmental, economic and integrated assessments as well as the conclusions discussed above, the following recommendations for individual groups of decision makers, especially science, industry and politics, can be given:

- The assessed innovative biotechnological conversion processes of glycerol to ethanol, butanol or PDO are currently still under development and still require significant efforts to reach market maturity. If these processes will be developed further in future, it should be considered that their environmental balance compared to the other options like direct material use or use for energy production is not necessarily better, but can be even notably worse in certain cases - especially for ethanol processing. Insofar, further subsidies for the development of the options investigated here to market maturity are not recommended from an environmental perspective. However, this situation may change if the future market will be saturated by bio-glycerol and no further material use options will emerge. Especially PDO production may then be a recommendable alternative to the use for energy production from an environmental and economic perspective. In this case a further support of research and development would be suitable.

- In particular, the further development of the biotechnological production of ethanol from glycerol is not recommendable, as this pathway is environmentally and economically disadvantageous compared to both other assessed biotechnological processes. A further development would only be reasonable, if other assessment criteria than those mentioned here would be considered more important and significant advantages regarding these aspects would be expected. A future use of glycerol-based ethanol as fuel may for example gain attention because conventional ethanol from agricultural biomass is increasingly associated with competitions about food and cultivating area, which would not be the case for glycerol-based ethanol.
- The further development of the biotechnological conversion processes should focus on increasing yields and on a significant reduction of the energy input for product purification. Based on the assessed evaluation parameters, neither the enhancement of yields nor the improvement of the energy efficiency should be given a priority, as both options have different impacts on the individual indicators especially concerning the environmental balance. A further scientific development of the existing approaches and subsequently efforts for an upscaling of these techniques, which are currently in a pilot stadium, are essentially required.
- Future projects on the development of sustainable biotechnological processes should focus from the beginning on the purification of the substances from the fermentation broth. This could result in objectives for example concerning the required product concentrations.
- Furthermore, biotechnological research should focus on additional substances, which can be produced from glycerol via biotechnology. This is most important, if the so called functional groups of the glycerol molecule which are chemically especially valuable can be utilised thereby.
- The transfer of insights gained from the research focuses mentioned here to other chemical feedstocks or products can be an additional benefit. This can strengthen the field of biotechnology in general.
- Other conversion techniques like chemical-catalytical processes should be considered besides the biotechnological processes because the latter generally have disadvantages of low product concentrations in the fermentation broth and hence of substantial energy demands for the purification of the target product.
- Focus areas of the further development of the glycerol utilisation in biogas plants are especially potential synergy effects concerning the cofermentation and the nutrient demand of the monofermentation plants. Scientific research and subsequent field trials are required for optimising the existing concepts. If this results in environmental advantages and an economically sustainable operation is possible, the market introduction could be subsidised.
- Searching for further options for a direct use of glycerol – apart from the already existing options like in the cosmetics or food industry – is highly recommended, as especially the

environmental balance of a direct use is in tendency is more favourable than for the conversion of glycerol to other substances. The main reasons are considerable losses and high energy demands, which are often associated with conversion processes. Glycerol only got into the focus for alternative use options in the cosmetics, food, fodder, pharmaceutical, chemical and other industries since the biodiesel production increased considerably and prices sank significantly because of that. Therefore, the potential for utilising glycerol in these industries is probably not yet fully exploited.

5.3 Outlook

The presented research project “Sustainable and integrated production of liquid biofuels, green chemicals and bioenergy from glycerol in biorefineries” was started with the background of an expected oversupply of glycerol resulting from the biodiesel production and hence a saturation of the current use options – accompanied by falling world market prices for glycerol. The development of new usage pathways especially in the field of biotechnological conversion and the analysis of their sustainability was hence defined as objective of this project. Caused by declining world market prices for glycerol, this relatively high-value chemical gets attractive for further alternative use options as well. The increasing direct material use of glycerol as in products of the cosmetics or pharmaceutical industry is one example. Thus the variety of use options is hardly foreseeable and may counteract the price decline by a rising demand. Apart from the direct material use, bio-glycerol can be used as well as a feedstock for chemical processes. Big chemical companies for example have the opportunity to independently implement new conversion processes largely independent from subsidies. One example is the recent opening of a big factory in Thailand by Solvay for the production of epichlorohydrin from glycerol. The previous process of chemical synthesis of glycerol is quasi inverted there in order to produce a precursor molecule for epoxy resins.

Hence, the glycerol pathways assessed in this study represent only a part of the future use options of glycerol resulting from biodiesel production (although an important one), if a considerable increase of the glycerol supply should really take place in the next years. Thus, it will be the subject of future research to identify further use options for glycerol and to assess their environmental impact, economic effects and technological performance – analogous to the evaluation criteria used in this study. Furthermore, a politically relevant and comprehensive rating of glycerol use options also has to take other aspects into account like the security of the energy and food supply, social aspects or the progress of knowledge, gained through development of high-tech processes, which is especially important for industrialised countries in Europe. This also must be left for further studies to investigate. Nevertheless, this study already shows a substantial potential for future alternative use options of glycerol resulting from biodiesel production if its supply considerably increases in the future.

With respect to defining a winning technology, the result is highly dependent on the future supply of glycerol from the biodiesel industry and therefore on the development of the biodiesel market. Direct material use is clearly the best option from both an environmental and economical point of view which is mainly a consequence of the energy input and lower yield of the innovative bioprocesses. However, a continuing increase in biodiesel production will lead to excess glycerol in the future and the market for material uses is then likely to become saturated. As this expected saturation can be delayed by new ways of using glycerol without conversion, these options should be investigated. After a saturation, the winning technology will be the biotechnological conversion of glycerol to either PDO or butanol (in combination with PDO). Since the high energy input and lower yield of the innovative bioprocesses are variables that are likely to be significantly improved with future efforts, the PDO process is estimated to be the future winning technology out of those that were assessed in this project from both an environmental and economical perspective.

6 References

/Amon et al. 2006/ Amon, T., Amon, B., Kryvoruchko, V., Bodiroza, V., Pötsch, E., Zollitsch, W.: Optimising methane yield from anaerobic digestion of manure: Effect of dairy systems and of glycerine supplementation, International Congress Series 1293: 217-20, 2006.

/ATCC 2012/ http://www.lgcstandards-atcc.org/BiosafetyLevels/tabid/1157/Default.aspx, Accessed 20.02.2012.

/Beta Analytic 2012/ http://www.betalabservices.com/biofuels/synthetic-ethanol.html. Accessed 20.02.2012.

/BAuA 2010/ Bundesanstalt für Arbeitsschutz und Arbeitsmedizin: Technical Rules for Biological Agents 466 - Classification of Prokaryotes (Bacteria and Archaea) into Risk Groups, *GMBl 2010, No. 68-80 of 06.12.2010, pp. 1428-1667,* http://www.baua.de/en/Topics-from-A-to-Z/Biological-Agents/TRBA/TRBA-466_content.html

/Borken et al. 1999/ Borken, J., Patyk, A., Reinhardt, G. A.: Basisdaten für ökologische Bilanzierungen (Basic data for ecological balances). Verlag Vieweg, Braunschweig / Wiesbaden, 1999.

/California Energy Commission 2012/ http://energyalmanac.ca.gov/gasoline/margins/index.php, Accessed 20.02.2012.

/CDC 2012/ http://www.cdc.gov/od/eaipp/, Accessed 20.02.2012.

/ClimateTechWiki 2012/ http://climatetechwiki.org/technology/ethanol. Accessed 20.02.2012.

/CML 2004/ Institute of Environmental Sciences (CML): CML's impact assessment methods and characterisation factors. Department of Industrial Ecology, Leiden, 2004.

/CML 2009/ Institute of Environmental Sciences (CML): CML Impact assessment version 3.6 (CML-IA). Department of Industrial Ecology, Leiden, 2009.

/Demirbas 2007/ Demirbas A.: Importance of biodiesel as transportation fuel. Energy Policy (9): 4661-4670, 2007.

/Department of Agriculture and Food 2006/ Department of Agriculture and Food, Government of Western Australia: Biodiesel Production and Economics, 2006.

/EC 1990/ Council Directive 90/679/EEC of 26 November 1990 on the protection of workers from risks related to exposure to biological agents at work (seventh individual Directive within the meaning of Article 16 (1) of Directive 89/391/EEC), adopted 20 November, 1990; revised 18 September 2000

/EC 2000/ EC DIRECTIVE 2000/54/EC of the European Parliament and of the Council of 18 September 2000, on the protection of workers from risks related to exposure to biological agents at work

/EC 2009/ Directive 2009/28/EC of the European Parliament and of the Council on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0016:0062:EN:PDF, 23 April 2009.

/Ecoinvent 2010/ Frischknecht, R. et al.: ecoinvent Data v2.2 – Ökoinventare für Energiesysteme. ESU-services, Uster, 2007.

/EFSA 2012/ European Food Safety authority (EFSA) http://www.efsa.europa.eu/en/topics/topic/gmo.htm), Accessed 20.02.2012.

/Eurostat 2007/ Eurostat: Energy, transport and environment indicators. European Communities, Luxembourg, 2007.

/Eurostat 2010/ http://epp.eurostat.ec.europa.eu/tgm/table.do?tab=table&init=1&language=en&pcode=tps00001&plugin=1; download February 2010.

/Fankhauser 1995/ Fankhauser S.: Valuing Climate Change: The Economics of the Greenhouse. London, 1995.

/GEMIS 2010/ Fritsche, U. et al.: Global Emission Model for Integrated Systems (GEMIS), Version 4.6. Öko-Institut e.V., Darmstadt, 2010.

/GLYFINERY 2012a/ www.glyfinery.net

/GLYFINERY 2012b/ Holm, A. K., Köppen, S., Reinhardt, G., Schorb, A., Gärtner, S., Krüger, M., Liebich, A.: Technological Assessment - Final Report (Deliverable 7.4). Prepared within the GLYFINERY project (Sustainable and integrated production of liquid biofuels, bioenergy and green chemicals from glycerol in biorefineries), Technical University of Denmark, Lyngby, 2012.

/GLYFINERY 2012c/ Reinhardt, G., Gärtner, S., Häfele, S., Keller, H., Köppen, S., Krüger, M., Liebich, A., Müller-Lindenlauf, M., Schorb, A.: Environmental Assessment - Final Report (Deliverable 7.5). Prepared within the GLYFINERY project (Sustainable and integrated production of liquid biofuels, bioenergy and green chemicals from glycerol in biorefineries), IFEU Heidelberg, 2012.

/GLYFINERY 2012d/ Reves J. B.: Economic assessment – Final report (Deliverable 7.6). Prepared within the GLYFINERY project (Sustainable and integrated production of liquid biofuels, bioenergy and green chemicals from glycerol in biorefineries), BioGasol, Ballerup, Denmark, 2012.

/GLYFINERY 2012e/ Reinhardt, G., Gärtner, S., Keller, H., Krüger, M., Müller-Lindenlauf, M., Reves J. B., Schorb, A.: Optimisation of product chains - Final Report (Deliverable 7.7). Prepared within the GLYFINERY project (Sustainable and integrated production of liquid biofuels, bioenergy and green chemicals from glycerol in biorefineries), IFEU Heidelberg and BioGasol Copenhagen, 2012.

/Hutňan et al. 2009/ Hutňan, M., Kolesárová, N., Bodík, I., Spalková, V., Lazor, M.: Possibilities of anaerobic treatment of crude glycerol from biodiesel production, 36th International Conference of Slovak Society of Chemical Engineering, May 25-26, 2009.

/IFEU 2011/ Continuously updated internal IFEU Database. Heidelberg, 2011.

/IPCC 1996/ Intergovernmental Panel on Climate Change (IPCC): Economic and Social Dimensions of Climate Change. Cambridge, New York, Melbourne, 1996.

/IPCC 2007/ IPCC Fourth Assessment Report, Chapter 2, Changes in Atmospheric Constituents and Radiative Forcing, 129-234, 2007.

/ISO 2006/ Deutsches Institut für Normung e.V. (German Institute for Standardisation): ISO 14040:2006(E) & ISO 14044:2006(E). Environmental management – Life cycle assessment – Requirements and guidelines. Beuth Verlag, Berlin, 2006.

/JRC 2011/ European Commission-Joint Research Centre - Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook - Recommendations for Life Cycle Impact Assessment in the European context, EUR 24571 EN, Publications Office of the European Union, Luxemburg, 2011.

/Klöpffer & Renner 1995/ Klöpffer, W. & Renner, I: Methodik der Wirkungsbilanz im Rahmen von Produkt-Ökobilanzen unter Berücksichtigung nicht oder nur schwer quantifizierbarer Umwelt-Kategorien. In: Methodik der produktbezogenen Ökobilanzen – Wirkungsbilanz und Bewertung. Umweltbundesamt (UBA), Berlin, 1995.

/Kryvoruchko et al. 2004/ Kryvoruchko, V., Amon, T., Amon, B., Gruber, L., Schreiner, M., Zollitsch, W.: Influence of nutrient composition on methane production from animal manures and co-digestion with maize and glycerine, International Scientific Conference: Bioecotechnologies and Biofuel in Agroindustry, June 3-4, pp 143-148, 2004.

/Kurian 2005/ Kurian, J. V.: A New Polymer Platform for the Future – Sorona from Corn Derived 1,3-Propanediol, Journal of Polymers and the Environment 13(2), 159-67, 2005.

/Leeuw 2002/ Leeuw, F. D.: A set of emission indicators for long-range transboundary air pollution. Bilthoven, 2002.

/Nelder 2009/ Nelder C.: How to invest in natural gas. Energy & Capital http://www.energyandcapital.com/articles/natural+gas-barnett-chesapeake/853. Accessed 20.02.2012.

/Neste Oil 2011/ Neste Oil. Annual report 2010

/Nordhaus 1994/ Nordhaus W.: Managing the Global Commons. The Economics of Climate Change. Cambridge (Mass.), London, 1994.

/Pehnt et al. 2010/ Pehnt M., Paar A., Bauer M.: CO_2-Vermeidungskosten. Entwicklung eines Rechners zum Vergleich verschiedener Energieversorgungsanlagen. Final Report. IFEU Heidelberg, 2010.

/Ravishankara et al. 2009/ Ravishankara, A. R., Daniel, J. S., Portmann, R. W.: Nitrous Oxide (N2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century. Sciencexpress, Science 326: 123, DOI: 10.1126/science.1176985, 2009.

/Seki et al. 2003/ Seki, H., Shiohara, M., Matsumura, T., Miyagawa, N., Tanaka, M., Komiyama, A. & Kurata, S.: Prevention of antibiotic-associated diarrhea in children by Clostridium butyricum MIYAIRI., Pediatr Int., Feb;45(1):86-90., 2003

/Shen et al. 2009/ Shen, L., Haufe, J., Patel, M. K.: Product overview and market projection of emerging bio-based plastics, Universiteit Utrecht, 2009.

/Short et al. 1995/ Short W., Packey D. J., Holt T.: A Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies. National Renewable Energy Laboratory, (NREL), Colorado, USA, 1995.

/SRI Consulting 1999/ Process Economics Program Yearbook International, 1999

/PB Power 2004/ PB Power: The Costs of Generating Electricity. The Royal Academy of Engineering, London, 2004.

/Taylor et al. 2010/ Taylor J., Halai I., Seng S.: Regional issues concerning biodiesel complicate the global market for glycerine. ICIS Chemical Business, September, 2010.

/Timmerhaus et al. 2004/ Timmerhaus K. D., Peters M. S., West R. E.: Plant Design and Economics for Chemical Engineers. McGraw Hill, 5., 2004

7 Annex: Additional detailed results

The annex contains additional results, which extend the main report.

7.1 Additional results of the environmental assessment

Additional results of the environmental assessment concerning life cycle stages, biotechnological conversion scenarios, use for energy production and normalisation by inhabitant equivalents are presented here.

7.1.1 Life cycle stages: Additional impact categories

The credits and expenditures resulting from different glycerol processing steps of the biotechnological conversion scenarios were studied for all environmental impact categories. The results for the other impact categories and the summary of all results can be found in chapter 4.2.1.

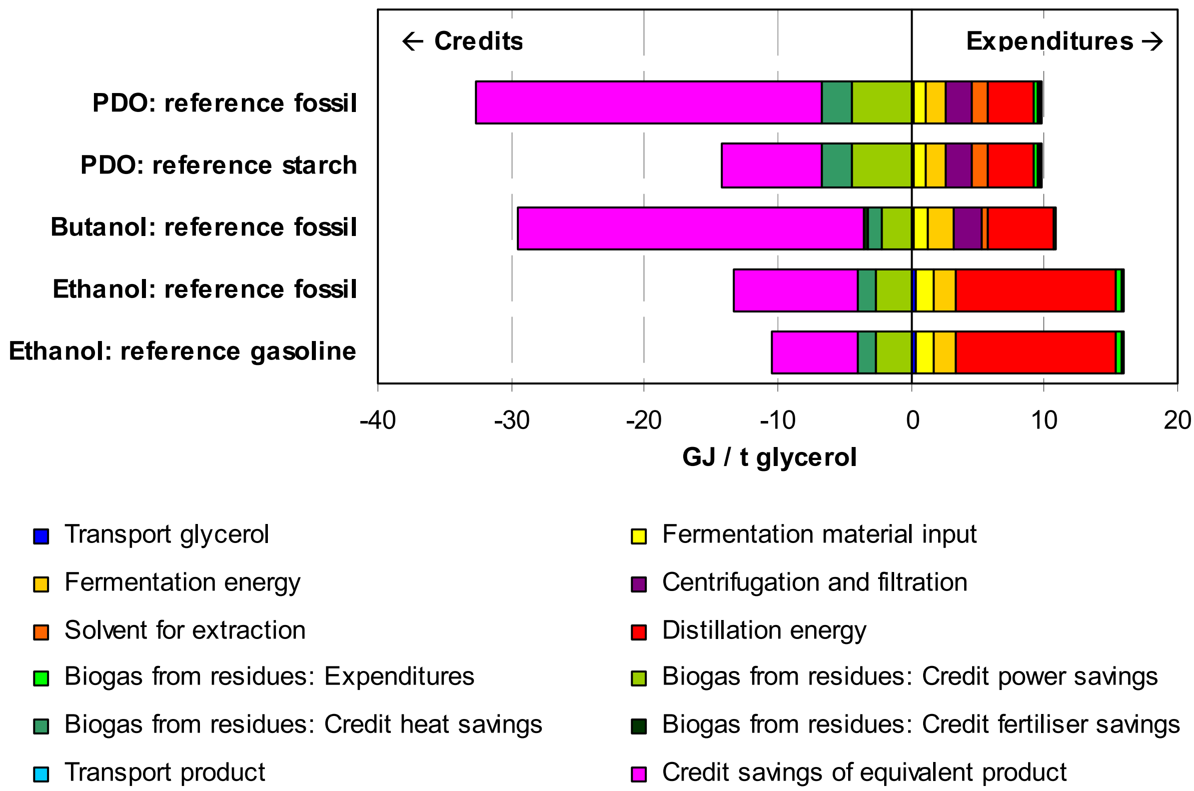


Fig. 7-1 Contribution of different glycerol processing steps to non-renewable energy consumption. Typical scenario.

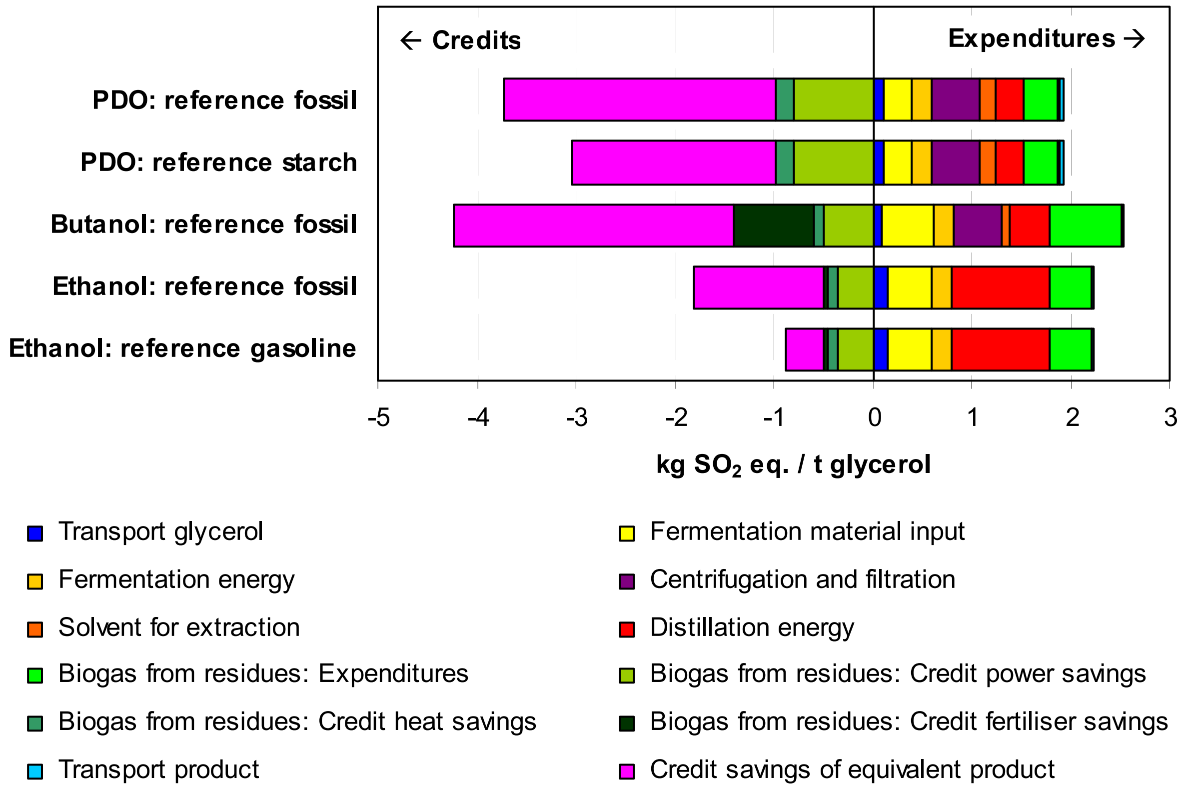


Fig. 7-2 Contribution of glycerol processing steps to acidifying emissions. Typical scenario.

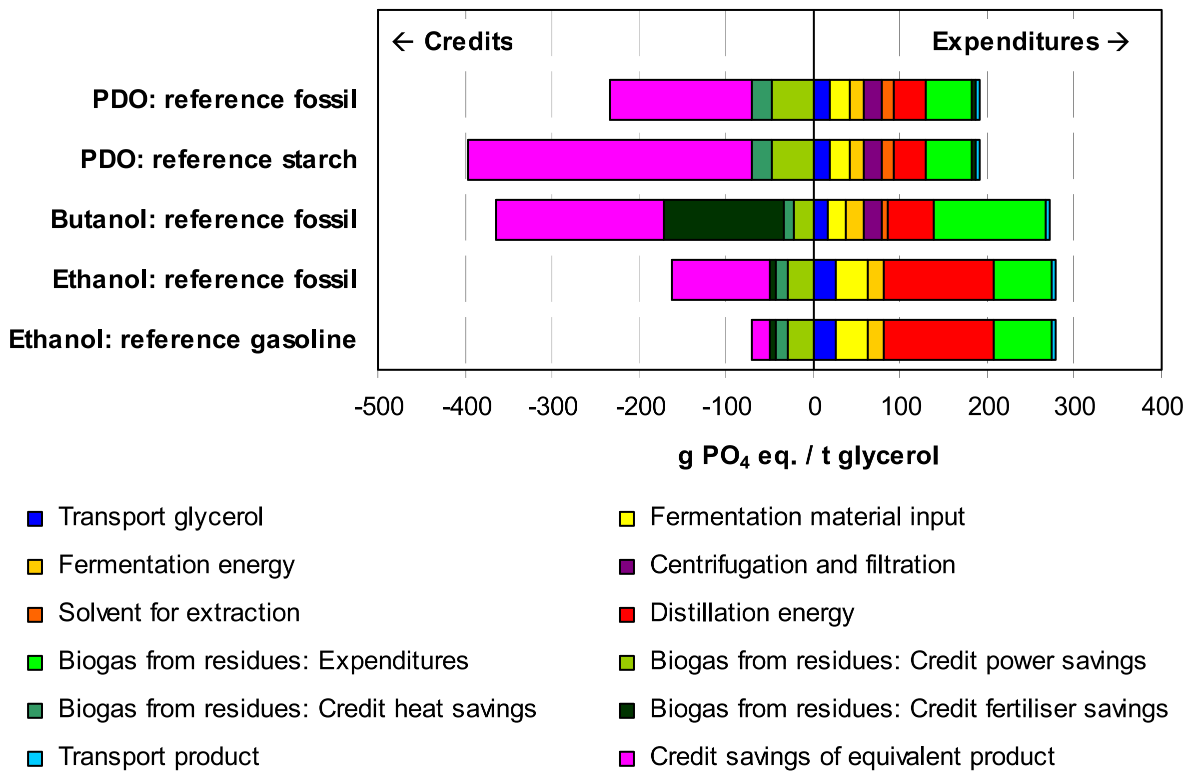


Fig. 7-3 Contribution of glycerol processing steps to eutrophication. Typical scenario.

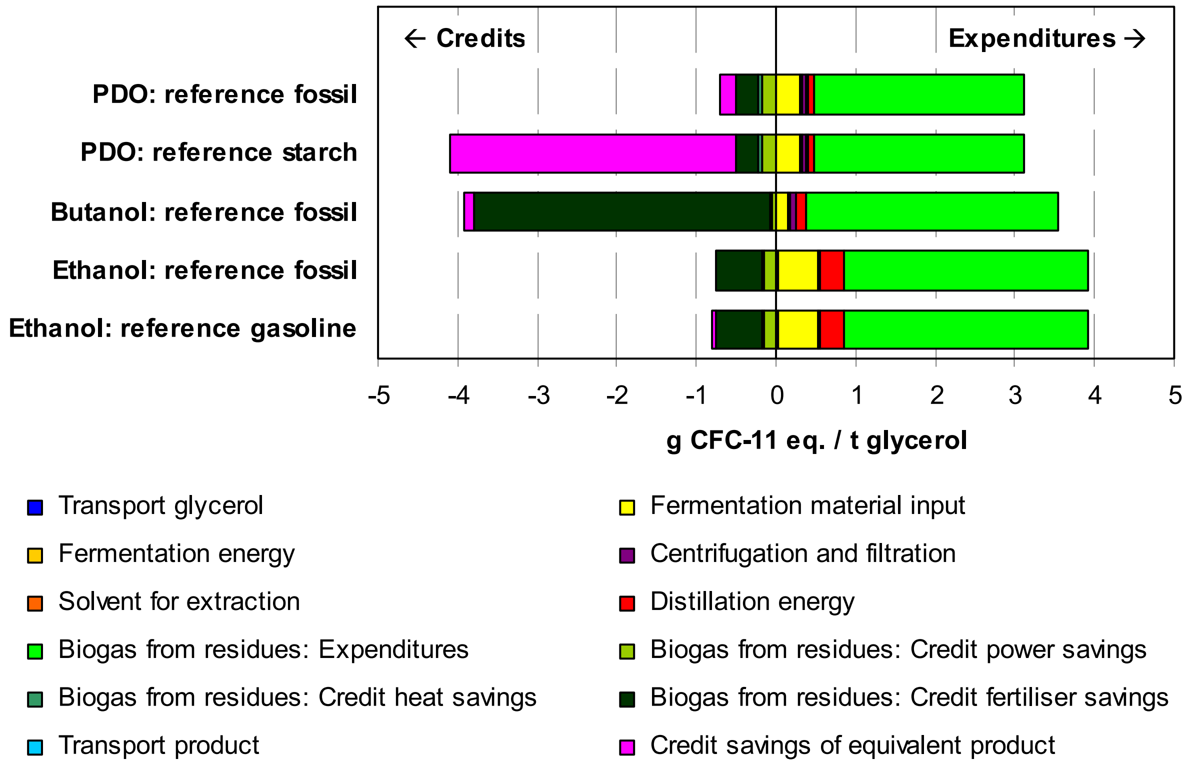
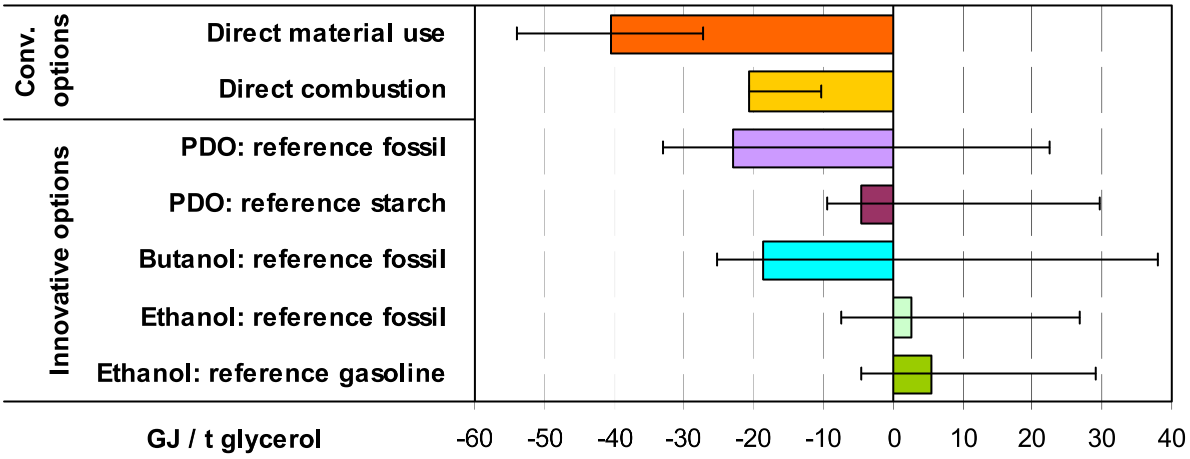


Fig. 7-4 Contribution of glycerol processing steps to ozone depletion. Typical scenario.

7.1.2 Biotechnological conversion scenarios: Additional impact categories

To provide a complete basis for the overall comparison, additional results from the environmental assessment of the basic scenarios are presented below.



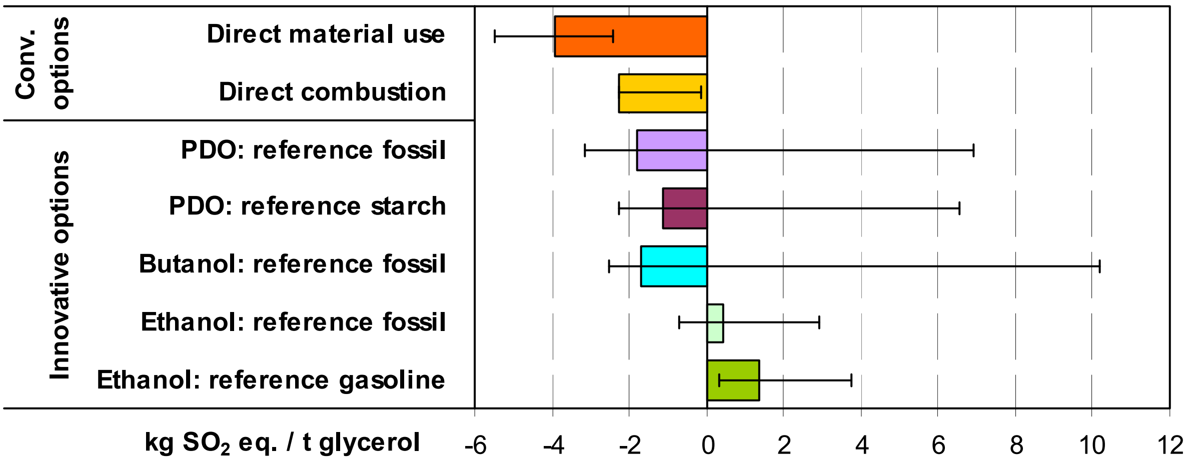


Fig. 7-5 Comparison of the environmental effects of innovative chemical and conventional scenarios for glycerol processing in additional impact categories: non-renewable energy demand (in GJ) and acidification (in SO_2 equivalents). Coloured bars show results for the typical scenario. Thin lines describe results for worst case and best case sub-scenarios (i.e. bandwidth). Note: For the scenario direct combustion, the typical case shows the lowest burdens in some categories.

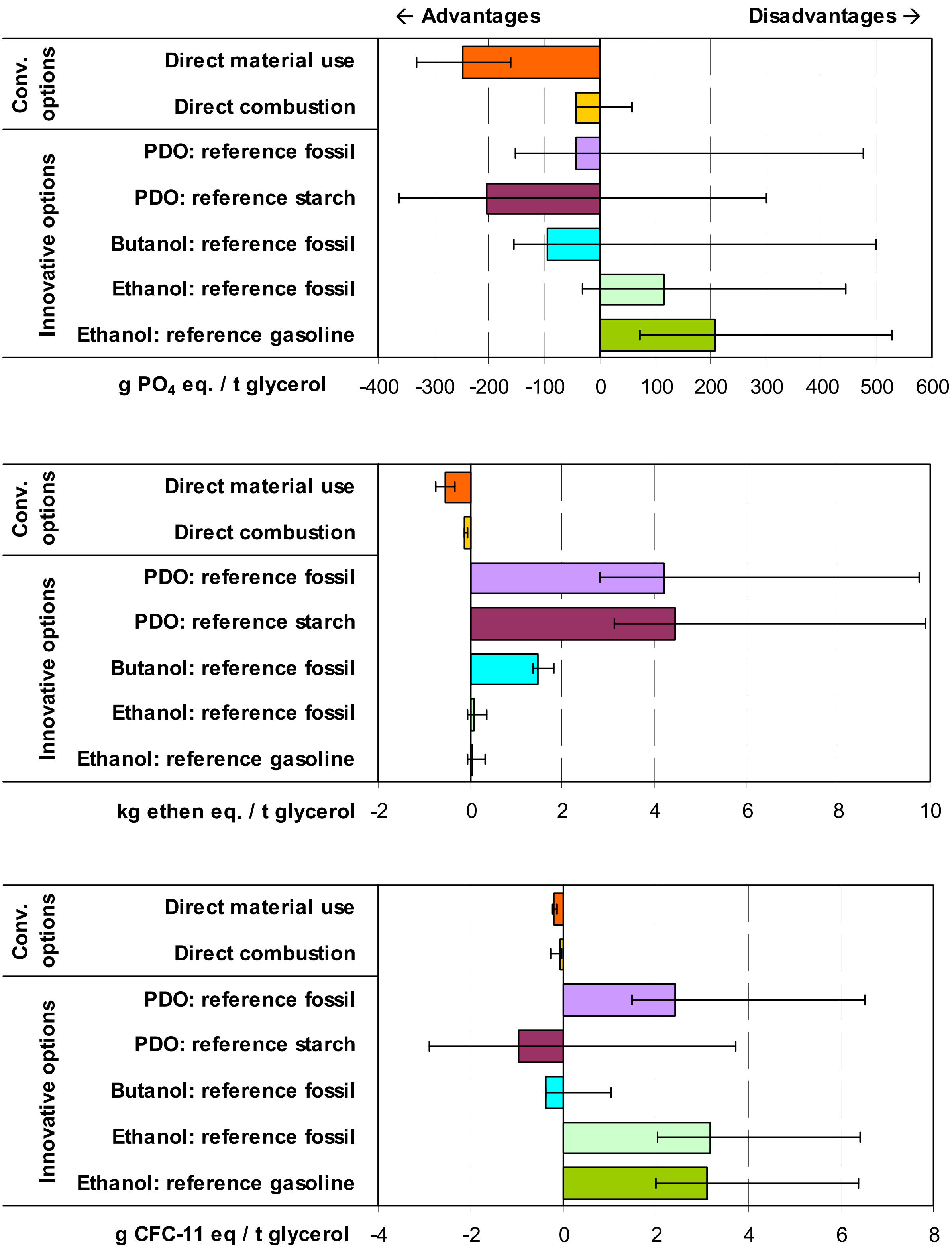


Fig. 7-6 Comparison of the environmental effects of innovative chemical and conventional scenarios for glycerol processing: terrestrial eutrophication (in PO_4 equivalents), photosmog (in ethene equivalents) and ozone depletion (in CFC-11 equivalents). Coloured bars show results for the typical scenario. Thin lines describe results for worst case and best case sub-scenarios (i.e. bandwidth). Note: For the scenario direct combustion, the typical case shows the lowest burdens in some categories.

How to read the figure (*on previous page*):

Example 1. Terrestrial eutrophication of material use scenario (first bar, Fig. 7-6 upper panel)

Direct material use of glycerol as replacement of diols from petrochemical sources saves 250 g PO_4 eq. emission per ton of glycerol. The bandwidth is about 350 (best case) to 150 (worst case) g PO_4 eq. savings per ton of glycerol.

Example 2. Terrestrial eutrophication of ethanol vs. gasoline scenario (last bar, Fig. 7-6 upper panel)

The processing of one ton of glycerol to ethanol for use as transportation fuel, which replaces gasoline, causes additional emissions of about 200 g PO_4 eq. in the typical case. The bandwidth of possible results is the additional emission of about 150 (best case) to 550 (worst-case) g PO_4 eq. per ton of glycerol.

Interpretation: Processing to ethanol (to replace gasoline) causes about 450 g PO_4 eq. more of emissions than direct material use.

7.1.3 Use for energy production: Additional impact categories

The main results for the production of biogas and biomethane from glycerol are presented in chapter 4.2.5. Fig. 7-7 shows results for additional environmental impact categories.

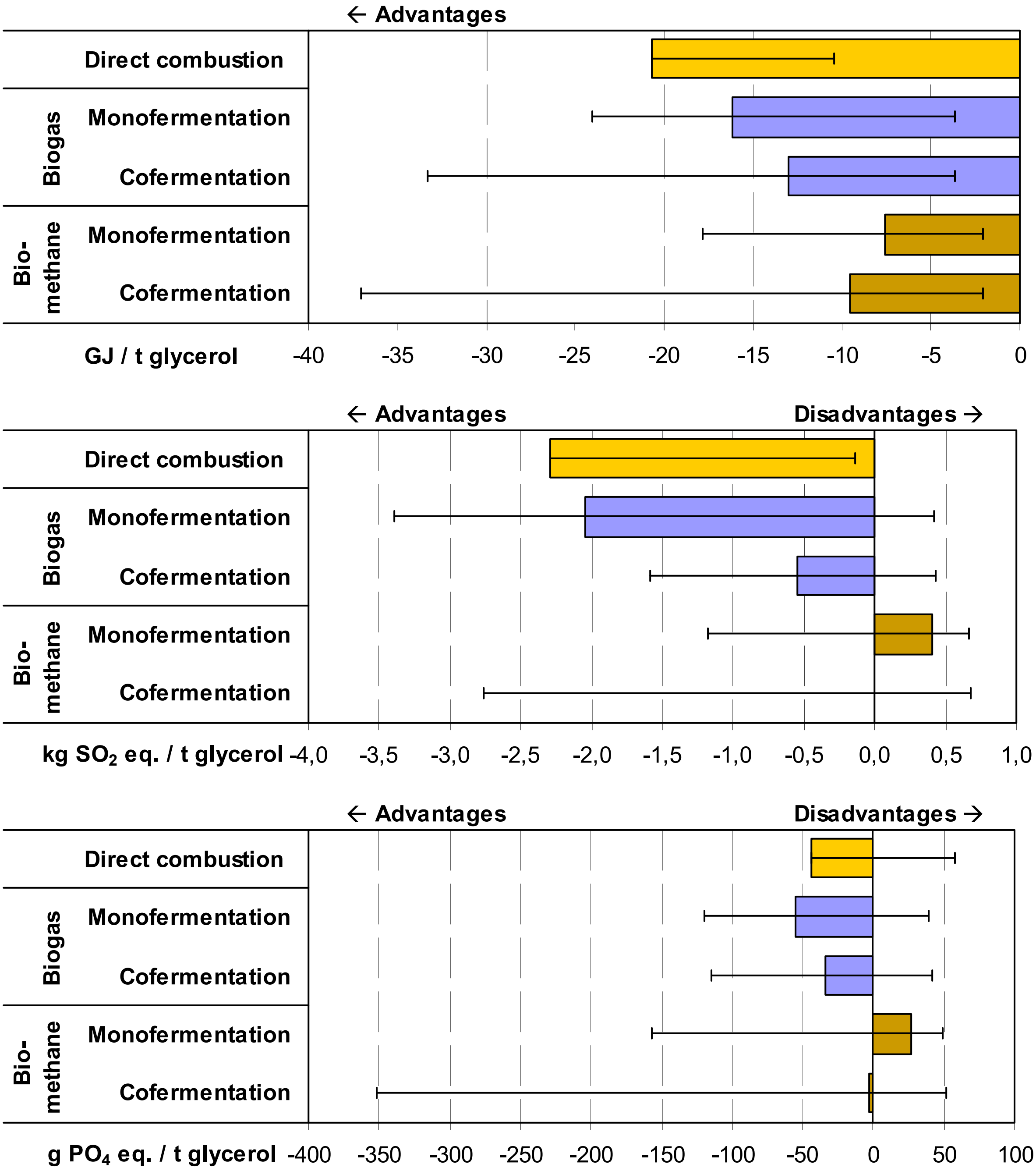


Fig. 7-7 Comparison of the environmental effects of energetic use of glycerol via conventional combustion and innovative biogas fermentation with and without refining to biomethane. For cofermentation, data for cofermentation with corn are shown. Data for manure cofermentation are almost identical. Coloured bars show the typical cases of the standard scenarios (as described in the scenario descriptions in chapter 3.3). Thin lines describe results for worst case and best case (i.e. bandwidth) over all scenarios. Note: For the scenario direct combustion, the typical case shows the lowest burdens in some categories.

7.1.4 Normalisation by inhabitant equivalents

One method to compare different environmental impact categories is the normalisation by inhabitant equivalents, which is explained in chapter 4.2.3.

Table 7-1 Emissions in the environmental impact categories and the resulting resident equivalents related to resident and year (base year: 2005) (based on /Eurostat 2007/ and /CML 2009/). Residents EU27 2005: 491,153,644 /Eurostat 2010/.

Impact category	Unit	Total emissions in Europe per year	Resident equivalent
Non-renewable energy demand	GJ cumulative energy demand from non-renewable sources	40,317,187,000	82
Climate change	t CO_2 equivalent	5,196,759,558	11
Acidification	kg SO_2 equivalent	23,845,833,000	49
Eutrophication	kg PO_4 equivalent	2,868,125,000	6
Photosmog (POCP)	kg C_2H_4 equivalent	9,997,577,000	20
Ozone depletion	kg CFC-11 equivalent	33,993,000	0.069

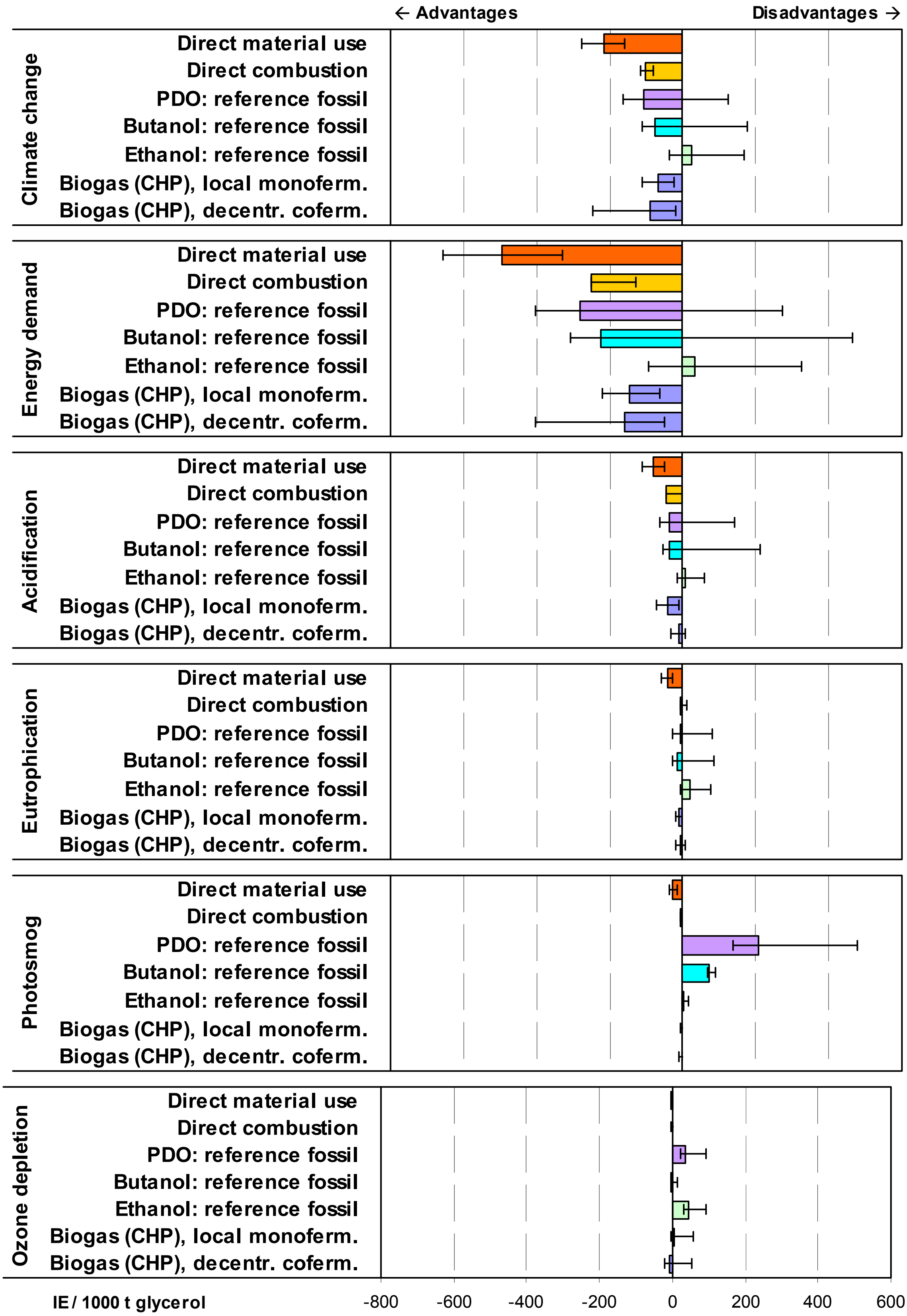


Fig. 7-8 Inhabitant equivalents for chosen scenarios. Coloured bars show results for typical case (internal use for combustion and monofermentation). Thin lines represent results for worst case and best case.

7.2 Additional results of the economic assessment

Additional results of the economic assessment concerning conventional pathways, biogas and biomethane pathways, alternative use options for ethanol and sensitivity analysis are presented here.

7.2.1 Detailed results on conventional pathways

Process economy of direct use of glycerol refined and sold as chemical and combusted to generate electricity. The main results are used in 4.3.2.

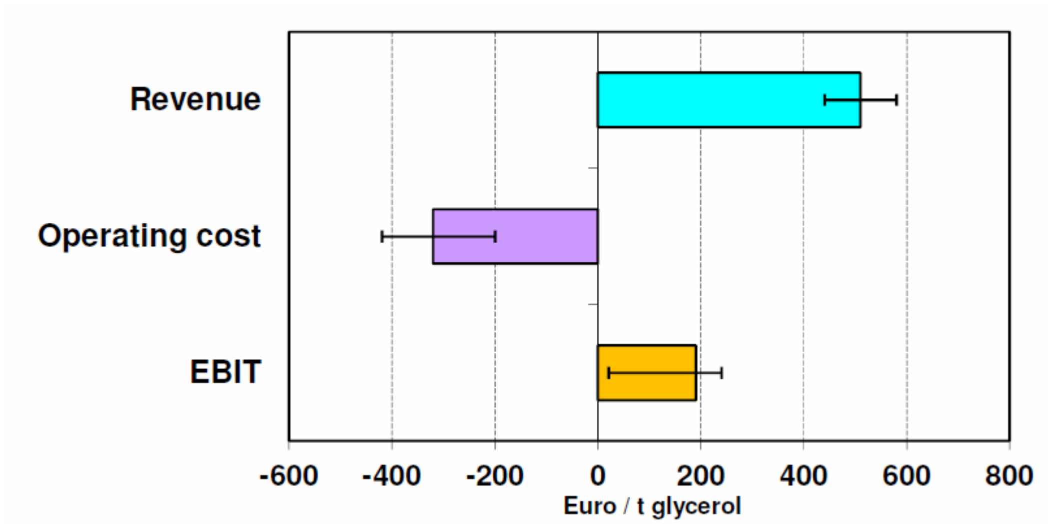


Fig. 7-9 Economics for direct use of glycerol in a chemicals refining plant. The error bars indicate the best and worst case

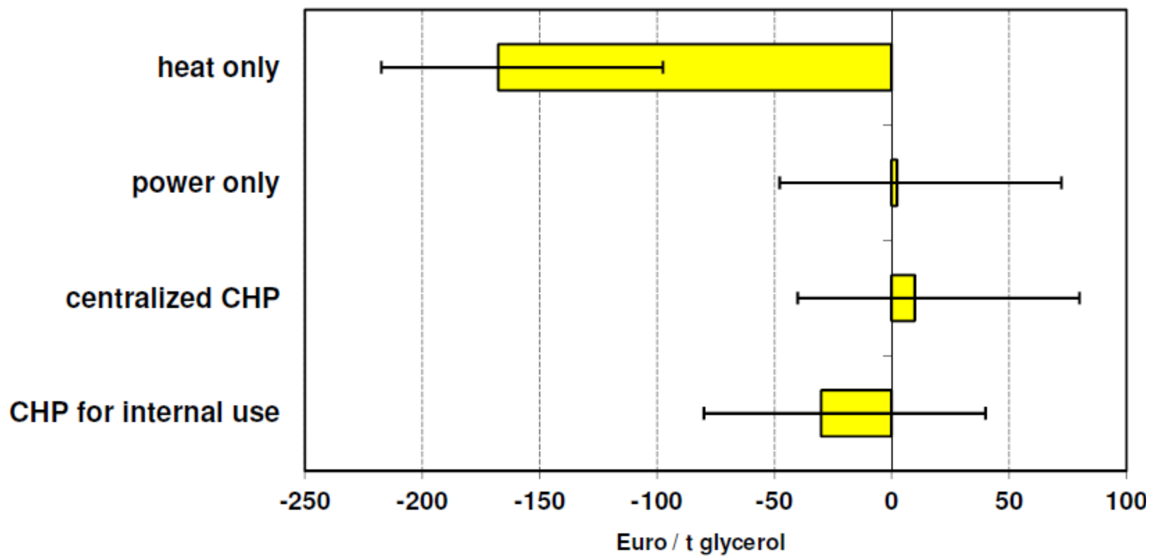


Fig. 7-10 EBIT for the scenarios for direct combustion. The error bars indicate the best and worst case.

7.2.2 Detailed results on biogas and biomethane pathways

Process economy for all scenarios for monofermentation, cofermentation with corn silage or manure. The main results are used in 4.3.2.

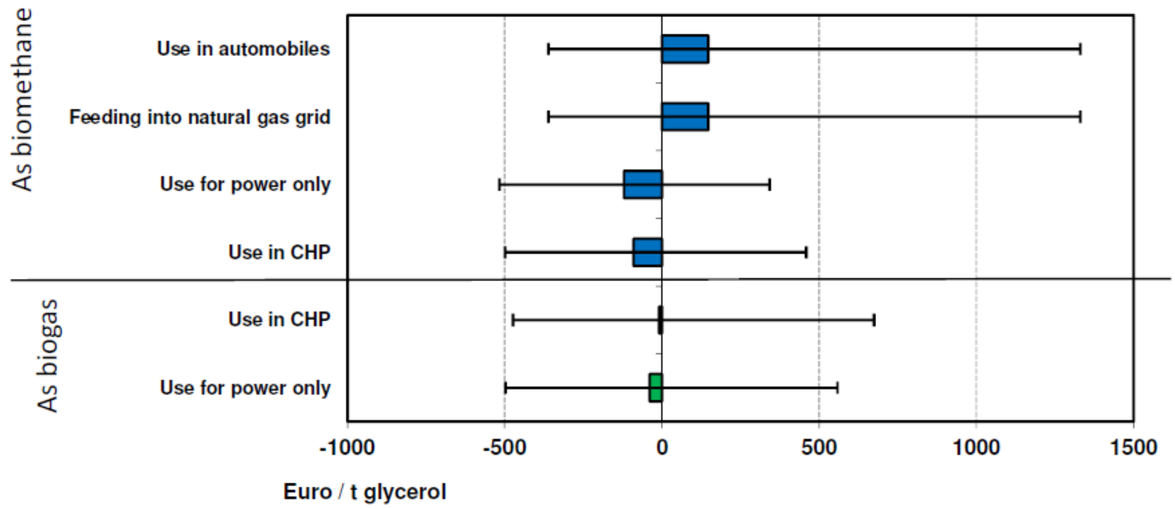


Fig. 7-11 EBIT for cofermentation with corn silage in the biogas and biomethane scenarios. The error bars indicate the best and worst case.

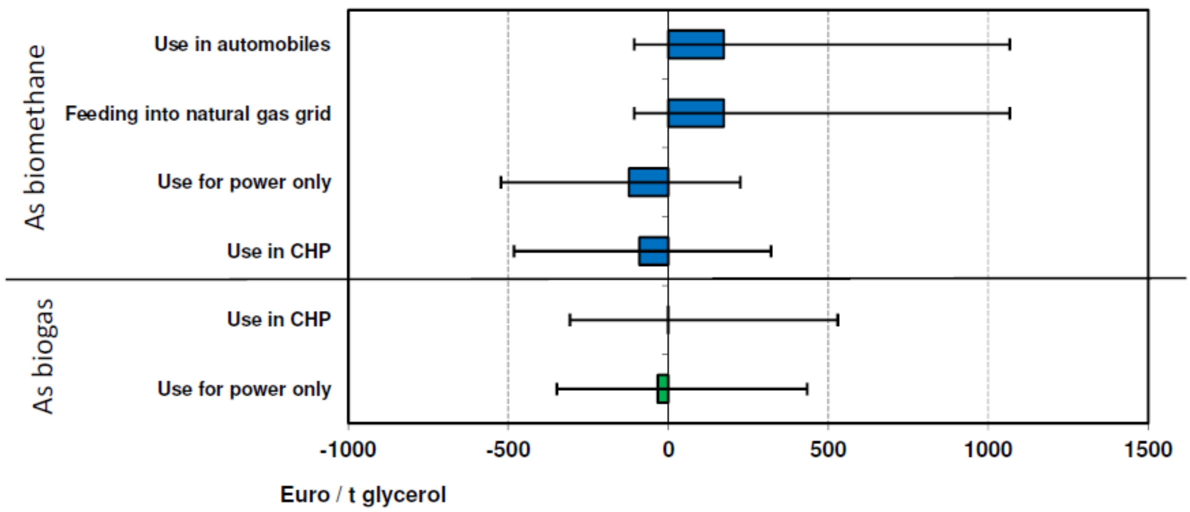


Fig. 7-12 EBIT for cofermentation with manure in the biogas and biomethane scenarios. The error bars indicate the best and worst case.

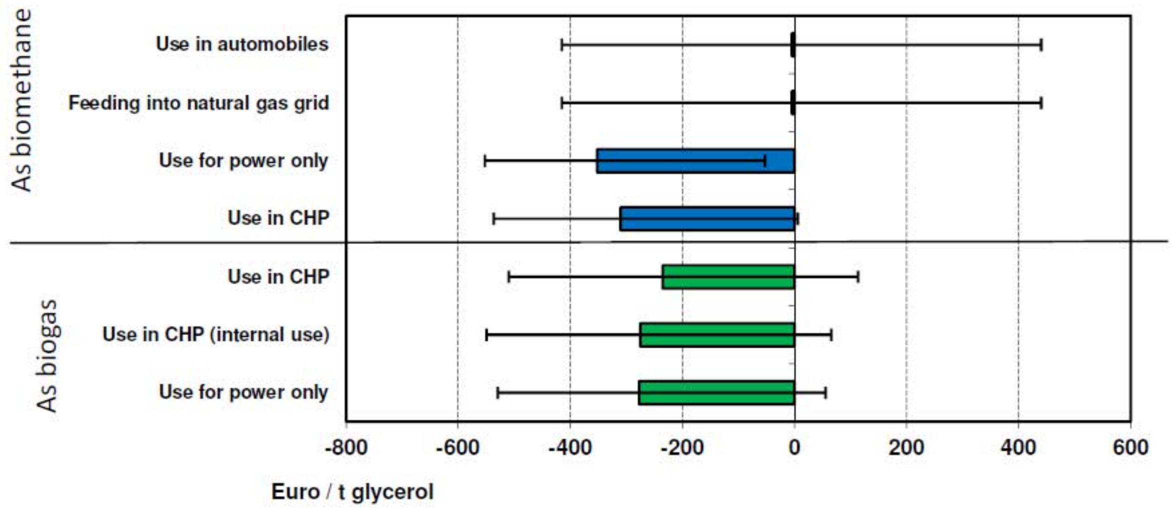


Fig. 7-13 EBIT for monofermentation in the biogas and biomethane scenarios. The error bars indicate the best and worst case.

7.2.3 Additional detailed results on alternative use options for ethanol

Process economy of the ethanol pathway when the ethanol is sold as fuel.

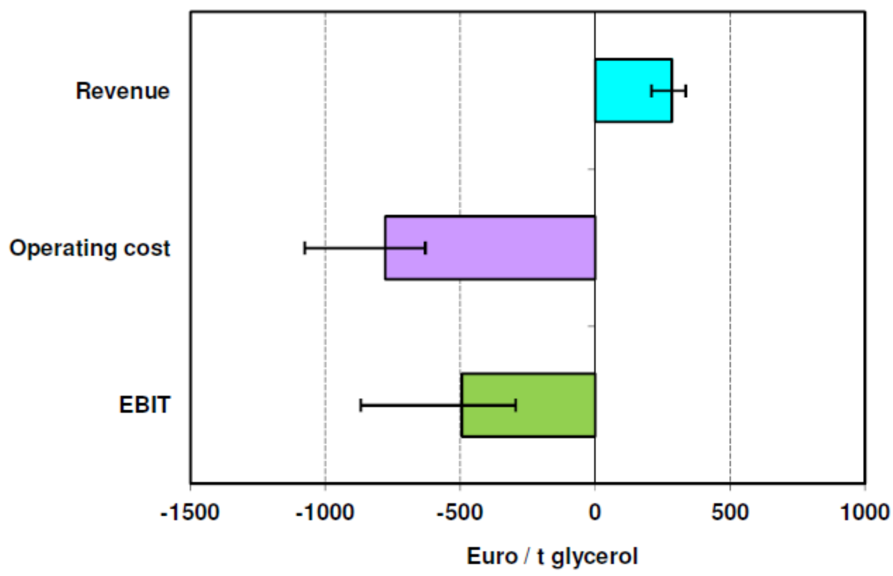


Fig. 7-14 Ethanol pathway plant economics when priced as a substitute the gasoline (to the left) and distribution of production cost in % of total production cost (to the right). The error bars indicate the best and worst case

7.2.4 Sensitivity analysis

Result of the sensitivity analysis for the chemical pathways referred to in 5.1.

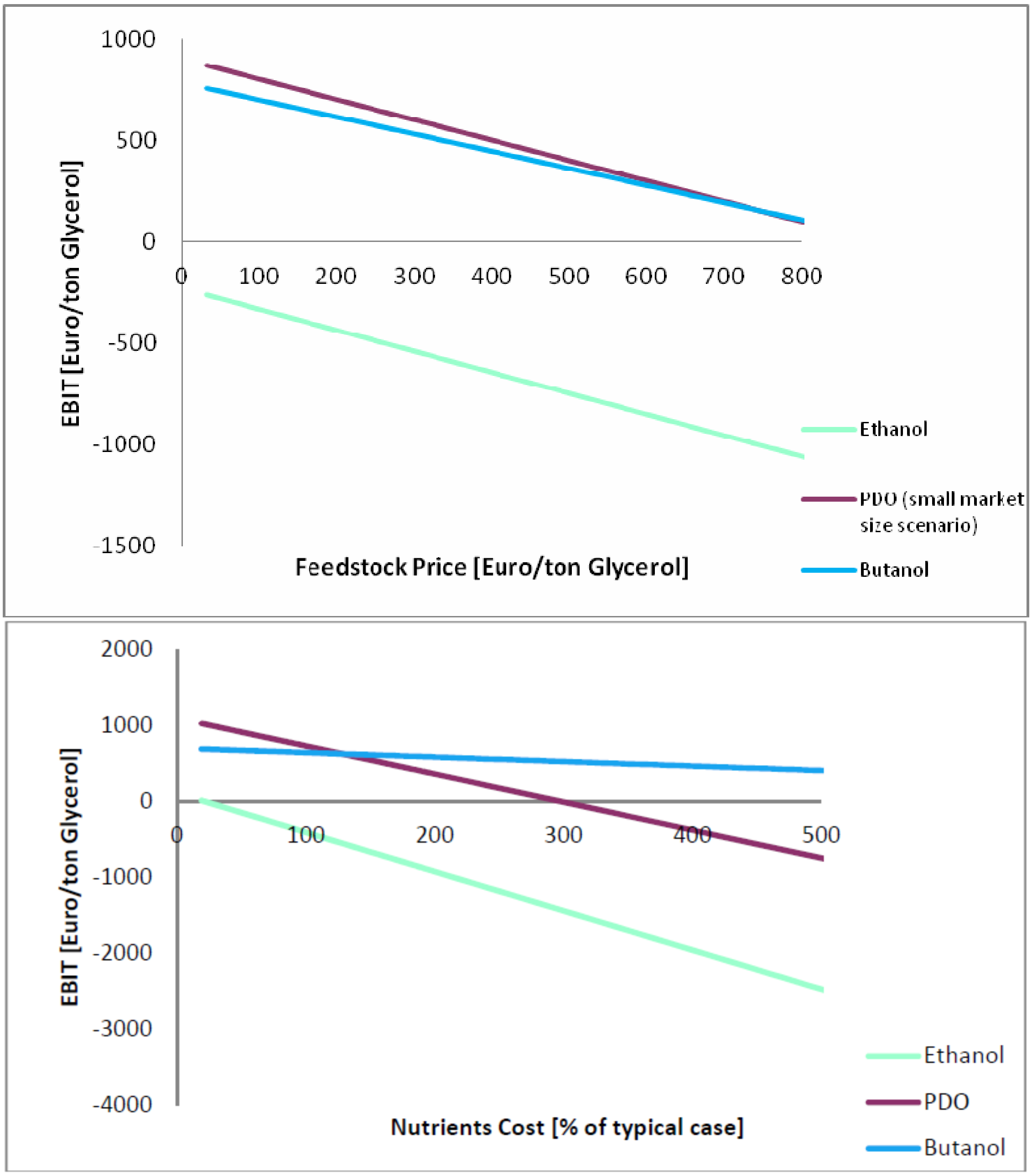


Fig. 7-15 *(continued on next page)*

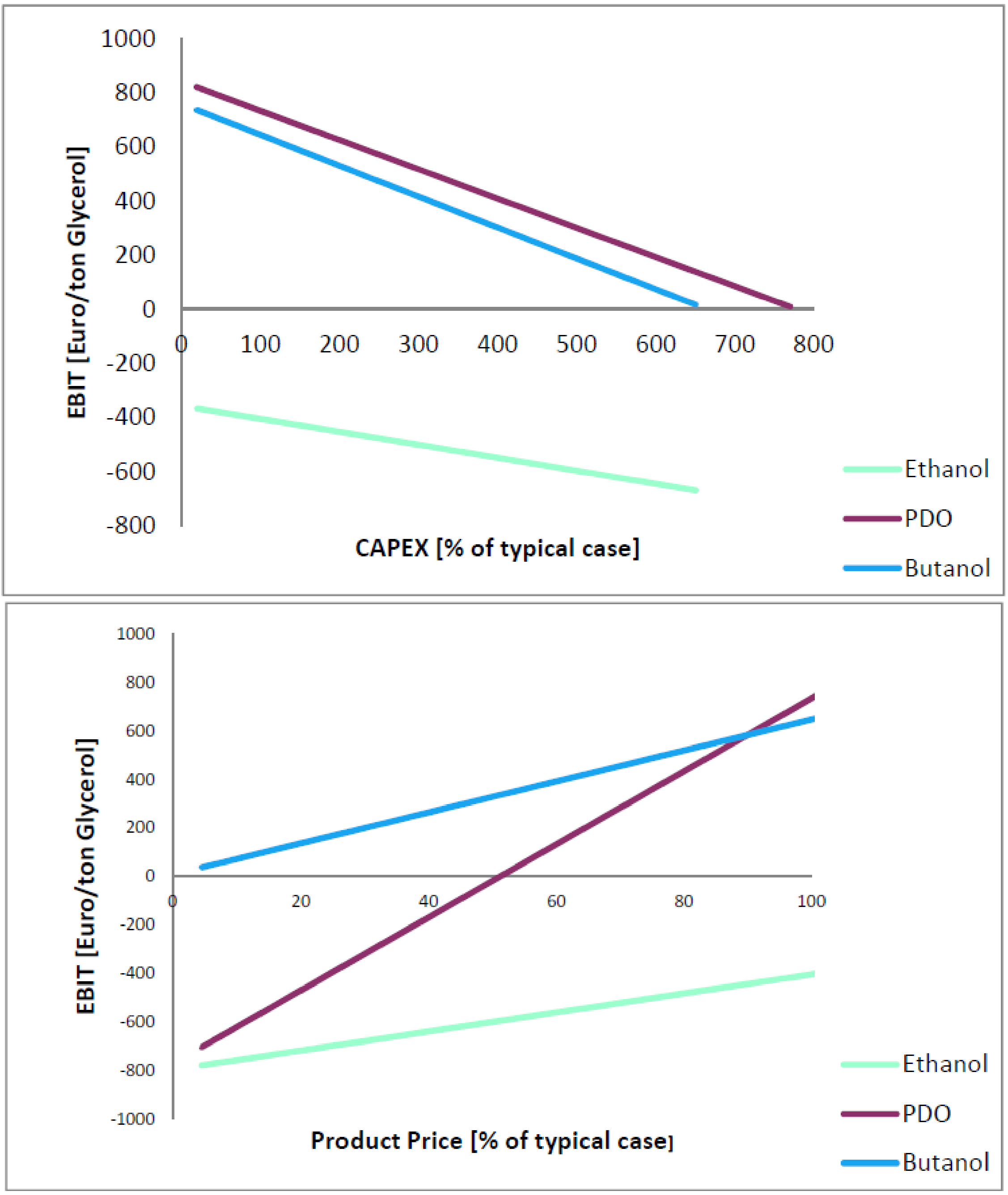


Fig. 7-15 Sensitivity of the chemical pathways

7.3 Additional results of the integrated assessment

Additional results of the integrated assessment are presented in this chapter.

7.3.1 Alternative ways of treating uncertainties

As discussed in chapter 4.4.1, uncertainties can be treated in two different ways depending on how dependent the compared scenarios are on shared parameters. Fig. 7-16 shows the results of both ways.

Benchmark: Direct material use	Direct material use	Direct combustion	Ethanol reference fossil	Ethanol reference gasoline	Butanol reference fossil	PDO reference fossil	PDO reference starch	Biogas monofermentation	Biogas cofermentation	Biomethane monofermentation	Biomethane cofermentation
	Local comparison										
Climate change		-	-	-	-	-	-	-	-	-	-
Energy demand		-	-	-	-	-	-	-	-	-	-
Acidification		-	-	-	-	-	-	-	-	-	-
Eutrophication		-	-	-	-	-	0	-	-	-	-
Photosmog		-	-	-	-	-	-	-	-	-	-
Ozone depletion		0	-	-	0	-	0	-	0	-	-
Earnings (EBIT)		-	-	-	+	0	0	-	0	0	0
	Global comparison										
Climate change		-	-	-	-	-	-	-	0	-	-
Energy demand		-	-	-	-	-	-	-	-	-	-
Acidification		-	-	-	-	-	-	-	-	-	-
Eutrophication		-	-	-	-	-	0	-	-	-	-
Photosmog		-	-	-	-	-	-	-	-	-	-
Ozone depletion		0	-	-	0	-	0	0	0	-	-
Earnings (EBIT)		-	-	-	+	0	0	-	0	0	0

Fig. 7-16 *(continued on next page)*

Benchmark: Direct combustion

	Direct material use	Direct combustion	Ethanol reference fossil	Ethanol reference gasoline	Butanol reference fossil	PDO reference fossil	PDO reference starch	Biogas monofermentation	Biogas cofermentation	Biomethane monofermentation	Biomethane cofermentation
Local comparison											
Climate change	+		-	-	0	0	-	0	0	-	0
Energy demand	+		-	-	0	0	-	0	0	-	0
Acidification	+		-	-	0	0	0	0	-	-	-
Eutrophication	+		-	-	0	0	0	+	0	0	0
Photosmog	+		-	-	-	-	-	0	0	-	0
Ozone depletion	0		-	-	0	-	0	-	0	-	-
Earnings (EBIT)	+		-	-	+	0	0	0	0	0	0
Global comparison											
Climate change	+		-	-	0	0	-	0	0	-	0
Energy demand	+		-	-	0	0	-	0	0	-	0
Acidification	0		-	-	0	0	0	0	-	-	-
Eutrophication	+		-	-	0	0	0	0	0	-	-
Photosmog	+		-	-	-	-	-	0	0	-	0
Ozone depletion	+		-	-	0	-	0	0	0	-	-
Earnings (EBIT)	+		-	-	+	0	0	0	0	0	0

Benchmark: PDO reference fossil

	Direct material use	Direct combustion	Ethanol reference fossil	Ethanol reference gasoline	Butanol reference fossil	PDO reference fossil	PDO reference starch	Biogas monofermentation	Biogas cofermentation	Biomethane monofermentation	Biomethane cofermentation
Local comparison											
Climate change	+	0	-	-	-		-	0	0	0	0
Energy demand	+	0	-	-	-		-	0	0	0	0
Acidification	+	0	0	0	0		0	0	0	0	0
Eutrophication	+	0	0	-	0		+	0	0	0	0
Photosmog	+	+	+	+	+		0	+	+	+	+
Ozone depletion	+	+	0	0	+		+	+	+	+	+
Earnings (EBIT)	0	0	-	-	0		0	-	-	-	0
Global comparison											
Climate change	+	0	-	-	0		-	0	0	-	0
Energy demand	+	0	-	-	0		-	0	0	-	0
Acidification	+	0	-	-	0		0	0	-	-	-
Eutrophication	+	0	-	-	0		0	0	0	-	0
Photosmog	+	+	+	+	+		0	+	+	+	+
Ozone depletion	+	+	0	0	+		0	0	0	0	0
Earnings (EBIT)	-	-	-	-	0		0	-	0	-	0

Fig. 7-16 Alternative benchmarking approaches for quantitative indicators with bandwidths. The results "+" or "-" indicate that the scenario performs better or worse, respectively, than the benchmark in any case (i.e. same performance of best, typical and worst case). "0" indicates that the comparisons are ambiguous or differ from the benchmark by less than 10 %. Local comparison refers to the comparison of best, typical, and worst cases amongst each other, which is the method of choice if common parameters exist as discussed in chapter 4.4.1. Global comparison refers to the comparison of all subscenarios of one glycerol use option (i.e. best, typical, and worst cases) to the typical case of the benchmark. This is valid in the case of independent parameters.

8 Abbreviations

BAuA	Bundesanstalt für Arbeitsschutz und Arbeitsmedizin
CAPEX	Capital expenditures. Sum of feed cost, direct cost, indirect cost and depreciation of equipment.
CDC	Centers for Disease Control and Prevention
CFC-11 eq.	Fluorochloroform equivalents, standard unit to aggregate emissions causing ozone depletion. Fluorochloroform (also: trichlorofluoromethane, R-11) is a refrigerant that was used in operating systems before its ban in 1995 because of is ozone depleting effect.
CHP	Combined heat and power generation
CO_2 eq.	Carbon dioxide equivalents, standard unit to aggregate greenhouse gas emissions for the environmental impact category "climate change"
dCost	Difference in production costs for the reference product and the production costs of product under investigation
dLUC	Direct land use change. Land use change in general is the conversion of one ecosystem into another, which may lead to changes e.g. in carbon stocks or biodiversity. Most relevant example is clearing of a carbon rich natural ecosystem to cropland. Direct land use change describes the land use change within the supply chain under consideration, e.g. clearing of rainforest to plant oil palms for biodiesel production.
EBIT	Earnings before interest and taxes. The EBIT is determined from the revenue, direct cost, feed cost, indirect cost, and depreciation of equipment and buildings.
Ethene eq.	Ethene equivalents, standard unit to aggregate emissions with the potential to cause photosmog (also: photochemical smog, summer smog) for the environmental impact category "photochemical ozone creation potential (POCP)".
FAME	Fatty acid methyl ester (biodiesel)
GHG	Greenhouse gases
GMO	Genetically modified organism
iLUC	Indirect land use change: Land use change effects outside of the system under consideration but caused by this system. E.g., cropland formerly used for food production is now used for bioenergy production and by that the former food production is displaced to other places like recently cleared forest land.
IE	Inhabitant equivalent. Relates environmental burdens caused by a process to the burdens caused by each inhabitant of a region in one year. Used for normalisation of environmental impact categories.

IRR	Internal rate of return
LCA	Life cycle assessment
LCI	Life cycle inventory
LUC	Land use change (see also dLUC and iLUC)
N_2O	Nitrous oxide
PDO	1,3-Propanediol or trimethylene glycol: The main application for PDO is the production of polytrimethyleneterephthalate (PTT).
PET	Polyethylene terephthalate (also simply termed "polyester"). A common polymer used to produce mainly textile fibres and bottles.
POCP	Photochemical Ozone Creation Potential (see ethene eq.).
PO_4 eq.	Phosphate equivalents, standard unit to aggregate emissions causing eutrophication.
PTT	Polytrimethylene terephthalate. A polymer, which is mainly used to produce a relatively new kind of fibre, which has superior characteristics compared to nylon and PET in certain fields of applications. A strong growth is predicted for the PTT market.
RME	Rapeseed methyl ester, biodiesel from rapeseed.
SO_2 eq.	Sulphur dioxide equivalents, standard unit to aggregate emissions causing acidification.
TE	Techno Economic model.