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A methodology to assess the contribution of biorefineries to a sustainable bio-based economy

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A methodology to assess the contribution of biorefineries to a sustainable bio-based economy

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Summary

Within this thesis for the first time an integrative methodology to assess the sustainability of biorefineries and bio-based products has been developed which is based on a fundamental understanding of sustainability as presented in the Brundtland report. The applied integrative concept of sustainability as developed by the Institute for Technology Assessment and Systems Analysis (ITAS) overcomes the widespread thinking in three pillars of sustainability and opens up new perspectives.

The methodology developed addresses innovative life cycle assessment evaluation methods on midpoint level as well as on the area of protection and adopts state-of-the-art assessment procedures e.g. to determine water deprivation. It goes far beyond the scope of conventional LCA studies and examines effects on human health, on the environment, on the development of knowledge and physical capital, and on regional development and acceptance.

In order to validate the developed method it was applied to an algae biorefinery currently under development and construction in the south of Spain. For this assessment for the first time extensive process data was collected of a real algae biorefinery which uses municipal waste water as a culture medium for microalgae. The use of waste water allows to reduce the demand for fresh water and avoids additional fertilisation of microalgae.

Moreover, the analysed algae biorefinery replaces conventional waste water treatment by a biological purification and produces biogas by an anaerobic pre-treatment of waste water as well as by anaerobic digestion of algae. After several purification steps the biogas can be used as automotive fuel and thus contributes to further development and increased use of biofuels.

On the one hand the sustainability assessment shows that this way of waste water treatment contributes to climate protection and to the conservation of fossil energy carrier. On the other hand approximately ten times more land is needed and twenty times more water is evaporated compared to conventional waste water treatment. The LCA calculations show, too, that the amount of harmful emissions into the air such as PM, NO2 or heavy metals and into water is inclined to be higher in the case of the algae biorefinery except for greenhouse gases and ozone depleting substances.

The research project also generates new knowledge which offers new action opportunities for future generations. In addition, the algae biorefinery increases the supply security in the south of Spain with regard to automotive fuels which proved to have a high acceptance within the general public. Yet, without any subsidies an investment for such an algae biorefinery still does not seem to be profitable but future developments can change this and will probably increase the employment rate in the south of Spain.

In summary it can be stated that the algae biorefinery has proved to be an attractive alternative to conventional waste water treatment which allows the expansion of biofuels and contributes not only to the conservation of fossil energy carriers but also to climate protection.

Zusammenfassung

Im Rahmen dieser Dissertation wurde erstmals eine auf Indikatoren gestützte integrative Nachhaltigkeitsbewertungsmethode für Bioraffinerien entwickelt, welche sich auf ein fundamentales Verständnis von Nachhaltigkeit wie im Brundtlandbericht beschrieben stützt. Das verwendete integrative Konzept der Nachhaltigkeit, welches im Institut für Technikfolgenabschätzung und Systemanalyse (ITAS) entwickelt wurde, überwindet das weitverbreitete Denken in drei Säulen der Nachhaltigkeit und eröffnet neue Sichtweisen.

Die Methodik adressiert innovative ökobilanzielle Bewertungsverfahren auf Midpoint- und Schutzgüter-Ebene und adaptiert neueste Bewertungsverfahren z. B. zur Beurteilung von Wasserknappheit. Sie geht deutlich über den Untersuchungsrahmen konventioneller Ökobilanzen hinaus und untersucht Auswirkungen auf die menschliche Gesundheit, die Umwelt, die Entwicklung von Wissens- und Sachkapital sowie auf Regionalentwicklung und Akzeptanz.

Zur Validierung der Methode wurde diese auf eine zurzeit in Südspanien in Entwicklung und Bau befindliche Algenbioraffinerie angewendet. Dazu wurden erstmalig umfangreiche Prozessdaten einer real existierenden Algenbioraffinerie erhoben, welche kommunale Abwässer als Kulturmedium für Mikroalgen nutzt. Die Nutzung solcher Abwässer erlaubt die Reduktion des Bedarfs an Frischwasser und vermeidet eine zusätzliche Düngung der Mikroalgen.

Darüber hinaus ersetzt die analysierte Algenbioraffinerie konventionelle Abwasserbehandlung durch eine biologische Reinigung und erzeugt Biogas zum einen durch eine anaerobe Vorbehandlung des Abwassers und zum anderen durch eine anaerobe Fermentation der Algen. Das Biogas kann nach seiner Aufreinigung als Kraftfahrstoff genutzt werden und trägt somit zum Ausbau von Biotreibstoffen bei.

Die Nachhaltigkeitsbewertung zeigt, dass diese alternative Abwasserbehandlung einen Beitrag zum Schutz des Klimas und zum Schutz fossiler Ressourcen leisten kann. Andererseits verbraucht eine derartige Algenbioraffinerie ca. 10 Mal so viel Fläche wie eine konventionelle Kläranlage, und ca. das 20-Fache an Wasser wird verdunstet. Die ökobilanziellen Berechnungen zeigen zudem, dass die Menge an schädlichen Emissionen in Luft und Wasser, außer solchen, die zum Klimawandel oder zum Ozonabbau beitragen, tendenziell bei der Algenbioraffinerie höher ist. Anderseits wird durch das Forschungsvorhaben neues Wissen generiert, welches von zukünftigen Generationen genutzt und weiterentwickelt werden kann. Durch die Produktion von Biomethan trägt die Algenbioraffinerie zur Energieversorgungssicherheit in Südspanien bei und leistet einen Beitrag zum Ausbau erneuerbarer Energien. Noch erscheint eine Investition ohne Subventionen nicht profitabel, aber zukünftige Weiterentwicklungen können dies ändern und die Beschäftigungsquote in Südspanien erhöhen. Eine hohe Akzeptanz von Algenbiotreibstoffen in der Gesellschaft wurde bereits mittels einer Umfrage im Rahmen der Arbeit festgestellt.

Letztendlich stellt die Algenbioraffinerie eine vielversprechende Alternative zur konventionellen Abwasserbehandlung dar und sollte weiter entwickelt werden.

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List of abbreviations

Symbol	Meaning	Unit
14-DCB	1,4 dichlorobenzene	
AB	Algae biorefinery	
ABE	Acetone-butanol-ethanol	
AD	Anaerobic digestion	
ADP	Abiotic depletion potential	Sb-eq.
ALO	Occupation of agricultural land	m^2*yr.
AoP	Areas of protection	
AR5	Fifth assessment report	
ATJ	Alcohol to jetfuels	
BC	Basic cations	BC-eq.*kg^{-1} soil
BOD	Biological oxygen demand	g*L^{-1}
BS	Base saturation	
BTL	Biomass-to-liquid	
CAPEX	Capital expenditures	€
CEC	Cation exchange capacity	CEC-eq.*kg^{-1} soil
CED	Cumulative energy demand	MJ
CF	Characterisation factor	-
CFC-11	Trichlorofluoromethane	
CHP	Combined heat and power	
CMS	Carbon molecular sieves	
CNG	Compressed natural gas	
COD	Chemical oxygen demand	g*L^{-1}
COL	Cost of operating labour	€
CUT	Cost of utilities	€
CRM	Cost of raw materials	€
CWU	Consumptive (blue) water use	m^3
cWWT	Conventional waste water treatment	
DAF	Dissolved air flotation	
DALY	Disability adjusted life-years	years
DIC	Dissolved inorganic carbon	mg $CaCO_3^-$*L^{-1}
DM	Dry mass	
DME	Dimethyl ether	
EEA	Eco-efficiency analysis	

Symbol	Meaning	Unit
EIA	Environmental impact assessments	
EL	Ethyl lactate	
EP	Eutrophication potential	PO_4^{3-}-eq.
EROI	Energy return on investment	-
ETBE	Ethyl-tert-butyl ether	
FAME	Fatty acid methyl ester	
FCI	Fixed capital investment	€
FDP	Fossil depletion potential	oil-eq.
FES	Fossil energy savings	oil-eq.
FF	Fate factor	
FFD	Fossil fuel depletion	
Fu	Functional unit	
GHG	Greenhouse gas	
GTL	Gas-to-liquid	
GWP	Global warming potential	CO_2-eq.
HEFA	Hydro-processed esters and fatty acids	
HRAP	High rate algal ponds	
HRT	Hydraulic retention time	
HVO	Hydrotreated vegetable oil	
IFPRI	International Food Policy Research Institute	
ILO	International Labour Organisation	
iLuC	Indirect land use change	
IPCC	Intergovernmental Panel on Climate Change	
ISCED	International standard classification of education	
LCA	Life cycle assessment	
LCC	Life cycle costing	
LCI	Life cycle inventory	
LCIA	Life cycle impact assessment	
LHV	Lower heating value	
LNG	Liquefied natural gas	
LuC	Land use change	
MEA	Macro-economic analysis	
MFA	Material flow analysis	

Symbol	Meaning	Unit
MFE	Mineral fertilise equivalent	
NGV	Natural gas vehicles	
NMVOC	Non-methane volatile organic compounds	
NPV	Net present value	
NREL	National Renewable Energy Laboratory of the U.S.	
ODP	Ozone depletion potential	CFC-11-eq.
ODS	Ozone depleting substances	
OPEX	Operating expenditures	€
PAHs	Polycyclic aromatic hydrocarbons	
PCF	Product carbon footprint	CO_2-eq.
PDF	Potentially disappearing fraction	species*yr.
PDO	1,3-propanediol	
PE	Per-capita equivalents	
PHA	Polyhydroxyalkanoates	
PLA	Polylactic acid	
PM	Particulate matter	
PM_{10}	Particulate matter with an aerodynamic diameter of less than 10 µm	
PMFP	Particulate matter formation potential	PM_{10}-eq.
POP	Persistent organic pollutant	
PPO	Pure plant oil	
PSA	Pressure swing adsorption	
PTT	Polytrimethylene terephthalate	
PUFA	Polyunsaturated fatty acids	
PVO	Pure vegetable oil	
RED	Renewable Energy Directive 2009/28/EC	
RTD	Research and technical development	
SKA	Synthetic kerosene aromatics	
SLCA	Social life cycle assessment	
SOC	Soil organic carbon	
SOL	Standard of living	
SPK	Synthesised paraffinic kerosene	
TA	Technology assessment	
TAG	Triglycerides	

Symbol	Meaning	Unit
TAP	Terrestrial acidification potential	SO_2-eq.
TKN	Total Kjeldahl nitrogen	$mg*L^{-1}$
TRL	Technology readiness level	
TSS	Total suspended solids	
UASB	Upflow anaerobic sludge blanket	
ULO	Urban land occupation	$m^2*yr.$
UP	Unit process	
VS	Volatile solids	
VSS	Volatile suspended solids	
WCED	World Commission on Environment and Development	
WHO	World Health Organisation	
WSF	Water scarcity footprint	m^3
WSI	Water stress index	-
Ww	Waste water	
WWT	Waste water treatment	

1 Introduction and aim

1.1 Motivation: Biorefineries as partial solution to global challenges?

Today mankind faces some grand challenges such as a growing world population, a rising world GDP, and the associated increasing demand on resources (Randers 2012). At the same time the economic growth along with the use of fossil energy sources intensifies the global warming with its multiple impacts on nature and humans. Value chains become more and more global, the depth of effects of human actions increases, and technologies become more and more complex.

The question as to whether we can push forward a more sustainable development through or despite technological progress cannot be answered easily. Scientists with critical stance towards emerging technologies claim that technological innovations do not »create« new resources but allow us to degrade faster energy, the material order, and biodiversity (Costanza et al. 2001). Following these ideas the only serious alternative would be asceticism which is often discussed under the term sufficiency (Durning 1992) and which is not likely to happen because of lacking acceptance in the society. On the other hand, the development and application of new technologies is seen as a major step towards more efficiency and sustainability (Grunwald 2002). They may enable a worldwide supply with goods even in a growing world population (Radermacher, Beyers 2011).

However, emerging technologies are not per se sustainable because their impacts depend on many parameters relevant for the entire life cycle. Today, technologies are often exclusively developed against technological and economic objectives, often neglecting environmental, political, and social requirements (Majer 2002) or zooming in on only a few aspects. This regularly leads to resource intensive innovations that conflict with the preservation of the natural environment for us as life basis. In order to develop sustainable technologies, cooperation between technology development, the development and application of appropriate methodologies to assess sustainability, also considering socio-economic development and coherences, systematic cross-sectional views as well as basic scientific research is needed and prerequisite for a sustainable economy (Grunwald 2002).

In particular the development of technologies in the field of renewable resources has the potential to contribute to the protection of limited resources and offers the chance to secure basic human needs especially for future generations. Such basic needs include for example nutrition, mobility, and the supply with energy and material products. The main difference of biomass utilisation against other regenerative energies such as solar radiation, tides or winds is that biomass provides usable carbon which usually exclusively comes from fossil sources such as crude oil. Biomass is therefore currently the only

renewable source which provides »renewable carbon« and can replace carbon from fossil sources as needed e.g. in chemical industry. In addition to the use of biomass, in future catalytic transformation of CO_2 to fuels and chemicals using solar energy also referred to as »solar fuels« may become an interesting alternative (Gómez Camacho 2003). However, the use of biomass is currently the most promising option and according to the European vision of a bio-based economy in the near future biomass will be used for the production of a wide range of food, health, fibres, and industrial products (European Technology Platforms 2011). Principally, the vision of a bio-based economy means the transition from a society depending on fossil fuels to a situation where agriculture will not only continue to provide food security but also a sustainable supply of renewable raw material for industry (Elvnert et al. 2011a; WBGU 2011). In order to achieve such a post-fossil economy, innovative bio-based products are required that can compete with conventional products made of fossil raw materials. Nowadays, bio-based products are often not price-competitive and therefore only occupy niche markets and/or are subsidised by the state. In Germany for example bioenergy is subsidised by the Renewable Energy Law (Bundesregierung 2014). A strategy to improve the competitiveness of bio-based products is to optimise the added value from biomass by developing more energy-efficient and integrated technologies with mostly zero-waste production processes (Elvnert et al. 2011a). Such integrated systems are currently under development and are being discussed under the term »biorefinery«.

On the European level, the development of biorefineries is mainly based on the political strategy to promote the use of renewable resources[1] in order to reduce environmental impacts such as global warming, to face rising fossil fuel prices and their potentially lacking supplies, to improve regional and national security as well as to stimulate the development of agricultural areas (WBGU 2009; Schmidhuber 2008; Thrän et al. 2008). In addition, new products from biorefineries may open up new customer segments allowing improvements of product quality or for price advantages (WBGU 2009).

Nevertheless, it remains to be proven whether the contribution of such biorefineries – as stand-alone plant or integrated into existing refineries – to a sustainable development is really advantageous compared to principally replaceable technologies such as conventional refineries currently in the market. For example the assumption that the use of biomass leads to a saving of greenhouse gas emissions has to be proved depending on the specific case. It is a prejudice that the use of biomass has a neutral impact on the climate since it only releases CO_2 to the environment that was previously absorbed by the plants during their growth. Greenhouse gases are for example released in the manufacture of fertilisers and pesticides, during farming processes, for transportation purposes (supply of biomass) as well as during the operation of biomass conversion systems. Moreover, the greenhouse gas balance depends

[1] In 2008 the EU Commission adopted the Directive of the European Parliament and of the Council on the Promotion of the Use of Energy from Renewable Sources.

on the efficiency of the entire chain of use and on the reference fossil technology that is (partly) replaced in each case (Zimmer et al. 2009). Finally, it is strongly affected by the choice of technology and corresponding characteristics such as the degree of efficiency (Chen et al. 2008).

An increasing demand for biomass caused by the set-up of new biorefineries can trigger the intensification of agriculture which implies increased use of fertilisers and pesticides causing environmental pollution (SRU 2007). Already today, the agricultural sector is one of the main sources of damage to soil, water, species, and biotopes which means there is in any case an urgent need for action to reduce agricultural impacts on the environment (Al-Riffai et al. 2010). Moreover, the increasing demand for biomass can cause negative indirect land use change effects (ILUC). Indirect land use change effects can occur when existing agricultural land is dedicated to non-food production and new land is converted to agricultural land in order to meet the demand for crops for food and feed. Possible effects of ILUC are deforestation, ecosystems' biodiversity loss, and substantial increases in greenhouse gas emissions. These impacts might be prevented or reduced if instead of dedicated crops biomass residues are used which do not require additional land. But also the use of residuals from agriculture and forestry should be limited from an ecological point of view e.g. because of a possible loss of organic carbon and minerals in soil (SRU 2007). On the other hand the increasing demand for biomass caused by biorefineries can provide new opportunities for biomass providers, biofuels producers, and other parties in the extended supply chain and can support the competitiveness in the agricultural sector (Rossi, Hinrichs 2011).

This short introduction has shown that impacts of biorefineries are complex. In order to make strategic decisions a comprehensive sustainability assessment of bio-based products is needed which apart from ecological impacts takes into account the economic feasibility and social impacts, too. Within this thesis a methodology is developed to assess the contribution of biorefineries and bio-based products to sustainable development which takes full account of the complexity of the problems involved but still remains applicable.

1.2 Aim of the work

The biorefinery concept offers new opportunities to realise a bio-based economy. In order to take this opportunity, new innovative and sustainable technologies for biomass processing have to be developed. To ensure that technologies developed in this field contribute to the goals of sustainable development, scientifically derived, applicable, and transparent criteria and indicators are needed as well as a suitable methodology for assessing the sustainability impacts (Elvnert et al. 2011b). The sustainability assessment methodology should be applied to the full value-chain starting from the sustainable provision and conversion of biomass up to end uses simultaneously covering all areas for action of sustainability: environmental, social, and economic ones (German Federal Government 2012). Based on the description

of needs of the present and future generations as described in the Brundtland Report (WCED 1987), a constantly developing normative framework is needed to define and to balance suitable criteria and indicators taking into account both inter- and intragenerational equity. Existing sustainability assessments, which are often based on the three-pillar-view on sustainability or even only consider one aspect such as greenhouse gas emissions, lack a framework that allows for a systematic trade-off between various sustainability indicators, e.g. between indicators focusing on the emissions of harmful substances into the air, soil or water, use of natural resources, impacts on human health, external safety, economic profitability or human rights. Often the focus of sustainability analyses is set by the political agenda, rather than the other way round. In this thesis an encompassing normative framework is applied that is able to fill in these gaps and provides a link between sustainability and human wellbeing as an intrinsic value. Apart from the methodology reliable data reflecting the properties of the analysed technologies are required.

In order to close crucial knowledge gaps, this thesis elaborates on many sustainability aspects which are still under debate in the scientific community. Key objectives of this thesis are therefore:

- Development of an integrated, science-based, rational, and transparent framework for sustainability assessments of biorefineries which covers the most important aspects of sustainability as identified within this thesis
- Derivation of valid sustainability criteria and indicators based on a normative framework which allow assessing sustainability impacts of biorefineries and principally also other biomass conversion routes
- Development of new tools as well as the integration of existing ones such as life cycle assessment (LCA), economic and social assessment into an integrated methodology
- Contextualisation, application, and validation of the developed methodology to an algae biorefinery
- Collection and generation of reliable data needed for the assessments
- Identification and analysis of conflicts of aims between sustainability criteria such as land use change, resource competition, price pressure on foodstuff, water scarcity, biodiversity protection, social compatibility etc., and subsequent issues
- Overall sustainability evaluation and interpretation of an algae biorefinery in comparison to a fossil reference in order to demonstrate the developed method

Although the methodology is developed with regard to biorefineries, it is also applicable for other biomass conversion technologies that are currently discussed under the term »bio-based economy«.

1.3 Outline of the work

The work is structured as follows: within the second chapter existing concepts, rules, and strategies to operationalise sustainability are presented. Chapter 2 also includes the selection of a sustainability concept that is used as basis for assessing the impact of biorefineries on a sustainable development. Furthermore, it provides a more detailed investigation of the selected integrative concept of sustainable development.

Chapter 3 presents the definition, classification and specification of biorefinery concepts. It also considers the contribution of biorefineries to resource conservation. In addition, success factors of biorefineries are discussed.

Against the background of the information provided in both chapters 2 and 3, in chapter 4 the methodology for the sustainability impact assessment of biorefineries is developed. The methodology includes the definition and clustering of generic sustainability criteria for biorefineries (chapter 4.1). These criteria are either derived from the integrative concept of sustainability developed by (Kopfmüller et al. 2001), through literature research or in consideration of regulatory provisions. Based on the criteria defined suitable indicators are generated in chapter 4.2. In chapter 4.3 instruments are developed and presented which are suitable for the calculation of indicators as defined in chapter 4.2. Finally, methods are suggested to balance the individual results. The balancing of indicators is intended to support the interpretation of the results.

In the second part of the thesis the developed methodology is applied to an algae biorefinery which is currently under development in Chiclana de la Frontera (south of Spain). In a first step specific sustainability criteria and indicators are identified for algae biorefineries following the methodology developed. In a second step an environmental assessment of the algae biorefinery is carried out via a life cycle assessment (LCA) approach. Apart from the LCA, further sustainability aspects are assessed using different approaches. Finally, conflicts of interests between different sustainability goals are discussed. Based on the experiences gained during the performance of the case study, the developed methodology for assessing the contribution of biorefineries to a sustainable development is validated and recommendations are given.

2 Concepts, rules, and strategies to operationalise sustainability

2.1 Genesis of the paradigm of sustainable development

The first debates on environment and sustainable development date back to the »Limits to Growth« debate in the early 1970s (Meadows 1972; Cole 1973) and deal with the issue whether or not continuing economic growth and industrial production would inevitably lead to severe environmental degradation and societal collapse on a global scale. At this time, the finiteness of natural resources was of central interest. Later on in the 80s, the function of nature as a sink for pollutants moved into the foreground. Economic and social issues were mainly seen as cause and consequence of environmental problems but were not regarded as separate pillars of sustainability.

Today the concept of sustainable development has gained broad acceptance as a consequence of a definition accepted worldwide. According to the Brundtland Commission of the United Nations on 20 March, 1987 »sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs« (WCED 1987, p. 41). This definition stresses the meaning of intra- and intergenerational justice with regard to a fair distribution and requires a global view on social and environmental problems. In particular, the responsibility for future generations, the fair distribution of the opportunity to satisfy human needs, and the protection of a dignified life are therefore key elements in recent sustainability concepts (Blazejczak et al. 2000; Kopfmüller et al. 2001). Additionally, there also exist other less well-known definitions such as »sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations.« (WCED 1987, p. 43). This definition stresses the idea of progress and highlights some important factors such as the orientation of technological development and the responsible utilisation of resources. Another definition of sustainability puts more emphasis on the economy: »Economic growth that provides fairness and opportunity for all the world's people, not just the privileged few, without further destroying the world's finite natural resources and carrying capacity« (Pronk, ul-Haq 1992). However, there seems to be an agreement about some constitutive elements of sustainable development (Jörissen 2005):

- Sustainability is a global concept,
- it is an integrative concept,
- sustainability requires responsibility for our common and future generations,
- it is an anthropocentric concept.

In order to specify and justify the term »sustainability«, the development of »sustainability science« was suggested (Komiyama, Takeuchi 2006; Clark et al. 2004) and effects of long-term trends on a transition to sustainability were studied (Kates, Parris 2003). Nevertheless, there can be little disagreement about the interpretation of this general definition of sustainable development which complies with all contradictory requirements but does not give concrete answers to crucial discussion points. That is why a large number of different rules and concepts for sustainable development were developed in the following period (Korhonen 2007). The following chapter 2.2 gives an overview about prominent rules and strategies of resources and environmental management.

2.2 Rules and strategies of resources and environmental management

In order to meet the needs of our and future generations, the economy should be maintained and be developed. A central question is »how we should treat natural environments in order that they can play their part in sustaining the economy as a source of improved standard of living?« (Pearce, Turner 1990).

Therefore practical guidelines on how to deal with natural resources, were suggested by Daly and Pearce and Turner (Daly 1990; Pearce, Turner 1990):

- harvest rates of renewable resources should equal regeneration rates,
- »waste emission rates should equal the natural assimilative capacities of the ecosystems into which the wastes are emitted« (Daly 1990, p. 2).

This first rule requires that the renewable resource stock should be held constant over time. The second rule in consideration of the definition of critical loads and critical levels gives a guideline for waste emission rates. The Enquête Commission on »Protection of Man and the Environment« of the German Parliament has suggested the additional rule that the time range of human interference must be counterbalanced against the time range of biological processes including the degeneration of waste and the regeneration of renewable resources or ecosystems (Enquête-Kommission 1994). This rule stresses the time range but is principally already covered by the first two rules (Kopfmüller et al. 2001).

Nevertheless, these two rules cannot solve the problem of exhaustible resources which must, by definition, decline over time. Two complementary ways to overcome this dilemma were suggested (Pearce, Turner 1990):

- »the quasi-sustainable use of non-renewables requires that any investment in the exploitation of a non-renewable resource must be paired with a compensating investment in a renewable substitute« (Daly 1990, p. 4),
- an increased efficiency of resource use (cf. chapter 2.2.1).

The first way allows a substitution between exhaustible and renewable resources. As a consequence renewable resources have to be expanded in order to compensate for declining exhaustible resource stocks (Pearce, Turner 1990). The second way focuses on the efficiency of technologies. According to this rule those technologies should be promoted which increase resource productivity, defined as the amount of value extracted per unit of resource, and allow an efficient recycling. In the best case backstop technologies will be developed which produce a close substitute for an exhaustible resource by using relatively abundant production inputs (Levy 2000). Technologies which only increase the resource throughput itself are not suitable to maintain exhaustible resources (Daly 1990). Precisely because they often enable a price reduction of products e.g. through economies of scale, the total consumption increases. This is also referred to as »rebound« effect, »boomerang« effect (Radermacher 2002) or »Khazzoom–Brookes effect« (Khazzoom 1980). Future biorefineries are promising both the substitution between exhaustible and renewable resources and increased resource efficiency. Nevertheless, it has to be proved individually if they really increase the resource efficiency compared to other present technologies.

Against the background that natural »capital stock generates, either autonomously or in conjunction with services from other capital stocks, a flow of services that may be used to transform materials, or the spatial configuration of materials, to enhance the welfare of humans« (Costanza et al. 1997, p. 254), a central question might be whether improvements in average standard of living can be achieved if the stock of natural resources declines. This question is displayed graphically in Figure 2-1 which shows a possible relation between the available natural capital stock (K_n) and standard of living (SOL). K_{min} reflects a minimum level of natural capital stock necessary to meet the subsistence standard of living. Less natural capital stock than K_{min} (e.g. in point L) means starvation. Less developed countries with low levels of K_n may improve the SOL through increasing natural capital e.g. through improving the efficiency of cultivation. At a point such as W further improvements in SOL may be achieved temporally through an overuse of natural capital which leads to a reduction of K_n. This means there is a trade-off between SOL and K_n which might be typical for industrialised countries.

In order to use natural resources sustainably as illustrated by the shaded area in Figure 2-1, the total throughput should be limited. Predominantly, three strategies are being discussed to achieve such a sustainable use of natural resources: efficiency, sufficiency and consistency. They are characterised as follows:

- Efficiency concentrates on the better utilisation of material and energy, especially on resources' productivity,
- sufficiency is characterised by reducing the consumption of material through reducing the demand of goods,
- consistency focuses on environmentally friendly technologies that use natural resources without endangering their continued existence.

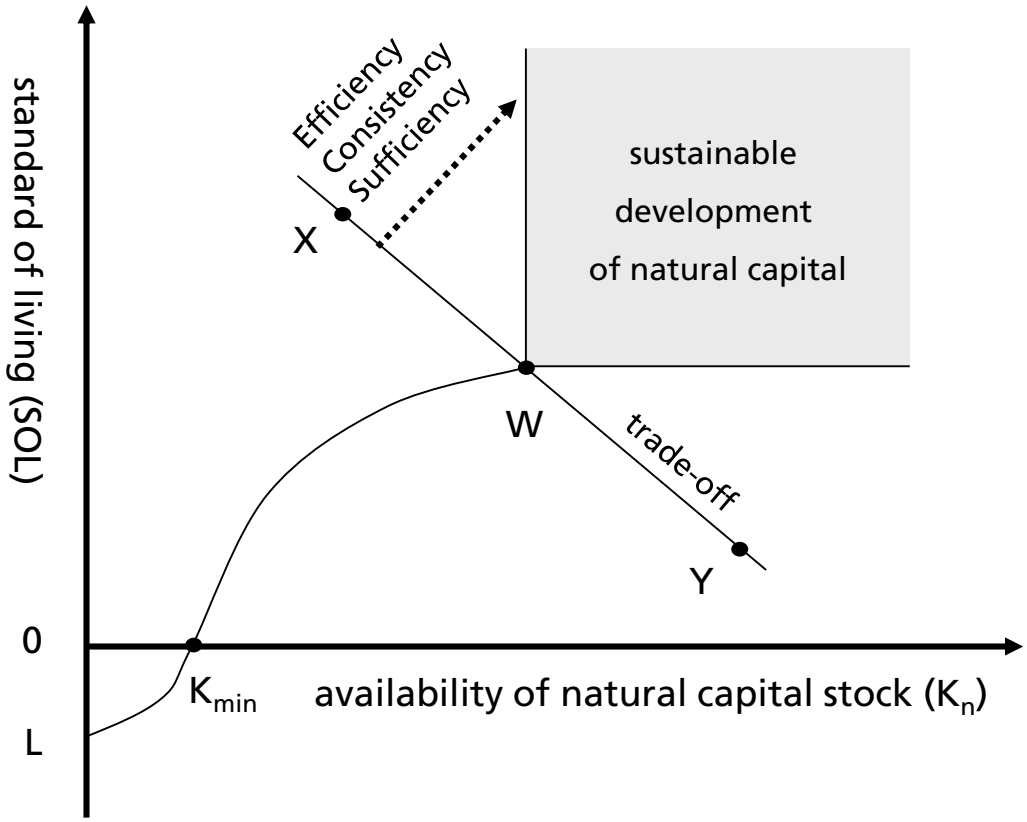

Figure 2-1: Possible relation between natural capital stock (K_n) and standard of living (SOL), in the style of (Pearce, Turner 1990)

Beside these three main strategies Paech has suggested to add risk reduction, avoidance of technologies which lead to unjustifiable risks, and the question of redistribution of goods (Paech 2006). According to Paech the innovation dynamics of modern market systems lead to increasing ecological risks (Paech 2006). The upcoming gap of knowledge and responsibility (Gleich 1997) cannot be managed by technological impact assessment any longer. Accordingly, the consequence for a sustainable development is to fall back on technologies with short space-time-relevant effect chains such as simple biotechnological processes. Avoidance in this context means not to use a technology due to irresponsible risks or ecological consequences which for example are associated with nuclear power. The question concerning the redistribution of goods refers to a policy of fair distribution which can advance a sustainable development. In the following subchapters the three main strategies efficiency, sufficiency, and consistency are described in more detail.

2.2.1 Efficiency

The term efficiency describes the relationship between efforts or inputs to outputs or outcomes. Under the motto getting more output from the same input or investing less to get the same outcome (working smarter), efficiency has been introduced into almost all fields of human activities as hegemonic

principle (Princen 2003) and is the basis for a successful economy. In the sustainability context, eco-efficiency is defined by a reduced use of materials or energy per product/service and rising productivity of resources with less use of natural feedstock (Linz 2004). According to the World Business Council for Sustainable Development (WBCSD) »Eco-efficiency is achieved by the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the earth's estimated carrying capacity« (Verfaillie, Bidwell 2000, p. 7). It can be represented as in equation (2-1).

$$Eco-efficiency = \frac{\text{Product or service value}}{\text{Environmental influence}} \tag{2-1}$$

Progress in eco-efficiency can be achieved by providing more value per unit of environmental influence or per unit of resources consumed. Eco-efficiency has by now been established as one of the leading principles of sustainability, at times it was even overestimated as »efficiency revolution« (Loske et al. 1996). Due to its high importance the international standard ISO 14045:2012 (DIN EN ISO 14045) was developed in order to provide principles, requirements, and guidelines for eco-efficiency assessment of product systems to the industry. Hennicke even believes that without an »efficiency revolution« sustainable energy systems cannot be achieved (Hennicke 2010).

Even if eco-efficiency is increased it requires investments in sophisticated technology and infrastructure and related adjustments. As the share of cost per product decreases, eco-efficiency leads or misleads to rising use of products and services if consistency is disregarded (Radermacher 2002). This is even more the case where efficiency may well prove to be an approach for nature preservation. In other words, »eco-efficiency achieved through technological improvements has, in the absence of effective limits on environmental resource consumption, been used to increase production rather than switch to an environmentally more benign input configuration« (Hukkinen 20 03, p. 14). Therefore, it has large starting potential on the route to sustainability (Jochem 2003), but when the amount of products and energy consumption exceeds the savings, the disadvantages become obvious (Radermacher, Beyers 2008). This phenomenon is often discussed under the term of »rebound« effect (Radermacher 2002). Dyllick also criticises that eco-efficiency can only lead to a relative improvement, but sustainability should orientate on the absolute quantities (Dyllick, Hockerts 2002). Beside eco-efficiency eco-effectiveness is further discussed by (McDonough, Braungart 2002). They suggest developing environmentally friendly designs and request a broader look on the whole product life cycle from »cradle to cradle«.

Besides efficiency sufficiency strategies can contribute to a sustainable development. Efficiency is to avoid an inefficient utilisation of physical resources, sufficiency is targeted at holistic approaches, and consequently both principles complement each other in various contexts.

2.2.2 Sufficiency

Sufficiency can be linked to the question: »How much is enough?« (Durning 1992). Here sufficiency is regarded in more detail as eco-sufficiency and describes steps, measures, and strategies in order to preserve resources through a change of man's behaviour in using these resources. Therefore, the objective of sufficiency is a lifestyle that preserves resources, especially by reducing the per capita consumption of goods (Scherhorn et al. 1997). The expected reduction of consumption can be explained as a result of a clever self-restraint of consumers (Bittlingmayer 2000). The savings induce financial profits while requiring only a limited additional benefit (Linz 2004). For example, the additional benefit to own a second or third watch is smaller than to own a first one since you can only use one watch at the same time. A sarcastic question might be how to dispose money environmentally friendly? According to a study carried out by the »Zukunftsinstitut« there is an upcoming so called group of »lifestyle of health and sustainability« (LOHAS) who cares about the environmental impacts of products (Kirig et al. 2007). In this context, eco-sufficiency as it involves reflection and potential changes of one's attitude to goods and services, is related to values such as the right measure, a good lifestyle, in short for the art of living, as was proposed in ancient philosophy (Linz 2004). It dates back to the ancient Greek Doctrine of the Mean[2], thus encompassing the idea of a good and happy life. With the focus being on a smart and careful management of resources, sufficiency is an attitude that opens up solutions to the challenges of an endangered world of today and provides prosperity to those parts of the population who now suffer from poverty and are marginalised. Nevertheless, sufficiency contradicts the common idea that economic growth is the source of wealth. In a market-driven society, sufficiency is often regarded as reduced standard of living instead of a possible way to a better life. Companies, too seldom take full responsibility for the use of their products because they claim only having little influence on customers' behaviour.

2.2.3 Consistency

The consistency strategies deal with the harmonisation of nature and technology, also related to »industrial ecology«, which includes the economy of entire industries along the ecosystem model (Socolow et al. 1994). The research on industrial ecology looks at sustainable design which means »designing human ecological-economic systems which fit in with natural ecological systems« (Kay 2002, p. 85), to preserve the well-being, resilience[3], and

[2] Aristotle describes ethical virtue as a »*hexis*« (»state«, »condition«, »disposition«) - a tendency or disposition, induced by our habits, to have appropriate feelings. An analysis about Aristotle's Doctrine of the Mean was published by Urmson 1973.

[3] »Resilience is the ability of a system to cope with change without collapsing« (Folke, Berkes 1995).

adaptability of both systems. Consistency strategies call for a new industrial revolution which may lead to a lasting and reliable sustainability of man's life and the economy, in which man's alienation from nature will be overcome through novel scientific, economic, and technological instruments (McDonough, Braungart 2002). Industrial processes are not to affect natural digestive processes and have to be harmonised. Environmentally relevant substances are to be fed into a separate process cycle or if not possible they are to be removed entirely from nature. The intelligent system does not generate wastes but products. According to Pauli, the ideal recycling management without emissions is organized in a way that the next phase of utilisation is equal or superior to the preceding one (Pauli 1997). In this theory, a nature-friendly economy is prioritised to reduced energy consumption and material flows.

Consistency approaches enjoy large acceptance since they promise a solution to the ecological challenges without lowering, even increasing the material standard of living. They promise a world of many chances not of constraints (McDonough, Braungart 2002), thus representing the hopes of the industrial society.

As a matter of fact, consistency strategies are indispensable for a future development, as the rising world population will need environmentally friendly technology to survive. In the future, for instance hydrogen produced by electrolysis from solar electricity production might be able to deliver energy without serious detrimental effects to nature and man (Huber 2000). Biotechnology could support the environmentally friendly production of goods by working at low temperature and low pressure conditions (Huber 2000). A further promising field is biomimetics, which translates biological processes and properties into novel technologies and products, and the closed looping of production processes (Gleich 1998; Rechenberg 1973). Nevertheless, the potential of recycling is restricted by the availability of recycling materials e.g. caused by growing markets, due to the accumulation of pollutants, by poor economic efficiency or, for instance, by the loss of quality.

2.3 Dealing with natural capital: strong and weak sustainability

According to the question how much natural capital can be substituted by man-made capital the principals of weak and strong sustainability were suggested (Dietz, Neumayer 2007). Weak sustainability requires the preservation of total net investment including the total value of aggregate economic activity (man-made capital) and natural capital (Hediger 2009). This requirement can be expressed by equation (2-2)

$$\frac{dU}{dt} = \frac{\partial U}{\partial Y}\frac{dY}{dt} + \frac{\partial U}{\partial N}\frac{dN}{dt} \geq 0 \qquad (2\text{-}2)$$

with U: social welfare, Y: income, t: time, N: natural capital.

Equation (2-2) demonstrates the requirement of weak sustainability that the social welfare expressed by the income (man-made capital) and the natural capital should not decrease in time. The fundamental difference between weak and strong sustainability is the question whether or not natural capital can be substituted by man-made capital (Grunwald, Kopfmüller 2006). Further differences deal with the compensation of future damages and the kind of discounting (Ott, Döring 2004). The main paradigm of weak sustainability is that natural capital is either abundant or replaceable both as an input into the production of goods and as direct benefit. The consequence is that natural capital can safely run down as long as man-made capital is created as a trade-off (Neumayer 2010). Solow defined this paradigm as follows: »In particular, earlier generations are entitled to draw down the pool (optimally of course!) so long as they add (optimally of course!) to the stock of reproducible capital« (Solow 1974, p. 41). According to the neoclassical theory of economic growth, non-renewable natural resources are a factor of production and easily may be substituted by man-made capital. Nevertheless, depreciation and capital consumption must also be taken into account.

Proponents of strong sustainability argue that natural capital is non-replaceable. In this case both types of capital have to be conserved or developed (Daly 1996; Ott, Döring 2004). The requirement of non-declining natural capital can be expressed by equation (2-3):

$$\frac{dN}{dt} = \frac{\partial N}{\partial S}\frac{dS}{dt} + \frac{\partial N}{\partial P}\frac{dP}{dt} \geq 0\,;\ \frac{\partial N}{\partial S} > 0\,,\ \frac{\partial N}{\partial P} < 0 \qquad (2\text{-}3)$$

with N: natural capital, t: time, S: stock of renewable resources, P: pollution.

This means that strong sustainability requires that the stock of renewable resources rises in time and that the pollution decreases in time.

According to the idea of strong sustainability, natural and man-made capital types cannot be substituted but are complementary elements. A conventional refinery, for instance, cannot be operated without depleting natural oil deposits, nor a sawmill without lumber. In addition, if the factors are complementary, the factor in shortest supply will be the limiting factor (Daly 1996). At present, our society changes from a society in which man-made capital has been the limiting factor into a society characterised by natural capital as increasingly limiting factor (Daly 1996).

According to Ott and Döring there are three arguments for a limited substitution (Ott, Döring 2004):

- it is unrealistic to produce without any natural capital or to substitute all natural services as there are limited recycling possibilities,
- natural capital delivers natural services like the regulation of biochemical circuits or photosynthesis, which cannot be provided by man-made capital,

- if some ecological functions may be replaced technologically, a replacement of all functions of an ecological system cannot be found at all.

In contrast, not to use any natural capital also means not to use the potential of non-renewable resources for the present and future generations. From an economic point of view the non-use of non-renewable resources »would be a waste of income[4] and welfare potential« (Hediger 2009, p. 28), as natural resources in the ground have no value in themselves. Consequently, maximising the capital value is a question of optimal timing of extraction and resource use (Gray 1914; Hotelling 1931). This is why both extreme positions of sustainability cannot be supported at all.

Next to weak and strong sustainability theories, there are also approaches called sensible sustainability (Serageldin, Steer 1994). Proponents of these approaches suggest to preserve a stock of capital considering a critical limitation of natural capital, regardless of increasing man-made capital (Nutzinger, Radke 1995; Kopfmüller 2006). Fundamental environmental goods like clean air, fresh water or fertile soils have to be preserved. Other goods have to be checked as to whether their use will affect future generations (Grunwald, Kopfmüller 2006). Especially goods which can only be used once – such as fossil fuels – have to be used carefully. Natural goods that can be destroyed irretrievably such as living species should also be protected in order to maintain the action options for further generations.

In recent works, Held and Nutzinger analysed the theoretical potential to substitute natural capital by man-made capital from an economic point of view (Held, Nutzinger 2001). Even if the substitution of natural capital is possible it might be disadvantageous when looking at the expenses and income of such an investment in comparison to a sustainable use of natural resources. For example, it is possible but economically not feasible to build up facilities on degraded land in which you produce food on nutritive solutions. Apart from the question of economic feasibility, substitution also can lead to less quality. For example, a destroyed ozone layer could be compensated by using a higher degree of sunblocker degree but also reduces life quality. From the point of view of Held and Nutzinger the question of substitution should be concentrated on how technical processes can be organised to strengthen the potential of natural resources (Held, Nutzinger 2001).

According to the attitude towards the principles of weak or strong sustainability, Figure 2-2 shows a certain number of sustainability concepts which will be introduced in more detail in chapter 2.4.

[4] According to (Hicks 1939), income is defined as the maximum amount that may be spent on consumption in one period without reducing real consumption expenditures in future periods.

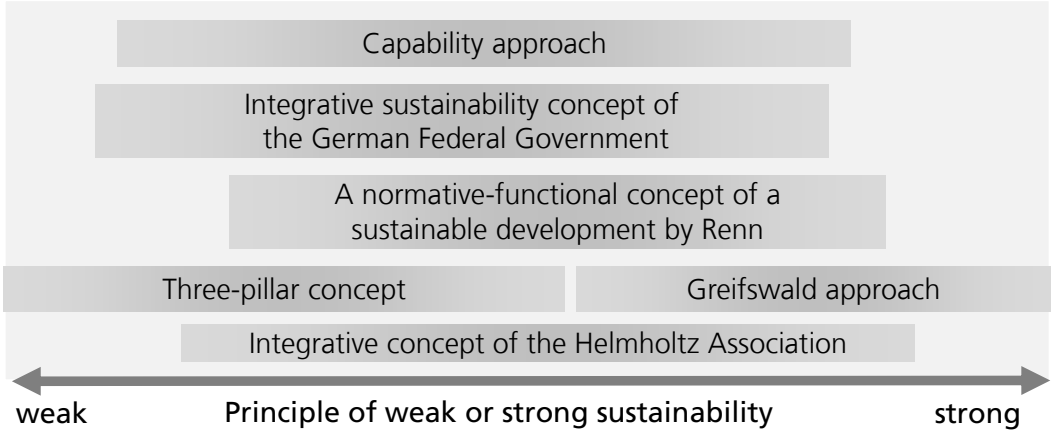

Figure 2-2: Sustainability concepts with regard to their attitude towards the principles of weak and strong sustainability

2.4 Sustainability concepts

The so called **one-pillar concept** prioritises environmental concerns against other sustainability concerns. However, proponents of this concept believe that the satisfaction of the needs of our current and future generations will only be possible if nature is maintained. Different studies tried to operationalise this concept with focus on a just distribution of natural resources (Loske et al. 1996; Umweltbundesamt 2002). From their point of view the key to sustainability is the limitation of economic activities within the ecological and social »crash barriers« (Loske et al. 1996). However, according to Grunwald and Kopfmüller the realisation of claims for justice and the assumption of responsibility principally require the integration of all three dimensions of social development (Grunwald, Kopfmüller 2006). That is why these concepts will not be analysed in more detail within this study.

Proponents of the **more-pillar concepts** stress the equal consideration of the sustainability dimensions economy, ecology and social concerns. The most popular pillar concept is the three-pillar concept which will be introduced in chapter 2.4.1.

Due to the fact that the underlying notions of future responsibility and just distribution are cross-dimensional, considerations on sustainability should not be made separately within these dimensions (Ott, Döring 2004; Schultz et al. 2008). Moreover, multi-pillar concepts do not include recommendations for action regarding which prioritisation should be chosen in the case of conflicts.

In order to tackle these problems, further **integrative concepts** were developed, as follows:

- The Greifswald approach,
- the integrative sustainability concept of the German Federal Government,
- a normative-functional concept of sustainable development submitted by Renn,

- the integrative concept of sustainability developed by the Helmholtz Association, and
- the capability approach by Amartya Sen.

These concepts are introduced in chapter 2.4.2.

2.4.1 Three-pillar concept

The three-pillar concept is currently the most widespread concept, in particular at political level. Tremmel detected that people when talking about sustainability mainly refer to the three-pillar concept (Tremmel 2003). This may be attributed to effective communication and good comprehensibility of this concept.

Historically, the three-pillar concept cannot be assigned to one particular author, being first mentioned in the middle of the 1980s (Diekers 1985; Barbier 1987). Starting from the paradigm of intergenerational justice, the concept focuses on the three dimensions: economy, ecology, and social aspects, emphasising the equal position between these three dimensions (Blazejczak et al. 2000). According to Graap, the equality between the three dimensions overcomes the isolation of ecological aspects and fully integrates them into the sustainable development of our society (Graap 2001). Other authors like Meyer-Abich do not believe in the apparent equality of all three dimensions (Meyer-Abich 2001). In his eyes ecological aspects are currently only additive benefits because of economic efficiency and social responsibility. That is why an equal realisation of all aspects is currently not possible. The three-pillar concept is referred to in many further works such as the development of sustainability indicators for the local agenda 21 as proposed by (Diefenbacher et al. 2009) and was adopted for the ideas, goals, and recommendations of the German Enquête Commission on »Protection of Man and the Environment« (Deutscher Bundestag 1998). European projects such as the EU-funded project »PROspective SUstaInability Assessment of TEchnologies (PROSUITE)« (Blok, Patel 2011) refer to the three-pillar concept, too. In order to get a full picture of sustainability impacts, the PROSUITE project included a guiding work package to integrate the three dimensions.

2.4.2 Integrative sustainability concepts

Against the background that the operationalisation of sustainability requires the integration of all dimensions, which is hardly practicable within the three-pillar concept, several integrative concepts have been developed.

In accordance with the idea of intra- and intergenerational justice Ott and Döring (2004; 2006) developed the **Greifswald approach**. Following this approach a »fair bequest package« of various goods should be maintained to assure a good life for future generations (intergenerational justice) (Ott 2009b).

A crucial question therefore is how many and which natural goods such a package should contain. This question is discussed through the conceptions of strong and weak sustainability as introduced in chapter 2.3. From the point of view of Ott and Döring, it will not be feasible to create prosperity only based on man-made capital even when considering technological progress and innovations. Besides, the uncertainty of future preferences, a better standardisation of strong sustainability, multifunctional ecosystems, the precautionary principle, a better freedom of choice for future generations, and for example difficulties in the identification of »critical« natural resources, are arguments in favour of the concept of strong sustainability (Ott, Döring 2004). In addition, a stronger consideration of eudemonia, which may be translated as the pursuit of happiness, supports the idea of protecting the basis of human life prior to material growth. Besides the conceptional view, Ott and Döring suggest to operationalise the strong sustainability concept by defining and implementing rules (Ott, Döring 2004). They support the »constant natural capital rule« (CNCR) which requires the maintenance of natural capital as well as an investment policy in scare natural capital. The following management rules already mentioned in chapter 2.2 and published by the German Advisory Council on the Environment are to illustrate the requirements mentioned (SRU 2002):

- The utilisation of a renewable resource must not exceed its regeneration rate,
- the utilisation of non-renewable resources has to be minimised. Its utilisation must be limited to an extent that permits a physically and functionally equal substitution, and
- the release of substances must not surpass its environmental capacity.

Within the Greifswald approach the so called bridging principles (Brücken-prinzipien) should connect efficiency, sufficiency, and resilience (cf. chapter 2.2). The question whether or not these three bridging principles are appropriate for this approach is discussed by (Paech 2006). Ott argues that efficiency is linked to economy and should be realised by modification of industrial processes with regard to potential rebound effects (Radermacher 2002). Resilience is linked to ecology and in this context means the conservation of natural capital, especially in terms of functionality, less in ecologically technical terms (Ott, Döring 2004). Resilience should be taken into consideration by securing natural capital with suitable securing and investment strategies. Sufficiency is associated with social aspects and mainly refers to appropriate lifestyles. In the sectors of agriculture, nature conservation, fishery and climate change, which are summarised as »dimensions of policy making« (Handlungsdimensionen), specific sustainability objectives are discussed and defined. Finally, the objectives are contextualised for the fields of implementation and suitable monitoring systems are developed.

Next to the Greifswald approach the **integrative concept of sustainability** also be referred to as HGF approach (Kopfmüller et al. 2001) was elaborated by the Helmholtz Association of German Research Centers (HGF) in the framework

of the project »Sustainable global development – perspectives for Germany« (Grunwald et al. 2000) and was applied to many sustainability impact assessments (Kopfmüller 2006). This approach tries to overcome the logic of the three pillars by defining three general goals of sustainable development which are, according to (Kopfmüller 2006):

- Securing human existence,
- maintaining of societal production potential, and
- preservation of the development and action potential of society.

These minimum conditions for a decent human life were described in detail through 15 substantial sustainability **what rules** which will be introduced in chapter 2.6. To realise a sustainable development, all these minimum conditions should be met simultaneously. By no means they encompass all desirable political, social, and economic claims, but build the basic framework of welfare. This means that there still remain further desirable goals which are not constitutive for the concept of sustainable development (Jörissen 2005).

To answer the question **how** these minimum requirements addressed by the 15 rules may be achieved, ten further instrumental sustainability rules are proposed. These rules refer to economic and political-institutional aspects of sustainable development and affect the following ten issues: internalisation of external social and ecological costs, adequate discounting, limitation of public debt, fair global economic framework conditions, fostering of international cooperation, society's ability to detect problems in society and nature and to respond on them, installation of conditions which allow reflecting options for political and social action, steering capacity, self-organisation, and balance of power (Kopfmüller et al. 2001).

Similar to the integrative concept of sustainability, the German Federal Government understands sustainability as a cross-sectional task (Bundesregierung 2008). Consequently, based on the report of the Enquête Commission on »Protection of Man and the Environment« of the German Parliament (Bundesregierung 2002) the **integrative sustainability concept of the German Federal Government** has defined four overarching goals:

- Intergenerational justice (conservation of resources, climate protection, innovation),
- standard of living (mobility, agriculture, health and nutrition),
- social cohesion/solidarity (employment, integration), and
- international responsibility (cooperation in development policies, opening-up of markets).

This concept also covers management rules, indicators, objectives, and monitoring. The proposed indicators and objectives are discussed and are used to measure sustainability in Germany and the success of policies. The latest indicator report of sustainable development in Germany was carried out in 2014 (Statistisches Bundesamt 2014). Besides, an environmental accounting

framework based on the indicators of the German sustainability strategy was published in 2012 (Statistisches Bundesamt 2012).

Starting from integrative concepts such as the integrative concepts mentioned before, a further integrative approach called **normative-functional concept of a sustainable development** was developed by Ortwin Renn which includes a methodology to deal with conflict of interests and rules (Renn et al. 2007). It makes the attempt to integrate normative and functional aspects of sustainability. The approach is based on the normative principles securing of ecological functions, enforcement of standards of justice, and preservation of the individual standard of living as a fundamental action leading to the implementation of sustainability postulates. According to these normative principles the three dimensions 1) system integrity, 2) justice, and 3) quality of life are regarded.

System integrity in this context means the continued existence of social and eco-systems, social systems consisting of interactions at least of two persons up to a worldwide society (Renn et al. 2007). The integrity of ecological systems mainly depends on the ability to maintain crucial functions even in the case of interior changes according to external developments or disturbances (Renn et al. 2007). Justice includes the intra- and intergenerational justice. From the point of view of Renn et al. justice is defined by a just distribution of freedom and also covers the access to resources (Renn et al. 2007). The access to essential resources as well as cultural ideas mainly influences the subjective well-being and therefore quality of life (Birnbacher, Schicha 1996). In order to become more sustainable, natural and cultural conditions of subjective well-being should be addressed positively (Renn et al. 2007).

The normative-functional concept also develops sustainability criteria, sub-criteria, and indicators based on the three dimensions mentioned and includes an expert-based methodology called cross-impact-analysis to assess interactions between system characteristics of the criteria. In contrast to the HGF approach that suggests a theory of »invulnerable core areas« following the ideas of the Federal Constitutional Court with regard to collisions of constitutional rights, the normative-functional concept by Renn proposes discursive procedures to solve conflicts of objectives and to define arrangements.

Finally, the **capability approach** suggested by Amartya Sen and further advanced in different directions by Martha Nussbaum, initially conceived in the 1980s as an approach to welfare economics, focuses on the capabilities of what individuals are able to do (Sen 2003; Nussbaum 2006). According to Sen the definition and assessment of capabilities should consider the importance of »effective freedoms«[5] in the assessment of a person's advantage, individual differences in the ability to transform resources into valuable functionings (»beings«, »doings«)[6], the great diversity of activities giving rise to happiness,

[5] Effective or real freedoms mean actual possibilities not hollow promises or paper freedoms.

[6] For example people with physical disabilities may need specific goods to achieve mobility.

that human welfare is affected by material and non-material goods, and the question about the distribution of opportunities within society (Wells 2012).

»The key idea of the capability approach is that social arrangements should aim to expand people's capabilities – their freedom to promote or achieve what they value doing and being« (Deneulin, Shahani 2009, p. 31). That means people should have the freedoms, here also referred to as capabilities, »to lead the kind of lives they want to lead, to do what they want to do and be the person they want to be« (Robeyns 2003, p. 7). The approach was applied to the policy debate in human development and inspired the creation of the Human Development Index[7] (HDI) developed by the United Nations Development Programme.

2.5 Selection of a sustainability concept to assess bio-based products

The main requirement on the sustainability concept for assessing the sustainability impact of bio-based products is to provide an appropriate conceptual framework in that sense that it fulfils the following three fundamental prerequisites.

1) The sustainability concept should be suitable to discuss sufficiently the contribution to sustainable development that bio-based products and fossil-based products may cause. Since the cultivation system of biomass does significantly affect the sustainability of bio-based products, the concept should also be suitable to assess sustainability effects caused by cultivation systems.

In order to ensure the clear reference to the concept of sustainable development, the concept

2) should be clearly based on the ideas presented in the report »Our Common Future« (WCED 1987) published by the World Commission on Environment and Development (WCED), with focus on the operationability and be internally consistent. By referring to the WCED-report that gives a worldwide accepted comprehensive definition of sustainable development, the probability increases that the sustainability concept addresses the most important aspects of sustainable development.

Furthermore, the concept of sustainability is often based on incommensurable[8] values making it difficult to come to final conclusions. Therefore, the sustainability concept should allow

3) the consideration of incommensurable values that cannot be easily compared. Despite seeming hardly possible, due to pragmatic requirements, the balancing of different values can be supported by an integrated assessment,

[7] The HDI appears in the annual development reports of the United States Development Programme (UNDP): http://hdr.undp.org/en/

[8] Incommensurable is defined here as the absence of a common measure for comparing values such as liberty or health.

which shows the relationships of different aspects and allows balancing various demands of a sustainable development.

Beside these three fundamental prerequisites, the concept is to be structured clearly and simple in that way that users can follow the approach starting from the theoretical background to its final application. To ensure the implementation in political and economic fields, the concept should also be accepted by decision makers and should have good communication qualities.

However, due to the different scope of each sustainability concept, as introduced in chapter 2.4, it is not possible to conduct a comparative quantitative analysis of all these requirements. Hence, their advantages and disadvantages are discussed in the following in order to select the most appropriate concept.

The **three-pillar concept** was used in many approaches (Deutscher Bundestag 1998; Blazejczak et al. 2000) and was also applied to assess the sustainability of emerging technologies within the EU-funded project »Development and application of a standardized methodology for the PROspective SUstaInability assessment of TEchnologies (PROSUITE)« (Blok, Patel 2011). On a political level it is well accepted because of its great level of awareness (Tremmel 2003), its easy structure (Kleine 2009) and easy communication features (Ott 2009a). According to Ott (2009a) the high level of connections to the political system also entails the danger of justifying different programmes and strategies with this vague concept of sustainability. Additionally, the approach to develop requirements on a sustainable development from the view of each pillar, often also referred to as dimension, may lead to sectoral optimisation and ignorance of interactions and conflicts of interests which cannot be integrated or solved afterwards (Schäfer 2003). However, an interdisciplinary view that can support balancing various demands, is often missing and the three pillars are often used as a »wish list of interests« (Brand, Jochum 2000; Hartmuth, Rink 2003). That is why many actors can easily agree on the three-pillar concept. As Daly said: »One way to render any concept innocuous is to expand its meaning to include everything« (Daly 1996, p. 9). In summary the required equality of all three dimensions is currently not given and priorities are often negotiated (Meyer-Abich 2001). The structural rigidity of the three-pillar concept cannot be overcome and there is no scientific methodology of weighting goals of sustainability (Jörissen 2005).

The integrative sustainability concept of the **German Federal Government** does not directly look at technologies or cultivation systems but throws a special light on the development of a society (Bundesregierung 2002). This also covers the topic of efficient and environmentally friendly energy systems preferably from renewable resources as presented in section IV »promote sustainable resources utilisation« of chapter F »Assume global responsibility« published in the report »Perspektiven für Deutschland« (Bundesregierung 2002). It is also widely sanctioned by politics and can be communicated easily because it refers to political activity areas. Nevertheless, the scale of the concept and the suggested indicators refer to the Federal Republic of Germany. Hence, the

concept may not be appropriate to assess the contribution of worldwide emerging biorefineries to a sustainable development.

The **capability approach** supports people in addressing the question of what needs should be fulfilled in order to develop their own individual account of a good life (Hillerbrand 2014). That means the approach is very useful for defining areas of protection and for identifying social evils and their causes. Thereby, it allows discussing the needs of humans with a clear focus on sustainable development. Because of its integrative character it opens a framework for balancing objectives of a sustainable development. Since it was developed in the context of human development as discussed by the United Nations Development Program, it has been mainly applied in measuring human welfare. However, it can be also adopted in the context of technologies such as biorefineries because technologies make it possible to enhance capabilities – as described in chapter 2.4.2 – significantly e.g. through their products or e.g. through the conservation of finite resources such as oil (Hillerbrand 2014). Despite of these advantages, the capability approach is difficult to break down to specific measurable indicators because, in contrast to existing eco-assessment tools such as life cycle assessment (LCA), it is was developed from a more conceptual perspective (Wu et al. 2014). For example it includes seven areas of protection (AoP) instead of three AoP which are typically used in life cycle impact assessment (LCIA) models. Nevertheless, it was successfully applied as a normative framework for defining areas of protection (AoP) as well as for defining impact categories within social life cycle assessment (SLCA) (Reitinger et al. 2011). It has not been applied for assessing the sustainability of bio-based products yet, maybe due to its conceptual nature or difficulty to transfer it to existing sustainability tools. Although it offers great opportunities it is not selected due to its difficulties in application.

The **normative-functional concept** of a sustainable development by Renn is mainly designed for politicians and sustainability on local up to global administrative levels and does not apply to companies or technologies (Renn et al. 2007). It also involves the stability of eco-systems but does not provide any precise differentiation between purposes of cultivation systems. The concept incorporates many scientific approaches such as the integrative sustainability concept of the German Federal Government or HGF-approach and complies with the standards laid down in the documents of the World Commission on Environment and Development. It is structured clearly and involves, next to an indicator system, a cross-impact analysis that delineates the degree of influences between sustainability criteria. Additionally, discursive methods are suggested as solution to conflicts between objectives and transformation. This also leads to a high complexity which is a constraint to the requirement of a simple structure. Currently, the concept does not receive much public attention but it is also based on similar sustainability criteria as those given by the integrative sustainability concept of the German Federal Government.

According to Schultz et al. the **Greifswald approach** as well as the **HGF concept of sustainable development** are two salient integrative conceptions of sustainable development (Schultz et al. 2008). Both conceptions describe the

complexity of sustainability within different levels of complexity (Ott 2006a) and define sustainability rules. However, instrumental rules (cf. chapter 2.4.2) are not defined within the Greifswald approach. Additionally, the Greifswald approach suggests rules and strategies of resource and environmental management as mentioned in chapter 2.2 which do not cover social aspects such as the right to work or the development of man-made and knowledge capital. On the contrary, the rules given by the HGF approach (see Table 2-1) are more open than those used in other approaches such as the Greifswald approach and allow a better adjustment to special topics such as biorefineries (Grunwald 2009).

The Greifswald approach suggests a theory of strong sustainability (cf. chapter 2.3) (Ott, Döring 2004). In contrast to the HGF approach, the Greifswald approach does not predominantly refer to the common notion of sustainability given by the WCED in order to operationalise the concept of sustainable development but specifies and intensifies the normative framework of sustainable development (Grunwald 2009). Thus, the Greifswald approach may not be accepted by politics and industry and cannot be communicated easily. Hence, the main difference between the Greifswald approach and the HGF approach is that the Greifswald approach tries to justify the principle of strong sustainability in general. In contrast the HGF approach tries to answer the question of substitutability case-specific which may lead to a »stronger« principle of sustainability than the authors of the HGF approach were aware of (Ott 2006a). From the perspective of the HGF approach, the substitution of natural capital is acceptable »to a limited extent, insofar as the basic functions of nature (including the immaterial) are preserved« (Schultz et al. 2008, p. 477).

An advantage of the Greifswald approach is that it was already applied to the topics agriculture, nature conservation, and climate change (Ott, Döring 2004). However, the HGF approach is also highly suitable for adaptation to specific fields, in particular technological areas (Kopfmüller et al. 2001). For example, the concept was already applied to assess the sustainability of energy systems where energy sector-specific criteria and indicators were developed, assessed, and balanced (Kopfmüller et al. 2000). In addition, the integrative concept was applied to many topics such as the development of regions, cities, or companies but also for evaluating the impact of a green biorefinery on a sustainable development (Kopfmüller 2006). It is applicable to develop theme-specific indicators and delivers a well-founded compass for sustainability-related evaluations and relevance decisions. Besides, it provides a clear and positive definition of sustainable development applied to different contexts on a scientific basis. Accordingly, it offers a clearly outlined way to operationalise the concept of sustainable development (Grunwald 2009). A discourse about how to deal with potential conflicts between objectives is also included.

The HGF approach as well as the Greifswald approach stresses the necessity of the integrated assessment of sustainability problems in the early analytical phase in a comprehensive way, including all dimensions of sustainability. The authors consider this to be the only way to master the overall complexity of basic goods and utilisation structures (Kopfmüller et al. 2001). On the other hand decision

makers might not be willing to use these concepts because a fundamental understanding of what sustainability means is needed.

In summary, the three-pillar concept lacks an integrative view on sustainability impacts of biorefineries which is mandatory for this thesis. The scope of the concept of the German Federal Government is not suitable to be applied to biorefineries, too. The capability approach, the Greifswald approach, the HGF approach as well as the normative-functional concept by Renn give a comprehensive and integrative view on sustainable development and develop recommendations for a sustainable future. They all contribute to knowledge of objectives, systems knowledge, and practical knowledge (Renn et al. 2007) which is needed to operationalise a sustainable development. However, the HGF approach seems to be superior to the capability approach, Greifswald approach, and normative-functional concept by Renn because its applicability has been shown in many studies, it fits to the common understanding on sustainable development, offers most wide-ranging and precise rules, and is most likely appropriate to communicate. Hence, the HGF-approach is applied in this thesis to evaluate the contribution of biorefineries to a sustainable development and is introduced in more detail in the next chapter. Nevertheless, the preferability of the concept should also be proven ex post. Due to the high complexity of all these concepts and limited time it is not done within this thesis.

2.6 A closer look at the selected integrative concept of sustainable development

As mentioned in chapter 2.4.2 the integrative concept of sustainable development (HGF approach) is a multidimensional approach that tries to operationalise sustainability by referring to constitutive elements of sustainable development and not by addressing sustainability dimensions directly. On the basis of the documents of the Brundtland Commission (WCED 1987), a global and enlightened-anthropocentric perspective as well as the claim for inter- and intragenerational justice were identified as constitutive elements. The enlightened understanding of anthropocentrism requests the protection of nature out of a well-understood self-interest of mankind (Schultz et al. 2008). The anthropocentric approach does not postulate rights to the natural environment or its constituents nor a value in itself. It rather refers to the long-term preservation of the various functions that nature fulfils for mankind (Schultz et al. 2008). Inter- and intragenerative justice are regarded as normative equally important. The idea of justice in this context encompasses the right of every generation to use the natural, economic, social, and cultural heritage and the duty to hold it in trust for future generations. This double role as beneficiary and fiduciary of a common heritage gives every generation collective rights which are linked to collective duties. These rights were specified according to the ideas that every human has the right of access to basic goods which allow a self-determined life (Kopfmüller et al. 2001). This view on justice

leads to an understanding of sustainability that is not only orientated on sustainable production methods and patterns of consumptions as well as on objective limits of natural carrying capacities but also addresses the organisation of a society under the idea of justice. Against the background of this definition of justice the following three general goals of sustainable development were defined (Kopfmüller et al. 2001):

- Securing human existence,
- maintaining of societal production potential, and
- preservation of the development and action potential of society.

In compliance with the definition that sustainability substantially is the continuous provision of minimum conditions for a decent human life (Kopfmüller et al. 2001), these three general goals are specified »by identifying minimum conditions for sustainable development that ought to be assured for all people living in future and present generations« (Schultz et al. 2008, p. 477). These conditions were described in detail through 15 substantial sustainability »what-rules« which are presented in Table 2-1.

Table 2-1: Substantial sustainability rules and their classification according to general targets of sustainable development (Grunwald, Kopfmüller 2006)

Securing human existence	Maintaining of societal production potential	Preservation of societal development and action potential
(1.1) Protection of human health	(2.1) Sustainable use of renewable resources	(3.1) Equal access for all people to information, education, occupation
(1.2) Ensuring satisfaction of basic needs	(2.2) Sustainable use of non-renewable resources	(3.2) Participation in social decision-making processes
(1.3) Autonomous subsistence based on own income	(2.3) Sustainable use of the environment as a sink	(3.3) Conservation of the cultural heritage and diversity
(1.4) Just distribution of chances for using natural resources	(2.4) Avoiding technical risks with potentially catastrophic impacts	(3.4) Conservation of the cultural function of nature
(1.5) Reduction of extreme income and wealth inequalities	(2.5) Sustainable development of physical, human and knowledge capital	(3.5) Conservation of social resources (tolerance, solidarity etc.)

Rule 3.1 calls for equal access for all people to information, education, and occupation. This claim should not be misunderstood to mean equal opportunities of all people that as people also have different wishes and capacities by nature, may be impossible to reach (Hillerbrand 2014). Depending e.g. on the genetic constitution of humans they of course have different opportunities. Therefore, rule 3.1 should rather be understood in the sense of

having the same access to social basic goods such as the possibility to go to school.

The substantial sustainability rules are deliberately formulated abstractly to ensure space for contextualised differentiation and will be adopted here to identify reliable sustainability criteria for biorefineries. That means a deep understanding on what is constitutive for sustainability in this context is still required.

In contrast to other integrative sustainability concepts, the HGF approach also defines instrumental requirements through »how rules« (cf. chapter 2.4.2). These rules address requirements on institutions to realise a sustainable structural change and will not be regarded within this thesis.

Furthermore, the HGF approach proposes an operationalising process by combining a normative »top-down approach« with a problem-oriented »bottom-up approach«. Through the definition of minimum conditions for sustainable development, a normative framework for identifying reliable sustainability criteria is given. This »top-down approach« is supplemented by taking into consideration scientific and political discourses on sustainable development (»bottom-up approach«).

The principle theoretical architecture is illustrated in Figure 2-3. Based on a normative framework, minimum conditions are defined for a sustainable development. These minimum conditions are translated into sustainability rules which are applied to a specific topic. Along with a public discourse goals, indicators, and scenario analysis are developed. Within this thesis the scientific and political discourses on a sustainable use of biomass is taken into consideration especially with regard to biorefineries.

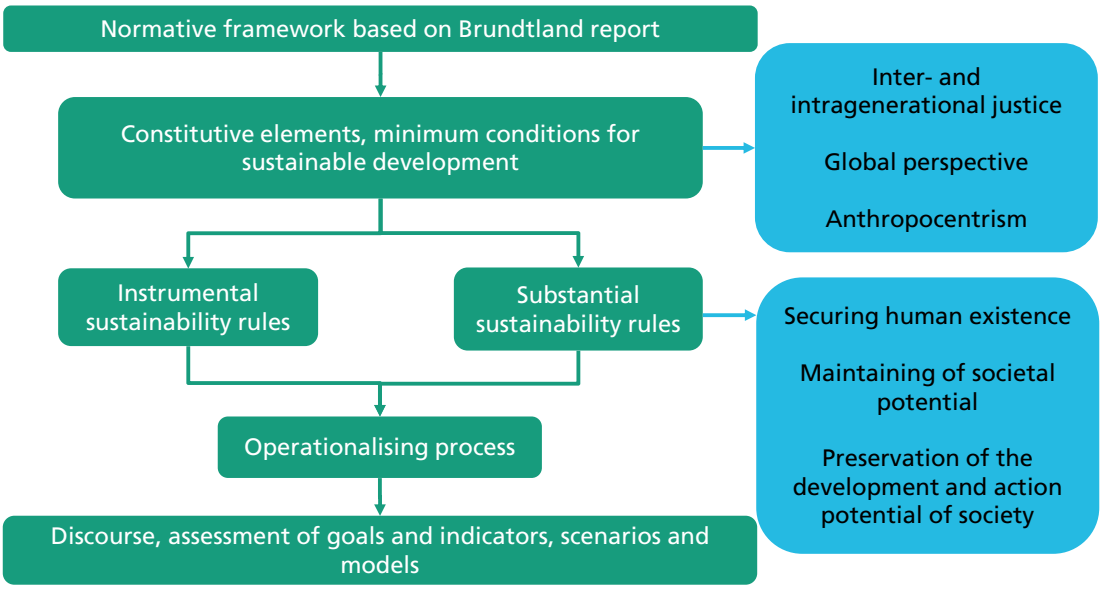

Figure 2-3: Principle structure of the integrative concept of sustainable development

The integrative concept of sustainable development is applied in chapter 4.1 to assess generic sustainability criteria of biorefineries at a global scale (technology perspective). That means not every criterion is important for each type of biorefinery and might not be suitable to assess the sustainability of one certain biorefinery plant.

In order to assess specific sustainability criteria for one biorefinery concept, a further contextualisation and specification in place and time is needed. This next step will be carried out for a concrete algal-based biorefinery described in the chapter 5.3.

Also included in the HGF concept is a theoretical discourse on justice as to how to assess the nexus of different results due to different requirements of rules or goals. The principle methodology is illustrated in Figure 2-4. Initially, every rule should be considered. Secondly, the key elements of a rule, which are essential for human life, are of greater importance than further requirements that do not affect the existence of life. A key element is characterised by its normative importance. The key element of the rule »Protection of human health« might be the protection of human life. One criterion to identify a key element of a rule is the irreversibility of damage. This criterion should be also taken into account even in the case of no presently cognoscible direct damage to human life such as the extinction of a seemingly useless species (Rescher 1997).

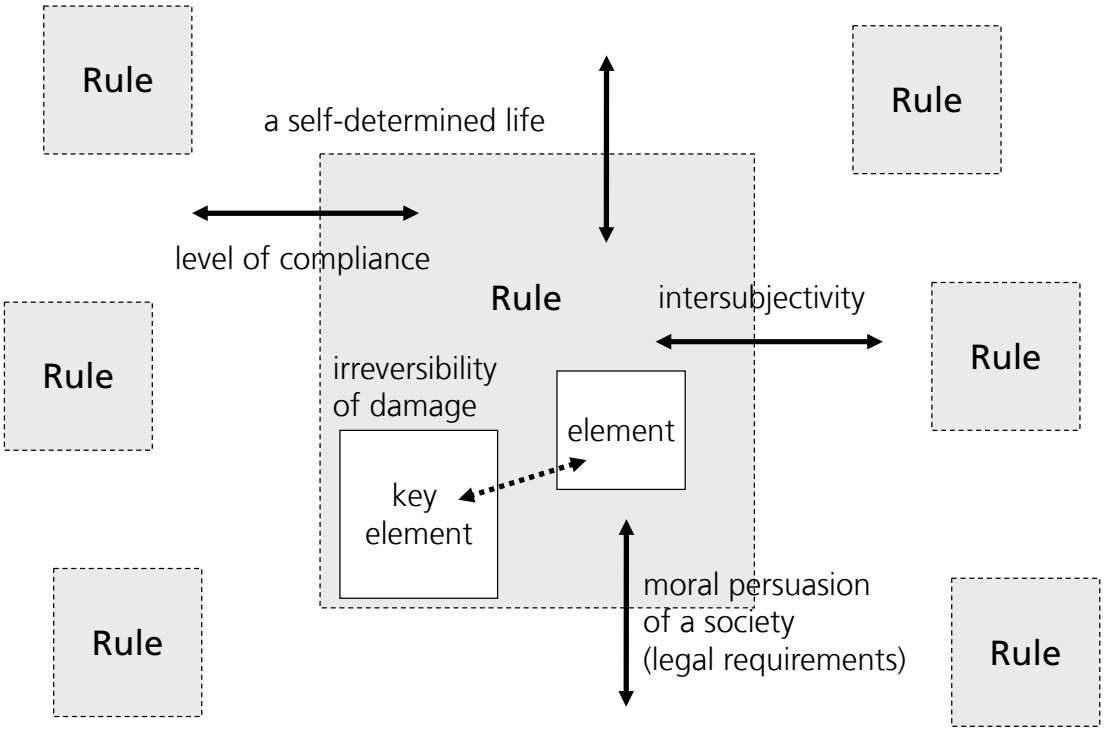

Figure 2-4: Principle methodology to weight and rank goals of sustainability

In order to weight goals of different rules, the level of compliance of a rule with its goals is of central interest. Further criteria to rank goals among rules are:

- The level of intersubjectivity,
- the moral persuasion of a society that may also be found in legal requirements, and
- the protection of a self-determined life.

Intersubjectivity means a »judgement on the same basis« and is not the same as general acceptance (Jansen 1998, p. 292). It can be achieved if the majority of people gave the same answer to one question regardless of their living situation. That means the more people rate a rule high the more important it is.

In contrast to intersubjectivity the moral persuasion of a society strongly depends on the living conditions of its residents. A rule might be ranked higher, the more it meets the general, moral perspective of a society.

In case of threatened infringement aspects of rules that protect fundamental individual liberties should be weighted high. By doing this the liberty of leading a self-determined life is protected.

This approach will be used as a basis for weighting and ranking sustainability goals of biorefineries.

3 Biorefinery concepts

3.1 Biorefinery definition

The term »biorefinery« was established in the 1990s (Kamm et al. 2010), although large-scale utilisation of biomass already existed in the last two centuries e.g. in the pulp and paper sector or sugar production. In the simplest form it is a concept of processing biomass into a spectrum of valuable products. Biorefinery concepts were developed in order to produce bio-based products as well as bioenergy and biofuels that can compete with their crude-oil-based equivalents more efficiently than today. The terms »bio-based« and »bio-based product« have been defined as »derived from biomass« and »product wholly or partly bio-based« by the working group CEN/BT/WG 209 (CEN 2010), whereas biomass was defined as »material of biological origin excluding material embedded in geological formations and/or fossilized«. The CEN/BT/WG 209 was disbanded in August 2010 and continued under the name CEN/TC 411 »bio-based products«.

Today the term »biorefinery« is widely spread and there are many definitions about what a biorefinery exactly is. The definition developed by the International Energy Agency (IEA), Task 42, has been widely accepted due to its general and comprehensive character: »Biorefining is the sustainable processing of biomass into a spectrum of marketable products and energy« and is characterised more precisely by the following keywords (van Ree 2010):

- Sustainable: maximising economics, considering social aspects, minimising environmental impacts, fossil fuel replacement, closed cycles
- Processing: upstream processing, transformation, fractionation, thermo-chemical and biochemical conversion, extraction, separation, downstream processing
- Biomass: wood and agricultural crops, organic residues, forest residues, aquatic biomass
- Spectrum: multiple energetic and non-energetic products
- Marketable: present and forecasted (volume and prices)
- Products: both intermediates and final products (i.e. food, feed, materials, chemicals, fuels, power, heat)

Besides this definition, Fraunhofer UMSICHT has defined a biorefinery as follows: Biorefinery is an integrated comprehensive concept for the conversion of renewable resources into chemicals, materials as well as combustibles and fuels, electric power and heat, thus contributing to a sustainable economy whilst biomass is being utilised to the maximum extent. This definition points to the idea that in order to optimise the added value from biomass and becoming price-competitive an integrated biorefinery strategy is needed that optimises the utilisation rate of biomass. Following this definition biorefineries combine and

integrate various innovative technologies such as biotechnologies in order to exploit all components in the biomass (Viikari et al. 2010). Moreover, the biorefinery concept also includes the management of sus-tainability aspects that advances its competiveness. Principally, the biorefinery concept also tries to close the material loops such as the carbon cycle or nutrient cycles, for instance the nitrogen, phosphorus and potassium cycles.

In contrast to more simple and conventional conversion technologies, which convert biomass into mainly one material or energetic product such as a biomass boiler, biorefineries always use several conversions steps resulting in intermediate products also referred to as »platforms« that are further processed into a variety of different energetic and material products. The term platform was defined in the context of biorefineries for the first time as »intermediates from which final products are derived« (Cherubini et al. 2009, p. 538). Later on it was further specified by the German Biorefineries Roadmap and VDI 6310 standard as »intermediate products that arise during primary refining and which serve as precursors for subsequent secondary refining« (German Federal Government 2012, p. 10; VDI 6310). The term platform, as defined here, should not be confused with »platform chemicals« that serve as basis for the production of numerous chemicals in conventional refineries. The question whether or not all processes of a biorefinery must be located at a certain place remains open although they should be predominantly at one place.

A general picture which types of biomass could be used in a biorefinery and how a biorefinery is interacting with its environment is illustrated in Figure 3-1.

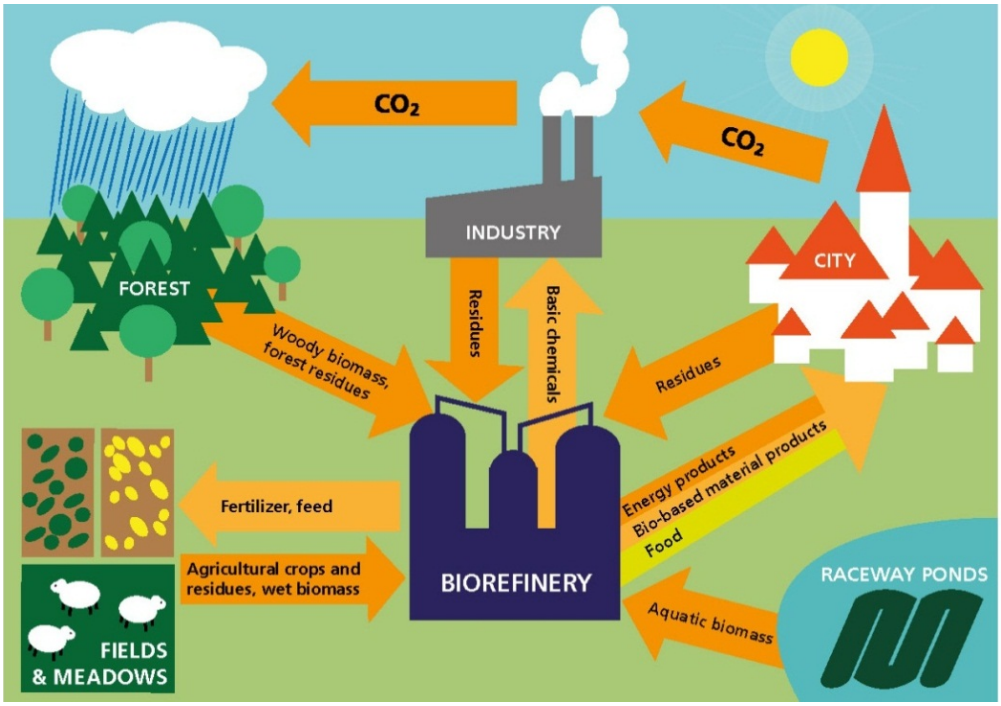

Figure 3-1: Schematic picture of a biorefinery with possible raw materials and products

3.2 Classification method for biorefinery systems

The process chain of biorefineries largely consists of system components for the pre-treatment and conditioning of biomass as well as for separation of biomass components (German Federal Government 2012). As mentioned before the associated processes are summarised under the term »primary refining«. The product, also referred to as platform, of such primary refining steps is further converted (secondary refining) into an intermediate product and finally into minimal one energetic main product, one bio-based main product, and/or at least food or feed.

These four basic elements biomass (feedstock), platform, conversion processes, and products can be used to systematically and clearly classify biorefineries as firstly suggested by (Cherubini et al. 2009). The classification method suggested by Cherubini, Jungmeier et al. focuses on the platform similar to the idea used in the petrochemical industry where the crude oil is fractionated into a large number of intermediates that are further processed into energy and chemical products (Cherubini et al. 2009). This platform-oriented classification approach leads to a manageable number of platforms which can be handled and supplemented if necessary. The classification method can be visualised as shown in Figure 3-2.

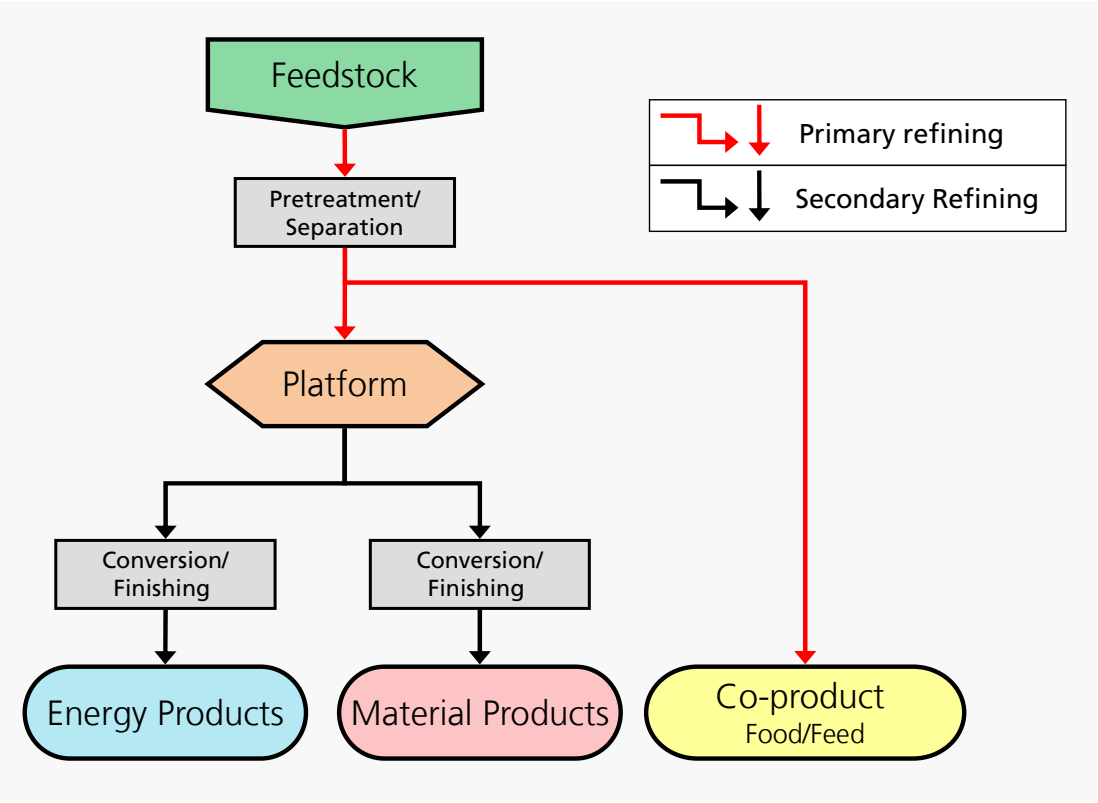

Figure 3-2: The different elements within the biorefinery concept according to Cherubini, Jungmeier et al. and Peters (Cherubini et al. 2009; Peters 2011)

According to this method a biorefinery can be defined as follows:

- number and name(s) of platform(s) (e.g. one platform C6 sugar) biorefinery for products (e.g. bioethanol and animal feed) from feedstocks (e.g. corn).

Additionally, the applied processes can be added in order to describe the biorefinery in more detail. Table 3-1 lists various feedstocks, platforms, products and processes which are typically used in biorefinery concepts and are applied for classification without the requirement of completeness.

The following chapters describe these four elements in more detail.

Table 3-1: List of possible elements for the classification of biorefineries according to Peters and the classification method first developed by Cherubini, Jungmeier et al. (Cherubini et al. 2009; Peters 2011)

Feedstocks	Platform	Processes	Products
Agricultural crops & woody biomass ▪ Oil plants ▪ Starch plants ▪ Sugar plants ▪ Grasses ▪ Forest wood ▪ Plantation wood ▪ Short-rotation wood ▪ Wood-like biomass **Aquatic biomass** ▪ Microalgae ▪ Macroalgae ▪ Sea grass **Biogenic waste and waste materials** ▪ Agricultural and forestry residues (e.g. straw, liquid manure, residues from forests, fruit peels) ▪ Biogenic waste products from the processing (e.g. stillage, whey, marc, brewers grain) ▪ Biogenic waste materials (e.g. used grease, waste wood)	▪ Low molecule carbohydrates (e.g. lactose, sucrose) ▪ Carbohydrates polymers (e.g. starch, inulin, pectin) ▪ Lignocellulosic components (lignin, cellulose, hemicelluloses) ▪ Proteins ▪ Plant fibers ▪ Organic juice ▪ Vegetable oils, lipids ▪ Pyrolysis oil ▪ Syngas ▪ Biogas	▪ Mechanical and physical treatment methods ▪ Thermo-chemical processes ▪ Chemical processes ▪ Biotechnological processes	**Materials** ▪ Chemicals ▪ Materials (e.g. bio-plastics, insulation material) ▪ Feed as co-product ▪ Food as co-product **Bioenergy** ▪ Solid, liquid, gaseous bioenergy carriers ▪ Electricity ▪ Heat ▪ Cooling

3.2.1 Raw materials for biorefineries

Raw materials (feedstocks) of biorefineries are various types of biomass which is a very heterogeneous and chemically complex renewable resource. Similar to the definition by the working group CEN/BT/WG 209 (CEN 2010) introduced in the chapter before, the VDI guideline 4631 defines biomass as »organic matter of recent phytoplankton and zoogenic material. This includes by-products, residues, and waste materials from phyto and zoogenic material which energy content originates from phyto and zoogenic material« (VDI 4631, p. 6). In contrast to fossil raw materials, biomass is not older than several hundred years and is characterised by a higher oxygen to carbon ratio compared to fossil raw

materials such as naphtha. Independent of the type of biomass about half of the biomass is made up of organic carbon. The main components of vegetable biomass are carbohydrates and lignin whereas animal biomass primarily consists of proteins and lipids. Microalgae also lack lignin and consist mainly of proteins, carbohydrates, and lipids. With regard to the availability of biomass for biorefineries, the largest amount of available biomass is terrestrial vegetable biomass. The most relevant feedstocks for biorefineries are summarised in Table 3-1 and are agricultural crops, woody biomass, aquatic biomass as well as biogenic waste and waste materials.

3.2.2 Platforms of biorefineries

As illustrated in Figure 3-2 platforms are defined as biomass components that result from primary refinery processes and are further processed into intermediate products and/or products through secondary refining processes. Possible platforms of biorefineries are listed in Table 3-1. Platforms are for example low molecular carbohydrates such as lactose or saccharose that can be extracted directly e.g. from sugar beet or sugarcane. Besides carbohydrates polymers such as starch or inulin that are present e.g. in wheat, maize, or in potatoes can make up a platform which can be further converted to sugars via hydrolysis.

Apart from carbohydrates polymers, celluloses and hemicelluloses, that are the main components in woody biomass, can also be used as platform to produce sugars via hydrolysis. Lignin, the third important component in woody biomass, is another platform which can be directly used as biofuel, gasified to syngas or e.g. used as raw material for phenolic chemicals.

Other platforms are organic juice and proteins e.g. extracted from grass that can be further processed to pharmaceutical products, fodder or biogas. Apart from proteins, plant fibres can be extracted from lignocellulosic materials such as grass and can for example be further processed to insulation material or fibre-reinforced plastics. In Brensbach, a city located in Germany, a 2-platform (organic juice and biogas) biorefinery was established that converts grass cuttings and manure to electricity, insulation material, carbon-reinforced plastics, and fertiliser.

Vegetable oil, another platform, can be extracted from oilseed crops such as rape, soy, sunflower, peanuts or for example from microalgae. The oils can be further processed e.g. to biodiesel, dicarboxylic acid or polyamides (Hill 2006). It should be mentioned that depending on the method of vegetable oil separation usually a significant amount of extraction meal or press cake is produced as by-product which is a popular animal feed due to its high protein content.

Pyrolysis oil can be produced for instance through intermediate or flash pyrolysis from nearly any biomass feedstock. It is a multi-component mixture of acids, alcohols, aldehydes, esters, ketones, sugars, phenols, guaiacols, syringols, furans, and terpens (Cherubini 2012). It can be used as fuel for stationary

generation of steam and power or the substances mentioned are extracted and further processed to products.

Syngas, another platform, is the product of the gasification process and mainly consists of CO, H_2, and CH_4. Products that can be obtained from syngas are for instance methanol, ethanol, hydrogen, ammonia, Fischer-Tropsch fuels, acetic acid or formaldehyde (Thoen, Busch 2010; Hamelinck et al. 2004).

Biogas that mainly consists of CH_4 and CO_2 can be produced via anaerobic digestion of biomass or by methanisation of syngas. Biogas can be used directly e.g. in a combined heat and power (CHP) plant for the production of electricity and heat, or it could be injected in the gas network after removing CO_2 and other undesired elements and can be used as transportation biofuel. Principally, biomethane could be also used as raw material for the production of chemicals via chemical conversion or via fermentation. However, today biomethane cannot compete economically with natural gas without subsidies (German Federal Government 2012).

3.2.3 Technologies and processes of biorefineries

Biorefineries require a huge spectrum of different technologies and processes. Even if conventional technologies can be applied, a further development of energy-efficient processes and methods for the supply, conditioning, and conversion of biomass is needed.

Principally mechanical, biotechnological, chemical, and thermochemical processes are of relevance (Fritsche et al. 2011).

Important processes in biorefineries are for example (Cherubini et al. 2009; VDI 6310):

- Mechanical/physical processes which do not change the chemical structure of the biomass components, for example
  - basic operations for changing material properties such as drying, pressing, milling, heating,
  - purification and separation processes such as filtration, distillation, extraction, crystallisation, adsorption, sieving,
  - transportation processes via truck, pipeline, conveyer belt etc.,
- biochemical processes, for example
  - fermentation processes using microorganisms such as aerobic and anaerobic fermentation,
  - enzymatic conversion using enzymes,
- chemical processes, for example
  - basic operations for changing molecular structures such as transesterification, hydrolysis, etherification, hydrogenation, oxidation, isomerisation, polymerisation, and methanisation,
  - chemically catalysed conversion processes, and

- thermochemical processes, for example
  - processes under high temperature and/or pressure with or without a catalytic means such as pyrolysis, gasification, hydrothermal upgrading, thermolysis, and combustion.

These basic processes have been developed for different applications e.g. in the field of bioenergy (Kaltschmitt et al. 2009) and are available in different levels of development. Levels of technology also referred to as technology readiness levels (TRLs), for instance, were defined by the U. S. Department of Energy (DOE 2011) and the European Commission (European Commission 2011). In total nine levels are distinguished: 1) basic principles observed, 2) technology concept formulated, 3) experimental proof of concept, 4) technology validation in laboratory, 5) technology validated in relevant environment, 6) demonstration in relevant environment, 7) demonstration in operational environment, 8) system complete and qualified, 9) successful mission operations. Depending on the raw material, processes have been developed at varying stages of development. Figure 3-3 gives an example of the technology readiness levels (TRL) of bio-chemical processes for different raw materials (Jungmeier et al. 2014, p. 16).

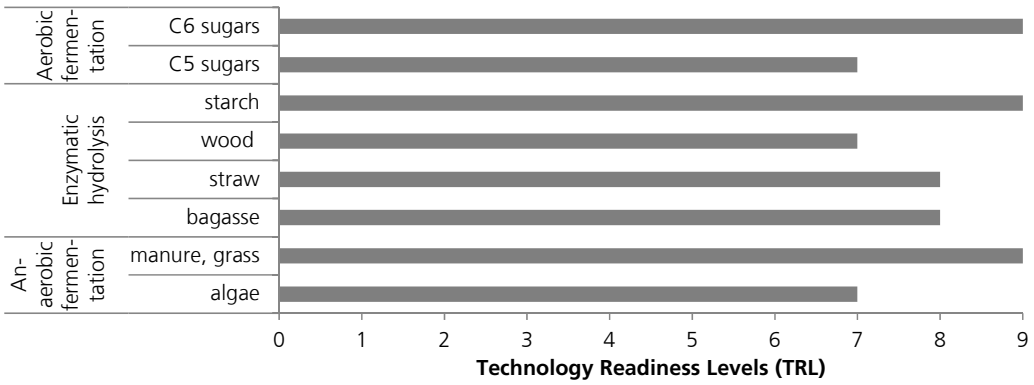

Figure 3-3: Example of technology readiness levels of bio-chemical processes for different raw materials (Jungmeier et al. 2014, p. 16)

In contrast to many existing simple biomass processing installations such as oil mills, biorefineries integrate several of these processes and technologies for example to expand the product range or to expand the usable biomass components.

3.2.4 Markets and products

Apart from platforms, biorefineries are characterised by material and energetic products whereas the assignment depends on their application. Energy products are used for providing electricity, heat or transportation service, while material products are used because of their chemical and physical properties or as food or feed. In the following typical energy products and groups of material products produced by biorefineries are described.

Energy products

Potential energy products produced by biorefineries are mainly biofuels, electricity, and heat. Biofuel is the most valuable type of energy since it allows storing energy chemically and direct application in transportation. Principally, biofuels can be distinguished into conventional biofuels produced from agricultural crops that could be used for food and feed production, too, and advanced biofuels that are produced from non-food and non-feed crops, respectively. The latter ones are also referred to as second generation biofuels and the conventional ones are also called first generation biofuels. Conventional biofuels are for example biodiesel (defined in EN 14214) manufactured from animal fats or vegetable oils such as rapeseed oil, soybean oil, palm oil, sunflower, and coconut oils (Demirbas 2010) and bioethanol e. g. produced from starch or sugar plants. In addition, biogas which mainly consists of CH_4 can be produced via anaerobic fermentation from a variety of energy crops and organic wastes and apart from the use for the production of heat and electricity it can be applied as an automotive fuel (Weiland et al. 2009). It is also possible to further convert biogas to syngas by oxidising methane and using the water-gas shift reaction. Afterwards syngas can be used to produce a FT-fuel by using the Fischer-Tropsch method (Lappas, Heracleous 2011). In case methane is used as feedstock for producing synthetic fuels it is referred to as »gas to liquids« (GTL).

According to the European Association for Bioindustries Europa Bio[9], advanced biofuels are defined as »those biofuels that have the potential to be produced in significant quantities and deliver a significant life cycle GHG emission saving while minimising competition for agricultural land. They also have the potential to be economically competitive as has already been realised for first generation ethanol in Brazil« (Alasti 2011, p. 16; Moreira, Goldemberg 1999). »Advanced biofuels may be produced for instance from waste, agricultural (food crop) residues, non-food (ligno) cellulosic biomass, crops grown on marginal land and algae« (Alasti 2011, p. 16). Examples of further advanced biofuels are ethanol or butanol produced from celluloses and thermo-chemically and catalytically produced Fischer-Tropsch diesel, methanol, dimethylether (DME), hydrogen, and synthetic natural gas (SNG).

Besides, bio-jetfuels are under development. The most promising bio-jetfuels are those made from fats and oils such as hydro-treated vegetable oils (HVO) or hydro-processed esters and fatty acids (HEFA). Apart from bio-jetfuel made from fats and oils those made from alcohols (ATJ) or made from syngas such as synthesised paraffinic kerosene (SPK)[10] attract attention (Pflaum et al. 2014). An overview about promising transportation biofuels, bio-jetfuels and process routes is given in Figure 3-4.

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[9] EuropaBio is a huge European biotech industry group, present on the internet at http://www.europabio.org/.

[10] In combination with additional aromatics it is called SKA: synthetic kerosene aromatics

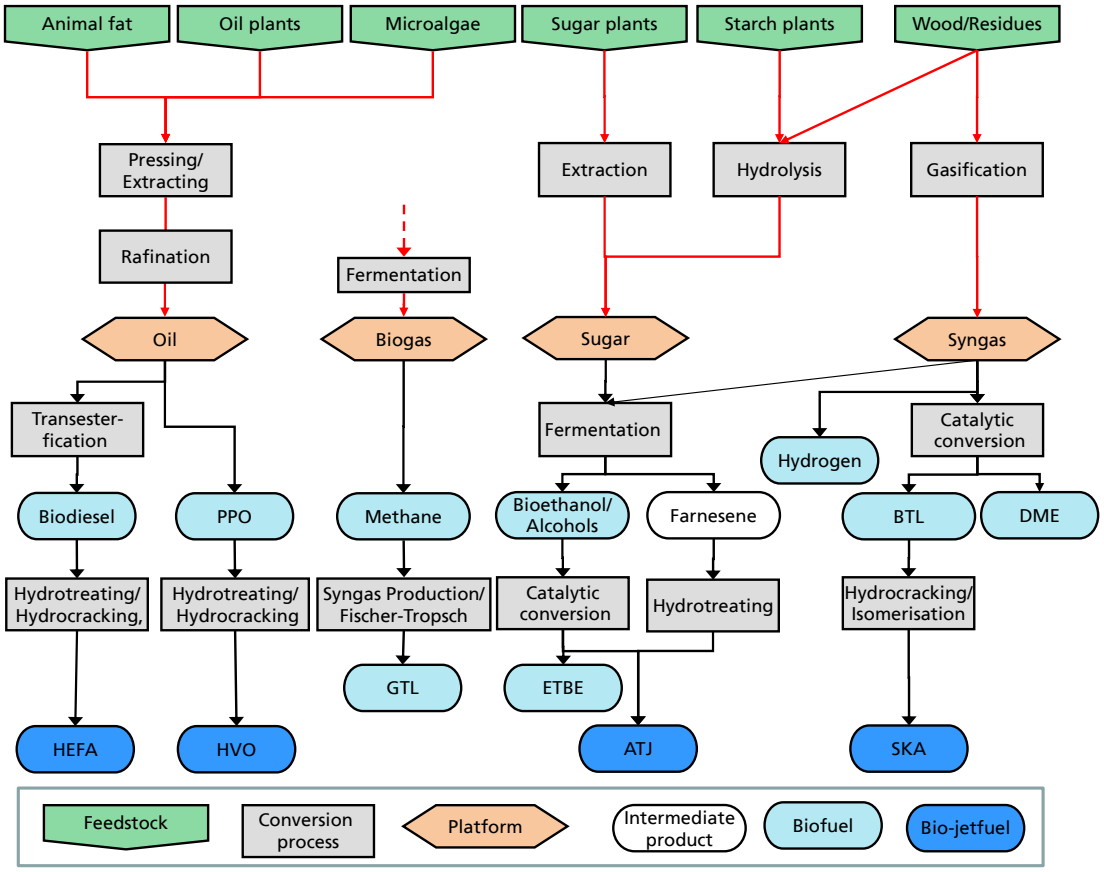


Figure 3-4: Transportation biofuels and bio-jetfuels (PPO: pure plant oil; HVO: hydro-treated vegetable oils; HEFA: hydro-processed esters and fatty acids; GTL: gas-to-liquid, ETBE: ethyl-tert-butyl ether, BTL: biomass-to-liquid, DME: dimethylether, ATJ: alcohol to jetfuels, SKA: synthetic kerosene aromatics synthesized paraffinic kerosene)

The dotted line in Figure 3-4 indicates that a variety of renewable raw materials can possibly be used for the production of biogas. Ethyl-tert-butyl ether (ETBE) which is synthesised via a catalytic reaction by mixing ethanol and isobutylene is commonly used as an oxygenate gasoline additive for premium fuels and is not used as pure fuel. Depending on the kind of biofuel it can be used e.g. in Otto engines (bioethanol, ETBE), diesel engines (biodiesel, PPO, GTL, BTL), in gas-powered vehicles (methane), in proton exchange membrane fuel cells (hydrogen) or for planes (HVO, HEFA, ATJ, SKA).

The production costs of advanced biofuels are currently higher than those of common fossil fuels caused by more complex conversion processes (IEA 2012). Technological improvements, increasing fossil fuel and CO_2-emission prices as well the coproduction of added-value bio-based products could make the production of advanced biofuels market competitive without any governmental support.

Material products

Principally, the number of chemical products that could be produced within a biorefinery approach is nearly unlimited. According to a study of the National Renewable Energy Laboratory of the U.S. (NREL) more than 300 chemicals were identified that could be produced from sugar and syngas (Spangenberg 2002). In the following the most important bio-based chemicals and working materials theoretically to be produced by a biorefinery are listed (German Federal Government 2012; Carus 2012):

- Basic chemicals and chemical intermediates such as lactic acid, succinic acid, ethanol or ethylene,
- fine chemicals and special chemicals (e.g. pesticides, pharmaceuticals, colorants),
- bio-based bulk chemicals (de Jong et al. 2012) and polymers such as polylactic acid, working materials and composites,
- bio-based synthetic fibres and natural fibres,
- wood powder and natural fibre reinforced materials as well as composites,
- varnish and colours such as astaxanthin,
- adhesives,
- detergents and body care products, and
- fertilisers.

As these materials have to compete with their fossil counterparts, especially cheap basic chemicals and chemical intermediates will hardly become competitive. Moreover, material products are in competition with biomass used for bioenergy generation which is often subsidised by the state in contrast to biomass used for material products. However, in the long term the use of biomass for materials promises higher added value and a large growth market in particular with regard to bio-polymers.

3.3 Technological concepts

3.3.1 Overview of biorefinery concepts

Some biorefinery concepts in particular in the starch and sugar industry, oilseed industry, and forest-based industries have already been established on an industrial scale (Elvnert et al. 2011a). Next to these biorefinery concepts that are mainly integrated into existing industrial value chains, a couple of highly integrated biorefinery concepts focussing on new industrial value chains are currently being developed. These concepts are only available at demonstration or laboratory scale. In the following existing biorefineries and those under development are introduced that process starch and sugar, oilseeds, green biomass such as grass, lignocellulosic materials, and aquatic (marine) biomass.

Biorefineries using starch and sugar e.g. from wheat, maize or sugar beet and producing starch derivatives, ethanol, organic acids and food or feed from the protein stream are already available at industrial scale (Elvnert et al. 2011a). It is assumed that these biorefineries will expand their range of feedstocks and products until 2030. Future products will probably be other alcohols, chemicals, and organic acids and maybe lipids that could be produced by fermentation of sugars. An alternative feedstock will be lignocellulosic feedstocks containing C5-sugars (pentoses) in hemicelluloses and C6-sugars mainly in celluloses. The remaining lignin will initially be used as energy carrier and maybe later as feedstock for new chemistry processes.

Biorefineries using oilseeds such as rape, sunflower, soybean, and olives as feedstock currently produce food and feed ingredients, biodiesel, and oleochemicals (Elvnert et al. 2011a). Until 2030 glycerol as the major by-product of the biodiesel process will be probably used as feedstock for making value-added products such as 1,3-propanediol. At the same time, further higher added-value applications such as oleochemicals and bio-jetfuels will be in the focus of development.

Another **biorefinery type will use wet biomass**, such as grass, clover, lucerne or alfalfa (Elvnert et al. 2011a). The green biomass can be pressed and separated into a fibre-rich press juice and nutrient-rich pressed cake. The fibres can be further processed into feed pellets, insulation material or for instance chemicals. Possible profitable products from the press juice are lactic acid and its derivatives, ethanol, proteins, and amino acids.

Examples of existing biorefineries using wood are integrated in pulp and paper mills extracting high value-added compounds from wood. However, a couple of further **biorefineries using lignocellulosic biomass** such as agricultural residues (e.g. straw, peelings, and husks), wood, woody biomass or organic waste are under development. In particular the thermochemical and biochemical process routes are under development. The thermochemical approach uses heat to convert lignocellulosic feedstocks e.g. to syngas which could be further processed into transport fuels such as Fischer-Tropsch diesel or methanol and a huge range of chemicals. The biochemical approach uses a primary biological refining step to fractionate lignocellulosic raw material into cellulose, hemicellulose, and lignin. These three fractions could be further processed into products. For instance, cellulose can be hydrolysed to sugars and further converted to alcohols, e.g. ethanol, organic acids or solvents via fermentation. Possible products from hemicellulose are xylose, gelling agents, barrier agents and, for example furfural. Lignin may be used as energy carrier or to produce binders and for instance adhesives.

Aquatic biorefineries as described in more detail in the next chapter only exist in laboratory or pilot scale. Commercial production of algae is mainly done for food products, including nutraceuticals and functional foods (Bajpai et al. 2014). Widespread products are for example powders made from *Spirulina*, polyunsaturated fatty acids (PUFA), polysaccharides from microalgae, carotenoids or food colorants. Other commercial products from algae are

animal feed e.g. used in aquaculture business (Pauw et al. 1984) or as substances used in cosmetics and pharmaceutical products (Bajpai et al. 2014).

Today, there is no commercial production of biofuels from algae (Benemann et al. 2012). The exception is bio jet-fuel produced from algae-oil that is produced by the company Solazyme Inc. using a heterotrophic process (Benemann et al. 2012). In their process microalgae are grown in darkness and are fed with sugars or starches to produce algal oils.

Nevertheless, aquatic biomass (microalgae and seaweed) is an interesting new biorefinery feedstock as high yields per hectare can be achieved and competition for land can be reduced. In addition, there is a huge amount of species (currently even not known) containing valuable components such as lipids, proteins, polysaccharides and further specific biomolecules such as pigments or vitamins (Darzins et al. 2010). Possible biofuels from aquatic biorefineries are e.g. biodiesel, hydrotreated vegetable oil, bioethanol, Fischer-Tropsch liquids, and biomethane (Petrick et al. 2013; Pandey et al. 2014).

In order to develop biorefineries in an industrial scale three demonstration projects[11] focusing on the production of biofuels from a 10 ha microalgae plant were funded by the EU-Commission in 2012.

3.3.2 Algae biorefineries

The maybe most discussed algae biorefinery concept separates algal biomass into algal lipids and algal biomass (German Federal Government 2012). The lipid fraction can be used for the production of biodiesel and PUFA and other high-value products such as pigments. Algae residues might be digested to produce biogas, electricity, heat, and fertiliser. In compliance with the classification scheme introduced in chapter 3.2 an overview of this technological concept is shown in Figure 3-5.

[11] The names of the three projects are as follows: Industrial scale demonstration of sustainable algae culture for biofuels production (All-Gas), Biofuel from algae technologies (BioFat), Demonstration of integrated and sustainable enclosed raceway and photobioreactor microalgae cultivation with biodiesel production and validation (InteSusAl)

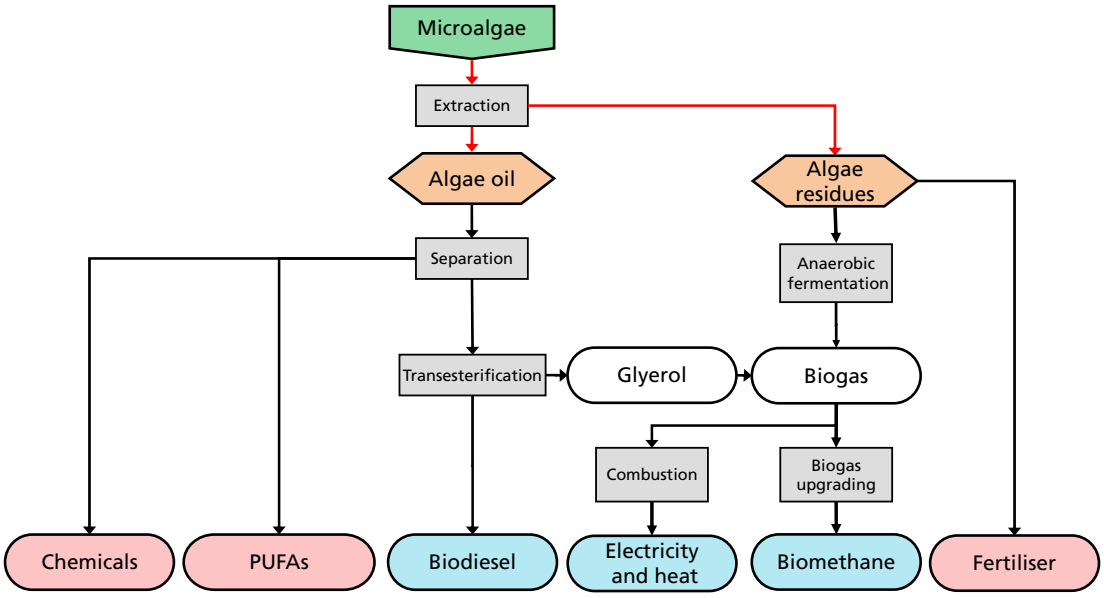


Figure 3-5: 2 Platform biorefinery (algae-oil, algae residues) for chemical products, biodiesel, PUFA, biomethane, and fertiliser from microalgae

Feedstocks

Microalgae have a simple cellular structure and a large surface-to-volume-body ratio which allows them to take up large amounts of nutrients (Sheehan et al. 1998). They can be either autotrophic or heterotrophic. Autotrophic organisms have chlorophyll a as their primary photosynthetic pigment and require mainly CO_2, salts, and a light energy source for growth, while heterotrophic algae need nutrients and an external source of organic compounds as energy source. Some photosynthetic algae species are mixotroph. This means they have the ability to use organic material as energy source, too. Prokaryotic algae, e.g. cyanobacteria (blue-green algae) (*Cyanophyceae*) lack membrane-bound organelles (plastids, mitochondria, nuclei, Golgi bodies and flagella) and are more similar to bacteria than to algae. In contrast eukaryotic microalgae do have these organelles that control the functions of the cell and have been categorised into many classes, basically differentiated according to their pigmentation, life cycle, and basic cellular structure (Demirbas, Demirbas 2010). The most frequently appearing classes are diatoms (*Bacillariophyceae*), green algae (*Chlorophyceae*), golden algae (*Chrysophyceae*), and red algae *(Rhodophyta).* Diatoms alone are estimated to comprise more than 100 000 species. The microalgae *Spirulina* (cyanobacteria) and *Chlorella* (*Chlorophyceae*) are the most cultivated around the world (Pandey et al. 2014). Microalgae mainly consist of carbohydrates, proteins, and lipids. The lipid content of many microalgae strains is naturally between 20 and 50 % dry weight (Brennan, Owende 2009). It can be increased through measures such as reducing the nitrogen level and controlling the light intensity, temperature, salinity or CO_2 concentration.

The only class of lipid, available in algal cells and relevant for the production of biodiesel, are triacylglycerides (or triglycerides, TAG) that are formed from fatty acids and glycerol as depicted in Figure 3-6.

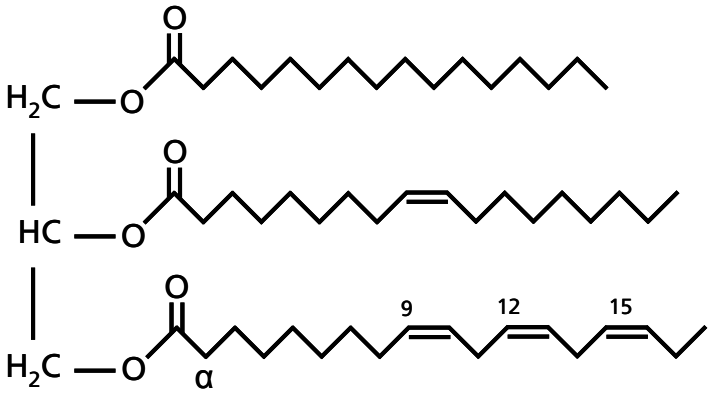


Figure 3-6: Chemical structure of an unsaturated triglyceride containing palmitic acid (C 16:0), oleic acid (C 18:1), and alpha-linolenic acid (C 18:3)

These lipids are used by algal cells as a storage compound and are particularly formed under stress conditions such as in a medium with low levels of nitrate or phosphate, high concentrations of Fe^{3+}, or high temperature (Liu et al. 2008). Apart from TAGs or neutral lipids, algae consist of a couple of other lipid types. For example phospholipids (polar lipids, two fatty acids and a phosphate group on glycerol) are particularly used in the cell membrane. Apart from phospholipids, for instance glycolipids (glycerol molecule combined with two fatty acids and a sugar molecule, e.g. galactosyldiacylglycerides) are found in chloroplast membranes. Sulfolipids (sulphate esters of glycolipids) also occur in chloroplast membranes (Darzins et al. 2010). Even though these lipid fractions are soluble in organic solvents, they are not convertible to biodiesel. Furthermore, there are also some types of neutral lipids that do not contain fatty acids such as hydrocarbons, sterols, ketones, and pigments (carotenes and chlorophylls) that cannot be used for biodiesel production either (Halim et al. 2012). For example Vieler et al. reported that 85 wt.% of the total content of lipid was represented in the thylakoids (photosynthetic membranes) when the green algae *Chlamydomonas reinhardtii* was cultivated under nutrient-sufficient conditions (Vieler et al. 2007). In contrast, only a small fraction of the total content of lipid in this *Chlamydomonas* species was triacylglyceride (TAG). Stephenson reported for *Chlorella vulgaris* cells grown over a period of 20 days under nitrogen-sufficient conditions a lipid content of averaged 13.7 wt.% of the total mass of dry cells (Stephenson 2009). A significant proportion (~ 27 wt.%) of the lipids were phospholipids which cannot be used for the production of biodiesel. Only around 3 wt.% of the lipids were TAGs. The most frequent fatty acids found in the total extracted lipids were palmitic acid (C16:0, 19 wt.%), linoleic acid (C18:2, 23 wt.%), and alpha-linolenic acid (C18:3, 21 wt.%) which according to (European Standard prEN 14214) is limited in biodiesel to 12 wt.%. In contrast, when *Chlorella vulgaris* was grown in nitrogen-deficient conditions over a period of 12 days, the lipid content had increased to almost 20 wt.% of the total mass of dry cells and the most present fraction (over half) was TAGs (Stephenson 2009). Moreover, the dominant fatty

acid was oleic acid (C18:1, 32 – 37 wt.%) and the more highly unsaturated fatty acids (C18:2, C18:3 and C16:2) were all reduced compared to levels under nutrient-sufficient conditions.

Primary refining

In the first step algae must be harvested which requires one or more solid-liquid separation steps (Molina Grima et al. 2003). There are several possibilities to harvest algae such as centrifugation, filtration or gravity sedimentation which can be supplemented by a flocculation step (Pandey et al. 2014). For lipid extraction the algae culture should be further dried e.g. by a thermal drying process. Afterwards lipids can be extracted using extracting agents such as hexane or ethanol (Halim et al. 2012; Halim et al. 2010; Shin et al. 2014). The extraction agent can be partly separated and can be recycled. Alternatively, a wet lipid extraction process was developed by Utah State University that allows extracting up to 79 % of the algal lipids from wet biomass by acid and base hydrolysis of the algal biomass followed by phase separation steps (Sathish, Sims 2014). Suitable lipids might be processed into valuable products. The lagging algae residues can be used as raw material for biogas production via anaerobic fermentation.

Platform

The primary refining step results in a lipid fraction and residual biomass containing proteins, carbohydrates, and further algae components.

Secondary refining and products

The triglycerides, which are non-polar components in the lipid fraction, can principally be used for producing biodiesel via transesterification as depicted in Figure 3-7.

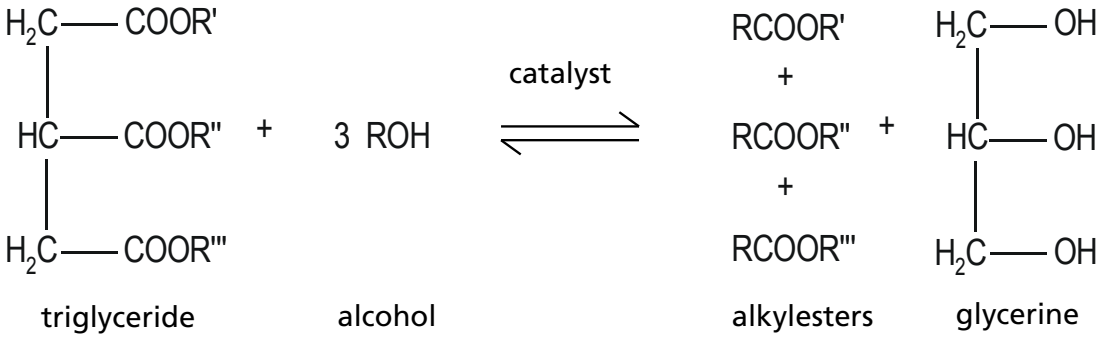


Figure 3-7: Transesterification reaction

However, biodiesel specifications as set by the European Biodiesel Standard EN 14214 have to be met (European Standard prEN 14214; European Standard prEN 14214). For instance, the phosphorus content in biodiesel is limited to 4 mg*kg^{-1} and the linolenic acid (C18:3) content to 12 % (m/m). To assure the low phosphorus content of less than 4 mg*kg^{-1}, phospholipids and other polar lipids, also referred to as gums, have to be removed from the crude oil by a degumming step and could be further processed into chemicals for chemical,

pharmaceutical or food industries. The residual fraction that accounts for approximately 70 % of the algal biomass can be further processed into biogas via anaerobic digestion. Fermentation residues from the biogas plant can be dewatered and nutrients can be recycled.

At laboratory scale there are several other algal biomass conversion pathways to produce bioenergy such as several forms of pyrolysis (Gong et al. 2014; Mu et al. 2014; Kebelmann 2012; Yanik et al. 2013; Xu et al. 2011), direct combustion (Mu et al. 2014; Lane et al. 2014) or hydrothermal liquefaction (Mu et al. 2014). However, none of these conversion pathways has been demonstrated yet at industrial scale, maybe due to technical hurdles and poor economic viability.

3.4 Contribution of biorefineries to resource conservation

Biorefinery concepts principally have the potential to produce a spectrum of products more efficiently than recent technologies by using an integrative approach that allows positive synergy effects (Bundesregierung 2012). Apart from a possible increase in efficiency, products produced by biorefineries may be recycled or reused within the economy via cascade utilisation (Bienge et al. 2010) or via natural ecosystem cycles through biodegradability and recirculation of nutrients. Moreover, their products can replace products made from fossil resources which allows for the maintenance of natural capital. However, products produced from exhaustible resources will only become obsolete if the average cost of production of the close substitute falls below the spot price of the exhaustible resource (Dasgupta, Heal 1979).

Apart from economic conditions, the influence of population growth and consumption patterns as discussed under the term sufficiency in chapter 2.2.2 has to be taken into account. Considering these perquisites the following resource management rule was defined: »From a macroeconomic perspective the scale of the economy (population times per capita resource use) must be within the carrying capacity of the region in the sense that the human scale can be maintained without resorting to capital consumption« (Daly 1990, p. 5).

That means the question about a limited resource throughput implies a trade-off between population size and per capita resource use in a region. With regard to available land for biomass cultivation and also considering different purposes such as food/feed, energy, and materials, a sustainable trade-off between these purposes and per capita resource use should be established. Which factors are important for the successful implementation of biorefineries will be discussed in the next chapter.

3.5 Challenges for the successful implementation of biorefineries

3.5.1 General requirements for the successful imple-mentation of biorefineries

In addition to common site requirements such as the availability of educated work forces in the region, price of site or existing infrastructure (Domschke, Drexl 1996), in particular the

- availability of sustainable biomass,
- synergy effects with integration into existing plants, and
- the marketability of biorefinery products

are crucial success factors for biorefineries (Fritsche et al. 2011). Biomass should be available in sufficient quantities at affordable prices and constant suitable qualities. Furthermore – with regard to acceptance – biomass production should be in compliance with the sustainability requirements called for in »Directive 2009/28/EC on the promotion of energy from renewable sources« (European Commission 2009a). In particular the use of non-food feedstocks often referred to as second generation feedstocks promise a good environmental performance and are characterised by relatively high yields and principally can be produced on low-productive land (IEA 2011; Fritsche et al. 2010). On the other hand agricultural crops such as sugarcane often allow higher yields per hectare, thus reducing competition for land. Moreover, the quality of food crops is often higher compared to non-food feedstocks and especially compared to residues, in the end allowing a higher product quality and higher product yields.

In addition to biomass availability and associated logistics, the integration of biorefineries in existing chemical parks can be a strategic advantage (Fritsche et al. 2011). Apart from chemical parks synergy effects are possible for example in the sugar, starch or pulp industry. The integration of biorefineries into existing biomass conversion plants or »Verbund« sites principally allows extending the product range to bio-based products by integrating biogenous material flows into available value chains of the production site (VDI 6310). Moreover, efficient energy and logistic concepts can be established and by-products can be fully used in order to reduce the demand for raw materials. In contrast to such a bottom-up approach, biorefineries might be developed top-down using a completely new design. This approach allows the optimisation of biomass provision by choosing a strategically situated site that is relatively close to the available raw materials. In addition, costs can be reduced in case of plant duplication and stakeholders might be integrated more easily (VDI 6310).

Nevertheless, apart from the question of possible benefits or disadvantages caused by the integration of biorefineries into existing sites, the scale of the biorefinery – which strongly depends on the type of biorefinery – is crucial for the choice of the location. For example large-scale integrated biorefineries,

which are mainly based on thermochemical processes, are predicted to likely emerge in Northern Europe and/or be associated with large ports (Elvnert et al. 2011a). In contrast, small/medium-scale integrated biorefineries, which are mainly based on biotech processes, will probably be built in rural areas across Europe.

In the end, only those biorefineries will be successful whose products are price-competitive and hence can be sold on the market. In particular, complementary to energy products such as biofuels or electricity, the sale of valuable material products can advance the profitability. Nevertheless, markets for valuable bio-based material products are often small and overcapacities should be avoided.

A survey conducted during a biorefinery conference in Tutzing in 2013 showed that apart from the aspects mentioned

- a lack of cooperation along the (potential) value chains covering different branches,
- the unclear question of operators,
- a lack of funding of demonstration plants,
- market development and overcoming barriers to market entry,
- the need for a biorefinery network,
- and difficulties of evaluating biorefinery concepts

are considerable obstacles for the realisation of biorefineries in industrial scale (Wagemann 6/12/2013).

3.5.2 Ways towards the realisation of algae biorefineries

Today, algae biorefineries are facing most of all technical and economic challenges. One big technical challenge is to bring algae production from pilot scale to demonstration or even industrial scale.

Besides, the production of algal biomass is very expensive compared to other types of biomass. According to Norsker, the production costs of microalgae are between 4 and 6 € per kg of dry mass assuming state-of-the-art technologies and a production area of 100 ha in the Netherlands (Norsker et al. 2011). Norsker found out that the production costs are strongly influenced by the irradiation conditions, mixing, photosynthetic efficiency of systems, and medium and carbon dioxide costs (Norsker et al. 2011). Therefore, a sunny site should be selected that allows for providing water and carbon dioxide at low price. Apart from the cultivation of microalgae, harvesting including dewatering and the extraction of algae lipids can contribute up to 36 % and 40 % respectively of the total costs of algae oil (Frost & Sullivan 2010). Therefore, optimising harvesting costs and the development of efficient extraction processes are seen as major challenges to make algal biofuels price-competitive (Elvnert et al. 2011b). One promising option to make algae biorefineries economically viable is the integrated extraction of high value chemicals while using residual biomass to produce energy or energy carriers (Bundesregierung 2012). Since the market

capacity for high value chemicals is usually limited, overcapacities should be avoided. Another possibility to reduce production costs of microalgae cultivation is to use waste water as growing medium (Benemann, Oswald 1996). As a result not only the need of fresh water can be reduced but also the demand for nutrients. On the other hand the cultivation of specific algae species or the extraction of specific algae components such as lipids becomes more difficult because algae cultures are hardly controllable. Moreover, the quality of extracted components varies a lot rendering its use as raw material for industrial applications nearly impossible.

Within this thesis an algae biorefinery using waste water as cultivation media is analysed in detail in chapter 5.

4 Design of a generic methodology to assess the sustainability impact of biorefineries

4.1 Definition of generic sustainability criteria of biorefineries

A top-down approach is applied in chapter 4.1.1 to identify sustainability criteria of biorefineries by using the substantial sustainability rules which were introduced in chapter 2.6 in Table 2-1 and reflect minimum conditions for sustainable development. To ensure a good interpretation of these rules, the developers of the concept, Juliane Jörissen and Jürgen Kopfmüller were involved in the development of sustainability criteria for biorefineries.

In addition, criteria can be found through a bottom-up strategy which looks at presently existing topic specific criteria in the scientific and political debate. They can be found by analysing topic related scientific papers, published sustainability criteria sets, sustainability standards, and certification schemes (chapter 4.1.2) as well as legal requirements (chapter 4.1.3). An overview of the methodology applied is given in Figure 4-1.

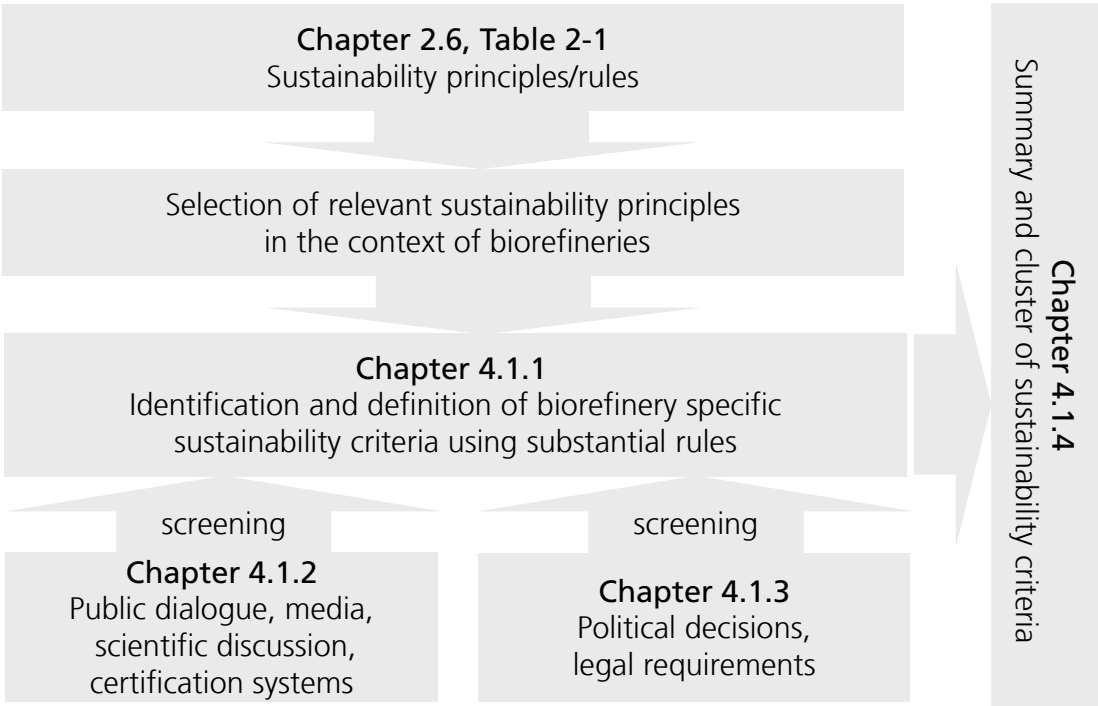


Figure 4-1: Methodology to assess sustainability criteria of biorefineries, relevant chapters are marked in bold font

In the intersection of infringement of rules and present problematic issues crucial criteria are filtered and clustered to a reasonable magnitude (chapter 4.1.4). Possible conflicts of interest can be avoided or reduced as a result. In addition, this approach assures to find and to select reliable sustainability criteria.

In order to measure the sustainability impact of biorefineries, suitable indicators (chapter 0) and instruments (chapter 4.3) are needed. For evaluating the sustainability impact of a specific biorefinery plant, a further contextualisation of the rules as well as an adaption of the scope is additionally required (chapter 5.3). To handle possible conflicts of interests between different goals of sustainability, interactions are discussed and criteria are ranked in chapter 5.9.

4.1.1 Identification and definition of biorefinery specific sustainability criteria using substantial rules

In a first step, the substantial sustainability rules of the HGF approach are used to identify relevant sustainability criteria for biorefineries. Not every rule might be important with respect to possible sustainability impacts of biorefineries. In the following only the context-relevant rules are discussed. Criteria are numbered according to the number of rules shown in Table 2-1 in chapter 2.6.

(1.1) Protection of human health

(1.1.1) This rule focuses on hazards and unacceptable **risks to human health** caused by anthropogenic environmental pollution. Negative effects on human health may result from exposure against particulate matter (PM), tropospheric ozone, NO and NO_2, and persistent organic pollutants (POPs) (WHO 2004). These pollutants are released into the air during the entire life cycle of bio-based products. Their life cycle mainly comprises the following life cycle stages: biomass production, transport, storage, preparation, further processing, assembly, retail, use, and end-of-life as shown schematically in Figure 4-2. In each life cycle stage emissions are released into the air, soil or water. In contrast to conventional refineries that process fossil resources such as naphtha or natural gas biorefineries depend on biomass that is often cultivated on fertile land.

In particular the production of biomass is often responsible for the majority of pollutants released during the entire life cycle. For example in case of first generation ethanol usually more than 50 % of the mentioned life cycle wide emissions result from planting, harvesting, and transportation of crops (Yu, Tao 2009). Especially the use of N-fertilisers for the cultivation of crops such as starch/sugar crops, oilseed crops or grasses causes NO_x, PM_{10}, and SO_2 emissions in the upstream chain and is the key contributor to eutrophication (Weiss et al. 2012). Furthermore, in contrast to fossil fuels which are transported by barge or through pipelines, the supply with biomass requires extra handling processes and truck transport e.g. for the transportation from the field to a plant.

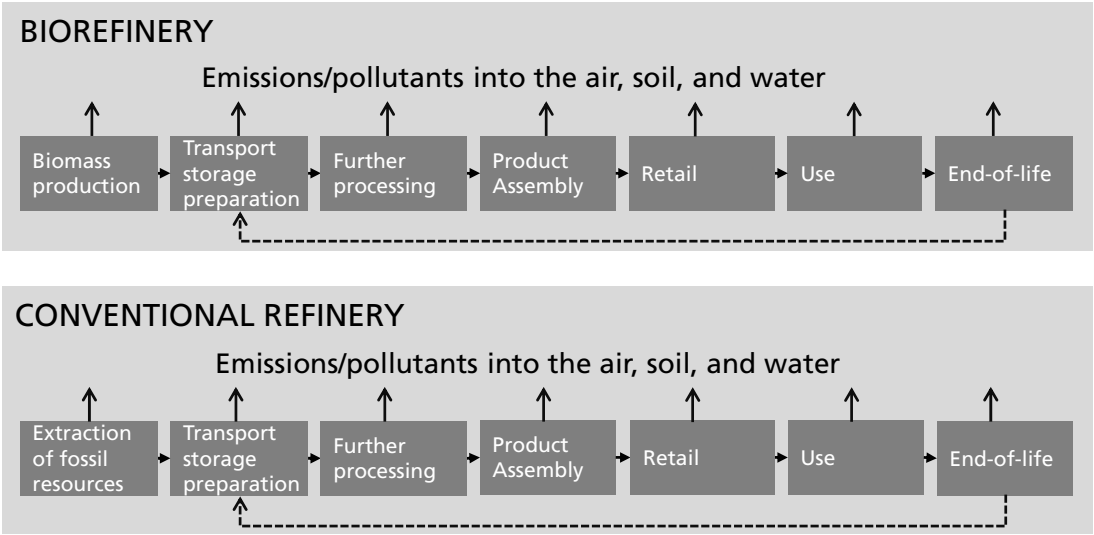


Figure 4-2: Schematic representation of the life cycle of products produced by biorefineries and conventional refineries, dotted line indicates possible recycling

Apart from NO_x, PM_{10}, and SO_2 emissions persistent organic pollutants (POPs) used in pesticides can affect humans and can show ecotoxilogical effects such as damage to the nervous and immune system, lowering the reproductive capacity or cause cancer (Kopfmüller et al. 2001). Therefore, POPs in pesticides such as aldrin, chlordane (complex organochlorine compounds), dichlorodiphenyltrichloroethane (DDT), dieldrin, endrin, hexabromobiphenyl, mirex, and toxaphene are restricted or forbidden by law. The use of non-food biomass also referred to as second generation feedstocks such as wood including those from short-rotation coppice, residues from agriculture, logging, and wood residues or municipal wastes offers the opportunity to reduce harmful air emissions as their cultivation does not require fertilisers or pesticides.

During further biomass processing steps within a biorefinery plant, human toxicological effects may result from chemicals applied e.g. for decomposing biomass into its components. Biorefineries which use »green chemistry« tentatively use less toxic compounds compared to traditional chemistry in order to claim reduced health and environmental impacts (Manley et al. 2008). In particular industrial (white) biotechnology offers the potential of substituting toxic substances and those that cannot easily be degraded and using energy-saving process conditions with low temperature and pressure as well as a moderate pH value (OECD 2001). In case where biodegradable materials such as biodegradable polymers are produced, toxic ingredients need to be avoided or minimised to ensure biodegradation in composting or digestion facilities (Rai et al. 2010). In the life cycle stages product assembly, retail, and use no significant health impacts are expected.

In the end-of-life stage harmful emissions are released into the air when biofuels are burned e.g. in a motor engine or in a waste incineration plant. Depending on the vehicle fuel, the use of biofuels instead of fossil fuels may cause less emissions of particulate matter (PM) and most other emissions (Demirbas 2010; Demirbas 2009). Kim and Choi have shown that the total

number and total mass of emitted PM by ethanol-diesel-blend-fuels could be decreased by about 11.7-15 % and 19.2-26.9 % respectively (Kim, Choi 2008). Nevertheless, a study from TNO reveals that implementing low blend biodiesel may lead to both positive and negative effects on PM and NO_x emissions (Verbeek et al. 2008). In contrast, synthetic (bio)diesel fuels may generally lead to emission reductions (Verbeek et al. 2008). A comparison of emissions from gasoline-fuelled vehicles and biomass-based E10-fuelled vehicles in China showed that E10 blends release less CO_2 and VOC in their lifecycles but produce more emissions of CO, CH_4, N_2O, NO_x, SO_2, and PM_{10} (Yu, Tao 2009). Fine particles with an aerodynamic diameter of less than 2.5 µm ($PM_{2.5}$), which are for example emitted by biomass burning (Ryu et al. 2007) or by using vehicle fuels, are of particular importance as they are alveolar and have a stronger impact on human health than coarse particles with an aerodynamic diameter between 2.5-10 µm (PM_{10}) (WHO 2004).

(1.2) Ensuring satisfaction of basic needs

(1.2.1) This rule requires the provision of basic goods that allow to live a decent life (Kopfmüller et al. 2001). In contrast to refineries which process fossil resources, biorefineries producing bio-based products from crops rely on agricultural land which is needed for biomass production. Hence, biorefineries processing crops compete with agricultural land used for food and feed production and with arable land used for other purposes. Competition for arable land may lead to higher prices of food which is problematic especially for the less well-off parts of the world population (FAO 2008; Rathmann et al. 2010; Schmidhuber 2006). There are very complex interactions and feedbacks between biomass demand, food prices, and environmental impacts. In order to understand these complex interactions an integrated approach addressing the so called food-energy-environment trilemma was suggested by (Tilman et al. 2009). Figure 4-3 illustrates some cause-effect-relations, which are represented as arrows, between the relevant interacting components.

One way to reduce land use competition is the use of agricultural residues or alternatively wood residues as feedstock. According to the International Energy Agency IEA only 10 % conversion of global agricultural and forestry residues to biofuels would be sufficient to replace roughly two-thirds of the total biofuels production in 2035 (IEA 2010). Nevertheless, the total supply potential for agricultural residues in Europe may be about 3.1 EJ yr^{-1} in 2030 and the total potential of European felling residues could amount up to 1.4 EJ annually (Wit, Faaij 2010). Compared to the total biomass potential in 2030 in Europe, which will probably be between 8.0 and 24.6 EJ yr^{-1}, residues will only account for a smaller share (Wit, Faaij 2010). Furthermore, the availability of agricultural residues depends on the cultivation of crops and cannot be discussed separately.

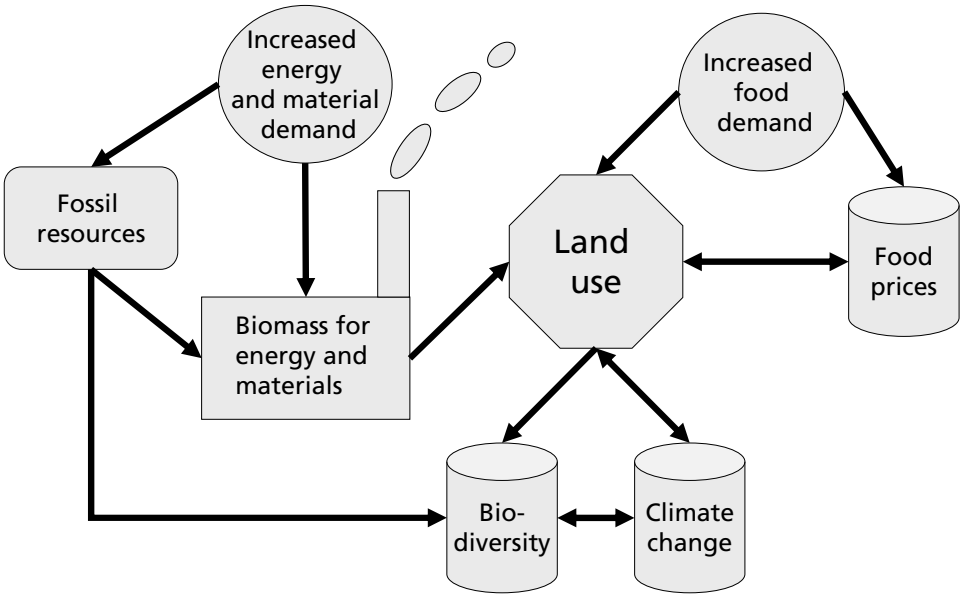


Figure 4-3: Competition for land use: interactions and feedbacks, in the style of (Harvey, Pilgrim 2011); start points are represented as a circle and important impacts of land use as a cylinder

Depending on whether the whole plant or only its residues are used, the scale of the biorefinery plant will be restricted to an economical level. Additionally, the use of residues often leads to more effort in quality assurance as the chemical composition of residues can vary strongly. Apart from the use of residues, the use of currently not used degraded land offers new opportunities to reduce land competition. For example the cultivation of microalgae in open pond systems has the potential to reduce the land conflict (Singh et al. 2010). But the use of dedicated lignocellulosic energy crops produced by short rotational plantations can also reduce land use competition due to lower site requirements and higher yields compared to agricultural crops (Mola-Yudego 2010). The intensification of farming reduces land competition, too, although it goes along with negative impacts on human health and biodiversity.

In the end, the use of biomass for energy and materials should not endanger the **food security** in a region which was defined by the World Food Summit of 1996 as existing »when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life« (World Food Summit 1996, p. 3). This comprises both physical and economical access to food that meets the peoples' dietary needs. In particular, the establishment of energy crop plantations and increasing food prices caused by an increasing demand for liquid biofuels might affect three dimensions of food security: food availability, access, and stability (Rossi, Lambrou 2009).

(1.3) Autonomous subsistence based on own income

(1.3.1) This rule focuses on the possibility of individuals to secure their own livelihoods. This objective can be met by gainful employment as well as other

forms of employment such as community-related work. Nevertheless, the securing of man's own livelihood mainly depends on **gainful employment** and remuneration. Therefore, everybody should have the opportunity to secure his or her own livelihood through gainful employment and should get the possibility of personal development for a decent life. Against this backdrop the development of rural regions is of great importance because available jobs are more limited in these areas than in urban agglomerations (Bryden, Bollman 2000). Therefore, it is an important sustainability goal of European policies and objective of the EU Sustainable Development Strategy to reduce regional imbalances (Eurostat 2009). Biorefineries might promote jobs in the agricultural sector due to their demand for biomass. The development of new bio-based products may also open up new markets. The progress in automation of processes can be discussed ambivalently as it has positive effects on the cost efficiency and maybe negative effects on the employment.

(1.4) Just distribution of chances for using natural resources

This rules looks at the intra- and intergenerational justice of using natural resources. These resources include environmental goods such as the atmosphere, fertile land or the sea.

(1.4.1) A topic closely related to the efficient use of area is the debate on **climate change**. From a scientific point of view it seems to be likely that if global warming exceeds a mean temperature rise of 2 °C it will lead to dangerous and nearly uncontrollable consequences such as the rise of sea levels, extreme weather events, a loss of genetic, species, and ecosystem diversity, acidification of the oceans, an abrupt cessation of ocean currents, dieback of the Amazon rainforest, unpredictable shifts in the monsoon system or irreversible destabilisation of large ice masses (Schellnhuber et al. 2009). Other impacts on society might be negative consequences on water supply, food production, health risks, an increase in environmental migration, loss in economic potential or security risks.

Apart from the use of regenerative energy sources such as solar power or wind power, the use of biomass has the potential of greenhouse savings (SRU 2007). Studies on biomass utilisation have shown that the greenhouse gas balance of bio-based products mainly depends on the type of biomass, utilisation path, the efficiency of conversion processes in the value chain as well as the choice of the reference system (Nitsch et al. 2004). One possible way to reduce the carbon footprint of transportation is the use of biofuels which can be produced by biorefineries.

However, not only biofuels or other forms of bioenergy but also bio-chemicals and further bio-based materials which can be produced by biorefineries, as described in chapter 3.2.4, promise greenhouse gas savings compared to their petrochemical counterparts. Figure 4-4 shows calculated greenhouse gas (GHG) emissions savings of a cradle-to-grave analysis of different bio-chemicals and materials compared to their petrochemical counterparts for current and future technologies. The future parameter values may be achieved after 20 - 30 years

of successful research and development. The results shown in Figure 4-4 are mainly influenced by the productivities, yields, and concentrations assumed for the fermentation stage (Hermann et al. 2007) as well as by the technology and feedstock applied. Especially sugarcane and lignocellulosic feedstocks will probably achieve GHG emissions savings of up to 90 %. But also products made from starch already allow GHG emissions saving today and will probably allow GHG emissions savings of up to approximately 50 % in future. Only the regarded chemicals adipic acid and acetic acid shown in Figure 4-4 currently lead to more GHG emissions than their fossil counterparts.

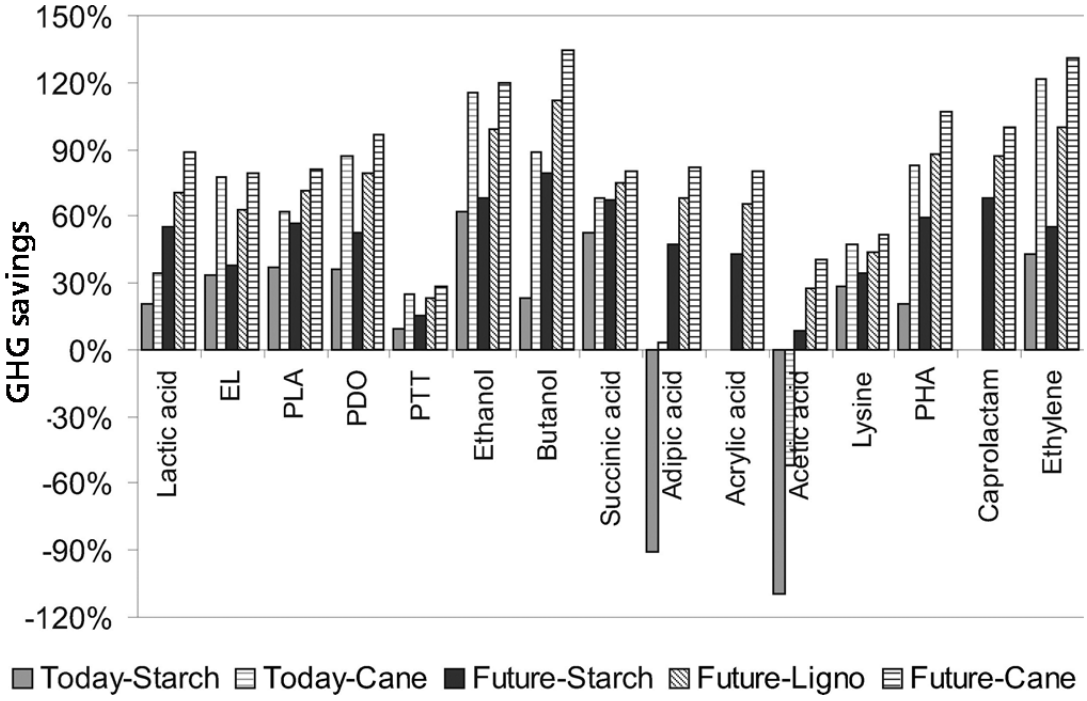


Figure 4-4: Greenhouse gas emission savings per tonne of industrial biotechnology chemical compared to their petrochemical counterparts for current and future technology, cradle-to-grave (Hermann et al. 2007).

In addition to greenhouse gases directly linked to the production chain, use and disposal of bio-based products and land use changes can have a strong influence on the greenhouse gas balance (Searchinger et al. 2008). Land use change (LuC) includes both emissions and absorptions of greenhouse gases. In total the contribution of LuC to the global warming potential is currently estimated to be around 12 % considering significant uncertainties (Herzog 2009).

LuC can be direct and indirect. Direct LuC means land use change from the current use – managed or unmanaged land – into another use e.g. for cultivating renewable raw materials such as energy crops. The effects arising from direct land use change are for example the release of CO_2 emissions or biodiversity loss and are called direct land use change effects. Indirect land use change (iLuC) results of cultivating currently productive land which means that

the original production would have to be realised elsewhere e.g. through the conversion of forests and meadows into agricultural land (Overmars et al. 2011). The effects resulting from this »displacement« are called iLuC effects. Although it is hardly possible to provide evidence, iLuC is estimated to have such a strong influence on the greenhouse gas balance of first generation biofuels[12] that the planned expenditure of using biofuels in the EU would probably lead to the production of additional GHG emissions even if the GHG emission savings required under the RED[13] will be met (Bowyer 2010). As a consequence, the additional use of conventional biofuels such as ethanol from starch or corn would not contribute to the achievement of EU climate change policy goals[14]. Figure 7-4 in appendix II summarises the calculated greenhouse gas emission of different biofuels given by the Renewable Energy Directive RED (European Commission 2009a) as well as estimated iLuC emissions calculated by the International Food Policy Research Institute (IFPRI) (Laborde 2011). As presented, especially second generation biofuels e.g. produced from lignocellulosic materials or from residues and biogas or biomethane respectively promise a high reduction potential in greenhouse gas emissions. Apart from using second generation feedstocks, iLuC can be further reduced e.g. by increasing crop yields for example through an intensification of agriculture or optimisation of crops. Apart from technical questions, governance also plays a great role, e.g. the protection of areas by law. Today, in the European Union the exclusion of areas with high carbon stock is exclusively regulated for biomass dedicated for biofuels although 27 % of the total global forestry and agricultural biomass is used as renewable raw materials, 15 % as food and 58 % as fodder. If only taking into account agricultural biomass, renewable raw materials will contribute to 8 %, food to 18 %, and fodder to 74 % (Carus, Raschka 2012).

(1.4.2) An increasing demand in developed countries for price-competitive biomass especially for wood and agricultural products such as maize, wheat or palm-oil will probably lead to imports of biomass from countries in middle and eastern Europe, from countries in the south of Africa, from countries in South America (especially Brazil), and from countries such as Indonesia (Fritsche et al. 2010). This development will probably strengthen the economic power in these countries since they will become exporters. At the same time the increasing demand for biomass entails the risk that small farmers, and particularly female farmers are punished off their land as reported by (Friends of the Earth Europe 2010). Hence, priority should be given to investing and developing farming that supports small farmers and small-scale ecological agriculture especially on continents such as Africa. A central key issue in this is the distribution and

[12] First generation biofuels are produced from sugar, starch, vegetable oil or animal fats using conventional technologies.

[13] EU Renewable Energy Directive (RED) on the promotion of the use of energy from renewable sources (Directive 2009/28/EC).

[14] The EU signed the Kyoto Protocol and agreed to cut 20 % of the greenhouse gases of 1990 levels by 2020.

access to land. It can be argued that the production of biomass for non-food products violates basic human rights when it jeopardises local food security or displaces local populations from the land they depend on for their daily subsistence (Weale et al. 2011). Hence fair property rights allowing the satisfaction of one's own needs as specified under (1.3.1) should be promoted by governance. In addition, future biorefineries which import biomass from developing countries should be developed in accordance with trade principles that are fair and recognise the rights of people to just reward (Weale et al. 2011). A possible way to ensure **fair wages** and fairer trade relationships is the introduction of fair-trade schemes[15] which recognise the rights of people to just reward. If decentralised structures are regarded, a great challenge will be to guarantee high biomass quality. This is often not possible e. g. for palm oil as logistics and climate conditions in non-developed countries are often unfavourable and biomass becomes mouldy.

(1.5) Compensation/Balancing of extreme income and wealth discrepancies

As discussed before, fair wages in particular in developing countries can reduce extreme income and wealth discrepancies. Additionally, the access to gainful employment, as mentioned under the rule 1.3 »Autonomous subsistence based on own income«, are crucial for securing of man's own livelihood. The access to gainful employment may reduce extreme income and wealth discrepancies, too.

(2.1) Sustainable use of renewable resources

Although biomass is a renewable resource, its regeneration depends on the preservation of the natural resources such as biodiversity, soil, and water. Besides, it is limited through the availability of arable land. Principally, the sustainable use of renewable resources requires that its use should not exceed its regeneration rate (Daly 1990; Pearce, Turner 1990). This means that the total use of biomass for biorefineries along with other forms of using biomass e.g. for food or feed should not exceed the nearby biomass production rate. An exception is the case if biomass is imported from regions with a higher biomass production than utilisation rate. Nevertheless, in this case nutrient cycles should be regarded critically.

(2.1.1) As mentioned before, biorefineries rely on biomass and accordingly on the availability of arable land. Although today's global biomass potentials are estimated between 200 to 500 EJ yr^{-1}, which represents 40 % to 100 % of current global primary energy use (Dornburg et al. 2008), about 62 % of harvested biomass is currently needed for food production (Thoen, Busch 2010) and its demand will likely increase due to the growing world population. In order to increase the availability of biomass, the area to produce biomass should be used as efficiently as possible. Yields of dedicated crops can be increased through agricultural activities such as tillage, drainage, intercropping or extensive usage of pesticides and fertilisers which cause negative effects on

[15] Gebana for example offers a Bio&Fair biofuel (http://www.gebana.ch).

biodiversity (McLaughlin, Mineau 1995), on climate change e.g. by increasing GHG emissions caused by the production of fertilisers, use of machinery or by N_2O emissions from fertilization, on soil e.g. through erosion or soil compaction and for example on water quality caused by the used pesticides or nitrogen inputs (SRU 2007). Besides, an increase in intensive growing of energy crops has considerable impacts on the countryside (Lindenau 2002). In contrast to crops, the use of lignocellulosic feedstocks does not lead to these environmental effects. For example, the cultivation of short-rotation plantations of fast-growing trees can cause improvements in biodiversity, flood retention or soil conservation (Splechtna, Glatzel 2005). Furthermore, the use of residues and wastes reduces the required area for biomass production (Cherubini, Ulgiati 2009).

The efficiency of using area under cultivation can be expressed as a function of yield per area and conversion efficiency (product yield). Hence, a suitable criterion to express the efficiency of using land is the amount of area in relation to the product yield which here is referred to as **area-efficiency**. Apart from the area-efficiency the type and quality of land used should be taken into account.

It should be considered that this criterion is strongly linked to the topic land use competition addressed by point 1.2.1 and climate change discussed under the point 1.4.1.

(2.1.2) In addition to renewable resources such as renewable raw materials, **biodiversity** can be seen as renewable resource, too (Schellnhuber et al. 1999). That is why this rule does not only include the sustainable extraction of renewable resources but also covers the protection of species and biodiversity. One approach to protect biodiversity is the conservation of hotspots of high biological diversity (WBGU 2009). These so-called hotspots are small areas in which a large number of wild species is found or which contain a large number of endemic species or unique ecosystems (Myers et al. 2000). In order to protect these species these areas must be excluded from feedstock production as required by the Renewable Energy Directive 2009/28/EC (European Commission 2009a), too. Nevertheless, these hotspots cannot stop the loss of biodiversity and should be completed by »mainstreaming of conservation through differentiated application of the principle of sustainable land use to all land used for agriculture or forestry« (WBGU 2009). With regard to global food security, it also seems to be important to maintain the biodiversity of crops or related wild plants (Stolton et al. 2006). It should be said in addition that according to Wilcove et al. invasive alien species cause more biodiversity loss than any other factor apart from habitat destruction (Wilcove et al. 1998). Therefore, biorefineries should favour biomass from typical regional plant species which are cultivated in a sustainable way. Sustainable land use, however, should be based on a »good farming practice« which e.g. in Germany is defined by law and gives ecological and safety standards that farmers must adhere to (BMELV 2010). Negative effects on biodiversity may be caused by genetic engineering e.g. through the invasive potential of genetically modified plants (Rath, Köck 2009) or increase of illnesses. However, genetic engineering also has the

potential to increase biomass yields (compare with 2.1.1) and may not be more harmful than natural biological evolution (Arber 2010, 2010).

As large-scale monocultures have a negative impact on agro-biodiversity (SRU 2007) this type of cultivation should be avoided from the perspective of biodiversity protection. On the contrary, unused degraded land and abandoned farmland should be used as areas for preferential biomass production since they go along with low direct negative effects and have the potential to promote positive ones e.g. through cultivation of short-rotation plantations. The use of unused degraded land also reduces the risk of negative effects by indirect land-use change (Hennenberg et al. 2010). In addition, negative impact on biodiversity can be reduced by the sustainable use of organic residuals and wastes as feedstock.

(2.1.3) The rule on the sustainable use of renewable resources should also be applied to the **protection of soil**. One risk to agricultural soils is the potential depletion of soil organic carbon (SOC) and minerals which may be related to intensive agriculture, crop residue removal, climate change, regional conditions such as soil quality, change in crop rotation, the humus reproductive performance of residues or e.g. land use changes (Brandão et al. 2010; Blanco-Canqui 2010; Bellamy et al. 2005; Münch 2008). Positive contributions to the humus balance can be achieved for example with forests, grasses, and legumes, whereas sugar beet, potatoes or corn reduce humus (Körschens et al. 2004). Apart from forests, the extensive planting of shortrotation plantations of fast-growing trees may also have a positive effect on the SOC content and can contribute to improving in biodiversity, flood retention or soil conservation in cleared landscapes (Baum et al. 2009; Rode et al. 2005; Reinhardt, Scheurlen 2004). But woody crops and perennial warm-season grasses also promise advantages such as sequestering SOC, reducing soil erosion, and improving soil properties (Blanco-Canqui 2010). For straw in Germany the humus reproductive performance was estimated to be between 80 - 110 kg humus $C*t^{-1}$ straw (Körschens et al. 2004) or even less by (Ebersteder 2008): 40 - 60 kg humus $C*t^{-1}$ straw. Due to complex and multiple effects of the influencing factors mentioned before, there are no generally accepted values of how many residues can be removed without affecting the carbon content of the soil. According to a model from Saffih-Hdadi and Mary, straw removal vs. incorporation would reduce carbon stocks by 2.5 - 10.9 % of the initial SOC after 50 years (Saffih-Hdadi, Mary 2008). However, a part of crop residue might be removed without significant effects. Several studies indicate that in Germany in total about 20 - 50 % of the straw could be used for energetic purposes or biorefineries without lowering the soil quality, also considering further existing types of straw use e.g. as feed. The studies mentioned are summarised in Table 4-1. Depending on the method applied for calculating the humus balance, in Germany about 8 - 13 million tonnes of straw (wet mass) per year could be available e.g. for biorefineries (Zeller et al. 2012; Weiser et al. 2011).

Apart from changes in SOC and mineral content, for instance erosion, changes in soil structural properties, and soil hydraulic properties as well as

eutrophication (cf. point 2.3.1) and contamination with pollutants (cf. point 2.3.3) can influence the soil quality

Table 4-1: Usable share of straw for energetic purposes of the total wheat straw in Germany according to different sources

Source	(Leible et al. 2003)	(Kaltschmitt et al. 2003)	(Fritsche et al. 2004)	(Simon, Wiegmann 2009)	(BE Bioenergie 2007)	(Münch 2008)
[%]	37-52	20	20-33	35	25	33

(2.1.4) Today, about one third of the world population and many ecosystems are suffering from water scarcity (Oki, Kanae 2006). One major reason is the huge demand of global fresh water for agricultural production which was estimated to be 85 % of the global fresh water demand (Shiklomanov, Rodda 2004). Furthermore, water scarcity will likely increase due to a higher agricultural production which is projected to double by 2050 (Tilman et al. 2002). One consequence will be the decrease of crop yields, and people, especially in the developing world, may probably suffer from malnutrition (Pfister et al. 2011). A further issue is that the share of water withdrawals for agriculture strongly depends on the location. For example the agricultural water withdrawal contributes to the total water withdrawal by around 90 % in Greece, 62 % in Spain, 55 % in Brazil, and only to 0.25 % in Germany (FAO 2011).

Since the cultivation of biomass or processes in biorefineries require **fresh water**, biorefineries could intensify the shortage of water in a region. In particular, the cultivation of energy crops is responsible for the largest amount of water use required for the production of bioenergy or biomaterials (Laser et al. 2009; Berndes 2002). By choosing feedstocks such as wood or residues which require little or no fresh water, biorefineries can reduce the water demand in their upstream chain. Attention should be paid to the cultivation of trees with deep roots such as eucalyptus which can negatively influence the ground water level and harm nearby agricultural fields.

Apart from species selection, water demand in agriculture can be reduced by good water management. Technical options to reduce water consumption in agriculture are for example drip irrigation or low-pressure sprinkling. It should be considered, too, that fresh water might be polluted by intensified agriculture which implies a loss of clean fresh water (Rai et al. 2010; SRU 2007). In total, the water requirements of energy derived from biomass may be about 70 to 400 times larger than of other primary energy carriers (Gerbens-Leenes et al. 2008; Gerbens-Leenes, Hoekstra 2011). With regard to the cultivation of microalgae, closed systems such as photobioreactors or the use of sea or waste water allows a reduction in fresh water demand (Benemann et al. 2012).

It should be taken into account that there is a strong influence and trade-off between land use change and water scarcity (Scanlon et al. 2007; Pfister et al.

2011). Additionally, climate change will have a strong influence on future water availability as well (Gheewala et al. 2011).

(2.2) Sustainable use of non-renewable resources

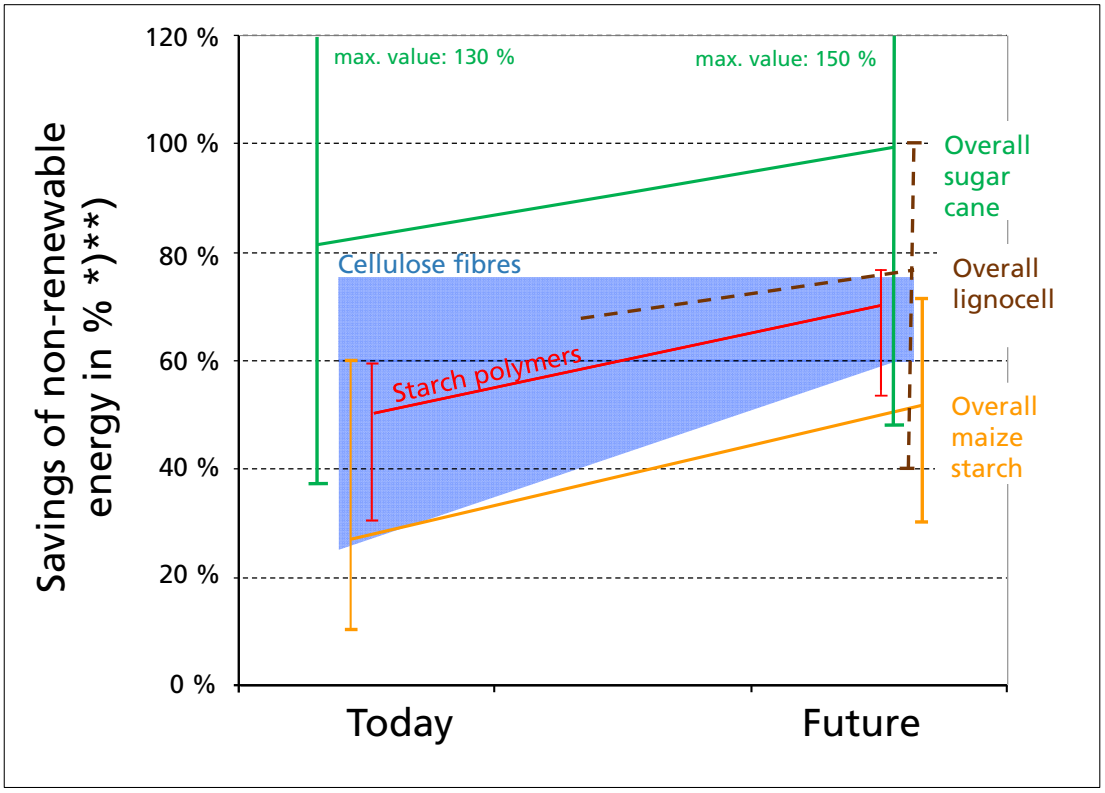
(2.2.1) As discussed in chapter 2.1, the question of how much natural capital should be substituted by man-made capital still remains open.

Nevertheless, to be sustainable the range of proven amounts of non-renewable resources should be principally constant over time (Kopfmüller et al. 2001). Exceptions are non-renewable resources that were or will be substituted partly or totally due to a changing shortage, health concerns or technological progress (Frondel et al. 2006). Asbestos, formerly one of the most important industrial raw materials, is a well-known example. For health concerns asbestos has been prohibited in Germany since 1993 and in the EU since 2005. But also technological progress in terms of conversion efficiencies, new processes or new recycling opportunities can increase the availability of non-renewable resources.

With regard to biorefineries non-renewable resources should be substituted by renewable resources as technically practical and energetically feasible. For example the heat demand of biorefineries should be covered by internal processes in order to **save non-renewable energy**. As shown in Figure 4-5, already today and in the future even more savings of non-renewable energy can be achieved by replacing fossil-based materials with bio-based materials (Rai et al. 2010). The orange line, green line, and dotted line in Figure 4-5 illustrate savings by biotechnological production of bulk chemicals compared to their petrochemical counterparts produced from maize starch, sugar cane, and lignocellulosic material. The values were calculated by the arithmetic mean of the results of the following 10 chemicals: succinic acid, acrylic acid, 1,3-propanediol, caprolactam, polylactide, polytrimethylenterephthalate, acetone/butanol/ethanol fermentation, ethyl lactate, ethanol, and ethylene (Patel et al. 2006). The highest savings are calculated for bio-based products produced from sugar cane which achieve savings of non-renewable energy up to 130 % today and 150 % in future. Bio-based chemicals from lignocellulosic materials will probably emerge in future and will achieve savings up to 100 %. The blue area in Figure 4-5 shows savings of non-renewable energy of cellulose fibres compared to polyethylene terephthalate fibres, for various types of cellulose fibres and different production technologies (Shen et al. 2009). The red line underneath the blue area represents starch polymers compared to petrochemical polymers (Patel et al. 2003).

To summarise the minimum savings of non-renewable energy of bio-based products can be expected to be in the region of 30 % today and 50 % in future. Depending on the product, the feedstock, and the technology level higher savings up to 70 % and beyond can be achieved.

High savings of non-renewable energy can be also achieved for an entire biorefinery. Savings up to 96 % were calculated, for example, for a »3 platform biorefinery (hemicelluloses, celluloses, lignin) for bioethanol and phenols from straw« in the year 2020 (Fritsche et al. 2011).



*) Ranges indicate values for individual products (not average values)
**) Savings of cradle-to-factory gate non-renewable energy compared to petrochemical

Figure 4-5: Savings of non-renewable energy by bio-based materials, system boundaries: cradle-to-factory gate (Rai et al. 2010)

(2.2.2) A **sustainable use of nutrients and metals** requires that nutrient levels are preserved and can be maintained indefinitely by the agricultural practices used (Reijnders 2006). Important nutrients are nitrogen, potassium, and phosphorus. Potassium and phosphorus come from mines while especially phosphorus becomes geochemically scarce (Cordell et al. 2009; Rosemarin et al. 2009). That is why phosphorus security is one of the greatest challenges of the 21st century and can be defined as ensuring that »all the world's farmers have access to sufficient phosphorus in the short and long term to grow enough food to feed for a growing world population, while ensuring farmer livelihoods and minimising detrimental environmental and social impacts« (Cordell 2010, p. 123). Moreover, nitrogen fertilisers are produced from scarce fossil raw materials as discussed before under point 2.2.1. Losses of nutrients occur due to agricultural activities and may result from erosion/runoff and leaching. Leaching of phosphorus may take place when soils are saturated with phosphorus and may result from poor nutrient efficiencies of biomass production. Today, only 30 - 50 % of applied nitrogen fertilisers (Cassman et al. 2002; Smil 1999) and about 45 % of phosphorus fertilisers (Smil 2000) is taken up by crops. These low efficiencies are typically for intensive high-yield agriculture (Tilman et al. 2002) but can also be found for trees. Accordingly, biorefineries should make increased use of feedstocks which are applicable to reduce or to avoid losses of

nutrients such as suitable woody biomass or municipal wastes. In order to meet plant growth requirements and to reduce fertiliser demand, technical solutions such as precision agriculture with computer controlled fertiliser systems, soil testing, and global positioning systems should be applied in agriculture (Han et al. 2011). The removal of residues should be regarded carefully since nutrients are deprived from soil and as a consequence soil quality can be lowered as already mentioned under the point 2.1.3.

Losses of phosphate in biorefineries may occur because phosphate often ends up in waste water. Hence an efficient recycling of phosphates should be developed and applied for biorefineries. Especially the cultivation of microalgae requires huge amounts of fertiliser which consist of around 8 % N and 1 % P of ash-free dry weight. Therefore, biorefineries using microalgae as feedstock should consider the option of using alternative nutrient sources such as municipal waste water and should establish an efficient recycling of nutrients. So far, several phosphorus recovery and reuse options have been suggested (Cordell et al. 2011). But a key challenge still remains to avoid an enrichment of pollutants in order to meet the quality requirements of fertilisers[16] to feed back to agriculture. In particular if biorefineries are coupled with biogas plants, attention should be paid to the nutrients available in fermentation residues. In case of biorefineries using gasifying processes, it should be examined if it is technically and ecologically feasible to recycle P and K from ashes.

Besides, the use of specific metals as catalysts (e.g. Pd, Rh, Ir or Ru) or for tractor batteries (e.g. Pb or Li) should be regarded critically. Nevertheless, the use of such metals is not rated with high importance to biorefineries since they are used in a similar order of magnitude in existing industrial operations, too which would principally be replaced by biorefineries. Moreover, there does not seem to be an acute or foreseeable scarcity of these materials (Rai et al. 2010).

(2.3) Sustainable use of the environment as a sink

(2.3.1) Considering that nature has a regulation function with regard to the ability to maintain crucial material, energetic, and biochemical processes and to compensate anthropocentric interferences (resilience), the release of substances should not exceed natures' capacity (Kopfmüller et al. 2001). With regard to biorefineries, especially the cultivation of biomass is accompanied by noxious **emissions into air, soil, and water** that have an **acidification** or **eutrophication potential**. Air emissions with the potential of acidification such as SO_2, NO_x, HCl, HF, NH_3, and H_2S may result from combustion processes, e.g. from burning of biofuels, pesticide and fertiliser production, electricity generation or e.g. from transport processes. The eutrophication potential (EP) of soil and water can be expressed by PO_4^{3-} equivalents and considers substances such as ammonia, ammonium, nitric acid, nitrate, phosphate, phosphorus, and nitrogen dioxide (Guinée et al. 2002). While disproportionate nitrogen loading is mainly responsible for coastal eutrophication (Boesch et al. 2001; Nixon

[16] See for example: Regulation (EC) No 2003/2003 of the European Parliament and of the Council of 13 October 2003 relating to fertilisers.

1995), the release of phosphorus leads to severe degradation and impairment of fresh water lakes, rivers, and some estuarine and coastal waters, in particular those which also receive high nitrogen loads (Howarth, Marino 2006). Intensive agriculture is mainly responsible for the release of eutrophying substances into soil and ground water that induces changes in biological soil activity and causes changes in local conditions for species, too (Reinhardt, Scheurlen 2004). Therefore, eutrophication of soils should be reduced or avoided by nutrient removal and eutrophication of water through measures to reduce erosion (Knickel et al. 2001). If a biogas plant for processing residues is integrated into a biorefinery system, fermentation residues should be fed back to field to that extent they do not cause local eutrophication.

In comparison to fossil reference products the use of dedicated crops for the production of bio-based products tends to be disadvantageous in the categories acidification and eutrophication (Oertel 2007). In contrast to dedicated crops the use of residues is beneficial or less disadvantageous compared to fossil products. With regard to energy carriers, solid energy carriers tend to be more favourable than liquid biofuels, whereas gaseous energy carriers lie in between (Oertel 2007). However, the acidification and eutrophication potential of biorefineries products have to be evaluated case-specifically since they strongly depend on local conditions, the established nutrient management, the product spectrum of a biorefinery, and for example the products they replace.

(2.3.2) Beside acidifying or eutrophying substances, **toxic emissions to water** have to be taken into account since they contribute to ecotoxicity and loss of biodiversity (cf. point 2.1.2) as well cause negative effects on human health as discussed under the point 1.1.1. Toxic substances could be present in agrochemicals such as fertilisers and pesticides that are applied during cultivation (Fritsche et al. 2006). Hence non-chemical pest treatment and organic fertilisers should be preferred. Biorefineries processing wood or residues instead of agricultural crops avoid the application of agrochemicals in the upstream chains. However, depending on the biorefinery concept, toxic substances emitted into water may also result from downstream processing. For example a lignocellulosic (cellulose, hemicellulose and lignin) biorefinery may release large amounts of salts as a consequence of using acids and bases such as sulphuric acid and sodium hydroxide for biomass pre-treatment. In such cases an effective waste water treatment must be applied.

(2.3.3) Apart from toxic emissions into air or water, **toxic substances** could be **released to soil**, too. As mentioned under point 2.3.2, toxic agrochemicals should be avoided by choosing suitable raw materials and/or improving agricultural practices. If nutrients are recycled within a biorefinery concept, toxic substances will probably accumulate. Hence, if fertiliser is produced in a biorefinery, toxic substances in the fertiliser should be reduced to a non-hazardous extent. Quality requirements on »EC fertilisers« are regulated in Annex 1 of the EU Regulation 2003/2003 (European Commission 2003). Apart from requirements concerning functionality such as providing nutrients in an effective manner and measurability with regard to sampling, analysis, and test

methods, EC fertilisers must not adversely affect human, animal or plant health or the environment (European Commission 2003).

(2.4) Avoiding technical risks with potentially catastrophic impacts

This rule requires that technological risks with possible disastrous consequences for human and nature should be avoided (Kopfmüller et al. 2001). Within this thesis the following types of technical risks are taken into account:

- 1st risks with a high probability of occurrence but with a locally limited magnitude of harms. This kind of risks may occur because of accidents during the transport of hazardous materials; e.g. small oil spills or fires,
- 2nd risks with a low probability of occurrence but with a high damage potential for environment and humans such as accidents at nuclear power-plants or in chemical plants,
- 3rd risks with a high uncertainty of both probability of occurrence and consequences because neither the probability of occurrence nor the magnitude of harm is known.

(2.4.1) Looking at different biorefinery concepts, the first category is of interest. Possible risks may result from fire hazard. Fire safety issues should cover the safety of biorefinery products, substances that may intervene on the whole value chain, process safety considerations, storage and transport as well as end-use considerations like explosion and fire safety in refuelling stations and vehicles (Marlair et al. 2009). In this context, the failure tendency of the plant and possible consequences to human and nature should also be regarded and be minimised. However, these risks occur in oil refineries, too and should be evaluated depending on the specific case.

Other risks addressed by point three may occur due to applications of genetic engineering. These risks do not focus on the escape of organisms – the impacts of which are estimated to be small – but may result from putting transgenic plants into market. Those transgenic plants may influence the composition of species (cf. point 2.1.2) but may also distribute specific plant ingredients and thus potential allergens in food. With regard to fossil reference products, disastrous consequences for humans and nature may result from the extraction and transport of oil. A disastrous accident was in 2010 when approximately 500 000 to 1 000 000 tonnes of oil were released into the Gulf of Mexico (Zeit/dpa 2010). However, even in 2011 several oil accidents happened, e.g. in Nightingale Island, in the North Sea, Bay of Plenty or in front of the Brasilian coast.

(2.5) Sustainable development of material, human, and knowledge capital

According to Kopfmüller et al., material, man-made, and knowledge capital should be developed in a way that the economic capacity will remain constant or will improve (Kopfmüller et al. 2001).

(2.5.1) In order to develop physical capital, the **supply safety of a region** is of central interest. Depending on the performance and production capacity of biorefineries located in a region, they can improve the local energy and food security. Depending on the implemented biorefinery concepts, they can supply the region e.g. with biofuels, other forms of energy products, bio-based chemicals, bio-based materials, food, and feed.

Germany, for example, is a highly globalised country with its industry strongly depending on fossil resources imported from foreign countries such as Russia, Norway, and Great Britain. With regard to peak oil, this dependency on fossil fuels can lead to a crucial security policy issue (Bundeswehr 2010). This dependency has been reduced with the support of the German government by the considerable expansion of biofuel production in Germany during the last 10 years so that in 2011 the share of biofuels reached around 5.6 % (Fritsche et al. 2012). But also looking at the EU, energy security plays a great role for the EU Commission policy (Belkin 2008). One instrument for promoting the energy security in the EU is the Strategic Energy Technology (SET) plan which was implemented by the European Commission and addresses the development of technologies for »bioenergy – power and heat generation« (EU 2009a). The main objective of the associated European Industrial Initiative on bioenergy[17] is »to bring to commercial maturity the most promising technologies, in order to permit large-scale, sustainable production of advanced biofuels and highly efficient combined heat and power from biomass« (EU 2009, pp. 5–6). As indicated in Figure 4-6, the EU and most other regions in the world as well want to expand the share of biofuels significantly by 2035.

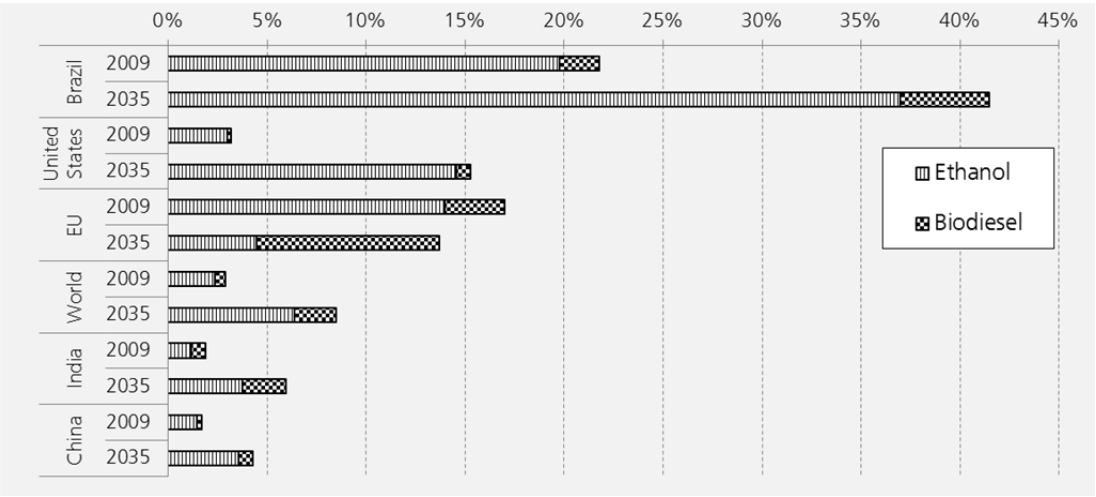


Figure 4-6: Share of biofuels in total road-fuel consumption in selected regions by type in the new policies scenario (IEA 2010)

[17] Homepage of Strategic Energy Technologies Information System (SETIS): http://setis.ec.europa.eu/about-setis/technology-roadmap/european-industrial-initiative-on-bioenergy

(2.5.2) Physical capital which can contribute to present and future social welfare should be maintained, adopted or developed. That means current **technology should be replaced smoothly** over time without destroying present physical capital. Hence, present physical capital should be used as far as possible as a source for the development of emerging technologies which are beneficial for our society. With regard to biorefineries integrated industrial sites – so called brown fields – might be favourable because existing infrastructure services can be used.

However, two strategies for developing biorefineries are conceivable as illustrated in Figure 4-7. One approach is the conversion of biomass into basic chemicals traditionally used by the chemical industry. These basic chemicals can be further processed into various (traditional) products by conventional synthesis routes (Kamm 2007). However, in this case the synthesis capability inherent in nature is a disadvantage because biomass needs first to be broken into basic components and oxygen needs to be removed. Moreover, bio-based basic chemicals are in competition with fossil-based chemicals optimised for many decades and made from relatively cheap fossil resources making a potential market entry more difficult. On the other hand these bio-based chemicals can directly replace fossil-based products as they are chemically identical. One example for this strategy is the fermentation of sugars from sugar cane or corn into ethanol (basic chemical) which can be further dehydrated into ethylene as an intermediate for several chemicals (Vennestrøm et al. 2011).

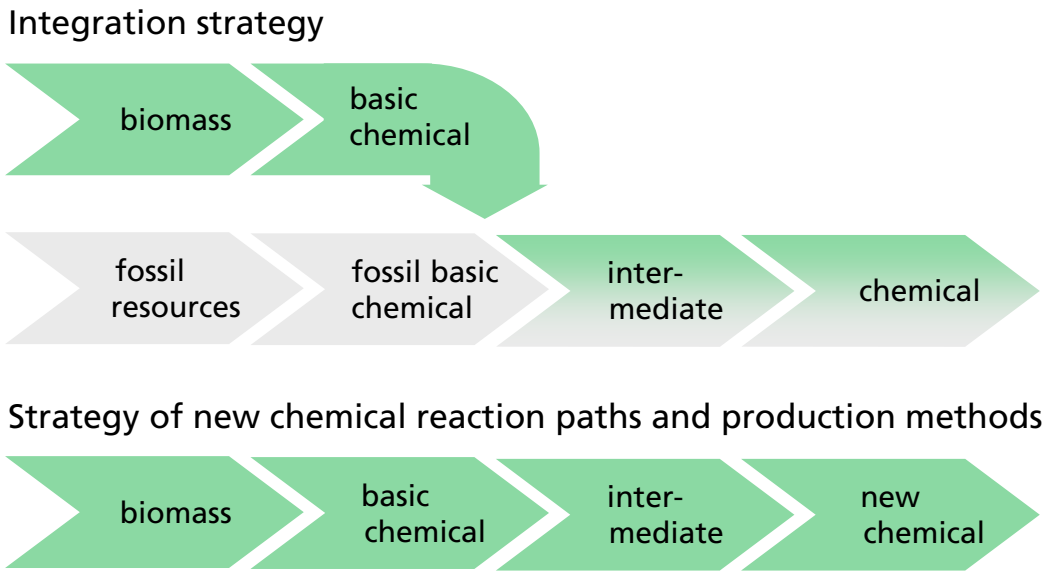


Figure 4-7: Two strategies on how to develop biorefineries; in the style of (Vennestrøm et al. 2011)

Alternatively, new chemical reaction paths and production methods have to be developed in order to efficiently process biomass into existing or new products. In this case the molecular structures of the feedstock may be used (suitable H/C ratio) in order to produce chemicals more energy efficiently. A high difference between the effective H/C ratio of feedstock and target chemical product

requires complex and costly conversion processes (Vennestrøm et al. 2011). Hence, higher energy saving potentials are estimated by producing chemicals from biomass rather than biofuels since chemicals such as ethylene glycol, acetic acid or acrylic acid have an similar H/C ratio similar to that of biomass. In contrast to such chemicals, biofuels have an H/C ratio between 1 and 2.3 which is similar to crude oil. Nevertheless, depending on the structure of biomass, selective chemistry can be extremely challenging. For example the molecular structures of lignin are so complex and various that the most economical way of processing lignin today seems to be the gasification to syngas. However, the development of new production methods requires the development of new chemical reaction paths, new infrastructure, and maybe new markets but also offers the chance of producing several products more efficiently. The investment in new physical capital required in case of the »new strategy« seems to be reasonable if higher energy savings and a higher added value can be reached.

(2.5.3) Looking at the development of human capital, the development and implementation of biorefineries are likely to trigger the **education of interdisciplinary qualified workers and scientists** in the various fields of science of technology (Rai et al. 2010). The development of new processes, materials, and biofuels will require huge RTD expenditure promoting the education of scientist. In particular experts with multidisciplinary backgrounds will be needed due to complex value chains associated with biorefineries. Besides, a huge demand for biomass can trigger the educational development in the agricultural sector.

(2.5.4) But also **non-personal knowledge** which is codified e.g. in publications, databases, laws, and patents can contribute to sustainable development, e.g. by giving information on how to produce in a resource-saving manner (Kopfmüller et al. 2001). It also offers new activity possibilities for future generations and will support future innovations which can provide new job opportunities (Weltbank 1998/99). Principally, innovations are distinguished into process-, product-, and organisationally-oriented in the field of empirical innovation research (OECD 1997). Biorefineries in particular have the potential to generate process innovations, e.g. through new methods making it possible to produce a given quantity at a lower cost and in safer working conditions and to generate product innovations e.g. through developing hitherto unknown or fundamentally altered bio-based products with new functionalities. Moreover, biorefineries have the potential to generate environmental innovations that aim at reducing the negative environmental impacts such as emissions caused by the production, use, consumption or disposal of goods and in the field of saving resources (Hemmelskamp 1997). Furthermore, the development of biorefineries has been promising potential for promoting innovations since most of the needed technologies are currently only available at pilot or demonstration scale (Fritsche et al. 2011). The knowledge gained about biorefinery technologies will offer new solutions to secure the supply with chemicals, fuels, and further bio-based products particularly in countries without access to oil. Nevertheless, a crucial prerequisite for a

successful innovation will be the economic competitiveness of these bio-based products.

(3.1) Equal opportunities for all people regarding education, career, information participation in social decision-making

(3.1.1) This rule principally requires that everybody should get the opportunity to realise their life plans and talents. This includes the access to education and information, to work or to come into a position. These requirements are often not met in developing countries where people and children are forced to work, cannot go to school nor realise their desires.

In particular the worldwide increasing demand on biofuels fostered by target-based policies makes it attractive for poorer countries to scale-up their biomass or own biofuels production rapidly. This fast development may support the violation of **human and labour rights** as codified in the »Universal Declaration of Human Rights« of the United Nations and in the Conventions of the International Labour Organisation such as the annually updated »ILO Declaration on Fundamental Principles and Rights at Work«. For example in 2007, Amnesty International highlighted the rescue of more than 2 000 sugar cane workers in Brazil from forced labour or conditions analogous to slavery (Amnesty International 2008). However, it is not possible to decide whether these violations of labour rights are caused by the entire Brazilian sugar cane industry or by the Brazilian sugar cane industry where it relates to bioethanol production. Hence, operators of biorefineries using biomass from developing countries or operating in such countries should carefully examine the compliance with labour rights. This can be done e.g. through certification systems such as those listed in Table 7-27 in appendix II. It should be mentioned that there is a strong link between the compliance with labour rights and fair-trade conditions as discussed under point 1.4.2.

(3.2) Participation in societal decision-making processes

(3.2.1) A technological transition from a fossil-based society to a bio-based society requires a social transformation (WBGU 2011). An important prerequisite for a successful transition is a broad acceptance which is characterised by a positive attitude of users towards a technology and the willingness to apply and to use it in a concrete situation (Dethloff 2004). According to Wüstenhagen et al. acceptance can be distinguished between socio-political acceptance, community acceptance, and market acceptance (Wüstenhagen et al. 2007). Many surveys show a broad agreement on public support for renewables (EORG 2003; WBGU 2011) which indicates a high socio-political acceptance. Moreover, »policy-sphere actors are aware of the very significant resources and support needed to operationalize the biorefinery concept Europe-wide« (Peck et al. 2009, pp. 379–380). On the other hand, NGOs, as one group of external stakeholders, have different positions towards bioenergy (Alasti 2011). In contrast to the socio-political dimension, often the community acceptance is far lower. This is apparent in a lack of local support and effective positive investment and site-selection decisions. Driving forces for the

acceptability of a bioenergy project at a local level are for example political factors such as power of local government or policies for urban planning and financial, socio-economic factors such as availability and perception of natural resources or attitude to foreign (non-local) investors, cultural factors such as trust in local institutions or historical experiences, and geographic factors such as climate and availability of suitable locations (Heiskanen et al. 2008). In particular community acceptance can be supported by the **participation** (integration) of all relevant stakeholders. Such a participation includes a dialogue with politics, entrepreneurs, and citizens on questions such as how to use natural resources, how a fair distribution of natural resources should look like, how to avoid competition with the food chain, how to protect the biodiversity, and for instance how to develop regional strategies. A deeper understanding of these topics might also trigger the **market acceptance** which describes the process of the market adoption of an innovation by consumers. Market adoption of technologies is not only bound to attitude and behaviour but most importantly to the willingness to spend money for a new technology product (Hoek 2012). In particular with focus on biorefineries the willingness to pay for bio-based products is of central importance.

(3.3) Preservation of cultural heritage and diversity making processes

There is no clear causal link between biorefineries and the preservation of cultural heritage and diversity making processes.

(3.4) Preservation of the cultural functions of nature

(3.4.1) According to this rule, cultural and **natural landscapes with individual characteristics and beauty should be preserved** (Kopfmüller et al. 2001). Based on the postulate that future needs should be met, the exclusive consideration of using nature as resource or as sink for pollutants does not seem to be adequate. In fact nature should also be seen as space for sensually, contemplative, spiritual, and aesthetical experiences (Knaus, Renn 1998; Acker-Widmaier 1999). Additionally, attractive landscapes are prerequisites for a high quality of life. Biorefineries may influence the landscape since they depend on the supply with biomass which may originate from different sources such as agriculture, forests, residues or wastes. The use of residues or wastes is estimated to have little impact on landscapes since no additional area is needed. On the other hand, sustainable cultivation methods have the potential to contribute to the entertainment and recreational value of nature. In particular old forms of agricultural management with small plots of fields not only contribute to the protection of ecosystems and species but also reflect agricultural history as part of cultural history (Grunwald et al. 2001). In contrast, intensive agricultural use leads to unification of landscapes which may be seen as negative. However, the questions whether a traditional landscape is more beautiful than an energy landscape will always remain a subjective assessment. Biorefineries using wood should only use wood which is produced in a sustainable way since forests fulfil – next to the supply with wood – several

other cultural functions such as places of recreation or places for sporting activities.

(3.5) Preservation of social resources (tolerance, solidarity etc.)

(3.5.1) The preservation of individual social resources such as the sense of justice, tolerance, solidarity or public interest orientation can promote the integrative capacity of a society (Kopfmüller et al. 2001). However, this topic is not crucial for the development of biorefinery concepts.

4.1.2 Comparison of sustainability criteria for biorefineries and biomass production with literature

In addition to the sustainability criteria found and discussed by the application of the substantial rules, further sustainability criteria mentioned in scientific literature and certification systems are analysed and are complemented if necessary. This approach ensures that the recent scientific and social discussion is taken into account.

The EU-funded project SUstainability assessment of TEchnologies (PROSUITE) for example provides a set of criteria to assess economic, ecological, and social impacts of biorefineries which is presented in Table 7-23 in appendix II (Rai et al. 2010). Most of the criteria mentioned were also found by using the substantial rules. However, financial risks have not been directly addressed yet. Financial risks may be affected by the following factors: future way of fossil fuel prices, competition among bioenergy, solar, wind, and other forms of energy if electric traction drives in passenger cars will be successful, market success of oil and gas-based conventional materials and materials made by coal-based chemistry, technological progress of biorefineries e.g. in case of 2nd generation biofuels, land availability or bad harvests due to infections, plagues or extreme weather conditions (Rai et al. 2010). However, these criteria seem to express something about the economic success of biorefineries but do not directly contribute to a sustainable development. Potential consequences of commercially successful biorefineries are already covered by criteria 1.3.1 »creation or preservation of work places« and 2.5.2 »performance and production capacity of technologies«. In order to avoid double counting indicators addressing financial risks are excluded. In addition the suggested indicators in Table 7-23 »product-market combinations« expressed as relation of energetic products and materials and »production costs and life cycle costs« likewise do not provide specific information with regard to sustainable development and will not be regarded afterwards. Under the topic »equity concerns« it is discussed that »developed countries« will have the knowledge to construct and operate biorefineries and are likely to benefit disproportionately from this development (Rai et al. 2010). Nonetheless, that does not seem to be a biorefinery-specific concern.

(Buchholz et al. 2009) identified 35 sustainability criteria on bioenergy derived from several studies (Cramer et al. 2006; van Dam et al. 2008; Fritsche et al. 2006; Lewandowski, Faaij 2006; Modi et al. 2005; Reijnders 2006; Smeets et al.

2005) as well as the bioenergywiki (Sustainable Bioenergy Wiki 2011). These criteria were clustered into environmental, social, and economic concerns and are listed in Table 7-24 appendix II. In addition to the criteria identified by the substantial rules microeconomic sustainability, economic stability, adaption capacity to environmental hazards and climate change, ecosystems connectivity, compliance with laws, planning, respecting minorities, social cohesion, and noise impacts are mentioned. As discussed before the economic criteria are already covered by criteria 1.3.1 »creation or preservation of work places« and 2.5.2 »performance and production capacity of technologies«. Adoption capacity to environmental hazards and climate change and ecosystems connectivity have been already addressed by criterion 2.1.2 »impact on biodiversity«. The compliance to law is a crucial prerequisite and will be further investigated in chapter 4.1.3. »Planning« refers to creating a management plan, implementing, and updating if necessary. However, a well-organised management plan supports an effective resource management that has already been addressed by the criteria mentioned under 2.2. The suggested social criteria »respecting minorities and social cohesion« are a part of the human and labour rights requested by criterion 3.1.1. Noise pollution is often experienced as a nuisance for instance in the case of traffic. If noise plays a major role it should be taken into account in criterion 1.1.1 human health. Apart from these general criteria sets for bioenergy, specific ones were developed e.g. with focus on farming (Breitschuh et al. 2008). An evaluation according to a criteria set as suggested by Breitschuh addresses the profitability of a farm, the protection of soil, investigates the energy demand of a farm as well as examines social issues such as job offer, age distribution, quota of women, qualification, holiday, working conditions, wage level, social activities, and property rights (Breitschuh et al. 2008). These criteria are appropriate to evaluate the structure of a farm but do not contain really new aspects. Therefore, these aspects are not regarded further.

Additionally, there is a huge number of organisations which have presented and proposed initiatives and certification systems on sustainability criteria for biomass and biofuels (Saotome et al. 2013). A summary of the best-known initiatives and certification systems is given by Table 7-27 in appendix II. One well-known initiative is the Roundtable on Sustainable Biofuels (RSB) which covers the following 12 principles of compliance: 1) legality, 2) planning, monitoring and continuous Improvement, 3) greenhouse gases, 4) human and labour rights, 5) rural and local development, 6) food security, 7) conservation, 8) soil, 9) water, 10) air, 11) technology, 12) Land rights (RSB 2010). These principles go along with the criteria already defined stressing the relevance of local conditions. The principle »conservation« focuses on the maintenance or enhancement of values of local, regional or global importance – so called »no-go areas«[18] – within the potential or existing area of operation. This principle refers to the protection of ecosystems and biodiversity (2.1.2) and also addresses the preservation of natural landscapes with individual characteristics

[18] No-go areas are defined in the document »RSB- IND-11-001-20-001«.

and beauty (3.4.1). In Germany, the Initiative Sustainable Supply of Raw Materials for the Industrial Use of Biomass (INRO) initiated by the Federal Ministry of Consumer Protection, Food and Agriculture has developed a certification scheme for the sustainable production of biomass dedicated to the production of bio-based materials (BMELV 2013). The majority of these criteria is derived from already existing certification schemes and legal requirements developed for biofuels which will be evaluated in the next chapter.

4.1.3 Sustainability criteria requested by legal requirements

In order to promote renewable energies in the European Union, a series of directives promoting energy from renewable resources and voluntary initiatives such as the 20-20-20 policy has been launched which requests a reduction in greenhouse gases by 20 % compared to 1990 and a 20 % share of renewable energies by 2020. Another example is the »Directive 2009/33/EC on the promotion of clean and energy-efficient road transport vehicles« (European Commission 2009c) which encourages manufactures to continue investigating in vehicle developments and to use alternative fuels such as compressed natural gas (CNG) or biofuels. To ensure a high quality standard of transport fuels and to reduce emissions in the transport sector, the fuel quality directive 2009/30/EC (European Commission 2009b) includes a GHG reduction target for fuels of 6 % GHG emissions by 2020 which could be achieved through cleaner production technologies or biofuels blending. In order to further reduce GHG emissions in the EU, the Commission has launched a European Union Emission Trading Scheme (EU-ETS) covering GHG emissions from the industrial and energy sector accounting for about 45 % of the EU25 total CO_2 emissions.

In particular the »Directive 2009/28/EC on the promotion of energy from renewable sources« (European Commission 2009a), abbreviated as RED, gives a mandatory target for a 20 % share of energy from renewable resources in gross final energy consumption and a mandatory target for a minimum 10 % share of energy from renewable sources in transport to be met by each member state until 2020. According to this directive each member state is obliged to adopt a national renewable energy action plan describing targets for the share of renewable energy in transport, electricity, heating, and cooling and measures to meet these targets as well as to periodically report its progress to the Commission. Besides, it defines sustainability criteria for biofuels and bio-liquids. In its articles 17-19 the following ecological sustainability requirements for biofuels and bio-liquids are demanded:

- GHG savings: 35 % since 2010/2013 for current plants; 50 % from 2017, and 60 % from 2018 compared to fossil fuel
- No raw materials from high biodiversity areas such as primary forests, nature protection areas, highly biodiverse grassland
- No raw materials from high carbon stock areas such as continuously forested areas, wetlands, peatlands

- EU biomass: the »cross-compliance« rules in the EU's common agricultural policy that reflect the minimum environmental requirements for agriculture in the EU
- Traceability: chain of custody certification based on a mass-balance basis

These requirements have to be met in order to:

- count toward the EU targets of 10% renewables in transport and a 20 % share of renewable energy,
- count toward obligations, and to
- be eligible for financial support.

Apart from the criteria mentioned member states have to report on bioenergy developments and availability of biomass resources, changes in commodity prices and land use, impact on biodiversity, water resources, water quality, soil quality as well as estimated net GHG savings. Furthermore, the Commission will monitor the origin of biofuels and their impact, including impact on land use, commodity price changes associated with the use of biomass for energy and associated effects on food security. Based on these assessments the Commission reports on environmental benefits and costs of biofuels, sustainability impacts of increased biomass demand and biomass using sectors, indirect land-use changes in relation to all production pathways, and impacts on the food security and availability of foodstuffs at affordable prices. Complementary to the Directive 2009/28/EC the European Commission has created a Biomass Action Plan in 2005 (COM(2005)/628) (European Commission 2005) in order to implement a coordinated and integrated approach in biomass policy. Apart from the commitment that countries which sell biomass have to ratify and to implement several ILO standards[19], no additional criteria for social sustainability are included in the RED. In summary, the RED compromises important sustainability criteria already detected by the substantial rules in particular with focus on environmental aspects but do not provide additional criteria.

4.1.4 Summary and cluster of sustainability criteria of biorefineries

In order to improve the structuring and clarity of criteria detected and to avoid double entries, a new assignment of sustainability criteria is defined. The following four categories A to D and clusters were identified:

[19] Conventions of the International Labour Organisation to be ratified and implemented are numbers 29, 87, 98,100, 105, 111, 138, 182.

- A: Impacts on human health and B: impacts on environment
    - Risks
    - Material flows
    - Agriculture and ecosystem
- C: Development of knowledge and physical capital
    - Physical capital
    - Human and knowledge capital
- D: Regional development and acceptance
    - Regional economy and supply
    - Acceptance

The structure of the criteria set and their allocation according to contents are illustrated in Table 4-2.

Table 4-2: Structure of the criteria set and their allocation according to contents

Cate-gory	Cluster	Assign-ment	Rule	Criteria
A Impacts on human health and **B** on environment	Risks	A.1	1.1.1	Human health
		A.2	3.1.1	Compliance to human and labour rights; Safe working conditions
		AB.3	2.4.1	Life cycle wide technological risks
	Material flows	B.1	2.2.1	Savings of non-renewable energy
		B.2	2.1.1	Area efficiency
		B.3	2.3.1	Further emissions into the air and water
		B.4	1.4.1	Climate protection
		B.5	2.1.4	Water deprivation
		B.6	2.2.2	Depletion of minerals (nutrients) and metals
		B.7	2.3.2	Groundwater and surface water contamination
	Agri-culture and eco-system	B.8	2.1.3 2.3.3	Protection of soil
		B.9	2.1.2	Impact on biodiversity and ecosystems
C Knowledge and physical capital	Physical capital	C.1	2.5.2	Development of physical capital which can contribute to present and future social welfare
	Human and know-ledge capital	C.2	2.5.3	Education of scientists and qualified workers
		C.3	2.5.4	Generation of new knowledge and innovation potential

Cate-gory	Cluster	Assign-ment	Rule	Criteria
D Regional development and acceptance	Region-al eco-nomy and supply	D.1	1.3.1	Impact on added value in the region to ensure living standard (creation or preservation of work places)
		D.2	2.5.1	Supply safety of a region
		D.3	1.4.2	Fair-trade conditions and fair property rights
	Accep-tance	D.4	3.2.1	Acceptance and participation
		D.5	3.4.1	Preservation of cultural heritage landscape and protected areas as protected good
		D.6	1.2.1	Food security

4.2 Definition of generic sustainability indicators for biorefineries

4.2.1 Requirements of indicators

The use of indicators is a common way of describing, monitoring, and evaluating complex systems. Principally, they are used for (McCool, Stankey 2004):

- characterising the current conditions and performance of a system,
- monitoring the effectiveness of actions and policies to move a system towards a more sustainable state,
- recognising changes in economic, environmental, social, and cultural systems.

Within this thesis indicators are used to describe the conditions and performance of biorefineries in comparison to its fossil counterparts. One major challenge is to develop indicators to measure social effects of biorefineries. In contrast to the evaluation of effects on nature and economic systems, which can be often measured in quantitative terms, social criteria are more difficult to assess both on the conceptual and on the empirical level. One crucial problem with the measurement of social effects associated with technologies is that »social indicators cannot be derived from an overarching functional societal theory because a consensual widely accepted theory does not exist« (Renn et al. 2006, p. 15). Hence the majority of social studies looks at the description and interpretation of social actions at the micro- or mesolevel. One way to select and mention social criteria and indicators is to look for shared opinions about norms and values. As the integrative concept of sustainability is based on the broadly accepted documents of the Brundlandt Commission, it already provides such a common understanding of values. In order to get a comprehensive picture of impacts associated with biorefineries, the scope of the indicators

should cover the whole life cycle from cradle to grave. In addition, according to Hirschberg et al. they should be (Hirschberg et al. 2007):

- **scientific:** measurable and quantifiable, meaningful, clear in value and content, appropriate in scale, no redundancy or double counting, robust and reproducible, sensitive and specific, verifiable, and hierarchical,
- **functional:** relevant, compelling, leading, possible to influence, comparable, and comprehensive,
- **pragmatic:** manageable, understandable, feasible, timely, covering the different aspects of sustainability, and allowing international comparison to the extent necessary.

Apart from these requirements mentioned, indicators should be robust and **directionally safe** in order to draw comparisons of bio-based and conventional products with respect to their contribution to sustainable development. Furthermore, the availability of data is a crucial prerequisite for choosing indicators.

4.2.2 Indicators addressed by life cycle assessment approaches

Against the background of data availability and further requirements of indicators mentioned in chapter 4.2.1, indicators which can be calculated by life cycle assessment (LCA)[20] and fit to the criteria suggested in Table 4-2 are selected. These indicators focus either on emissions and consumption of materials, so called »midpoint« indicators, or on the impact on protection areas human health, ecosystem quality, and resource availability, so called »endpoint« indicators. The impact on the ecosystem quality can be measured in »loss of species during a year« that is calculated by multiplying the »potentially disappearing fraction« (PDF) with the »species density«. The impact on human health can be measured in disability adjusted life-years (DALYs) (Hofstetter 1998). Both endpoint indicators mentioned incorporate many scientific models such as the »USES-LCA 2.0 toxicity model«[21] which refer to midpoint indicators calculated e.g. within the ReCiPe life cycle impact assessment (LCIA) method (Goedkoop et al. 2013). Although endpoint indicators focussing on »areas of protection« are more understandable to decision makers (Bare et al. 2000) and fit well to the substantial rules »protection of human health« and »sustainable use of renewable resources«, their calculations require a lot of assumptions and value choices and hence go along with a high uncertainty. On the other hand midpoint indicators minimise the amount of forecasting and effect modelling incorporated into the LCIA, thereby reducing the complexity of the modelling.

[20] The life cycle assessment method is introduced in chapter 4.3.1.

[21] The uniform system for the evaluation of substances adapted for LCA purposes (USES-LCA), is a multimedia fate, exposure, and effects model. It is used to calculate toxicity indicators for life cycle impact assessment purposes and can be downloaded at http://cem-nl.eu/useslca.html

Hence they achieve a higher level of societal consensus and are less comprehensive.

However, there is the risk of double counting because endpoint indicators use data that is already covered by midpoint indicators such as infra-red forcing or amount of hazardous wastes. With regard to the weighting of indicators, midpoint indicators contributing to endpoint indicators should therefore be discussed in combination with the endpoint indicators.

Within this thesis the ReCiPe LCIA method is used which will be introduced in chapter 4.3.1 and covers the endpoint indicators DALY, PDF, and increased cost. An overview of the endpoint categories, indicators and characterisation factors is given in Table 4-3.

Table 4-3: Overview of the endpoint categories, indicators, and characterisation factor units (Goedkoop et al. 2013)

Name of impact category	Name of indicator	Unit
Damage to human health	Disability-adjusted loss of life years (DALY)	Year
Damage to ecosystem diversity	Loss of species during a year (PDF* species density)	Species* year
Damage to resource availability	Increased cost	$

The endpoint indicator DALY as suggested by the ReCiPe framework is applied to represent the criterion **impacts on human health (A1).**

It is calculated through the following principal steps (Goedkoop, Spriensma 2000):

- Fate analysis: linking an emission to a temporary change in concentration
- Exposure analysis: linking this temporary concentration change to a dose
- Effect analysis: linking the dose to a number of health effects
- Damage analysis: links health effects to DALYs

The indicator DALY refers to human health statistics on life years both lost and disabled. Values for disability-adjusted life years have been investigated for a wide range of diseases, including various cancer types, vector-borne diseases and non-communicable diseases (Goedkoop, Spriensma 2000; Frischknecht et al. 2000; Murray, Lopez 1996). DALY is calculated as the sum of years of life lost (YLL) and years of life disabled (YLD) (Goedkoop et al. 2013) as shown in equation (4-1):

$$DALY = YLL + YLD, \text{ with } YLD = w*D \qquad (4\text{-}1)$$

whereas w is a severity factor between 0 (complete health) and 1 (dead), and D is the duration of the disease. For calculating DALY the impact categories climate change, human toxicity, ionising radiation, ozone depletion, particulate

matter formation, photochemical oxidant formation, and water deprivation are considered.

In order to assess **impacts on biodiversity and ecosystems (B10)**, the endpoint indicator »loss of species during a year« is applied. In compliance with the ReCiPe model it is assumed that the diversity of species adequately represents the quality of ecosystems. The indicator refers to characterisation factors for terrestrial systems, fresh water systems, and marine water systems and is calculated as follows (Goedkoop et al. 2013):

$$CF_{ED} = PDF_{terr}*SD_{terr} + PDF_{fw}*SD_{fw} + PDF_{mw}*SD_{mw} \quad (4\text{-}2)$$

CF_{ED} = the endpoint characterisation factor for ecosystem damage

PDF_{terr} = the characterisation factor in PDF*m^2*yr., and SD_{terr} the species density factor for terrestrial systems, in species*m^{-2}

PDF_{fw} = the characterisation factor in PDF*m^3*yr., and SD_{fw} the species density for fresh water systems in species*m^{-3}

PDF_{mw} = the characterisation factor in PDF*m^3*yr., and SD_{mw} the species density for marine water systems in species*m^{-3}

For calculating the loss of species during a year the impact categories land occupation, climate change, fresh water ecotoxicity, fresh water eutrophication, marine ecotoxicity, terrestrial acidification, terrestrial ecotoxicity, and water deprivation are considered.

Apart from the endpoint indicators DALY and loss of species during a year, further 13 midpoint indicators are taken into account that are covered by the ReCiPe LCIA method and are presented in Table 4-4.

Table 4-4: Impact categories, indicator names and characterisation factor (CF) names in the ReCiPe method (Goedkoop et al. 2013)

Criterion	Name of impact category	Name of indicator	Name of CF	Unit of midpoint indicator
B1	Fossil fuel depletion	Lower heating value	Fossil depletion potential (FDP)	kg oil-eq.
B2	Agricultural land occupation	Occupation	Agricultural land occupation potential (ALU)	m^2*yr.
	Urban land occupation	Occupation	Urban land occupation potential (ULO)	m^2*yr.
	Natural land transformation (NLT)	Transformation	Natural land transformation potential (NLTP)	m^2 (natural land)
B3a	Terrestrial acidification	Base saturation	Terrestrial acidification potential (TAP)	kg SO_2-eq. to air

Criterion	Name of impact category	Name of indicator	Name of CF	Unit of midpoint indicator
B3b	Particulate matter formation	Pm_{10} intake	Particulate matter formation potential (PMFP)	kg PM_{10}-eq. to air**
B3c	Photochemical oxidant formation	Photochemical ozone concentration	Photochemical oxidant formation potential (POF)	kg NMVOC***
B3d	Ozone depletion	Stratospheric ozone concentration	Ozone depletion potential (ODP)	kg CFC-11-eq. to air ****
B4	Climate change	Infra-red radiative forcing	Global warming potential (GWP)	kg CO_2 -eq. to air
B6	Mineral resource depletion	Grade decrease	Mineral depletion potential (MDP)	kg Fe-eq.
B7a	Fresh water ecotoxicity	Hazard-weighted concentration	Fresh water ecotoxicity potential (FETP)	kg 1,4 DCB-eq. to fresh water *****
B7b	Fresh water eutrophication	Phosphorus concentration	Fresh water eutrophication potential (FEP)	kg P-eq. to fresh water
B7c	Marine eutrophication	Nitrogen concentration	Marine eutrophication potential (MEP)	kg N-eq. to fresh water

* The precise reference extraction is »oil, crude, feedstock, 42 MJ per kg, in ground«

** PM_{10}: particulate matter with an aerodynamic diameter of less than 10 µm

*** NMVOC: non-methane volatile organic compound

**** CFC-11: chlorofluorocarbon

***** 1,4DCB: 1,4 dichlorobenzene equivalents

The majority of these characterisation factors is well established within many LCIA methods such as CML2002, EDIP97, EcoIndicator99 or Impact2002 as listed in Table 7-28 in appendix II (JRC 2010a).

In order to address the impact category **fossil fuel depletion (B1)** the characterisation factor »fossil depletion potential (FDP)« is used. The midpoint characterisation factor (CF) for each non-renewable $resource_{i...n}$ is calculated as ratio of the cumulative energy demand using the lower heating value of the non-renewable resource i…n ($CED_{non.renew.,i...n}$) and the cumulative energy demand of oil (CED_{ref}) with the heating value of 42 $MJ*kg^{-1}$ oil (Goedkoop et al. 2013). The fossil fuel depletion (FFD) is expressed in equation (4-3).

$$FFD = \sum_{i}^{n} m_{i,n} * \frac{CED_{non.renw.,i...n}}{CED_{ref}} \tag{4-3}$$

The CFs used only refer to fossil fuels[22] and are consistent with the CFs used in the ecoinvent database[23] and compiled by (Frischknecht et al. 2007). Since the cumulative non-renewable energy demand ($KNRA_{foss}$)[24] as defined in VDI 4 600 (VDI 4600) is an appropriate characteristic value to assess the fossil primary energy input of products and services, it could be calculated in addition. In order to achieve fossil energy savings, the quotient between oil equivalents or $KNRA_{foss}$ respectively of the reference system and the biorefinery has to be higher than one.

In order to address impacts of **land use (B2)** two basic types of land use elementary flows are taken into account (Koellner et al. 2013; Milà i Canals et al. 2007a):

- Occupation of a certain area of land during a certain time [m^2*yr.; land use type i, region k]
- Transformation of a certain area of land [m^2, initial land use type i → final land use type j, region k]

Both types of land use should be combined if occupation follows a transformation (Goedkoop et al. 2013). In case the occupation occurs in an area that has already been converted (transformed), no allocation of any of the transformation impacts to the production system that occupies an area is made. To calculate the midpoint indicators occupation and transformation, the amount of area occupied or transformed is used. A further differentiation is made between occupation of agricultural land (ALO) and urban land occupation (ULO) (Goedkoop et al. 2013). However, to calculate the endpoint indicator PDF for occupation and transformation, the land use type (initial/reference land use type) and related species density (SD) has to be taken into account. Land use classification schemes for LCA have been developed e.g. by ecoinvent (Weidema et al. 2011) and ReCiPe (Goedkoop et al. 2013).

In order to calculate the indicator »base saturation« (BS) that is applied to express the impact **terrestrial acidification (B3a)** the CF »terrestrial acidification potential (TAP)« expressed in SO_2-equivalents is used. The TAP is represented in equation (4-4) and refers to acidification for plant species in forest ecosystems on a European scale and is based on fate factors derived from an atmospheric deposition model combined with a dynamic soil acidification model.

TAP is calculated by dividing the fate factor of a substance x (FF_x) by the fate factor of SO_2 that equals to one, whereas FF_x is calculated as quotient of the

[22] Uranium is not a fossil fuel and is treated in the section »metals«.

[23] ecoinvent, the Centre for Life Cycle Inventories, is a Competence Centre of the Swiss Federal Institute of Technology Zürich (ETH Zürich) and further institutions and is supported by Swiss Federal Offices.

[24] $KNRA_{foss}$ is equivalent to the sum of the cumulative energy demand of all non-renewable resources (CED) required for a product or service.

change in base saturation (ΔBS) in an area with the size j (A_j in m^2) and the change in emissions of the acidifying substance ΔM_x.

$$TAP = \frac{FF_x}{FF_{SO_2}} = FF_x \quad ,with\ FF_x = \frac{\sum_j (\Delta BS_j * A_j)}{\Delta M_x} \tag{4-4}$$

A_j: the size of forest area j [m^2]
M_x: change in the emission of acidifying substance x [kg*yr.$^{-1}$]

BS is calculated according to equation (4-5) and represents the degree to which the adsorption complex of a soil is saturated with basic cations, cations other than hydrogen and aluminium. It is defined as the sum of basic cations (BC in equivalents*kg^{-1} soil) divided by the total cation exchange capacity (CEC equivalents*kg^{-1} soil) of the soil and multiplied by 100 (Vries et al. 2002).

$$BS = \frac{BC}{CEC} = \frac{[K]+[Ca]+[Mg]+[Na]}{[H]+[K]+[Ca]+[Mg]+[Na]} \tag{4-5}$$

Indicator **PM_{10} intake (B3b)** refers to the exposure to fine particulate matter with a diameter of less than 10 µm (PM_{10}) which can cause various health problems and reduce the life expectancy (WHO 2003). PM can either be emitted by natural or anthropogenic sources. Since mainly anthropogenic sources are influenced by human activities only these emissions are taken into account for calculating the indicator PM_{10} intake. Apart from direct emissions of PM_{10} SO_4^{2-}, NH_4^+, and NO_3^- aerosols are considered which result from SO_2, NH_3, and NO_x emissions (Goedkoop et al. 2013). The characterisation factors »particulate matter formation potential (PMFP)« expressed as PM_{10}-equivalents refer to the intake fraction of PM_{10} that is modelled for Europe using the atmospheric fate model EUTREND (van Jaarsveld 1995; van Jaarsveld et al. 1997). The following midpoint characterisation factors for particulate matter formation are applied (Goedkoop et al. 2013):

Emitted substance	Particulate matter formation potential (kg PM_{10}-eq.*kg^{-1})
PM_{10} to air	1
NH_3 to air	0.31
NO_x to air	0.21
SO_2 to air	0.19

Indicator **photochemical oxidant formation (B3c)** addresses the risks that are associated with the exposure to ozone which can cause airway inflammation and can damage lungs. Ozone is formed as a result of photochemical reactions of NO_x and non-methane volatile organic compounds (NMVOCs) and is usually

not directly emitted into the atmosphere (Goedkoop et al. 2013). Since the chemistry of ozone formation is complex because it is effected by the presence of precursors, due to the short lifetime of ozone under specific conditions, and strong influence of meteorological factors, a dynamic model referred to as LOTOS-EUROS was applied in the ReCiPe method (Schaap et al. 2008). The model was used to calculate the intake fractions for ozone due to emissions of NO_x and NMVOCs (Goedkoop et al. 2013).

The indicator **ozone depletion (B3d)** addresses ozone depleting substances (ODS), which are mainly chemicals that contain chlorine or bromine atoms. Their release leads to an increase of the stratospheric ozone destruction rate and finally results in harmful solar ultraviolet UV-B passing through the atmosphere. In the ReCiPe method the ozone depletion potential (ODP) was defined as a relative measure of the ozone depletion capacity of an ODS and uses CFC-11 (trichlorofluoromethane) as a reference (Goedkoop et al. 2013).

The indicator **infra-red radiative forcing (B4)** is used to assess the impact on climate change. For calculating the global warming potential (GWP) the commonly accepted CO_2-equivalency factors published in the IPCC report 2007 (IPCC 2007) and 2013 (Myhre, Shindell 2013a) are applied using equation (4-6):

$$GWP_i(T) = \frac{AGWP_i(T)}{AGWP_{CO_2}(T)} \tag{4-6}$$

whereas $GWP_i(T)$ describes the GWP of substance i with a time horizon T. Usually a time horizon of 100 years is selected. The absolute global warming potential (AGWP) is the time-integrated radiative forcing due to a one kg pulse emission of gas i, usually expressed in $W*m^{-2}*yr.*kg^{-1}$. GWP for gas »i« is obtained by dividing the $AGWP_i$ by the AGWP of CO_2 (Myhre, Shindell 2013b). The carbon footprint of a product (PCF) can be calculated by the following equation (4-7) and is expressed in kg CO_2-equivalents.

$$PCF = \sum_{i}^{n} GWP_{i...n} * x_{i...n} \tag{4-7}$$

In equation (4-7) $x_{i...n}$ corresponds to the absolute mass of emissions into the air of the greenhouse gases i to n.

Another important environmental indicator is **fresh water consumption**. Fresh water consumption is defined here as water which becomes unavailable due to evaporation or product integration. In the water modelling principles provided by the PE International AG fresh water consumption is defined as fresh water lost to the watershed due to water vapour to air[25], evapotranspiration, water incorporated into products, and water release to sea (PE INTERNATIONAL

[25] Evaporated water is denoted water vapour (elementary flow) in the GaBi inventory system while steam is considered a technical flow (as product output from e.g. steam generation, i.e. valuable substance).

2012a). Indicators for assessing water consumption exist on both inventory and impact assessment level (Berger, Finkbeiner 2010). Within the ReCiPe method, water use is exclusively calculated on inventory level and expressed as the midpoint indicator »water depletion« (Goedkoop et al. 2013). The suggested characterisation factors of the ReCiPe method differentiate between the water origins: lake, river, well in ground, unspecified natural origin. However, impacts on water availability should be analysed with regard to the specific region, considering the use of water, the availability and variability in precipitation, and further socio-economic impacts. Socio-economic impacts should be calculated at endpoint level capturing the contribution to DALY and PDF.

A suitable method for carrying out a comprehensive impact assessment of consumptive fresh water use on both midpoint and endpoint level was suggested by (Pfister et al. 2009). On midpoint level, a regional »water stress index« (WSI) is introduced which serves as a CF for the impact category »water deprivation« and ranges from 0 - 1, whereas 1 means the highest water stress. All values above 0.5 imply severe water stress and should be regarded carefully. An overview about the worldwide water stress at the watershed level per m^3 of water consumed is illustrated in Figure 4-8.

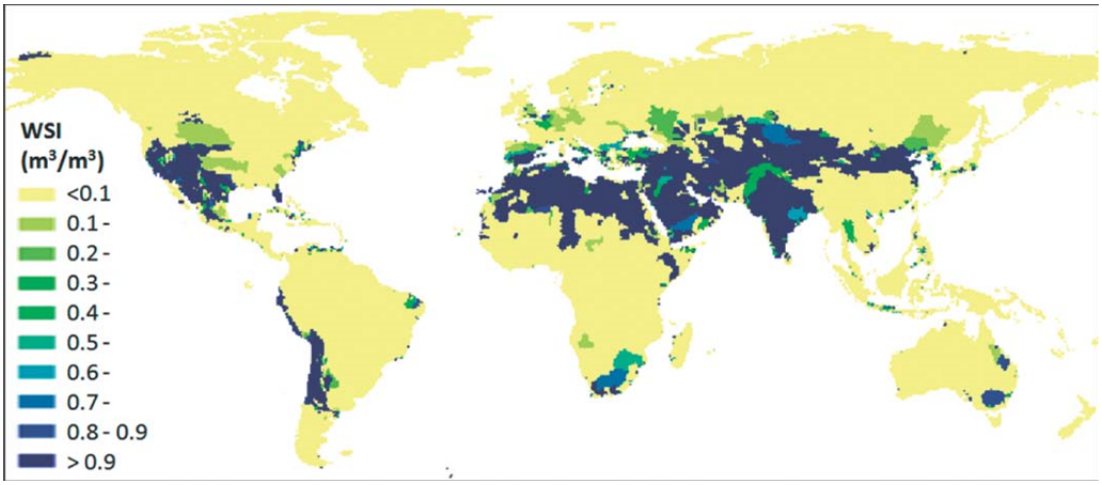


Figure 4-8: Characterisation of water stress index at the watershed level per m^3 of water consumed (Pfister et al. 2009).

In order to calculate the WSI, an indicator which expresses the local water scarcity is needed. The indicator used for calculating WSI is the withdrawal-to-availability (WTA) ratio, which is defined in equation (4-8) as the ratio of total annual fresh water withdrawal for human uses by different users j in a specific region i ($W_{i,j}$) to the annually available renewable water supply in that region (A_i).

$$WTA_i = \frac{\sum_j W_{i,j}}{A_i} \tag{4-8}$$

Based on WTA, the WSI is calculated according to the logistic function (4-9):

$$WSI = \frac{1}{1 + e^{-6.4*WTA} * \left(\frac{1}{0.01} - 1\right)} \tag{4-9}$$

It should be mentioned that the method suggested by Pfister only accounts for blue water consumption which includes the consumption of any surface and groundwater, and in the case of agricultural production particularly irrigation water (Pfister et al. 2009). Green water – which refers to rain water – is not taken into account. In addition, water pollution is excluded, too, which is usually addressed by the term »grey water«. Based on the blue water consumption and the regional specific WSI water deprivation is addressed by the **water scarcity footprint (WSF) (B5)** that is calculated according to equation (4-10).

$$WSF = \sum_i \frac{CWU_i * WSI_i}{WSI_{global}} \tag{4-10}$$

CWU_i = consumption of blue water in region i

WSI_i = regional water stress index in region i

WSI_{global}: global average water stress index (value 0.602)

In order to assess the impact of water consumption on human health (criterion A1) the method refers to the impact pathway of malnutrition due to a lack of irrigation water caused by water consumption. Based on regional specific data and considering damage factors for malnourished people, $DALY_{water}$ can be calculated (Pfister et al. 2009). The value of $DALY_{water}$ can then be added to DALY to get the total DALY value.

In order to assess ecosystem damage (criterion B10) caused by vegetation damage due to water shortage, net primary production (NPP) has been selected as a proxy of PDF. The damage to ecosystem quality (ΔEQ) at a site i can be estimated according to equation (4-11) by multiplying primary production due to water shortage ($NPP_{wat\text{-}lim}$) by the ratio of water consumption ($WU_{consumptive}$) to precipitation (P).

$$\Delta EQ_i = NPP_{wat-\lim,i} * \frac{WU_{consumptive,i}}{P_i} \tag{4-11}$$

$NPP_{wat\text{-}lim}$ is used as approximation for PDF. The ratio of $WU_{consumptive}$ to P reflects the area-time equivalent necessary to recover the consumed (blue) water by annual precipitation. In compliance to DALY ΔEQ can be added to PDF, too. Table 4-5 summarises the suggested midpoint indicators for blue water consumption and water deprivation.

Table 4-5: Indicators to address water in an LCA

Criterion	Name of impact category	Description	Unit of CF
	Blue water consumption	Input (ground water + lake water + river water + fossil ground water) – Output (ground water + lake water + river water + fossil ground water)	m^3
B5	Water deprivation	Water scarcity footprint (WSF) according to formula (4-10)	m^3

Within the ReCiPe framework the indicator **mineral resource depletion (B6)** is assessed based on data on marginal cost increase due to the depletion of a resource (grade decrease) using background data on worldwide deposits and commodity costs. These values are put into relation to those from iron leading to iron equivalents. Since only reliable values for 20 commodities are reported in the ReCiPe method, e.g. a CF for phosphate is missing.

Alternatively, the CFs for »abiotic depletion potential« developed within the CML 2002 method (Guinée et al. 2002) can be used to measure mineral resource depletion. Its choice is recommended by the Joint Research Centre of the European Union (JRC 2010d) and it covers phosphate. For this reason, it is selected and introduced in Table 4-6.

Table 4-6: Impact categories, indicator names and characterisation factor (CF) names for abiotic depletion in the CML method (Guinée et al. 2002)

Criterion	Name of impact category	Name of indicator	Name of CF	Unit of CF
B6	Abiotic depletion	Depletion of the ultimate reserve in relation to annual use	Abiotic depletion potential (ADP)	kg Sb-eq.

The method refers to data on reserves and extraction rates of resources instead of costs. In contrast to the ReCiPe method, the CF is weighted with the reference resource antimony instead of iron. Hence, the indicator result is expressed in kg of the reference resource antimony. Equation (4-12) is applied to calculate the abiotic depletion potential.

$$abiotic\ depletion = \sum ADP_i * m_i \quad ,with\ ADP_i = \frac{DR_i}{(R_i)^2} * \frac{(R_{ref})^2}{DR_{ref}} \tag{4-12}$$

ADP_i: abiotic depletion potential of resource i,

M_i: quantity of resource i extracted [kg],

R_i: ultimate reserve of resource I [kg],

DR_i: extraction rate of resource i [kg*yr.$^{-1}$],

R_{ref}: ultimate reserve of the reference resource antimony [kg],

DR_{ref}: extraction rate of R_{ref} [kg*yr.$^{-1}$].

The characterisation factor for **fresh water ecotoxicity (B7a)** refers to an updated version of the multimedia fate, exposure and effects model »Uniform System for the Evaluation of Substances Adapted for LCA« (USES-LCA) version 2.0 (Goedkoop et al. 2013). The midpoint characterisation factor for fresh water ecotoxicity includes the fate factor and the chemical-specific part of the effect factor.

Aquatic eutrophication is caused by nutrient enrichment of the aquatic environment and leads to an increasing production of phytoplankton (algae) and duckweed. In Europe freshwaters are typically limited by phosphorus, whereas nitrogen usually limits the production of algal biomass in marine waters (Crouzet et al. 1999). Therefore, one indicator is defined for **phosphor enrichment of fresh water (B7b)** and one for **nitrogen enrichment of seawater (B7c)**. Emission of N from a sewage treatment plant to fresh water (which will reach coastal waters) accordingly accounts for marine eutrophication and P emission from SWP to fresh water accounts for fresh water eutrophication (Goedkoop et al. 2013). The same applies to N or rather P emissions to soil and air from manure or fertiliser. NH_3 and NO_2 emissions into air are exclusively considered for marine eutrophication. As nutrient enrichment in water bodies leads to biodiversity losses a function describing this relationship is used to assess the endpoint indicator »loss of species during a year«.

4.2.3 Complementary sustainability indicators

Indicators referring to knowledge, physical capital, regional development, acceptance as well as labour rights are not covered by traditional LCA approaches since LCA was developed in order to assess environmental impacts of products and processes. In compliance with the Renewable Energy Directive (RED) (European Commission 2009a) the indicators **compliance to labour rights (A2)** and **exclusion of usage of high-quality landscapes (D5)** are suggested.

With regard to **compliance to labour rights**, the RED requires that biomass is only imported from countries that have ratified and implemented each of the following conventions of the International Labour Organisation (ILO) that have been identified by the ILO's governing body as being fundamental to the rights of human beings at work. Table 4-7 gives an overview about the fundamental ILO conventions according to the relevant issue.

Table 4-7: Eight fundamental ILO conventions to the rights of human beings at work (ILO 1930, 1957, 1958, 1951, 1948, 1949, 1973, 1999)

Issue	ILO convention
Freedom of association and collective bargaining	▪ Freedom of association and protection of the right to organise convention (No. 87) ▪ Right to organize and collective bargaining convention (No. 98)
The abolition of forced labour	▪ Forced labour convention (No. 29) ▪ Abolition of forced labour convention (No. 105)
Equality	▪ Discrimination (employment and occupation) convention (No. 111) ▪ Equal remuneration convention (No. 100)
The elimination of child labour	▪ Minimum age convention (No. 138) ▪ Worst forms of child labour convention (No. 182)

In compliance with the RED, the minimum requirements for human and labour rights as recommended by the Roundtable on Sustainable Biofuels (RSB) should be fulfilled (RSB 2010). The following RSB criteria are taken into account (RSB 2010, pp. 17–29):

- »Workers shall enjoy freedom of association, the right to organise, and the right to collectively bargain«
- »No slave labour or forced labour shall occur«
- »No child labour shall occur, except on family farms and then only when work does not interfere with the child's schooling and does not put his or her health at risk«
- »Workers shall be free of discrimination of any kind, whether in employment or opportunity, with respect to gender, wages, working conditions, and social benefits«
- »Workers' wages and working conditions shall respect all applicable laws and international conventions, as well as all relevant collective agreements. Where a government regulated minimum wage is in place in a given country and applies to the specific industry sector, this shall be observed. Where a minimum wage is absent, the wage paid for a particular activity shall be negotiated and agreed on an annual basis with the worker. Men and women shall receive equal remuneration for work of equal value«
- »Conditions of occupational safety and health for workers shall follow internationally-recognised standards«
- »Operators shall implement a mechanism to ensure the human rights and labour rights outlined in this principle apply equally when labour is contracted through third parties« (RSB 2010)

Suitable indicators to measure the compliance with minimum requirements are given by the RSB certification scheme (RSB 2010).

With regard to the criterion D5 »Exclusion of usage of high-quality landscapes«, the RED excludes the following types of land (European Commission 2009a, p. 37):

- »Primary forest and other wooded land, namely forest and other wooded land of native species, where there is no clearly visible indication of human activity and the ecological processes are not significantly disturbed«,
- areas designated: a) by law or by the relevant competent authority for nature protection purposes; or b) for the protection of rare, threatened or endangered ecosystems or species,
- highly biodiverse grassland,
- land with high carbon stock such as wetlands and forested areas.

Technical risks (AB3) which are caused by disturbances in transport and operation are usually neglected in LCA since it requires great effort, a good data basis (which is often missing), a regional context, and the possibility to quantify information (Klöpffer, Grahl 2009). Landscape destruction caused by accidents, for instance, cannot be quantified objectively since the evaluation of landscapes will always remain subjective. In addition, the allocation of risks to a functional unit is problematic since product components may run through many technical installations in their life cycle (Kurth et al. 2004).

In technical contexts, risks are often defined as product of »probability of occurrence« and »extent of damage«. Accordingly, the risk indicator is defined as shown in equation (4-13).

$$\text{Risk impact} = \text{probability of occurrence} \times \text{extent of damage} \tag{4-13}$$

In order to evaluate the risk impact more precisely, an indication of the uncertainties of these two influencing factors is useful.

Changes in **soil quality (B8)** are generally not included in LCA since they strongly depend on local conditions. One approach to integrate it in LCA was the development of the so called »Land use indicator value calculation« LANCA® tool that focuses on land use impacts on soil degradation (Beck 2010). Several soil properties are investigated, such as erosion resistance, mechanical filtration, physicochemical filtration, groundwater replenishment, and biotic production. Due to its high input data requirements it is very work-intensive and often not feasible. Several other authors suggested similar indicators in order to assess erosion regulation, fresh water regulation, and water purification which are important functions soil should fulfil (Saad et al. 2011; Baitz 2002). However, soil fertility also depends on further soil properties such as soil organic carbon (SOC) and nutrient content. SOC is the most reported soil attribute because it is related to many other soil quality indicators such as cation

exchange capacity or soil life activity. It is assumed that - as a result of land use changes due to human activities - most agricultural soils now contain lower SOC pools than their potential (Milà i Canals et al. 2007b). Since no generally accepted criteria and indicators for measuring changes in soil quality exist, case-related indicators should be selected taking into account the goal of investigation with regard to regional conditions.

Another difficult question is how to measure the **development of physical capital (C1)** which can contribute to present and future social welfare. In order to assess the present contribution of a product to social welfare, the costs of a product in comparison to its benefit might be a useful indicator (cost-benefit ratio). Since products from biorefineries will mainly replace conventional (fossil-based) products, the cost-benefit ratio of conventional products should be compared to bio-based products produced by biorefineries. Based on the assumption that the benefits of bio-based products are equal to those of conventional ones, it is sufficient to only compare the estimated production costs of conventional products with bio-based products.

However, most biorefinery technologies are still only available on laboratory or pilot scale and there is a high uncertainty in process-related data (Stuart, El-Halwagi 2013). Crucial process-related uncertainties are the conversion efficiency of biological processes, the recycling rate of chemicals and bio-chemicals in large-scale production, and the scale-up of purification and separation systems in commercial production (Stuart, El-Halwagi 2013). Principally, for calculating production costs data is needed for capital expenditures (CAPEX) and operating expenditures (OPEX). CAPEX consists of fixed capital investment (FCI) and working capital investment which can be calculated directly from the plant design. In case of missing information a couple of methods are available to estimate CAPEX (Sinnott 1999). Lange suggested estimating FCI of chemical plants on the basis of total rated power of the process equipment (Lange 2001). In the European-funded project »Biocore« (Piotrowski et al. 2013) the formula of Lange was converted into equation (4-14).

$$\text{FCI [Mill. EUR 2010]} = 3.3 * \text{Rated Power [MW]}^{0.55} \qquad (4\text{-}14)$$

Based on FCI, CAPEX can be estimated by adding 4 % for working capital: CAPEX=FCI*1.04 (Piotrowski et al. 2013). According to Turton et al., OPEX can be estimated based on the following variables: 1) FCI, 2) cost of operating labour (COL), 3) cost of utilities (CUT), and cost of raw materials (CRM) (Turton et al. 2012). All variables apart from operating labour costs can be derived from material and energy balances of a biorefinery. In order to estimate OPEX that consists of direct costs, fixed costs, and general expenses multiplication factors can be applied to the four variables mentioned. Multiplication factors useful for biorefineries are presented in (Piotrowski et al. 2013). Based on CAPEX and OPEX along with an estimation of future revenues, the net present value (NPV)

of a biorefinery can be estimated. In case of a positive NPV the investment is feasible even though an investment in conventional technology might be favourable due to a higher net present value. The NPV is calculated according to equation (4-15).

$$NPV = -C_0 + \sum_{i=1}^{T} \frac{C_i}{(1+r)^i} \tag{4-15}$$

with C_o= initial investment; C= cash flow, r= discount rate, and T= time.

In order to allow a fair comparison, future cost degressions should be considered, e.g. those achieved by scaling effects or by process optimisation. Cost degressions can be estimated for example by applying learning curves and choosing a future reference year such as 2030 (Fritsche et al. 2011).

Apart from methodological challenges, in particular data availability is often problematic. Even cost information for conventional products already on the market is often hard to access.

Apart from direct economic impacts, the good education of developers and workers is a crucial prerequisite for a successful economy. **Education of scientists and qualified workers (C2)** strongly depends on activities contributing to education. Possible activities are:

- Academic qualifications (e.g. bachelor, master or PhD)
- Vocational training
- Training courses, workshops, seminars
- Web-based information platforms, leaflets

These kinds of activities referring to the construction and operation of a biorefinery should be quantified.

The **generation of new knowledge and innovation capacity (C3)** is closely related to education. New knowledge and innovation capacity could be measured as number of publications or patents in a field published during a certain time period. Apart from publications and patents the increase in new knowledge and innovation capacity will probably correlate with RTD expenditure and/or private investments during development, construction, and operation of a biorefinery. For collecting relevant information, Table 4-8 can serve as record sheet. The recorded figures can be applied for a direct comparison.

Table 4-8: Key indicators for assessing new knowledge and innovation capacity

Key Indicator	Number per year	Increase	Region
Publications [-]			
Patents [-]			
RTD expenditure [€]			
Private investments [€]			

In order to assess **employment effects in rural areas (D1)**, which includes creation or preservation of work places, area-related manpower requirements for providing biomass (E_B) should be assessed as well as manpower requirements for operating a biorefinery (E_O) if located in rural areas. In contrast to the production of non-bio-based goods, the production of agricultural products is strongly limited by the availability of cultivation land. That means an expansion of land dedicated to the production of energy crops often goes along with a reduction of land intended for food or feed production. Hence, the amount of workplaces also depends on the work intensity of land management (Distelkamp et al. 2011). That is the reason why manpower requirements should be assessed in relation to the cultivated area. For calculating the total manpower requirements equation (4-16) can be used.

$$Employment\ \ effects = E_B + E_O \tag{4-16}$$

Further employment effects are supposed to be generated in the RTD sector and are linked to construction works. However, these employment effects only last for a short while and not necessarily take place in rural areas.

In order to get a statement about the quality of jobs, the qualification level of the jobs created or retained can be assessed additionally. Qualification levels can be defined based on the required educational level as defined in the International Standard Classification of Education (ISCED) (UNESCO 1997; Sellke et al. 2011). The ISCED standard comprises seven levels of education (UNESCO 1997), whereas the first three levels »pre-primary education«, »primary education«, and »lower secondary education« can be grouped together to reduce the amount of education levels. Depending on data availability further grouping is possible. If multinational enterprises are operating in developing countries the principals as recommended by the Tripartite Declaration and listed in Table 7-26 in appendix II should be taken into account.

A suitable indicator to assess the improvement of the **security of supply in a region by biorefineries (D2)** is to measure the regional (future) market share of bio-based products. The market share can be expressed according to equation (4-17) as ratio of the amount of annually sold products (m to n) from a

biorefinery P_B to the amount of annually sold conventional products P_R (reference) in a defined region.

$$Market\ share = \frac{\sum_{i=m}^{n} P_{B(i)} * 100}{\sum_{i=m}^{n} (P_{R(i)} + P_{B(i)})}, \tag{4-17}$$

with m to n products.

It should be mentioned that biorefineries using imported biomass such as wood as feedstock may not increase the regional supply safety since they depend on imports, too.

In order to protect and support biomass producers such as small farmers especially in developing countries, it should be analysed in addition whether biomass trade complies with the following **fair trade principals**[26] **(D3)**:

- creating opportunities for economically disadvantaged producers,
- fair prices for growers (farmers receive a fair, market-based price for their crops),
- safe and good working conditions (also covered by ILO standards),
- democratic decision-making.

In order to address the **acceptance of biorefineries (D4)** the willingness to buy their products can be assessed. The willingness to buy a product can be estimated e.g. through a survey among households and is expressed in a monetary value such as Euro. Acceptance may be also increased through participation of stakeholders for example in site location search.

In order to **preserve natural landscapes (D5)** with individual characteristics and beauty, raw material obtained from land with high biodiversity value should not be used. Landscape areas worthy of protection are for example primary forest and other wooded land, highly biodiverse grassland or further threatened or endangered ecosystems. This claim goes along with the requirements regulated by DIRECTIVE 2009/28/EC in article 17 that apart from the protection of valuable areas and biodiversity they also contribute to the preservation of natural landscapes with individual characteristics and beauty.

In addition, the use of land for energy and materials should not endanger the **food security (D6)** in a region. To ensure that, it has to be initially checked if people living close to cultivation areas suffer from hunger. This requirement can be indirectly investigated, for instance, through analysing the child mortality in that region. If there are hints that people suffer from hunger the impacts of cultivating biomass for biorefineries should be investigated closer. Positive or

[26] World Fair Trade Organization (2009) 10 standards of fair trade, available at: http://www.wfto.com/index.php?option=com_content&task=view&id=2&Itemid=14.

negative effects on food security cannot be measured for certain since apart from the availability of food in a region the physical and economic access to sufficient food e.g. affected by the distribution of incomes, food prices or the efficiency of food distribution network as well as 2) local conditions such as hygiene, water quality, and health care strongly influence the food security. Furthermore, the stability of markets e.g. affected by weather events influences food security (FAO 2012; ECOFYS 2013). Potential benefits for food security or risks to food security in a region can be assessed by using the multiple indicator gained from the »operator level food security assessment tool«[27] provided by the Food and Agriculture Organization of the United Nations (FAO) (FAO 2012). The tool addresses indicators referring to 1) changes in the supply of food to the domestic market, 2) resource availability and efficiency of use, and 3) physical displacement, change in access to resources, compensation and income generation.

An overview about all sustainability indicators referring to the sustainability criteria proposed in Table 4-2 is shown in Table 4-9. The indicators are assigned according to the structure introduced in chapter 4.1.4.

Table 4-9: Sustainability indicators for biorefineries

Category	Cluster	Assign-ment	Name of indicator	Unit
A Impacts on human health and **B** on environment	Risks	A.1	Disability adjusted life-years (DALYs)	Years
		A.2	Compliance to human and labour rights	Yes/no
		AB.3	Risk impacts	[-]
	Material flows	B.1	Fossil energy savings (oil equivalent, $KNRA_{foss}$)	kg oil equivalent, MJ
		B.2	Required land differentiated according to land use type	m^2*yr.
		B.3	Terrestrial acidification, PM_{10} intake, photochemical oxidant formation, ozone depletion	kg SO_2-, PM_{10}-, NMVOC-, CFC-11-eq.
		B.4	Infra-red forcing	kg CO_2-eq.
		B.5	Water deprivation	m^3*WSI
		B.6	Minerals consumption	kg Sb-eq.
		B.7	Fresh water ecotoxicity, fresh water and marine eutrophication	kg 1,4-DB-eq., kg P-eq.

[27] The Operator level food security assessment tool is available online at: http://www.fao.org/energy/befs/operator-tool/en/

Category	Cluster	Assign-ment	Name of indicator	Unit
	Agri-culture and eco-system	B.8	Change in soil characteristics (SOC, mineral content, physical attributes)	%*yr.$^{-1}$
		B.9	Potentially disappearing fraction (PDF)	Species*yr.
C Knowledge and physical capital	Physical capital	C.1	Relative additional costs compared to reference	%
	Human and know-ledge capital	C.2	Educational activities	Numbers
		C.3	Publications, patens, RTD expenditure and private investments during development, construction, and operation of a biorefinery	Numbers, €
D Regional development and acceptance	Reg-ional eco-nomy and supply	D.1	Manpower requirements for providing biomass plus manpower requirements for operating a biorefinery especially in low-infrastructure regions	Manpower requirements per ha
		D.2	Market share of bio-based products related to fossil counterparts (in the future)	%
		D.3	Compliance to fair trade principals	Qualitatively
	Accept-ance	D.4	Willingness to buy bio-based products	€
		D.5	Exclusion of usage of high-quality landscapes (anthropogeneous)	Yes/no
		D.6	Multiple indicators: case-specific analyses	-

4.3 Instruments to evaluate sustainability impacts of biorefineries

An analytical method to quantify flows and stocks of materials or substances in a well-defined system is the **material flow analysis (MFA)**. MFA was developed in the field of industrial ecology in order to assess the physical consequences of human activities on nature (Fischer-Kowalski 1998). MFA is complementary to **life cycle assessment (LCA)** which is a common methodology to determine the potential environmental impacts of products, processes, and technologies across the entire life cycle and the comparison of their environmental performance (JRC 2010c; Finnveden et al. 2009). LCA is standardised through the ISO standards 14040 and 14044 (DIN EN ISO 14040; DIN EN ISO 14044) and is the only internationally standardised environmental

assessment method. In order to specify these broad ISO standards, the international reference life cycle data system (ILCD) provides a common basis for consistent, robust, and quality-assured life cycle data and studies (JRC 2010a). In recent years it has become increasingly popular to calculate greenhouse gas (GHG) balances which are called **product carbon footprints (PCF)** and are regulated additionally through ISO14067 »Carbon Footprints of Products« (DIN ISO 14067). Moreover, LCA has been used more and more for assessing the environmental performance of biofuels and bioenergy as well (Rettenmaier et al. 2010). However, LCA is not appropriate to address local impacts because it does not provide the framework for a comprehensive local risk assessment study, identifying which impacts can be expected due to the operation of a facility at a specific site (Guinée et al. 2002). In addition, LCA typically is a steady-state approach[28] and future technological developments can only be assessed through scenarios. In order to assess future impacts of technologies several instruments for **technology assessment (TA)** were suggested such as historical analogy, delphi expert opinion survey, morphological analysis, relevance tree analysis or cross-impact analysis which are summarised in the VDI guideline 3780 »Technology Assessment Concepts and Foundations« (VDI 3780). In order to address local environmental impacts, **environmental impact assessments (EIA)** were developed mainly to explore the possible environmental effects of a proposed project. Principally, the expected environmental effects of a project are compared to the environmental effects of alternative actions or no action. In the EU, the EIA is regulated in the Council Directive 85/337/EEC of 27 June 1985 (EU 1985) which is mandatory to carry out for certain public and private projects. The EIA Directive was amended by the Directives 97/11/EC, 2003/35/EC and 2009/31/EC. Nevertheless, the choice of methods how to evaluate local environmental impacts within an EIA is not regulated.

In order to assess further social impacts of products, the Society of Environmental Toxicology and Chemistry (SETAC) and United Nations Environmental Programme (UNEP) have suggested guidelines for **social life cycle assessment (SLCA)** of products (Andrews et al. 2009). In addition, several tools to assess economic impacts such as **life cycle costing (LCC)**, full cost accounting (FCA) and total cost assessment (or accounting) were suggested (Norris 2001; Hunkeler, Rebitzer 2003). These economic impacts can be put into relation to environmental impacts, for instance assessed by LCA. The ratio of economic indicators to environmental indicators can be analysed through an **eco-efficiency analysis (EEA)** as proposed by the World Business Council for Sustainable Development (Verfaillie, Bidwell 2000), further developed by BASF (Saling et al. 2002) and ISO-standardised in ISO 14045 (DIN EN ISO 14045). Next to key business indicators, macroeconomic effects such as effects on employment may be analysed by **macro-economic analysis (MEA)** which is not a standardised method. Besides, accepted instruments to measure impacts on human or knowledge capital are still missing. A summary of the instruments

[28] All state variables are constant.

according to the subject of study and assignment to the impact categories proposed in chapter 4.1.4 is given in Figure 4-9.

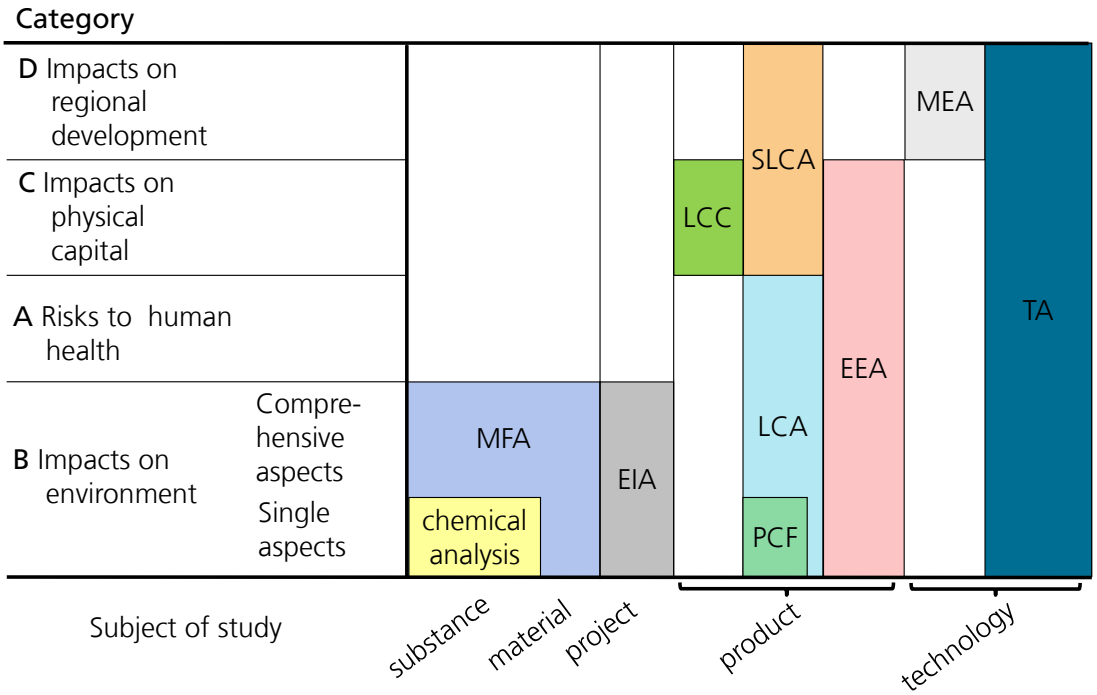


Figure 4-9: Instruments to measure sustainability impacts of biorefineries

Against the background of the instruments mentioned, in the following chapter appropriate instruments will be suggested to measure sustainability impacts of biorefineries. However, some indicators exclusively count on statistical and literature data.

4.3.1 Life cycle assessment

Life cycle assessment according to ISO 14040 and 14044 includes four phases as illustrated in Figure 4-10 and is applied to address impacts of biorefineries on human health and on the environment. The LCA covers the indicators A1, B1-B8, and B10 suggested in Table 4-9 in chapter 4.2.3.

The **goal and scope definition** phase determines the boundaries of the investigated system, the level of detail for the LCA, the allocation method and functional unit for the calculations, and the life cycle impact assessment (LCIA) categories to be examined. The following key methodological issues and assumptions are applied for assessing the environmental impacts and impacts on human health of biorefineries.

Goal: The goal of an LCA study on biorefineries could be to analyse if, with regard to environmental impacts and impacts on human health, the investigated biorefinery concept or existing conventional technologies are favourable to produce a spectrum of products. A complementary question

might be to balance emissions into soil, water, and air that can be saved by replacing conventional products by bio-based ones. Another goal could be to answer the question which biorefinery concept is environmentally most favourable to produce a specific product or service. A comparison between different biorefinery concepts in general is not appropriate because the product portfolio is different in most cases (Fritsche et al. 2011).

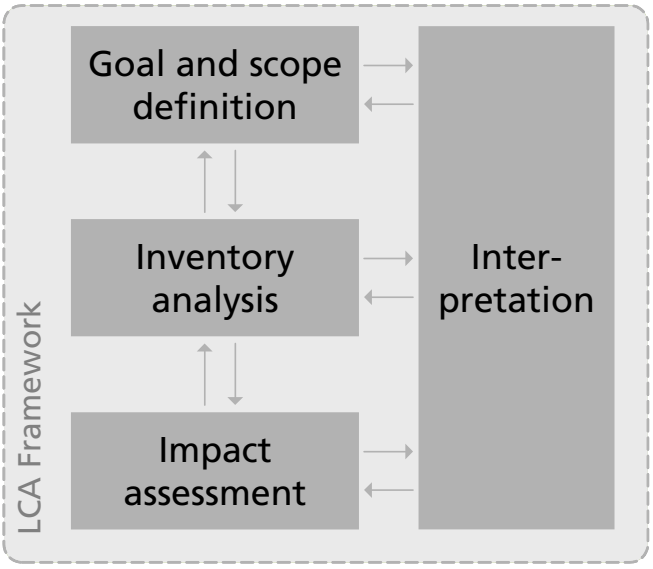


Figure 4-10: Methodological LCA approach according to ISO 14040 and 14044

Scope: Principally, following the idea of life cycle thinking[29] as promoted by the EU Commission, the entire life cycle of biorefinery products should be taken into account covering cultivation, harvesting, biomass processing, utilisation, and, if necessary, disposal. Since the choice of system boundaries can have a strong influence on the result and can lead to misleading conclusions, system boundaries should be regarded carefully (JRC 2010b). One method to systematically and quantitatively set the system boundaries is the relative mass, energy, and economic value (RMEE) protocol that was proposed by Raynolds (Raynolds et al. 2000). Before setting system boundaries data is gathered e.g. about biomass provision and primary and secondary refining processes. Data includes for example information about consumption of energy and materials or emissions released by each process. A predefined cut-off ratio is then applied to the functional unit on the basis of mass, energy, and economic value.

Allocation method: The allocation method should fit to the question defined by the goal. Since biorefineries are characterised by multiple final products (energetic and material ones), there is no objectively justifiable allocation method. The ISO standards suggest firstly avoiding allocation by dividing the unit process into two or more subprocesses or secondly by expanding system boundaries if possible (ISO/TR 14049; DIN EN ISO 14040; DIN EN ISO 14044).

[29] Homepage European Platform on Life Cycle Assessment: http://eplca.jrc.ec.europa.eu

Since dividing the unit process is often impossible due to lacking information, system expansion is the most applied method in reviewed LCA biofuels studies (Pandey et al. 2011). In the case »where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them« (DIN EN ISO 14044, p. 29). Following the methodology stipulated in the Renewable Energy Directive (RED) (European Commission 2009a) for calculating greenhouse gas emissions of biofuels, the life cycle impacts of producing biofuels are allocated by the lower heating value. However, an allocation by the heating value for material products, food or feed does not seem to be adequate. But an allocation by mass is problematic as well due to possible great differences in the relation of price and mass. An allocation based on market value can be misleading, too, since the market value of products and services is highly variable over time.

Therefore, a suitable way to deal with this problem is the expansion of the system boundaries as recommended by ISO 14044 (DIN EN ISO 14044). That means the additional functions related to the co-products are included. This approach is illustrated in Figure 4-11.

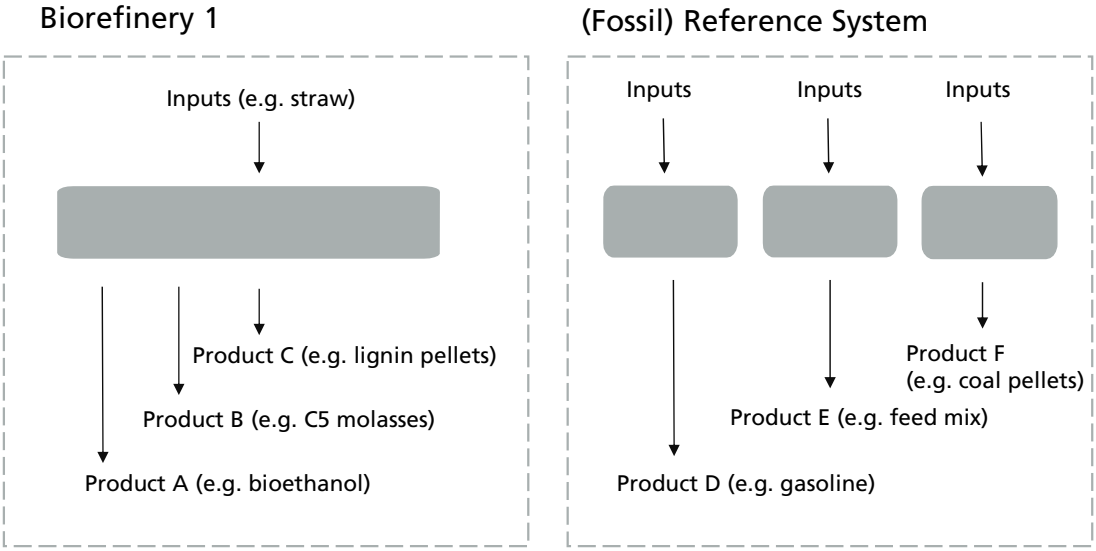


Figure 4-11: Methodological approach to compare a biorefinery concept with a (fossil) reference

In order to assess the environmental performance of a biorefinery product (e.g. biofuel) compared to a conventional product (e. g. fossil fuel) either a system expansion or an allocation considering the co-products of the production system has to be conducted (ISO/TR 14049). In the case of system expansion the so called »avoided burden« approach, also referred to as »credit« method, can be applied. In this method the expanded part represented by the complementary product is subtracted from the overall system so that only the product of focus is left. This approach is illustrated in Figure 4-12.

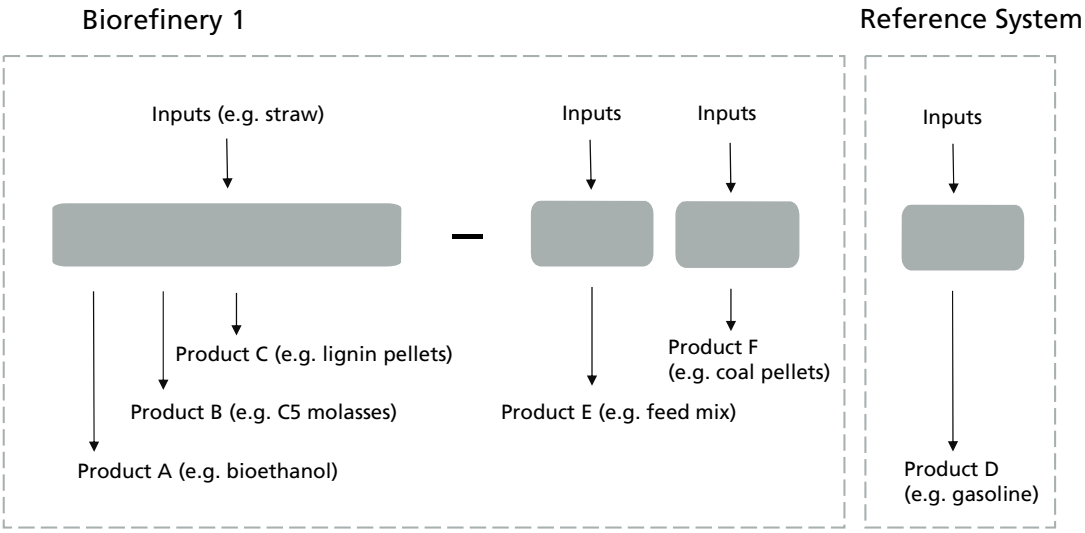
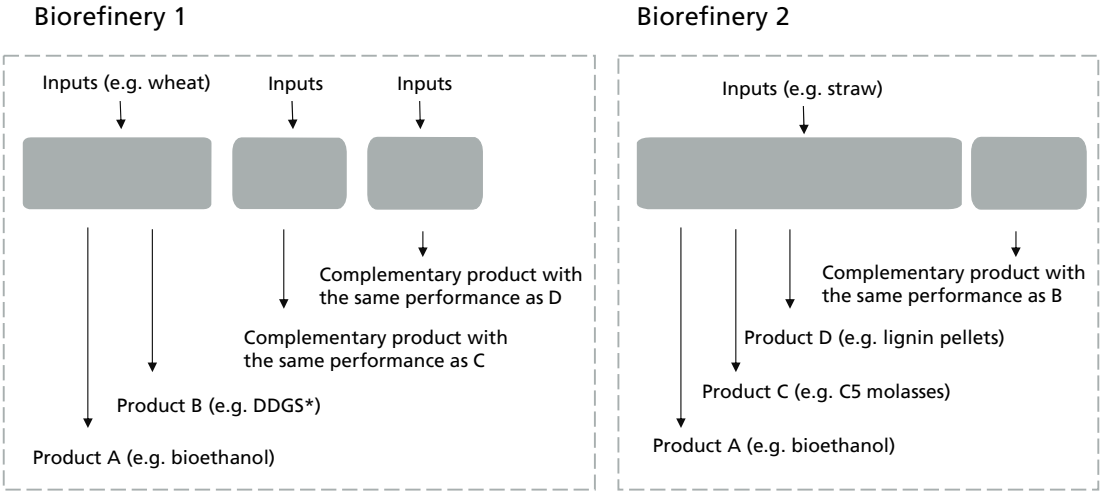


Figure 4-12: Avoided burden approach to compare a biorefinery concept with a (fossil) reference

Nevertheless, an allocation might be reasonable to avoid too large and complex systems. The allocation can be conducted on a proportion of quantities such as mass and volume or on the basis of energy or exergy content. If physical relationships are not suitable e.g. due to great differences in value, allocation should be made on the basis of economic values such as costs or prices.

If the question occurs which biorefinery concept is environmentally most favourable to produce a specific product, the product system of both biorefineries has to be expanded including the missing benefits that are additionally produced in the other biorefinery. Hence, the two biorefinery concepts to be compared have to fulfil the same performance. This approach is illustrated in Figure 4-13.



* Distillers' dried grains

Figure 4-13: Methodological approach to compare two biorefinery concepts producing the same product (e.g. bioethanol)

As the choice of allocation method has a huge influence e.g. on the calculated energy demand and greenhouse gas emissions of biofuels (Gnansounou et al. 2009), a sensitivity analysis should be carried out.

Functional unit: If a biorefinery concept is compared with a (fossil) reference the functional unit »amount of products produced per year« should be used. If only one product is regarded the functional unit has to refer to the investigated product.

Reference system: Against the background that biorefineries will mainly replace fossil-based products in order to decarbonise the industrial economy, biorefinery systems should be compared with a »theoretical« fossil reference system producing the same amount of products and services. If there exist no fossil-based reference products e.g. if a biorefinery produces food or feed, it is also possible to compare these products with the conventional production of food and feed as it is usual today.

Life cycle impact assessment (LCIA): As mentioned in chapter 0, there are a lot of LCIA methods to evaluate environmental effects. An overview about existing LCIA methods is given in Table 7-28 in appendix II. Most LCIA methods focus only on midpoint indicators. In contrast, the ReCiPe method developed by (Goedkoop et al. 2013) which is a follow-up of Eco-indicator 99 and CML 2002 methods, integrates and harmonises the midpoint and the endpoint approach in a consistent framework (JRC 2010a). Within this approach nearly all impact categories have been redeveloped and updated in the last years. In addition, in 2011 the ReCiPe method was integrated into the software »Ganzheitliche Bilanzierung« GaBi, version 4.4.131, service pack 18.

An overview about the LCIA categories assigned to midpoints and endpoints (area of protection) and mostly captured by the ReCiPe method is illustrated in Figure 4-14.

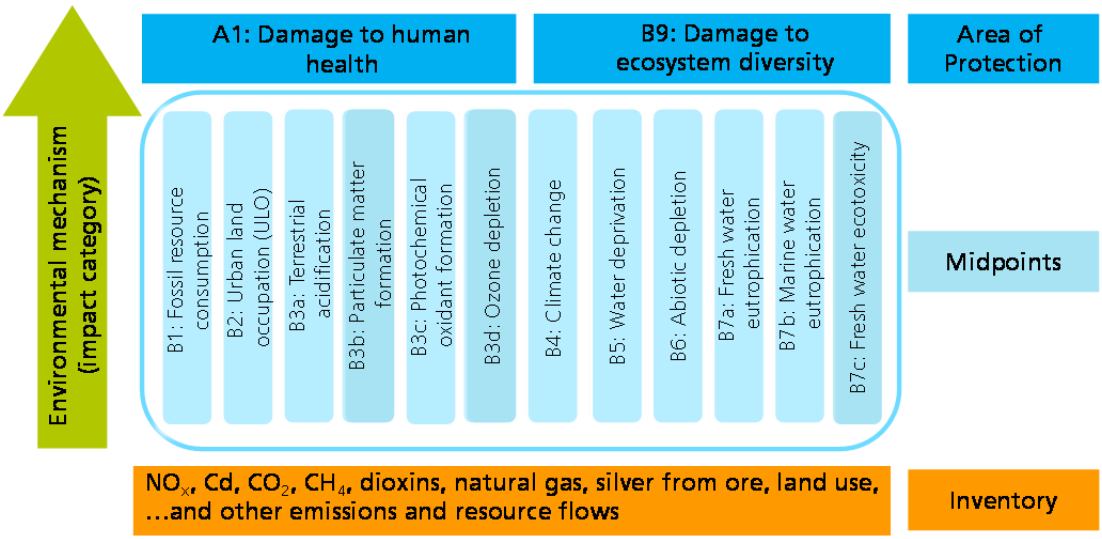


Figure 4-14: Impact categories covered by the LCA approach in the style of (JRC 2010c); bottom: LCI, middle: midpoint indicators, top: area of protection

The adjusted ReCiPe-method is illustrated in Figure 4-15. The representation sketches the relations between the »LCI result«, the environmental mechanism that equals to the impact category, the midpoint indicator, and the endpoint indicator that corresponds to the areas of protection of »human health«, »resources«, and »ecosystems«. Since the indicator »water deprivation« (B5) is not covered by the ReCiPe method, it has to be calculated separately. Besides, impacts of water deprivation on endpoint level (DALY and PDF) have to be integrated into the ReCiPe method.

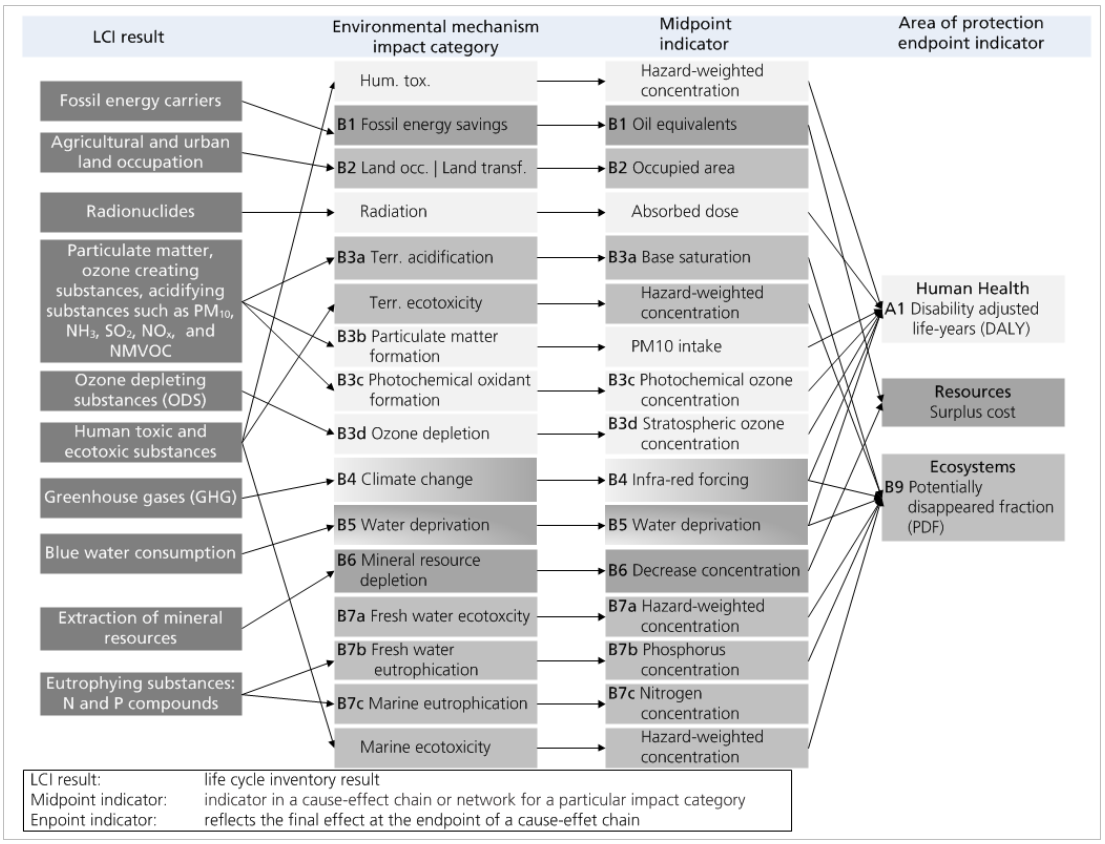


Figure 4-15: Indicators captured by the adjusted ReCiPe method

Looking at the greenhouse gas balance of biorefineries non-CO_2 emissions from soils should be taken into account. This includes N_2O emissions which evolve from nitrogen fertiliser application and organic matter decomposition in soil and can have a strong influence on the GHG balance (Cherubini, Strømman 2010). The contribution of N_2O emissions to the GHG balance vary very strong depending on local situations such as soil type, climate, crop or tillage method. N_2O emissions have a greenhouse effect which is 298 times higher than CO_2 (IPCC 2007). Further attention should be paid if agricultural residues are used as raw material in a biorefinery. One way to consider the removal of residues is to assume that a part of residues remains in the field to prevent negative effects on soil quality. The other possibility is to assess environmental effects caused by residual removal by making up a balance of a reference use for agricultural

residues. A reference use might be the application of residues as fodder or the application on the field to provide organic matter and nutrients to the soil.

Possible normalisation and ranking of results: In order to prioritise environmental impacts, weighting factors developed for life cycle assessment can be applied. Such weighting factors have been defined at midpoint and endpoint level or are based on integrated modelling approaches by economists (Huppes et al. 2012). Weighting methods either address individual or collective preferences and relate to either revealed or stated preferences. Each method has advantages and disadvantages and all suffer from inconsistency and incompleteness. According to ISO 14040, »there is no scientific basis for reducing LCA results to a single overall score or number since weighting requires value choices« (DIN EN ISO 14040). Therefore, »weighting shall not be used in LCA studies intended to be used in comparative assertions intended to be disclosed to the public« (DIN EN ISO 14044).

Examples of weighting sets at midpoint level are the »building for environmental and economic sustainability« BEES method (Lippiatt 2007), the method developed by the Netherlands Oil and Gas Exploration and Production Association (NOGEPA) (Huppes et al. 2007) or the survey conducted by PE International in 2012 (PE INTERNATIONAL 2012b). They are based on different expert panels and are summarised in Table 7-29 in appendix II.
As these weighting factors reflect collectively stated preferences, they might be used for the decision of prioritisation. They can be also used in combination with a previous normalisation to get a single indicator such as Eco-indicator 99 (Goedkoop, Spriensma 2000). Alternatively, monetarisation methods can be applied such as the EPS-method (Steen 1999), Eco-Costs ’99 (Vogtlander, Bijma 2000), Stepwise 2006 (Weidema 2009) or ExternE (AEA Technology, Metroeconomica 2005). All these methods allow calculating a monetary value for impacts that are usually not considered in profitability analyses. In this way different options become comparable although transparency is getting lost caused by weighting methods which are complex and difficult to understand.

The **life cycle inventory (LCI)** phase lists all relevant process inputs such as energy or materials and outputs such as products, waste, and emissions for each intermediate step of the entire chain of production. The amounts calculated should refer to the defined functional unit.

In the **life cycle impact assessment (LCIA)** phase, the LCI data are used to calculate the environmental impact categories such as fossil fuel depletion, climate change, fresh water eutrophication etc. by means of characterisation factors. The environmental impact categories suggested for analysing biorefineries were summarised in Table 4-4 in chapter 4.2.2.

In the **interpretation phase**, the results of LCIA are discussed and interpreted with regard to the goal of the study. Significant impacts and influencing factors are identified and regarded in more detail through sensitivity analyses. In particular, the quality of the results is evaluated by analysing uncertainties. Three types of uncertainty are of particular importance (JRC 2010c):

- Stochastic uncertainty,
- uncertainty due to the choice of assumptions in goal and scope,
- lack of knowledge of the studied system and future developments.

Stochastic uncertainty of final results can be assessed either through an analytical solution considering the distribution of each process data or through simulation. In LCA Monte-Carlo Simulation is an especially suitable method to consider stochastic uncertainty. Choice uncertainties result from the choice of assumptions such as system boundary settings, LCI modelling principles, choice and availability of LCI data sets to viably represent the background processes, and choice of LCIA methods. A pragmatic approach to handle it is to define a »reasonably best case« and a »reasonably worst case«. The third type of uncertainty results from the lack of knowledge about the system. This uncertainty can be addressed, for instance, by performing a qualified peer review and through the integration of experts. However, if future systems are modelled there will always remain some uncertainty. Finally, the results are used to derive recommendations for action.

4.3.2 Complementary instruments and information to evaluate additional sustainability effects

This chapter describes instruments or tools that can be applied to measure additional sustainability effects not already covered by LCA methods. Since no specific tools exist for some indicators, not all additional indicators are addressed in this chapter.

Social life cycle assessment (sLCA) can be applied to measure and to manage the compliance to human and labour rights (criterion A2). Social impacts in the field of labour can occur along the entire production chain of biorefinery products. In contrast to environmental impacts, impacts on people are related to the conduct of companies engaged in the product chain (Dreyer et al. 2010). An efficient method to check if labour and human rights are of interest is to identify critical aspects in the value chain by using the social hotspots database[30] (Benoit et al. 2010). If problematic conditions are detected in a relevant region and type of company, a more detailed analysis should be conducted. An appropriate instrument to measure impacts on people is social life cycle assessment (sLCA) as suggested by (Dreyer et al. 2010). Only those impacts on people are considered which can be influenced by the company, e.g. a biorefinery operator. Since violations of labour rights occur in many different ways and extent and are very complex to measure, a multi-criteria indicator model to assess the company performance was suggested (Dreyer et al. 2010). This model refers to the fundamental ILO conventions as introduced in Table 4-7 in chapter 4.2.3. It includes four impact categories, namely: 1) forced labour 2) child labour, 3) discrimination, and 4) restrictions of freedom of association,

[30] Social Hotspots Database website: http://socialhotspot.org

right to organise, and collective bargaining. Based on these impact categories the performance indicators 1) abolition of forced labour, 2) minimum wages for employment, 3) non-discrimination, and 4) freedom of association/right to organise, and collective bargaining were defined. In order to manage these aspects and reduce the risk that violations actually occur, for each indicator the management effort (will and ability to integrate managerial measures) of an involved company should be scored (Dreyer et al. 2010). In order to successfully implement such a management system in a company, relevant and managerial measures have to be identified and established in the company. This also includes the communication and delegation of responsibilities for compliance and an effective control mechanism (Jørgensen et al. 2008).

In order to measure the risk impact to nature and humans (criterion AB3), a **risk analysis** based on an analysis of conditions and consequences can be applied (VDI 3780). The central event is the failure of a system which is assigned to a certain probability of event. Using a fault tree analysis and accident sequence analysis respectively the overall probability of failure from partial probabilities of component failure is assessed taking into account connections between components. The analysis of consequences (risk level) investigates the different chains of damaging effects by assigning to the impact (extent of the damage) and the likelihood of consequences.

As a basis for managing risks, the »risk priority« can be calculated by dividing a calculated risk level by the estimated control effort of the risk. A table as follows systematically can be used as a useful tool to define and illustrate risk priorities.

Type of risk	Impact (I)	Likelihood (L)	Risk level (R= I*L)	Control effort (C)	Risk priority (R/C)

Apart from these pragmatic approaches, risk impacts might be assessed in LCA. This could be done by further developing the suggested endpoint indicators DALY and PDF since accidents will probably influence human health and ecosystem quality. Nevertheless, an accepted model is still missing. Alternatively, new impact characterisation factors (risk indicators) could be developed which describe specific technological risks. Such a new characterisation factor was developed to assess the impact of released genetic modified organisms (Klöpffer et al. 2001). With regard to risks associated with fossil fuels, a database from Intertanko[31] can be used to assess the worldwide probability of oil transport accidents by ship and Concawe offers data of pipeline incidents in Europe (Burton, den Haan 2011). However, the impacts of oil spills on human health and environment still remain unclear.

[31] Website of Intertanko: http://www.intertanko.com

In order to estimate and to compare the total cost of assets in their life cycles, **life cycle costing (LCC)** can be used (criterion C1). According to BS ISO 15686:5, LCC is a »methodology for the systematic economic evaluation of the life cycle costs over the period of analysis, as defined in the agreed scope« (BS ISO 15686-5:2008). In general, the following four main cost categories are assessed: investment (construction), operation, maintenance, and end-of-life disposal expenses. In contrast to whole life costs (WLC), LCC excludes non-construction costs[32], income, and external environmental costs[33] (BS ISO 15686-5:2008). To be consistent, ideally real and discounted costs (for future payments) should be used.

Apart from the products' performance of costs and revenues, their acceptance has a huge influence on the market penetration. There are different methodological approaches to examine the market acceptance of products, e.g. qualitative research, interviews with different stakeholders via various media, surveys or literature reviews. In order to address a high number of possible consumers with reasonable effort, a **quantitative online survey** is an appropriate method. It can be used to assess the willingness of consumers to buy a product (criterion D4). Such a standardised empirical approach offers a high reliability of statistical results and advantages regarding data evaluation (Raithel 2006; Schnell et al. 2005). Nevertheless, a representative sample from a defined population is necessary to obtain valid scientific results which is – according to relevant literature – hardly possible for a web survey in a scientific context (Schnell et al. 2005; Wilde et al. 2008). Therefore, results derived from online surveys should be interpreted with care since it can merely be an approximation to reality rather than a generalisable empirical result (Hoek 2012).

4.4 Dealing with conflict of aims

Sustainability objectives – as codified by the substantial sustainability rules and introduced in chapter 2.6 in Table 2-1 – may be in conflict with each other. Environmental impacts addressed by LCA might be weighted and ranked as described in 4.3.1. In order to prioritise all identified goals of sustainability, criteria might be evaluated according to the level of intersubjectivity or the moral persuasion of a society (Kopfmüller et al. 2001). In particular criteria that are essential for human life are of greater importance than further requirements. Accordingly, human health, impacts on biodiversity and ecosystems, food security as well as availability of water are of particular

[32] Non-construction costs are e.g. site costs, taxes on non-construction items, marketing expenses, interest payments, and finance charges.

[33] External costs are not included in what the business bases its price on. In economics, an externality is a »cost or benefit which results from an activity or transaction and that affects an otherwise uninvolved party who did not choose to incur that cost or benefit« (Spellman 2015, p. 233).

importance. Since the endpoint indicators DALY – that refers to human health – and PDF – that is assigned to impacts on biodiversity and ecosystems – refer to central areas of protection they should get the highest priority. As shown in Figure 4-15 in chapter 4.3.1 these two indicators already consider most of the other midpoint indicators addressed by LCA. Even the indicator »water deprivation«, as introduced in chapter 4.2.2, contributes to these two endpoint indicators.

The need for food security is closely linked to impacts on human health which among other aspects depends on the protection of soil, availability of water, and increasingly on impacts of climate change. Besides, the compliance to human and labour rights directly influences human health. Other harmful emissions into the air and water are usually limited to certain areas and are therefore ranked lower. Depending on the nature of technological risks, they might be ranked higher or lower depending on their influence on human health.

For future generations in particular the availability of fossil resources and minerals will probably play a great role. In contrast to this area efficiency and preservation of cultural heritage will be of less importance. Economic power, education and acceptance affect the life of today's people and societies strongly, whereas new knowledge or the supply safety of a region will probably be more important in the distant future.

Apart from these considerations the opinions of experts are regarded in the context of bioenergy systems. A comprehensive ranking of social, economic, and environmental criteria for bioenergy systems was carried out by (Buchholz et al. 2009). 46 experts were requested to rate the importance of different criteria for assessing the sustainability of bio-energy systems. They could choose between low, medium, high, and critical, with critical meaning mandatory to include it in a sustainability assessment. The average rating of importance of the selected criteria assigned to the categories A to D which were defined in chapter 4.1.4 is shown in Figure 4-16.

According to the expert survey impacts on global warming (B.4), saving fossil resources (B.1), and protection of soil (B.8) are the most important criteria. This means the majority of experts considers the preservation of the environment as the ultimate limiting factor for sustainability. But also impacts on regional development and acceptance such as acceptance and participation (D.4) or food security (D.6) were ranked highly. The criteria education of scientists and qualified workers (C.2) and generation of new knowledge and innovation potential (C.3) were not considered in the survey. It should be noted that the high ranking of environmental impacts might be affected by the biophysical science background of most experts (Buchholz et al. 2009).

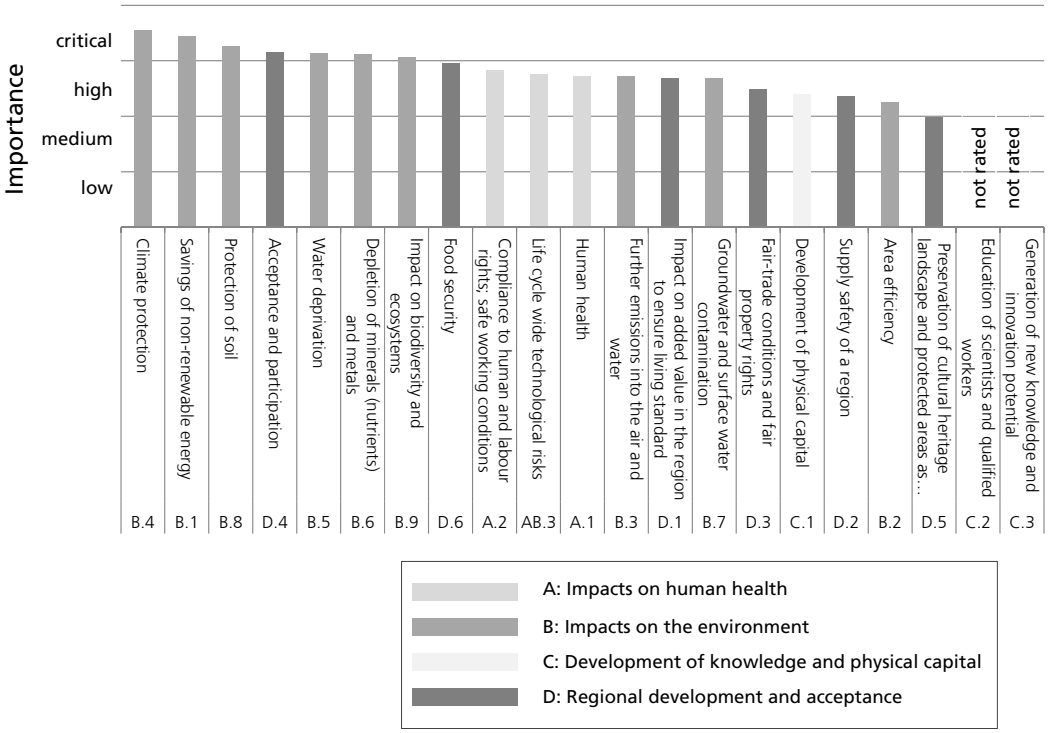


Figure 4-16: Importance ranking of sustainability criteria according to (Buchholz et al. 2009)

A possible ranking of relevance taking all these considerations into account is presented in Figure 4-17. Figure 4-17 differentiates between the three areas of protection (AoP), namely human health, biodiversity/ecosystems, and resources as well as further aspects. In particular the AoPs »human health« and »biodiversity/ecosystems« are of special importance because they form the basis for the livelihoods of humans.

Apart from the final classification and prioritisation of sustainability criteria for biorefineries, decision-making support is needed during the development and construction of a biorefinery. From the engineer's perspective prioritisation rules can help with orientation (Hubig, Reidel 2003). Such rules have been defined by Patricia Werhane, Hans Lenk, and Christoph Hubig (Hubig, Reidel 2003):

1. In the first place engineers should square decisions with their conscience. Only then they should consider options for future viability.
2. »Consideration of moral rights of individuals« prior to cost-benefit analysis.
3. »To seek a compromise which considers everyone equally« in the case of insoluble conflicts between »equivalent level of fundamental rights.«
4. Only after considering all moral rights of each party one should vote for the less damaging solution for all parties.

Only after applying the rules two to four weighting of potential benefits against any damage.

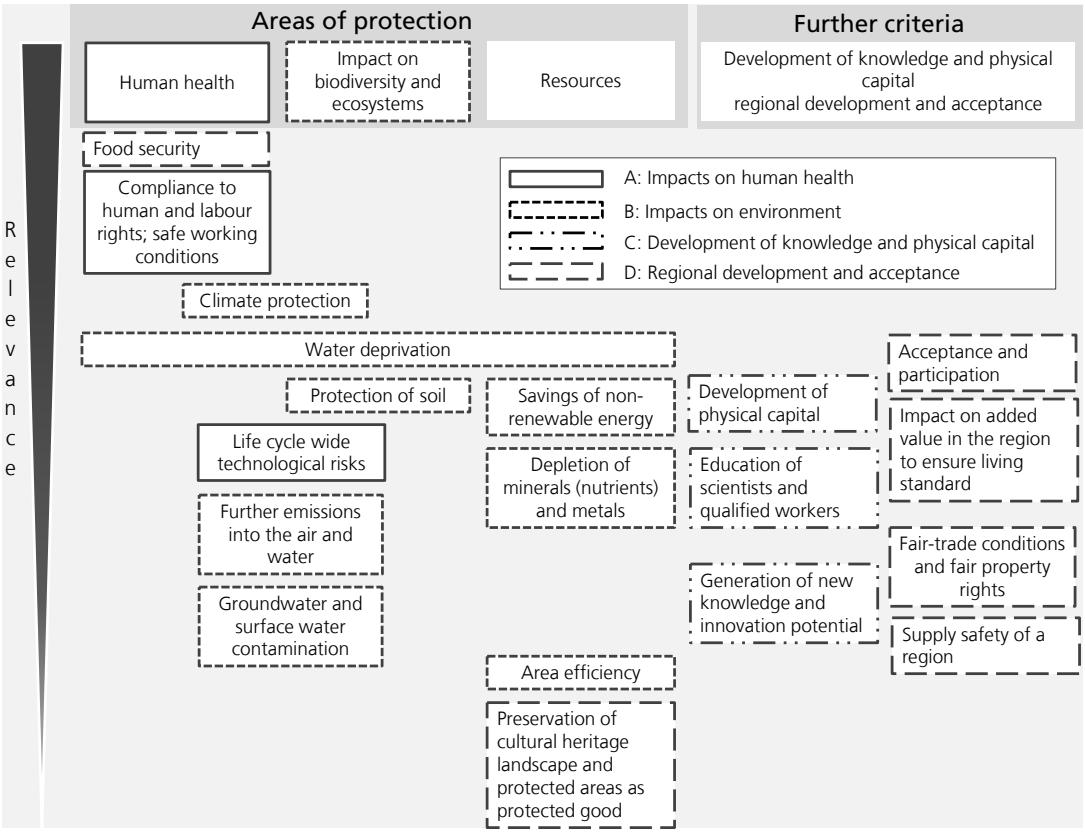


Figure 4-17: Possible ranking of relevance of sustainability criteria

Additional rules that support prioritisation decisions are (Hubig, Reidel 2003):

- Global, continental, regional, and local environmental compatibility are to be distinguished and considered. Systemically relevant environmental impacts or each broader one are to be preferred.
- In case of »urgency« preference is be given first to environmental compatibility than to economic benefit.
- In case of conflicts human and social compatibility are to be preferred to environmental compatibility.
- Real humanity is to be preferred to abstract claims and universal principles.
- High priority is to be given to bases and quality of life of future generations.
- Future generations are to be given the possibility to fall back to multiple options (availability of resources and technologies).

As these rules directly address the development of technologies and are the most comprehensive and universal ones, they should be applied during the development of new biorefineries. The final decision of prioritisation, however, requires the consideration of all groups of stakeholders in a fair way.

5 Specification, application, and validation of the generic methodology for an algae biorefinery in the context of bio-based economy

5.1 Objective of the case study

Against the background of the debate on sustainable development as introduced in chapter 2 and the selected integrative concept of sustainable development (Kopfmüller et al. 2001), a sustainability assessment of an algae biorefinery is carried out in chapter 5. The investigated algae biorefinery is located in Chiclana de la Frontera in Andalusia (Spain) and purifies waste water, produces biofuels (biomethane), and generates fertiliser from microalgae. In the future, where appropriate, possibly further algae components such as proteins will be extracted and purified. A map of the production site is shown in appendix II in Figure 7-5.

The biorefinery concept includes a combination of several conversion technologies which are jointly applied in order to purify waste water and to produce bioenergy from algal biomass. The algae biorefinery is compared with a (fossil) reference system which provides the same products and services based on conventional technologies. The reference products and services include purification of waste water with a conventional waste water treatment plant, provision of natural gas for transportation service, and mineral fertiliser production.

This case study is carried out to validate, check, and further improve the sustainability assessment methodology developed within chapter 4. In the following chapter 5.2 the algae biorefinery is classified according to the methodology which was introduced in chapter 3.2. The selection of sustainability criteria specific for algae biorefineries addressed by the sustainability assessment is presented in chapter 5.3.

5.2 Classification of the algae biorefinery

According to the classification method for biorefinery concepts as introduced in chapter 3.2, the investigated biorefinery can be labelled as:

- One platform (algae biomass) biorefinery for waste water purification, bioenergy (biomethane), and fertiliser from microalgae

At the same time of the preparation of this dissertation the biorefinery concept is being developed within the EU-funded project »Industrial scale demonstration of sustainable algae cultures for biofuel production« (All-Gas). In compliance

with the classification scheme introduced in chapter 3.2, a schematic illustration of the technological concept is shown in Figure 5-1.

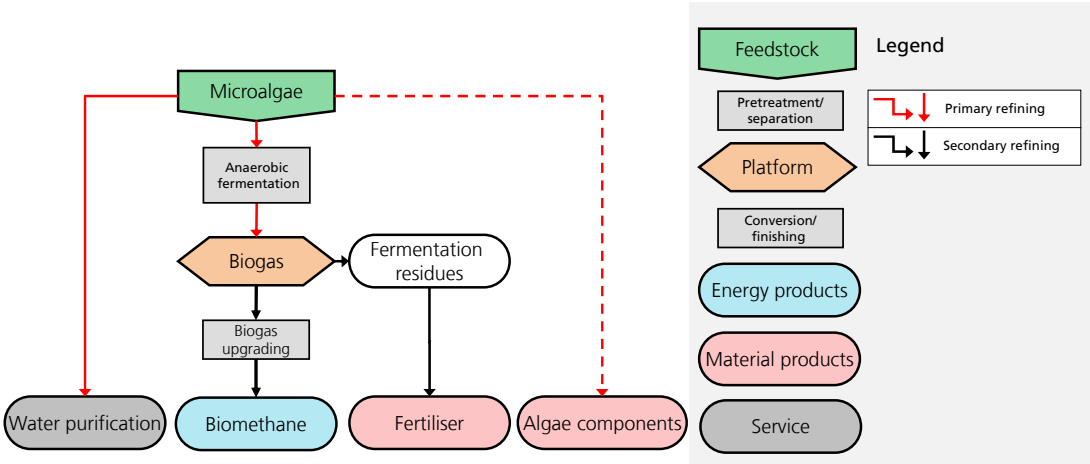


Figure 5-1: One platform (algae biomass) biorefinery for waste water purification, bioenergy (biomethane), and fertiliser from microalgae, in the style of (Cherubini et al. 2009; Peters 2011)

The biorefinery concept at the current stage of development does not meet the requirements of a biorefinery as defined in chapter 3 because no secondary refining is applied. Nevertheless, the biorefinery concept offers the opportunity for further developments with regard to valorisation of algal biomass. Furthermore, it can make a contribution to the development of a bio-based economy.

Feedstocks

The investigated biorefinery uses a polyculture of microalgae (cyanobacteria and eukaryotic microalgae) cultivated in anaerobically treated municipal waste water in an open raceway pond system. By cultivating algae in waste water the energy and cost intensive secondary and tertiary treatment of waste water is displaced by algae production (Christenson, Sims 2011) and efficiencies over 99 % of ammonium and orthophosphate removal can be achieved (Woertz et al. 2009b). Resistant algae species such as *Scenedesmus*, *Microactinum* and *Ankistrodesmus* are typically found in waste water because predators such as rotifers can easily eat fast growing algae species such as *Chlorella vulgaris* (Fulton 2009). Apart from predators climate conditions and the composition of waste water have a strong influence on the composition of species. Although the composition of the culture and growth-conditions in waste water are not controllable, lipid accumulation of mixed algae cultures cultivated in municipal waste water was measured to range from 4.9 to 11.3 % of volatile suspended solids (VSS) by weight (Woertz et al. 2009b).

Primary refining

In order to harvest microalgae and cyanobacteria cultivated in open ponds, gravity settlers are used to pre-concentrate the biomass. In order to improve

harvesting efficiencies and reliability of the harvesting process, dissolved air flotation (DAF) is applied using flocculation agents.

Platform

The primary refining step results into dewatered algal biomass which is further treated by anaerobic digestion. The output of anaerobic fermentation is biogas and fermentation residues containing proteins, carbohydrates, and further algae components. The biogas is upgraded to biomethane fulfilling the Swedish standard on biogas SS 155438 (Swedish standard 155438) using pressure swing adsorption (PSA). The technical requirements for the Swedish Standard are summarised in Table 7-30 in the appendix. The biomethane is pressurised and used as automotive fuel. Alternatively, the biomethane could also be used as fuel for a combined heat and power plant (CHP) which produces electricity and thermal energy.

Secondary refining and products

Today, no secondary refining is conducted. However, given that fermentation residues are rich in nitrogen and phosphorus they can be further processed into marketable organic fertilisers. Due to their sulphur and nitrogen content they are not suitable as solid fuel e.g. for use in a biomass boiler because of corrosion problems and nitrogen oxide emissions. Alternatively, algae biomass or fermentation residues could be dried and further converted into pyrolysis oil, gas, char, and liquids using intermediate pyrolysis (Kebelmann 2012). Pyrolysis oil can principally serve as feedstock for the production of biofuels or bio-chemicals. However, until now no commercial products from pyrolysis oil have been developed.

5.3 Specification of sustainability criteria and indicators for an algae biorefinery

Based on the selected integrative concept of sustainable development (Kopfmüller et al. 2001) which was introduced in chapter 2.6 and the biorefinery-specific sustainability criteria which are listed in Table 4-2 in chapter 4.1.4 as well as the indicators defined in chapter 0, a further contextualisation of the criteria and indicators is carried out. Following the structure of criteria defined in chapter 4.1.4, possible sustainability criteria and indicators are discussed and specified against the background of algae biorefineries.

5.3.1 Health impacts and risks

Criterion A1: Human Health

Endangering emissions such as NO_x, CO, NMVOC or PM will be emitted from the combustion of biofuels (EPA 2002). However, these emissions will occur, too, when using fossil fuels such as diesel or compressed natural gas (CNG) in

vehicles. Emissions into the air will also occur when algal biomass is burned in a biomass boiler (Lane et al. 2014) or indirectly by consuming electricity or additional fuels for internal processes. Another potential source of harmful emissions is the production of fertilisers which are commonly needed for the cultivation of algae. With regard to the algae biorefinery under investigation impacts from nutrient production are avoided because nutrients are exclusively provided by waste water and can be recycled from fermentation residues. Toxic substances such as heavy metals which originate from waste water need to be avoided or minimised in the final products such as organic fertilisers. Besides, the harvesting of algae requires one or more solid–liquid separation steps. If flocculation agents are used to aggregate microalgal cells in order to support sedimentation processes, non-toxic and effective flocculants or coagulants should be used (Molina Grima et al. 2003). Another potential source of toxicological substances are extraction agents such as hexane typically used for the extraction of algae components such as lipids or proteins (Halim et al. 2010). Further impacts on human health may result from the use of additional herbicides or pesticides in agricultural fields which are close to the algae cultivation facilities. Maybe it is necessary to control undesirable organisms such as bacteria, protozoa, water fleas, and further insects as well wild algae that can occur in open ponds (Klöck 2010). In order to assess impacts on human health caused by harmful emissions into the air, soil or water the LCIA endpoint indicator »disability adjusted life-years« [DALY] is selected as suggested in chapter 4.2.2 and visualised in chapter 4.3.1 in Figure 4-15.

Criterion A2: Compliance to human rights and labour rights

The investigated algae biorefinery is currently under construction in the south of Spain and the demand on energy and consumables will be covered to a large extent by European countries. All member states of the European Union have ratified the eight core labour standards since 2007 such as conventions on forced labour, freedom of association, discrimination, and child labour (ILO 2012). Therefore, no negative impacts on humans or violation of labour rights are expected to occur in the entire value chain. Consequently, criterion A2 is excluded from the sustainability assessment.

Criterion AB3: Life cycle wide technological risks

Apart from negative impacts on humans and on the environment that are caused by normal operation conditions – which were already addressed by criterion A1 – accidents and risks not recognised could also have strong impacts on the environment and society.

A possible risk to the environment and human health is the distribution of specific plant ingredients from genetically modified algae strains (Tabatabaei et al. 2011). These ingredients could change the composition of species in the vicinity or could cause allergies. Moreover, genetically modified microalgae can be transported by air over long distances and can even survive rough conditions in a dormant stage (Rösch et al. 2009). On the other hand genetic engineering of designer algae is inherently not associated with risks for the eco-systems

because these algae are probably not robust and competitive enough to disseminate under natural conditions. As genetically modified algae will probably not survive in waste water, the investigated algae biorefinery will use exclusively robust local species instead of genetically modified ones.

Further risks for humans and nature may result from accidents in oil production, e.g. caused by oil spills of deep water oil production or leaks during oil transport (Burton, den Haan 2011). These risks will be regarded although the allocation of accidents to the use of oil is extremely difficult and goes along with a high uncertainty.

5.3.2 Environmental impacts

Criterion B1: Savings of non-renewable energy

Savings of non-renewable energy can be achieved through the substitution of non-renewable resources by renewable ones such as algal biofuels or electricity produced from renewable energies. In order to achieve fossil energy savings the value of the indicator »fossil fuel depletion« (FFD), as introduced in chapter 4.2.2, of the reference system ($FFD_{ref.}$) must exceed the FFD value of the algae biorefinery ($FFD_{alg.}$). The difference of both indicator values can be expressed as fossil energy savings (FES) as described in equation (5-1). In order to save non-renewable energy FES should be positive.

$$FES = FFD_{ref.} - FFD_{alg.} \tag{5-1}$$

Several LCA studies have shown that algae-based transportation fuels can consume more fossil resources than fossil transportation fuels themselves. Main influencing factors are the energy demand for cultivation e.g. due to CO_2 supply or energy needed for water mixing, for harvesting, and for drying of algae (Singh, Olsen 2011; Clarens et al. 2011; Lardon et al. 2009; Dufour et al. 2011; Smith et al. 2009). Alternatively, the energy return on investment (EROI) can be calculated in order to analyse whether the system generates more usable energy than it consumes.

Criterion B2: Area efficiency

Arable land is an increasingly scarce resource facing a worldwide growing demand for food, biofuels, settlement, industry, and e.g. for traffic. As a result agricultural production is intensified with negative consequences for sustainable land use. Alternatively, cropland is expanded at the expense of destroying natural ecosystems such as rainforests. The production of algae promises two big benefits: firstly marginal land can be used to avoid land use change (transformation) and secondly less land is required compared to other biofuels due to higher biomass yields per ha (Sengupta et al. 2015). As in the case of the investigated algae biorefinery non-arable land will be used which means that negative land transformation does not occur. Since the biorefinery is

constructed within the city, land efficiency can be calculated as the midpoint indicator »urban land occupation«. In order to include the impact of land use on biodiversity covered by the endpoint indicator PDF the land use type »sealed surface« is considered.

Criterion B3: Further emissions into the air

Acidification of soil results from atmospheric deposition of inorganic substances such as NO_x, NH_3, and SO_2. Looking at algae biorefineries apart from acidifying emissions caused by the combustion of algal biofuels and emissions that occur in the upstream chains of energy generation needed for the operation of the algae biorefinery, the production of fertilisers can highly contribute to these emissions (Lardon et al. 2009). Therefore, avoiding the use of fertilisers by using waste water will reduce the acidification potential. An appropriate indicator to calculate the acidification potential is the ReCiPe indicator »terrestrial acidification potentials for Europe« as introduced in chapter 4.2.2. The indicator is expressed in kg SO_2-equivalents using the characterisation factors 0.56 for NO_x, 2.45 for NH_3, and 1 for SO_2 which refer to a time frame of 100 years.

Apart from acidifying substances particulate matter formation and photochemical oxidant formation are considered, taking into account PM_{10}-, NH_3-, NO_x-, SO_2-, and NMVOC-emissions into the air (Goedkoop et al. 2013). In addition, emissions of chlorofluorocarbons (CFCs) are considered which contribute to stratospheric ozone depletion.

Criterion B4: Climate Protection

On the one hand microalgae have proven to grow more quickly when fed with carbon dioxide and hence are able to sequester CO_2 (Muhs et al. 2009). On the other hand the supply with carbon dioxide, the energy demand for cultivation, harvesting and drying of algae, and further material and energy demands in upstream processes as well the end-of-life stage of algae-based products is accompanied by GHG emissions. In order to save GHG emissions the total life cycle wide GHG emissions of all algae biorefinery products and services should be lower than the carbon footprint of the corresponding reference system used for comparison. Estimates for carbon dioxide emissions of algal biomass cultivation in raceway ponds range from smaller than 10 g CO_2-eq.*MJ^{-1} (Kadam 2001) via approximately 30 g CO_2-eq.*MJ^{-1} (Jorquera et al. 2010) up to around 70 g CO_2-eq.*MJ^{-1} (Sander, Murthy 2010). The values strongly depend on the assumptions made in the studies e.g. for algae yields or technology used for CO_2 supply (Garofalo 2012). The investigated algae biorefinery seeks to lower these GHG emissions by replacing energy required for conventional waste water treatment, avoiding extra fertiliser, and using flue gas as CO_2 source from a nearby biomass boiler.

Apart from GHG emissions directly associated with the production of algae products, GHG emissions caused by land use change could affect the greenhouse gas balance. Although microalgae have a higher photon conversion efficiency than oilseed crops (Schenk et al. 2008) and hence are less area-intensive, large-scale algae systems will require significant amounts of land, too

(Christenson, Sims 2011). In addition, suitable land should not exceed two percent slope to avoid cost-prohibitive site preparation (Muhs et al. 2009). It should be noted that in reality measured algae yields in industrial scale raceway ponds are often substantially lower than calculated potential yields. For algae cultivated in waste water annual yields up to 73 $t*ha^{-1}$ were calculated based on real annual measurements at a site located in New Zealand (Woertz et al. 2014).

On the other hand the cultivation of algae does not require good soil quality and can thus be placed at marginal sites in arid regions (Jörissen et al. 2009). As marginal land will be used in the case of the investigated algae biorefinery no additional GHG emissions from land use change are expected.

A well-established indicator to address climate change is the infra-red forcing (cf. chapter 4.2.2) expressed in kg CO_2-eq. that is used in this case study.

Criterion B5: Water deprivation

Water is a key resource required for agriculture, drinking water, and the production of energy and has also become increasingly scarce in Spain (Rio Carrillo, Frei 2009). Several studies have shown that algae biomass can have a lower water footprint compared to other types of biomass although production and processing of algal biomass goes along with a high water demand making an efficient water recycling necessary (Subhadra, Edwards 2011; Harto et al. 2010). Yang et al. found out that in particular cultivation, harvesting, and drying of microalgae causes water losses in algal biodiesel production (Yang et al. 2011). According to their study, fresh water usage can be reduced by 84 % through the recycling of harvest water and by 90 % through using sea or waste water instead of fresh water. In order to overcome a high demand on fresh water the investigated algae biorefinery will use waste water. Independent of whether waste water or fresh water is used, blue water consumption occurs by evaporation of water reservoirs. The amount of evaporation mainly depends on air temperature, wind, and relative humidity. In case of open pond systems the mixing processes can trigger evaporation losses (Lundquist et al. 2010b). If sea water is used as culture media during summer time, additional fresh water will probably be needed to avoid too high salt concentrations (Klöck 2010). Since impacts of water usage strongly depend on regional conditions the blue water consumption of the algal biorefinery is weighted by the regional water scarcity that is expressed by the water stress index (WSI) defined by (Pfister et al. 2009). Therefore, equation (4-10) already introduced in chapter 4.2.2 is used. Water deprivation also contributes to impacts on human health and ecosystems that are covered by the criteria A1 and B9.

Criterion B6: Depletion of minerals (nutrients) and metals

Nutrient supplies for algal cultivation have a considerable impact on cost, ecological impacts, and production siting (DOE 2010) since algae have an extraordinary high nutrient content (5-12 % N and 0.3-0.5 % P) in relation to most other crops making recycling of residues a key challenge (Lundquist et al. 2010b). Depending on the cultivated algae species the biochemical optimum of the N to P ratio varies from 8 to 45 (Klausmeier et al. 2004). In comparison,

average domestic waste water has a N:P molar ratio of about 11 (Tchobanoglous, Burton 1991). This means that even when waste water is used to provide nutrients, additional phosphorus or nitrogen may be needed in order to reach the accurate ratio. In case of open pond systems using nutrients from waste water in combination with biogas and oil production, Lundquist et al. have calculated that no additional nutrients will be needed if nutrients and flue gas from biogas incineration are recycled (Lundquist et al. 2010b). This advantage contrasts with the disadvantage that only mixed algae and bacteria cultures grow in waste water (Christenson, Sims 2011) with typically low and fluctuating lipid content and lipid composition making it difficult to be used as raw material for the production of high added-value products. According to Woertz et al. lipid accumulation of mixed cultures in municipal waste water usually ranges from 4.9 to 11.3 % (Woertz et al. 2009a) and can even rise to 29 % when grown with anaerobic digester effluent (Woertz et al. 2009b).

Apart from the demand for phosphorus further minor amounts of metals might be needed e.g. to produce flocculation agents needed for harvesting algae. For measuring the abiotic resource depletion of metals and minerals the CML-indicator »abiotic depletion of minerals and metals« as suggested in chapter 4.2.2 is used. This indicator excludes the depletion of fossil fuels which is covered by the CML-indicator »abiotic depletion of fossil fuels«.

Criterion B7: Groundwater and surface water contamination

The cultivation of algae in waste water can improve the water quality because chemical and organic contaminants, heavy metals, and pathogens from waste water are removed while producing biomass for biofuel production (Muñoz, Guieysse 2006). Depending on different conditions of algae cultivation such as the retention time of algae in open ponds, the nitrogen and phosphorus content in waste water can almost completely be removed (Brennan, Owende 2009). Because of the generation of oxygen by autotrophic microalgae, hazardous or toxic compounds such as polycyclic aromatic hydrocarbons (PAHs), phenolics, and organic solvents can be biodegraded by bacteria. Hence, the production of oxygen reduces or eliminates the need for external mechanical aeration (Muñoz, Guieysse 2006). In addition, some algae species such as *Spirulina sp*. are able to absorb heavy metal ions such as Cr^{3+}, Cd^{2+}, and Cu^{2+} (Chojnacka et al. 2005). Compared to conventional waste water treatment, waste water treatment with algae might be affected more strongly by annual fluctuations. For this reason, changes in water quality in the course of time should be regarded carefully. If fermentation residues or their derivatives are applied as fertiliser to agricultural land, groundwater and surface water contamination can result e.g. from nutrient inputs caused by erosion or drainage (Grunwald et al. 2001).

Apart from these potential sources of water contamination, the use of pesticide inputs can contribute to groundwater contamination. Since undesirable organisms such as bacteria, protozoa, insects, and wild algae can grow in open ponds, the cultivation of algae in open ponds can trigger the use of herbicides or pesticides over large areas (Klöck 2010) and hence could have an indirect

effect on groundwater quality. Appropriate indicators for assessing changes in groundwater and surface water quality are fresh water eutrophication and fresh water ecotoxicity. Both indicators are considered at midpoint level as well as by the endpoint indicators DALY and PDF addressed by criteria A1 and B9. In addition, marine eutrophication is regarded in accordance with the ReCiPe indicator »marine eutrophication« as introduced in chapter 4.2.2.

Criterion B8: Protection of soil

In contrast to agricultural crops, algae cultivation systems do not need fertile soil and can be principally placed anywhere (Muhs et al. 2009). Hence, the protection of soil only needs to be regarded if fertile land is used as space for algae production. The algal biorefinery located in Chiclana de la Frontera does not use fertile land, thus rendering this aspect irrelevant.

Criterion B9: Impact on biodiversity and ecosystems

Although open ponds will probably be built on degraded land, their installation over large areas will inevitably disrupt the natural habitats of native wildlife (Muhs et al. 2009). Moreover, such regions are often valuable habitats for rare and protected plants and animals (Klöck 2010). Such impacts can be examined adequately by an environmental assessment such as described by the »Directive 85/337/EEC on the assessment of the effects of certain public and private projects on the environment« (EU 1985). Alternatively, biodiversity impacts can be addressed by the LCIA endpoint indicator »loss of species during a year« (PDF) as introduced in chapter 4.2.2 which considers impacts of urban land occupation (B2), the release of acidifying gases (B3), climate change effects (B4), water deprivation (B5), fresh water ecotoxicity and fresh water eutrophication (B7), and terrestrial ecotoxicity. Although the indicator PDF goes along with a high uncertainty it is selected in order to reduce the costs for analyses.

5.3.3 Impacts on knowledge and physical capital

Criterion C1: Development of physical capital which can contribute to present and future social welfare

Investments in new production plants should be economically viable. Hence, the investigated biorefinery should compete with conventional products and services available on the market today. One possibility to investigate the economic preferability is to compare the costs of production of algae-based products/services to those of (fossil) reference products/services presently on the market. However, this requires comprehensive information on both production systems: the algae system and the conventional system. Alternatively, in order to evaluate the profitability of a capital investment the capital value can be calculated. The minimum requirement for a feasible investment is that the capital value is larger than zero. In order to consider further technical improvements in algae biorefineries, changes in market prices, and changing

interest rates, their influence on the capital value is investigated by the economic assessment.

Apart from the economic feasibility, overcapacities on the market should be avoided. Against the background of an expected growth in global transport energy demand of 1.3 % per year from 2008 to 2035 (IEA 2010), no overcapacities for fuels are expected. Although the production of high value co-products can support the economic profitability of algae biorefineries, their markets might be limited. Cognis Australia for example currently produces over 80 % of the world's natural β-carotene market from a total of approximately 960 ha of extensive ponds (Darzins et al. 2010).

Criterion C2: Education of scientists and workers

Technologies to produce biofuels from algae are still under development and engineers, scientists, qualified workers, and investors are needed to make the use of algae as raw material economically feasible. The development, for instance, of new algae production systems, harvesting technologies, extraction or conversion techniques will require huge RTD expenditure promoting the education of (young) scientists. During the development, construction, and operation of the algal biorefinery several educational activities may accompany the basic work. These activities should be listed and quantified.

Criterion C3: Generation of new knowledge and innovation capacity

Today, two kinds of innovations focussing on algae are being discussed in the scientific community. Firstly, microalgae are seen as a very promising contribution to the substitution of crude oil. This estimation is supported by the theoretical productivities of microalgae. Secondly, biofuels from algae are estimated to remain as a co-product or a secondary application of future large-scale facilities where other high-value products such as specific oils or pigments are produced (Oltra 2011). In addition, the development of new technologies, for instance of new harvesting techniques, could be applied to other fields of sciences, too. Against this background a large amount of money has been invested to push research and development and to generate knowledge and innovation capacities in the last years. Some academic institutes have set up dedicated algae research centres and venture capital money has been raised for algae research, above all in the USA. The big oil companies Chevron, BP, and Exxon Mobil as well as many start-ups have made great investments in algal fuels research (Rösch, Maga 2012). In addition, public authorities have increased financial support to promote technological improvements. It is assumed that the amount of RTD expenditure spent for development and construction of an algae biorefinery is therefore a suitable indicator to assess the generation of new knowledge and innovation capacity.

5.3.4 Impacts on regional development and acceptance

Criterion D1: Impact on added value in the region to ensure living standard (creation or preservation of work places)

This criterion looks at the estimated increase of added value in Chiclana de la Frontera and employment effects associated with the development, construction, operation, and maintenance of the algae biorefinery as well as with regard to the marketing of algae products. In particular the operation of the biorefinery plant and commercialisation of the products is estimated to create long-term employment. However, a crucial perquisite for positive employment effects is the competitiveness of algal products in comparison to conventional products. Hence, the investment in this technology should generate profits preferably to the same extent as conventional products and services. Apart from the price-competitiveness of algal products, only degraded land should be used for algae production to avoid conflicts with other value-added chains. Additional workplaces will only be created if these requirements are met.

Criterion D2: Supply safety of a region

The worldwide theoretical contribution of algae considering the availability of crucial resources such as land, water, and CO_2 to the final energy consumption is estimated to be significant (van Harmelen, Oonk 2006; Darzins et al. 2010). Nevertheless, a mandatory prerequisite to significantly increase the market share of algae products is to become price-competitive. However, as a first step the share of algae products and services in the market of Andalusia is investigated.

Criterion D3: Fair-trade conditions and fair property rights

The unequal allocation of property rights as well as difficult labour conditions can have negative effects on social life. With regard to the investigated algae biorefinery no negative effects concerning those aspects are expected even when considering the entire value chain. For this reason this aspect is excluded from the analysis.

Criterion D4: Acceptance and participation

In order to assess the acceptance of new algal biofuels it should be investigated what motorists think about them. In particular, it should be assessed which technical and ethical concerns and advantages are associated with these new fuels and if people are willing to pay a premium price for them. Therefore, the customers' willingness to pay for algae products should be assessed. Apart from potential buyers of algae-based products, the interests of various groups of stakeholders such as people living close to an algae biorefinery should be considered e.g. in finding suitable locations for microalgae production plants.

Criterion D5: Preservation of cultural heritage landscape and protected areas as protected good

Large-scale microalgae plants will change the landscape and can exert a local influence on nature which provides space for sensual, contemplative, spiritual, religious, and aesthetic experience. The cultural functions of landscapes could be affected even when marginal land is considered (Rösch, Maga 2012). Therefore, high-quality landscapes and areas worth to be protected should be excluded as locations for algae cultivation. Since the location in Chiclana de la Frontera is not considered worthy of protection as it is located on marginal land, this aspect is not regarded further.

Criterion D6: Food security

Impacts of algae cultivation on food security could be both negative and positive. Negative impacts may result from the competition for water and land. In case of the investigated algae biorefinery no competition for land occurs since marginal land is applied. As a result of using waste water as a cultivation medium for algae cultivation, competition for fresh water is avoided, too.

Positive contribution to food security can be achieved if algae are produced for dietary supplement for humans. Algae can also add implicitly to food supply by providing feed supplements for aquaculture and feedstock (Pauw et al. 1984). With regard to the investigated algae biorefinery the use of algae produced in waste water for food or feed is legally and technically difficult since harmful substances in the waste water might contaminate food or feed. Because neither positive nor negative impacts on food security are expected this criterion is not investigated further.

A summary of the criteria and indicators applied to the sustainability assessment of the investigated algae biorefinery is given in Table 5-1. Table 5-1 also shows the assignment to the substantial rules introduced in Table 2-1 in chapter 2.6 as well as an assignment to the categories defined in Table 4-2 in chapter 4.1.4.

Table 5-1: Summary of the criteria and indicators applied to the sustainability assessment of the investigated algae biorefinery as well as the assignment to the sustainability substantial rules as introduced in Table 2-1 in chapter 2.6

Principles	Criteria	Indicator	Unit
Protection of human health	A1: Human health	Disability adjusted life-years (DALY)	Years
Avoiding technical risks with potentially catastrophic impacts	AB3: Life cycle wide technological risks	Discussion of possible risks	-
Sustainable use of non-renewable resources	B1: Savings of non-renewable energy	Fossil energy savings (FES), alternatively EROI	kg oil-eq., -
	B6: Depletion of minerals (nutrients) and metals	Abiotic depletion potential	kg Sb-eq.

Principles	Criteria	Indicator	Unit
Sustainable use of renewable resources	B2: Area efficiency	Urban land occupation (ULO)	m^2*yr.
	B5: Water deprivation	Water scarcity footprint	m^3
	B9: Impact on biodiversity and ecosystems	Loss of species during a year	Species*yr.
Sustainable use of the environment as a sink	B3: Further emissions into the air	Base saturation, PM_{10} intake, Stratospheric ozone concentration, Photochemical ozone concentration	kg SO_2-eq., kg PM_{10}-eq., kg CFC-11-eq., kg NMVOC-eq.
	B4: Climate protection	Infra-red forcing	kg CO_2-eq.
	B7: Water contamination	Phosphorus concentration Nitrogen concentration Hazard-weighted concentration	kg P-eq., kg N-eq., kg 1.4 DCB-eq.
Sustainable development of physical, human and knowledge capital	C1: Development of physical capital which can contribute to present and future social welfare	Cost of production or net present value	€
	C2: Education of scientists and qualified workers	Educational activities	Type and amount
	C3: Generation of new knowledge and innovation capacity	RTD expenditure in algae project	€ per project
Autonomous subsistence based on own income	D1: Impact on added value in the region to ensure living standard	Amount of additional workplaces or net present value	Units or €
Sustainable development of physical, human and knowledge capital	D2: Supply safety of a region	Market share of algae products in Andalusia	%
Participation in social decision-making processes	D4: Acceptance and participation	Willingness to pay for algae products, participation in site location search for algae plants	€, dimension-less

5.4 Life cycle analysis: goal and scope

A common goal and scope definition was developed in cooperation with the partners of the European Algae Cluster to ensure comparability (Bradley et al. 2015). The following goal and scope definition mainly follows these assumptions.

5.4.1 Goal definition

The intended application of the study is to compare the overall environmental impacts associated with an algae biorefinery in comparison to a (fossil) reference. Since a central benefit of the algae biorefinery is the purification of waste water, the environmental burdens associated with the purification of waste water are compared to those of conventional waste water treatment. In addition, the environmental performance of biomethane produced from microalgae and used as automotive fuel is benchmarked against CNG and diesel.

The following comparisons are made:

- Comparison of waste water treatment performed in the algae biorefinery with conventional waste water treatment
- Comparison of biomethane produced by the algae biorefinery with other automotive fuels: CNG and diesel
- Comparison of an algae-based biorefinery with a comparable »basket« of conventional products (CNG, energy, fertiliser) and services (waste water treatment)

The LCA study is intended to include a comparative examination intended to be disclosed to the public. The usability and transferability of the results is to be discussed carefully because the application of microalgae for waste water purification refers to a very specific topic. Nevertheless, the LCA study aims at improving the knowledge on microalgae technology risks and opportunities and hence has a mainly descriptive character. The LCA study can be used to support governmental decisions on funding algae R&D activities, too. Correspondingly, the study addresses scientists, policy makers, financiers, and the public in general.

5.4.2 Scope definition

The system to be studied is an energy driven biorefinery that produces and processes microalgae whereby the function of the systems is to purify waste water as well as to produce biomethane and if applicable electricity and organic fertilisers from algae. This algae biorefinery is compared with a reference system which consists of the following four processes: 1) conventional waste water treatment, 2) the provision and use of compressed natural gas (CNG) or diesel

as automotive fuel, 3) the conventional generation of thermal energy and electricity, and 4) the production of mineral fertiliser.

The study considers the potential environmental impacts that can be attributed to the algae biorefinery or algal products respectively over its life cycle. It covers the upstream and downstream processes of the system and end-of-life impacts using attributional modelling. Future products e.g. gained from extracting algae components such as proteins or lipids are not investigated due to the lack of reliable information.

5.4.3 Products and reference system

The algae biorefinery will mainly replace conventional waste water treatment plants and natural gas or diesel used as automotive fuel. Alternatively, biomethane could be used as fuel for the use in a combined heat and power (CHP) plant. Fermentation residues produced by anaerobic digestion of algae are assumed to be applied on agricultural fields and substitute mineral fertilisers to a certain degree. In the future algae components such as proteins might be extracted from microalgae before or after digestion or from intermediates produced from microalgae. Within this LCA study the products and services set out in Figure 5-2 are exclusively taken into account.

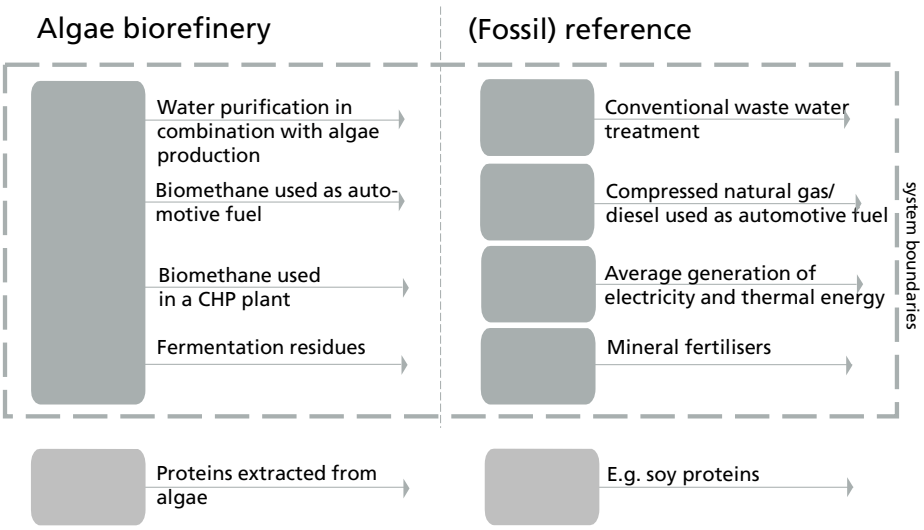


Figure 5-2: Comparison of the algae biorefinery with a (fossil) reference

Products possibly produced in the future are illustrated in light grey and are outside of the system boundaries.

5.4.4 Functional unit

The functional unit sets the scale for comparison of different products or production systems.

In order to determine potential environmental impacts caused by the algae biorefinery, the functional unit

- »1 m^3 treated waste water« (fu 1)

is selected. The amount of treated waste water directly refers to the amount of microalgae cultivated, harvested, and further processed into multiple products.

In order to analyse the environmental performance of biomethane produced within the algae biorefinery and used as automotive biofuel, the functional unit and reference flow respectively

- »1 MJ CNG (LHV) used in a gas engine« (fu 2),

is selected. This functional unit was used in other studies for algal biofuels, too (Lardon et al. 2009; Sander, Murthy 2010), and allows a comparison between the algae cluster projects (Bradley et al. 2015).

5.4.5 System boundaries

The LCA study follows the idea of life cycle thinking choosing a »cradle-to-grave« approach. As presented in Figure 5-3 the system boundaries encompass (1) anaerobic waste water pre-treatment, (2) cultivation of microalgae in primary treated waste water, (3) harvesting of algae, (4) biogas production from algal biomass, (5) biogas upgrading and provision at a service station, (6) application of fermentation residues on the field, and (7) CO_2 and energy generation in a biomass boiler.

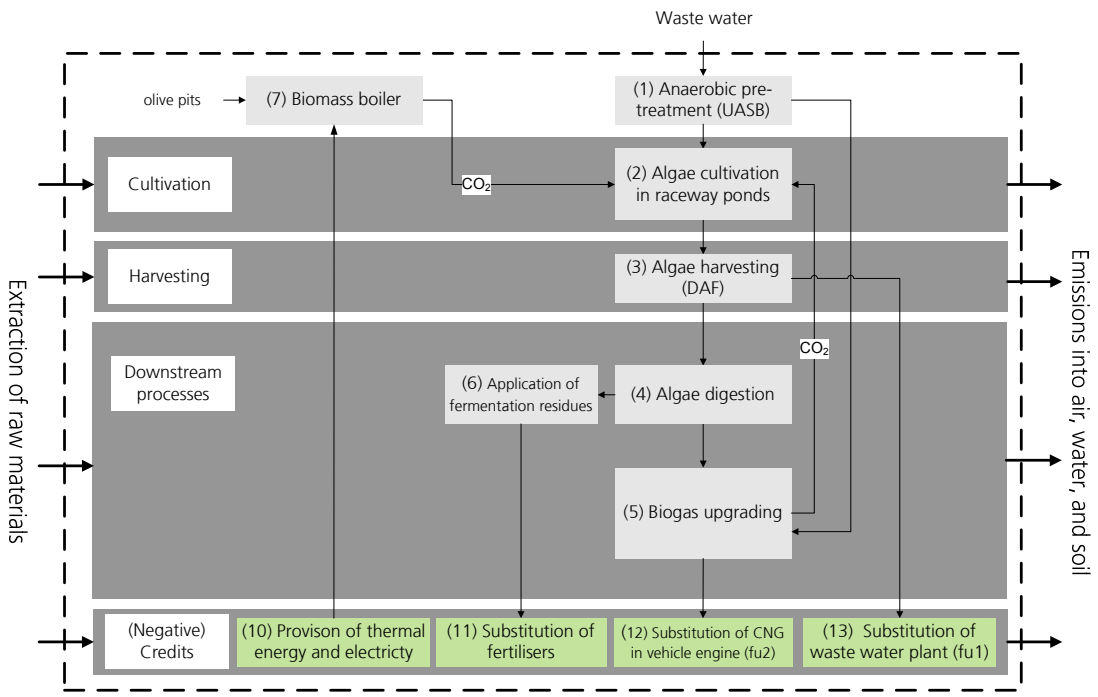


Figure 5-3: System boundaries of the algae biorefinery which purifies waste water and produces biomethane, fertiliser, and thermal energy

In addition, it includes (10) the provision/substitution of thermal energy and electricity, (11) the substitution of fertiliser, (12) the substitution of compressed natural gas (CNG) in a vehicle engine, and (13) the substitution of conventional waste water treatment. The use of biomethane in a CHP plant instead of its use as automotive fuel is investigated within a scenario analysis (cf. chapter 5.4.8).

All relevant upstream production chains are included in the LCA study encompassing the extraction of all necessary resources for the production of materials and energy.

The construction of raceway ponds (PVC lining) is taken into account as Stephenson et al. found out to be relevant (Stephenson et al. 2010). In contrast further non-disposable capital equipment such as infrastructure (streets, machinery etc.) and maintenance are not included to ensure comparability to other LCA studies. A summary of the included and excluded processes is given in Table 5-2.

Table 5-2: LCA boundary conditions

Included	Excluded
Disposable capital equipment	Non-disposable capital equipment and maintenance
Raceways, harvesting assets, and biogas plant	Distance travelled between algae facility and biofuel facility
Grid electricity and heat	Transportation of employees
Internally generated electricity and heat	Anything after the initial production of the by-products
Processing of materials	Overhead (heat and lighting) of manufacturing facilities
Operation of primary equipment	
Waste and recycling	
Transport of raw and ancillary materials	
Internal transportation of materials	
Organic processes	
Vehicle engine	

It is assumed that a petrol station is located close to the algae biorefinery which means that transportation costs of biomethane can be neglected. However, the required pressure of biomethane needed for refuelling is taken into account.

5.4.6 Cut-off criteria

A method to systematically and quantitatively set the system boundaries is the »relative mass, energy, and economic value« (RMEE) protocol that was developed by Raynolds et al. and was already introduced in chapter 4.3.1

(Raynolds et al. 2000). Within this case study the RMEE method is applied using a cut-off ratio of 1 %. As economic values are rarely available, only mass and energy values are used. The cut-off criteria are applied to the functional unit »1 m³ treated waste water« (fu 1).

5.4.7 Solving multifunctionality of processes

If a unit process produces more than one product or service, an allocation procedure between the products/services is needed. This is the case for example for unit process 4 »biogas production from algal biomass« which apart from biogas also produces fermentation residues. In such a case an allocation procedure is used to attribute shares of the total environmental impact to the different products and services.

In order to describe the full effects of change (Tillman 2000) from conventional waste water treatment along with the use of fossil energy carriers to an algae-based waste water treatment, system expansion – as introduced and justified as method of choice in chapter 4.3.1 – is chosen to deal with allocation of the foreground system. The approach to solve multifunctionality by system expansion is illustrated in Figure 5-4. Depending on the choice of the functional unit, credits and negative credits are given to the other by-products.

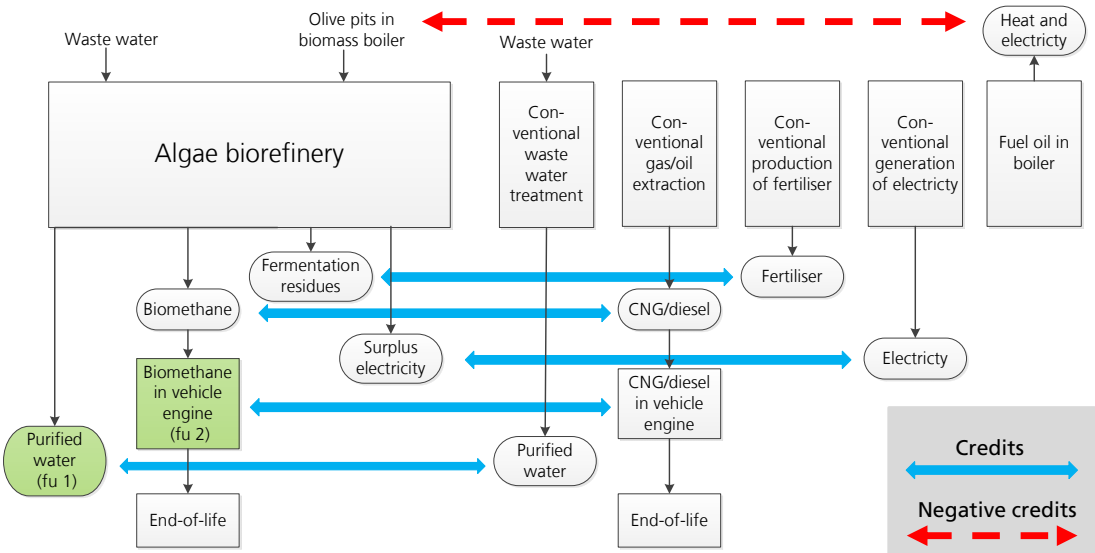


Figure 5-4: System expansion in order to solve multifunctionality

Further allocation procedures will be applied if needed for assigning burdens of background datasets such as country-specific electricity grid mixes. Water that is fed back to the algae cultivation system is modelled as closed-loop recycling if no changes occur in the inherent properties (ISO/TR 14049).

Because of the selection of system expansion instead of other allocation procedures the choice of the reference products (cf. chapter 5.4.3) has a strong impact on the overall results. Depending on the choice of the reference

products even contradictory results are possible (Cherubini 2012). Therefore, a sensitivity analysis will be performed which analyses the impact of choice as described in the next chapter.

5.4.8 Uncertainty, sensitivity, and scenario analyses

According to Huijbregts there are six types of uncertainty and variability in LCA (Huijbregts 1998). The following types of uncertainty and variability were identified to be relevant for algae biorefineries:

- Uncertainty due to unavoidable methodological choices in the LCA study such as allocation methods, functional unit, system boundaries, cut-off rules,
- parameter uncertainty, due to imprecise, incomplete, outdated or missing values of data needed in the inventory analysis or in the impact analysis,
- model's uncertainty, due to a linear model for growing algae and aggregated background data, and
- temporal variability in the life cycle inventory due to changing weather conditions for growing and processing algae.

In order to address the effects caused by the chosen methods, assumptions, and used data, an uncertainty analysis can be carried out (Björklund 2002). In this LCA study the uncertainty analysis is carried out mainly by scenario analysis. In total, the LCA model contains 252 process parameters for defining primary data which describe for example the yields of processes or efficiency of equipment used. Several of these process parameters are described in chapter 7.1 in the appendix.

The scenario analysis investigates the influence of the following process parameters:

- Scenario 1: higher anaerobic digestion temperature; thermophilic (55 °C) conditions for anaerobic digestion instead of mesophilic (35 °C) conditions → 0.156 Nm^3 CH_4*kg^{-1} VS added
- Scenario 2: higher anaerobic digestion temperature; maximum biogas yield at thermophilic (57 °C) conditions according to literature data (Ras et al. 2011) → 0.24 Nm^3 CH_4*kg^{-1} VS added
- Scenario 3: higher methane yields of UASB reactors
- Scenario 4: higher COD load of waste water entering UASB reactors
- Scenario 5: higher algae productivity per ha
- Scenario 6: lower C uptake of microalgae from CO_2 in combustion gas and from dissolved organic carbon
- Scenario 7: lower nitrogen content in microalgae which influences the greenhouse gas emissions caused by the application of fermentation residues on the field

These parameters were selected because they strongly influence the amount of biogas produced (scenarios 1-5), strongly influence the amount of external CO_2 needed for growth of algae (scenario 6), and strongly influence the amount of GHG emissions which strongly depend on the dinitrogen monoxide emissions caused by the application of fermentation residues on the field (scenario 7). The variation of parameter values is prepared on the basis of realistic deviations from the base line scenario.

In addition, the effects of varying the reference system considered for system expansion are analysed. The following uncertainties are investigated:

- Substitution of the electricity mix: EU-28 grid mix in 2011, EU-28 grid mix in 2020 (Bradley et al. 2015), Spanish electricity mix in 2011
- Substitution of diesel instead of CNG

Finally, the scenario is investigated which impacts occur if biomethane is used in a CHP plant instead of using it as automotive fuel which promises higher savings of GHG emissions (Strauch, Maga 2014).

In addition, a contribution analysis is carried out by decomposing the LCA result. The contributions of all process units, as defined in Figure 5-3, are shown individually, providing a quick overview of the important contributors.

Finally, an expert review is carried out by John Benemann and Ian Lunquist from MicroBio Engineering Inc.

In order to deal with temporal variability, statistical data covering several years is needed. Due to limited availability of time for carrying out the LCA study this aspect is not regarded in detail.

5.4.9 Data collection and data quality

Primary data, also referred to as foreground data, must in the first place represent the »true« inventory of the processes with regard to technology, geography, and time (representativeness) and secondly the used background data, also referred to as generic data or secondary data, must actually represent the true process (appropriateness) (JRC 2010b). Most available LCA studies on algal biofuels are based on theoretical primary data including (Batan et al. 2010), (Campbell et al. 2010), (Lardon et al. 2009), (Sander, Murthy 2010), and (Stephenson et al. 2010). Only very few contain real data such as (Passell et al. 2013) and (Beal et al. 2012). Nevertheless, this data came from pilot scale facilities and the author of this thesis does not know any articles in the peer reviewed literature that refer to real data from algae-biofuel facilities in industrial scale.

In this study the used primary data is based on information compiled within the All-Gas project and complemented, if necessary, by further information sources such as literature, recipes and formulations, part lists, patents, process engineering models, stoichiometric models, process and product specifications and testing reports, legal limits, market shares and sizes, data of similar

processes, BAT reference documents etc. as recommended by the ILCD handbook (JRC 2010b). Extrapolation will be used to transfer the times of operation of the facilities to a full year. Generic data is used for modelling the background system and is mainly taken from the GaBi 6.0 database (PE INTERNATIONAL 2014) and is complemented by the databases provided by ecoinvent (ecoinvent Centre 2014) and the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) (U.S. Department of Energy 2013).

The data refers to the market and conditions found in Andalusia (Spain) and the year 2014. However, some datasets and corresponding technologies may refer to earlier times. Furthermore, the composition of the poly-algae culture can differ strongly from time to time resulting in a different technological performance and product quality.

The larger part of the installed technology is currently under development and technological improvements that have not been realised in the All-Gas project yet are not considered. In addition, the biorefinery system includes technologies with different technology readiness levels (TRLs) as introduced in chapter 3.2.3 (DOE 2011; European Commission 2011). An estimation of the TRL for the algae biorefinery is presented in Figure 5-5. According to this estimation, a good portion of the technologies applied have been only established in laboratory scale. In particular, the integration of all technologies at demonstration scale has not been demonstrated, yet.

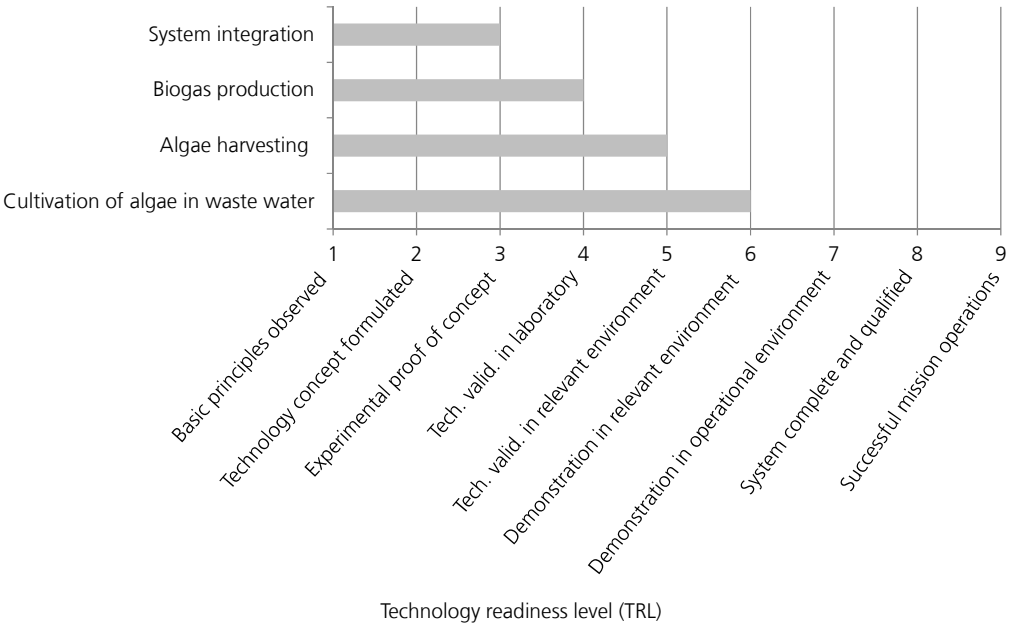


Figure 5-5: Technology readiness level (TRL) of the waste water algae biorefinery

Apart from the TRLs the performance of the biorefinery system strongly depends on the size of the pond systems and on the way in which it is operated.

For the comparison of the algae biorefinery with the defined reference system, the scale of the technology and the technology readiness levels (TRLs) of each technology applied should be kept at the back of the reader's mind.

5.4.10 C-storage in biorefinery products

By growing algae, CO_2 is taken from the atmosphere and stored in biomass. This biomass is used to mainly produce biomethane which is combusted in vehicles promptly. Hence, the carbon content returns to the atmosphere resulting in a zero balance. Bio-based products that will probably be produced by algae biorefineries in the future will exist for more than one year resulting in a temporary C uptake. However, the time frame of CO_2 sequestration is too short to be relevant so that CO_2 sequestration is neglected.

In accordance with the ILCD handbook carbon dioxide and methane emissions are differentiated between fossil and biological sources. Greenhouse gas emissions resulting from land use change are inventoried as fossil carbon dioxide (JRC 2010b). The uptake of carbon dioxide by microalgae or bacteria is inventoried under the category »resources from air« (JRC 2010b). For calculating the carbon footprint biogenic carbon dioxide emissions are not taken into account because CO_2 uptake by organisms is equal to CO_2 emissions released later on in the lifecycle. According to the fifth IPCC report biomethane is given the characterisation factor 28 and fossil methane 30 kg CO_2-eq.*kg^{-1} for a time frame of 100 years (Myhre, Shindell 2013b).

5.4.11 Impact indicators and life cycle impact assessment methods

According to the sustainability indicators identified in chapter 5.3 and described and summarised in Table 5-1, the following life cycle impact categories are selected: A1: damage to human health, B1: fossil fuel consumption, B2 urban land occupation, B3a: terrestrial acidification, B3b: particulate matter formation, B3c: photochemical oxidant formation, B3d: ozone depletion, B4: climate change, B5: water deprivation, B6: abiotic depletion, B7a: fresh water eutrophication, B7b: marine water eutrophication, B7c: fresh water ecotoxicity, and B9: loss of species during a year.

For calculating these indicators in most cases the ReCiPe method (Goedkoop et al. 2013) described in chapter 4.3.1 is applied. Exceptions are the impact categories B5: water deprivation and B6: the abiotic depletion potential which are not covered properly by the ReCiPe method. For water deprivation the water scarcity footprint is calculated using the water stress index defined by (Pfister et al. 2009). In case of the abiotic depletion potential the CML2002 method is used which was developed by Guinée et al. along with the corresponding characterisation of factors version 4.2 last updated in April 2013 (Guinée et al. 2002).

Apart from the characterisation factors used in ReCiPe which are taken from the fourth IPCC report (IPCC 2007), in addition updated numbers are taken into account from the fifth IPCC report (Myhre, Shindell 2013a). Moreover, GWP100 that refers to a lifetime of greenhouse gases in the atmosphere of 100 years, GWP20 is included in the sensitivity analysis in order to address short term effects of greenhouse gases (Bradley et al. 2015).

5.5 System description and life cycle inventory

This chapter presents the assumptions made for the unit processes introduced in chapter 5.4.5 and visualised in Figure 5-6. A more detailed description of each unit process is given in chapter 7.1 in the appendix I. The calculation of the energy balance is presented in chapter 5.5.2. The following chapter 5.5.3 will show the carbon and nutrient cycle of the algae biorefinery and in chapter 5.5.4 the blue water consumption and resulting water deprivation will be described.

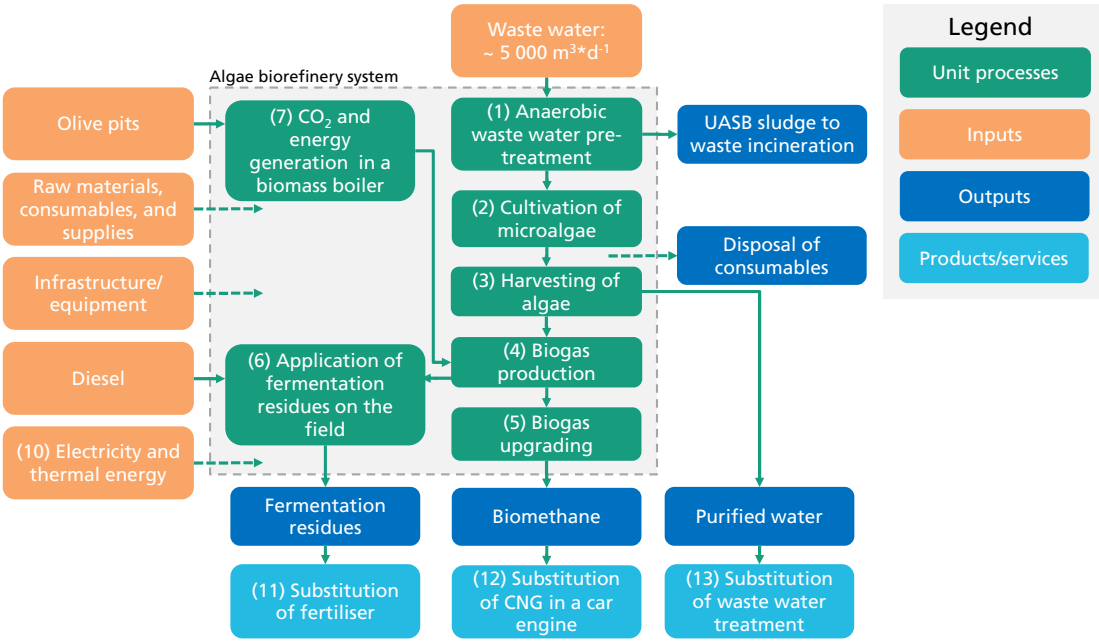


Figure 5-6: Schematic illustration of the algae biorefinery in compliance with the designed LCA model which additionally includes all upstream production chains

The corresponding LCA model consists of four graphical layers which jointly combine primary data with background data. An example of three different layers is illustrated in Figure 7-6 and Figure 7-7 in appendix II. A summary of the main material and energy flows (primary data) used in the first two layers for describing the unit processes one to seven is given in Table 7-31 and in Table 7-32 in appendix II. The primary data shown in these tables was generated by applying 252 process parameters which specify technical properties of the algae biorefinery system and allow applying technical modifications in the entire LCA model.

5.5.1 System description

The algae biorefinery system starts with the removal of oil, grease, and sand from municipal waste water followed by an anaerobic pre-treatment as described in more detail in chapter 7.1.1 in the appendix. Therefore, optimised upflow anaerobic sludge blanket (UASB) digesters are used that produce biogas with a methane content of around 80 % methane and reduce the total and soluble COD in the waste water by 60 % and 45 % respectively. Nitrogen and phosphorus concentrations, however, remain unchanged during the anaerobic treatment of the waste water, although the ammonia concentration could generally be increased. Some biogas remains dissolved and is stripped from the treated waste water and the H_2S content in the entire biogas is reduced by more than 90 % using a biofilter. The pre-treated waste water is pumped to high rate algae ponds (HRAPs) with a total area of 10 ha with dimensions of 250x18x0.3 m (LxWxH) each. The pond water velocity is kept at 0.3 $m*s^{-1}$ by paddle wheel mixers 12 hours a day or alternatively by a low energy flow buster with a submergible impeller. The slightly increased velocity is applied to prevent sediment accumulation. In order to trigger algae growth, carbon dioxide is injected that is provided externally through a piping system coming from biogas upgrading and from flue gas produced in a biomass boiler which is fed with olive pits. The biomass boiler is described in chapter 7.1.7. A detailed description of algae cultivation is given in chapter 7.1.2 in the appendix.

In annual average, CO_2 is provided 12 hours per day. The overall CO_2 uptake is measured to be higher than 90 % (Aqualia 2014). Apart from the external supply of carbon dioxide, CO_2 produced by bacteria and waste water alkalinity is taken into account. This internal CO_2 production accounts for around two thirds of the total CO_2 demand that was determined to be 1.67 kg CO_2*kg algae DM^{-1}.

After the algae cultivation stage with an average hydraulic retention time of six days, algae harvesting is done via a coagulation-flocculation system described in detail in chapter 7.1.3. Algae biomass is recovered using a dissolved air flotation (DAF) unit with a recovery yield of 95 % and a solid content of 4 % after harvesting. The DAF effluent contains less than 10 and 1 $mg*L^{-1}$ total nitrogen and phosphorus respectively and thus fulfils the requirements of the legislation (threshold 10 - 15 and 2 $mg*L^{-1}$ N and P respectively). From thickened algal biomass, valuable components such as proteins or lipids could be extracted in the future. In this model the harvested algal biomass is anaerobically treated in a mesophilic digester at 35 °C. The required thermal energy to maintain this temperature is provided by a nearby boiler burning olive pits and if necessary is complemented by thermal energy produced by an external power plant operated with natural gas. In the anaerobic digester, low biogas yields were achieved of around 0.11 L CH_4*g VS^{-1} added probably due to ammonia toxicity and due to the unavailability of the biomass substrate to anaerobic bacteria because of the thick cellular membrane of algae or bacteria. In order to increase biogas yields, digestion can be performed at thermophilic conditions resulting in yields of up to 0.16 L CH_4*g VS^{-1} added. Alternatively, algae could be pre-

treated in order to accelerate hydrolysis which is the first step of anaerobic digestion and enhances biogas production (Passos et al. 2013). However, in this case it would probably be necessary to first harvest and concentrate the algae to approximately 15 to 20 % prior to pre-treatment e.g. conducted by thermal hydrolysis and then to dilute them prior to digestion to overcome issues of ammonia toxicity. Both, pre-concentration and thermal pre-treatment are energy-demanding steps and therefore this option has been excluded. Technical parameters of the algae fermentation process are presented in chapter 7.1.4.

The fermentation residues resulting from the biogas plant contain around 2.8 % solids and 1.28 $g*L^{-1}$ ammonium. It is assumed that they are transported to nearby agricultural fields and are applied as liquid fertiliser. Further assumptions concerning the application of fermentation residues on the field such as the amount of released greenhouse gas emissions are summarised in chapter 7.1.6.

Biogas from the UASB reactors and the biogas plant is upgraded to biomethane as described in chapter 7.1.5. A pressure-swing-adsorption (PSA) process is used for the separation of CO_2 and CH_4. The PSA contains 6 absorbers filled with carbon molecular sieves (CMS). The CO_2 enriched stream is injected into high rate algal ponds (HRAPs) and the upgraded biogas is intended to be used as automotive fuel sold at a petrol station close to the algae biorefinery. Therefore, the biomethane is pressurised from 5 bars (after PSA) to 300 bars required at the petrol station. The main assumptions used in the LCA model are presented in Table 5-3.

Table 5-3: Assumptions used for the LCA model, base line scenario

Description	Value	Unit	Notes
Methane yield from UASB digesters	0.15	m^3 CH_4* kg COD^{-1}	Optimised UASB design without heating
Average net productivity of algal biomass	18	g VSS * $m^{-2}*d^{-1}$	Before harvesting also including bacteria, assumed achievable on an annual basis
Nitrogen content in algae biomass	8	wt.%	Polyculture of microalgae cultivated in pre-treated waste water
Carbon content in algae biomass	45	wt.%	Average value
Lipid content in algae biomass	5	wt.%	5 % lipids, 50 % protein, 13 % carbohydrates
Low heating value of methane	50	$MJ*kg^{-1}$	35.9 $MJ*m^{-3}$ at an assumed density of 0.718 $kg*m^{-3}$ at standard temperature and pressure
Pump efficiency	70	%	Commercial pumps values
Average hydraulic retention time in ponds	6	Days	Varies from 4.5 to 10.9 days depending on season and weather

Description	Value	Unit	Notes
Linear water velocity in pond channels	0.3	$m*s^{-1}$	0.3 $m*s^{-1}$, 12 h daytime, no mixing in the night; could be reduced to 0.25 $m*s^{-1}$
Mixing energy required	418	$kWh*d^{-1}*10\ ha^{-1}$	12 h mixing$*d^{-1}$, paddlewheels: 0.34 W* m^{-2} → 418 $kwh*d^{-1}$; new design: 0.1 $W*m^{-2}$ → 120 $kwh*d^{-1}$
Harvesting efficiency in DAF	95	%	40 $g*L^{-1}$ (4 %) biomass in concentrate, flocculants are used
Hours per day of flue gas sparging	12	$h*d^{-1}$	Annual average; sufficient CO_2 dissolved in ponds mornings and evenings
Average energy requirement for flue gas distribution	0.0027	$kWh*kg^{-1}$	According to the GREET model (U.S. Department of Energy 2013), only for pumping, 1.2 m sump depth
Concentration of CO_2 in flue gas	11.5	vol%	Calculated for the biomass boiler operated with olive pits
Overall use efficiency of CO_2	90	%	Experimental data shows that new injection system with 1 m depth and small bubbles can reach a CO_2 transfer efficiency in HRAPs of about 95 %
Anaerobic digester HRT	32.4	days	Digester with 1 800 m³ and heated to 35 °C
Methane yield from anaerobic digestion	0.11	L $CH_4*g\ VS^{-1}$	Experimental data from pilot-scale digesters; corresponds to a theoretical yield of 0.46 L $CH_4*g\ VS^{-1}$ and 21 % biodegradability
Fugitive methane emissions from AD plant	2.2	wt.%	Methane slip from AD plant (Cuhls et al. 2014)

Further assumptions concerning the substitution or rather provision of thermal energy and electricity are summarised in chapter 7.1.8. The substitution of mineral fertiliser is explained in chapter 7.1.9. Assumptions for the substitution of CNG or diesel in a vehicle engine are presented in chapter 7.1.10 and those for substitution of a conventional waste water plant are summarised in chapter 7.1.11.

5.5.2 Energy balance

The energy analysis includes direct energy flows such as the electricity and fuel consumption of the algae biorefinery as well as the amount of biomethane produced. The main direct energy flows are presented in Figure 5-7. A detailed overview of electricity consumptions of each unit process (UP) is given in Table

5-4. All values presented in Figure 5-7 and Table 5-4 refer to the operating of the algae biorefinery for one day.

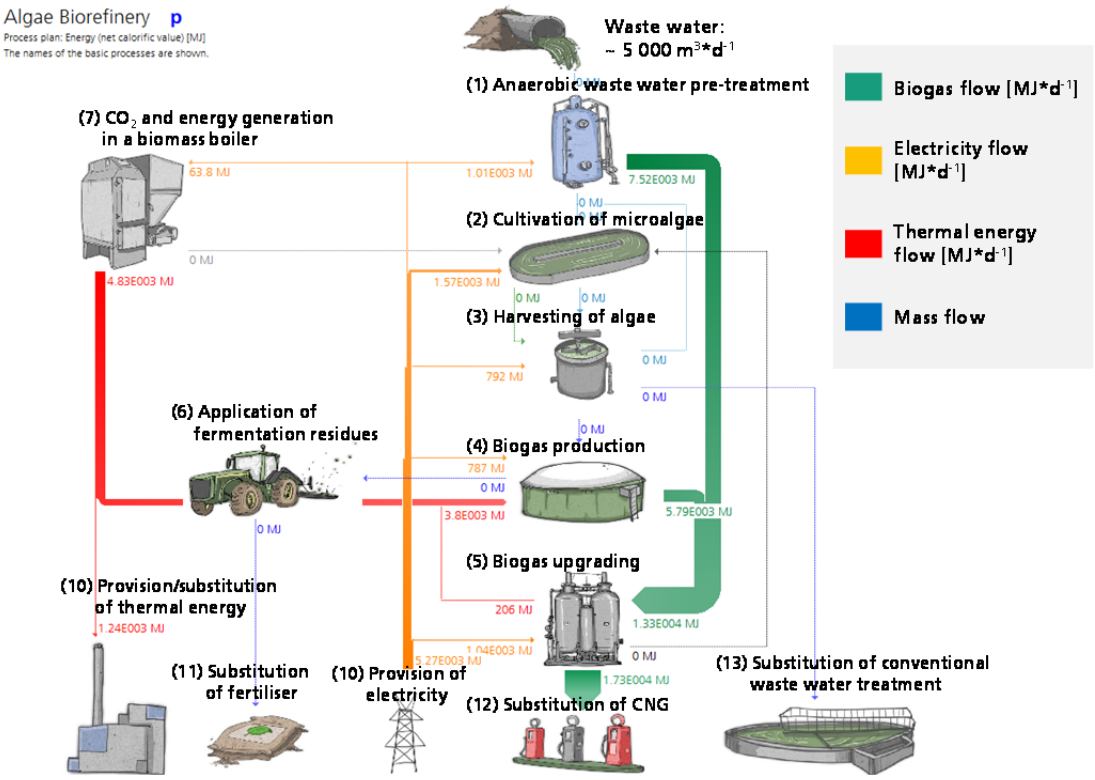


Figure 5-7: Direct energy flows of the algae biorefinery per day of operation, base line scenario, own illustration in LCA software GaBi

In Table 5-4 the cumulative primary energy demand (CED), which is equal to the primary energy demand, is reported regional-specific for the EU, Spain, and for the expected electricity mix of the EU in 2020. Background data for the electricity grid mixes and the thermal energy generation are presented in the appendix in chapter 7.1.8. In total around 5 300 MJ electricity are consumed per day which is equal to approx. 15 000 MJ CED. In addition, 3 800 MJ thermal energy are required for heating up the biogas plant reactor. In the year 2020 the total CED will probably increase slightly. However, the CED from fossil resources will decrease by approximately 17 %.

Table 5-4: Electricity consumption and related cumulative primary energy demand (CED) of the algae biorefinery in MJ per day, UP: unit process

UP	Process	Electricity consump-tion [MJ]	Total CED: EU grid mix [MJ]	Total CED: ES: grid mix [MJ]	Total CED: EU grid mix 2020 [MJ]
1	Primary treatment of waste water	90	255	265	256
1	Pumping waste water to UASB	490	1 386	1 442	1 394
1	Methane stripping	73	206	215	208

UP	Process	Electricity consump-tion [MJ]	Total CED: EU grid mix [MJ]	Total CED: ES: grid mix [MJ]	Total CED: EU grid mix 2020 [MJ]
1	UASB reactor	58	165	172	166
1	H_2S removal with a biofilter	127	360	375	362
1	Pumping waste water to HRAP	177	500	520	503
2	Flue gas transfer into pond	66	188	195	189
2	Water mixing	1 506	4 264	4 436	4 288
3	Pumping water to DAF	312	882	917	887
3	Thickening with DAF	481	1 360	1 415	1 368
4	Pumping to digestion	9	26	27	26
4	Stirring anaerobic digestion	778	2 201	2 290	2 214
5	Biowasher	28	81	84	81
5	Biogas drier	83	235	245	236
5	PSA	546	1 544	1 607	1 553
5	Compression to 300 bar	379	1 073	1 117	1 079
7	Air supply of boiler	63	180	187	181
	Total thermal energy	3 811	4 363	4 449	no value
	Total electricity	5 266	14 906	15 509	14 990

Besides, indirect energy flows are taken into account which result from material inputs that contain embedded energy. One example is the embedded energy in activated carbon used for the fine desulphurisation step applied in the biogas upgrading process. Also considering the primary energy demand of indirect energy flows, approx. 30 000 MJ CED are needed per day, whereas approx. 50 % are caused by electricity consumption. The distribution of CED caused by indirect energy flows of each process area as well as the distribution of CED from electricity is shown in Figure 5-8. The CED of indirect energy flows from the anaerobic pre-treatment of waste water is mainly caused by the disposal of UASB sludge. In the algae cultivation step the indirect CED is for the most part influenced by the production of the pond liner made of polypropylene. Indirect CED from harvesting is traced back to the flocculants used in DAF and in the case of anaerobic digestion it is determined by the biogas plant itself. In the biogas upgrading process the consumption of active carbon and further chemicals contributes to the indirect CED. For the application of fermentation residues the demand for diesel for transport and distribution affects the indirect CED. In the case of incineration of olive pits in a biomass boiler the provision of olive pits mainly influences the indirect CED.

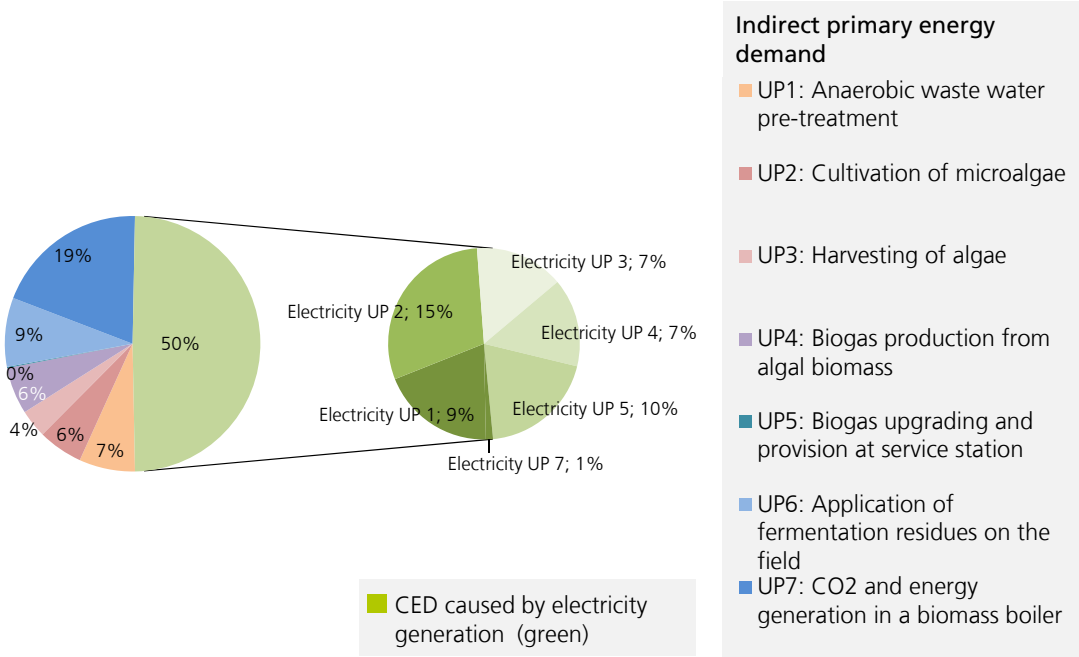


Figure 5-8: Distribution of the total primary energy demand of indirect energy flows and electricity by process area (EU-27 electricity mix, 2011), UP 6 has no electricity consumption

To summarise, the CED can be traced back to each process area as presented in Figure 5-9. The cultivation of algae (UP 2) is the most electricity consumptive step which makes up around 20 % of the total CED. In addition, the generation of CO_2 and thermal energy in a biomass boiler causes nearly 20 % of the total CED.

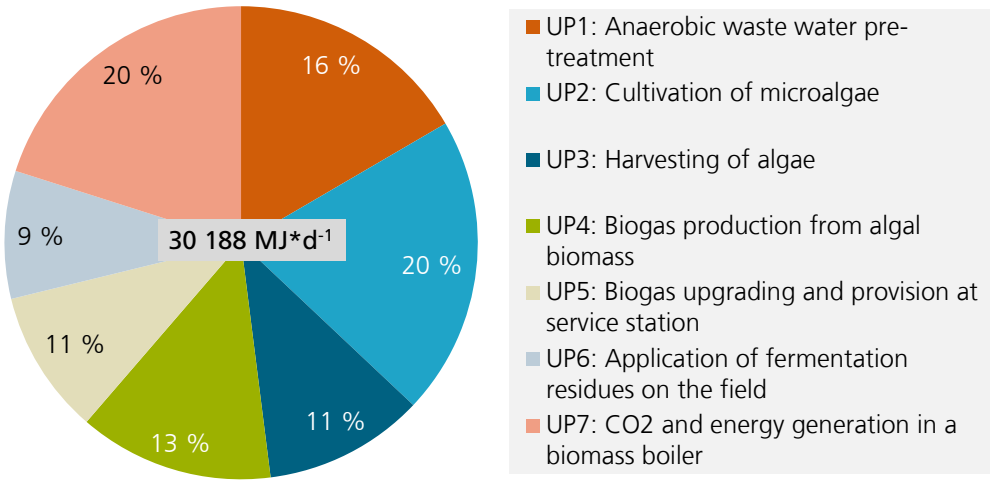


Figure 5-9: Distribution of total primary energy consumption by process area also considering indirect energy flows (European energy mix)

The anaerobic pre-treatment of waste water (UP 1) contributes to 16 % of the total CED. Apart from the UASB process itself UP 1 considers the disposal of

UASB sludge and the pre-desulphurisation of biogas produced by the UASB reactors. The production of biogas by anaerobic digestion of algae is responsible for around 13 % of CED, whereas the provision of thermal energy is attributed to UP 7»CO_2 and energy generation in a biomass boiler«.

Primary energy can be saved by substituting fertiliser, by replacing CNG with biomethane used as automotive fuel and by substituting conventional waste water purification. The savings are in total ca. 21 000 MJ primary energy per day for biomethane, 34 000 MJ for water purification, and 2 000 MJ for fertiliser as shown in Figure 5-10.

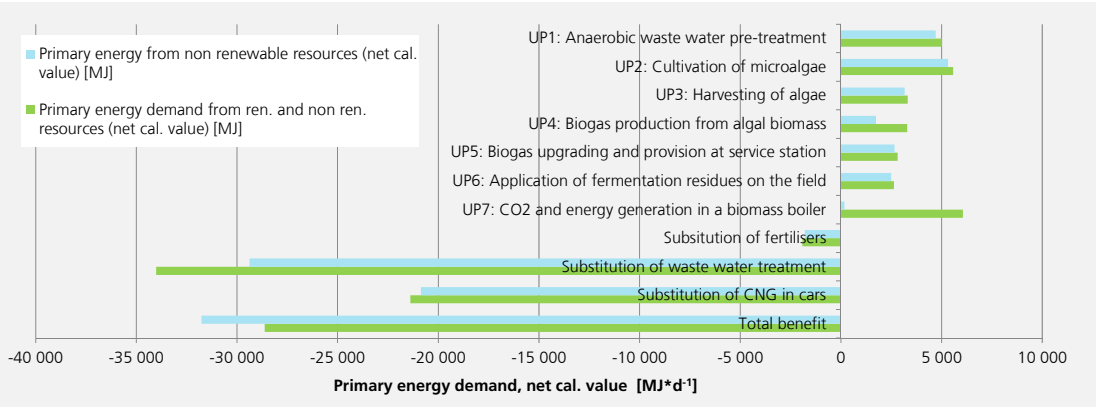


Figure 5-10: Fossil (blue bars) and total (green bars) primary energy demand of each unit process per one day of operation

In order to evaluate whether an energy production technology provides more usable energy than it consumes the ratio of energy produced to energy consumed, also referred to as energy return on investment (EROI), can be calculated (Mulder, Hagens 2008). When the EROI is higher than one the system provides more usable energy than it consumes.

Based on the direct and indirect energy flows given in Figure 5-9 the second-order energy return on investment, as defined by Mulder and Hagens and applied for algae biofuels by Beal et al., can be calculated (Mulder, Hagens 2008; Beal et al. 2011). For calculating the EROI of biomethane produced in the algae biorefinery equation (5-2) is applied.

$$EROI_{BM} = \frac{EC_{BM} + EC_{CP}}{E_{BM}} = \frac{LHV_{BM} * \rho_{BM} + EC_{CP}}{E_{BM}} [-] \qquad (5\text{-}2)$$

EC_{BM} is the energy content of biomethane, EC_{CP} is the primary energy of the co-products fertiliser and water purification, and E_{BM} is the direct and indirect energy required to produce biomethane. Also, in equation (5-2) LHV is the lower heating value of biomethane (49.8 MJ*kg^{-1}), and ρ_{BM} is the biomethane density (0.72 kg*m^{-3} at 0 °C and 1 013 bars). With regard to the investigated algae biorefinery an EROI of 2 is calculated which means that the system has a

positive energy balance. Solar energy that is converted into algal biomass or bacteria is neglected within this calculation.

5.5.3 Carbon and nutrient cycle

The primary inorganic nutrients needed for algae growth are C, N, and P. Algae can use CO_2 from five major sources: (I) from CO_2 diffused from the atmosphere; (II) from the respiration of heterotrophic forms such as bacteria, (III) from bicarbonate alkalinity, (IV) from anaerobic fermentation and (V) from flue gas. Algae grown in waste water have a carbon content of approximately 45 %. Therefore, around 1.67 kg CO_2*kg^{-1} algae DM is needed to provide the carbon. In order to satisfy this demand, the investigated algae biorefinery provides CO_2 by (II) bacteria growth, (III) by alkalinity as bicarbonate in UASB effluent, and by further external sources, namely (IV) CO_2 from biogas upgrading, and (V) CO_2 from flue gas produced in a biomass boiler. In addition, CO_2 losses of the external sources are minimised to just 10 % through the provision of CO_2 via an innovative carbonation sump developed by Aqualia Gestión Integral del Agua S.A. (Godos et al. 2014). CO_2 produced by bacteria growth is calculated to be 1.37 g CO_2*g^{-1} BDO consumed within the HRAPs.

In contrast to the sources I, II, IV, and V that directly provide CO_2, the alkalinity makes CO_2 available by a continual readjustment of the concentrations of the various carbon compounds making up the CO_2-$HC0_3^-$- $C0_3^{2-}$ system. These three forms of dissolved inorganic carbon (DIC): carbon dioxide (CO_2), bicarbonate (HCO_3^-), and carbonate (CO_3^{2-}) are available depending on the present pH-value in water. At pHs below 5, dissolved CO_2 accounts for nearly 100 % of the DIC; at a pH of about 8.3 nearly 100 % of the DIC is in the form of HCO_3^-, and from a pH of 12, approximately 100% of the DIC is CO_3^{2-} (Knud-Hansen 1998). The chemical reactions are shown in the following equations (5-3), (5-4), and (5-5) (Goldman et al. 1971).

$$2(HCO_3^-) \rightleftharpoons CO_3^{2-} + H_2O + CO_2 \tag{5-3}$$

$$HCO_3^- + H_2O \rightleftharpoons H_2O + CO_2 + OH^- \tag{5-4}$$

$$CO_3^{2-} + H_2O \rightleftharpoons CO_2 + 2(OH^-) \tag{5-5}$$

Apart from CO_2 HCO_3^- can also be utilised by many algal species (Prins, Elzenga 1989). Carbonate can generally not be used for algal uptake (Knud-Hansen 1998). In the LCA-model an average pH-value of 7.3 is assumed and a total alkalinity of 405 mg $CaCO_3$*L^{-1} was measured after UASB treatment. At this pH more than 99 % of DIC is available as CO_2 and HCO_3^-. Experiments have shown that in average approximately 58 % of the available DIC is used for algae growth. Reasons for this limitation might be for example changing pH-levels

over the course of the day. For the LCA the use of 58 % of DIC is assumed. The contribution of each carbon source to the CO_2 demand is calculated according to Clescerl et al. and is shown in Table 5-5 (Clescerl et al. 1999).

Table 5-5: Carbon dioxide demand of algae and carbon dioxide sources (base scenario)

Description	Value [kg CO_2*kg^{-1} algae DM]	Notes
CO_2 demand of algae	1.67	Polyculture, 10 ha ponds
CO_2 production by bacteria (II)	0.63	Provided by cellular respiration of bacteria
CO_2 production alkalinity (III)	0.64	Due to CO_2, HCO_3^-, CO_3^{2-} in waste water (pH 7.3)
CO_2 external requirement to transfer to ponds	0.445	90 % transfer efficiency
CO_2 production by biogas upgrading (IV)	0.18	From separation of CO_2 from biogas (UASB and anaerobic digestion of algae) via PSA
CO_2 provision by flue gas (V)	0.29	From burning of olive pits in a biomass boiler

Next to carbon algae need nitrogen to grow. The TKN, also referred to as total Kjeldhal nitrogen, which corresponds to organic nitrogen, ammonia (NH_3), and ammonium (NH_4^+), was measured to be 50 mg*L^{-1} in the waste water inflow. Around 80 % of this nitrogen (40 mg*L^{-1}) is removed during the algae cultivation step. There are two ways of nitrogen removal: 1) nitrogen uptake in cell synthesis, and 2) nitrogen stripping. The latter was assumed to be 5 % of TKN inflow (2.5 mg*L^{-1}). Nitrogen uptake in cell synthesis by bacteria was calculated to be 0.124 (g N-NH_4^+*g^{-1}*VSS)*70 (mg VSS*L^{-1}) = 8.7 mg*L^{-1}. The remaining nitrogen (28.8 mg*L^{-}1) is used for algae growth. Algae were measured to have a final nitrogen content of approximately 8 %.

The phosphorus content of waste water algae is around 1 % of weight. This leads to an uptake of phosphorus of about 23 kg P*d^{-1} which is equal to 47 % of P-removal during algae cultivation.

5.5.4 Blue water consumption and water deprivation

Chiclana de la Frontera is located on the southern coast of Spain in Andalusia on the »Costa de la Luz« in the province of Cadiz. The annual average temperature is around 18 °C, approaching the maximum with 32 °C in August, and minimum daily temperatures of 7 °C in January (IPCC 2014). The region is characterised by approximately 3 000 hours of sunshine per year. The average precipitation is about 550 mm, with November and December being the

wettest months and the summer months the driest ones despite possible heavy rainfall events. The mean wind velocity ranges between 10 and 15 km*h^{-1}. At a nearby weather station in Jerez de la Frontera the mean wind velocity was 10.8 km*h^{-1} during the period 1997-2014 (WetterOnline 2014).

For cultivating algae in open ponds, municipal waste water is applied. This waste water was originally treated in a waste water plant and was then either used for irrigation of golf courses or released into the sea. The highest blue water losses of the algae biorefinery result from the evaporation in the cultivation step followed by the application of fermentation residues on the field.

Water evaporation (V) over a pond is calculated according to the methodology for estimating the evaporation of a lake as described in (Neuwirth 1980) using the equation (5-6).

$$\text{Evaporation (V)} = -2.414 + 1.5857 * n * (0.0475 + 0.040 * \bar{u}) * (\bar{E}_H - \bar{e}_z) \qquad (5\text{-}6)$$

With n = days per month, $\bar{u}$ = mean wind velocity per month, $\bar{E}_H$ = average saturation vapour pressure per month, and $\bar{e}_z$ = average water vapour pressure of the ambient atmosphere per month two meters above the water surface. The variable $\bar{e}_z$ is calculated based on the average monthly relative humidity measured in Jerez de la Frontera in 2013 (WeatherOnline 2014). The ambient saturation vapour pressure is derived from the average temperature in Chiclana de la Frontera of each month during the period 1960-1990 (IPCC 2014). The calculation of the parameters is reported in Table 7-33 in appendix II. By adding up the monthly evaporation over the 10 ha pond and dividing the number by 365 days, around 550 m^3 of water evaporate per day in annual average. In comparison, in Chiclana de la Frontera around 151 m^3 of water are precipitated in annual average on an area of 10 ha (IPCC 2014). The corresponding temperatures and precipitation values (IPCC 2014) are illustrated in appendix II in Figure 7-8. The water balance of the algae biorefinery is presented in Figure 5-11.

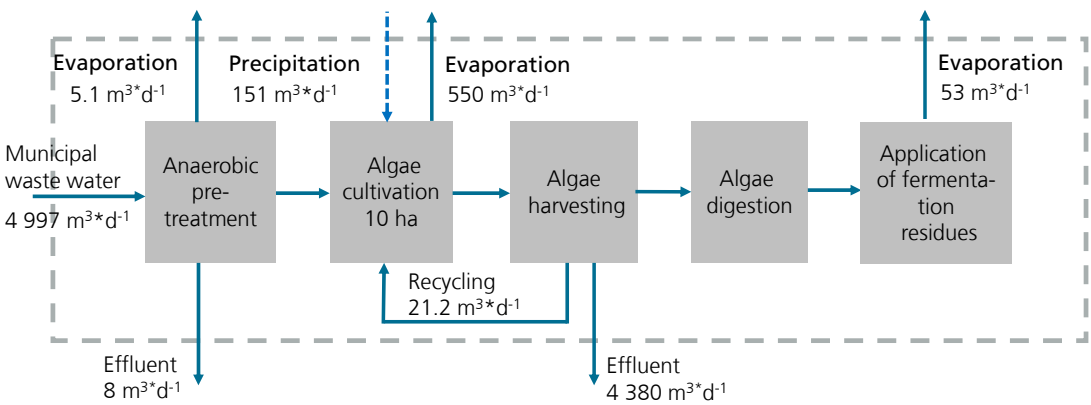


Figure 5-11: Blue water balance of the algae biorefinery; values refer to one day of operation, dotted arrow indicates green water which is not considered

Although precipitation is shown in the flow chart, it is not considered for blue water consumption because it refers to green water. The total direct blue water consumption is 608 m^3*d^{-1} calculated as the sum of evaporation losses from the ponds (550 m^3*d^{-1}), UASB sludge disposal (5.1 m^3*d^{-1}) and application of fermentation residues as fertiliser (53 m^3*d^{-1}). Each day 4 380 m^3 of purified waste water are released from the harvesting process and further 8 m^3 accrue from the dewatering of UASB sludge.

Apart from the blue water consumption that is directly linked to the algae biorefinery, blue water consumption also arises in the upstream chains. Blue water consumption occurs in the production of the installations e.g. in production of concrete bricks or polypropylene liner for the ponds or in the production of operating materials such as diesel, flocculation agents or activated carbon. However, also considering small credits for the biomethane and fertiliser, in total these upstream chains account for less than one m^3 of blue water consumption per day. Higher amounts of blue water consumption go along with the provision of olive pits (73.4 m^3*d^{-1}) and the need of electricity which accounts for 5.4 m^3*d^{-1} (European electricity mix of 2011 is assumed).

Depending on the location of electricity or thermal energy generation the WSF per kWh electricity varies between 9.22 kg water*kWh^{-1} (Andalusia) and 2.42 kg water*kWh^{-1} (Europe) as well as for thermal energy from natural gas between 0.13 kg water*kWh^{-1} (Andalusia) and 0.04 kg water*kWh^{-1} (Europe). Table 7-34 in appendix II shows in detail the blue water consumption and water scarcity footprint of electricity generation and provision of thermal energy from natural gas for Andalusia and Europe. In addition, irrigation water can be avoided by the application of the fermentation residues which accounts for 53 m^3 blue water per day.

In order to calculate the water scarcity footprint as introduced in chapter 4.2.2 direct and indirect blue water consumption are taken into account. The water stress index (WSI) of Chiclana de la Frontera is »one« due to the prevailing arid climate conditions. A map showing the WSI according to Pfister et al. in the region of Chiclana de la Frontera is given in Figure 7-9 in appendix II (Pfister et al. 2009).

Based on the blue water consumption balance as discussed before, equation (5-7) shows the water scarcity footprint (WSF) associated with one day of operation of the algae biorefinery.

$$WSF = \frac{608 + 73.4\,(olive\ pits) + 5.4\,(elec.) - 53}{0.602} = 1088\ m^3 \qquad (5\text{-}7)$$

The WSF of the algae biorefinery is compared with the WSF of conventional waste water treatment which causes around 30 m^3 blue water consumption. This is equal to a WSF of 50 m^3*d^{-1} which is much lower compared to the WSF of the algae biorefinery. Figure 5-12 illustrates the daily water scarcity footprints of the algae biorefinery compared with conventional waste water treatment.

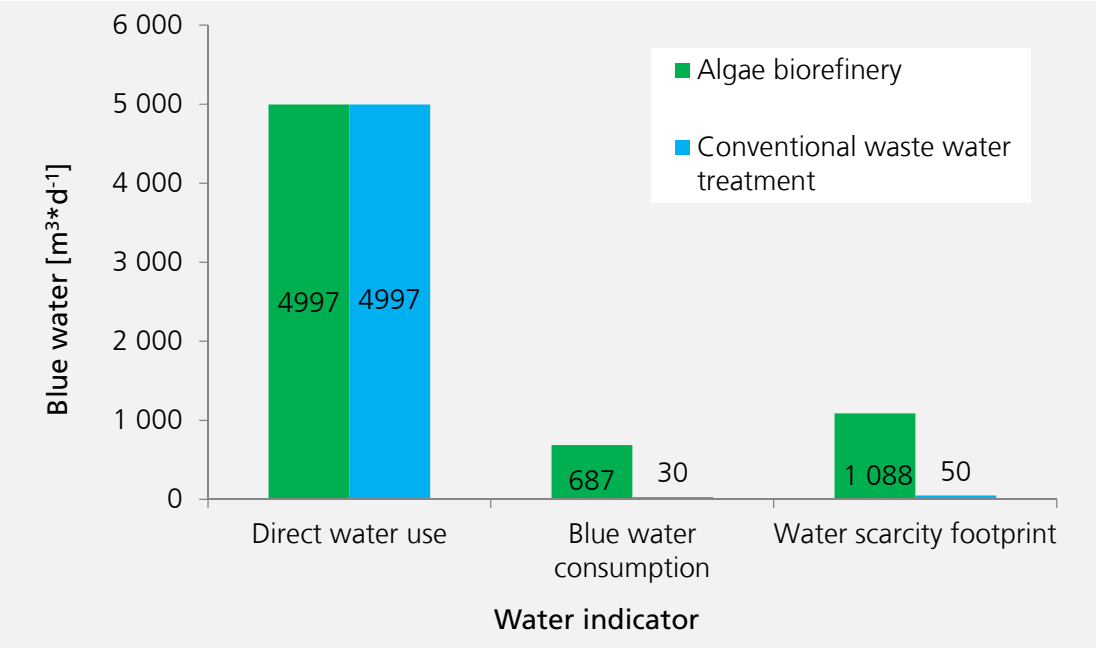


Figure 5-12: Comparison of the daily WSF of the algae biorefinery with conventional waste water treatment

However, in Chiclana a huge part of treated waste water is released to the sea which would mean a high WSF for both options due to the definitively loss of blue water.

5.6 Results of the life cycle impact assessment

5.6.1 Comparison of impact indicators for conventional waste water treatment with the algae biorefinery approach

The following LCA results refer to the functional unit »1 m^3 treated waste water« (fu 1) and the base line scenario. Fu 1 is used to compare the environmental burdens of the algae biorefinery to conventional waste water treatment. As shown in Figure 5-13 the net greenhouse gas emissions per m^3 of waste water treated by the investigated algae biorefinery (AB) are 0.28 kg CO_2-eq. and those of conventional waste water treatment (cWWT) are 0.47 kg CO_2-eq. This means the AB allows greenhouse gas reductions of about 47 % compared to cWWT.

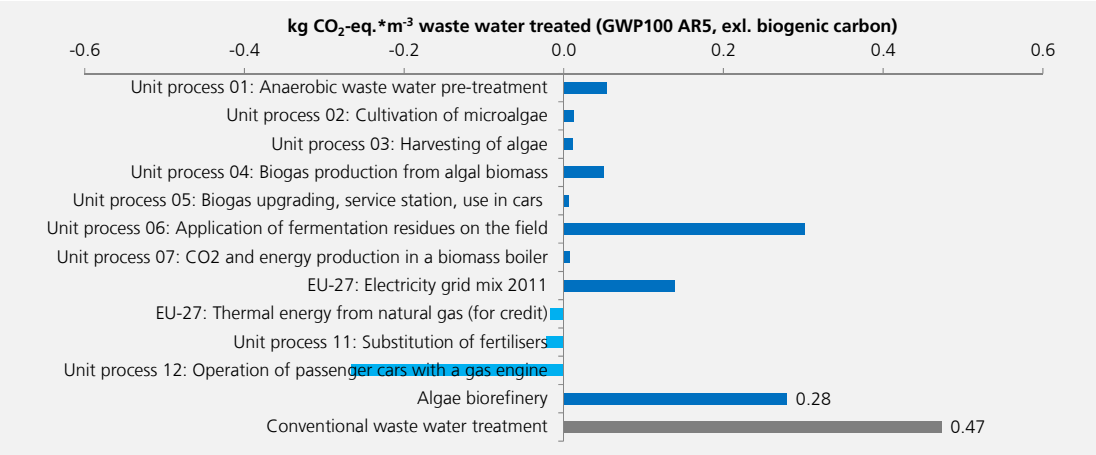


Figure 5-13: Comparison of GHG emissions caused by the treatment of one m³ of waste water

The main benefit results from the substitution of the automotive fuel CNG by biomethane which is produced by the AB. On the other hand the application of fermentation residues causes significant greenhouse gases, in particular nitrous oxide emissions as shown in Figure 5-14.

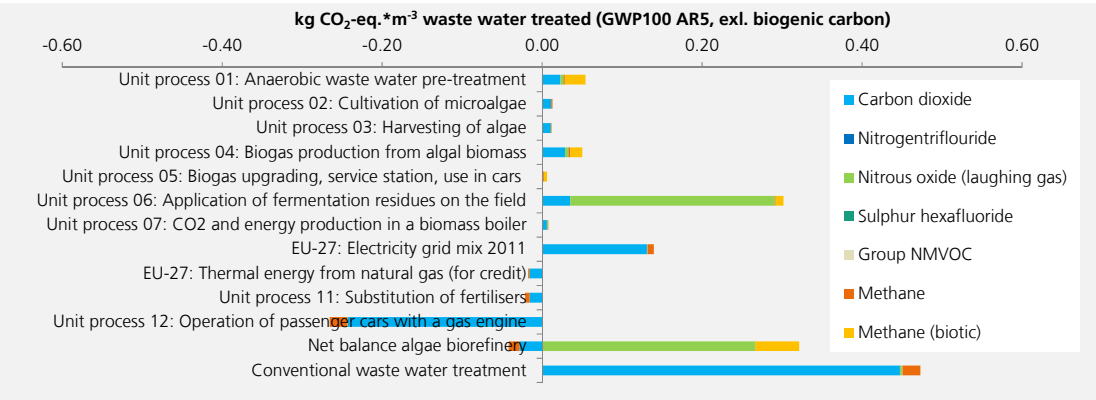


Figure 5-14: Contribution analysis of global warming potential per m³ of waste water treated (GWP100 AR5 excl. biogenic carbon)

Apart from nitrous oxide emissions, that contribute to more than 85 % of the GWP net balance, fossil carbon dioxide emissions contribute to the GWP of the AB, in particular with regard to electricity production. On the other hand fossil carbon dioxide emissions are avoided mainly by replacing CNG with biomethane resulting in a net negative carbon dioxide emissions balance.

Losses of biogenic biomethane into the atmosphere which occur for example during and after the anaerobic treatment of waste water in the UASB reactors, in the biogas plant, during storage and application of fermentation residues, and in the biogas upgrading process contribute to less than one fifth of the GWP net balance, too.

Greenhouse gas emissions in conventional waste water treatment are caused by the consumption of chemicals such as flocculants, the electricity demand in particular because of secondary treatment, the construction of the waste water plant, the disposal of waste from waste water pre-treatment, and by the disposal of primary and secondary sludge. The contribution of each part to the total GHG emissions of 0.47 kg CO_2-eq. per m^3 of treated waste water are presented in Figure 5-15.

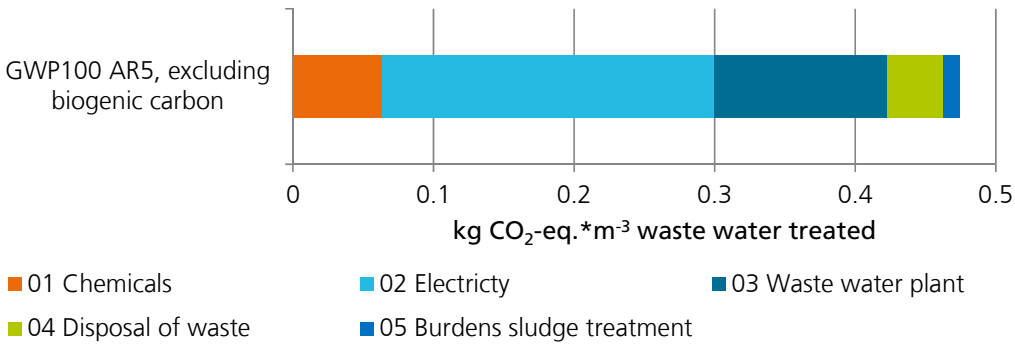


Figure 5-15: Contributions to the GWP of one m^3 of treated waste water in a conventional waste water plant

The underlying assumptions for the conventional waste water treatment are presented in the appendix in chapter 7.1.11. In the same chapter an overall view of the potential environmental impacts for the treatment of one m^3 of waste water is given in Table 7-22.

The use of fossil resources is closely related to GHG emissions which can be expressed in kg oil-eq. as introduced in chapter 4.2.2. This indicator sums up the use of all fossil resources such as oil or natural gas and relates them to an oil of 42 MJ heating value. The indicator is very similar to the primary energy demand from non-renewable resources which additionally covers the use of uranium. The difference of both indicators, in particular, becomes visible with regard to electricity consumption since in the year 2011 in Europe around 28 % of electricity came from nuclear power.

The amount of kg oil-eq. calculated per m^3 of waste water treated by the AB compared to conventional waste water treatment is shown in Figure 5-16. On the one hand the AB allows savings of 0.04 kg oil-eq. per m^3 of waste water treated since more fossil resources are substituted than consumed. On the other hand conventional waste water treatment in total consumes 0.11 kg oil-eq. per m^3 of waste water treated. The major consumption of fossil resources of the AB is caused by the consumption of electricity, followed by the consumption of diesel needed for the application of fermentation residues on the field.

With regard to urban land occupation (B2) the AB requires 0.074 m^2*a per m^3 of waste water treated, whereas conventional waste water treatment requires 0.007 m^2*a per m^3 of waste water treated. This means around 10 times more land is needed for the AB.

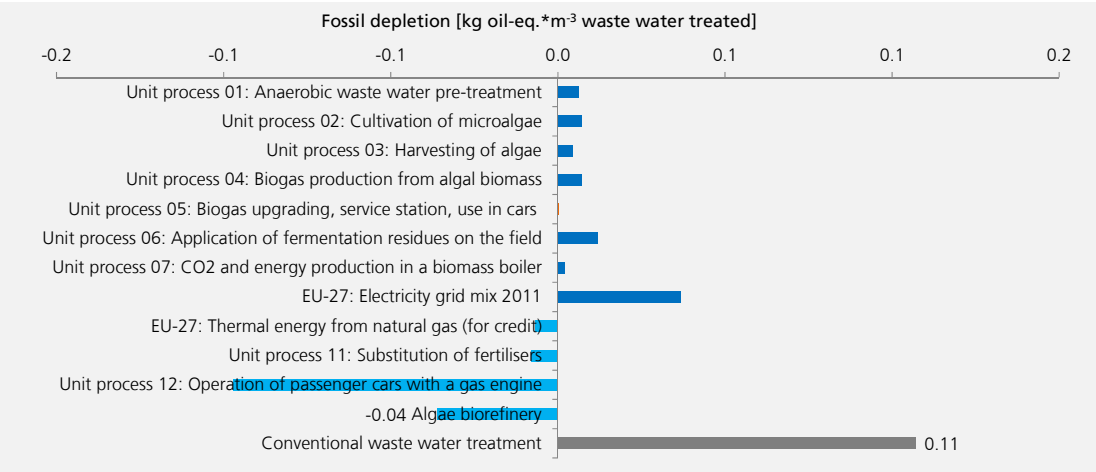


Figure 5-16: Comparison of the fossil depletion potential caused by the treatment of one m^3 of waste water

The ozone depletion potential (B3) of the AB is smaller compared to conventional waste water treatment since ozone-depleting substances e.g. occurring in the upstream processes of the production of flocculants typically be used in conventional waste water treatment can be avoided.

The particulate matter formation potential of the AB is calculated to be 0.0025 kg PM_{10}-eq.*m^{-3} waste water treated which is around 2 times higher compared to conventional waste water treatment (0.0007 kg PM_{10}-eq.*m^{-3} waste water treated). In particular emissions from tractor transport of fermentation residues (59 %) and emissions from burning olive pits (17 %) contribute to the higher emissions of particulate matter.

The photochemical oxidant formation potential of the AB is 0.00308 kg NMVOC-eq.*m^{-3} waste water treated. This value is around twice as much compared to conventional waste water treatment. The highest contribution to the photochemical oxidant formation potential of the AB comes from nitrogen dioxide emitted by the biomass boiler which accounts for approximately 59 %.

The acidification potential is calculated to be 0.015 kg SO_2-eq.*m^{-3} waste water treated which is around seven times higher than conventional waste water treatment (0.0019 kg SO_2-eq.). The main reason are ammonia emissions that occur due to the application of fermentation residues on the field. They cause around 72 % of the acidification potential.

With regard to the depletion of minerals and metals the abiotic depletion potential is calculated to be 2.65E-07 kg Sb-eq.*m^{-3} of waste water treated, whereas for conventional waste water treatment 2.19E-06 kg Sb-eq.*m^{-3} are calculated. This means around 90 % of minerals and metals can be saved by replacing conventional waste water treatment by the AB. Main reason (68 %) is the consumption of iron(III) chloride which is used as flocculation agent in conventional waste water treatment and requires sodium chloride, gold, and copper in its upstream chains. A further 27 % of the abiotic depletion potential of conventional waste water treatment refers to construction materials of the

facilities. The abiotic depletion potential of the AB is probably underestimated since for some facilities such as the UASB reactors or the biomass boiler no data was available.

Looking at fresh water ecotoxicity nearly the same values were calculated for both systems, the AB and conventional waste water treatment. Main contributions are metals such as copper(II) passing waste water treatment. Since no exact measurements have been conducted yet with regard to water quality after treatment no reliable statement can be made.

Fresh water eutrophication potential as well as marine eutrophication potential is calculated to be negative compared to conventional waste water treatment. The main reasons for this are phosphate, ammonia, and nitrate emissions from UASB sludge treatment and disposal. However, the application of fermentation residues probably also has a higher contribution to the eutrophication than calculated because no direct eutrophying emissions into the water have been included in the LCI due to a lack of data. The eutrophication potential also strongly influences the impact on biodiversity which is also calculated to be worse. The contributions of each unit process (UP) to the total environmental impacts per m^3 of waste water treated for each impact category are summarised in Table 5-6.

Table 5-6: Dominance analysis, the percentages indicate the share of environmental burden of each unit process (UP) to the total environmental burdens per m^3 of waste water treated

	Name of indicator	UP1	UP2	UP3	UP4	UP5	UP6	UP7	Elec.	Heat	UP11	UP12
		Share of environmental burdens [%]										
A1	DALY	16	2	2	15	2	71	10	20	-2	-3	-33
B1	Fossil depletion	17	20	12	20	0	33	6	102	-18	-22	-270
B2	Urban land occupation	1	96	0	3	0	0	0	0	0	0	0
B3	Ozone depletion	66	0	11	21	0	0	0	1	0	0	0
B3	Particulate matter formation	4	1	1	14	2	59	17	7	0	0	-3
B3	Photochemical oxidant formation	11	1	1	12	3	11	59	9	-1	-1	-7
B3	Terrestrial acidification	2	0	0	15	1	72	7	4	0	0	-2
B4	GWP100 AR5 excl. biogenic carbon	19	5	4	18	2	108	3	50	-6	-8	-95

	Name of indicator	UP1	UP2	UP3	UP4	UP5	UP6	UP7	Elec.	Heat	UP11	UP12
		Share of environmental burdens [%]										
B5	WSF	1	87	0	0	0	0	12	1	0	0	0
B6	Abiotic depletion	41	1	13	43	1	1	4	9	0	-8	-5
B7	Fresh water ecotoxicity	84	0	3	10	0	0	2	0	0	0	0
B7	Fresh water eutrophication	90	0	2	7	0	0	0	0	0	0	0
B7	Marine eutrophication	67	0	0	5	0	23	4	1	0	0	0
B9	PDF total	9	32	2	9	1	56	16	23	-3	-3	-43

An overview about the LCIA results is given in Table 7-35 in appendix II.

5.6.2 Comparison of impact indicators for algae-based biomethane with CNG used in a car engine

The following LCA results refer to the functional unit »1 MJ CNG (LHV) used in a gas engine« (fu 2). In principle the analysis shows similar results compared to the results presented for fu1. Maybe the biggest difference is the changed scale due to the other reference flow and that a credit is given now for waste water treatment instead of for biomethane. As a consequence the relative contributions vary without changing direction of results. For example, the GWP of 1 MJ biomethane used in a car engine is calculated to be 0.02 kg CO_2-eq.*MJ^{-1} whereas the operation of the defined passenger car with CNG causes around 0.08 kg CO_2-eq.*MJ^{-1}. A detailed comparison is given in Figure 5-17.

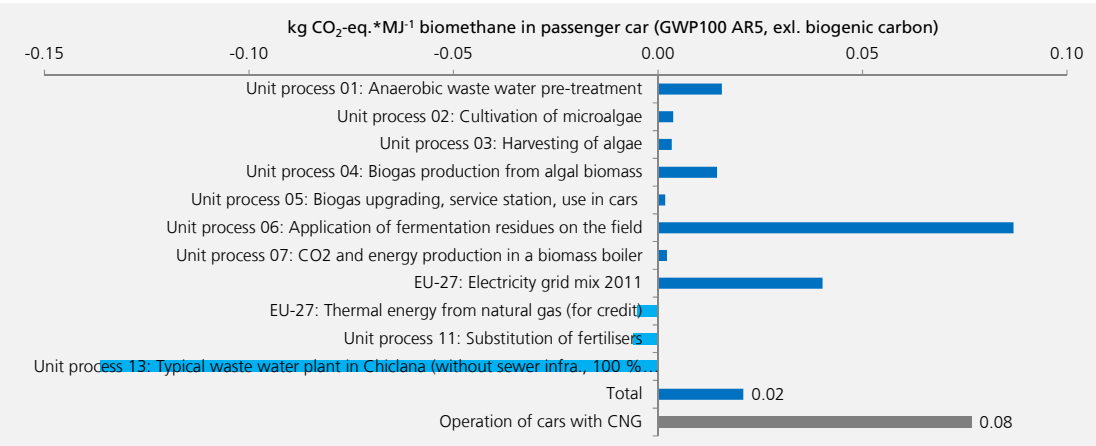


Figure 5-17: Comparison of GHG emissions caused by burning 1 MJ biomethane or CNG in a passenger car

With regard to depletion of fossil resources, the use of biomethane produced by the AB significantly contributes to savings of fossil resources. As presented in Figure 5-18, the use of biomethane reduces the use of fossil resources by 0.013 kg oil-eq.*MJ^{-1} biomethane. In contrast the incineration of 1 MJ CNG causes the depletion of fossil resources by 0.028 kg oil-eq.

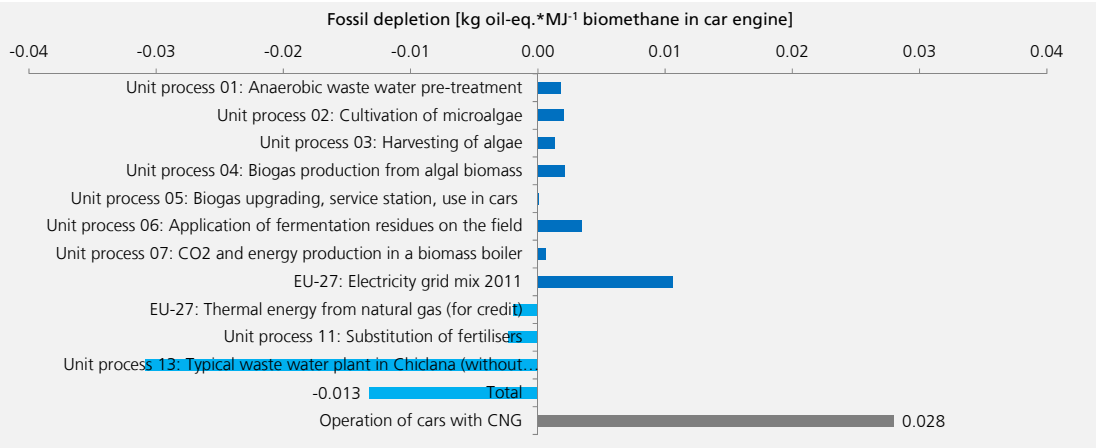


Figure 5-18: Comparison of the fossil depletion potential caused by burning 1 MJ biomethane or CNG in a passenger car

Further advantages of biomethane compared to CNG can be found with regard to ozone depletion and probably with regard to abiotic depletion potential. The other investigated impact categories show, in opposition to the categories mentioned before, disadvantages. An overview about the LCIA results is given in Table 7-36 in appendix II.

A short comparison of the environmental performance of the algae-based waste water treatment (fu 1) and algae-based biomethane production (fu 2) to their references is presented in the next chapter.

5.6.3 Summary of system comparison

Table 5-7 gives an overview on the potential benefits or drawbacks if conventional waste water treatment or respectively CNG is replaced as automotive fuel in a car engine. Negative values imply that the AB leads to additional environmental impacts whereas positive values indicate an improvement.

As shown in Table 5-7 the AB reveals clear benefits with regard to the protection of the climate, protection of fossil resources, ozone depletion, and probably also due to depletion of minerals and metals. However, independent of the selected functional unit negative impacts are calculated with regard to impacts on human health, occupation of land, emissions of particulate matter, photochemical oxidant formation, acidification, water deprivation, eutrophication, and impacts on biodiversity. Since data for calculating fresh water ecotoxicity is not reliable, no clear statements can be made.

Table 5-7: System comparison of environmental burdens caused by the algae biorefinery compared to conventional waste water (ww) treatment and CNG in passenger car (base scenario); negative deviations indicate additional environmental impacts and positive ones less impacts

		Relative changes of environmental burdens [%]	
	Indicator	per m^3 ww (fu 1)	per MJ fuel in car engine (fu 2)
A1	DALY [years]	-21	-52
B1	Fossil depletion [kg oil-eq.]	> 100	> 100
B2	Urban land occupation [m^2*a]	> -100	> -100
B3	Ozone depletion [kg CFC-11-eq.]	89	> 100
B3	Particulate matter formation [kg PM_{10}-eq.]	> -100	> -100
B3	Photochemical oxidant formation [kg NMVOC-eq.]	> -100	> -100
B3	Terrestrial acidification [kg SO_2 eq.]	> -100	> -100
B4	AR5 GWP100, excl. biogenic carbon [kg CO_2-eq.]	41	73
B5	Water scarcity footprint [m^3]	> -100	> -100
B6	Abiotic depletion [kg Sb-eq.]	88	> 100
B7	Fresh water ecotoxicity [kg 1,4-DB-eq.]	uncertain	uncertain
B7	Fresh water eutrophication [kg P-eq.]	- 65	> -100
B7	Marine eutrophication [kg N-eq.]	> -100	> -100
B9	Potentially disappearing fraction (PDF) [species*year]	-30	-42

5.6.4 Scenario and sensitivity analysis

A scenario analysis is carried out in order to understand the influence of different process parameters on the potential environmental impacts investigated by the LCA study. The selection of variable parameters was already explained in the goal and scope definition of the LCA study in chapter 5.4.8. The exact process parameters used for the sensitivity analysis are summarised in Table 5-8. The explanation why these values were chosen is given later on in this chapter together with the results calculated.

Table 5-8: Parameter values considered in the base scenario and scenarios 1-6 introduced in chapter 5.4.8

		Scenario						
Parameter	Base line	1	2	3	4	5	6	7
Digestion temperature [°C]	35	**55**	**57**	35	35	35	35	35
Degradation of VS [%]	27	**39**	**60**	27	27	27	27	27
Methane yield UASB [m^3 CH_4*kg^{-1} COD]	0.15	0.15	0.15	**0.2**	0.15	0.15	0.15	0.15
COD of waste water [g*m^{-3}]	590	590	590	590	**800**	590	590	590
Algae productivity incl. bacteria [g VSS*m^{-2}*d^{-1}]	18	18	18	18	18	**25**	18	18
C uptake of algae culture [%]	90	90	90	90	90	90	**70**	90
N content of algae [%]	8	8	8	8	8	8	8	**5**

In scenario one a thermophilic digestion is assumed using a temperature of 55 °C in the fermenter. Experiments in the All-Gas project showed that the biomethane yield increases to 0.156 L*kg^{-1} VS added when using this temperature (Aqualia 2014). Assuming a theoretical methane yield of 0.41 Nm^3 biomethane per kg algae (VS) as described in chapter 7.1.4 a degradation of 39 % of VS is calculated in order to get the measured biomethane yields. The LCA results of scenario one show an approximately 50 % higher fossil depletion potential compared to the base line in particular due to the higher demand on thermal energy which is provided by incinerating natural gas. Even the amount of GHG emissions increases by approximately 13 % as shown in Table 5-9. The other parameters do not change significantly making this scenario unattractive.

In scenario two a thermophilic digestions is assumed, too using a slightly higher digestion temperature of 57 °C and assuming a much higher biomethane yield of 0.24 Nm^3 CH_4*kg^{-1} VS added as reported by (Ras et al. 2011). Such high average biomethane yields have not been achieved in the All-Gas project yet but show a possible upper limit. LCA results of scenario 2 show a slight increase of the fossil depletion potential by 4 % and GHG emissions are reduced by 10 % compared to the base line. Furthermore, for algae cultivation less external CO_2 from burning olive pits is needed since more CO_2 is separated from biogas. Therefore, a lower quantity of olive pits is incinerated in the biomass boiler which leads to less nitrogen dioxide emissions into the air. As a consequence the photochemical oxidant formation potential is lowered by 26 % compared to the base line.

Scenario 3 assumes the optimisation of biomethane yields in the UASB rectors as measured occasionally under favourable conditions. Since no extra fossil energy is needed but at the same time biomethane yields are increased the fossil depletion potential is decreased by 40 % compared to the base line. The

amount of GHG emissions is also totally decreased by 12 % as well as the photochemical oxidant formation potential for the same reasons as mentioned before.

Table 5-9: Evaluation of different scenarios of process parameter variations compared to the base scenario; reference flow is one m^3 of waste water treated

		Scenario						
	Parameter	1	2	3	4	5	6	7
A1	DALY [years]	3%	-9%	-5%	-1%	10%	1%	-24%
B1	Fossil depletion [kg oil-eq.]	51%	4%	-40%	-38%	-55%	-31%	0%
B2	Urban land occupation [m^2*a]	0%	0%	0%	0%	0%	0%	0%
B3	Ozone depletion [kg CFC-11-eq.]	0%	0%	0%	0%	0%	0%	0%
B3	Particulate matter formation [kg PM_{10}-eq.]	-2%	-8%	-1%	0%	20%	8%	-21%
B3	Photochemical oxidant formation [kg NMVOC-eq.]	-8%	-26%	-5%	-1%	44%	28%	0%
B3	Terrestrial acidification [kg SO_2 eq.]	-1%	-4%	-1%	0%	15%	3%	-27%
B4	AR5 GWP100, excl. biogenic carbon [kg CO_2-eq.]	13%	-10%	-12%	-9%	-6%	-10%	-36%
B6	Abiotic depletion [kg Sb-eq.]	0%	-1%	-1%	14%	2%	1%	0%
B7	Fresh water ecotoxicity [kg 1,4-DB-eq.]	0%	0%	0%	32%	0%	0%	0%
B7	Fresh water eutrophication [kg P-eq.]	0%	-1%	0%	30%	2%	1%	0%
B7	Marine eutrophication [kg N-eq.]	-1%	-2%	0%	24%	6%	2%	-8%
B9	Potentially disappearing fraction (PDF) [species*year]	3%	-13%	-7%	-5%	9%	3%	-18%

Scenario 4 investigated the effects of a higher COD load in the municipal waste water which temporally can happen during a year. Instead of 590 $g*m^{-3}$ a COD load of 800 $g*m^{-3}$ is assumed leading to higher amounts of biogas produced by the UASB reactors. These higher amounts of biogas allow savings of fossil resources of 38 % as well as a reduction of GHG emissions by 9 %. On the other hand the fresh water ecotoxicity potential is increased by 32 % due to the production of higher amounts of UASB sludge which are needed to be disposed. At the same time both the marine and the fresh water eutrophication

potential are increased due to an increasing release of nitrogen and phosphorus emissions into the water that occur due to the disposal of UASB sludge.

In scenario 5 a higher average algae production rate of 0.025 $kg*m^{-2}*d^{-1}$ is assumed which might be achieved in future after several optimisation steps. A higher algae production rate leads to higher amounts of biogas produced by algae fermentation but also leads to higher amounts of fermentation residues that are needed to be disposed. At the same time more external CO_2 is needed for algae growth which means more olive pits are needed to be incinerated in the biomass boiler. All these changes together lead in the end to a reduction of the fossil depletion potential by 55 % and to a 20 % higher particulate matter formation potential mainly caused by an increasing number of transportation processes required for transporting a higher amount of fermentation residues. The high savings of fossil fuels, however, will be only realised if the thermal energy produced by the biomass boiler is used and does not get lost as waste heat. In addition, the higher algae production rate causes a 44 % higher photochemical oxidant formation potential and a 15 % higher acidification potential induced by burning of more olive pits. The total GHG emissions are slightly reduced by 6 % compared to the base line. The marine eutrophication potential, of the other parts, increases by 6 % due to higher amounts of ammonia emissions caused by the application of a higher amount of fermentation residues on the field.

In scenario 6 the consequences of a lower uptake of carbon dioxide by algae on the environmental impacts are investigated. Other studies dealing with algae growing in waste water show that the overall use efficiency of CO_2 might be only 75 % which considers losses in CO_2 transfer (sparging) and from ponds (outgassing) (Woertz et al. 2014). For the sensitivity analyses even only 70 % uptake of carbon dioxide is assumed. The consequences in the LCA model are less fossil fuel consumption and less GHG emissions because of higher credits are given for surplus thermal energy produced by burning of additional olive pits. These results, however, will be only valid if the surplus thermal energy produced by the biomass boiler really replaces thermal energy produced from natural gas. Moreover, the higher amount of olive pits to be incinerated in order to fulfil the CO_2 demand of algae causes a 28 % higher photochemical oxidant formation potential. To conclude, a lower uptake of carbon dioxide by algae means that more external CO_2 is needed. As a consequence, more olive pits are to be incinerated and more thermal energy is produced which should be used for other worthwhile purposes. Without using this higher amount of thermal energy, e.g. during the summer time, a smaller uptake of CO_2 means additional environmental burdens.

In the last of the seven scenarios the nitrogen content of algae is decreased from 8 % to 5 %. This would have several positive effects although the water quality of the treated waste water would probably be worse due to a lower uptake of nitrogen from the waste water. Positive effects are less ammonia emissions in the field which results in a 21 % lower particulate matter formation potential since ammonia is a precursor gas for the formation of particulate matter. Moreover, the acidification potential is reduced by 27 %

since ammonia also contributes to the acidification potential. At the same time the marine eutrophication potential is reduced by 8 % due to less nitrogen emissions into the water. Finally a lower nitrogen content in the fermentation residues results in less dinitrogen monoxide emissions in the field which means that the total global warming potential is reduced by 36 %.

Apart from changes in process parameters the effects of changing the electricity mix and the reference system are regarded. The following uncertainties are studied:

- Substitution of energy mix: EU-28 grid mix in 2020 (Bradley et al. 2015), Spanish grid mix 2011,
- substitution of diesel instead of CNG,
- use of biomethane in a CHP plant instead of use as automotive fuel.

The results are summarised in Table 7-37 in the appendix. The balancing of the Spanish electricity mix instead of the European one shows less than 6 % changes in the final results in each impact category. More important changes go along with the change to the estimated future European electricity mix in 2020 as described in chapter 7.1.8. Consequences are minus 10 % fossil depletion potential per m^3 waste water treated compared to the base line scenario and a 7 % lower global warming potential. An overview of the greenhouse gas emissions per m^3 of waste water treated for each scenario is shown in Figure 5-19. The lowest greenhouse gas emissions were calculated for scenario seven which assumes a lower nitrogen content in microalgae. However, this means that the cultivated algae take up less nitrogen from the waste water resulting in a reduced water purification performance. Therefore, further research is needed to detect waste water algae species which store less nitrogen and to analyse the consequences in more detail.

Another technical solution is to use the produced biomethane not for transportation purposes but to use it as a fuel in an efficient combined heat and power (CHP) plant operated with biomethane. An efficient methane-driven CHP plant with 1.2 MW provided e.g. by the MWM GmbH can reach an electrical efficiency of 43.6 % and a thermal efficiency of 43.5 % (ASUE 2011). In this case a further compression of the biomethane after the PSA is not needed and losses at the petrol station can be avoided. On the other hand the gewitra mbH has measured in average approximately 4 % biomethane emissions from such a CHP plant resulting in significant GHG emissions (Liebetrau et al. 2013). Furthermore, it is assumed that 100 % of the thermal energy produced by the CHP plant can be used and replaces »European thermal energy from natural gas« as described in chapter 7.1.8. In case of the electricity produced, the European electricity mix in 2011 is replaced. For calculating emissions into the air other than GHG emissions, which are released by the CHP plant, the GaBi dataset »GLO: Gas CHP« is used. A comparison of the LCIA results to the base line scenario is presented in Table 7-37 in the appendix. The results show 20 % higher GHG emissions compared to the base line scenario in particular due to the higher methane emissions of the CHP plant compared to the ones released

by vehicle engines which are lower than 0.007 % according to the ecoinvent dataset »ES: operation, passenger car, natural gas ecoinvent« (Jungbluth et al. 2007). The low vehicle emissions are requested by the emissions standards and are achieved at the expenses of less efficiency caused by a high pressure loss at the catalyst. Another reason is that the credit for the produced electricity is relatively small since the European electricity mix has a comparatively low carbon footprint of 0.47 CO_2-eq.*kWh^{-1}. However, in case of using biomethane in a CHP plant the particulate matter formation potential is reduced by approximately 8 % compared to the base line scenario, in particular, because of the substitution of the EU electricity mix. For the same reason the abiotic depletion potential is reduced by 16 %. With regard to the other impact categories no significant changes occur.

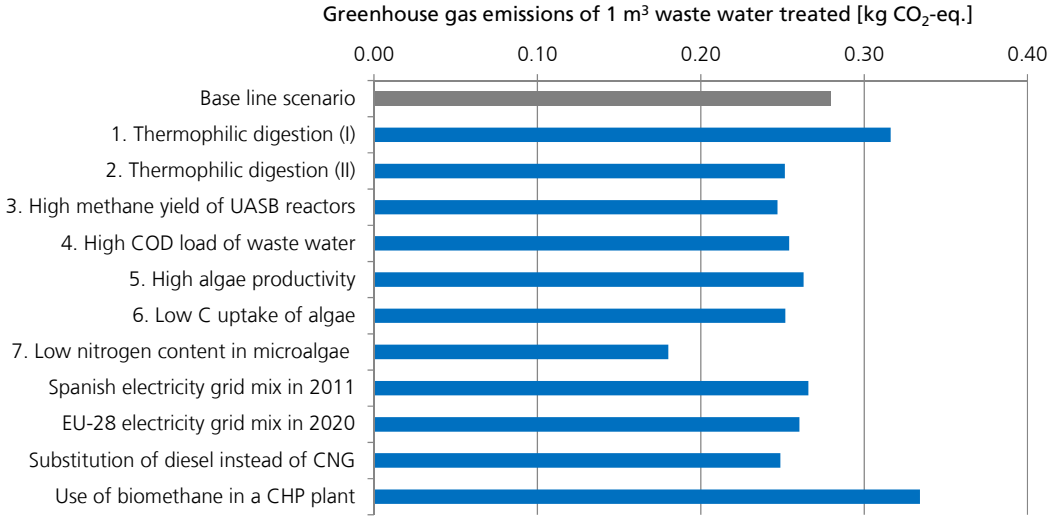


Figure 5-19: Greenhouse gas emissions caused by one m^3 waste water treated in the investigated algae biorefinery in different scenarios

Finally it is investigated for the base line scenario how the choice of the characterisation factors used for calculating the global warming potential (GWP) influences the GWP per m^3 of waste water treated. Therefore, the consequences of selecting the characterisation factors from the fourth IPCC report (IPCC 2007) and from the fifth IPCC report (Myhre, Shindell 2013a) are analysed. Moreover, apart from GWP100 that refers to a lifetime of greenhouse gases in the atmosphere of 100 years, GWP20 is included in the sensitivity analysis in order to address short term effects of greenhouse gases (Bradley et al. 2015). The GWP100 per m^3 of waste water treated is 0.28 kg CO_2-eq. according to the fifth IPCC report (AR5) and 0.30 kg CO_2-eq. using the characterising factors (CF) from the forth report (IPCC 2007). As shown in Figure 5-20 GWP20 is 0.36 kg CO_2-eq. using data from AR5. This means GHG emissions are rated higher in the short term. Relevant changes from the fourth IPCC report to the AR5 mainly refer to the CF of methane and those of nitrous oxide. While methane and biotic methane is rated higher in AR5 (25 instead of 22.3 and respectively 30 instead of 28), nitrous oxide emissions are rated lower

(265 instead of 298). Since nitrous oxide emissions strongly influence the GWP per m³ of waste water treated, the GWP according to AR5 is a bit smaller compared to the one referring to IPCC 2007. However, the new CF for methane in AR5 shows that it is very important to reduce the biomethane losses in the system as far as possible.

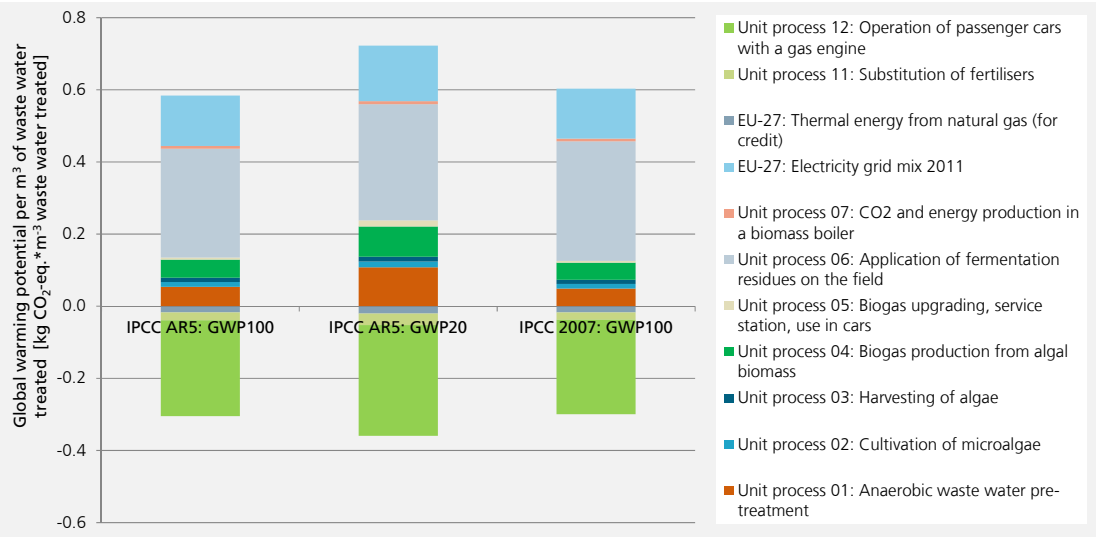


Figure 5-20: Global warming potential per m³ of waste water for GWP100 (Myhre, Shindell 2013b; IPCC 2007) and GWP20 (Myhre, Shindell 2013b)

5.7 Life cycle interpretation

5.7.1 Evaluation strategy

The goal of this interpretation is to analyse whether, from an ecological point of view, the investigated algae biorefinery will be an interesting alternative to conventional waste water treatment and whether it can play a feasible component as part of the bio-based economy in order to extend the biofuel production. In order to evaluate the reliability of the LCA results data quality and consistency are analysed in chapter 5.7.2. Since miscellaneous LCIA indicators are accompanied by a different degree of uncertainty and consequently LCIA results refer to different model accuracy uncertainties caused by the choice of the LCIA methods are discussed in chapter 5.7.3. Against this background results of the LCI analysis (cf. chapter 5.5) and of the LCIA (cf. chapter 5.6) are evaluated in chapter 5.7.4. Finally, limitations with regard to the information value of the LCA study are discussed in chapter 5.7.5.

5.7.2 Evaluation of data quality and completeness

In LCA the following four data quality aspects are of special interest: 1) completeness and 2) technological, 3) geographical, and 4) time-related representativeness.

With regard to data integrity roughly all relevant processes were included. However, in particular some data for equipment are missing due to lack of knowledge of the studied system and possible future developments. For example the production of pumps, manufacturing of the UASB rectors or the production of the DAF unit was not included in the LCI. Nevertheless, no significant changes are expected since such equipment normally only contributes to a small part of the environmental impacts. One exception might be impacts on the abiotic depletion potential (ADP elements) since such equipment is mainly made of metal.

Most of the primary data was collected based on the technology installed in Chiclana de la Frontera and suitable background was chosen. Around 60 % of the data used is estimated to be completely technological representativeness and further 40 % partly representativeness. Approximately 50 % of the background data is site-specific whereas the other 50 % are partly geographically representative. With regard to the representativeness of time more than 80 % of the data used is up-to-date which means it is valid for the year 2014.

When considering both background and primary data approximately 7 % of the data used in the LCA model was measured, 25 % was calculated, 60 % were taken from literature, and 8 % of the data was estimated by experts. The majority of primary data refers to measured data. In contrast to many other LCA studies looking on biofuels from algae not only laboratory data was used but data referring to demonstration scale.

To summarise, it can be noted that the data used for the LCA study has a good data quality with regard to each of the four data quality aspects. Consequently the results are rated to be reliable.

5.7.3 Evaluation of uncertainty in LCIA methods

An evaluation of existing LCIA methods according to their reliability was carried out by (JRC 2010d) and is presented in Table 7-38 in appendix II. The endpoint indicators DALY and PDF, as used in this dissertation, are not recommended by the Joint Research Centre since they are accompanied by a high uncertainty. The indicator fresh water ecotoxicity is recommended but must be applied with caution. In contrast the impact categories ozone depletion, climate change, and particulate matter formation are recommended and were rated satisfactory (JRC 2010d). The other LCIA methods are recommended, too, but require some improvements. Against this background the LCA results are discussed in the next chapter with regard to both goals the assessment of the environmental performance of waste water treatment and the assessment of the environmental performance of biomethane derived from algae.

5.7.4 Evaluation of the results

The results show that waste water treatment by microalgae compared to conventional waste water treatment offers the possibility to protect the climate and to save fossil resources. On the other hand the algae biorefinery requires more space, has a higher water scarcity footprint, and causes higher emissions that contribute to eutrophication, acidification, particulate matter formation, and photochemical oxidant formation. There are several reasons for these results such as the generation of a higher amount of residues compared to conventional waste water treatment that are needed to be disposed and which result from the anaerobic treatment of waste water in UASB reactors and from the digestion of algae in a biogas plant.

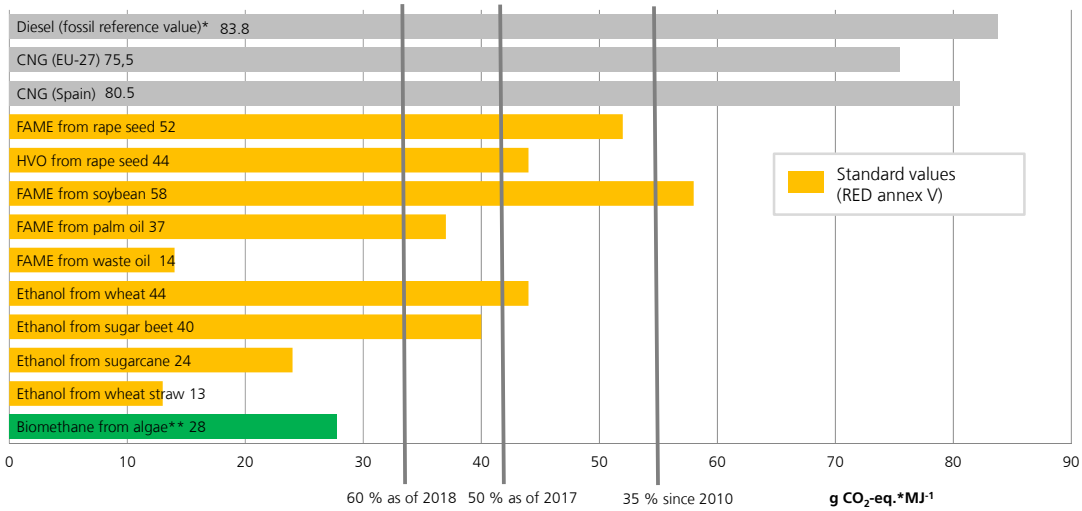
However, there are still uncertainties with regard to the choice of reference processes used to calculate credits. On the one hand it needs to be investigated in more detail whether fermentation residues from algae really can replace conventional fertilisers and what are the local impacts of their application on the field. On the other hand water purification by algae allows removing nitrogen which is not considered for the conventional waste water treatment. In order to remove nitrogen from waste water an additional tertiary treatment is needed that would require additional resources.

Moreover, today the majority of treated waste water in Chiclana de la Frontera is fed into the receiving water which ends in the sea after several hundreds of meters. This means the fresh water is lost in any way making it difficult to decide whether the water footprint of the algae biorefinery really is higher compared to conventional waste water treatment.

It should be mentioned, too that the algae biorefinery still is, in contrast to conventional waste water treatment, under development and a lot of processes can be improved. Furthermore, the production of biomethane which is used as automotive fuel contributes to the goals of the EU which aims to have in average 10 % biofuels on the market by 2020. Since the »share of energy from biofuels produced from cereal and other starch-rich crops, sugars and oil crops and from other crops grown as main crops primarily for energy purposes on agricultural land shall be no more than 7 % of the final consumption of energy in transport in the Member States in 2020« (European Parliament 2015) in particular advanced biofuels such as those made from wastes and algae shall be developed and promoted. Moreover, the additional production of biofuels helps contributing to the greenhouse gas reduction goals of the EU. In order to guarantee that biofuels really reduce greenhouse gas emissions the EU has defined in the RED thresholds for greenhouse gas saving of biofuels (European Commission 2009a). According to the RED, the greenhouse gases of biofuels must be, until 2017, 35 % lower compared to fossil diesel, lower than 50 % until 2018, and lower than 60 % from 2018 on. Exclusively those biofuels that will meet these reduction levels and will fulfil further sustainability requirements count towards the national renewable energy targets. It may be mentioned in this context that there is a political discussion whether biomethane as biofuel should be compared to CNG or to fossil diesel. However, at the beginning of

2015 there has not been any decision on this. Therefore, biomethane is compared to fossil diesel which has the defined value of 83.8 g CO_2-eq.*MJ^{-1}. According to the LCA results presented in chapter 5.6, biomethane produced by the algae biorefinery causes approx. 28 g CO_2-eq. per MJ. This means more than 60 % of greenhouse gas emissions are saved compared to fossil diesel. This means the GHG saving targets for biofuels until 2017 can be met. However, the GHG emissions caused by the biomethane produced by the algae biorefinery were not calculated according to the calculation rules given by the RED. The RED stipulates the use of allocation by energy and does not allow the application of system expansion as done within this LCA study. The allocation by energy would, however, make no sense with regard to the investigated algae biorefinery since the main benefit results from the purification of waste water.

An overview about greenhouse gas emissions of different biofuels compared to diesel and CNG is given in Figure 5-21.



* EU standard value (RED annex V); fossil reference value refers to diesel
** Biomethane from algae biorefinery: credits are given for waste water purification and for the application of fermentation residues on the field, GWP100: IPCC (2007)

Figure 5-21: Comparison of greenhouse gas emissions of different biofuels according to (European Commission 2009a) to fossil diesel and CNG, different allocation approaches were applied

The greenhouse gas emissions of biofuels shown in Figure 5-21 are the standard values given by the RED in annex V (European Commission 2009a). The GHG values for burning 1 MJ Spanish and European CNG in a passenger car are calculated separately with the GaBi software. The LCA model developed uses average data for natural gas from a medium pressure network that is further pressurized to 300 bar and then used in a car engine. Tailpipe emissions are calculated according to the values reported in Table 7-21 in chapter 7.1.10 in appendix I.

As shown in Figure 5-21, the GHG emissions of 1 MJ diesel compared to 1 MJ CNG from Spain are very similar. The reason therefore is that approximately 66.3 % of the natural gas in Span is imported as liquefied natural gas (LNG) to

a large extent from North African countries such as Egypt, Libya, Nigeria (PE INTERNATIONAL 2015). This means significant additional energy is consumed to convert firstly natural gas to the liquid form. As a consequence, the use of CNG instead of diesel in Spain does not contribute to GHG savings, in particular if the car engine operating with CNG is less efficient compared to a diesel engine. However, the use of biomethane as fuel allows both significant reductions in GHG emissions and saving of fossil resources. Moreover, the sensitivity analysis has shown that from a climate protection point of view the use of biomethane as an automotive fuel is probably preferable to the use as fuel in a CHP plant.

5.7.5 Limitations

The results presented in the chapters 5.5 and 5.6 are – according to the author's opinion – reliable within the defined scope. However, if the applied technologies change the LCA results will vary from the results presented before. In particular significant changes are expected with regard to different handling options for fermentation residues. Furthermore, the continued development of the algae biorefinery will probably allow significant improvements that are not considered by the results presented.

The results are only valid for the LCIA methods selected. However, the choice of LCIA indicators and methods was done against the background of a sustainable development as defined by the integrative concept of sustainability. Therefore, all relevant sustainability impacts that can be assessed by LCA were included within the LCA study. Nevertheless, the selected LCIA methods refer to different levels of accuracy as described in chapter 5.7.3. In particular, the endpoint indicators DALY and PDF are based on a high uncertainty and therefore should be interpreted with caution.

It should be also mentioned that the results refer to the situation to be found in south Andalusia and can vary strongly depending on the choice of location. In particular, algae growth and thermal energy demand strongly depend on the local climate conditions.

Furthermore, the results are only valid for the data presented in appendix I and cannot be transferred to other algae biorefineries.

5.8 Assessment of complementary sustainability indicators

5.8.1 Life cycle wide technological risks

A possible risk to the environment is that the waste water treatment operating with microalgae does not work appropriately during the entire year leading to temporarily additional emissions into the sea. In addition, small amounts of robust waste water algae might be released into the sea possibly influencing the marine ecosystem. However, the risk of damage is limited to the local region and, hence is estimated to be small. By reducing the amount of fossil fuels needed for waste water treatment as described in chapter 5.6, possible risks caused by oil spills can be avoided. Moreover, the extraction of unconventional oil or gas deposits such as oil from tar sands, oil shale or gas extraction by hydraulic fracturing is associated with many risks for humans and the environment even in case of no accidents (Bardi 2013). In addition, the extraction of natural gas e.g. by hydraulic fracturing causes significant higher GHG emissions compared to conventional natural gas in the range of 20 g CO_2-eq.*MJ^{-1} according to different studies in the US, UK, EU, and Germany (Fritsche et al. 2014). In case of oil extracted from a depth of 6 000 m GHG emissions were calculated to be between 104 and 125 g CO_2-eq.*MJ^{-1} (Agentur für Erneuerbare Energien e.V. (AEE) 4/10/2015).

5.8.1 Development of physical capital and impact on added value in the region to ensure living standards

Due to a high uncertainty in the economic assessment of the algae biorefinery caused by the early stage of development, employment effects can hardly be assessed. The calculation of differential cost is also hardly possible. Therefore, a cost-benefit analysis is carried out which uses a relatively simple model that was introduced by (Turton et al. 2012). As introduced in chapter 4.2.3 this model is based on the idea that all costs concerning operational expenses (OPEX) can be estimated by using the economic figures fixed capital investment (FCI), cost of operating labour (COL), cost of utilities (CUT) and cost of raw materials (CRM) only. By means of these four cost categories along with the help of certain multiplication factors, it is possible to make detailed estimations on several further costs (Piotrowski et al. 2013). Consequently, this approach does not need much information and thus, is cyclopedic in its application. However, this approach works only at the expense of accuracy because the model can only give an approximation of real costs. In the following the estimations for 1) FCI, 2) COL, 3) CUT, and 4) CRM are described:

1) Estimation of FCI: Since the final construction costs of the whole algae biorefinery are not fully available yet the components of the FCI are (partly)

estimated by (Delrue et al. 2012) who built up a cost model for biodiesel from algae.

2) Estimation of COL: The labour costs are based on estimations as well. Since the All-Gas project is still in its pilot phase, many engineers, technicians, and scientists are involved in building up a prototype of such a biogas-facility with algae cultivation. Of course, many of these employees are not needed for the basic later operation of the plant. Therefore, estimations focus on a number of employees that is realistic for normal business in the future.

3) Estimation of CUT: All costs of utilities are calculated with current market prices. The costs for the provision of thermal energy are set to zero because in the base line scenario all the heating is provided by incineration of olive pits which belong to raw material rather than utilities. Fresh water is only needed in a low amount e.g. for the biogas washer. In particular, CUT consists of costs for electricity consumption.

4) Estimation of CRM: All annual costs for the consumption of raw materials are estimated with current market prices. Raw materials comprise olive pits, activated carbon, sodium hydroxide, coagulants, polymers, and UASB sludge disposal. Costs for algal biomass are a one-time investment and thus, not included in (annual) costs of raw materials.

A summary of all costs assumed is given in Table 7-39 in appendix II.

In order to apply the method for cost estimation of the algae biorefinery some technology specific factorial corrections were applied. The annual depreciation is calculated with the FCI and a depreciation factor. Within this thesis depreciation has been corrected from 15 years (factor 0.067) to 20 years (factor 0.05). Overhead costs, which include expenses for security, canteen, general management, office facilities etc., have been corrected by the factor 0.5. It is assumed that there is no canteen, no advertising, only reduced expenses for security and that office facilities and general management do not exceed a certain degree and/or are already included in the costs for administration.

Revenues are generated from selling biomethane at a service station, for waste water treatment and if possible for the fermentation residues. Since the biomethane is not considered to work as heating gas but rather as a fuel for vehicles, the price for it is linked to the price of diesel which is assumed to be substituted. Since the heating value of the biomethane is 16 % higher than the heating value of diesel, a 16 % higher price is assumed in order to connect the price to the eventual performance of the fuel. Furthermore, it is assumed that biomethane is exempted from tax. A fee of 0.23 €*m^{-3} of waste water treated is assumed which is a value at the upper limit. With regard to the fermentation residues only the value of nitrogen and phosphorus are taken into account. 0.91 € per kg N-content and 0.8 € per kg P_2O_5-content are assumed (Landwirtschaftskammer Niedersachsen 7/8/2014). Potassium and water are not taken into account. The assumptions for the value of products and services generated in the algae biorefinery are summarised in Table 5-10.

Table 5-10: Assumptions for revenues generated by the algae biorefinery

Products and services	Benefit [€*year^{-1}]	Source/remark
Water purification	419 746	0.23 €*m^{-3} (estimated)
Biomethane	204 190	1.61 €*kg^{-1}, based on a diesel price of 1.38 €*kg^{-1}
Fermentation residues	22 884	1.14 €*m^{-3}, value for N and P_2O_5

For evaluating the economic feasibility of the algae biorefinery the net present value (NPV) is calculated. It is calculated by summing up all cash flows (discounted with a certain interest rate over the time periods), starting with the initial investment. The cash flow in each period is calculated as the difference between revenue and OPEX minus the depreciation.

Dynamic factors that were introduced and that affect the NPV and/or future cash flows are the interest rate, a technical efficiency growth rate, future development of diesel prices and a productivity growth rate. All factors were chosen as an annual average over the entire period of 20 years.

The interest rate is the main determinant used for discounting. It reflects the future development of the economy and was chosen to be 4 % in the base scenario.

Annual improvement in efficiency gives potential for future cost reduction which means a reduction of OPEX. This efficiency growth factor is to incorporate factors such as improved energy efficiency and improved technology. In the base scenario it is assumed to be 0.75 % per year.

Since future prices for fossil fuels such as natural gas and diesel will probably increase due to higher exploration and extraction costs (Boyce, Nøstbakken 2011) a dynamic rate of 2.5 % for biomethane prices is introduced.

The last dynamic growth rate indicates growing productivity and thus affects the output. By means of optimisation of algae digestion and thus higher methane yields or more suitable algae species, the output quantity can be increased almost steadily. In this base line 1.1 % is assumed.

Based on the assumptions made a NPV of – 1 353 210 € is calculated making an investment uneconomically. The referring development of OPEX and revenues during a time period of 20 years is shown in Figure 5-22.

In order to get an overview over the impact of changes in parameters on the NPV a sensitivity analysis was conducted. The simulation of different scenarios such as good case, normal case or bad case shows how the profitability of the project depends on the chosen uncertainty parameters, whereas the sensitivity analysis of one single parameter shows the direct impact of that particular factor while all other parameters are held constant (ceteris paribus). Uncertainty parameters that were used in the sensitivity analysis are the interest rate, development of prices, growth in efficiency, and productivity growth.

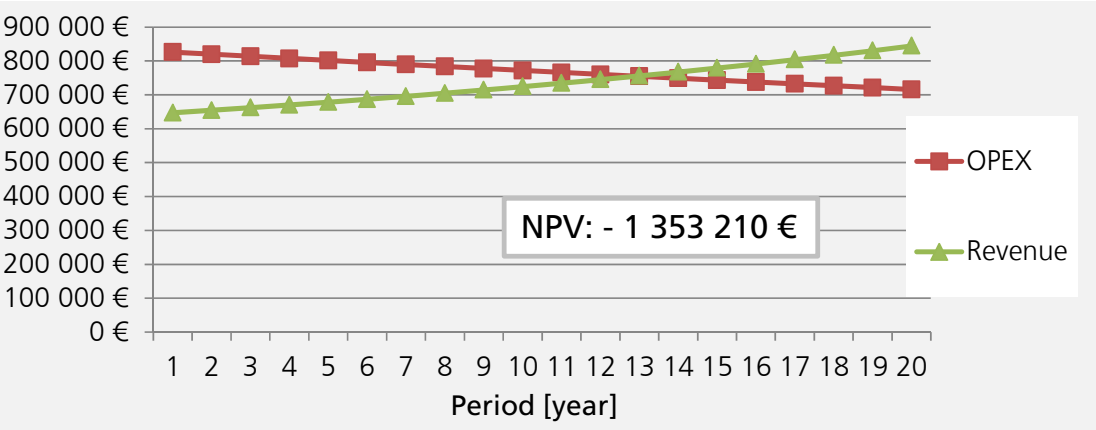


Figure 5-22: Calculated OPEX and revenues of the algae biorefinery in a time period of 20 years

The sensitivity analysis especially focuses on the interest rate and the development of prices since these are the two variables that are defined exogenously. The interest rate (IR) is varied between 2 % and 10 % whereas the price level (PL) is varied between – 1 % and 5 %. The results are shown in Figure 5-23.

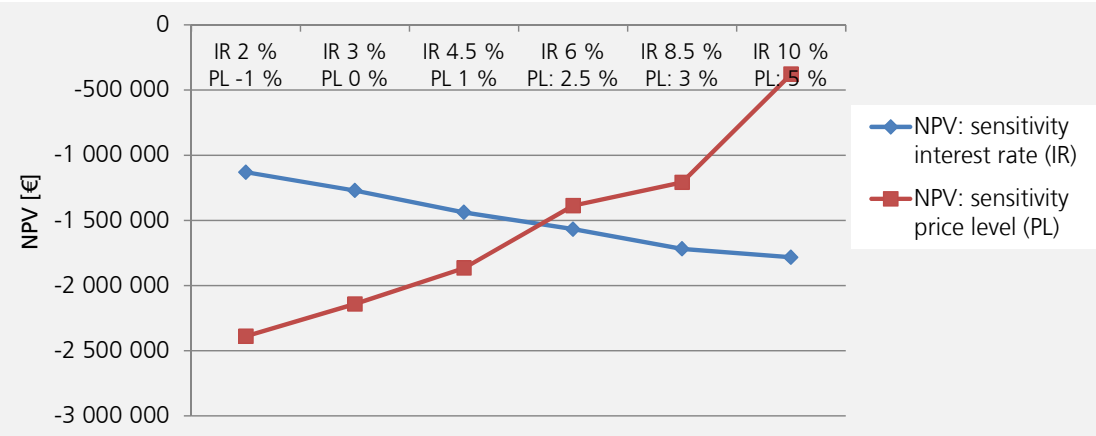


Figure 5-23: Sensitivity analysis of interest rate (IR) and price level (PL) on the NPV

The results clearly show that the future development of the biomethane/diesel price has a strong impact on the NPV. In case of an increase of the biomethane/ diesel price by 5 %, a NPV of approximately – 350 000 € is calculated. On the other hand a higher interest rate lowers the NPV.

A sensitivity analysis of just one single parameter may be the most detailed method to analyse the (direct) impact of one factor. However, it is not suited for an analysis with the overall purpose to make a realistic appraisal of the future. The different parameters may interact with each other and it is probable that more than just one parameter will change in reality. Therefore, a further analysis for the algae biorefinery was conducted: the what-if-analysis. It distinguishes

between three cases: good case, normal case, and bad case. The assumptions made for the parameters in the three cases can be seen in Table 5-11.

Table 5-11: Arrangement of parameters for the three cases

Dynamic factor	Good case [%]	Normal case [%]	Bad case [%]
Interest rate	0.75	4	8.00
Efficiency growth	1.50	0.75	0.00
Price development	4.00	2.5	0.10
Productivity growth	3.00	1.1	0.30
NPV [€]	2 407 950	-1 402 390	-2 643 748

The good case scenario shows that the algae biorefinery can be profitable if very optimistic factors are applied. With these extreme scenarios, the analysis can support decision-making as it gives an upper and lower boundary for estimating the profitability.

Since the chosen dynamic parameters are probably going to differ from real future values, uncertainty was simulated in 1 000 different scenarios applying Monte Carlo simulation. By means of this, not only one factor is changed while the others are held constant but all factors are changed at the same time. This happens with the generation of random numbers which are defined within a fixed range: namely the values used in the good case and bad case scenario. When a random number has been generated for all four parameters, the specific NPV for that scenario is calculated. This procedure is repeated 1 000 times in order to get a representative result and a realistic overview. A statistical evaluation reveals further information about average NPV, median, standard deviation, minimum and maximum value and the probability of a negative NPV which equals the share of negative NPVs in the 1 000 scenarios. The probability of a negative NPV is calculated to be approximately 95.4 %. This means at this time under current assumptions an investment in such an algae biorefinery is probably not profitable. Further statistical values are summarised in Table 5-12.

Table 5-12: Statistical data for the NPV in 1 000 scenarios

Average [€]	Median [€]	Variance [€]	Standard deviation [€]	Minimum [€]	Maximum [€]
-1 277 711	-1 332 688 €	4.32E+11	657 255	-2 740 071	1 068 025

5.8.2 Education of scientists and qualified workers

During the development and construction of the facilities several innovative companies (Aqualia, BDI Bio Energy International, Hygear B.V., Volkswagen AG) and leading European research facilities (University of Southampton, Fraunhofer-Gesellschaft) were involved. The All-Gas project has a volume of

11.8 million Euros, of which 7.1 million Euros are funded by the EU. Direct RTD costs account for 1.7 million Euros of which approximately one million Euros are personnel costs. In total around 4.7 million Euros are direct personnel costs including demonstration activities. Most of the people involved have a Bachelor (level 6), Master (level 7) or doctoral or equivalent level (level 8). Some of them use the project to receive an additional qualification or title. A summary of the person month and related education level according to the International Standard Classification of Education ISCED is given in Table 5-13 (ISCED 2011).

Table 5-13: Person month and educational levels in the All-Gas project

Type of work	Education level according to (ISCED 2011)	Person months
RTD	Level 7 to 8	198
Demonstration (construction)	Level 5 to 8	504
Management and other activities	Level 5 to 7	146
Operation of plant	Level 5 to 7	60

5.8.3 Generation of new knowledge and innovation capacity

Although many projects aiming at developing biofuels from microalgae have been supported by public bodies in the last years, demonstration projects are still missing (Bradley et al. 2015). The All-Gas project is one of three EU-funded demonstration projects that seeks to demonstrate the sustainable large-scale production of biomethane based on the low-cost cultivation of microalgae. In doing so, the project addresses upscaling issues that are essential for innovations in the field of algae technology. The construction of the demonstration plant for the first time with an expenditure of around 3.5 million Euros including investment in laboratories and pilot plant tests allows identifying the main cost drivers and optimisation potentials from an ecological and economic point of view. This new knowledge can be used in the long term to establish algae biorefineries on the market.

5.8.4 Supply safety of a region

The investigated algae biorefinery replaces the automotive fuels CNG or alternatively diesel by biomethane. In this way the dependence on natural gas or respectively mineral oil is reduced. In total in the base line scenario approximately 127 tonnes of biomethane are produced per year. Considering a lower heating value for biomethane of 49.8 $MJ*kg^{-1}$ and of 44.9 $MJ*kg^{-1}$ for CNG and 43.0 $MJ*kg^{-1}$ for diesel respectively, the amount of produced biomethane is equal to 141.6 t CNG or 148 t diesel per year respectively. In Andalusia the consumption of automotive fuels in 2013 was 4 224.3 kilotonnes of oil equivalent (Agencia Andaluza de la Energía 2013a). This means the

contribution to automotive fuels in Andalusia could be approximately 0.0035 %.

5.8.5 Acceptance and participation

A quantitative survey on the acceptance of conventional, advanced biofuels, and algal-based biofuels was conducted in 2012 using as basic framework the trichotomous model of acceptance set by Lucke (Lucke 1995; Hoek 2012). A total of 263 participants from Germany with a valid driver's license represent the survey's sample. The majority of participants surveyed was aged from 17 to 36 (55 %). Only 3 % of participants stated to be older than 67 (Hoek 2012). 83 % of the surveyed people stated to use only conventional fuels because of compatibility (36 %), ethical reasons (28 %), ecological unsustainability of biofuels (17 %), social unsustainability of biofuels (13 %), price/engine modification costs (3%), availability (1 %), use of natural gas (1 %) or lack of information (1 %). In contrast 17 % of the respondents use 1st generation biofuels (E10) because these contribute to climate protection (29 %), are cheaper (41 %), the respondents want to take responsibility for future generations (16 %) or for example to promote the industrial sector (4 %). Apart from questions concerning 1st generation biofuels such as bioethanol and biodiesel, 82 % of the respondents stated to prefer 2nd generation biofuels made from lignocellulosic feedstocks above fossil fuels assuming the same price-performance ratio. 94 % would prefer such 2nd generation biofuels above first generation biofuels.

Assuming that biofuels from algae will be available on the market, 78 % of the respondents stated to be willing to use algal biofuels. However, only half of respondents consider algal biofuels as promising. In comparison with 2nd generation biofuels, conventional biofuels, and fossil fuels the majority would prefer algal biofuels above fossil fuels and conventional biofuels. Only 2nd generation biofuels are seen as more favourable against algal biofuels as shown in Figure 5-24.

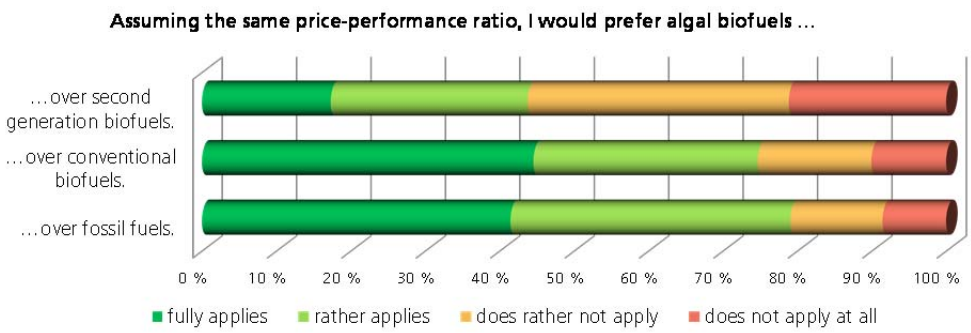


Figure 5-24: Comparison between attitudes towards algal biofuels and other fuel types (Hoek 2012)

31 % of the respondents stated that they are willing to pay an extra charge over fossil fuels, 48 % are not willing to and 21 % do not know. As shown in Figure 5-25 around 40 % of the proponents are even willing to pay up to 10 cents*L^{-1} more for algal biofuels compared to fossil fuels.

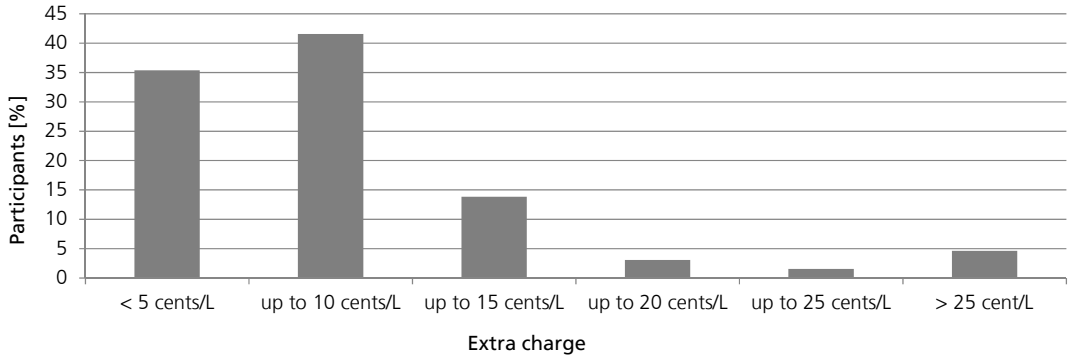


Figure 5-25: Willingness to use algal biofuels for different price premia over fossil fuels (Hoek 2012)

Around 90 % of the surveyed people ask for ecological and social sustainability of algal biofuels as shown in Figure 5-26. However, only around 60 % are convinced that algal biofuels really contribute to the protection of the environment and improve the quality of life.

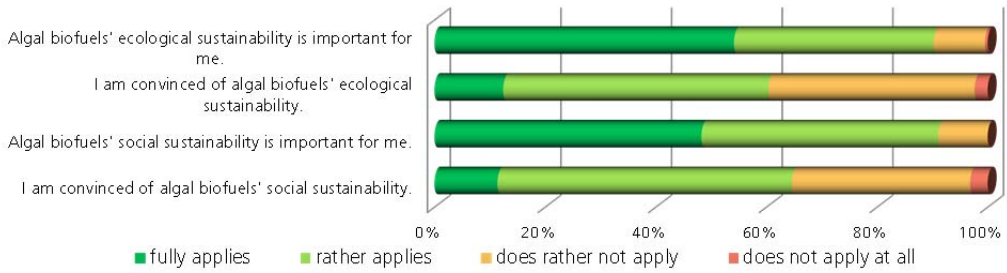


Figure 5-26: Attitudes towards sustainability issues of algal biofuels (Hoek 2012)

In particular, doubts were expressed concerning negative impacts of large scale production of microalgae on the marine ecosystem and negative impacts on the tourism industry (Hoek 2012). In addition, the production of algal biofuels is stated not to be competitive due to the present high energy costs caused by the production process. In contrast, positive employment effects are expected for the Mediterranean region. Moreover, the avoidance of food competition is highlighted positively.

Apart from the acceptance of algal biofuels, the acceptance of the technology is of interest. A German study addressing the acceptance of biogas plants was conducted in 2012 (Kabasci et al. 2012). Although 93.2 % of the questioned 364 residents living in German regions with a high biogas plant density support regenerative energy, only 46.9 % support the use of biogas plants in their

region and even 31.5 % reject it. The main reasons of rejection are increasing odour nuisance (56.8 %), missing information about the feedstock of the biogas plant (55.5 %), missing information about national energy laws and directives (54.2 %), irregular information during the construction (53.8 %), competition for land with food production (53.3 %), lacking information (53.4 %) and knowledge (48.8 %) on technical issues, an increase in genetically modified organisms (47.5 %), changes in local landscape (46.2 %), increasing traffic volume (44.9 %), the loss of value of land (42.8 %), potential risk to groundwater (41.1 %), and dissatisfaction with the choice of location (40.8 %) (Kabasci et al. 2012). Therefore, technical measures should be implemented to reduce odour nuisances. In addition, people affected should be informed in time and regularly to avoid rejection due to missing information.

5.9 Overall evaluation and recommendations

As introduced in chapter 4.4 there are several approaches to weight and to rank different criteria and to deal with conflicts of interests. In order to compare different technical approaches based on LCA indicators the Euclidean distance of a chosen option compared to a reference might be used as a measure for environmental impacts (Sengupta et al. 2015). However, the evaluation carried out here covers more indicators than those that can be calculated by LCA. This means the approach developed by Sengupta et al. is not sufficient for this purpose (Sengupta et al. 2015). Moreover, all approaches that use weighting and ranking rely on value orientations and can be discussed controversially. Since the investigated algae biorefinery is still under development and several indicator values are highly uncertain, an argumentation-based comparison of the investigated algae biorefinery with conventional waste water treatment based on the calculated indicators seems to be the most appropriate way to come to a final evaluation.

Furthermore, several other technical approaches for processing waste water with algae are conceivable and were investigated during the preparation of this case study. They will be discussed additionally in order to present future options and to exclude alternatives that are not promising. An evaluation of sustainability criteria by means of indicators is given in Table 5-14 which compares the algae biorefinery approach with conventional waste water treatment.

Table 5-14: Evaluation of sustainability criteria by means of indicators in order to compare the algae biorefinery with conventional waste water treatment

Principles	Criteria	Indicator	Evaluation
Protection of human health	A1: Human health	Disability adjusted life years (DALY)	Negative with high uncertainty
Avoiding technical risks with potentially catastrophic impacts	AB3: Life cycle-wide technological risks	Amount of used oil multiplied by the probability of oil transport accidents	Slightly positive
Sustainable use of non-renewable resources	B1: Savings of non-renewable energy	Fossil energy savings (FES)	Positive
	B6: Depletion of minerals (nutrients) and metals	Abiotic depletion potential (ADP)	Positive with high uncertainty
Sustainable use of renewable resources	B2: Area efficiency	Urban land occupation (ULO)	Negative
	B5:Water deprivation	WSF	Negative
	B9: Impact on biodiversity and ecosystems	Loss of species during a year	Negative with high uncertainty
Sustainable use of the environment as a sink	B3: Further emissions into the air	Base saturation, PM_{10} intake, Stratospheric ozone concentration, Photochemical ozone concentration	Negative, negative, positive, Negative
	B4: Climate protection	Infra-red forcing	Positive
	B7: Water contamination	Phosphorus concentration Nitrogen concentration Hazard-weighted concentration	Negative, negative, uncertain
Sustainable development of physical, human and knowledge capital	C1: Development of physical capital which can contribute to present and future social welfare	NPV	Probably negative
	C2: Education of scientists and qualified workers	Educational activities	Positive
	C3: Generation of new knowledge and	RTD expenditure in algae technology	Positive

Principles	Criteria	Indicator	Evaluation
	innovation capacity		
Autonomous subsistence based on own income	Impact on added value in the region to ensure living standard	Amount of additional workplaces	Probably positive
Sustainable development of physical, human and knowledge capital	D2: Supply safety of a region	Market share of algal products in Andalusia	Slightly positive
Participation in social decision-making processes	D4: Acceptance and participation	Willingness to pay for algal products, participation in site location search for algae plants	Positive

The results show that waste water treatment by microalgae offers the possibility to protect the climate and to save fossil resources. These advantages can even be improved in the future by developing or modifying technologies that allow an efficient treatment of fermentation residues. For example, it will probably be advantageous to develop new processes for producing high grade fertiliser from the fermentation residues since algae have a very high nitrogen content of more than five mass percent. However, it needs to be investigated with regard to the specific case whether an additional expense for such processes really decreases the total greenhouse gas emissions.

On the other hand the algae biorefinery requires almost 10 times more space compared to conventional waste water treatment and has a WSF that is 20 times higher. The WSF, however, should not be rated too high since usually the major part of the treated waste water is discharged to the sea which means the »real« WSF of conventional waste water treatment is much higher. Moreover, the application of fermentation residues does not only provide nutrients but also irrigation water. In this way water is used beneficially.

The evaluation of potential impacts on biodiversity through the endpoint indicator PDF shows a tendency to higher impacts caused by the algae biorefinery compared to conventional waste water treatment. This assessment is based on various assumptions in the impact assessment model which do not necessarily reflect the local conditions. Hence, further advanced on-site investigations are needed to support this statement.

With regard to the sustainable use of the environment as a sink, the algae biorefinery appears to be disadvantageous since a higher acidification potential, a higher particulate matter formation potential, a lower ozone depletion potential, and a higher photochemical oxidant formation potential also referred to as »smog« is calculated.

Water contamination related to eutrophying substances are evaluated to be higher in case of the algae biorefinery compared to conventional waste water

treatment. This is mainly because of the management of residues from the UASB reactors and the biogas plant. Therefore, further developments and investigations are needed to efficiently manage nutrients cycles. Fresh water ecotoxicity could not be evaluated for certain since reliable data is still missing.

One positive aspect is that the development of such an algae biorefinery supports the education of scientists and qualified workers. The new knowledge gained during the development and during operation of the demonstration plant will give new action alternatives to mankind and will help making a bio-based economy become reality.

If the investigated algae biorefinery or a future version of it will not only be technically but also economically feasible the algae biorefinery will probably have positive impacts on the added value in the region and will generate new workplaces. However, the calculation of the NPV shows that at this time that without considering subsidies or technical modifications an operation of the algae biorefinery as defined by the system boundaries is probably not economically feasible. This means that a current investment in the suggested algae biorefinery probably does not contribute to long-term social welfare. On the other hand future technical developments can strongly influence the economical feasibility. Maybe new processes will be developed in order to extract valuable components from the fermentation residues or from algal biomass prior digestion. They have the potential to increase the revenues and probably also to improve the entire economic efficiency.

One possible way is to pyrolise the fermentation residues and to receive pyrolysis oil, gas, char, and liquids (Kebelmann 2012). Pyrolysis oil can principally serve as feedstock for the production of biofuels or biochemicals. However, until now no commercial products from pyrolysis oil have been developed. Alternatively, fatty acids such as palmitic or linolenic acid can be gained from algal biomass which are known to have antibacterial and antifungal activity (Pohl et al. 2011). The extraction of carbohydrates, hydrolysis, and fermentation to acids such as lactic acid could be also an interesting alternative. However, experiments with lactic acid fermentation from algae conducted in the EU-funded project ECLIPSE show that maximum 17 % by weight of microalgae are fermentable sugars. This means that the yield of polylactic acid (PLA) from algae, which is the most widespread biopolymer on the market, would be only approximately 10 % by weight. Moreover, in terms of economic feasibility one kg of sugars from algae must not exceed a price of 0.22 € in order to compete with a PLA market price of approximately 2 €*kg^{-1}. Such a low price is far off todays' production costs of microalgae. However, there are still various opportunities to lower the production price of microalgae e.g. through innovative low energy-consuming water mixing devices such as those developed in the All-Gas project.

The production and supply with bio-based products derived from algae will strengthen the supply safety in Andalusia. Moreover, the investigation of acceptance of algae biofuels shows a positive picture. The majority of people is

willing to buy algae-based biofuels and probably further products produced from algae in the future, too.

The question whether or not the investigated algae biorefinery has a higher contribution to a sustainable development than conventional waste water treatment cannot be answered definitely. The algae biorefinery offers several advantages over conventional waste water treatment such as less GHG emissions, less consumption of fossil resources, and for example new alternatives for producing biofuels. On the other hand it shows drawbacks such as a higher demand on land and higher harmful emissions into the air. Therefore, the algae biorefinery should be developed further in order to reduce negative impacts and to reduce costs. The LCA analysis shows that in particular the management of residues from waste water pre-treatment and from anaerobic digestion of microalgae has a significant influence on several LCA indicators. This means special attention should be paid to this aspect. Finally, waste water treatment using algae will in some parts of the world probably be an attractive action possibility for future generations. The cornerstones for this were laid within the All-Gas project and the sustainability analysis gives starting points to further improve waste water treatment using microalgae in order to contribute to a sustainable development.

6 Conclusion and outlook

6.1 Validation of the generic methodology

A biorefinery-specific indicator system was developed based on the integrative concept of sustainability. Several tools were selected and further developed in order to assess the identified sustainability indicators. Since a further contextualisation is needed in the case of specific biorefineries the developed methodology to assess the contribution of biorefineries to sustainable development was specified and applied to an algae biorefinery currently under development. The application to this algae biorefinery shows that not all aspects and assigned indicators which were identified by the generic methodology are relevant for all biorefineries. For example the cultivation of microalgae does not require fertile soil making this aspect irrelevant. The application of the methodology shows, too that the sustainability assessment can be limited by the availability of data. For example due to the limited availability of economic data a simplified method was used to carry out the economic assessment for the algae biorefinery. Another example is the availability of data with high quality for algae cultivation which requires a consistent data acquisition over several years. Such long-term measurements are necessary for example because of changing weather conditions in the seasons, changing waste water composition, changing composition of algae species or the presence of natural predators.

A further challenge is the assessment of biorefineries which are still under development. In the case of the algae biorefinery several assumptions were made e.g. which refer to the disposal of residues from the UASB reactors and from the biogas plant. These assumptions are conservative estimations which need to be revised after demonstration, optimisation, and detailed investigation of the whole plant over a time period of several years. In principle, suitable methods for estimating optimisation potentials and scaling effects are still needed in order to evaluate biorefineries of different levels of development.

The evaluation of multiple aspects probably remains the most difficult part since the comparison of incommensurable values is not possible by definition. However, a careful consideration of all identified aspects against the background of the integrative sustainability concept, of scientific, political, and social discourses, and the identification of conflicts of interests can be of help in decision making. Although there are still many drawbacks associated with the algae biorefinery under investigation the positive aspects already present at this time make it look worthwhile to further develop this technological approach.

Despite various challenges as already mentioned which occurred during the application of the developed methodology to assess the contribution of biorefineries to sustainable development, the methodology was proven to be suitable and should be applied in future, too. One disadvantage of the methodology still remains the high effort and the required understanding of the

integrative concept of sustainability. Depending on the extent of available resources and time the amount of indicators might be reduced to a reasonable extent. This would on the other hand mean that there still remains the risk that essential sustainability impacts are overlooked.

6.2 Conclusion

The work carried out within this thesis goes far beyond previous sustainability assessments. Most other studies looking at waste water algae exclusively investigate the technical feasibility, efficiency of nutrient removal, and e.g. effects of technical parameters. Only a few studies investigate some LCA indicators such as GWP or CED (Woertz et al. 2014). Some other studies give a more comprehensive view on possible environmental impacts from algal biofuels but are exclusively based on literature data (Mu et al. 2014). However, there is no study in literature which gives a comprehensive analysis of sustainability impacts based on data collected from pilot or demonstration scale plants. Moreover, no study comprises the development of biorefinery-specific indicators based on an in-depth understanding of sustainability such as given by the integrative concept of sustainability up to the actual evaluation of a real biorefinery under construction.

Such a comprehensive evaluation also raises new issues that are worthwhile being investigated further. It would be interesting to further improve the data basis by collecting data over a period of several years, to analyse several further technical solutions e.g. for treating fermentation residues, to refine the economic assessment based on actual costs under operation, to develop further life cycle impact assessment methods on endpoint level that are more robust or to analyse in detail the innovation capacity of algal biorefineries.

However, this thesis is a good starting point to understand possible sustainability impacts of biorefineries and, in particular, to optimise the algae biorefinery under investigation from the perspective of a comprehensive understanding of sustainability.

6.3 Outlook

Today we are living in a growth-oriented world which mainly derives its prosperity from the increasing use of mineral and fossil resources. This trend goes along with a shortage of fossil fuels and causes huge problems such as climate change. Attempts to extend the availability of mineral and fossil resources lead to the exploitation of non-conventional resources such as tight gas and gas or oil from tar sands and shale. The energy return on energy invested (EROI) of these non-conventional resources is much lower compared to conventional extraction of oil and gas (Bardi 2013). This will intensify the shortage of fossil resources and will accelerate the emission of greenhouse

gases. Moreover, the average ore content sinks constantly rendering mining more energy intensive.

One strategy to tackle these shortages is to increase the efficiency by technological improvements. By doing so the availability of non-renewable resources can be extended but always only for a limited period of time. In some cases technology progresses might even lead to an increase rather than to a decrease rate of the consumption of resources, as first observed by the economist William Stanley Jevons. In 1865 Jevons recognised that the increased efficiency of coal-use led to the increased consumption of coal in a wide range of industries. This effect is also discussed under the terms Jevons' paradox (Alcott 2005), rebound effect or boomerang effect.

Another strategy to counteract the shortage of fossil resources is to substitute fossil fuels by renewable sources of energy. Biorefineries producing bio-based materials and bioenergy can be one component of replacing fossil resources by regenerative ones. In particular biorefineries with a high potential of replacing fossil resources should be further developed. For this purpose, a sustainability assessment – as suggested within this thesis – should be carried out in parallel to technological developments. The development of highly efficient biorefineries will offer new opportunities to future generations to secure their long-term prosperity.

Finally, despite an increase in efficiency and substitution of fossil resources by renewable ones mankind will probably be forced to consume less resources in future.

Maybe the most important question will be how and in which economy we want to live in future. I imagine a bio-based economy which considers the limits of available resources also including the intake capacity of ecosystems.

As Kenneth Ewart Boulding already said in 1973: »*Anyone who believes that exponential growth can go on forever in a finite world is either a madman or an economist*« (Boulding 1973, p. 248).

7 Appendices

Appendix I contains a detailed technical description of the algae biorefinery system as well as important process parameters and life cycle inventory data.

7.1 Appendix I: Technical description and life cycle inventory of the investigated algae biorefinery

7.1.1 Unit process 1: Anaerobic waste water pre-treatment

In a first step municipal waste water from Chiclana de la Frontera is treated to remove oil, grease, and sand. The amount of waste water is dosed according to the uptake of nitrogen for algae growth taking into account nitrogen losses due to bacteria synthesis and stripping. Afterwards the waste water as specified in Table 7-1 is pre-treated anaerobically in optimised upflow anaerobic sludge blanket (UASB) digesters. Generally the rate of reaction in the conversion of acid intermediate products to methane is limited by the operational temperature which should optimally be above 20 °C. Therefore, full scale anaerobic treatment of municipal sewage was restricted to tropical areas (Chernicharo, C. A. L. et al. 2009; Seghezzo et al. 1998). In the last years the feasibility of low temperature (< 20 °C) application has been demonstrated using novel strains of methanogenic organisms that are tolerant towards low temperatures (O'Reilly et al. 2009; McKeown et al. 2009). Furthermore, conventional UASB reactors are usually operated with industrial waste water e.g. from the paper industry on considerably higher COD loads of several kg of COD per m^3. However, progress was achieved and UASB reactors were developed that are working with COD loads of less than 1 kg m^{-3}, too (Zhang et al. 2013).

The UASB reactors installed in Chiclana de la Frontera were redesigned and improved to work efficiently at low temperatures and even at comparatively low COD loads as found in Chiclana de la Frontera. The anaerobic treatment of the waste water in the developed UASB reactors as specified in Table 7-1 at a temperature of around 20 °C showed a removal of 50 - 70 % of total COD and an average methane yield of 0.15 m^3 CH_4*kg^{-1} COD. The theoretical maximum at standard temperature and pressure would be 0.35 m^3 CH_4*kg^{-1} COD. The UASB reactors are operated at local temperatures without any heating.

Table 7-1: Waste water characteristics in Chiclana de la Frontera

Water quality variable	Median	Unit	Remarks/reference
COD before UASB	590	mg*L^{-1}	(Aqualia 2014)
Raw waste water BOD	350	mg*L^{-1}	(Aqualia 2014)
Total Kjeldahl Nitrogen	50	mg*L^{-1}	(Aqualia 2014)

Water quality variable	Median	Unit	Remarks/reference
(TKN) of raw waste water			
Raw waste water P	10	$mg*L^{-1}$	(Aqualia 2014)
Raw waste water H_2CO_3	550	$mg*L^{-1}$	(Aqualia 2014)
Raw waste water SO_4^{2-}	190	$mg*L^{-1}$	Equals to 63 mg $S\text{-}SO_4^{2-}*L^{-1}$
Raw waste water HCO_3^-	550	$mg*L^{-1}$	(Aqualia 2014)

The methane produced in the UASB either goes to the effluent gas or remains in solution. Depending on the temperature approx. 33 % of the methane stays in the anaerobic effluent as dissolved methane. The dissolved methane in the UASB effluent is recovered via a methane stripper operated under vacuum. A loss of 1 % methane is assumed that is released to atmosphere. The anaerobic treatment of the waste water reduces inorganic components in that way that nitrogen is present in the effluent as ammonia (NH_3) or the ammonium ion (NH_4^+). This is an advantage since algae can use these substances better than nitrogen in its oxidised form. Approximately 90 % of the sulphate in the waste water will be reduced to H_2S. In order to lower the H_2S content in the biogas, the biogas is treated in a desulphurisation system using a biofilter. It is assumed that the UASB sludge is dewatered to a water content of 73 % by addition of flocculation agents followed by mechanical dewatering (Jungbluth et al. 2007). The liquid is recycled internally into the waste water treatment plant. The dewatered sludge is transported to a municipal solid waste incinerator plant (MSWI) where it is incinerated and thermal energy and electricity is produced. Solid residues from the incineration process are assumed to go to landfilling. Based on a price allocation, 64.1 % of environmental burdens are attributed to the disposal service and 32.6 % or 3.3 % to sold heat or to sold electricity respectively (Jungbluth et al. 2007). In order to model these processes the ecoinvent2.2 dataset »disposal, digester sludge, to incineration, future, allocation price« is used.

The essential process parameters used for the UASB reactor, methane stripper, and biofilter are presented in Table 7-2.

Table 7-2: Unit process 1: Anaerobic waste water pre-treatment parameters

Parameter	Value	Unit	Remarks/reference
Amount of waste water	4 997	m^3*d^{-1}	The amount of waste water is defined according to the algae nitrogen needs; ca. 25 000 PE
Amount of waste from initial treatment	74	$kg*d^{-1}$	Oil, grease, and sand that goes to landfill
Anaerobic sludge production	0.2	kg $TS*kg^{-1}$ COD	(Aqualia 2014)
Anaerobic digestion COD efficiency	60	%	COD is reduced from 800 to 320 $mg*L^{-1}$

Parameter	Value	Unit	Remarks/reference
Pumping efficiency	70	%	For pumping the water to the inlet of the UASB reactors
Pumping height	7	m	Corresponds to the height of the UASB reactors
Anaerobic reactor running time	24	$h*d^{-1}$	(Aqualia 2014)
Methane yield per kg COD	0.15	m^3 CH_4* kg COD^{-1}	Corresponds to the amount of biogas obtained for biogas upgrading = 372.45 Nm^3*d^{-1}
CH_4 in biogas	80	%	CH_4 content was increased due to new design
CH_4 losses to atmosphere	1	%	Estimated, corresponds to 2.98 kg biotic CH_4 per day
Electricity biofilter	0.09	$kWh*m^{-3}$ biogas	For a biofilter operating at 8 000 ppmv H_2S, H_2S level is less than 300 $mg*m^{-3}$ after filter (Aqualia 2014)
SO_4^{2-} reduced in UASB	90	%	(Aqualia 2014)
H_2S in raw biogas	11.5	$g*Nm^{-3}$	(Aqualia 2014), equals 1.1 % (v/v)

7.1.2 Unit process 2: Cultivation of microalgae in primary treated waste water

Microalgae are grown in 10 ha open raceway ponds using effluent from UASB reactors. In order to guarantee an adequate mixing of water to maintain cells in suspension, to prevent thermal and oxygen stratification, to allow an effective use of the available solar irradiation, and to disperse nutrients (Weissman, Goebel R.P. 1987) a theoretical minimum mixing velocity of about 0.05 $m*s^{-1}$ is required (Andersen 2005; Fon Sing et al. 2011). In practice, however for large ponds flow velocities of at least 0.2 - 0.3 $m*s^{-1}$ are required. Craggs et al. report an average horizontal water velocity (V) of 0.2 $m*s^{-1}$ to be sufficient to mix waste water around a 1.25-ha HRAP (Craggs et al. 2012). Another study from Park and Craggs on high rate algae ponds reveal 0.15 $m*s^{-1}$ to be sufficient (Park, Craggs 2011). In order to avoid too much gravity settling, this study assumes 0.3 $m*s^{-1}$ despite high electricity consumptions.

Depending on the head losses, channel dimensions, and velocity the hydraulic power requirement (P) can be calculated according to equation (7-1) (Andersen 2005):

$$P = \frac{Q(w,d,V) * \rho * h * g}{\eta} \qquad (7\text{-}1)$$

with P: power [W], Q: quantity of water in motion [m^3*s^{-1}] (Q: width (w) [m] * depth (d) [m]* velocity (V) [m *s^{-1}]), ρ: liquid density [$kg*m^{-3}$], h: head loss [m], g: 9.81 [$m*s^{-2}$], η: electrical efficiency of the paddle wheel [-].

The proportion of inlet power transferred to the liquid (η) is estimated to be 0.17 which is an average value for paddle wheels operating over a flat bottom. However, other LCA studies report a value of 0.4 which means much lower energy requirements (Rogers et al. 2014; Lundquist et al. 2010b). The head loss due to friction is calculated with Mannings's equation (7-2) (Andersen 2005):

$$V = \frac{1}{n} * R^{\frac{2}{3}} * (h * L^{-1})^{\frac{1}{2}} \Leftrightarrow h = \frac{V^2 * n^2 * L}{R^{4/3}} \qquad (7\text{-}2)$$

with V: mean velocity [$m*s^{-1}$], R: mean hydraulic radius [m] (with R=dw/(w+2d), d: channel depth and w: channel width), h: head loss [m], L: channel length [m], and n: Manning's friction coefficient [$s*m^{-1/3}$]. The Manning's friction coefficient is estimated to be 0.012 for smooth plastic on granular earth (Oswald 1988). The calculation of power consumption neglects the dissipation in curves and losses caused by sumps. However, the water velocity influences the final electricity consumption much more than these losses as shown in (Lundquist et al. 2010b). Table 7-3 summarises the design parameters of the raceway ponds applied.

Table 7-3: Unit process 2: Design parameters for open raceway ponds

Characteristic	Value	Unit	Remark/references
Depth (d)	0.3	m	Typical depth
Length (L)	250	m	Design parameter
Width (w)	18	m	Design parameter
Surface area	100 000	m^2	Corresponds to 10 ha
Pond volume	30 000	m^3	Calculated
Mean liquid velocity	0.3	$m*s^{-1}$	All-Gas experiments; lower speeds might be feasible: 0.2 (Craggs et al. 2012), 0.15: (Park, Craggs 2010)
Mixing energy required for paddlewheels	418	$kWh*d^{-1}*10\ ha^{-1}$	12 h mixing*d^{-1}, 3.5 kW*ha^{-1} → 418 kWh*d^{-1}
Residence time	6	days	Calculated
Flue gas daily injection period	12	$h*d^{-1}$	In particular during sunny hours
Flue gas from biomass boiler	2 312	$kg*d^{-1}$	Amount is calculated by the carbon balance, cf. chapter 5.5.3
Amount of sumps	2	units *$HRAP^{-1}$	Design parameter

Characteristic	Value	Unit	Remark/references
Input flow rate	5 000	m^3*d^{-1}	Including recycling of water from DAF
Evaporation losses	550	m^3*d^{-1}	cf. chapter 5.5.4

Using equation (7-1) for a time period of 12 $h*d^{-1}$ an electricity demand of 418 kWh (3.5 $kW*ha^{-1}$) for waste water mixing is required. A low energy flow buster with a submergible impeller was developed in the All-Gas project that reduces the electricity demand by more than three times as mentioned in chapter 5.5.1. Further electricity is required for pumping primary treated waste water to the ponds and for the provision of CO_2 from biogas upgrading and flue gas via a new injection system with a depth of 1.2 m and small bubbles. It is assumed that the algae culture captures 90 % of the gaseous CO_2 injected (Sheehan et al. 1998). The material and energy demands for the cultivation of microalgae in open ponds are summarised in Table 7-4.

Table 7-4: Material and energy consumption for algae cultivation in open raceway ponds per day

Unit process	Inputs	Value	Unit	Remark/references
Raceway lining	Polypropyl-ene (PP) foil	19.1	$kg*d^{-1}$	PP foil with a thickness of 0.75 mm, 10 years lifetime (Andersen 2005)
Raceway construction	Concrete hollow blocks (clay)	94	$kg*d^{-1}$	44 cm height, 21.5 cm depth, density 650 $kg*m^{-3}$, 20 years lifetime
Pumping waste water to HRAPs	Electricity	49.09	$kWh*d^{-1}$	70 % pumping efficiency, 2.5 m pressure loss
Mixing water in raceway	Electricity	418.42	$kWh*d^{-1}$	120 kWh are possible with low energy flow buster
CO_2 injection	Electricity	18.4	$kWh*d^{1}$	Sump depth: 1.2 m, combined compressor and motor total efficiency: 67 %

Depending on the environmental conditions, biomass yields differ strongly (Craggs et al. 2013). Since waste water is used for microalgae cultivation, the flexibility in adjustment of nutrient ratio and concentration as well as pH adjustment is very low. Furthermore, microalgae growth can be limited by the presence of undesirable microorganisms and microalgae predators, the presence of toxic compounds in waste water, and the presence of organic nitrogen as the main source of nitrogen. First measurements over a time period of nearly one year showed that in average a yield of 18 g $VSS*m^{-2}*d^{-1}$ can be achieved. The main assumptions for algae productivity are summarised in Table 7-5.

Table 7-5: Algal productivities measured in experimental waste water treatment high rate algal ponds

Criterion	Value	Unit	Remarks/references
Species	Polyculture of micro-alage		Dominant: *Chlorella, Secenedesmus, Micractinium, Further: Navicula, Euglena, Chlamydomonas, Cyclotella, Golenkinia, Kirchneriella*
Biomass concentration	404	mg VSS*L^{-1}	Calculated for bacteria and algae
Average annual algae productivity	18	g VSS*m^{-2}*d^{-1}	Also considers bacteria, amount is equal to 59 t*ha^{-1}*a^{-1} (Aqualia 2014), (Menger-Krug et al. 2012)
	23.3	g*m^{-2}*d^{-1}	Goal of the All-Gas project: 85 t*ha^{-1}*a^{-1}
	16.7	g*m^{-2}*d^{-1}	New Zeeland (Park, Craggs 2010)
	22	g*m^{-2}*d^{-1}	California (Lundquist et al. 2010b)
Nitrogen removal	80	%	Cf. chapter 5.5.2
Phosphorus removal	47	%	Cf. chapter 5.5.2

Some of the waste water algae species shown in Table 7-5 were analysed with regard to protein, lipid, and carbohydrates content. The results are presented in Table 7-6. Depending on many factors such as the availability of nutrients and light or the presence of microalgae predators, the composition of species can vary a lot. For this study an average protein content of 50 %, lipid content of 5 %, and a carbohydrate content of 13 % is assumed. The remaining biomass consists of refractory materials e.g. in the cell walls that can hardly be extracted and measured. Furthermore, the ash content of waste water algae can reach up to 40 % of dry matter (Aqualia 2014). High levels of proteins and low levels of lipids are typical for algae grown in nutrient-rich media such as waste water (Pandey et al. 2014).

Table 7-6: Protein, lipid, and carbohydrates content measured in waste water algae

Species	Protein [% DW]	Lipids [% DW]	Carbohydrates [% DW]	Source
Scenedesmus obliquus	45 - 55	08-12	10 - 15	(Becker, Venkataraman 1982)
Scenedesmus quadricuata	47	1.9	no value	(Becker 1994)
Scenedesmus sp.	33	12	27	(Voltolina 1999)
Chlorella vulgaris	51 - 58	14 - 22	12 - 17	(Becker 1994)
Chlorella pyrenoidosa	57	2	26	(Becker 1994)

Species	Protein [% DW]	Lipids [% DW]	Carbohydrates [% DW]	Source
Chlorella pyrenoidosa	55	12.2	31.8	(Oh-Hama, T., Miyachi, S. 1988)
Micractinium pusillum	no value	24	no value	(Abou-Shanab et al. 2011)
Mixed algae culture	no value	08 - 29	no value	(Woertz 2007)
Mixed algae culture	no value	4.9 - 11.3	no value	(Woertz et al. 2009b)
Mixed algae culture	no value	2 - 10	no value	(Mu et al. 2014), neutral lipids
Chlamydomonas rheinhardii	48	21	17	(Becker 1994)
This study	50	5	13	

7.1.3 Unit process 3: Harvesting of algae

As microalgae suspensions typically show a concentration between 0.02 % and 0.06 % total suspended solids (TSS) dewatering is an energy intensive process (Uduman et al. 2010). Several studies have reported a contribution of the costs for harvesting to be more than 30 % of the total cost in case of algal production in open ponds (Salim et al. 2011). Common processes for harvesting microalgae are flocculation, centrifugation, and micro screening (Schenk et al. 2008). Various flocculation methods have been applied to aggregate the microalgal cells to increase the effective »particle« size and hence simplify sedimentation, centrifugal recovery, and filtration (Molina Grima et al. 2003). The most common flocculation agents are multivalent salts, and synthetic cationic polymers such as polyacrylamide, though these can inhibit direct reuse of algae growth media (Salim et al. 2011). Moreover, the algal chemical sludge is only restrictedly suitable for anaerobic digestion since microbiological activities might be inhibited (Schenk et al. 2008). Cabirol et al. for example have shown that aluminium and sulphate can inhibit the specific methanogenic activity of methanogenic and acetogenic bacteria used for anaerobic digestion of sludge from waste water (Cabirol et al. 2003). In contrast to these chemical agents chitosan, a biopolymer principally derived from the exoskeletons of crustaceans, can be applied as flocculation agent. Beach et al. measured for example for *Neochloris oleoabundans* recovery efficiencies of approximately 95 % when using chitosan at the same time being less energy intensive and having lower environmental impacts than harvesting algae using ferric sulphate, centrifugation or filter press (Beach et al. 2012). Other low-cost harvesting techniques are microbial flocculation (Lee et al. 2009) and bio-flocculation (Salim et al. 2011). In the case of bio-flocculation one flocculating microalga is used to concentrate the non-flocculating microalga of interest. Another option is autoflocculation – a spontaneous floc formation e.g. due to excreted organic macromolecules and inhibited release of microalgae daughter cells – that can be initiated by an increase in pH value (Schenk et al. 2008). However, it is still unclear if

these methods are efficient for multi-algae cultures cultivated in large-scale open ponds using secondary treated waste water.

As being most promising cost and energy efficient alternatives in this study dissolved air flotation (DAF) using aluminium chlorohydrate and polymers is investigated. The parameters applied for harvesting of algae are summarised in Table 7-7

Table 7-7: Harvesting of waste water algae with dissolved air flotation (DAF)

Criterion	Value	Unit	Remarks/references
Algae slurry (microalgae/bacteria/ water)	4 450	m^3*d^{-1}	Water coming from HRAPs considering water losses caused by evaporation
Polymer: anionic flocculant ZETAG®8160 polyacrylamide (polycarboxylate)	3	$mg*L^{-1}$	(Aqualia 2014), relative low concentration compared to literature data (Uduman et al. 2010)
Coagulants: polyaluminium chloride	20	mg*L-1	(Aqualia 2014)
Electricity to pump water to DAF inlet	87	$kWh*d^{-1}$	Height 5 m, 24 h, 70 % pump efficiency
Electricity for operating DAF	133.5	$kWh*d^{-1}$	(Aqualia 2014), 0.03 $kWh*m^{-3}$ water; similar value compared to (Lee et al. 2010): 0.035 $kWh*m^{-3}$ water
Biomass harvesting efficiency	95	%	(Aqualia 2014); slightly smaller number in (Frank et al. 2011): 90 %
Final biomass concentration	4	%	Microalgae and bacteria in DAF effluent

7.1.4 Unit process 4: Biogas production from algal biomass

It is assumed that the total biomass containing algae and bacteria with a loading rate of 4 g TSS L^{-1} is put into a mesophilic stirred tank anaerobic digester working at 35 °C in order to produce biogas. The theoretical (maximum) methane yield depends on the biomass composition and amounts to 0.851 m^3 methane*kg^{-1} protein ($C_6H_{13.1}O_1N_{0.6}$), 0.415 m^3 methane*kg^{-1} carbohydrate $(C_6H_{10}O_5)_n$ and 1.014 m^3 methane*kg^{-1} lipid ($C_{57}H_{104}O_6$) (Sialve et al. 2009). The assumed protein composition ($C_6H_{13.1}O_1N_{0.6}$) was derived from the average composition in amino acids weighted by their frequency in *Chlorella vulgaris* (Sialve et al. 2009). In this thesis a theoretical methane yield of 0.41 Nm^3*kg^{-1} VS is taken into account by assuming a biomass composition of 50 % proteins, 13 % carbohydrates, and 5 % lipids. In other studies where microalgae was grown in municipal waste water without nutrient limitation similar compositions characterised by high protein content and lower lipid and carbohydrate content were observed, too (Batista et al. 2014). However, actual measured methane yields are less due to a limited

digestibility of algae and bacteria. Without pre-treatment, a hydraulic retention time (HRT) of 32 days, and at mesophilic conditions (35 °C) a digestibility of 27 % VS (reduction from 77 % VS before to 56 % VS after digestion) was calculated based on the observed biomethane yield at the pilot plant in Chiclana de la Frontera of 0.109 $Nm^3CH_4*kg^{-1}$ VS added. Biogas yields can be increased under thermophilc conditions (~57 °C) (Golueke et al. 1957). In the pilot plant in Chiclana de la Frontera a biomethane yield of 0.156 Nm^3 CH_4*kg^{-1} VS added was measured under thermophilic conditions at 55 °C which is equal to a degradation of VS of 39 %.

The biomethane yields observed fit to another biogas study performed with *C. vulgaris* where 0.15 - 0.24 m^3 biomethane*kg^{-1} VS (28 d HRT) were achieved under thermophilic conditions (Ras et al. 2011). The methane yield can further be increased by longer HRT and thermo-chemical pre-treatment (Chen, Oswald 1998; Lundquist et al. 2010a; Lundquist et al. 2010b), however, these measurements would lead to higher ammonia concentrations in the fermentation broth and as a consequence to toxicity effects making the process unstable (Golueke, Oswald 1959).

Around 55 m^3 effluents from DAF per day are treated in the biogas plant with an initial biomass content of 4 % resulting in an average biomethane yield of 286 Nm^3 per day. The main characteristics of the anaerobic digester are summarised in Table 7-8. The reactor volume is estimated to be 1 800 m^3, the maximum size needed in the summer time to allow a constant biomass input.

Table 7-8: Characteristics of the anaerobic digester

Parameter	Value	Unit	Remarks/references
VSS after harvesting	1 710	kg VSS*d^{-1}	(Aqualia 2014)
Total suspended solids (TSS) after harvesting	2 221	kg TSS*d^{-1}	(Aqualia 2014)
Volatile matter before digestion	77	% VS [g-VS/g-TS]	(Aqualia 2014), 90 % (Collet et al. 2011)
Biodegradability [anaerobic digestion algae efficiency]	(1-(56/77))*100 = 27 (removed VS)	%	(Aqualia 2014), 56 % for *Chlorella* (Collet et al. 2011); 70 % (Menger-Krug et al. 2012)
Methane yield efficiency (y_{B1})	0.109/ 0.156	Nm^3*kg^{-1} VS added	(Aqualia 2014), mesophilic/thermophilic conditions
Biomethane content in biogas	65	%	(Aqualia 2014), (Menger-Krug et al. 2012)
Reactor volume (not always fully utilised)	1 800	m^3	1 digester, 9.5 m height, 0.55 m free top space, diameter 16 m
Heat transfer co-efficient (U-value) of digester	0.4	$W*m^{-2}*K^{-1}$	(Krassowski 2/2/2015), for concrete of medium density
Reactor heating requirement to	0.0232/	$kW*m^{-3}$ reactor	Mesophilic/thermophilic conditions, calculated including

Parameter	Value	Unit	Remarks/references
35 °C/55 °C; temp. input flow 20 °C, ambient temp. and soil temp. 25 °C	0.047	volume	heat losses in AD and heat transfer losses
Heat exchanger efficiency of AD	90	%	Aqualia
Electricity consumption digester	5 W*m^{-3} reactor*1 800 m^3*24 h = 216	kWh*d^{-1}	(Aqualia 2014), power consumption stirring with a vertical mixer
Electricity for pumping from DAF unit to AD plant	2.5	kWh*d^{-1}	10 m height, 60 % pump eff., 24 h*d^{-1}
Hydraulic retention time (HRT)	32.4	days	(Aqualia 2014), 46 days in (Collet et al. 2011)
Operating time	24	h*d^{-1}	(Aqualia 2014)
Anaerobic sludge after digestion (DM)	1 897	kg*d^{-1}	Calculated

Apart from greenhouse gases caused by the energy demand of the anaerobic digester, fugitive methane emissions from the digester or management of fermentation residues can have a strong influence on the greenhouse gas balance (Strauch, Maga 2014). In literature there are no specific values for fugitive emissions from digestion plants using algae as raw material. Moreover, the amount of emissions strongly depends on the technical equipment and operational management (Strauch, Maga 2014). Moller et al. estimated methane emissions from 0 to 3 % of the methane produced (Moller et al. 2009). Other authors estimate around 1.8 % (Olesen et al. 2004) or 0.2 – 2 % (Frank et al. 2012). For the substrate »bio-waste« comprehensive emission measurements are available (Cuhls et al. 2014). They measured on average 2.2 % methane losses which are also assumed for this study. This means that the processing of 2.2 t algae DM per day causes around 2.7 kg methane being released into the air which is not available for biogas upgrading any longer. Due to the absence of more precise data, the emission factors for nitrous oxides, ammonia, and NMVOCs, as presented in Table 7-9, are used for the LCA model.

Table 7-9: Greenhouse gas emissions from AD plant (Cuhls et al. 2014)

Parameter	Nitrous oxides [g]	Ammonia [g*t^{-1}]	NMVOC [g]
AD plant for bio-waste (1 t, 40 % DM)	15	780	230
Algae (1 t DM)	38	1 950	575
Algae (2.221 t DM*d^{-1})	84	4 331	1 277

7.1.5 Unit process 5: Biogas upgrading and provision at a service station

The upgrade of biogas to the provision at the service station consists of several process steps as illustrated in Figure 7-1.

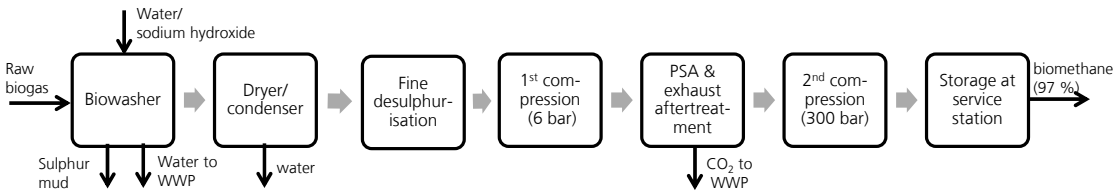


Figure 7-1: Biogas upgrading process and provision of biomethane at a service station

Biogas from UASB reactors and biogas plant containing on average 65 Vol % CH_4, 27.9 Vol % CO_2, 5.4 Vol % H_2O, 0.76 Vol % H_2S, 0.5 Vol % O_2, 0.5 Vol %N_2, and 0.01 Vol % NH_3 goes to a biowasher where the major part of H_2S and ammonia is partly removed. H_2S is mainly converted to elementary sulphur and is sorted out as sulphur mud (Urban et al. 2009). Afterwards, the biogas is blown to a dryer where the water is removed by cooling and condensation. In a next step the raw biogas goes through a fine desulphurisation step using activated carbon filters. Therefore, granular activated carbon is used which can be reactivated after reaching its loading capacity (Kienle, Bäder 1980). In the activated carbon filter H_2S is adsorbed and reacts to elemental sulphur and water. The elemental sulphur is captured inside the pores of the material. Capacities of up to 300 g S*L^{-1} active carbon (~60 %) can be reached which means that for 1 Nm^3 biogas with a H_2S level of 100 vppm 0.0003 kg active carbon (density 0.5 kg*L^{-1}) is needed. For this study a capacity of 30 % is considered as conservative estimate which means a consumption of 0.0005 kg activated carbon per Nm^3 raw biogas.

For the separation of CO_2 and CH_4 a pressure-swing-adsorption (PSA) with 6 adsorbers filled with carbon molecular sieves (CMS) is used. The raw biogas is filled into the adsorber unit, pressurised up to 6 bar, and separated into methane-rich product gas and CO_2-rich lean gas. The lean gas contains around 1.5 % methane which is burned in an exhaust treatment system. After exhaust treatment the gas

flow still contains 0.2 % methane which contributes to climate change. Waste heat is used to provide thermal energy to the biogas plant. Heat losses are assumed to be 10 %. The CO_2-rich exhaust gas is used as input for algae cultivation and the biomethane flow is further pressurised to 300 bar to be applicable for a transportation fuel at a service station.

It is assumed that the service station is close to the algae biorefinery rendering extra transport redundant. A small natural gas service station is assumed covering an area of 35.5 m^2 and having a life span of 50 years. LCI-data for the infrastructure is taken from tables 19.5 and 19.6 of the 17th ecoinvent 2.0 report (Jungbluth et al. 2007).

Methane emissions of a service station occur due to gas leakages during the filling process of the tank. They were calculated to be about 0.018 % (Jungbluth et al. 2007). Additional losses of around 0.001 % result from the annual revisions of the service station. In total 0.02 % losses of biomethane (CH_4, CO_2 and H_2S) are assumed (Jungbluth et al. 2007).

Surplus electricity is needed for the compression of the biomethane from 6 bar after biogas upgrading to 300 bar needed for the filling process at the service station. The specific compressor work (scw) is calculated according to equation (7-3) for isotropic compression.

$$Scw = \frac{\kappa}{\kappa - 1} * R * T_1 * \left[\left(\frac{p_2}{p_1} \right)^{\left(\frac{\kappa}{\kappa - 1} \right)} - 1 \right] \qquad (7\text{-}3)$$

Scw [kJ*kg^{-1}]: specific compressor work

κ [--]: 1.31 (for methane at 20 °C)

R [kJ*kg^{-1}*K^{-1}]: universal gas constant (0.287 kJ*kg^{-1}*K^{-1})

T1 [K]: temperature (293.15 K; 20 °C)

p_2 [bar]: end pressure for the service station (300 bar)

p_1 [bar]: pressure input after PSA (6 bar)

According to equation (7-3), 0.272 kWh*kg^{-1} biomethane are needed to increase the pressure from 5 bar to 300 bar. Assuming a compressor efficiency of 90 %, electricity consumptions accounts for around 0.3 kWh*kg^{-1} biomethane. Attention must be paid to possible nitrogen inputs which can affect the fuel quality. Table 7-10 summarises the parameters for biogas upgrading to fuel quality. Although the values given in Table 7-10 mainly refer to higher throughputs, they are used for this study as a first estimation.

Table 7-10: Biogas upgrading parameters

General parameters	Value	Unit	Remark/references
Raw biogas flow	27.5	Nm^3*h^{-1}	Biogas from UASB and algae digestion
Parameter for biowasher	**Value**	**Unit**	**Remark/references**
Electricity consumption of biowasher	0.012	$kWh*Nm^{-3}$ raw biogas	Based on 500 Nm^3 biogas*h^{-1} (Urban et al. 2009)
Sodium hydroxide	0.0016	$kg*Nm^{-3}$ raw biogas	Based on 500 Nm^3 biogas*h^{-1} (Urban et al. 2009)
Water	0.042	$kg*Nm^{-3}$ raw biogas	Based on 500 Nm^3 biogas*h^{-1} (Urban et al. 2009)
H_2S concentration after biowasher	approx. 100	ppmv	(Urban et al. 2009)
Sulphur mud	No values available	$kg*Nm^{-3}$ raw biogas	Disposal is neglected
Waste water	0.042	$kg*Nm^{-3}$ raw biogas	Disposal is neglected
Parameter for power of the dryer	**Value**	**Unit**	**Remark/references**
Electricity	0.035	$kWh*Nm^{-3}$ raw biogas	Calculated
Parameter for fine desulphurisation incl. compression and PSA	**Value**	**Unit**	**Remark/references**
Electricity	0.23	$kWh*Nm^{-3}$ raw biogas	CarboTech Membrane 350 Nm^{3*} h^{-1} (5 bar)
Activated carbon	0.0005	$kg*Nm^{-3}$ raw biogas	30 % loading capacity of activated carbon
Methane losses of PSA	1.5	%	Average value from survey of manufacturers conducted by Fraunhofer UMSICHT in 2014
Methane slip after combustion of lean gas	0.2	%	Threshold in Germany
CO_2 losses	4.5	%	(Aqualia 2014)
Lifetime of carbon molecular sieves	10	years	Material demand is neglected in this study
Lubricants	0.0000411	$kg*Nm^{-3}$ raw biogas	For lubrication of compression and other systems (ADEME 2011)
Waste heat from exhaust gas treatment	0.08	$kWh_{th}*Nm^{-3}$ raw biogas	Calculated according to methane content, 10 % losses

Parameter for compression to 300 bar	Value	Unit	Remark/references
Compressor efficiency	90	%	estimated
Electricity for 2nd compression (6 bar to 300 bar)	0.272/0.9= 0.303	kWh*kg^{-1} biomethane	calculated
Biomethane losses at service station	0.02	%	(Jungbluth et al. 2007)

Activated carbon production from hard coal also considering reactivation and disposal was modelled in GaBi based on values given in the PhD thesis carried out by (Meier 1997).

7.1.6 Unit process 6: Application of fermentation residues

There are several technical options to process digestate (Rehl, Müller 2011). Possible scenarios are for example the open storage and further field application with a splash plate or drag hoses, the composting of a separated solid phase in windrows and further field application with a compost spreader or for example a closed post-rotting process of the solid fraction and a further application of the finished compost or even mechanical and solar drying and further application as solid conditioner. Another conceivable approach could be return the digestate to the ponds which was shown to cause inhibitory effects on microalgae growth (Uggetti et al. 2014).

Due to the low solid content of the fermentation residues of approximately 3 %, a direct application on the field appears to be an attractive solution. Advantages are 1) that no energy is needed for an additional concentration step, 2) that the high water content can be used for irrigation, and 3) that the use of conventional fertilisers can be reduced or avoided. Disadvantages are 1) the energy demand for transportation, 2) higher GHG emissions on the field compared to GHG emissions caused by composting, and 3) the need of larger storage capacities. The chemical composition of the digestate is presented in Table 7-11.

Table 7-11: Elemental composition of fermentation residues

	Results [% dry basis]							Energy content [MJ*kg^{-1} DM]	
Element	H	O	C	S	N	P	Cl	HHV	LHV
Digestate	6.2	31	52.1	0.88	7.7	1	0.84	21.5	19.7

Emissions into the air from the storage and application of algae digestate on the field have not been measured yet. They depend strongly on the type of soil, application technique, climate conditions, time of application, and the composition of the digestate, and therefore are highly variable (Yoshida et al. 2013). However, in

case of fermentation residues produced by fermentation of bio-waste or manure, measurements of GHG emission are available in literature (Moller et al. 2009; Bruun et al. 2006; Cuhls et al. 2014; Wulf 2002). Although these measurements were carried out in northern European countries under different conditions, these values are used as a first approximation. Table 7-12 summarises emissions factors of digestate application for methane, ammonia, nitrous oxide, and biogenic carbon dioxide.

Table 7-12: Emission factors in literature for the application of digestate on the field

Emission factors				References	Remark
CH_4	NH_3	N_2O	CO_2 (biotic)		
0.02* NH_3, max. 8 g*t^{-1} digestate	0.3*NH_4^+-N	0,0125(1)* MFE(2)+ 0.05 org. N		Table 5-10 in (Cuhls et al. 2014)	Application of liquid digestate
No value is given	0.075 up to 0.114	0.013 up to 0.017(3)	0.86 up to 0.96 CO_2-C(4)	(Bruun et al. 2006; Moller et al. 2009)	Denmark (digestate from bio-waste)

(1) In the first year approx. 1.25 % of soluble nitrogen is converted to N_2O if good agricultural practice is applied ((IPCC 2007)).

(2) MFE: Mineral fertilise equivalent.

(3) Emissions coefficients represent the difference between normal agricultural practice only using inorganic fertilisers and use of digestate supplemented with inorganic fertilisers according to Danish legislation.

(4) The rest fraction of carbon remains in the soil.

Greenhouse gas emissions from the storage of digestate were measured to contribute to around 1 % of direct GHG emissions from biomass treatment, storage, and application and are therefore neglected within this study (Cuhls et al. 2014). During anaerobic digestion of algae around 40 % of N is converted to ammonium (N-NH_4^+). That corresponds to 1.28 g N-NH_4^+ *L^{-1} digestate and around 66 kg N-NH_4^+*d^{-1}.

In general, the fertilisation effect of organic fertilisers can range from 5 to 85 % if good fertilisation practice is applied (Reinhold 2008). According to Reinhold, the fertilisation effect of organic fertilisers expressed as mineral nitrogen can be approximated by means of NH_4^+-N + NO_3-N (Reinhold 2008). Due to a low content of NO_3 measured in the digestate NO_3 is neglected. Consequently, the mineral fertilise equivalent (MFE) is estimated to be equal to the amount of N-NH_4^+ = 70 kg*d^{-1}. Following to a large extend the calculation formulas given by (Cuhls et al. 2014) which were presented in Table 7-12, emissions caused by the application of algae digestate were calculated and are shown in Table 7-13. The amount of organic nitrogen is calculated based on the nitrogen content of algae considering ammonium release during fermentation.

Table 7-13: Emissions caused by application of algae digestate

	Emissions of 51 m^3 digestate (base line scenario, 1 day)				
	CH_4 [kg*d^{-1}]	NH_3 [kg*d^{-1}]	N_2O [kg*d^{-1}]	CO_2 (biotic) [kg*d^{-1}]	C fixed in soil [kg*d^{-1}]
Algae digestion residues	0.02* 70 *1.2 = 1.68	0.3 * 70 = 21	0.0125 * 70 + 0.05*91 = 5.4	0.9*988* 44/12= 3 260	0.1*988= 99

The amount of ammonia that is not emitted into the air is available to the plants. As in (Knappe et al. 2012) it is assumed that the amount not emitted replaces nitrogen from mineral fertiliser by 100 %. In chapter 7.1.9 further assumptions for the substitution of fertiliser are described.

Apart from direct emissions caused by the application of digestate indirect emissions occur due to transport and use of agricultural machinery. The assumptions are for this summarised in Table 7-14.

Table 7-14: Assumptions for transportation and application of digestate to agricultural land

Parameter	Value	Unit	Remark/references
Average distance to the location of spreading	25	km	Estimated
Diesel consumption of large trucks > 16 t	ca. 0.02	L*t^{-1}*km^{-1}	GaBi dataset: »GLO: truck 14-20 t, Euro 4«
Diesel for application of digestate on land	ca. 0.376	L*t^{-1}	(KTBL 2009); Gabi dataset: »GLO fertilising, liquid manure trailing horse distributor«

Emission factors for HC, NO_x, CO, CO_2, and benzo(a)pyrene emissions into the air caused by fertilising using a trailing horse distributor are taken from the GaBi-dataset: »GLO fertilising, liquid manure trailing horse distributor«.

7.1.7 Unit process 7: CO_2 and energy generation in a biomass boiler

Olive pits from the Andalusian olive oil industry are used as fuel in a biomass boiler. An overall boiler efficiency of 90 % is assumed. The chemical composition of the olive pits, as analysed by Aqualia, is presented in Table 7-15 (Aqualia 2014). For comparison, the chemical composition of olive pits from Portugal are shown in the third line of Table 7-15 (Vicente et al. 2014).

Table 7-15: Elemental composition of olive pits

	Results [wt.% dry basis]								Energy content (MJ*kg^{-1} DM)	
Element	H	O	C	S	N	P	Cl	Ash	HHV	LHV
Olive pits (Andalusia)	5.9	40.2	52.43	0.04	0.96	1.54	0.02	1	20.34	19.13
Olive pits (Vicente et al. 2014)	6.59	41.6	50.9	<0.01	0.21	No value	No value	0.7	No value	18.5
Threshold for pellets DIN 51 731	–	–	–	0.08	0.30	–	0.03	-		17.49-19.49

Based on the presented chemical composition of the olive pits corresponding exhaust gases caused by their incineration were calculated stoichiometrically. In the case of the Portuguese olive pits (Vicente et al. 2014), exhaust gases were measured in combination with an automatic pellet stove and an output of 9.5 kW. The corresponding emission factors are presented in Table 7-16.

Table 7-16: Emissions factors for burning 1 kg of olive pits

Source	(Vicente et al. 2014)	Andalusia (calculated stoichiometrically)
kg CO_2 * kg^{-1} input	1.87	1.92
Pollutant	Emissions [mg*MJ^{-1} input]	Emissions [mg*MJ^{-1} input]
CO	1 477	no value
NO	89	1 075
NO_2	3	no value
CH_4	30	no value
C_2H_6	15	no value
C_2H_4	13	no value
C_6H_{14}	185	no value
HCHO	38	no value
PM_{10}	156	no value
SO_2	70	42
NH_3	0.4	no value

For the LCI the calculated emission factors for the olive pits from Andalusia are applied and missing values are, as a first approximation, complemented by the

values published in (Vicente et al. 2014). Further assumptions of the biomass boiler are presented in Table 7-17.

Table 7-17: Assumptions for burning olive pits in a biomass boiler

Parameter	Value	Unit	Remark/references
Boiler type			Huber boilers
Amount of olive pits per day	277	$kg*d^{-1}$	According to CO_2 needs
Thermal energy output	1 337	$kWhth*d^{-1}$	90.2 % efficiency
Water content of olive pits	13	%	(Aqualia 2014)
Air requirement	5.56	Nm^3*kg^{-1} biomass	Based on oxygen need for combustion
Electricity for air supply	17.62	$kWh_{el}*d^{-1}$	(Aqualia 2014)
Flue gas	7.16	$kg*kg^{-1}$ biomass (DM)	Calculated, 12 % excess air
Ash from olive pits	3	$kg*d^{-1}$	(Aqualia 2014)

Olive pits are a waste product of the olive oil industry and account for around 12 wt.% of the olive (Russo et al. 2008). There are two ways to receive them. Food industries in Andalusia (Spain) are marketing around 300 000 t pitted olives per year (Driss Alami, S. B. 2010), resulting in a market for olive pits of approximately 22 000 $t*y^{-1}$ (Esencia de Olivo 2014). Alternatively, in the olive oil industry, the entire olive, including the pit, is pressed until it becomes a paste which is separated into a solid and a liquid fraction, either by the traditional process or by a continuous system (centrifuge): 3-phase process or 2-phase process (Anatoliki S.A. 2008). The milled pit fraction can be recovered from the solid phase consisting of skin, pulp, and pits also referred to as olive pomace. Recovered milled pits accounted for around 360 000 tonnes in 2011 in Andalusia (Agencia Andaluza de la Energía 2013b). In contrast to olive pomace pits can be used directly as fuel and therefore offer low environmental impacts (Russo et al. 2008). For modelling the life cycle inventory for olive production, agricultural data for olives grown in Ribera Baja (Andalusia) is used (Molero Cortés 2006). In addition, an olive oil mill is assumed using a continuous 3-phase oil extraction process followed by a pit recovery system. According to Caputo et al. the pomace contains 20 % pits (Caputo et al. 2003). Following data provided by »The Olive Centre« the assumed »Olive waste pit recovery machine SN-2000« recovers up to 18 % (The Olive Centre 2014). For the allocation of burdens between olive oil and pits (pomace), the commodity price of olive oil (2 665 $€*t^{-1}$, January 2014) is used (IndexMundi 2014) and the price provided by Aqualia for olive pits: 195 $€*t^{-1}$ (Aqualia 2014). The corresponding LCA model is shown in Figure 7-7 in appendix II.

7.1.8 Unit process 10: Provision/substitution of thermal energy (10) and electricity (10a)

Thermal energy is needed for heating up the digester as described in chapter 7.1.4 and is produced by the biomass boiler as discussed in chapter 7.1.7. It is assumed that additional thermal energy is produced in natural gas specific heat plants considering the national and regional specific technology standards of the heat plants with regard to efficiency, firing technology, flue-gas desulphurisation, NO_x-removal and de-dusting. For comparison to other LCA studies funded within the Algae Cluster, an average European thermal energy mix from natural gas is assumed. Background data is taken from the GaBi-dataset »EU-27: Thermal energy from natural gas EU-27« with the reference year 2011. In addition, the Spanish situation is taken into account for the sensitivity analysis. In this case the GaBi-dataset »ES: Thermal energy from natural gas PE« with the reference year 2011 is applied. The potential environmental impacts caused by the provision of 1 MJ thermal energy produced in natural gas heat plants are presented in Table 7-18.

Table 7-18: Potential environmental impacts caused by the provision of 1 MJ thermal energy produced in natural gas heat plants

Criterion	LCIA method	Impact category and unit	EU-27: Thermal energy from natural gas (2011)	ES: Thermal energy from natural gas (2011)	ES: Process steam from natural gas 95% PE	EU-27: Process steam from natural gas 95% PE
A1	ReCiPe 1.08 (H) endpoints	DAILY total [years]	6.91E-05	0.000	0.000	7.27E-05
B1	ReCiPe 1.08 (H) midpoints	Fossil depletion [kg oil-eq.]	0.027	0.028	0.029	0.028
B2	ReCiPe 1.08 (H) midpoints	Urban land occupation [m^2*a]	no values	no values	no values	no values
B3	ReCiPe 1.08 (H) midpoints	Ozone depletion [kg CFC-11-eq.]	1.28E-12	0.000	0.000	1.35E-12
B3	ReCiPe 1.08 (H) midpoints	Particulate matter formation [kg PM_{10}-eq.]	1.72E-05	0.000	0.000	1.81E-05
B3	ReCiPe 1.08 (H) midpoints	Photochemical oxidant formation [kg NMVOC]	6.99E-05	0.000	0.000	7.36E-05
B3	ReCiPe 1.08 (H) midpoints	Terrestrial acidification [kg SO_2-eq.]	5.05E-05	0.000	0.000	5.31E-05
B4	IPCC AR5	GWP100, excl. biogenic carbon [kg CO_2-eq.]	0.070	0.074	0.078	0.074
B4	IPCC AR5	GWP100, incl. biogenic carbon [kg CO_2-eq.]	0.070	0.074	0.078	0.074
B4	IPCC AR5	GWP20, excl. biogenic carbon [kg CO_2-eq.]	0.080	0.087	0.092	0.085
B4	IPCC AR5	GWP20, incl. biogenic carbon [kg CO_2-eq.]	0.080	0.087	0.092	0.085
B4	ReCiPe 1.08 (H) midpoints	Climate change, default, excl. biogenic carbon [kg CO_2-eq.]	0.069	0.073	0.077	0.073
B4	ReCiPe 1.08 (H) midpoints	Climate change, incl. biogenic carbon [kg CO_2-eq.]	0.069	0.073	0.077	0.073
B5	PE International (2012)	Blue water consumption [kg]	0.017	0.022	0.023	0.017
B5	Pfister (2009)	Water deprivation [kg]	0.011	0.037	0.038	0.012
B6	CML 2001 - Apr. 2013	Abiotic Depletion (ADP elements) [kg Sb-eq.]	2.83E-09	0.000	0.000	2.98E-09
B7	ReCiPe 1.08 (H) midpoints	Freshwater ecotoxicity [kg 1,4-DB-eq.]	1.29E-06	0.000	0.000	1.36E-06
B7	ReCiPe 1.08 (H) midpoints	Freshwater eutrophication [kg P-eq.]	3.37E-09	0.000	0.000	3.54E-09
B7	ReCiPe 1.08 (H) midpoints	Marine eutrophication [kg N-eq.]	2.21E-06	0.000	0.000	2.32E-06
B9	ReCiPe 1.08 (H) endpoints	PDF total [species*year]	0.124	0.137	0.144	0.131
		Total primary energy demand (net cal. value) [MJ]	1.145	1.167	1.229	1.205
		Primary energy from non renewable resources (net cal. value) [MJ]	1.138	1.162	1.224	1.198
		Primary energy from renewable resources (net cal. value) [MJ]	0.007	0.005	0.005	0.007

With regard to the electricity demands, this brings a regional aspect to the LCA, too. In order to allow comparisons to other LCA studies, the Algae Cluster agreed to use the average EU-28 energy mix for 2011 provided by PE International (Bradley et al. 2015). However, the algae biorefinery is located in Spain and therefore the Spanish average energy mix for 2011 is regarded in addition. Apart from local differences, there is also a time factor. It is expected that by the year 2020 the European electricity grid will contain a far higher penetration of renewable and low carbon energy sources (European Commission 2009a), that is why the GWP impact of electricity used will be lower. In order to assess the changes by time, the predicted

European energy mix in 2020 as described in (Bradley et al. 2015) is regarded additionally. Table 7-19 presents the potential environmental impacts caused by the provision of one kWh electricity at the consumer's.

Table 7-19: Potential environmental impacts caused by the provision of one kWh electricity at consumer's

Criterion	LCIA method	Impact category and unit	EU: Electricity grid mix in 2011	ES: Electricity grid mix in 2011	EU: Electricity grid mix in 2020
A1	ReCiPe 1.08 (H) endpoints	DAILY total [years]	8.20E-07	7.55E-07	7.33E-07
B1	ReCiPe 1.08 (H) midpoints	Fossil depletion [kg oil-eq.]	0.125	0.125	0.112
B2	ReCiPe 1.08 (H) midpoints	Urban land occupation [m^2*a]	no values	no values	no values
B3	ReCiPe 1.08 (H) midpoints	Ozone depletion [kg CFC-11-eq.]	3.51E-10	1.65E-10	9.10E-11
B3	ReCiPe 1.08 (H) midpoints	Particulate matter formation [kg PM_{10}-eq.]	5.68E-04	5.85E-04	5.36E-04
B3	ReCiPe 1.08 (H) midpoints	Photochemical oxidant formation [kg NMVOC]	9.83E-04	1.15E-03	9.80E-04
B3	ReCiPe 1.08 (H) midpoints	Terrestrial acidification [kg SO_2-eq.]	0.002	0.002	0.002
B4	IPCC AR5	GWP100, excl. biogenic carbon [kg CO_2-eq.]	0.473	0.425	0.408
B4	IPCC AR5	GWP100, incl. biogenic carbon [kg CO_2-eq.]	0.472	0.425	0.406
B4	IPCC AR5	GWP20, excl. biogenic carbon [kg CO_2-eq.]	0.524	0.487	0.450
B4	IPCC AR5	GWP20, incl. biogenic carbon [kg CO_2-eq.]	0.525	0.487	0.451
B4	ReCiPe 1.08 (H) midpoints	Climate change, default, excl. biogenic carbon [kg CO_2-eq.]	0.477	0.430	0.411
B4	ReCiPe 1.08 (H) midpoints	Climate change, incl. biogenic carbon [kg CO_2-eq.]	0.476	0.429	0.409
B5	PE International (2012)	Blue water consumption [kg]	3.547	5.554	2.877
B5	Pfister (2009)	Water deprivation [kg]	2.416	9.225	1.960
B6	CML 2001 - Apr. 2013	Abiotic Depletion (ADP elements) [kg Sb-eq.]	8.27E-08	1.07E-07	1.21E-07
B7	ReCiPe 1.08 (H) midpoints	Freshwater ecotoxicity [kg 1,4-DB-eq.]	1.45E-04	1.01E-04	1.40E-04
B7	ReCiPe 1.08 (H) midpoints	Freshwater eutrophication [kg P-eq.]	5.93E-07	2.93E-07	5.34E-07
B7	ReCiPe 1.08 (H) midpoints	Marine eutrophication [kg N-eq.]	5.07E-05	4.50E-05	6.61E-05
B9	ReCiPe 1.08 (H) endpoints	PDF total [species*year]	3.85E-09	3.43E-09	3.42E-09
		Total primary energy demand (net cal. value) [MJ]	10.190	10.602	10.248
		Primary energy from non renewable resources (net cal. value) [MJ]	8.421	7.502	6.997
		Primary energy from renewable resources (net cal. value) [MJ]	1.770	3.100	3.251

7.1.9 Unit process 11: Substitution of fertiliser

It is assumed that the farmer complies with national regulations regarding the use of organic fertilisers. Avoided environmental impacts from substitution of mineral fertilisers can be estimated from the nutrient content in the digestate which is available for the plant in connection with inventories of fertiliser production. The mineral fertiliser equivalents were calculated to be around 70 kg N*d^{-1} as described in chapter 7.1.6. Considering the losses of nitrogen through ammonia emissions around 49 kg N*d^{-1} are replaced. With regard to phosphorus and potassium a 1:1 substitution is assumed as in many other LCA studies, too (Hélias, Brockmann 2014; Moller et al. 2009). The average phosphorus content in algal biomass and bacteria is estimated to be 1 %. The potassium content in *Chlorella* was found to be 8.8 g*kg^{-1} and in *Scenedesmus* 10.2 – 10.7 g*kg^{-1}. In this study 9 g potassium per kg dry algae are assumed. Avoided environmental burdens from the substitution of inorganic fertilisers is estimated from the nutrient content in the digestate as presented in Table 7-20 in connection with background data of fertiliser production. As background data the GaBi 6.1 datasets »DE: Potassium chloride (agrarian) PE«, »DE: Ammonia (liquid, agriculture) PE«, and »GLO: Rock phosphate mix (32.4 % P_2O_5) PE« are used. The application of mineral fertiliser also leads to N_2O emissions which according to (IPCC 2007) are estimated to be 0.0125*49.33 kg N substituted = 0.617 kg N_2O*d^{-1}. These emissions are considered as a credit and are subtracted

from the N_2O emissions caused by the application of fermentation residues on the field.

Table 7-20: Assumptions for the substitution of mineral fertiliser

Type of fertiliser			
	$N\text{-}NH_3$ [kg*d^{-1}]	$P\text{-}P_2O_5$ [kg*d^{-1}]	$K\text{-}K_2O$ [kg*d^{-1}]
Algae digestate	70-21=49	21	19

7.1.10 Unit process 12: Substitution of CNG in a vehicle engine

Biomethane is used as transportation fuel and replaces compressed natural gas (CNG) or diesel. Tailpipe emissions from a European average diesel passenger car fulfilling the Euro 4 norm with an engine size of 1.4-2 L are presented in Table 7-21. As driving cycle a share of 30 % motorway, 39 % rural area, and 31 % urban area is assumed. Emission data is taken from the GaBi-database: »GLO: car diesel (diesel driven, Euro 4, passenger car | consumption mix | engine size 1.4-2 L)« last updated in 12/2014 (PE INTERNATIONAL 2014). The consumption of diesel is 0.0457 kg* km^{-1}. For the natural gas vehicle (NGV) data is taken from the EU-funded project Biogasmax (Bach et al. 2010) where 13 in-use NGVs with three-way catalyst (12 x Euro 4; 1 x Euro 15) were investigated. As driving cycle the warm-start common artemis driving cycle (CADC) is selected that represents real-world European urban, rural, and motorway driving behaviour for cars (André 2004). The consumption of natural gas is calculated to be 0.0465 kg*km^{-1} based on CO_2 emissions. As the biomethane nearly has the same composition as natural gas, the same emission factors are applied.

Table 7-21: Tailpipe emissions from diesel, CNG, and biomethane of Euro-4 vehicles

Fuel	Diesel, low sulphur [kg*km^{-1}] (PE INTERNATIONAL 2014)	Natural gas [kg*km^{-1}] (Bach et al. 2010)	Methane (97 vol-%) [kg*km^{-1}] (Bach et al. 2010)
Carbon monoxide, fossil	0.00002869	0.000302	
Carbon monoxide, biogenic			0.000302
Carbon dioxide, fossil	0.138	0.1276	
Carbon dioxide, biogenic	0.007265		0.1276
Methane, fossil	2.258E-7		
Methane, biogenic			
Hydrocarbons (HC)		0.000012	0.000012
Nitrogen oxides	NO_2: 0.0002657	0.000043 NO: 0.00003;	0.000043 NO: 0.00003;

Fuel	Diesel, low sulphur [kg*km^{-1}] (PE INTERNATIONAL 2014)	Natural gas [kg*km^{-1}] (Bach et al. 2010)	Methane (97 vol-%) [kg*km^{-1}] (Bach et al. 2010)
	NO: 0.0002657	NO_2: 0.00000	NO_2: 0.00000
Particulates > 2.5 µm, and < 10um	3.125 E-6		
Particulates < 2.5 µ m	0.00000145		
Particulates > 10 µ m	2.728E-7		
Dinitrogen monoxide	4.667E-6		
Ammonia	0.000001	0.000025	0.000025
Sulphur dioxide	9.142E-7		
NMVOC	9.184E-6	0.000001	0.000001
Benzene	0.00000015	0.00000046	0.00000046
Toluene		0.00000009	0.00000009

Further tailpipe emissions not considered in Table 7-21 are taken from ecoinvent data »ES: operation, passenger car, natural gas ecoinvent« (Jungbluth et al. 2007).

7.1.11 Unit process 13: Substitution of conventional waste water treatment

Currently the existing waste water treatment plant in Chiclana de la Frontera, also referred to as »El Torno plant«, consists of the following steps: 0) pre-treatment, 1) primary clarifier, 1a) odour control, 2) aeration, 3) secondary clarifier, 4) sludge thickening, 5) aerobic sludge digestion, and 6) sludge dewatering. Besides, waste from pre-treatment and dewatered sludge is disposed. The corresponding flow diagram is shown in Figure 7-2.

In total 0.0134 kg hypochloride, 0.0022 kg caustic, and 0.00082 kg polymers are added per m^3 waste water. The electricity consumption per m^3 waste water measured in 2013 was 0.75 kWh*m^{-3} neglecting the energy consumption for odour control. In detail the following energy consumptions in kWh*m^{-3} are taken into account: (0) pre-treatment (mechanical) 0.0138, (1) pumping 0.0473, (1) primary clarifier 0.0041, (2) activated sludge (aeration) 0.2973, (3) secondary clarifier 0.0041, (4) sludge aerobic digestion 0.3243, (5) sludge dewatering 0.0135, and (6) sludge thickener 0.0135. 0.274 kg TSS are produced per m^3 waste water. Assuming 20 % dryness after dewatering, around 0.96 kg sludge per m^3 waste water has to be disposed of via an external company. In Andalusia the sludge is typically sent to a landfill, for which you have to pay for transport and taxes.

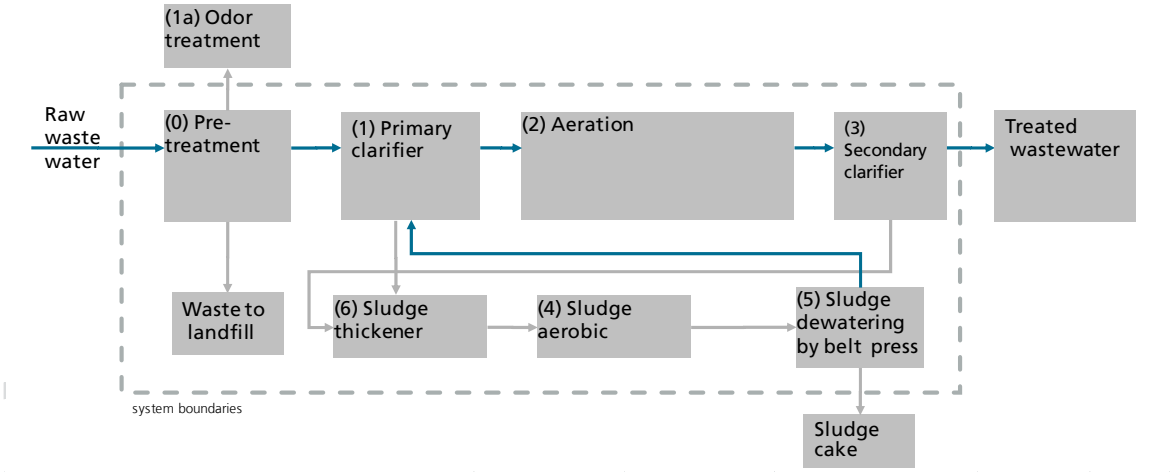


Figure 7-2: Flow diagram of the El Torno plant

In Europe the most popular sludge management options are (Yoshida et al. 2013):

- Incineration of sludge along with landfill of ash,
- anaerobic digestion of sludge in combination with drying and incineration or land application,
- lime stabilisation and further land application, and
- composting of sludge and further land application.

Advantages of windrow composting are further reduction of sludge mass through degradation of organic matter and evaporation of water as well as reduction of organic pollutants and inactivation of pathogens present in the sludge (Poulsen, Hansen 2003). Negative impacts might be the accumulation of heavy metals and other pollutants in soils and possibly the opening of new transmission pathways for infectious diseases (Gerba, Smith 2005).

A typical European waste water treatment plant also contains the anaerobic digestion of sludge along with the combustion of biogas in a combined heat and power (CHP) plant that satisfies the thermal energy demand of the digestion plant and provides a part of the electricity requirements. In order to assess such a waste water plant the Excel®-based waste water treatment model »13_WWTPv2« developed by Doka is used (Doka 2009). In this model the dewatered digester sludge is either incinerated or used for land application. It is assumed that 100 % of digester sludge goes to incineration.

Based on the waste water composition presented in Table 7-1, an average gross electricity demand of 0.604 kWh*m^{-3} is calculated for 1) aeration in the activated sludge bed, 2) sludge digestion, and 3) pumps. Taking into consideration an electricity production of 0.11 kWh*m^{-3} through burning biogas in a CHP plant, around 0.49 kWh*m^{-3} are needed from external sources. Besides, around 0.47 MJ*m^{-3} waste water thermal energy is needed for sludge digestion and space heat. This energy demand is completely covered by the thermal energy produced by the

CHP plant. In total, the primary energy from non-renewable resources (gross cal. value) is calculated to be 8.28 MJ*m^{-3} of waste water.

As shown in Figure 7-3 the primary energy demand also includes the transportation and incineration of digester sludge as well as the disposal of slag to landfill. The sewer infrastructure is excluded from the balance since the same infrastructure is needed for the algae biorefinery. In order to make a conservative comparison the »typical European« waste water treatment plant is used as reference. However, in the south of Spain oxidation ditches are widespread which have a higher electricity demand. Moreover sewage sludge is often directly disposed on the field which causes higher GHG emissions compared to anaerobic treatment, dewatering, and incineration.

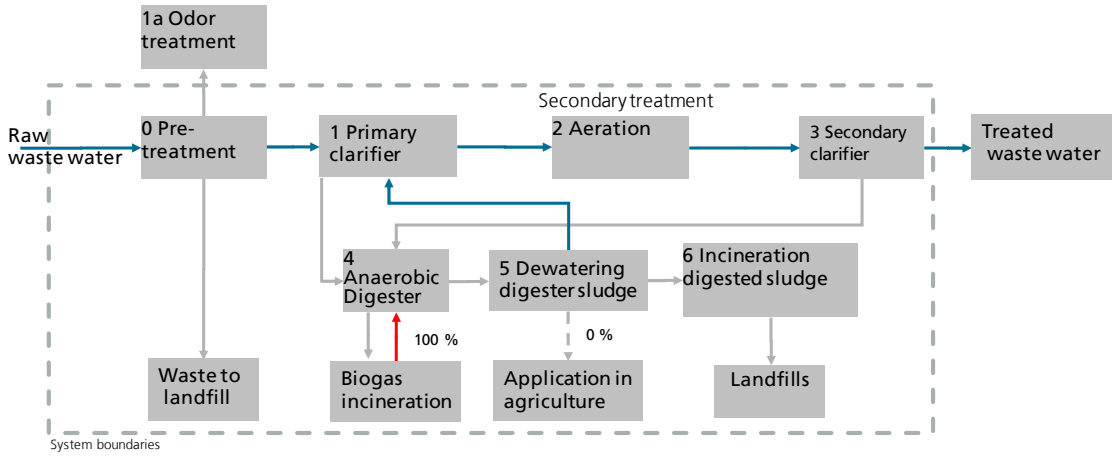


Figure 7-3: System boundaries applied to a typical European waste water treatment plant

The potential environmental impacts of treating one m^3 waste water in such a »typical European« waste water treatment plant are summarised in Table 7-22.

Table 7-22: Potential environmental impacts caused by the treatment of one m³ waste water as defined in Table 7-2, calculated based on the LCA-model of (Doka 2009), electricity: EU grid mix 2011

Criterion	LCIA method	Impact category and unit	Total	01 Chemicals	02 Electricty	03 Waste water plant	04 Disposal of waste	05 Burdens sludge treatment
A1	ReCiPe 1.08 (H) endpoints	DAILY total [years]	9.57E-07	1.78E-07	3.73E-07	3.09E-07	6.42E-08	3.29E-08
B1	ReCiPe 1.08 (H) midpoints	Fossil depletion [kg oil-eq.]	0.107	0.017	0.061	0.024	0.001	0.003
B2	ReCiPe 1.08 (H) midpoints	Urban land occupation [m^2*a]	6.92E-03	6.98E-04	0.00E+00	5.65E-03	4.70E-05	5.22E-04
B3	ReCiPe 1.08 (H) midpoints	Ozone depletion [kg CFC-11-eq.]	7.42E-08	6.61E-08	8.15E-11	6.13E-09	6.08E-10	1.25E-09
B3	ReCiPe 1.08 (H) midpoints	Particulate matter formation [kg PM_{10}-eq.]	7.30E-04	1.29E-04	2.89E-04	2.52E-04	1.30E-05	4.75E-05
B3	ReCiPe 1.08 (H) midpoints	Photochemical oxidant formation [kg NMVOC]	1.39E-03	1.77E-04	5.65E-04	4.00E-04	5.21E-05	1.97E-04
B3	ReCiPe 1.08 (H) midpoints	Terrestrial acidification [kg SO_2-eq.]	1.89E-03	3.74E-04	1.02E-03	3.51E-04	3.08E-05	1.12E-04
B4	IPCC AR5	GWP100, excl. biogenic carbon [kg CO_2-eq.]	0.45	0.06	0.21	0.12	0.04	0.01
B4	IPCC AR5	GWP100, incl. biogenic carbon [kg CO_2-eq.]	0.47	0.06	0.21	0.12	0.06	0.01
B4	IPCC AR5	GWP20, excl. biogenic carbon [kg CO_2-eq.]	0.50	0.07	0.24	0.13	0.04	0.01
B4	IPCC AR5	GWP20, incl. biogenic carbon [kg CO_2-eq.]	0.52	0.07	0.24	0.13	0.06	0.01
B4	ReCiPe 1.08 (H) midpoints	Climate change, default, excl. biogenic carbon [kg CO_2-eq.]	0.45	0.06	0.21	0.12	0.04	0.01
B4	ReCiPe 1.08 (H) midpoints	Climate change, incl. biogenic carbon [kg CO_2-eq.]	0.47	0.06	0.21	0.12	0.06	0.01
B5	PE International (2012)	Blue water consumption [kg]	4.08	0.52	2.74	0.31	0.04	0.47
B5	Pfister (2009)	Water deprivation [kg]	6.78	0.87	4.55	0.51	0.06	0.77
B6	CML 2001 - Apr. 2013	Abiotic Depletion (ADP elements) [kg Sb-eq.]	2.21E-06	1.47E-06	5.27E-08	6.53E-07	1.36E-08	2.09E-08
B7	ReCiPe 1.08 (H) midpoints	Freshwater ecotoxicity [kg 1,4-DB-eq.]	9.00E-03	2.43E-03	4.98E-05	5.13E-03	8.06E-04	5.84E-04
B7	ReCiPe 1.08 (H) midpoints	Freshwater eutrophication [kg P-eq.]	1.05E-04	6.60E-05	1.44E-07	3.58E-05	7.73E-07	2.53E-06
B7	ReCiPe 1.08 (H) midpoints	Marine eutrophication [kg N-eq.]	7.20E-05	2.12E-05	2.22E-05	1.79E-05	3.65E-06	7.13E-06
B9	ReCiPe 1.08 (H) endpoints	PDF total [species*year]	3.97E-09	5.88E-10	1.68E-09	1.25E-09	3.27E-10	1.19E-10

7.2 Appendix II: Additional tables and figures

7.2.1 Additional tables

Table 7-23: Economic, ecological, and social aspects of biorefineries (Rai et al. 2010); criteria in italics are not directly addressed by the HGF-approach

Economic aspects	Ecological aspects	Social aspects
Product-market combinations	Depletion of energy sources (non-renewable energy use)	Employment effects
Production costs and life cycle costs	Depletion of non-energy resources	Need of education and skills
Contribution to sectoral growth and GDP	Climate change, acidification, eutrophication	*Equity concerns*
Energy security	Fresh water utilisation	Possibilities for dialogue and public acceptance
Financial risks of biorefineries	Land use effects	
	Solid and liquid waste, waste water	
	Particulate matter/respiratory effects	
	Toxicity (terrestrial, marine, fresh water and human toxicity)	
	Biodiversity/invasive species/gene modification	

Table 7-24: Environmental, social, and economic criteria of biofuels and bioenergy systems, adopted from (Buchholz et al. 2009); criteria in italics are not directly addressed by the HGF-approach

Economic aspects	Ecological aspects	Social aspects
Employment generation	Greenhouse gas balance Land use change	Food security Land availability for other human activities than food production
Macroeconomic sustainability	Waste management	Standard of living
Microeconomic sustainability	Natural resource efficiency Energy balance	Cultural acceptability
Economic stability	Soil protection Use of chemicals, pest control, and fertiliser	Working conditions of employees
	Water management	Participation
	Exotic species applications Species protection Crop diversity Use of genetically modified organisms	Respect for human rights
	Ecosystems protection	Monitoring of criteria performance
	Potentially hazardous atmospheric emissions other than greenhouse gases	*Compliance with laws*
	Adaptation capacity to environmental hazards and climate change	*Property rights and rights of use*
	Ecosystems connectivity	*Planning*
		Respecting minorities
		Social cohesion
		Noise impacts *Visual impacts*

Table 7-25: Sustainability indicators for bioenergy published by The Global Bioenergy Partnership (GBEP 2011)

Economic aspects	Ecological aspects	Social aspects
Productivity	Life cycle GHG emissions	Allocation and tenure of land for new bioenergy production
Net energy balance	Soil quality	Price and supply of a national food basket
Gross value added	Harvest levels of wood resources	Change in income
Change in the consumption of fossil fuels and traditional use of biomass	Emissions of non-GHG air pollutants, including air toxics	Jobs in the bioenergy sector
Training and re-qualification of the workforce	Water use and efficiency	Change in unpaid time spent by women and children collecting biomass
Energy diversity	Water quality	Bioenergy used to expand access to modern energy services
Infrastructure and logistics for distribution of bioenergy	Biological diversity in the landscape	Change in mortality and burden of diseases attributable to indoor smoke
Capacity and flexibility of use of bioenergy	Land use and land use change related to bioenergy feedstock	Incidence of occupational injury, illness and fatalities

Table 7-26: Excerpt of the principles of the tripartite declaration of principles concerning multinational enterprises and social policy regarding companies operating in developing countries (International Labour Office 2001, 2002). Numbers in brackets in second column refer to article number of the Declaration, adopted from (Dreyer et al. 2006)

Issue	Principle of conduct
Job creation	Increase employment opportunities and standards (16)
Local/national recruitment in developing countries	Use of national labour (18)
Generation of employment and technology development	Use of technologies that generate employment and take part in development of new technology in host countries (19)
Stimulation of economic growth in developing countries	Use of national suppliers (20)
Stability of employment	Ensure stability of employment through effective manpower planning (25)
Skill formation and development	Strive to raise education and skill level of employees in developing countries (31)
Wages, benefits and conditions of work	Ensure best possible wages within the framework of government policies (34)

Table 7-27: Environmental and socio-economic sustainability criteria for biomass and biofuels in different initiatives launched, adopted from (Soimakallio et al. 2009)

	EU RED 2009	RFA 2011	RSB 2010	NEF 2011	RSPO 2007	BSI 2011	RTRS 2010	FSC 2011	PEFC 2010	GBEP 2011
Applicability	BF	BF	BF	BM, BF	BF	BF	BM	BM	BM	BM
Climate change	✓	✓	✓	✓	✓	✓		(✓)		✓
Energy balance			(✓)	✓		✓				
Air quality		✓	✓	(✓)	✓	✓		(✓)		✓
Water quality	(✓)	✓	✓		✓	✓	✓	✓	✓	✓
Use of water		✓	✓		✓	✓	✓	(✓)	(✓)	✓
Soil quality	(✓)	✓	✓		✓	✓	✓	✓	✓	✓
Ecotoxicity	(✓)	✓	(✓)		✓	✓	✓	✓	✓	
Human toxicity				✓		✓				
Biodiversity	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Sustainable land use and competition with other resources	✓		✓	(✓)	✓		(✓)	✓	✓	✓
Genetically modified organisms (GMOs)			✓		✓		✓	✓	✓	
Waste management and recycling		(✓)	✓		✓	(✓)	(✓)	✓	(✓)	
Worker rights	✓	✓	✓	✓	✓	✓	✓	✓	✓	
Land rights		✓	✓		✓	(✓)	✓	(✓)	(✓)	
Economic impacts			✓		✓	✓	✓	✓	✓	✓

Abbreviations used in Table 7-27

BM	Biomass
BF	Biofuels
EU RED 2009	DIRECTIVE 2009/28/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC
RFA	Renewable Fuel Association (UK), Renewable Transport Fuel Obligation (RTFO) Biofuel Sustainability Meta-Standard

RSB	Roundtable of Sustainable Biofuels
NEF	Nordic Ecolabelling of Fuels, Swan labelling
RSPO	Roundtable of Sustainable Palm Oil
BSI	Better Sugarcane Initiative, Bonsucro Production Standard, version 3.0 March 2011
RTRS	Round Table on Responsible Soy Association
FSC	Forest Stewardship Council
PEFC	Programme for Endorsement of Forest Certification Schemes
GBEP	Global Bioenergy Partnership

Table 7-28: Different LCIA methods to evaluate environmental effects; adopted from (JRC 2010a)

Environmental effects	CML 2002	Eco-indicator 99	EDIP97	EDIP2003 (3)	EPS 2000	IMPACT 2002+	LIME	LUCAS	ReCiPe	Swiss Ecoscarcity 07	TRACI	MEEuP
Climate change	o	E	o	o	E	o	E	o	M E	o	o	o
Ozone depletion	o	E	M	M	E	o	E	o	E	o	o	o
Respiratory inogranics		E	o	o	E	E	M		M E	o	M	M
Human toxicity (1)	M	o	M	M	E	M E	E	o	M E	o	M	M
Ionising radiation	o (2)	o	o	o	o	o			o	M E		
Ecotoxicity	o		M	M	E	M E	o	o	M E	M	M	M
Ozone formation	M	E	M	M	E	E	M E	o	M E	o	M	M
Acidification	M	E	M	M	o	M E	M E	o	M E	o	M	M
Terrestrial eutrophication	M	E	M	M	o		o	o	o	o	o	M
Aquatic eutrophication	M		M	M	o	M E	E	o	M E	o	M	M
Land use	o	E			E	o	E	o	M E	M E		
Resource consumption	M	E	M	M	E	E	E	o	E	water	o	water
Others			Work environment; road noise	Work environment; road noise			Indoor air			Endocrine disruptors		
Developer	CML	PRé	DTU	DTU	IVL	EPFL	AIST	CIRAIG	RUN + PRé + CML + RIVM	E2 + ESU_sevices	US EPA	VhK
Country	NL	NL	DK	DK	SE	CH	JP	CA	NL	CH	USA	NL

Abbreviations and symbols used in Table 7-28.

Key	
o	Available in the methodology but not investigated further
M	Midpoint model available and analysed further
E	Endpoint model available and analysed further
Remarks	
(1)	Cancer and non-cancer effects sometimes taken separately
(2)	Optional study specific impact category
(3)	EDIP97 for resources, EDIP2003 for the other impact categories
Abbreviations methods	
CML	Centrum Voor Millieuwetenschappen

2002	
EDIP97	Environmental design of industrial products
EDIP 2003	Environmental design of industrial products
EPS 2000	A systematic approach to environmental priority strategies in product development
LIME	Life cycle impact assessment method based on endpoint modelling
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
MEEuP	Methodology Study Eco-design of Energy-using Products
Authors	
CML	Instititute of Environmental Sciences (CML), Leiden University, Centrum Voor Milieukunden: http://www.cml.leiden.edu/
PRé	Product ecology consultants: http://www.pre.nl/
DTU	Technical University of Denmark: http://www.dtu.dk/English.aspx
IVL	Swedish Environmental Research Institute: http://www.ivl.se/english/startpage/about/owner.4.7df4c4e812d2da6a41680009932.html
EPFL	University of Michigan Risk Science Center: http://www.sph.umich.edu/riskcenter/
AIST	National Institute of Advanced Industrial Science and Technology: http://www.aist.go.jp/index_en.html
CIRAIG	Interuniversity Centre for the Lifecycle of Products, Processes and Services: http://www.ciraig.org/en/index_e.html
RUN	Radboud Universiteit Nijmegen: http://www.ru.nl/
RIVM	Centrum Voor Milieukunden, Rijksinstitut voor Volksgezondheid en Milieu: http://www.rivm.nl/
ESU	ESU-services GmbH: http://www.esu-services.ch/de/ourservices/
US EPA	US Environmental Protection Agency: http://www.epa.gov/
VhK	Van Holsteijn en Kemna: http://www.vhk.nl/

Table 7-29: Midpoint panel weighting, based on (Huppes, van Oers 2011)

Midpoint impact category	EPA[34] science advisory board (BEES) [%]	BEES[35] stakeholder panel [%]	NOGEPA[36] [%]	PE Int. LCIA survey 2012 (ReCiPe1.08 H) [%]
Global warming	16	29	32	11
Ozone depletion	5	2	5	7
Acidification	5	3	6	7
Eutrophication	5	6	13	8
Photochemical ozone formation	6	4	8	8
Human Health	11	0	16	0
Human health cancerous		8		
Human health non-cancerous		5		
Human health criteria pollutants	6	9		8
Ecotoxicity	11			
Fresh water ecotoxicity		7	6	7
Marine ecotoxicity			8	7
Terrestrial ecotoxicity			5	7
Abiotic resource depletion (fossil fuel)	5	10	not rated	8
Ionising radiation	not rated	not rated	not rated	6
Water intake	3	8	not rated	not rated
Indoor air quality	11	3	not rated	not rated
Land use/habitat alteration	16	6	not rated	
Agricultural land occupation				8
Urban land occupation				8

[34] EPA: Environmental Protection Agency of the US.

[35] BEES: Building for Environmental and Economic Sustainability.

[36] NOGEPA: Netherlands Oil and Gas Exploration and Production Association.

Table 7-30: Specifications for biogas according to Svensk Standard SS155438 Type A

Criterion	Concentration
CH_4 content	97 ± 1 vol%
Dew point	-10°C at 8 bar
H_2O	Max. 32 mg m^{-3}
CO_2 + O_2 +N_2	Max. 4 vol%,
O_2	Max. 1 vol%
Total S	Max. 23 mg m^{-3}
Total N (without N_2)	20 mg*m^{-3}

Table 7-31: Input-output balances of primary data used for UP one to three

UP1: Anaerobic waste water pre-treatment & methane stripping

INPUTS					OUTPUTS				
MATERIALS	VALUE	UNIT	VALUE	UNIT	MATERIALS	VALUE	UNIT	VALUE	UNIT
WASTE WATER	4 996 530	$kg*d^{-1}$			3) UASB EFFLUENT	4 983 264	$kg*d^{-1}$		
1) PRIMARY TREATMENT OF WASTE WATER			24.98	$kWh*d^{-1}$	3) BIOGAS	372.5	Nm^3*d^{-1}	2969.8	$kWh*d^{-1}$
2) ELECTRICITY FOR PUMPING WW TO UASB			136.02	$kWh*d^{-1}$	3) ANAEROBIC SLUDGE	13 266	$kg*d^{-1}$	545.4	$kWh*d^{-1}$
3) ELECTRICITY FOR METHANE STRIPPING			20.26	$kWh*d^{-1}$	METHANE SLIP	2.98	kg*d-1		
3) ELECTRICITY FOR UASB REACTOR			16.20	$kWh*d^{-1}$	SOLID WASTE TO LANDFILL	74	kg*d-1		
3) HEAT FOR UASB REACTOR			0	$kWh*d^{-1}$					
3) ELECTRICITY FOR PUMPING WW TO METHANE STRIPPING			not needed due to inclination	$kWh*d^{-1}$					
4) ELECTRICITY FOR H2S REMOVAL WITH BIOFILTER			35.33	$kWh*d^{-1}$					
5) ELECTRICITY FOR ODOR CONTROL			excluded	$kWh*d^{-1}$					
6) ELECTRICITY FOR PUMPING WW TO PONDS			49.09	$kWh*d^{-1}$					

UP2: Cultivation of microalgae in primary treated waste water

INPUTS					OUTPUTS				
MATERIALS	VALUE	UNIT	VALUE	UNIT	MATERIALS	VALUE	UNIT	VALUE	UNIT
1) INPUT WATER FROM UASB & RECYCLING	5 000 000	$kg*d^{-1}$			ALGAE AND BACTERIA	2 338	$kg*d^{-1}$		
1) FLUE GAS	2 312	$kg*d^{-1}$			EVAPORATED WATER	550 000	$kg*d^{-1}$		
1) ELECTRICITY TO TRANSFER FLUE GAS INTO POND			18.43	$kWh*d^{-1}$	POND EFFLUENT	4 450 000	$kg*d^{-1}$		
2) LINERS MADE OF PP FOR PONDS	19.11	$kg*d^{-1}$			CO_2 (BIOTIC) INTO THE AIR	80.2	$kg*d^{-1}$		
2) CONCRETE HOLLOW BLOCK FOR PONDS	93.59	$kg*d^{-1}$							
2) ELECTRICITY FOR WATER MIXING			418.42	$kWh*d^{-1}$					
2) CO_2 FROM BIOGAS	166.89	Nm^3*d^{-1}							

UP3: Harvesting of algae

INPUTS					OUTPUTS				
MATERIALS	VALUE	UNIT	VALUE	UNIT	MATERIALS	VALUE	UNIT	VALUE	UNIT
ALGAE AND BACTERIA	2 337.66	$kg*d^{-1}$			RECYCLED WATER	16 736	$kg*d^{-1}$		
POND EFFLUENT	4 450 000	$kg*d^{-1}$			WET BIOMASS @ 4 %	55 519	$kg*d^{-1}$	12 139	$kWh*d^{-1}$
ELECTRICITY FOR PUMPING WATER TO DAF			86.53	$kWh*d^{-1}$	EFFLUENT DAF	4 379 966	$kg*d^{-1}$		
ELECTRICITY FOR THICKENING WITH DAF			133.5	$kWh*d^{-1}$					
COAGULANTS	89.0	$kg*d^{-1}$							
POLYMERS	13.35	$kg*d^{-1}$							

Table 7-32: Input-output balances of primary data used for UP four to seven

UP4: Biogas production from algal biomass	INPUTS					OUTPUTS				
	MATERIALS	VALUE	UNIT	VALUE	UNIT	MATERIALS	VALUE	UNIT	VALUE	UNIT
	WET BIOMASS at 4 % SOLIDS CONTENT	55 519	$kg*d^{-1}$			BIOGAS	286.47	Nm^3*d^{-1}	1 856	$kWh*d^{-1}$
	REQUIRED THERMAL ENERGY AD			1 059	$kWh*d^{-1}$	NO_2 EMISSIONS INTO THE AIR	0.08	$kg*d^{-1}$		
	WASTE HEAT FROM PSA LEAN GAS			57.2	$kWh*d^{-1}$	AMMONIA EMISSIONS INTO THE AIR	4.33	$kg*d^{-1}$		
	ELECTRICITY FOR MIXING AD			216.0	$kWh*d^{-1}$	NMVOC INTO THE AIR	1.28	$kg*d^{-1}$		
	BIOGAS PLANT (INFRASTRUCTURE)	0.000137	$pieces*d^{-1}$			EFFLUENT AD	55 053	$kg*d^{-1}$		
	ELECTRICITY FOR PUMPING TO DIGESTION			2.52	$kWh*d^{-1}$	ANAEROBIC SLUDGE (RESIDUES DM)	1 897	$kg*d^{-1}$		
						WASTE HEAT	144.6	kWh		

UP5: Biogas upgrading and provision at a service station	INPUTS					OUTPUTS				
	MATERIALS	VALUE	UNIT	VALUE	UNIT	MATERIALS	VALUE	UNIT	VALUE	UNIT
	TOTAL BIOGAS INPUT	659	Nm^3*d^{-1}			BIOMETHANE (97 % PURITY)	483.2	Nm^3*d^{-1}	4 816	$kWh*d^{-1}$
	ELECTRICTY FOR BIOWASHER			7.9	$kWh*d^{-1}$	CARBON DIOXIDE	166.9	Nm^3*d^{-1}		
	WATER FOR BIOWASHER	27	$kg*d^{-1}$			USED ACTIVATED CARBON	0.33	$kg*d^{-1}$		
	NaOH FOR BIOWASHER	1	$kg*d^{-1}$			METHANE EM. FROM PSA TO AIR	0.65	$kg*d^{-1}$		
	ELECTRICTY FOR DRIER			23.1	$kWh*d^{-1}$	METHANE EM. FROM STATION TO AIR	0.065	$kg*d^{-1}$		
	ELECTRICITY FOR PSA			152	$kWh*d^{-1}$	WASTE HEAT FOR BIOGAS PLANT			57	$kWh_{th}*d^{-1}$
	ACTIVATED CARBON	0.33	$kg*d^{-1}$							
	LUBRICANTS PSA	0.03	$kg*d^{-1}$							
	ELECTRICTY FOR COMPRESSION			105	$kWh*d^{-1}$					

UP6: Application of fermentation residues	INPUTS					OUTPUTS				
	MATERIALS	VALUE	UNIT	VALUE	UNIT	MATERIALS	VALUE	UNIT	VALUE	UNIT
	FERMENTATION RESIDUES	55 053	$kg*d^{-1}$			NH_3 EMISSIONS TO AIR	21	$kg*d^{-1}$		
	DIESEL FOR TRANSPORT	30	$kg*d^{-1}$			N_2O EMISSIONS TO AIR	4.82	$kg*d^{-1}$		
	DIESEL FOR APPLICATION	21	$kg*d^{-1}$			CH_4 EMISSIONS TO AIR	1.71	$kg*d^{-1}$		
						EVAPOTRANSPIRATION	53 313	$kg*d^{-1}$		
						CO_2 BIOTIC TO AIR	3 262	$kg*d^{-1}$		
						CARBON FIXED IN SOIL	99	$kg*d^{-1}$		

UP7: CO_2 and energy generation in a biomass boiler	INPUTS					OUTPUTS				
	MATERIALS	VALUE	UNIT	VALUE	UNIT	MATERIALS	VALUE	UNIT	VALUE	UNIT
	OLIVINE KERNELS (DM)	277	$kg*d^{-1}$	1 482.8	$kWh*d^{-1}$	ELECTRICITY			0	$kWh*d^{-1}$
	AIR	1 743	$kg*d^{-1}$			EXCESS HEAT			1 337	$kWh_{th}*d^{-1}$
	ELECTRICITY FOR AIR SUPPLY			17.62	$kWh*d^{-1}$	ASH	3	$kg*d^{-1}$		
						FLUE GAS	2 213	$kg*d^{-1}$		
						CO_2 IN FLUE GAS	472	$kg*d^{-1}$		
						SO_2 IN FLUE GAS	0.22	$kg*d^{-1}$		
						CO IN FLUE GAS	0.00	$kg*d^{-1}$		
						NO_2 IN FLUE GAS	8.74	$kg*d^{-1}$		

Table 7-33: Climate indicators for the calculation of monthly evaporation in a 10 ha pond in Chiclana de la Frontera

Month	n [d]	$\bar{u}$ [km*h^{-1}]	$\bar{e_z}$ [mbar]	Relative humidity [%]	$\overline{E_H}$ [mbar]	V [mm* month^{-1}]	V in 10 ha pond [m^3* month^{-1}]
January	31	9.7	11.41	85	13.42	40.68	4 068
February	28	10.4	12.24	85	14.40	42.04	4 204
March	31	12.3	12.78	80	15.97	82.31	8 231
April	30	12.9	13.25	75	17.67	116.02	11 602
May	31	12.0	11.70	55	21.27	245.82	24 582
June	30	11.4	13.19	50	26.37	313.44	31 344
July	31	10.3	15.89	50	31.77	356.39	35 639
August	31	9.9	17.71	55	32.21	313.56	31 356
September	30	10.2	20.28	70	28.97	185.92	18 592
October	31	10.2	16.91	75	22.54	123.78	12 378
November	30	10.0	10.22	60	17.04	142.67	14 267
December	31	10.2	11.82	85	13.90	44.28	4 428
Average per month		**10.8**	**13.9**	**69**	**21.3**	**167.2**	**16 724**

Table 7-34: Blue water consumption and water scarcity footprint of electricity and natural gas in Spain and Europe

Region	GaBi 6.1 dataset	Blue water consumption [kg blue water* kWh^{-1}]	WSI (Anda-lusia)	WSI (Euro-pean average)	WSF (Anda-lusia)	WSF (Europe average)
ES	Electricity grid mix PE	5.55	1		9.22	
EU-27	Electricity grid mix PE	3.55		0.41		2.42
ES	Thermal energy from natural gas	0.08	1		0.13	
EU-27	Thermal energy from natural gas	0.06		0.41		0.04

Table 7-35: Potential environmental impacts caused by the treatment of one m³ waste water

Criterion	Impact category and unit	UPs 01: Anaerobic waste water pre-treatment	UP2: Culti-vation of microalgae	UP 03: harvesting of algae	UP4: Biogas produ-ction from algal biomass	UP5: Biogas upgrading, service station, use in car	UP6: Appli-cation of fermen-tation residues on the field	UP7: CO_2 and energy produc-tion in a biomass boiler	EU-27: Electricity grid mix 2011	EU-27: Thermal energy from natural gas (for credit)	UP11: Substitu-tion of fertiliser	UP12: Operation of passenger car with gas engine	Total algae biorefinery	Reference: Conven-tional waste water treatment
A1	DALY total [years]	1.85E-07	2.38E-08	2.89E-08	1.74E-07	1.96E-08	8.39E-07	1.25E-07	2.40E-07	-2.51E-08	-3.13E-08	-3.90E-07	1.19E-06	9.85E-07
B1	Fossil depletion [kg oil-eq.]	6.28E-03	7.13E-03	4.47E-03	7.18E-03	1.53E-04	1.18E-02	2.08E-03	3.67E-02	-6.64E-03	-8.01E-03	-9.71E-02	-3.59E-02	1.07E-01
B2	Urban land occupation [m^2*a]	3.87E-04	7.13E-02	6.11E-05	2.52E-03	2.59E-07	0.00E+00	1.61E-06	0.00E+00	0.00E+00	0.00E+00	-4.51E-05	7.42E-02	6.90E-03
B3	Ozone depletion [kg CFC-11-eq.]	5.30E-09	2.13E-12	8.71E-10	1.70E-09	2.53E-11	2.47E-13	5.16E-12	1.03E-10	-3.18E-13	-7.35E-13	-1.68E-11	7.99E-09	7.40E-08
B3	Particulate matter formation [kg PM_{10}-eq.]	9.08E-05	1.29E-05	3.37E-05	3.52E-04	4.65E-05	1.44E-03	4.16E-04	1.66E-04	-4.26E-06	-9.46E-06	-8.58E-05	2.46E-03	7.19E-04
B3	Photochemical oxidant formation [kg NMVOC]	3.48E-04	2.55E-05	3.68E-05	3.70E-04	8.57E-05	3.46E-04	1.83E-03	2.88E-04	-1.73E-05	-2.57E-05	-2.01E-04	3.08E-03	1.31E-03
B3	Terrestrial acidification [kg SO_2-eq.]	2.27E-04	3.72E-05	4.17E-05	2.22E-03	1.24E-04	1.06E-02	1.08E-03	5.98E-04	-1.25E-05	-2.33E-05	-2.68E-04	1.46E-02	1.87E-03
B4	GWP100, excl. biogenic carbon [kg CO_2-eq.]	0.05	0.01	0.01	0.05	0.01	0.30	0.01	0.14	-0.02	-0.02	-0.27	0.28	0.47
B4	GWP20, excl. biogenic carbon [kg CO_2-eq.]	0.11	0.02	0.01	0.08	0.02	0.32	0.01	0.15	-0.02	-0.03	-0.31	0.36	0.51
B4	Climate change, default, excl. biogenic carbon [kg CO_2-eq.]	0.05	0.01	0.01	0.05	0.01	0.33	0.01	0.14	-0.02	-0.02	-0.26	0.30	0.47
B5	Blue water consumption [kg]	1.02	110.12	0.00	0.08	0.01	0.05	15.08	1.07	0.00	-0.04	-0.23	127.16	6.83
B5	Water deprivation [kg]	0.70	75.00	0.00	0.05	0.01	0.03	10.27	0.73	0.00	-0.02	-0.15	86.60	4.65
B6	Abiotic Depletion (ADP elements) [kg Sb-eq.]	1.09E-07	3.63E-09	3.54E-08	1.13E-07	2.89E-09	1.68E-09	9.96E-09	2.42E-08	-7.00E-10	-2.02E-08	-1.36E-08	2.65E-07	2.19E-06
B7	Fresh water ecotoxicity [kg 1,4-DB-eq.]	8.27E-03	4.18E-05	2.72E-04	9.55E-04	2.65E-05	5.25E-06	2.33E-04	4.25E-05	-3.20E-07	-3.01E-06	-4.28E-05	9.80E-03	8.99E-03
B7	Fresh water eutrophication [kg P-eq.]	1.56E-04	3.74E-07	3.82E-06	1.26E-05	4.02E-09	2.44E-07	1.17E-07	1.74E-07	-8.33E-10	-2.51E-08	-6.71E-08	1.73E-04	1.05E-04
B7	Marine eutrophication [kg N-eq.]	1.19E-03	1.21E-06	1.80E-06	8.58E-05	5.71E-06	4.09E-04	7.25E-05	1.49E-05	-5.46E-07	-1.75E-06	-8.16E-06	1.77E-03	7.46E-05
B9	PDF total [species*year]	4.63E-10	1.58E-09	9.62E-11	4.52E-10	4.29E-11	2.74E-09	7.96E-10	1.13E-09	-1.36E-10	-1.65E-10	-2.09E-09	4.91E-09	4.03E-09

Table 7-36: Potential environmental impacts caused by the incineration of 1 MJ biomethane/CNG in a passenger car

Criterion	Impact category and unit	UP5 01: Anaerobic waste water pre-treatment	UP2: Culti-vation of microalgae	UP 03: harvesting of algae	UP4: Biogas produ-ction from algal biomass	UP5: Biogas upgrading, service station, use in car	UP6: Appli-cation of fermen-tation residues on the field	UP7: CO_2 and energy produc-tion in a biomass boiler	EU-27: Electricity grid mix 2011	EU-27: Thermal energy from natural gas (for credit)	UP11: Substitu-tion of fertiliser	UP 13: Conven-tional waste water treatment	Total algae biorefinery	Refernce: operation car with CNG
A1	DAILY total [years]	5.34E-08	6.86E-09	8.32E-09	5.02E-08	5.64E-09	2.42E-07	3.59E-08	6.92E-08	-7.22E-09	-9.03E-09	-2.84E-07	1.71E-07	1.12E-07
B1	Fossil depletion [kg oil-eq.]	1.81E-03	2.05E-03	1.29E-03	2.07E-03	4.41E-05	3.41E-03	6.00E-04	1.06E-02	-1.91E-03	-2.31E-03	-3.09E-02	-1.32E-02	2.80E-02
B2	Urban land occupation [m^2*a]	1.11E-04	2.05E-02	1.76E-05	7.25E-04	7.46E-08	0.00E+00	4.65E-07	0.00E+00	0.00E+00	0.00E+00	-1.99E-03	1.94E-02	1.30E-05
B3	Ozone depletion [kg CFC-11-eq.]	1.53E-09	6.15E-13	2.51E-10	4.90E-10	7.28E-12	7.13E-14	1.49E-12	2.96E-11	-9.15E-14	-2.12E-13	-2.13E-08	-1.90E-08	4.83E-12
B3	Particulate matter formation [kg PM_{10}-eq.]	2.62E-05	3.73E-06	9.72E-06	1.01E-04	1.34E-05	4.15E-04	1.20E-04	4.80E-05	-1.23E-06	-2.73E-06	-2.07E-04	5.26E-04	2.47E-05
B3	Photochemical oxidant formation [kg NMVOC]	1.00E-04	7.34E-06	1.06E-05	1.06E-04	2.47E-05	9.98E-05	5.27E-04	8.30E-05	-4.99E-06	-7.42E-06	-3.77E-04	5.71E-04	5.81E-05
B3	Terrestrial acidification [kg SO_2-eq.]	6.53E-05	1.07E-05	1.20E-05	6.40E-04	3.57E-05	3.05E-03	3.10E-04	1.72E-04	-3.60E-06	-6.71E-06	-5.39E-04	3.74E-03	7.72E-05
B4	GWP100, excl. biogenic carbon [kg CO_2-eq.]	1.56E-02	3.74E-03	3.36E-03	1.45E-02	1.75E-03	8.69E-02	2.19E-03	4.03E-02	-4.99E-03	-6.17E-03	-1.36E-01	2.08E-02	7.66E-02
B4	GWP20, excl. biogenic carbon [kg CO_2-eq.]	3.12E-02	4.57E-03	3.75E-03	2.43E-02	4.80E-03	9.29E-02	2.40E-03	4.43E-02	-5.74E-03	-9.24E-03	-1.48E-01	4.50E-02	8.84E-02
B4	Climate change, default, excl. biogenic carbon [kg CO_2-eq.]	1.42E-02	3.67E-03	3.33E-03	1.36E-02	1.45E-03	9.55E-02	2.22E-03	3.99E-02	-4.92E-03	-5.90E-03	-1.35E-01	2.77E-02	7.55E-02
B5	Blue water consumption [kg]	2.94E-01	3.17E+01	0.00E+00	2.19E-02	2.24E-03	1.43E-02	4.34E+00	3.10E-01	-1.15E-03	-1.04E-02	-1.97E+00	3.47E+01	6.52E-02
B5	Water deprivation [kg]	2.00E-01	2.16E+01	0.00E+00	1.49E-02	1.52E-03	9.77E-03	2.96E+00	2.11E-01	-7.85E-04	-7.09E-03	-1.34E+00	2.37E+01	4.44E-02
B6	Abiotic Depletion (ADP elements) [kg Sb-eq.]	3.14E-08	1.05E-09	1.02E-08	3.25E-08	8.33E-10	4.83E-10	2.87E-09	6.98E-09	-2.02E-10	-5.81E-09	-6.31E-07	-5.50E-07	3.91E-09
B7	Fresh water ecotoxicity [kg 1,4-DB-eq.]	2.38E-03	1.20E-05	7.84E-05	2.75E-04	7.64E-06	1.51E-06	6.73E-05	1.23E-05	-9.23E-08	-8.67E-07	-2.59E-03	2.47E-04	1.23E-05
B7	Fresh water eutrophication [kg P-eq.]	4.49E-05	1.08E-07	1.10E-06	3.64E-06	1.16E-09	7.04E-08	3.37E-08	5.01E-08	-2.40E-10	-7.22E-09	-3.03E-05	1.96E-05	1.93E-08
B7	Marine eutrophication [kg N-eq.]	3.43E-04	3.48E-07	5.17E-07	2.47E-05	1.64E-06	1.18E-04	2.09E-05	4.28E-06	-1.57E-07	-5.04E-07	-2.15E-05	4.91E-04	2.35E-06
B9	PDF total [species*year]	1.33E-10	4.55E-10	2.77E-11	1.30E-10	1.24E-11	7.89E-10	2.29E-10	3.25E-10	-3.91E-11	-4.74E-11	-1.16E-09	8.55E-10	6.01E-10

Table 7-37: Evaluation of the change of electricity mix, substation of diesel instead of CNG in a passenger car, and use of biomethane in a CHP plant

	Parameter	Electricity mix Spain 2011	Electricity mix EU-27 2020	Substitution of diesel instead of CNG	Use of biomethane in a CHP plant
A1	DAILY [years]	-2%	-2%	-9%	0%
B1	Fossil depletion [kg oil-eq.]	-1%	-10%	9%	0%
B2	Urban land occupation [m^2*a]	0%	0%	0%	0%
B3	Ozone depletion [kg CFC-11-eq.]	-1%	-1%	0%	-1%
B3	Particulate matter formation [kg PM_{10}-eq.]	0%	0%	-8%	-8%
B3	Photochemical oxidant formation [kg NMVOC-eq.]	2%	0%	-24%	-3%
B3	Terrestrial acidification [kg SO_2 eq.]	0%	0%	-4%	-5%
B4	AR5 GWP100, excl. biogenic carbon [kg CO_2-eq.]	-5%	-7%	-11%	20%
B6	Abiotic depletion [kg Sb-eq.]	3%	4%	0%	-16%
B7	Fresh water ecotoxicity [kg 1,4-DB-eq.]	0%	0%	-1%	0%
B7	Fresh water eutrophication [kg P-eq.]	0%	0%	0%	-1%
B7	Marine eutrophication [kg N-eq.]	0%	0%	-5%	-1%
B9	Potentially disappearing fraction (PDF) [species*year]	-3%	-3%	-14%	5%

Table 7-38: Classification of LCIA methods according to (JRC 2010d); level »I«: recommended and satisfactory, level »II«: recommended but in need of some improvements, level »III«: recommended, but to be applied with caution

	Parameter	Level of classi-fication (JRC 2010d)	Remark
A1	DAILY total [years]	No evaluation	No methods recommended
B1	Fossil depletion [kg oil-eq.]	No evaluation	Life cycle inventory unit: corresponds to CED
B2	Urban land occupation [m^2*a]	No evaluation	Life cycle inventory unit
B3	Ozone depletion [kg CFC-11-eq.]	I	
B3	Particulate matter formation [kg PM_{10}-eq.]	I	Evaluation refers to RiskPoll model and $PM_{2.5}$
B3	Photochemical oxidant formation [kg NMVOC-eq.]	II	
B3	Terrestrial acidification [kg SO_2 eq.]	II	
B4	AR5 GWP100, excl. biogenic carbon [kg CO_2-eq.]	I	
B6	Abiotic depletion [kg Sb-eq.]	II	
B7	Fresh water ecotoxicity [kg 1,4-DB-eq.]	II/III	Evaluation refers to USEtox model
B7	Fresh water eutrophication [kg P-eq.]	II	
B7	Marine eutrophication [kg N-eq.]	II	
B9	Potentially disappearing fraction (PDF) [species*year]	No evaluation	No methods recommended

Table 7-39: Assumptions for prices and investments used for calculating the net present value of the algae biorefinery

Economic figures	Price [€*year^{-1}], investment [€]	Source/remark
Fixed capital investment (FCI)	1 762 073 €	
Biogas purification system	732 193	Complete purification system (Strauch, Maga 2014); Investment adjusted to small scale with equation: $y = 708982e^{0,0016x}$ (x=Nm^3 biomethane per hour)
UASB reactors	50 000	Estimated
10 ha HRAP ponds	444 000	Estimation based on (Delrue et al. 2012): 14.8 €*m^{-3}
Harvesting equipment (DAF)	18 000	Estimated based on (Aqualia 2014)
Digester	132 881	Estimation based on 1.5 Mio. for 250 m^3*h^{-1} incl. digester and storage of fermentation residues
Biomass boiler	52 000	Estimated based on (Aqualia 2014)
Infrastructure	300 000	Estimated
Others	33 000	Estimated based on (Aqualia 2014)
Cost of operating labour (COL)	225 000	
Whole plant	225 000	5 persons with an average salary of 45 000 €
Cost of utilities (CUT)	10 257	
Electricity	1 514	Industrial price: 0.1 €*kWh^{-1}
Fuel (diesel)	8 727	For transport and application of fermentation residues
Water	15	1.5 €*m^{-3}
Cost of raw materials (CRM)	43 032	
Olive pits	13 160	0.13 €*kg^{-1} (Aqualia 2014)
Activated carbon	183	1.5 €*kg^{-1} (Strauch et al. 2015)
Sodium hydroxide	135	0.35 €*kg^{-1} (Ereev, Patel 2011)
Coagulant	8 127	0.25 €*kg^{-1} (Aqualia 2014)
Polymers	17 066	3.5 €*kg^{-1} (Aqualia 2014)
Sludge disposal	4 361	9 €*m^{-3}, 20 % DM (Aqualia 2014)

7.2.2 Additional figures

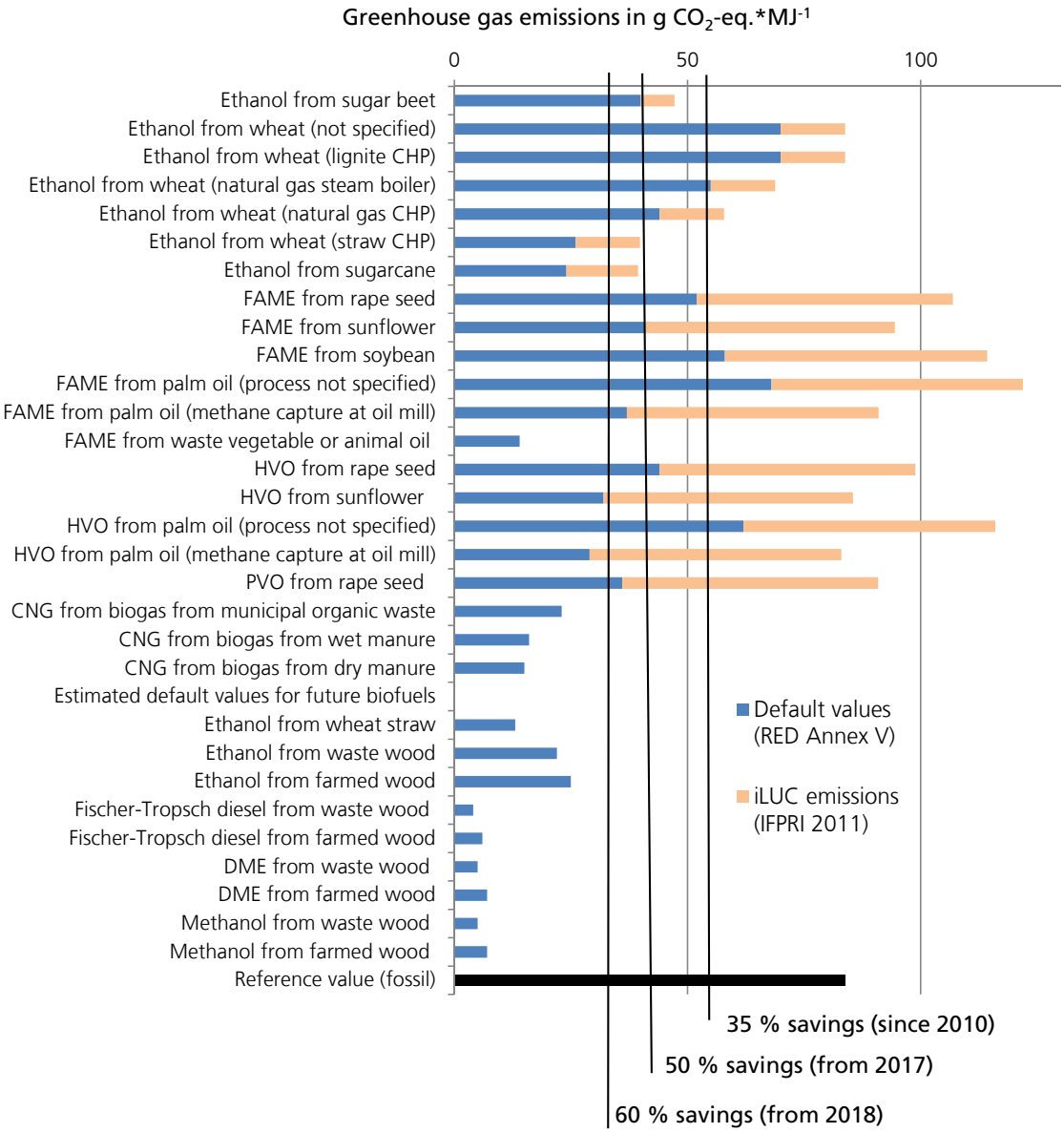


Figure 7-4: Greenhouse gas default values of the RED (European Commission 2009a) and modelled indirect land use change emissions according to IFPRI (Laborde 2011)

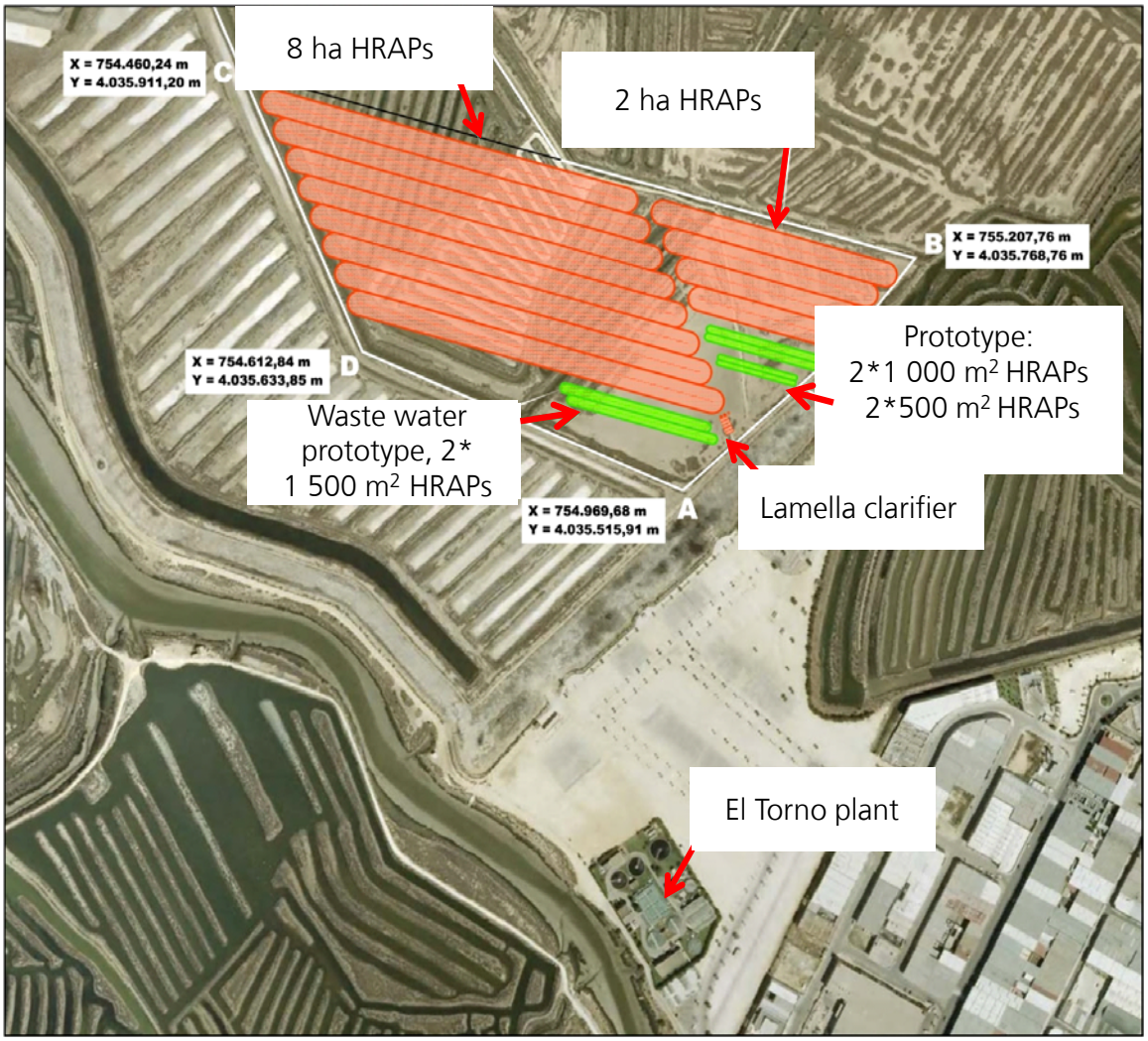


Figure 7-5: Plant location in Chiclana de la Frontera (Andalusia, Spain), Map data ©2015 Google

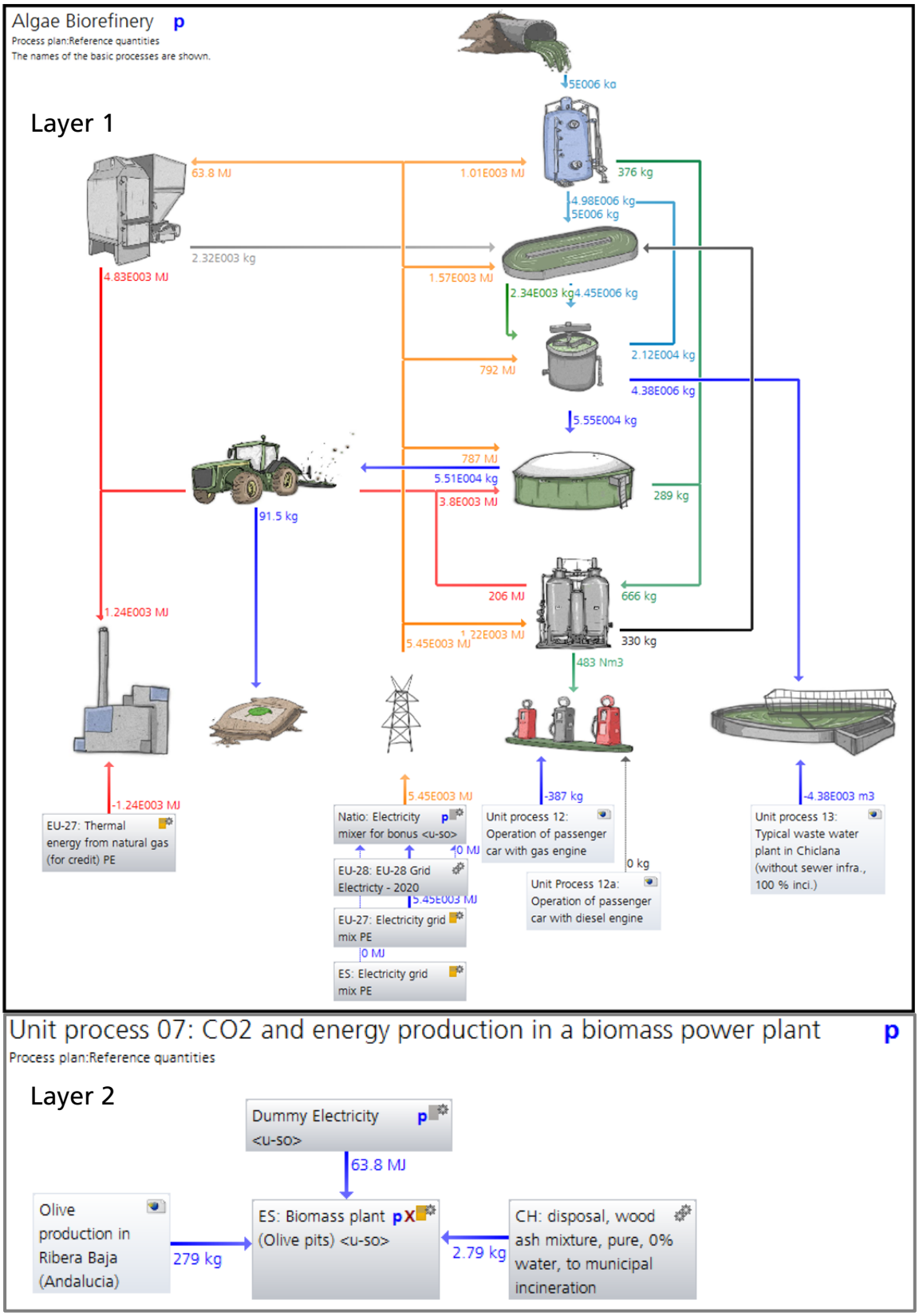


Figure 7-6: Small section of the LCA model produced in Gabi 6.0; LCA model of the algae biorefinery (layer 1) and LCA model of the biomass boiler (layer 2)

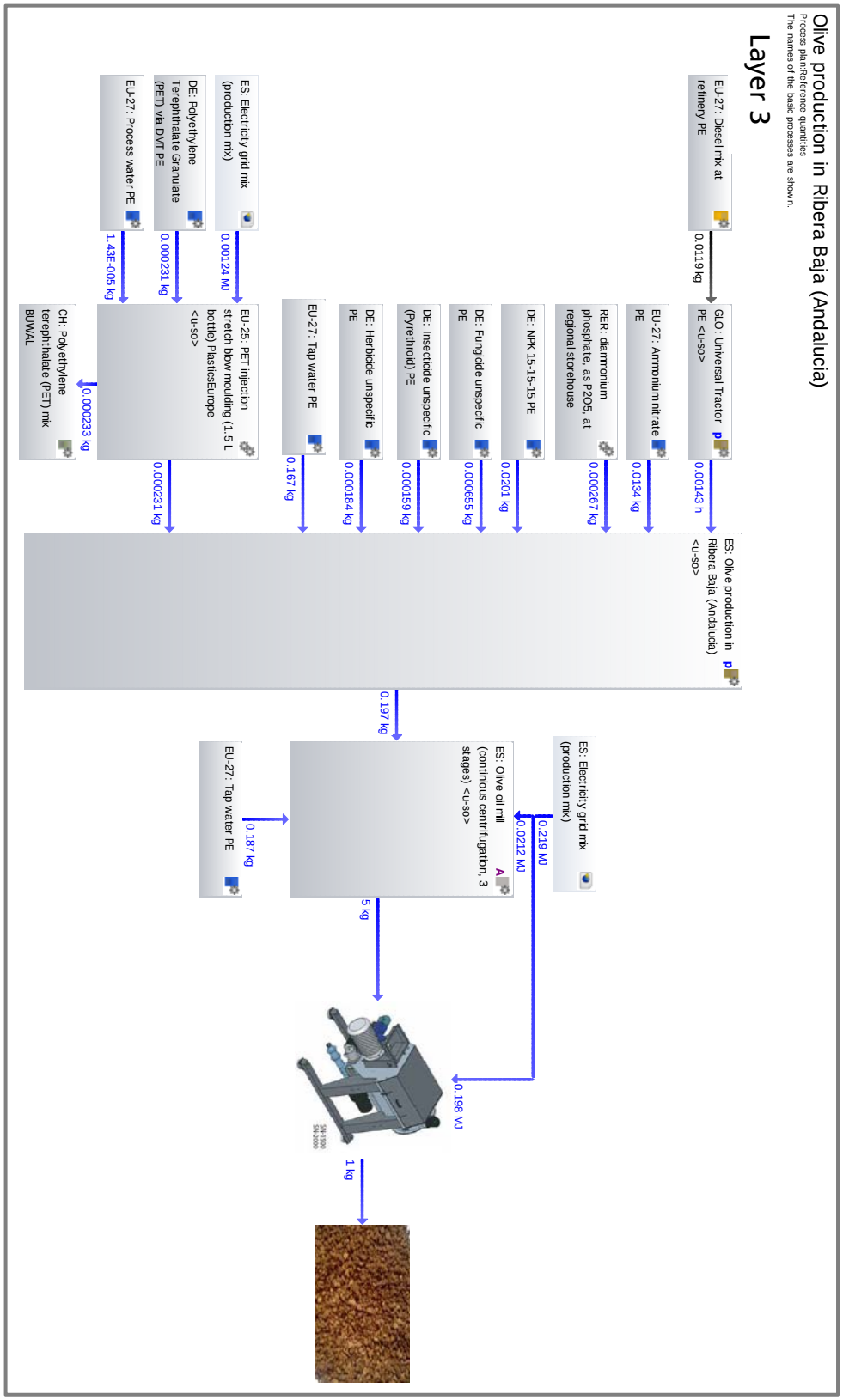


Figure 7-7: Small section of the LCA model in Gabi; LCA model for the production of olive pits to be incinerated in the biomass boiler (layer 3), reference flow 1 kg olive pits, allocation by price

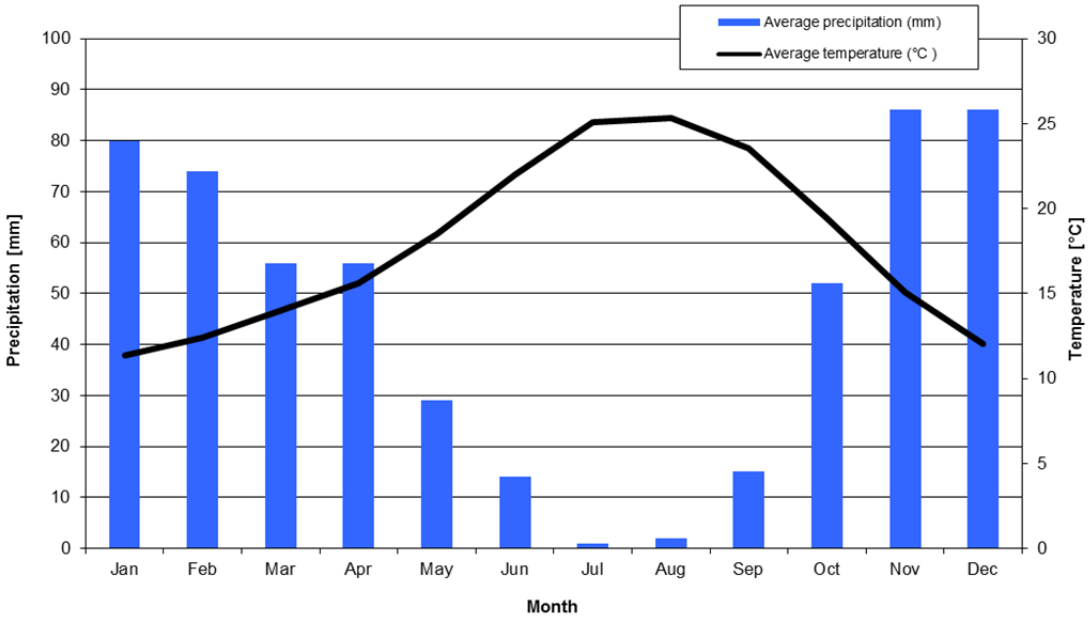


Figure 7-8: Climate chart Chiclana de la Frontera, figures refer to the time frame 1960-1990 and were taken from the IPCC data distribution centre (IPCC 2014)

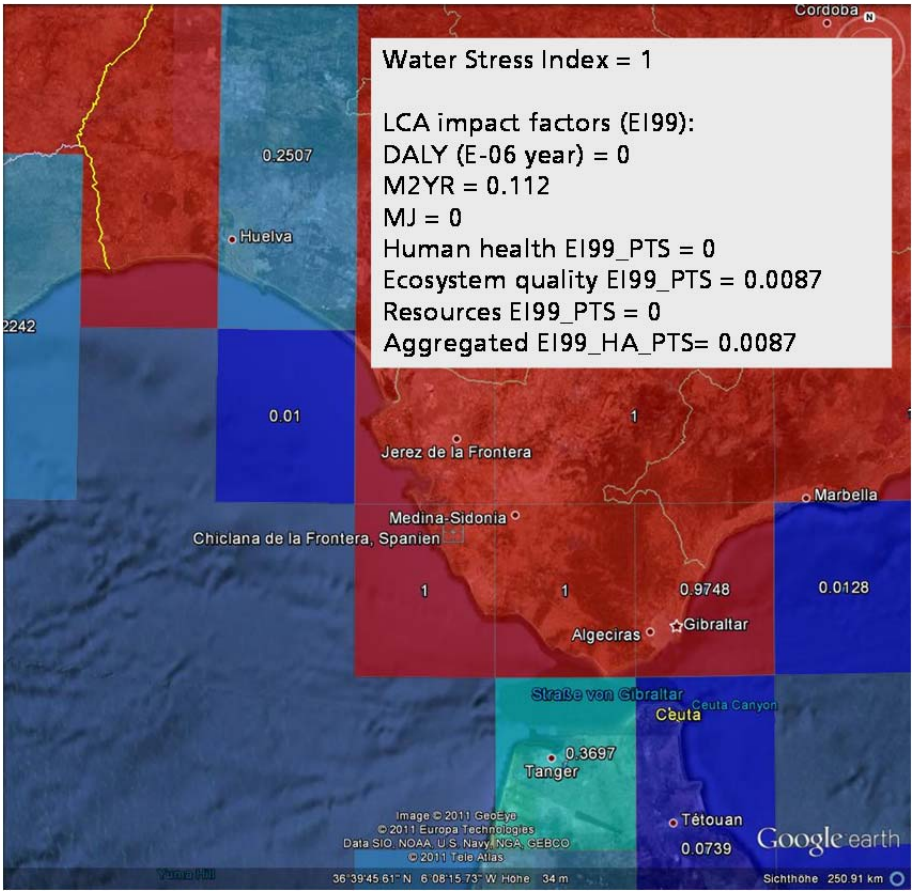


Figure 7-9: Water stress index according to Pfister et al. in the region of Chiclana de la Frontera (Pfister et al. 2009), © 2011 GeoEye

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