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Abstract

Environmental life cycle costing has been applied to determine the economic viability of exclusive biogas production and coupled hydrogen and biogas production from microalgae in a photobioreactor (PBR). Exclusive biogas production consists of the production steps photoautotrophic biomass production and anaerobic digestion. Coupled hydrogen and biogas production considers the steps photoautotrophic biomass production, photobiologically hydrogen production and anaerobic digestion of the residual algal biomass. This study especially evaluates the economic performance of a novel staggered PBR design with an appearance of interconnected roofs. The novel PBR design aims at minimizing energy consumption and at providing optimal light conditions for the growth of the microalgae species *Chlamydomonas reinhardtii* and for hydrogen generation. Membrane aeration through diffusion instead of air sparging is a difference to conventional PBRs.

In a German production setting for 2011, environmental life cycle costs for exclusive biogas production amount to 0.99 Euro/MJ. For coupled production, costs of 0.81 Euro/MJ biogas and 12.17 Euro/MJ hydrogen could be determined. These costs considerably exceed the market prices of 0.02 Euro/MJ biogas and 0.04 Euro/MJ hydrogen. Operating costs amount to 72 percent of life cycle costs for biogas and to 69 percent for hydrogen respectively. Major cost contributors to operating costs are personnel and overhead costs with a share of more than 70 percent. The investment costs consist to about 92 percent of those for the PBR, of which 61 percent are material costs for the membrane.

In the given setting, the choice of a production location such as Spain with higher incident solar irradiation and mainly lower personnel costs compared to Germany results in a reduction of life cycle costs by about 50 percent for a similar production system. A future projection with experience curves for Germany has shown that hydrogen life cycle costs would be expected to amount to about 80 times the market prices by 2030 under consideration of technology learning. Biogas production for a German setting is expected to amount to about 15 times of the projected market price by 2030.

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List of abbreviations

AEMET	Spain’s State Meteorological Agency
BMELV	German Federal Ministry of Food, Agriculture and Consumer Protection
BGK	German Federal Compost Association
BMJ	German Federal Ministry of Justice
C	Carbon
CBA	Cost-benefit analysis
CEN	European Committee for Standardization
CH_4	Methane
C/N	Carbon-to-nitrogen ratio
CO_2	Carbon dioxide
DBFZ	German Biomass Research Centre
DEHSt	German Emissions Trading Authority
Destatis	German Federal Statistical Office
DIN	German Institute for Standardization
DW	Dry weight, dry matter or total solids
DWD	Germany's National Meteorological Service
EC	European Commission
ECB	European Central Bank
EG	European Community
EU	European Union
FNR	German Agency for Renewable Resources
FTE	Fulltime equivalent
GHG	Greenhouse gas
H_2	Hydrogen
HHV	Higher heating value
HRT	Hydraulic retention time

HVP	High-value product
HydroMicPro	Hydrogen from Microalgae: With Cell and Reactor Design to Economic Production
IAB	Institute for Employment Research
IFA	Institute for Occupational Safety and Health of the German Social Accident Insurance
IEA	International Energy Agency
ISO	International Organization for Standardization
KI	Plastic information agency
LCA	Life cycle assessment
LCC	Life cycle costing
LCI	Life cycle inventory
LHV	Lower heating value
N	Nitrogen
N/A	Not applicable
NH_3	Ammonia
NREL	United States National Renewable Energy Laboratory
P	Phosphorus
P_2O_5	Phosphorus pentoxide
PCE	Photon conversion efficiency
PBR	Photobioreactor
PET	Poly(ethylene terephthalate)
PMMA	Poly(methyl methacrylate)
SWB	South-Western German Commodity Exchange
TS	Total solids, dry weight or dry matter
VDI	Association of German Engineers
VS	Volatile solids or organic matter

List of units

a	Year
cm	Centimeter
°C	Degree celsius
d	Day
EJ	Exajoule
EUR	Euro
g	Gram
h	Hour
ha	Hectare
J	Joule
K	Kelvin
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt hour
l	Liter
m	Meter
m^2	Square meter
m^3	Cubic meter
MJ	Megajoule
ml	Milliliter
mm	Millimeter
MPa	Megapascal
µm	Micrometer
nm^3	Standardized cubic meter
t	Ton
USD	United States dollar
W	Watt

1 Introduction

1.1 Background

Microalgae are cultivated for various purposes. These include food and feed provision, fine and bulk chemicals, wastewater treatment as well as energy production (Richmond 2004b; Pulz and Gross 2004). Energy production has been investigated to a large extent with focus on biomass, biodiesel, biogas or hydrogen production (Wijffels and Barbosa 2010). Hydrogen can be generated from dead or active biomass. The former has been determined to be economically favorable at the moment and determined to be competitive with other technologies for hydrogen production such as electrolysis fed by wind power (Ni et al. 2006)[1]. Concerning the latter, photobiological hydrogen production is still at an early development stage and not marketable yet (Holtermann and Madlener 2011).

The following reasons for the consideration of microalgae in energy production – including the special case of hydrogen and biogas – have been derived in prior studies:

- High areal biomass production rate (Chisti 2007)
- Higher photon conversion efficiency (Hankamer et al. 2007)
- CO_2 capture and reuse of CO_2-containing flue gases (Brennan and Owende 2010)
- High energy content (Chisti 2008)
- No competition for fertile land with food crops (Duffy et al. 2009)
- Use of wastewater – treatment and fertilizer at no charge (Kong et al. 2010) – and salt water for marine algae species (Kumazawa and Mitsui 1981)

[1] Wind power has been described as one of the economically favorable hydrogen production possibilities (Turner 2004).

- Large potential for genetic modifications for yield optimization or adaptation to environmental conditions (Beer et al. 2009; Radakovits et al. 2010)

In particular, this study is embedded in the research project *Hydrogen from Microalgae: With Cell and Reactor Design to Economic Production* (HydroMicPro) that is developed in the framework of the program ”Basic research Energy 2020+” by the German Federal Ministry of Research and Education. The aim of the project is to develop a biotechnologically and for processing optimized photobioreactor (PBR) that should be used in Germany at a first step. Additionally, the microalgae used should be genetically modified to raise efficiency to achieve economic marketability and ensure environmentally sustainable hydrogen production (Patyk and Weiss 2012; Posten and Schaub).

1.2 Goal

This project aims at identifying the environmental life cycle costs for two alternative final products from photoautotrophically grown algal biomass – species Chlamydomonas reinhardtii. One alternative is biogas. The other is the coupled production of hydrogen and biogas. To asses, whether the intended final products – hydrogen and biogas – and the production technology are econonmically favorable, costs for the two products in the two production alternatives are determined.

The environmental life cycle costing (LCC) model is the basis for identifying major cost drivers and for revealing optimization potential for future production. Additionally, the project sheds light on the question, when – i.e., under which conditions – the economic break-even point from the producer perspective for the indicated products is met, should be answered. In doing so, the perspective of a producer is taken opposed to a consumer perspective because only for the former the major difference to other production options of biogas and hydrogen exists. The consumer related life cycle costs should be rather independent from the production method of the energy carrier if they are compared per unit of energy.

The environmental LCC model will be developed with a life cycle assessment (LCA) model that is developed in parallel to unite evironmental and economic sustainability and to show trade-offs between both perspectives in further studies.

1.3 Environmental life cycle costing

LCC embraces all costs arising the life cycle of a product that are attributable to different agents – e.g. consumer, producer or supplier (Swarr et al. 2011)[2]. The specific characteristics of environmental LCC are given in the following chapter in context to other LCC types. The subsequent chapter deals with typical structure, how to conduct environmental LCC and which phases exist. The second to last subchapter explains cost allocation methods if coupled products need to be treated. The last chapter discusses alternative environmentally orientated economic analyses.

1.3.1 Overview and context

There are three types of LCC (Lichtenvort et al., 2008):

- Traditional LCC
- Environmental LCC
- Societal LCC

The traditional LCC covers internal costs that arise from either a producer or a consumer perspective. The considered costs comprise investment and operating costs and often exclude disposal or other end-of-life costs (Lichtenvort et al. 2008).

Environmental LCC has been developed to be combined with a LCA. To set both analyses in relation, the system boundaries as well as the functional unit have to be harmonized. It goes beyond traditional LCC as it includes more life cycle stages – especially end-of-life costs – and costs are likely to be covered by an agent in the future, but are currently not to be considered. The latter costs comprise externalities such as emissions which are currently not taxed or possible future recycling obligations for a product (Swarr et al. 2011). If externalities do not fall within the definition in the foregone sentence, they are only considered in the LCA. This differentiation is necessary to avoid double counting of environmental impacts (Lichtenvort et al. 2008). Since environmental LCC is conducted in accordance with a LCA, which is a steady-state model, no dynamic modeling of cash flows – i.e. discounting – is conducted to avoid discrepancies (Huppes et al. 2008). It is applied in this study and for simplicity only denoted as LCC instead of environmental LCC.

[2] An overview of definitions for traditional and environmental LCC is given by Höhne (2009).

Societal LCC derives its ideas from the methodology of cost-benefit analysis. It extends the costs considered to also include the costs arising from external effects that are not expected to be covered by the consumer or manufacturer in the near future. Society has to bear the costs for these effects (Rebitzer, Hunkeler, and Jolliet 2003).

1.3.2 Structure

Being a complementary analysis to LCA and missing a standardized procedure, environmental LCC should follow the LCA procedure. It consists of four steps (Lichtenvort et al. 2008; Swarr et al. 2011):

- Definition of goal and scope
- Economic life cycle inventory
- Interpretation and identification of hot spots
- Sensitivity analysis and discussion

The goal definition should state the application, aim and reason for conducting the study. Additionally, the intended audience can be indicated. Within scope definition, the system boundaries should be determined and justified. This requires to identify the relevant up- and downstream processes (Swarr et al. 2011). Additionally, the alternatives to be compared should be defined. The choice of alternatives needs to be in accordance with the respective alternatives in the LCA as well as the same functional unit defined (Lichtenvort et al. 2008). External effects towards the environment are considered in the LCA and are not included if not to be paid by the producer in the near future. It is necessary to distinguish between aspects in the LCA and the LCC to avoid double counting of environmental impacts (Lichtenvort et al. 2008). Lastly, data sources, year of study as well as the geographic location with the relevant currency should be stated (Swarr et al. 2011).

The economic life cycle inventory (LCI) is based on physical flows comparable to a LCI for a LCA.[3] It should include a cost classification system. Additionally, the currency and period of the cost data should be harmonized. Material flow analyses and energy balances may support the economic life cycle inventory (Swarr et al. 2011). Preferably actual cost data should be taken and if not available cost estimation techniques such investment cost estimation methods or other fore-

[3] The LCI for the LCA and the environmental LCC might differ as the former is always based on physical flows, whereas the latter needs to consider some monetary flows such as costs of capital that are not associated with any physical flow (Swarr et al. 2011).

casting techniques can be applied. Low-impact cost items that account in total less than one to five percent may be excluded from the analysis (Lichtenvort et al. 2008).

The LCC should reveal the hotspots of the respective technology. The interpretation of the results can be quantitative or qualitative. The former is often the net present value or the payback period if discounting is applied and the revenue is also considered. For a pure cost analysis, a comparison of life cycle costs per functional unit with other products could be conducted. Additionally, the interpretation could be also based on qualitative criteria such as security of supply or competition for arable land. To identify hot spots, scenarios with varying assumptions and possible future pathways could be calculated (Lichtenvort et al. 2008).

A sensitivity analysis should reveal to which extent the output reacts to changes of input parameters of the LCC model to assess the robustness of estimated parameters. Due to the disadvantage that within a sensitivity analysis only one parameter might be varied, a Monte Carlo simulation can be regarded as an alternative with the trade-off of less transparent results (Lichtenvort et al. 2008).

1.3.3 Life cycle phases

In general, environmental LCC distinguishes – comparable to LCA – four life cycle phases, for which an inventory of production steps is established. The first is the development phase, which considers apart from all costs related to research, planning and design of a production or a product. The second is the construction phases, which considers all costs related to the setting up of the production facilities. In the following use phase, operating costs for the production are to be identified. A final decommissioning phase includes all costs associated with recycling and disposal of the production facilities and for restoring the original state of the production site (Swarr et al. 2011).

1.3.4 Cost allocation for coupled products

If more than one product is obtained from a production system and no differentiation between the costs of the product is possible, allocation methods would be necessary. For LCC, no standard procedure is prescribed and rather managerial and technical judgment is required. Allocation is widely applied and accepted (Swarr et al. 2011). To ensure consistency of LCC and LCA methods, the LCA standard procedure is also reviewed and considered. It is prescribed by ISO 14044:2006 (CEN 2006). The basic requirements are that inputs and outputs before and after allocation sum up to the same amount. If different allocation options are regarded reasonable, a sensitivity analysis should be applied for the judgment of the alternatives. If possible, allocation should be avoided either by creating sub-processes, which are separable between the coupled products, or by extending the system boundaries with supplementary functions, which cover the coupled products. If allocation is necessary, the mode of choice is to allocate emissions through underlying physical properties of products such as mass or energy content. If physical properties are not feasible or suitable, other allocation keys could be applied. This could be the economic value – i.e. the market price – of the co-products (CEN 2006).

1.3.5 Other tools for environmentally-oriented economic analysis

Apart from LCC and the special case of environmental LCC used in this study, other tools for environmentally-oriented economic analysis are reviewed in this section.

Cost-benefit analysis (CBA) considers and monetizes all social costs and benefits of a policy or a project (Pearce 2006). Using money as exclusive category for quantification – also for complex environmental or societal issues, results may be oversimplified and misleading (Finnveden and Moberg 2005), however easy to communicate (Ness et al. 2007). As mentioned in chapter 1.3.1 for societal LCC the risk of double counting in combination with LCA persists (Pearce 2006).

Eco-efficiency combines as a ratio of economy and environment both sides of a product. Setting the latter in the denominator, this ratio enables the user to identify the highest economic output at a given environmental damage or vice versa. Compared to the above named tools, it denies converting one of the two components into monetary units (Heijungs 2007; Jeswani et al. 2010), which is inadequate or imprecise e.g. for CBA (Gluch and Baumann 2004). Lacking a methodological framework and a clear definition of environmental impacts to be included, this method is not mature for application yet (Jeswani et al. 2010).

Total cost assessment is a tool that combines LCA with a scenario-based risk analysis that may be applied at product, process or building level. It includes internal (direct, indirect, contingent and intangible) as well as external costs (Norris 2001). Including the latter is very likely to generate double-counting such as environmental destruction that is already accounted for in a LCA (Lichtenvort et al. 2008).

Hybrid LCA or economic input-output LCA model means that a process-based LCA is a LCA based on economic Input-Output analysis. The economic Input-Output analysis uses regular monetary values. The monetary outputs at sector level are translated in LCA values by sector specific indices (Haes et al. 2004). As this project is at product level, an analysis at sector level would not fulfill the requirements of precision.

Activity-based costing is a full-cost method that distributes overhead costs to processes and raw material to enable a use-related distribution (Cooper and Kaplan 1988; Gale and Stokoe 2001). In the environmental context, it can be applied to quantify savings from environmental-friendly measures or even used with the focus on environmental costs as a key category. The latter especially relates to costs that are often neglected by producers or consumers as they are outside their responsibility such as end-of-life costs (Bartolomeo et al. 2000). Within this study, the focus is set on the production of a single product or two coupled products so that overhead is automatically attributed to the products. Further distribution is neither necessary nor possible. So activity-based costing is not an adequate tool as it is normally applied to relate high overhead costs to different products (Cooper and Kaplan 1988)

1.4 Cost calculation methods

1.4.1 Temporal, capacitive and regional adjustments

If cost data from former studies is used, temporal, capacitive and country-specific adjustments will be necessary (Kerdoncuff 2008). Cost data needs to be temporarily adapted to consider inflation, which is done by price indices. Capacitive adjustment is often done for investment costs by applying the exponential or power law shown in Equation 1. To obtain the investment costs for the required capacity Inv_{scaled}, the investment costs of the original production equipment $Inv_{original}$ are multiplied by the ratio of the size of the scaled up equipment $Size_{scaled}$ and of the original equipment from the original study $Size_{original}$, which is adjusted by an exponential factor n. Adjustment by n, which is typically between 0.3 and one is done to consider economies of scale (Gerrard 2000).

$$Inv_{scaled} = Inv_{original} * \left(\frac{Size_{scaled}}{Size_{original}}\right)^n$$

Equation 1: Scaling of equipment[4]

[4] Adapted from Gerrard (2000).

Country-specific adjustment may be warranted given different labor costs for the production and installation of equipment. Additionally, cost items might only be available in different currencies and exchange rates need to be applied (Kerdoncuff 2008). Here, it does not make any difference, whether inflation adjustment or currency conversion is done first, as in functioning markets both should equalize each other (Campa and Goldberg 2002; Samuelson 1948).

1.4.2 Investment cost estimation methods

First, the different types of investment costs for a production plant need to be defined. Those are the major equipment, subcomponents such as piping and construction as well as installation costs. Major equipment – i.e. machinery and apparatus – are defined first in the estimation process and represent in general 25 to 40 percent of the investment costs (Remmers 1991).

The investment costs estimation methods can be divided into three major groups. Those are universal methods, factor methods and the detailed estimation of investment costs. They mainly differ in terms of data requirements as well as time and financial resources consumed, which increase the more detailed an estimation method is. In choosing the appropriate method, this trade-off between accuracy and time as well as financial resource consumption should be considered and a combination that is optimal for the aim of the project should be chosen. The trade-off varies through the different stages of the planning process of a project. At earlier stages, the provision of information is more resource consuming and a less precise investment cost estimate might be sufficient (Gerrard 2000; Kerdoncuff 2008).

Universal methods determine investment costs as one value and therefore allow a very rough estimate (Kerdoncuff 2008). A common approach is to determine the investment costs by dividing the annual sales of the products of a plant by the turnover-ratio. The turnover ratio is the quotient of investment costs and annual return (Woods 1975). This method is applied if data is available only for other comparable production facilities. The estimation error is at about 40 percent (Schwind 1979).

Factor methods only calculate the investment costs of the major equipment in detail. Further investment costs are added by multiplying the major equipment costs by one global installation factor, modular installation factors or installation subfactors (Kerdoncuff 2008). The first option – also called Lang method – summarizes all subcomponents and installation costs in one factor. The second option divides the production process in functional modules, for which specific installation factors are calculated, which do not differ between categories of components or installation costs. These factors are also very production method specific and difficult to confer. The last method uses installation sub-factors for the relevant categories, which are based on the total major equipment costs. It requires industry or production type specific installation subfactors for reliable results (Gerrard 2000). The proceeding is based on the empirical relationship that investment costs of major equipment are often proportional to the total investment costs (Remmers 1991). It is applied if detailed knowledge of the processes, of capacities of important equipment and design data is available. The estimation error is between ten and 15 percent (Schwind 1979).

A detailed estimation of investment costs requires a direct estimation of each investment position. Therefore, a detailed plan on materials used, spatial plant set-up and further specification are needed. This is the most time consuming and information requiring method. This level of detail will be necessary if e.g. a company is contracting a construction of a new production plant (Gerrard 2000). The estimation error for this method is up to five percent (Schwind 1979).

1.4.3 Modeling of experience curves

If producers and consumers of a technology gain experience, the costs for manufacturing and usage typically decline. This relationship is expressed in Equation 2 with the production costs of the first unit produced C_0, the cumulative production A, the costs per unit after producing A units of a product C_{cum} and the experience index b.

$$C_{cum} = C_0 * A^{-b}$$

Equation 2: Experience curve[5]

b is normally not indicated, but can be obtained through the progress ratio, which is 2^{-b}. The progress ratio indicates at which rate the costs per unit will decrease if the production is doubled (Pienkos and Darzins 2009). The underlying mechanisms for the cost decline are mainly learning-by-doing effects (Balat and Kırtay 2010; McDonald and Schrattenholzer 2001). In detail, there are three groups of explaining mechanisms (Gerrard 2000):

- Changes in the production (new processes, labor efficiencies, economies of scale)
- Product changes (innovations, design, standardization)

[5] Adapted from Junginger et al. (2008).

- Varied input prices

The production related changes positively affect the producer and those of the product mainly the user, whereas varied input prices can be related to both (Junginger et al. 2008).

The experience curve approach assumes endogenous learning – meaning that cost reductions are attributable to industry-internal or user-related developments described above (Romer 1994). Cost reductions cannot be sufficiently explainable by macroeconomic exogenous variables such as saving rates, which are independent from the actual technology, which is the fact for macroeconomic growth theories (Solow 1956). The major characteristic of endogenous learning is that it implies that cost reduction only occurs if a technology is applied and reflects the positive effects of earlier action, i.e. investments, better (Junginger et al. 2008).

Endogenous learning for energy systems can be modeled in two approaches, a top-down one, which is used in macroeconomic models, and a bottom-up, which is used in system-engineering models. Top-down models are closer to exogenous learning approaches and generic parameters for technology improvement such as increased energy efficiency is assumed as a function of technology independent parameters – i.e. the energy price (Junginger 2005). Apart from this component that is rather comparable to exogenous learning, further research and development investments raise the cost decline rate (Kahouli-Brahmi 2008). The top-down approach allows improved modeling of technology diffusion and spill-over effects within an industry. Bottom-up models will use technology specific progress ratios for modeling the cost decline and will allow separate modeling of sub-systems if a production system is composed of differing technologies (Junginger et al. 2008; Kahouli-Brahmi 2008; Berglund and Söderholm 2006).

1.5 Background on microalgae and production options

1.5.1 Biology

Microalgae are eukaryotic oxygenic photosynthetic organisms – microalgae *sensu stricto*. The identifying characteristic is a nucleus with a membrane and plastids bound in membranes. They can be found in most of the ecosystems types, but predominately in marine or freshwater environments. In the broader sense, prokaryotic oxygenic cyanobacteria are included (Tomaselli 2004).

C. reinhardtii is a unicellular, mixotrophic green algae[6] with a diameter of about ten µm with two flagella for locomotion (Merchant et al. 2007). In general, *C. reinhardtii* reproduces vegetatively, but under nitrogen starvation haploid gametes for sexual reproduction are formed (Beck and Acker 1992). A stigma with photoreceptors enables *C. reinhardtii* to determine intensity and direction of incident light for phototaxis. This optimizes photosynthesis and cell nutrition (Schmidt et al. 2006).

1.5.2 Biomass production

Apart from the focus on photoautotrophic biomass production in this study, heterotrophic and mixotrophic production exist (Brennan and Owende 2010). For photoautotrophic production, two production systems are mainly used: open pond and PBR. A third system is a hybrid system, for which a PBR is used to cultivate the inoculum, which is in consequence grown in an open pond (Schenk et al. 2008).

Open ponds could be circular or raceway ponds. Both are commonly made of concrete or from compacted earth coated with plastic. In a circular pond, the culture is circulated by a rotating arm, which requires a high energy input for rotation and more expensive concrete walls compared to raceway ponds (Tredici 2004). The more common ones are raceway ponds. The production area is divided in grids of rectangles, which contain an oval channel. The nutrients and algal biomass are driven by a paddle wheel through the channel. Finishing one loop, the algal biomass is harvested as shown in Figure 1 (Brennan and Owende 2010; Schenk et al. 2008).

[6] Kingdom *Protista* – Division *Chlorophyta* – Class *Chlorophyceae* – Order *Volvocales*– Family *Chlamydomonadaceae* – Genus *Chlamydomonas* (Dangeard 1888)

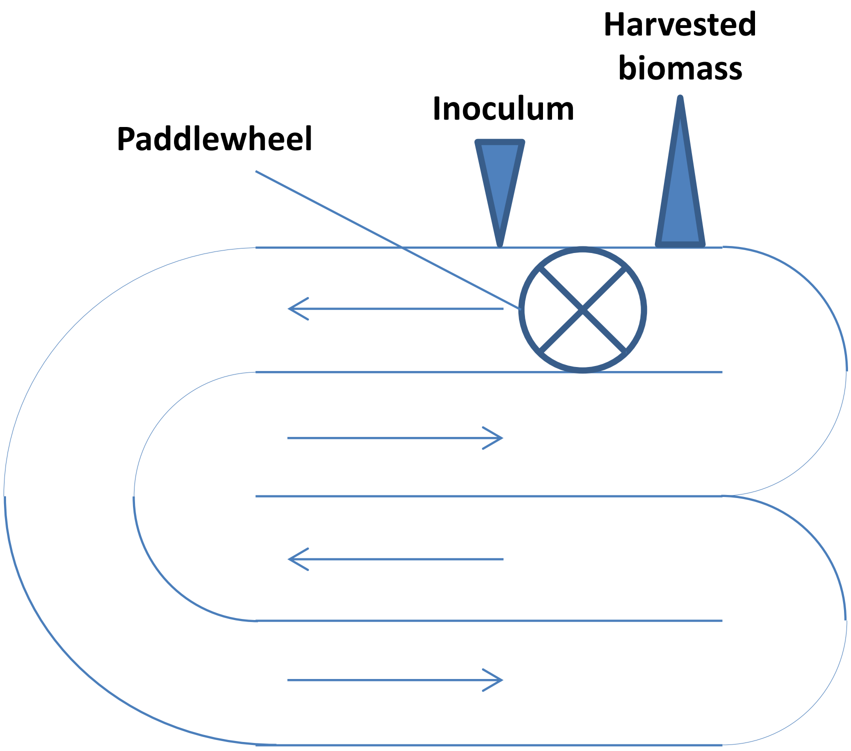

Figure 1: A schematic raceway pond[7]

Three types of PBR could be commonly found (Brennan and Owende 2010; Schenk et al. 2008):

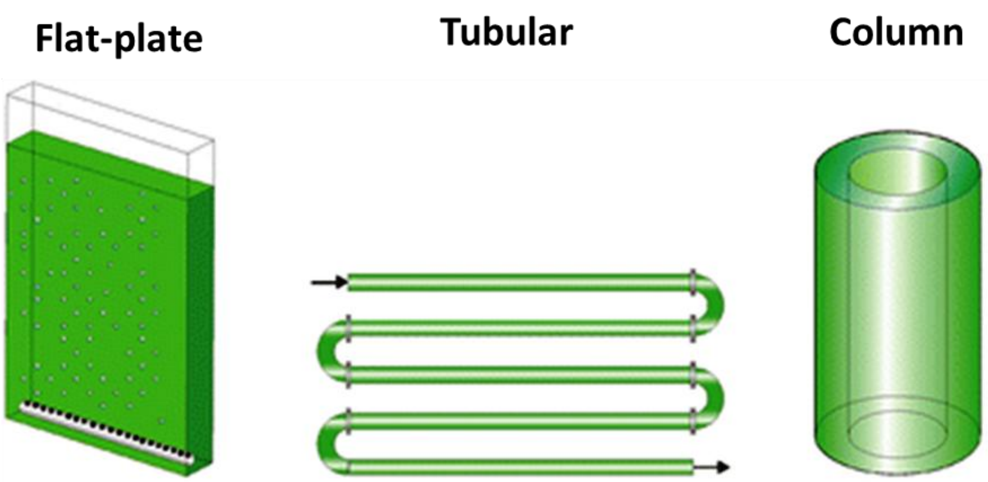

Figure 2: Different designs for photobioreactors[8]

[7] Adapted from Chisti (2007).

In common for all PBRs is that more than 90 percent of incident light passes through the PBR wall to reach the algal culture. The culture is prevented from atmospheric gas exchange and contamination (Brennan and Owende 2010; Schenk et al. 2008).

Flat-plate PBR are characterized by their flexible orientation for optimal exposure to solar irradiation with a short light path (Ugwu, Aoyagi, and Uchiyama 2008) and their high density of algal biomass up to 80 g/l, which is the result of the thin culture layer of each plate (Hu et al. 1998; Richmond 2004a). They accumulate less dissolved oxygen and have a higher photosynthetic efficiency compared with tubular PBRs (Cheng-Wu et al. 2001). Less energy for culture circulation and a higher biomass yield per culture volume are possible (Schenk et al. 2008).

Tubular PBRs are limited in their size due to the risk of accumulating oxygen and depleting CO_2 as well as a fluctuating pH with increased size (Eriksen 2008). An advantage compared with flat-plate PBRs is the light delution effect of tubular PBR. Hence, *C. reinhardtii* reaches light saturation at relatively low sunlight intensities. Direct solar irradiation results in lower efficiencies, photoinhibition or -bleaching (Melis et al. 2000; Schenk et al. 2008).

Annular or column PBRs offer the highest mass transfer rates, more efficient mixing and easily controllable growth conditions (Eriksen 2008) with a biomass yield comparable to tubular PBRs (Sánchez Mirón et al. 2002). Aeration is often provided from the bottom. Irradiation reaches the culture from the inside or the outside (Schenk et al. 2008).

Comparing open ponds and PBRs, the major arguments favoring the former are the comparably easy construction and the associated low costs as well as the lower energy requirement for culture processing. PBRs are preferable in terms of higher biomass productivities per culture volume and area, lower evaporative losses and the protection against contamination through competing species. Additionally, such closed systems permit reliable control of nutrient and CO_2 concentration as well as parameters such as temperature and pH value (Brennan and Owende 2010; Schenk et al. 2008). Especially in circumstances of high outside temperature, temperature control is provided either by water sprinklers for evaporative cooling (Tredici, Zittelli, and Benemann 1999; Cheng-Wu et al. 2001) or by internal or external heat exchangers (Jorquera et al. 2010; Chisti 2007).

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[8] Adapted from Schenk et al. (2008).

A hybrid system can reduce the contamination risk of open ponds as the inoculum from the PBR is grown to an extent that the desired algal species should be able to successfully compete with other species. Higher costs of construction and higher energy requirement of closed PBRs could be reduced to a minimum – the inoculation PBR (Schenk et al. 2008).

1.5.3 Hydrogen production and recovery

Hydrogen is produced photoautotrophically through direct biophotolysis. The photosynthetic system in algal cells absorbs light, which is used for water splitting, which results in a hydrogen and oxygen output. To obtain hydrogen instead of algae using the energy for CO_2 fixation, sulfur-deprived conditions need to be created (Hallenbeck and Benemann 2002). In a sulfur-deprived medium, protein synthesis is perturbed as sulfur is not available for amino acid synthesis. Especially, blocked synthesis of the protein D1 for the photosystem II hinders the splitting of water into hydrogen and oxygen. Additionally, respiration in chloroplasts and mitochondria reduce the cellular concentration of oxygen, which in collaboration lead to anoxic conditions within 24 hours (Hankamer et al. 2007; Melis et al. 2000). To create anoxic conditions, centrifugation and washing of the algal culture for oxygen and sulfur removal and acetate addition for enhanced oxygen consumption are the preferred mode (Kosourov et al. 2002; Kruse, Rupprecht, Bader, et al. 2005). Without sulfur deprivation, anoxic conditions could not be ensured and the enzyme hydrogenase, which is necessary for hydrogen production, would be inhibited (Happe et al. 2002; Melis et al. 2000).

Continuous hydrogen recovery from the PBR is necessary to ensure high hydrogen yields. In particular, accumulated hydrogen in the PBR leads to production repression and interspecies hydrogen transfer resulting in methanogenesis. For hydrogen recovery the following possibilities exist (Nath and Das 2004):

- Nitrogen or argon sparging (Hawkes et al. 2002; Mizuno et al. 2000)
- Steam stripping through evaporation on large surfaces (Van Groenestijn et al. 2002)
- Stripping through gas circulation (Van Groenestijn et al. 2002)
- Membrane recovery in a separate reactor (Nielsen et al. 2001; De Vrije and Claassen 2003)
- Membrane recovery in the PBR (Teplyakov et al. 2002; Tredici, Zittelli, and Benemann 1999)

1.5.4 Harvesting options

Harvesting is a one- or two-step solid-liquid separation process, which is dependent on algae – e.g. size – and culture characteristics – e.g. biomass density. The major harvesting techniques for algal biomass are (Brennan and Owende 2010; Molina Grima et al. 2003; Schenk et al. 2008):

- Centrifugation
- Gravitational sedimentation
- Filtration
- Flocculation

Centrifugation is a fast and energy intensive harvesting option, which depends on settling properties of the cells, culture residence time and settling depth (Molina Grima et al. 2003). The high harvesting efficiency – over 95 percent – comes at the cost of high energy consumption (Heasman et al. 2000; Bosma et al. 2003).

Gravitational sedimentation is slower and requires less energy. Relevant settling properties are the cell diameter (Stoke's radius), the biomass density in the culture and the sedimentation velocity (Nurdogan and Oswald 1996). The major disadvantages are that it requires more time and space than other harvesting techniques (Schenk et al. 2008) as well as the limited applicability to large algae – a minimum cell size of 70 µm is required (Munoz and Guieysse 2006).

Filtration can be divided into conventional filtration for cell sizes larger than 70 µm (Mohn 1980) and micro- or ultrafiltration with a membrane for species recovery with a cell size smaller than 30 µm (Petrusevski et al. 1995). Both techniques use pressure or suction applications, with lower pressure and fewer suction being required in conventional filtration. At larger scales, micro- or ultrafiltration – suitable for small cell diameters – is less advantageous due to high maintenance costs, membrane clogging and filter cakes (Schenk et al. 2008).

Flocculation is the aggregation of algal cells to obtain a larger particle size. Conventional flocculation applies inorganic chemicals as flocculants (Schenk et al. 2008), whereas auto-flocculation functions by the change of environmental conditions to induce flocculation (Rösch, Skarka, and Patyk 2009). Both can be applied as a preparatory step to the other harvesting techniques listed above. Applying inorganic chemicals such as aluminium or ferric chloride turns harvesting very costly and unsuitable for large scale application (Schenk et al. 2008). Additionally, downstream processing of algal biomass is limited such as animal feed and biogas production through anaerobic digestion could not be applied with flocculant containing algal biomass (Lee, Lewis, and Ashman 2009). Auto-flocculation can be seen as the cheapest harvesting method and especially allows all further processing options. The disadvantage is that the response and the response time of algal biomass to the change of environmental conditions fluctuate (Schenk et al. 2008).

1.5.5 Biogas production options

Biogas is generated by anaerobic digestion. This requires a feedstock, bacteria and anaerobic environmental conditions (Deublein and Steinhauser 2010). The parameters determining the digester technology are the totals solids concentration, the digester configuration, the number of processing stages and the digestion temperature (Deublein and Steinhauser 2010; Nordberg 2006; Schnürer and Jarvis 2010).

The total solids (TS) concentration varies between 20 and 35 percent for a dry fermentation process with a feedstock such as energy crops and a wet fermentation process with a feedstock such as manure, algal biomass or other diluted solid substrates with two to ten percent total solids (Deublein and Steinhauser 2010; Schnürer and Jarvis 2010). As a maximum, wet fermentation should not exceed a total solids concentration of 13 percent (Weiland 2003).

The digester configuration options are batch, sequential batch, continuously mixed or plug flow. All are applicable to a dry feedstock, but only the options batch and continuously mixed digestion are suitable for a wet feedstock (Nordberg 2006; Nordberg and Nordberg 2007).

If one-stage digestion process is chosen, hydrolysis, acidogenesis and methanogenesis occur within a single biogas reactor with a pH between seven and eight. A two-stage process has two separate biogas reactor chambers with hydrolysis and acidogenesis as well as a pH between 5.5 and 6.5 in the first and methanogenesis with a pH of seven to eight in a second chamber (Schnürer and Jarvis 2010).

Either mesophilic digestion temperatures between 35 and 40 °C or thermophilic temperatures between 55 and 60 °C are mainly chosen for digestion (Schnürer and Jarvis 2010). For few digester configurations, cryophilic temperatures between ten and 25 °C can be applied (Nordberg 2006).

Additionally the following parameters need to be considered (Schnürer and Jarvis 2010):

- The organic loading rate, which is the amount of volatile solids (VS) that is added to the digester per day on average should be between two and five kg VS/(m^3 biogas reactor*d) (Deublein and Steinhauser 2010). Specifically for mesophilic temperatures, the organic loading rate is typically between two and three kg VS/(m³ biogas reactor*d) and between four and five for thermophilic temperatures (Schnürer and Jarvis 2010).

- The carbon-nitrogen (C/N) ratio should be between 20 and 30 for an optimal biogas yield (Sialve, Bernet, and Bernard 2009). Lower C/N ratios result in larger ammonia formation and inhibit methane generation. A larger C/N ratio results in a lack of nitrogen which restricts the protein formation of the digesting microorganism and therefore lowers the biogas production rate (Deublein and Steinhauser 2010).
- The residence time of the substrate in the digester is typically in an interval between 15 and 50 days, which mainly depends on the digestion temperature and the ingestate composition. Thermophilic digestion temperatures allow for faster biomass decay due to the higher activity of microorganisms at higher temperatures (Schnürer and Jarvis 2010). A feedstock such as organic waste that can be solved in water is faster degradable than highly fiber- and cellulose-containing substrate such as energy crops as the hydrolysis is often the limiting factor concerning the decay rate. For a liquid ingestate with a low TS concentration, the residence time is called hydraulic retention time (HRT) and – for solid ingestates – solids retention time (SRT), which are typically equal apart from the case that some residues are returned to the digester for repeated digestion (Schnürer and Jarvis 2010).

1.5.6 Further processing and product options

Commercial production of microalgae originates from research for new protein sources in the middle of the last century. Currently, rentable production of algal products is possible in the sectors of human nutrition, animal feed or in the chemical and pharmaceutical industry. Examples for the former are food colorants and supplements such as Carotenoids – e.g. β-carotin used as provitamin A. Animal feed options range from the use in aquaculture to livestock. The chemical and pharmaceutical industry often uses pigments as colorants and other extracts for cosmetics (Pulz and Gross 2004; Spolaore et al. 2006).

Given the focus on microalgae for energy production, an overview of the possibilities for energy generation is provided in Figure 3 in order to locate the production of hydrogen and biogas within this framework.

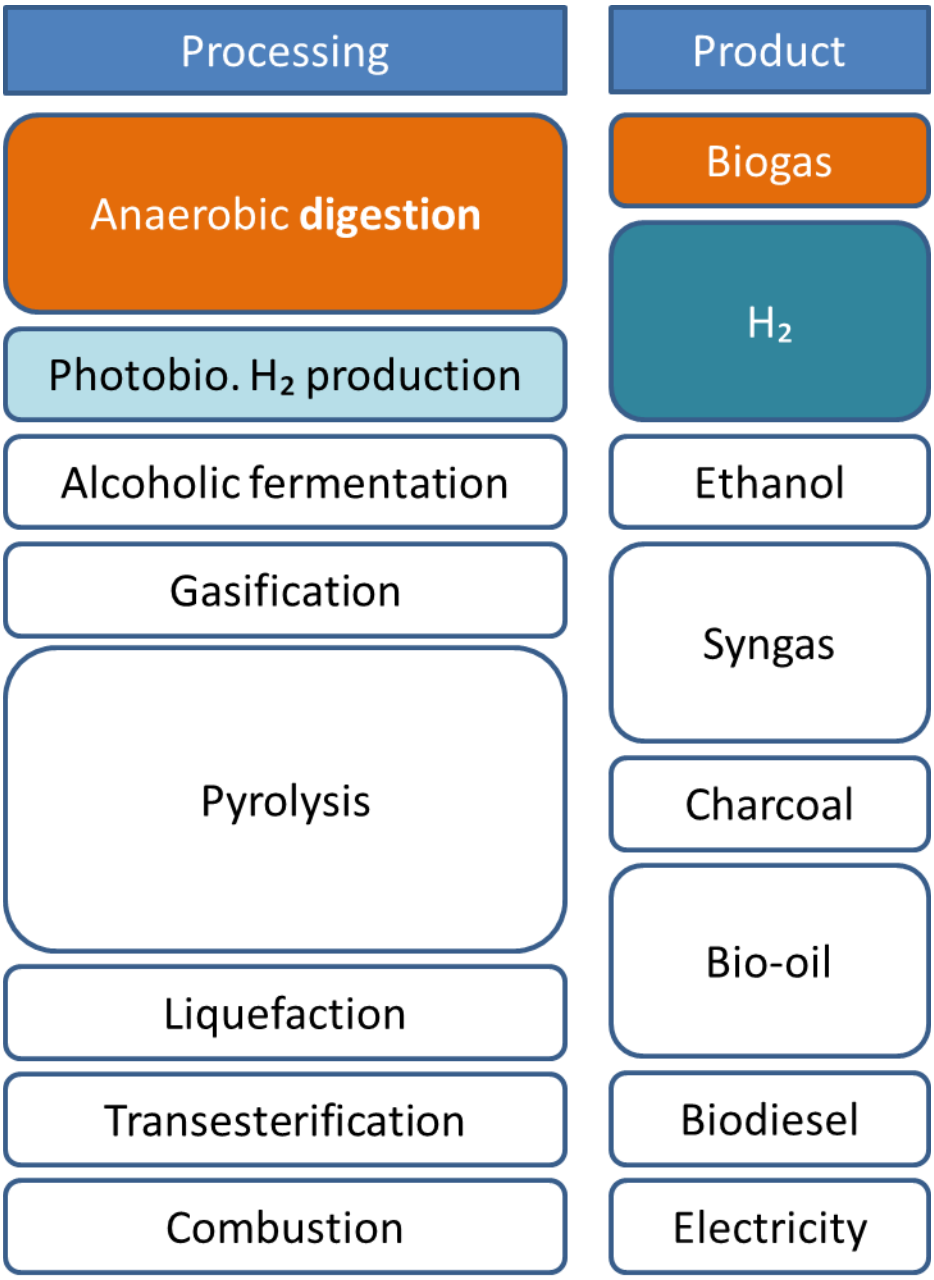

Figure 3: Processing and product options for algal biomass for energy[9]

[9] The biofuel options are collected from (Amin 2009; Brennan and Owende 2010; Chisti 2007; Tsukahara and Sawayama 2005). Of the named options, the production of oil for biodiesel accompanying biogas and hydrogen production is not advisable for *C. reinhardtii* as a significant increase of the content of both the biodiesel precursor triacylglycerols and of fatty acids (Rodolfi et al. 2009), which significantly facilitate the extraction of biodiesel, requires P limitation of the algal biomass (Weers and Gulati 1997), which is not targeted as explained in chapter 0.

1.6 Existing research

Environmental LCC is applied in various fields of interest, such as the automotive sector (Schau et al. 2011), furniture production (Michelsen, Fet, and Dahlsrud 2006) or renewable energy production such as bioethanol from sugarcane (Luo, van der Voet, and Huppes 2009). Specifically for biogas production as to be done in this study, Hong and Zhou (2011) examine the environmental life cycle costs for the feedstock straw. Environmental LCC for hydrogen production based on wind power has also been conducted by Lee et al. (2010). To the best of my knowledge, only one study develops an economic analysis with a life cycle perspective to energy generation from microalgae (Colosi et al. 2012), but does not deal with hydrogen and biogas production. Other types of economic analyses on energy generation from microalgae either for hydrogen (Benemann 2000; Burgess et al. 2004; Holtermann and Madlener 2011; Tredici, Zittelli, and Benemann 1999; Wade 2004) or biomass production (Acién et al. 2012; Molina Grima et al. 2003; Norsker et al. 2011) in PBRs have been developed. The further processing of the biomass to biogas has been included in studies for large-scale open ponds – 100 to 400 ha production area (Lundquist et al. 2009; Zamalloa, Vulsteke, et al. 2011).

The combined photobiological hydrogen production and the use of the residuals for anaerobic digestion are not treated in other economic studies (Chisti and Yan 2011). More important, the existing studies on photobiological hydrogen do not consider most of the utilities such as nutrients or water (Wade 2004), do not consider the anaerobic hydrogen production phase (Holtermann and Madlener 2011) or exclude relevant investment costs such as gas handling (Benemann 2000; Burgess et al. 2004; Nath and Das 2004; Tredici, Zittelli, and Benemann 1999). Existing studies for algal biomass neglect water supply-costs and estimate production costs for halophyte algae that are grown in saltwater, which is free of charge (Acién et al. 2012; Molina Grima et al. 2003; Norsker et al. 2011). This assumption strongly delimits the choice of production locations to coastal areas and is not applicable for the freshwater species *C. reinhardtii*. Existing studies considering cooling of PBRs use water sprinklers for evaporative cooling in arid seasons and disregard the problem of water scarcity (Cheng-Wu et al. 2001; Tredici, Zittelli, and Benemann 1999). Technological and processing improvements that are recently applied in PBRs such as heat exchangers instead of water sprinklers for cooling, that could also be applied in humid climates and reduce water consumption (Sierra et al. 2008; Chisti 2007), are not considered in existing economic analyses.

2 Material and methods

In this chapter, the scope of this study is defined by system boundaries, production processes and geographic location. In the subchapter on the economic life cycle inventory, all relevant production processes and facilities are treated in detail. In the last subchapter, scenarios are calculated, which should allow for future projections and facilitate the identification of hot spots.

2.1 Scope definition

2.1.1 System boundaries and processes

In this study, the following general assumptions are made:

- All input factors (microalgae, water, nutrients, cleaning utilities, electric power, heat, land) are bought and not generated within the system.
- All equipment and utility costs are indicated and calculated as for delivered goods, i.e. without transport costs.
- The first production step is the biomass generation in the PBR and the last is – with or without hydrogen production – the anaerobic digestion of biomass to obtain biogas. Further processing such as the purification of hydrogen or biogas is not included. This is even not necessary for photobiologically produced hydrogen, which already has a purity of 98 percent (Kruse, Rupprecht, Bader, et al. 2005). Biogas can be sold without further purification (Volk 2011). Therefore, if available, the biogas market price is taken for comparison. If not, the price for natural gas is taken, but considering that the obtainable price for biogas is lower due to the required purification.
- Byproducts and waste such as the digestate from the anaerobic digestion are either recycled or disposal costs are considered.

- The life cycle costs only consider the production process. Costs for distribution or marketing are not considered due to the given focus on production optimization.

As stated in chapter 1.2, this study differentiates between the final outputs in the base case exclusive biogas production and coupled hydrogen and biogas production. For this reason, two production systems need to be modeled and are displayed in Figure 4. The major data sources apart from knowledge gained within the project *HydroMicPro* to model these systems are articles in peer-reviewed journals that describe comparable production systems or different statistical offices of the German authorities.

Biogas production comprises three major steps. First, biomass is produced by growing *C. reinhardtii* in PBRs. Secondly, the biomass is harvested. Lastly, the biomass is converted to biogas by anaerobic digestion in a biogas reactor with the digestate as a byproduct.

Coupled hydrogen and biogas production consists of four major steps. Hydrogen production through direct biophotolysis only consists of two steps (Hankamer et al. 2007). First, biomass is produced by growing mutants of *C. reinhardtii* in the PBR. In a second step, the PBR with the produced biomass is turned to anaerobic conditions and so that the green algae *C. reinhardtii* can produce hydrogen. The produced hydrogen is compressed for storage and transport. To capture the maximum energy possible, the residual biomass is harvested and digested to generate biogas (Weiss, Patyk, and Schebek 2011).

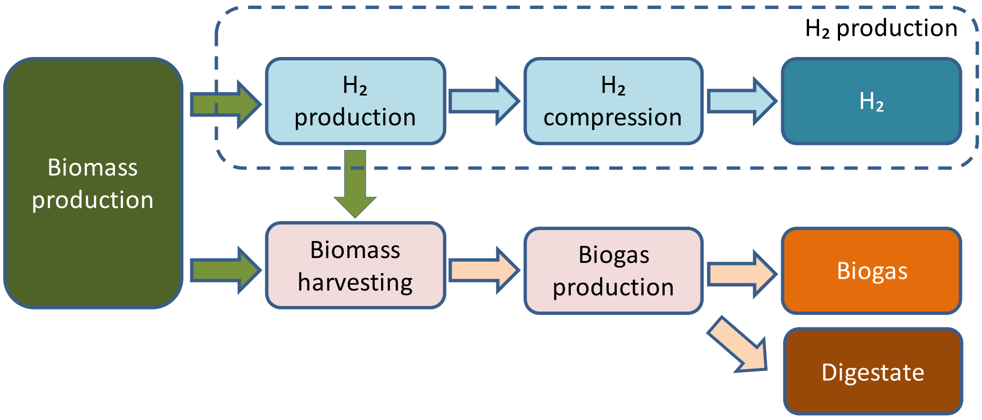

Figure 4: Production system of hydrogen and biogas production with C. reinhardtii[10]

[10] Adapted from Weiss et al. (2011).

The functional unit is defined as one MJ of hydrogen and methane[11] respectively (Weiss, Patyk, and Schebek 2011). Energetic values are chosen to allow a comparison of associated costs between both energy carriers.

Generic parameters defining the production system are chosen in accordance with the LCA model. The production system should be built on one ha and requires an additional 25 percent for supporting production facilities (Norsker et al. 2011). The lifetimes displayed in Table 1 are chosen in accordance with the studies, from which PBR, technical equipment and infrastructure costs are taken – see Table 6 in chapter 2.2.6.

Table 1: General conditions and parameters for the production system

General conditions and parameters	Value	Unit	Source
Net production area	1	ha	Weiss et al., 2011
Land area	1.3	ha	Norsker et al., 2011
Lifetime PBR and technical equipment	10	a	Weiss et al., 2011/Deublein and Steinhauser, 2008
Lifetime buildings and concrete works	20	a	Deublein and Steinhauser, 2008
Operation days PBR	252	d/a	Weiss et al., 2011
Batches for H_2 and biogas	18	1/a	Weiss et al., 2011
Batches for biogas	36	1/a	Weiss et al., 2011
Personnel for PBR operation	3	FTE	Norsker et al., 2011

For the German setting, 252 operation days per year are assumed as light and temperature conditions would not result in sufficient algal biomass yields on more operation days (Weiss, Patyk, and Schebek 2011). Assuming subtropical or tropical climatic conditions, which allow higher annual biomass yields, 300 to 330 operations days are realistic (Stephens et al. 2010). By dividing the annual production period by batches of seven days, 36 operation times of the PBR per year will be possible if biogas is produced exclusively. For coupled production of both hydrogen and biogas, only 18 batches could be conducted due to two production phases requiring seven days each. The staff employed for PBR related production facilities is both at a small scale – 60 and 30 m³ PBR volume respectively (Molina Grima et al. 2003; Acién et al. 2012) – and a large scale – 577 m³ PBR volume (Norsker et al. 2011) – three FTEs. The latter even has a production area similar to this study. The PBR volume in this study will be described in detail in chapter

[11] Methane is chosen as its energetic value is uniform per standard cubic meter, whereas the energetic value of biogas, which is the final output, is not fixed due to varying composition. The share of CO_2, methane and other gases changes with the substrate properties and production parameters (Deublein and Steinhauser 2010). Nevertheless, most of the energy content of biogas from *C. reinhardtii* occurs as methane (Mussgnug et al. 2010) so that an adequate approximation of the energetic value of biogas is given through the methane yield.

2.2.3 and is 250 m³. Scaling is not applicable as the number of FTE is not varied for this kind of small scale PBR production facilities. Larger ones reduce the number of FTE per PBR volume and area such Norsker et al. (2011) with seven FTE for a 100 ha production facility with 577,000 m³ PBR volume.

For biogas production in the chosen plant type with a reactor volume of 431 m³ described in chapter 2.2.3, additional 500 working hours are necessary per year (Deublein and Steinhauser 2010).[12]

2.1.2 Geographic location

The focus of the whole research project is set on Germany (Posten and Schaub). All relevant environmental conditions and collected data are considered accordingly. Such clear focus enables a more realistic set up of the production plant as the annual yield is largely depending on environmental conditions such as solar irradiation and temperature. Apart from the biomass and hydrogen yield, it also affects the temperature dependent equipment such as cooling facilities and the anaerobic digester. Additionally, cost items such as labor costs are country-specific. If data requires a more precise location, the city of Karlsruhe is chosen.

2.2 Economic life cycle inventory

The economic life cycle inventory describes and justifies the chosen production processes and systems – named in chapter 2.1.1 – for hydrogen and biogas production. It is divided in the four life cycle phases: development, construction, use and decommissioning. Afterwards, the necessary cost data and cost calculation methods are determined. The last subchapters deal with the energy consumption and the biomass as well as energetic yields of *C. reinhardtii* for the production system in this study.

2.2.1 Development phase

In this study, costs related to the research activities associated with the product are not considered. Currently incurred costs of Euro 2.1 million for the research and development activities for the whole project *HydroMicPro* are funded by the German Federal Ministry for Education and Research (Landgraf 2009). To compare the costs of biogas and hydrogen with market prices of other bioenergy

[12] To obtain a fulltime equivalent, the required working hours have to be set in relation to the annual German working hours per employee, which amount to 1658 hours in 2011 (IAB 2012).

sources, government funding should not be included. It cannot be assumed that it is included in market prices as in a functioning market firms should only be able to pass on the cost incurred by them. Other costs for research and development have not been identified so that this phase is omitted in the following.

2.2.2 Construction phase

The construction phase to set up the facilities for the production system – described in chapter 2.2.3 – is assumed to take one year. This assumption is based on a similar time period need for a comparable facility of one ha production area and 700 m³ PBR volume in Klötze near Wolfsburg, Germany (Roquette; Pulz 2001).

2.2.3 Use phase

Biomass production

Biomass is produced under aerobic conditions. This is similar to a two-phase hydrogen production process, with a first step being of aerobic biomass production (Kruse, Rupprecht, Bader, et al. 2005). The aerobic growth phase of *C. reinhardtii* requires – apart from the algal culture – the input of freshwater, CO_2 and nutrients as well as solar irradiation (Kruse, Rupprecht, Bader, et al. 2005; Morweiser et al. 2010; Wade 2004). The input of nutrients[13] is given in relation to the algal dry weight in Table 2.

Table 2: Nutrient and CO_2 input

Input parameters	Value	Unit	Source
N application	91	kg/t DW algae	Own calculations
P application	22	kg/t DW algae	Own calculations
CO_2 requirement	1.8	t/t DW algae	Norsker et al., 2011

To obtain the nutrient input rates of N and P, the molecular composition of *C. reinhardtii* under excess nutrient application is used, which is 7.57 percent for N and 1.87 percent for P of the algal dry weight (Weers and Gulati 1997). It is necessary to supply nutrients in excess. Lacking empirical data on the optimal excess input of N and P for *C. reinhardtii*, this study assumes that N and P are supplied at a rate of 1.2 times the stoichiometric N and P content of algal biomass. Despite

[13] Other nutrients such as potassium or magnesium are not included as they are required in low amounts and their share on total costs is by far below five percent. A detailed overview of other nutrients required by *C. reinhardtii* is given by Kliphuis et al. (2011).

this inaccuracy, a too low nutrient supply is only a possible problem for the first culture medium preparation as the culture medium with the excess supply of nutrients is recycled two times. Hence, sufficient nutrients should be supplied, when the culture medium is reused. A very high excess supply might be economically unfavorable, but does not significantly increase the biomass production costs as a larger share of the nutrients are recovered through the algal digestate and resold as described in chapter 2.2.3. Some authors might argue that nutrient limitation increases the calorific value of algal biomass, but is also associated with a decline of algal biomass productivity (Griffiths and Harrison 2009; Illman, Scragg, and Shales 2000; Rösch, Skarka, and Wegerer 2011; Brennan and Owende 2010). For *C. reinhardtii*, a significant increase of the calorific value under nutrient limitation has been identified for P, but not for N limitation (Weers and Gulati 1997). P limitation also leads to a drop of the photosynthesis rate by up to 75 percent (Wykoff et al. 1998). Further reasoning in favor of excess application of P is that due to the binding of P ions with metal ions the actual bioavailability of input P is below 100 percent (Chisti 2007).

The necessary CO_2 supply varies depending on the algal species between 1.65 (Morweiser et al. 2010) to 1.85 (Posten 2009) times the algal dry weight. Lacking empirical data on an adequate application of *C. reinhardtii* and for the given PBR design, CO_2 is considered as 1.8 times the algal dry weight as shown in Table 2 (Norsker et al. 2011; Wijffels and Barbosa 2010).

Nutrient losses occur during the entire production process. For the biomass production, it is assumed – since no experimental data is available – that the excess of N and P is lost by culture medium discharge. This is 20 percent of the stoichiometric N and P content of the algal dry matter. As the algal ingestate contains about 94 percent of water (Mussgnug et al. 2010), it is likely that it also contains excess N and P, which is assumed to be conferred to the anaerobic digester and not immediately lost during the biomass cultivation. The amount of excess N and P in the algal ingestate is determined by the ratio of water content of the ingestate and the total culture water used. Other nutrient losses such as NH_3 outgassing are not calculated, but assumed to be covered by the loss attributed to culture medium discharge.

The required annual amount of freshwater for the culture medium can be determined by the PBR volume, which is 25 l/m² (Posten and Schaub; Weiss, Patyk, and Schebek 2011). The culture medium is renewed after three batches. Without renewal, both expensive filtration and sterilization steps for culture medium water recycling would be mainly necessary due to culture contamination by bacteria

(Alabi, Tampier, and Bibeau 2009) and the accumulation of salts and growth inhibiting organic substances, e.g. toxic fatty acids, of which the latter are generated by *C. reinhardtii* itself (Borowitzka and Moheimani 2010; McCracken, Middaugh, and Middaugh 1980).

The PBR type most comparable to the different types described in chapter 1.5.2 is a flat-plate PBR. The major difference to the conventionally vertically orientated flat-plate PBRs is the inclined alignment of the plates with an appearance of interconnected roofs as shown in Figure 5. This wave or staggered orientation is more likely to provide incident light with a moderate intensity, which should be close to the optimal section of the light saturation curve for *C. reinhardtii* for most of the cultivation area. Light excess – larger than 200 W/m² – resulting in heat excess and algal biomass degeneration (Acién et al. 2012; Norsker et al. 2011; Posten and Rosello-Sastre 2011) could be avoided by such PBR design (Posten et al. 2011). The choice of a flat-plate design with a film thickness between one and ten mm allows high cell densities with low energy requirements for mixing the culture medium due to the minimized light gradient (Norsker et al. 2011; Posten et al. 2011). Inlet and outlet openings follow the flow direction parallel to the waves to reduce the flow resistance (Posten et al. 2011).

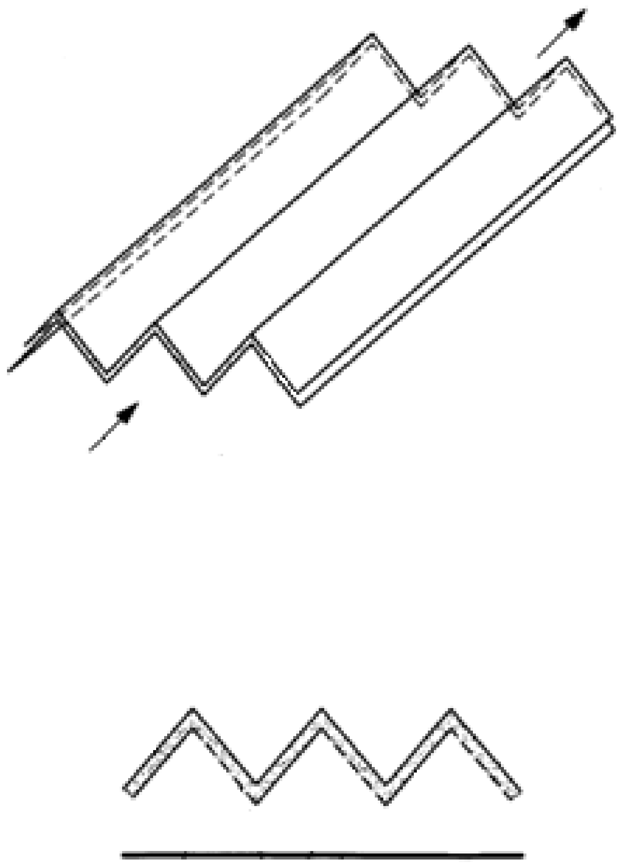

Figure 5: PBR design[14]

The material requirement can be derived from the displayed PBR design. The height of the PBR is ten cm (Posten et al. 2011) and each module has a size of one m² with a volume of 25 l/m² as already indicated above. This results in a PBR material requirement of 2.5 times the ground surface and additional side coverage with a height of ten cm at two sides of the PBR production area. A material commonly used for PBRs is poly(ethylene terephthalate) (PET) (Norsker et al. 2011) with a thickness of one mm[15]. The amount of PET is reduced by the area covered by a low pressure polymeric membrane[16], which covers 50 percent of the bottom as shown in Figure 5. The application of a membrane technology reduces the en-

[14] Adapted from Posten et al. (2011). An additional upper plate shown by the authors of the patent will only be necessary if there is an additional membrane on the upper side. We do not consider a membrane on the surface of the PBR as it would shade the algal culture and therefore reduce biomass and hydrogen generation.

[15] It is specifically comparable to the type used for beverage packaging (Posten 2012).

[16] Currently, the most suitable material for an aeration membrane for a PBR has not been identified yet (Lehr et al. 2011), but a suitable material could be polyimid (Bauer 2012).

ergy consumption for aeration (Posten 2009; Posten et al. 2011). The more efficient membrane aeration technology of PBR-internal hollow fibers (Fan et al. 2008; Verrecht et al. 2008) could not be used due to the thin culture volume layer and the disturbance of culture circulation. For the bottom, a plate of poly(methyl methacrylate) (PMMA) with a thickness of three mm is taken[17].

As a first step of the operation, the cleaned PBR is filled with a culture medium of tap water and nutrients as well as the inoculum from a culture medium preparation unit with a feed pump. For the inoculum preparation and the pumping as well as the cleaning of the PBR, one day per batch – six production days – is assumed (Weiss, Patyk, and Schebek 2011) as otherwise a biofilm is likely to form (Ferrell and Sarisky-Reed 2010). The mixing of the PBR is effected by the culture medium feed pump. The necessary volumetric flow rate can be derived from the dilution rate, which should be equal to the growth rate (Janssen et al. 1999), which is 0.03 per hour (Weiss, Patyk, and Schebek 2011). This would result in an average residence time of the algal biomass of 33.3 h and would be expected to provide sufficient mixing if continuous production was assumed (Norsker et al. 2011). The volumetric flow rate can be derived by dividing the PBR volume by the residence time – resulting in 7.5 m^3/h – and is taken as the volumetric flow rate necessary for mixing in batch production. It is aerated by the integrated membrane at the bottom of the PBR. The bottom is covered – as described above – by an additional plate to provide a void, in which CO_2 enriched air with a CO_2 concentration of ten volume percent[18] is feed in. Due to the higher partial pressure of CO_2 in the void, CO_2 will diffuse into the culture through the membrane (Posten et al. 2011). The culture medium should not exceed 30 °C[19]. On days with air temperatures which are expected to result in higher culture medium temperatures, the culture medium is not only circulated in the PBR, but also through a heat exchanger with the volumetric flow rate determined for culture circulation (Acién et al. 2012; Sierra et al. 2008).

[17] The density of poly(ethylene terephthalate) is 1.38 g/cm^3 (IFA 2012a) and for poly(methyl methacrylate) 1.2 g/cm^3 (IFA 2012b) at 20 °C. The densities for both materials are necessary as the prices are given per mass.

[18] The aeration process needs to consider the inhibitive effect of oxygen saturation, which might arise for oxygen concentrations larger than 120 to 200 percent of the oxygen concentration of ambient air (Posten and Rosello-Sastre 2011).

[19] Higher temperatures deteriorate the growth rates and increase death rates of *C. reinhardtii* (Morweiser and Franz 2012), which could be derived from the optimum curves shown by Franz et al. (2011) as well. This upper temperature limit of optimal growth conditions is equally confirmed for *Chlorella* spp. (Dauta et al. 1990). The production period excludes with 252 production days per year the cold periods. Therefore, the heating requirement should be minimal and if included, the results should not be significantly altered. So heating is disregarded.

A heat exchanger requires less energy and especially water and, in contrast to water sprinklers, is independent of environmental conditions (Sierra et al. 2008). It is also applicable to humid climates. The functioning of evaporative cooling could still only be demonstrated in arid climates such as Israel (Chisti 2008). The temperature of the culture medium estimate is based on the relationship with the parameters air temperature as well as heat exchanger temperature and solar irradiation (Morita, Watanabe, and Saiki 2001). Against this background, Equation 3 summarizes the named relationship for PBRs.

$$b = 0.399d + 0.592e + 0.00617E + 0.329$$

Equation 3: Calculation of culture medium temperature[20]

The culture temperature in the PBR *b* is dependent on the temperature in the heat exchanger *d*, the air temperature *e* and the solar irradiation *E*. Inserting 30°C for *b* and the average solar irradiation in summer for Stuttgart[21] in southern Germany – 640 W/m² (Zinßer et al. 2008), Equation 3 can be solved for *d* and *e* – assuming similarity of both, which is justifiable that there should be no significant temperature difference between air and heat exchanger if no cooling water is circulated. Hence, the air temperature at which cooling is necessary can be derived – it equals 26.4 °C. For the weather station Stuttgart-Echterdingen, this temperature limit is exceeded by on average 2.4 °C on 28.9 days per year[22], which represents the average cooling capacity of the heat exchanger. To determine the necessary maximum capacity of the heat exchanger, the temperature maximum of 37.7 °C resulting in a culture temperature of 41.6 °C is considered. The heat exchanger requires a cooling capacity of 11.6 °C. The temperature of the outflowing cooling water $T_{water\ out}$ of 27 °C is determined by subtracting a terminal temperature difference of approximately three °C from the culture medium temperature goal of 30 °C – $T_{culture\ out}$. A crossflow shell-and-tube heat exchanger is used (Selbaş, Kızılkan, and Reppich 2006; Wärmeatlas 2006), which is suitable for PBRs (Jorquera et al. 2010). As

[20] Taken from Morita et al. (2001).

[21] Other calculations based on climate and solar irradiation data in chapter 2.2.8 are based on Karlsruhe. As climate data for Karlsruhe for the long-term was not freely available, those for Stuttgart were taken as it is a weather station within the same climate zone – characterized by solar irradiation and temperature data. The used characterization of climate zones is set up for the aim to indicate the heating and cooling requirement of buildings (DIN 2006).

[22] To calculate the average of temperatures per day exceeding 26.4 °C, the daily temperature maxima for the longest available period 1953 to 2011 are considered (DWD 2012).

only the minimal amount of cooling water possible is applied[23], the overall heat transfer coefficient decreases to a minimum (Sierra et al. 2008). The minimal overall heat transfer capacity for the chosen type of heat exchanger U is 150 W/m²*K (Wärmeatlas 2006). The parameters are indicated in Table 3 and can be used in the standard heat balance for a heat exchanger:

$$m_{water} * cp_{water} * (T_{water\ in} - T_{water\ out}) = U * A \frac{(T_{culture\ in} - T_{water\ in}) - (T_{culture\ in} - T_{water\ out})}{\ln\left(\frac{(T_{culture\ in} - T_{water\ in})}{(T_{culture\ in} - T_{water\ out})}\right)}$$

Equation 4: Heat balance[24]

The value in Equation 4 to be solved for is the heat transfer area A, which is used to calculate the investment costs of the heat exchanger (Selbaş, Kızılkan, and Reppich 2006).

Table 3: Heat exchanger parameters

Heat exchanger parameters	Value	Unit	Source
$Q_{culture}$	125	l/min	Own calculations
cp_{water}	4.2	J/(g*K)	Linstrom and Mallard, 2011
$cp_{culture}$	1.3	J/(g*K)	Biller and Ross, 2011
$T_{water\ in}$	20	°C	DIN, 2008
$T_{water\ out}$	27	°C	Own calculations
$T_{culture\ in\ (average)}$	33	°C	Own calculations
$T_{culture\ in\ (peak)}$	41.6	°C	Own calculations
$T_{culture\ out}$	30	°C	Morweiser and Franz, 2012
U	150	W/m²*K	VDI, 2006
Operating hours heat exchanger	5	h/d	Cheng-Wu et al., 2001

[23] Heating the cooling water to the possible maximum minimizes the volumetric flow rate of the cooling water and as a consequence the related energy if further cycles of the same water were necessary. The amount of pumped water will be varied depending on the temperature of the culture medium. A higher culture temperature requires a higher volumetric flow rate and is consequently associated with higher water consumption.

[24] Adapted from Sierra et al. (2008).

To obtain the mass flow rate of water m_{water}, the first law of thermodynamics is used (Planck and Ogg 1945). The first part of Equation 4 is separately set up for both the algal culture and the cooling water with the values in Table 3 and solved for m_{water}. To obtain the latter, the volumetric flow rate of the culture $Q_{culture}$ of 125 l/min – equal to 7.5 m³/h – is taken and multiplied by the density of water. The volumetric flow rate is the one applied for medium circulation to avoid self-shading of the algal biomass, which is explained above. Additionally, the inlet and outflow temperatures for the culture – $T_{culture\ in}$ and $T_{culture\ out}$ – and the cooling water – $T_{water\ in}$ and $T_{water\ out}$ – are inserted as well as the heat capacities of water cp_{water} and the culture $cp_{culture}$ (Biller and Ross 2011).

Hydrogen production and recovery

Hydrogen with *C. reinhardtii* is generated by direct biophotolysis. The first prerequisite for anaerobic conditions is sulfur deprivation, which is obtained through adapted sulfate concentration in the culture medium. The sulfur concentration has to be chosen so that it will be completely consumed until the intended start of the anaerobic hydrogen production phase (Lehr et al. 2011). This approach is preferable for economic reasons. The conventional approach – described in chapter 1.5.41.5.3 – applying a centrifuge and consequential washing of the algal culture with acetate addition are associated with higher investment and operating costs and consume biomass, from which acetate needs to be generated (Lehr et al. 2011).

The continuous hydrogen recovery process should be conducted for this project through membrane separation (Posten and Schaub) with a polymeric membrane (Lehr et al. 2011) as the costs for the alternative with a higher selectivity – a Palladium coated membrane –, would be about 1,000 to 10,000 times more expensive than a polymeric one and is not available for commercial application yet (Iaquaniello et al. 2011). The membrane recovery is conducted in a separate reactor. The membrane is not integrated in the PBR as it would decrease the algae growth and the hydrogen production rate due to shading. Moreover, the overall membrane costs would be significantly higher if most of the PBR surface needed to be covered. Apart from the cost increase due to the larger production area, membrane costs increase the less pressure is applied for a similar recovery rate (Baker 2002) since high pressure could not be applied to the PBR (Lehr et al. 2011). To buffer fluctuating hydrogen production rates, storage facilities are necessary for constant discharge of hydrogen for the intended use, for feeding to a distribution network or in accordance with transport intervals (Wade 1998). During hydrogen production, 50 percent of the algal biomass, which has been generated in the foregone biomass production phase, is respired (Rupprecht 2011).

Harvesting

Harvesting of algal biomass is necessary for biogas production and conducted after six growth days for exclusive biogas production and after 13 days for coupled hydrogen and biogas production. Therefore, the culture medium is centrifuged after the biomass and hydrogen production phase respectively (Weiss, Patyk, and Schebek 2011). The resulting algal substrate is either stored or pumped to the biogas reactor. The yield – described in chapter 2.2.8 – is associated to a water content of *C. reinhardtii* substrate of 94 percent (Mussgnug et al. 2010). Departing from this volumetric water content, it is assumed that after centrifugation the remaining water and the contained nutrients are recycled and returned to the culture medium preparation unit for refilling the PBR. As evaporation in a closed PBR should be minimal (Borowitzka and Moheimani 2010), it can be expected that, apart from the water in the algal substrate, the remaining input water can be recycled for two times as explained in chapter 2.2.3.

Other harvesting techniques such as gravitational sedimentation and conventional filtration are not possible because they require a cell size of at least 70 µm (Munoz and Guieysse 2006; Mohn 1980). Membrane microfiltration is a harvesting alternative for *C. reinhardtii* for small facilities of less than two m^3/d. For larger scales, centrifugation is the less energy-efficient, but more economical alternative (MacKay and Salusbury 1988). Flocculation is not included as it is not economically viable due the expensive flocculation chemicals (Schenk et al. 2008), which also do not allow for anaerobic digestion (Lee, Lewis, and Ashman 2009). Auto-flocculation without flocculation chemicals application requires further research to identify relevant changes of environmental conditions for applicability on the used strain of *C. reinhardtii.* Recent research on auto-flocculation has only shown success for one genetically modified strain of *C. reinhardtii* (Mendez et al. 2011). Whether the described change of environmental conditions – N withdrawal – similarly results in auto-flocculation of other strains such as the strain used for hydrogen production, is questionable. Therefore, experiments on the used strain are required. Applied auto-flocculation experiments for other microalgae species have also shown that even once successful environmental conditions did not turn out to be reliable in all experimental set ups (Schenk et al. 2008; Rösch, Skarka, and Patyk 2009) and require further research (Williams and Laurens 2010).

Biogas production

Biogas is generated by anaerobic digestion of the algal ingestate in combination with other feedstocks (Weiss, Patyk, and Schebek 2011). Co-digestion is effected to both raise the biogas yield per unit substrate as the C/N ratio of algal biomass is about five (Sialve, Bernet, and Bernard 2009) and to continuously use the biogas reactor at full capacity – also for varying algal biomass yields. The VS content amounts to six percent for the *C. reinhardtii* ingestate used for anaerobic digestion (Mussgnug et al. 2010). The VS content equals 95 percent of TS of the biomass of *C. reinhardtii* as an ash content of five percent of the dry weight can be determined for *C. reinhardtii* under different nutrient regimes (Kliphuis et al. 2011). This results in a TS concentration of about 6.3 percent of the algal ingestate. A common feedstock used to equalize the low TS concentrations and C/N ratios is maize (Rösch, Skarka, and Wegerer 2011; Sialve, Bernet, and Bernard 2009) with a C/N ratio of 40 and a TS concentration of about 30 percent (Lukehurst, Frost, and Al Seadi 2010; Deublein and Steinhauser 2010). To obtain an optimal C/N ratio of 25 for anaerobic digestion from the range indicated in chapter 1.5.5, the TS share of maize on overall TS needs to be about 57 percent. For the suitable minimum C/N ratio of 20, this share of maize on TS should be 42 percent. Assuming the density of water for the algal ingestate, which should be mostly correct for low TS concentration (Deublein and Steinhauser 2010) such as microalgae and a density of 0.7 kg/l for maize (Deublein and Steinhauser 2010), TS for maize ingestate of 210 kg/t wet weight and for algal ingestate of 63 kg/t wet weight could be obtained. Setting 210 kg TS from maize to 57 percent to obtain a C/N ratio of 25, the remaining 43 percent of TS equal 158 kg from algae. The share of algal biomass on the wet weight of the mixed ingestate would amount to 78 percent. The TS concentration of the mixed ingestate would be about 11.5 percent and the VS concentration 10.9 percent. Such a TS concentration requires a wet fermentation process (Nordberg and Nordberg 2007; Weiland 2003).

A required wet fermentation process delimits the processing options to a batch or a continuously mixed digestion (Nordberg 2006; Nordberg and Nordberg 2007; Deublein and Steinhauser 2010), of which specifically a continuously mixed flow through process is chosen. A continuously mixed digestion as a one-step process is chosen (Mussgnug et al. 2010) as the biogas yield is expected to be higher and the costs to be lower than for a batch configuration (Deublein and Steinhauser 2010). Additionally, the algal biomass is continuously centrifuged and therefore, a possibility to continuously add algal biomass pellets to the digester would only be given with a flow through process. An adequate digestion temperature for anaerobic digestion of algal biomass has been determined in the mesophilic range at 38°C (Mussgnug et al. 2010). This minimizes the heat requirement and allows a more stable digestion as more microorganisms are active at lower temperatures. But the residence time is on average longer (Schnürer and Jarvis 2010). To minimize the heat requirement, mesophilic temperatures are applied. The trade-off of the chosen option is that the TS concentration should not increase further for the applied wet fermentation technology. If algal biomass is not available to the required share the wet weight of 78 percent on the ingestate, liquid manure from pigs with comparable characteristics to algal biomass can be used[25]. Additionally, algal biomass is annually produced on 252 of 365 days – indicated in chapter 2.1.1 – so that the remaining period of the year requires an alternative co-substrate for maize to avoid nonoperation periods of the biogas plant.

The bioreactor used for anaerobic digestion has a volume of 431 m³ and the following facilities, on which also energy and heat consumption is based (Deublein and Steinhauser 2010):

- Preparation tank for the fermentation ingestate and a pump for delivering the substrate to the bioreactor
- Silo for the co-ingestate such as maize and screw conveyors for the transport to the bioreactor
- Two agitators for mixing the ingestate
- Heating pipes for the fermentation at mesophilic temperatures
- Aeration by a compressor
- Gasholder for biogas storage
- Storage tank for the digestate

Sterilization, which will be required if pig manure is used, is not considered in this calculation as the related costs are not attributable to algal biomass and but to animal manure. Costs could arise for additional equipment or from the necessity to apply thermophilic temperatures instead of mesophilic temperatures (Al Seadi 2005). Co-digestion conducted with algal biomass and maize excluding animal manure does not require additional sterilization. Mesophilic digestion provides sufficient sterilization and pathogen removal (Al Seadi 2005) and fulfil the criteria

[25] Liquid pig manure typically has a TS concentration of five percent and a VS content of 90 percent (Deublein and Steinhauser 2010). The C/N ratio equally amounts to about five (Schnürer and Jarvis 2010).

of pest- and phyto-hygiene[26] of the German fertilizer regulation for an ingestate composition without animal manure (BMJ 2008).

The required share of the biogas reactor volume of 431 m³ for algal ingestate on the total reactor volume can be calculated with Equation 5 with the parameters for the actual algal biomass yield in Table 4. The required parameters are the daily yield of dry weight algal biomass M_{Ing}[27], the amount of dry weight per volume ingestate ρ_{Ing}[28], the required residence time HRT_{Ing} and the required volume for air and fixture in relation to the ingestate volume f_{airfix}.

$$V_{BR} = \frac{M_{ing}}{\rho_{ing}} * HRT_{ing} * (1 + f_{airfix})$$

Equation 5: Volume of the biogas reactor[29]

The daily yield of algal dry weight biomass in Table 4 relates to exclusive biogas production. The coupled hydrogen and biogas production amounts to 25 percent of the indicated dry weight of algal biomass. Originally only 50 percent of the biomass is produced per year for the latter case. Additional 50 percent thereof are respired as described in chapter 0.

Table 4: Biogas reactor volume parameters for algal biomass

Parameters	Value	Unit	Source
M_{Ing}	148	kg DW/d	Own calculations
ρ_{Ing}	63	kg DW/m³	Own calculations
HRT_{Ing}	32	d	Mussgnug et al., 2011
f_{airfix}	25%	of ingestate volume	Deublein and Steinhauser, 2008

The HRT_{ing} used in the original study for *C. reinhardtii* is in accordance with the interval in chapter 1.5.5. For a share of algal biomass on the wet weight of the

[26] Salmonella, heat-resistant viruses and fungal pathogens such as *Synchytrium endobioticumare* need to be eliminated (BMJ 2008).

[27] The average daily yield can be obtained by multiplying the actual daily yield of algal biomass dry weight – see chapter 2.2.8 – with the biomass production days and by dividing it by 365 days afterwards, which is the assumed operation time of the biogas reactor. The average daily yield does not reflect the actual ingestate contribution of algal biomass to the biogas reactor per batch of seven days, but the share of the costs of the biogas reactor, which are attributed to the algal ingestate.

[28] Multiplying the total solids concentration with the density of water as justified above, the amount of dry weight per volume ingestate is obtained.

[29] Adapted from Deublein and Steinhauser (2010).

mixed ingestate of 78 percent[30], an organic loading rate of 2.8 kg VS/(m³ biogas reactor*d)[31] – being in the range for mesophilic temperatures – indicated in chapter 1.5.5 – is obtained. This distribution would result in a required biogas reactor volume for algal biomass of 336 m³ and for maize of 95 m³ under consideration of 25 percent of the ingestate volume for air and fixture. This distribution of the biogas reactor volume between algal biomass and maize is necessary to obtain the C/N ratio of 25 and does not reflect the reactor volume required for the actual biomass yield.

The economically required volume for algal biomass will be 94 m³ for exclusive biogas production and 24 m³ for coupled hydrogen and biogas production if the parameters in Table 4 are used. The parameters imply 365 production days per year for algal biomass production and the results are used to allocate the costs for the biogas plant to algal biomass as the biogas plant is operated on 365 days per year.

Considering the actual processing for the case of exclusive biogas production, algal biomass is only produced on 252 days per year and due to continuous centrifugation provided with 3.4 t wet weight per day, which equal an algal biomass yield of 214 kg DW/d. The actual biogas reactor volume required is 136 m³ for 252 days per year, which equals 32 percent of the total biogas reactor volume and the wet weight of the ingestate. The remaining 46 percent of the wet weight that should be attributed to algal biomass need to be filled up by pig manure to allow wet digestion. The C/N ratio will amount to 26.2, the TS concentration to 10.9 percent and the organic loading rate to 2.6 kg/ VS/(m³ biogas reactor*d). For the case of coupled hydrogen and biogas production, 0.8 t wet weight algal biomass per day, which equal an algal biomass yield of 54 kg DW/d, are produced. This requires a biogas reactor volume of 34 m³ on 252 days per year, which equals eight percent of the total biogas reactor volume and the wet weight. The remaining

[30] If the biogas reactor were operated with the share of liquid pig manure on the total wet weight of the mixed ingestate, the total solids concentration of the mixed ingestate would amount to 10.5 percent, the organic loading rate to 2.5 kg/(m³ biogas reactor*d) and the C/N ratio to 27, which are in the suitable ranges – shown in chapter 1.5.5. A mixture of pig manure and algal biomass would have values in range between the one for co-digestion of maize and algal biomass and the one of co-digestion of maize and pig-manure

[31] Using the *HRTing* for algal biomass also as residence time for maize as solid ingestate, which are typically equal (Schnürer and Jarvis 2010) and the VS concentration of 10.9 percent of the mixture, assuming a density of one for the mixture and considering additional 25 percent of the ingestate volume for air and fixture in the biogas reactor, this organic loading rate is obtained. The density of one for the mixture can be assumed considering that the watery algal biomass ingestate will dilute the maize silage (Nordberg 2012).

70 percent of the wet weight that should be attributed to algal biomass need to be filled up by pig manure. The C/N ratio will amount to 26.8, the TS concentration to 10.6 percent and the organic loading rate to 2.5 kg/ VS/(m³ biogas reactor*d).

The share of maize on the wet weight of the ingestate of 22 percent and on the reactor volume of 95 m³ is unchanged in any of the cases.

The major waste product from anaerobic digestion is a digestate, which contains most of the initial N and P input in organic and inorganic forms (Rösch, Skarka, and Wegerer 2011; Sialve, Bernet, and Bernard 2009; Zamalloa, De Vrieze, et al. 2011). Recovery rates of nutrients from the algal digestate have been estimated by two studies, however not for *C. reinhardtii* (Rösch, Skarka, and Wegerer 2011; Zamalloa, De Vrieze, et al. 2011). The most important parameters determining the nutrient composition of the digestate are the HRT and the digester temperature (Rösch, Skarka, and Wegerer 2011). Rösch et al. (2011) use a HRT of 30 days, which is comparable to 32 days in this project (Mussgnug et al. 2010). The other study uses 22 days (Zamalloa, De Vrieze, et al. 2011). All studies assume mesophilic digestion temperatures (Mussgnug et al. 2010; Rösch, Skarka, and Wegerer 2011; Zamalloa, De Vrieze, et al. 2011). The nutrient recovery rates by Rösch et al. (2011) are used for the following reasons: The HRT coincides with the setting of this project, the digestion temperature is similar for both studies and the values for the model algae represent average values (Rösch, Skarka, and Wegerer 2011) instead of those for a single study for another algae species (Zamalloa, De Vrieze, et al. 2011).

The following table shows the nutrient loss and recovery during anaerobic digestion. The indicated N loss is attributable to NH_3 outgassing during storing and processing. The remaining N and P fractions are comprised in the digestate. The anaerobic digestion does not mineralize the whole N and P content of the ingestate. Only the mineralized share of N and P is plant available. The remaining unconverted N and P are still organically-bound and not plant available (Kehres 2009).

Table 5: Nutrient loss and recovery during anaerobic digestion[32]

Nutrient distribution	Value	Unit
N loss	15%	of ingestate N
Organic N recovery	20%	of ingestate N
Inorganic N recovery	65%	of ingestate N
P loss	0%	of ingestate P
Organic P recovery	20%	of ingestate P
Inorganic P recovery	80%	of ingestate P

2.2.4 Decommissioning phase

Dismantling of the production facilities after ten or 20 years respectively is not considered as the production should be conducted for an indefinite time period so that no disposal cost need to be considered. The recycling of material after renewal of the production equipment is assumed to be negligible compared with the costs of other life cycle phases as determined for another microalgal biomass production system (Zamalloa, Vulsteke, et al. 2011).

2.2.5 Cost calculation methods

Temporal and regional adjustments

Temporal adjustment is done by harmonizing all cost items to prices of 2011. Due to the focus on Germany, inflation adjustment for the specific services and products is taken from the Federal Statistical Office of Germany. As producer-related cost items are treated, the producer price indices are chosen for adjustment (Destatis 2012b) and labor costs are adjusted by the labor cost index (Destatis 2012a).

Personnel, utility and PBR costs are taken from German data sources or are estimated for a German setting. An adjustment of the investment costs of the production equipment – apart from the PBR, which is directly calculated – is not done as the data is mainly taken from other studies in the EU. These studies should not bear significant price differences as there is a common internal market, which should allow rather similar prices. Other cost data from European studies, but denoted in US Dollar are converted by the average annual exchange rate provided by

[32] Data taken from Rösch et al. (2011).

the European Central Bank (ECB 2012). An exchange already comprises price differences between countries (Samuelson 1948; Goldberg and Knetter 1996) and further adjustment is not necessary.

Investment cost estimation methods

To estimate the investment costs, the factor method is used as the major processes and characterizing capacities are known.[33] Specifically, installation subfactors are applied as those can be obtained from several other literature studies for algal biomass production in PBRs (Molina Grima et al. 2003; Norsker et al. 2011; Acién et al. 2012) as well as biogas production (DBFZ 2010; Deublein and Steinhauser 2010; FNR 2006, 2008).

Capacitive adjustment – Scaling of major equipment

The costs for the equipment specified in chapter 2.2.6 are related to a capacity, which needs to be adjusted to the requirements of the production facility of this project. For up- or downscaling of the costs of the production equipment, linearity is not assumed as economies of scale can be realized (Gerrard 2000). For PBR-related production equipment – numbers two to eight except from five in Table 7 in chapter 2.2.6 – an exponential scaling factor for the ratio of capacities of 0.85 is taken (Acién et al. 2012) and inserted for *n* in Equation 1 in chapter 1.4.1.
For hydrogen recovery, compression and storage – numbers nine to eleven in Table 7 – the respective factor is 0.8 (Wade 1998).

In detail, the PBR is adjusted by multiplying the intended total reactor volume of 250 m³ with the costs per module for the volume in Table 7. Normally, economies of scale can be realized. However, no economies of scale are assumed for the PBR itself as scaling is done by increasing the number of modules and not by constructing larger modules. For the heat exchanger, no economies of scale with increased heat transfer area per module can be realized (Selbaş, Kızılkan, and Reppich 2006) so that the costs linearly increase with the size and linear upscaling is applied.

The culture medium preparation unit for a PBR volume of 30 m³ (Acién et al. 2012) is scaled up by the respective PBR volume of 250 m³. The CO_2 supply station is adjusted by the dispensing capacity, which is 27.4 kg/h in the original study, and has in this study 37.5 kg/h. Under the assumption that CO_2 uptake only

[33] A detailed cost estimation would not be suitable as the intended production system is not marketable. Some production equipment is only available for laboratory applications and the final set up at production scale is not realizable yet – e.g. the PBR has not be built in the intended design.

occurs during the day, the whole amount of CO_2 needs to be supplied within twelve production hours (Norsker et al. 2011), which reflect the average light-dark cycle. With a CO_2 requirement of 1.8 g/g DW algal biomass, a production rate of one g DW algal biomass/(l*d) (Weiss, Patyk, and Schebek 2011) and a PBR volume of 250 m³, the supply capacity are the above indicated 37.5 kg/h.

The culture medium feed pump should be used in order to fill and empty the PBR as well as to circulate the culture. Therefore, the higher pumping capacity of both purposes is chosen. A pump given by Norsker et al. (2011) has a capacity of 12.5 m³/h. For culture circulation, a pumping capacity of 7.5 m³/h is required. The necessary time for cleaning and maintenance per batch is estimated to be five hours (Weiss 2012). Consequently, the 250 m³ PBR should be pumped out within 19 hours, which equals a pumping capacity of 13.2 m³/h. The filling and emptying pumping capacity is taken for scale-up as the pumping capacity required for circulation is lower. A second pump with characteristics comparable to the culture medium feed pump is installed to pump the culture medium and the cooling water through the heat exchanger. To determine the costs of the pumps, the culture medium feed pump described by Norsker et al. (2011) is taken and scaled to the capacity required for pumping of cooling water at peak temperatures – described in chapter 2.2.3.

The centrifuge and the associated feed pump are scaled down to be able to process the PBR volume of 250 m³ within one batch period – seven days for biogas production and 14 days for combined hydrogen and biogas production. 24 hours of processing in seven days result in a necessary capacity of 1.7 m³/h and for 14 days in 0.7 m³/h, which is the basis for scaling from the capacity of 22 m³/h from the original study given in Table 7.

Scaling of the hydrogen recovery equipment is done by the hydrogen production volume – under consideration of negative economies of scale, to which the capacity of the recovery equipment is fitted and which is in the original study 39 kg H_2/h (De Vrije and Claassen 2003). The hydrogen production rate to be met is a production of 0.27 kg H_2/h[34]. The storage and compression equipment is based on the yield, which will be described in chapter 2.2.8. For the compression and storage equipment, the size of the original equipment is for a hydrogen production of 300 kg/d and a storage capacity of a four days production (Wade 2004).

[34] This is obtained by taking the maximum concentration of six g DW algal biomass/l for a PBR volume of 250 m³ and a hydrogen production rate of two ml/g DW of algal biomass into account.

The costs for biogas production are attributed by the share that the algal ingestate on the total biogas reactor volume of 431 m³ has, which is described in chapter 2.2.3.

Cost allocation for coupled hydrogen and biogas production

Producing biogas as the only product, cost allocation is not necessary. In contrast to that, the coupled production of hydrogen and biogas requires a method to allocate the costs to each product. Allocation is necessary as sub-processes differentiating between hydrogen and biogas production cannot be created in the biomass production phase. Hence, the biomass growth is necessary for both the biogas and the hydrogen production. Similarly, the production system cannot be extended by an additional functional unit as only some processes can be separated for biogas and hydrogen – e.g. anaerobic digestion or hydrogen recovery and storage. The EU recommends in directive 2009/28/EG an allocation based on physical properties such as the energy produced (EU 2009). This is not applicable to hydrogen and biogas as such an approach does not reflect any difference in the process-specific conversion efficiencies, processing steps, equipment and utilities.

Instead of using the common allocation approaches for LCA, this study assumes that hydrogen is the main product from coupled hydrogen and biogas production. Biogas is a byproduct that uses the residual biomass. Investment and operating costs are hence attributed to hydrogen production in a first step. Only those costs directly relating to biogas such as the biogas plant are excluded from the hydrogen production costs. However, attributing only latter costs without the biomass production costs would underestimate the actual biogas production costs. It is more likely that the algal biomass would be bought. Adequate costs for algal biomass could be obtained from the case of exclusive biogas production, when the production facility is adapted and optimized for biomass production – e.g. no biomass loss occurs due to hydrogen production and the whole production period can be used for biomass. This implies that the willingness to pay more for algal biomass for biogas production would not be higher if hydrogen was generated with it before. It would be equal to the case of optimized biomass production conditions. The costs for algal biomass from the case of exclusive biogas production are allocated to the hydrogen production costs and increase the costs for biogas. The costs are separately allocated for the construction and the use phase.

2.2.6 Cost data

The cost categories occurring relevant for this study are investment and operation costs. The former are those related to the construction phase, whereas the latter occur during the use phase.

Construction phase – Investment costs

Investment costs arise for the production and storage equipment, for supporting facilities – buildings, control unit and piping –, the plant installation, land leasing and cost of capital, which are the relevant cost items identified by several other comparable studies (Acién et al. 2012; Molina Grima et al. 2003; Norsker et al. 2011). The PBR construction costs are estimated by using the following material costs as shown in Table 6.[35] The price for PBR module with a volume of 25 l in Table 6 is obtained by using the material requirements described in chapter 0.

Table 6: PBR material costs[36]

PBR material	Price per unit	Currency	Year	Unit	Source
PET for packaging	1,606	EUR	2011	t	KI, 2012a
PMMA	3,145	EUR	2011	t	KI, 2012b
Flat-sheet polymer membrane	50	EUR	2011	m²	Own estimation

The cost values for the production equipment other than the PBR are taken from comparable production facilities for algal biomass production in PBRs or hydrogen production. As a cost analysis on the recovery technology for hydrogen production from photoautotrophic microalgae does not exist yet, the costs from a study for heterotrophically produced hydrogen in PBRs is taken (De Vrije and Claassen 2003). The land leasing costs for low value or non-arable agricultural land are regarded an adequate price for algal biomass production and processing (Zamalloa, Vulsteke, et al. 2011; Stephens et al. 2010). The price for non-arable land is deducted from the price of arable land through an estimated discount of about 40 percent, which is recommended in a comparable study in Spain (Zamalloa, Vulsteke, et al. 2011). Applying this discount on the average land leas-

[35] Using only material costs instead of a complete module might underestimate the total costs. Therefore, we add a lump sum of 25 percent of the material costs for module manufacturing. As a comparable PBR does not exist yet, we need to assume such a lump sum.

[36] The indicated flat-sheet polymer membrane price could not be exactly determined as the most suitable material for the PBR has not been identified yet. The price of flat-sheet was proposed to be between 10 to 100 USD in 2002 (Baker 2002) that the estimate is about the mean of the price span.

ing costs in Germany of 204 Euro/ha in 2011 (Destatis 2011), the costs in Table 7 are obtained.

To fund the above listed cost items, the costs of capital need to be calculated. Therefore, the average effective interest rate for loans provided to non-financial corporations by German banks is taken. In December 2011, it equaled 3.4 percent for a volume of more than one million Euro, a fixed interest rate and a ten years maturity (Bundesbank 2012). An amortizable loan and a payback period of ten years are assumed in accordance with the lifetime of the PBR as well as the technical equipment and the period of the interest rate fixing. Therefore, 50 percent of the investment costs for PBRs and technical equipment and 25 percent of buildings and concrete works with a lifetime of 20 years form the average capital commitment, based on which cost of capital need to be calculated.

Table 7: Investment cost items (construction phase)

Production equipment	Price per unit	Currency	Year	Capacity	Source
Photobioreactor	103	EUR	2011	25 l	Own calculations
Culture medium preparation unit	6,000	EUR	N/A (2011)	4 m^3/h	Acién et al., 2012
Culture medium feed pump	6,000	EUR	2007	12.5 m^3/h	Norsker et al., 2011
Carbon dioxide supply station	3,006	USD	2001	27.4 kg/h	Molina Grima et al., 2003
Cooling system	25	USD	2005	m^2 (heat transfer area)	Selbaş et al., 2006
Pump for cooling system	6,000	EUR	2007	12.5 m^3/h	Norsker et al., 2011
Centrifuge	183,000	EUR	2007	22 m^3/h	Norsker et al., 2011
Centrifuge feed pump	6,000	EUR	2007	12.5 m^3/h	Norsker et al., 2011
Hydrogen recovery	196,803	EUR	2000	39 kg H_2/h	De Vrije and Claassen, 2003
Storage compressor	578,000	USD	2003	2 Mpa	Wade, 2004
High-pressure storage	913,000	USD	2003	1200 kg H_2	Wade, 2004
Biogas plant	500	USD	2007	1 m^3	Deublein and Steinhauser, 2008
Other investment costs	**Price per unit**	**Currency**	**Year**	**Unit**	**Source**
Buildings	30%			of equipment costs	Norsker et al., 2011
Control unit	15%			of equipment costs	Acién et al., 2012
Piping	20%			of equipment costs	Acién et al., 2012
Installation costs	30%			of equipment costs	Norsker et al., 2011
Land leasing costs	122	EUR	2010	1/ha	Own calculations
Cost of capital	3.4%		2011	of investment	Bundesbank, 2012

Use phase – Operating costs

In the use phase, three groups of cost items occur – labor, utility and other operating costs, which are mostly confirmed by other comparable studies (Acién et al. 2012; Molina Grima et al. 2003; Norsker et al. 2011) and displayed in Table 8. Personnel costs consist of the actual employees and overhead costs for supervision and administration staff. For the required utilities other than energy, please refer to chapter 2.2.3. Some additional possible utilities are excluded as they would amount to by far less than five percent of total life cycle costs and consequently do not significantly alter the outcome of this study. These are utilities for cleaning, initial starter cultures of *C. reinhardtii*, sulfur and other nutrients – e.g. potassium and magnesium. Maintenance costs for buildings and equipment as well as land leasing costs are considered. The nutrients in the digestate can be resold as fertilizer. To determine the price for the digestate, the P content is fully considered. For N, only the inorganic share of the actual concentration in the digestate is valuable for resale (Kehres 2009)[37]. The lack of data does not allow for determining the C-humus content of the digestate, which also contributes to the digestate price. Nevertheless, the major share of the digestate price for other ingestates such as manure or maize is attributable to the nutrients (Kehres 2009). Additionally, the C/N ratio of *C. reinhardtii* is even lower than for other ingestates – discussed in chapter 2.2.3 – so that the actual digestate price should only be slightly higher for algal ingestate than the one exclusively based on the nutrient content.

Relevant costs covering external effects are represented by the wastewater discharge fee, which is to be paid for each abstracted m³. Other costs for external effects to be included according to the definition in chapter 1.3.1 could not be identified yet. Relevant external effect categories for the environment for a comparable production system have been identified as GHG-emissions and air pollutants. For society, those are mainly security of supply as well as the competition for arable land, which is evident for other biofuels (Kovacevic and Wesseler 2010). Currently, none of these categories is likely to be charged for renewable energy production from microalgae for the following reasons. First, GHG emissions and other air pollutants from biomass and renewable biogas as well as hydrogen production do not fall within the framework of the European emission trading scheme for GHGs and air pollutants for the current and the future trading period (EC 2009; DEHSt 2009). Secondly, negative external effects of fertilizer are already charged by the wastewater treatment fee and no further nutrient leaching is expected in PBRs. Thirdly, the indicated social benefits from algal biomass production are not planned to be covered by state intervention such as subsidies at the moment (Kovacevic and Wesseler 2010).

[37] Other sources propose to consider the inorganic N and additionally five percent of the organic N (BGK 2010). Only the plant available share is considered to avoid an overestimation of the fertilizer value of the digestate. Therefore, only the inorganic share of N is used to determine the digestate price.

Table 8: Operating cost items (use phase)

Utilities	Price per unit	Currency	Year	Unit	Source
Water	1.65	EUR	2010	m³	Destatis, 2011
Fertilizer N	1,050	EUR	2008/09	t (pure nutrient)	BMELV, 2011
Fertilizer P_2O_5	1,300	EUR	2008/09	t (pure nutrient)	BMELV, 2011
Electricity	0.11	EUR	2011	kWh	Destatis, 2011
Heat	0.04	EUR	2010	kWh	Thrän et al., 2010
CO2	184	EUR	2007	t	Norsker et al., 2011

Other operating costs	Price per unit	Currency	Year	Unit	Source
Maintenance - PBR-related equipment	4%			of equipment costs	Norsker et al., 2011
Maintenance - PBR-related equipment	0.5%			of buildings	Norsker et al., 2011
Maintenance - Biogas plant	3%			of equipment costs	Deublein and Steinhauser, 2008
Maintenance - Biogas plant	0.5%			of concrete works	Deublein and Steinhauser, 2008
Land leasing costs - Germany	122	EUR	2010	1/ha	Own calculation
Insurance	0.6%			of depreciation	Acién et al., 2012
Cost of capital	3.4%		2011	of investment	Bundesbank, 2012
Wastewater discharge	2.34	EUR	2010	m³	Destatis, 2011

2.2.7 Energy consumption

The two required energy types are electrical power and heat and are indicated in Table 9.

Table 9: Power requirement of the production equipment

Production equipment	Value	Unit	Source
Biomass production			
Culture medium preparation unit	0.28	kWh/m³	Acién et al., 2012
Culture medium feed pump (filling and emptying)	0.13	kWh/m³	Norsker et al., 2011
Culture medium feed pump (circulation)	30	W/m³	Weiss et al., 2011
CO_2 pumping	0.02	kWh/kg	Khoo et al., 2011
Pump for cooling system	0.13	kWh/m³	Norsker et al., 2011
Hydrogen production and recovery			
Hydrogen recovery	2.0	kWh/kg	De Vrije and Claassen, 2003
Storage compressor	3.2	kWh/kg	Wade, 2004
Harvesting			
Centrifuge and centrifuge feed pump	5	kWh/m³	Morweiser et al., 2010
Biogas plant			
Agitators	13.4	kW	Deublein and Steinhauser, 2010
Pump	0.6	kW	Deublein and Steinhauser, 2010
Screw Conveyors	0.8	kW	Deublein and Steinhauser, 2010
Air compressor	0.5	kW	Deublein and Steinhauser, 2010

The indicated power requirements are mainly taken from the same studies that are also the source for costs and capacities to obtain harmonized values. They are listed in Table 1. For biomass production and harvesting, the power requirement is given per PBR volume. The indicated energy requirement for CO_2 pumping is related to the amount of CO_2 pumped. For hydrogen recovery and storage, the required energy is related to the amount of hydrogen produced. The biogas plant power requirement is related to the total plant described in chapter 2.2.3 with a reactor volume of 431 m³. Efficiency gains and losses concerning energy consumption due to scaling are not considered at this point since they are already regarded in the scaling factors for the investment cost calculation in chapter 2.2.5.

The operation times and operation hours differ between the case of exclusive biogas production and the case of coupled hydrogen and biogas production. For biogas production, the culture medium preparation and the centrifuge as well as the centrifuge feed pump are operated 36 times per year – see Table 1 – for the total PBR volume of 250 m³ each time. Annually, the culture medium feed pump is operated 36 times for filling and emptying the PBR. Additionally, it is operated for six days each batch – see chapter 2.2.3 – and twelve hours per day to circulate the culture medium. Twelve hours reflect the average light-dark cycle (Weiss, Patyk, and Schebek 2011; Posten and Rosello-Sastre 2011). The cooling system is operated on 28.9 days per year for five hours as indicated in chapter 2.2.3. The biogas plant is operated year-round and 24 h/d (Deublein and Steinhauser 2010). The share of algal biomass of the biogas reactor volume determines the power consumption attributable to the feedstock algal biomass.

For hydrogen and biogas production, the culture medium preparation unit and the centrifuge as well as the centrifuge feed pump are operated 18 times per year – see Table 1 – for the PBR volume of 250 m³ each time. Annually, the culture medium feed pump is operated 18 times for filling and emptying the PBR. Additionally, it is operated for 13 days each batch – see chapter 2.2.3 – and twelve hours per day to circulate the culture medium. For the cooling system and biogas production, the power requirement is similar to the case of exclusive biogas production.

The required heat for the biogas plant is 25.8 kW and – similarly to the power consumption – allocated by the required capacity for algal biomass of the total biogas reactor volume.

2.2.8 Yield

In one biomass production batch of six days, a biomass concentration of six g DW/l PBR volume is obtained (Weiss, Patyk, and Schebek 2011). This corresponds to an average yield of one g DW/(l PBR*d). With a PBR volume of 25 l/m², an energetic content of the biomass of 20 MJ/kg and a solar irradiation for the case of Karlsruhe of about 160 W/m², a photon conversion efficiency (PCE) of about 3.65 percent is obtained (Weiss, Patyk, and Schebek 2011). The hydrogen production of two ml/(g DW*h) could be determined in laboratory experiments for a comparable production system without acetate addition and with adapted sulfur provision (Kim et al. 2010). With the above given biomass productivity, it corresponds to a PCE of 0.3 percent assuming 12 h/d hydrogen production. During the hydrogen production phase, 50 percent of the algal biomass, which has been generated in the foregone biomass production phase, is respired (Rupprecht 2011).

Table 10: Parameters for yield determination

Yield parameters	Value	Unit	Source
Production biomass	1	g DW/(l PBR*d)	Weiss et al., 2011
Biomass concentration (after 6 days)	6	g DW/l PBR	Tredici, 2010/Tredici, 2004
Biomass respiration (H_2 production)	50%	of algal biomass	Rupprecht, 2011
Production H_2	2	ml/(g DW*h)	Weiss et al., 2011
CH_4 yield (after H_2 production)	0.48	l/g VS	Mussgnung et al., 2010
CH_4 yield (without H_2 production)	0.39	l/g VS	Mussgnung et al., 2010
Ash content	5%	of TS	Kliphuis et al., 2011
Lower heating value H_2	121	MJ/kg	Linstrom and Mallard, 2011
Lower heating value CH_4	36.1	MJ/nm³	Linstrom and Mallard, 2011

To determine the actual methane yield per dry weight algal biomass, the yield per volatile solids is multiplied with the dry weight of algal biomass, from which the ash content of five percent is subtracted (Kliphuis et al. 2011). The produced energy is determined by multiplying the volumetric methane yield with the lower heating value for methane. More methane is produced after hydrogen production due to the higher starch and lipid content (Doebbe et al. 2010), which is easier degraded than fresh biomass without foregone hydrogen production (Mussgnug et al. 2010).

2.3 Scenario analysis

This chapter contains four scenarios. The first one, *Scenario 2030 – Technology learning*, is a future projection of the LCC results to be determined for 2011 in this study. The second one, *Location change*, should illustrate the cost change if the microalgae were produced in Spain instead of Germany in a setting with lower input costs, another, mainly warmer climate and higher solar irradiation. The third scenario, *Hydrogen as a byproduct*, investigates, whether hydrogen production can be economically viable if produced as a byproduct. It should also show, which minimum price needs to be realized for the residual biomass. The last one, *Break-even scenario*, should reveal the necessary cost reduction to achieve economic viability of hydrogen and biogas production from microalgae in the given production system.

Another common scenario for microalgae production – up-scaling of the production facility – as done by Norsker et al. (2011) – is not calculated in this study. The PBR with the rather fragile structure – thin PBR walls – does not allow high pumping pressures (Posten et al. 2011), which would be necessary for larger scales. Additionally, large scale production facilities are more likely to be contaminated and would require additional sterilization equipment (Acién et al. 2012). Up-scaling would therefore require setting up several similar production facilities, which would result in negligible economies of scale.

2.3.1 Scenario 2030 – Technology learning

Application of experience curves

Both the technological and economic performance of algal biomass production in PBRs and hydrogen recovery technologies are expected to increase, which results in a sharp decline of investment and operating costs (Acién et al. 2012; Brennan and Owende 2010; Burgess and Fernández-Velasco 2007; Ferrell and Sarisky-Reed 2010; van Beilen 2010; Vasudevan et al. 2012; Verrecht et al. 2008). Additionally, the algal biomass yield will ameliorate due to genetic engineering and improved growth conditions (van Beilen 2010; Wijffels and Barbosa 2010). The experience curve effect is for the technology of biogas production not expected to be as distinct as for the other two subsystems. The latter is at a rather mature state in comparison with the former technologies (Junginger et al. 2006). To estimate the investment costs and the operation and maintenance costs in 2030, we use an experience curve approach based on endogenous learning in a bottom-up approach. A bottom-up approach is chosen because subsystems with differing progress ratios can be modeled (Junginger et al. 2008). An overall progress ratio would not reflect the reality, in which technology learning mainly differs between the subsystems algal biomass production in PBRs, hydrogen recovery technologies and biogas production as well as the biomass yield for the given plant design. Furthermore, the algal biomass production system, hydrogen recovery technologies – i.e. membrane and storage – and biogas production facilities are also produced separately and used for various applications[38], which all contribute to the experience effect.

For algal biomass production systems and hydrogen recovery technologies, a global market is assumed so that investments are considered for the whole world market. This is suitable if both technologies are at an early development stage with low production volumes so that economic viability for producers of both technologies is only given if their production is aimed at the global market (Singh and Gu 2010; Iaquaniello et al. 2011). Moreover, local conditions should not require larger differences for both technologies. Only minor adjustments related to e.g. the size of the cooling equipment might depend on the region. For biogas production, the experience curve effect can be seen as rather local or EU-wide than worldwide (Junginger et al. 2006). This is due to the fact that the facilities for anaerobic digestion regionally differ due to various factors. Those can be e.g. the legislation for sanitary requirements of biogas plants, which is uniform in the EU (Holm-Nielsen, Al Seadi, and Oleskowicz-Popiel 2009), but different in other regions. Another major factor with large effects is the climate. Less heating is required in warmer climates and the improvement of technologies such as isolation becomes unnecessary (Sreekrishnan, Kohli, and Rana 2004).

For PBR algal biomass production systems, progress ratios could not be found yet. The comparability to other biomass production systems is also not given. A technology with comparable characteristics could be low-temperature solar thermal collectors. They are also transparent for incident solar irradiation and water is pumped through flat-plate or tubular collector. The progress ratio is about 94 percent (Holtermann and Madlener 2011). The commercial production of algal biofuels is expected to increase from zero to about five percent of total biofuels by 2030. Therefore, open pond production facilities with a volume of 170.1 million m^3 by 2030 would be required (Darzins, Pienkos, and Edye 2010). Using the ratio 0.076 of the biomass production rates per volume culture medium of open ponds and PBRs – derived from Chisti (2007), who uses similar system characteristics for both systems –,a theoretically necessary PBR volume of about 13 million m^3 in 2030 could be obtained. It is assumed that the share of algal biomass produced in PBRs will increase. An optimistic estimate of the current share of PBRs on total

[38] Algal biomass is produced in PBRs for various purposes described in chapter 1.5.6 and not only for those described in this study. The same is valid for hydrogen recovery technologies – e.g. additionally used for dark fermentation – and biogas production – e.g. from manure or other wastes.

algal biofuel production of 52 percent (Singh and Gu 2010)[39] is taken. This would result in an installed PBR volume of 6.8 million m³ by 2030. This value and additional 10 percent of the installed capacity for the annual replacement of PBRs – lifetime of ten years – are the cumulative capacity for the period 2011 to 2030 – indicated in Table 11.

The progress ratio for the algal biomass production system does not reflect the changes in the algal biomass yield, which is also likely to increase for the above named reasons and improved processing. Therefore, the progress ratio would need to be lowered – equal to an increase of the experience effect – to consider these additional effects. Missing an estimate for a progress ratio related to the yield increase, the progress ratio is not increased, but yield increases expressed in an increase of the photon conversion efficiency from 3.65 to five percent for biomass production and for hydrogen production from 0.3 to one percent are assumed (Franz et al. 2011; Lehr et al. 2011). Both values are the realizable maxima under ideal algal biomass production conditions (Tredici 2010; Kruse, Rupprecht, Mussgnug, et al. 2005; Lehr et al. 2011). This should have an effect comparable to an increased progress ratio.

The costs of the hydrogen recovery technology are mainly determined by those for the membrane. The experience index for this technology is estimated to be 25 percent, which equals a progress ratio of about 85 percent (Iaquaniello et al. 2011). In 2005, about 670,000 m² of polymer membrane surface have been installed in Europe (Lesjean and Huisjes 2008), which is 19 percent of the world market (Furukawa 2008). Membranes are expected to have an average lifetime of ten years, which resulted in a worldwide annual production of about 353,000 m² in 2005. Afterwards, an annual increase of the production volume of membranes is expected to be seven percent on average until 2030 (Baker 2002). In total, a cumulative production from 2011 to 2030 can be derived as shown in Table 11.

The progress ratio per unit biogas produced is about 88 percent as derived for Denmark (Junginger 2005)[40]. The increase of the biogas production volume is expected to increase in the EU from eight EJ in 2010 to twelve EJ by 2030

[39] Other authors argue that the current commercial production is predominately conducted in open ponds (Benemann 2011). It is likely that the share of PBRs will rise as PBRs are at an earlier development stage than open ponds as the major research effort on PBRs has been in recent years. Therefore, they are only commercially used for selected HVPs at the moment (Brennan and Owende 2010).

[40] The experience curve is not based on increased investments in biogas plants as the number of plants was too small for an empirically reliable dataset in the underlying case of Denmark and the redesign of existing plants also results in technological improvements. Additionally, the decline in operating costs is considered by using the amount of biogas produced (Junginger et al. 2006).

(Wiesenthal and Mourelatou 2006), which implies an increase of production capacity by four EJ. These and additional ten percent of the installed capacity for the regular replacement of biogas plants are the cumulative capacity – shown in Table 11.

Table 11 summarizes the above mentioned parameters for applying experience curves. For hydrogen recovery, the experience index could be directly inserted in Equation 2 in 1.4.3. The progress ratios given for the PBR and the biogas plant need to be converted to the experience index in chapter 1.4.3. The missing factors for current costs C_0 are the current life cycle costs, which are shown in chapter 3.3 and are attributed to the three technologies as displayed in the following table.

Table 11: Experience curve parameters for technology learning by technology

Experience curve parameters	Value	Unit	Source
PBR			
Progress ratio	94%		Holtermann and Madlener, 2011
A (cumulative production)	14,244,211	m³ PBR	Own calculation
Hydrogen recovery			
b (experience index)	25%		Iaquaniello et al., 2011
A (cumulative production)	21,695,016	m² polymer membrane	Own calculation
Biogas plant			
Progress ratio	88%		Junginger, 2005
A (cumulative production)	23	EJ biogas	Own calculation

Specific factors explaining experience curves

Some possible improvements that cannot be realized currently might explain a share of the projected cost reductions, which are mainly relevant for reduced operating costs and yield increase. The latter has been described already in chapter 0.

The personnel costs, having a major share in operating costs, might be reduced due to the use of less and cheaper staff – possible due to larger automation of production – as already assumed in optimistic studies for biomass and hydrogen production from *C. reinhardtii* (Wade 2004; Acién et al. 2012). Accordingly, a personnel reduction to one FTE is assumed and the gross labor costs for personnel from the wastewater treatment sector are used, which only amount to about two thirds of the costs for the personnel from the energy sector used in the base case (Destatis 2012a).

Genetically optimized algae should be able to have a higher yield under less favorable growth conditions such as that they might develop a higher tolerance level for photoinhibition, toxicity from flue gases or wastewater as well as oxygen during the hydrogen production phase (Stephens et al. 2010; Wijffels and Barbosa 2010; Kruse, Rupprecht, Bader, et al. 2005; van Beilen 2010). These improvements would provide the opportunity to cut CO_2 costs and revenues could be generated from carbon capture. Here the average price for CO_2 certificates in 2011 of 13.81 Euro per t CO_2 is taken (DEHSt 2011).

Specifically energy consumption is targeted in research (Posten 2009; Posten et al. 2011; Sierra et al. 2008) so that further improvements are expected. This could include the use of auto-flocculation and conventional filtration to harvest algal biomass instead of centrifugation, which is associated with a lower energy consumption of 0.88 kWh/m³ than centrifugation with five kWh/m³ (Molina Grima et al. 2003). Additionally, Sierra et al. (2008) propose that the energy consumption for culture circulation could decline to 15 from 30 W/m³ in the base case. For biogas production, technology learning often shows effects comparable to up-scaling so that a decline of the electricity consumption to three percent of the biogas produced and of the heat consumption to 9.6 percent of the biogas produced (Pöschl, Ward, and Owende 2010) is assumed. Hydrogen compression and storage energy is expected to decline by 50 percent (Burgess and Fernández-Velasco 2007).

2.3.2 Location change

Apart from the technological improvements, which are expected to be possible by 2030, the effect of change of the production location today is investigated. This could be a location change with higher solar irradiation rates. It results for the area of Madrid in Spain[41] instead of Karlsruhe – representatively chosen for Germany as indicated in chapter 2.1.2 – in an annual production increase of biomass and hydrogen[42]. For *C. reinhardtii,* it is about one third for a similar production system

[41] A Spanish production location is chosen as this option – compared with the tropic options given by Franz et al. (2011) – rather allows for using mostly similar production equipment. For example, the lifetime of the PBR and the technical equipment are likely to vary with the climatic conditions. Equipment such as the biogas reactor might even not be suitable for the tropics as discussed in chapter 2.3.1.

[42] There is no quantifying study of the production increase of hydrogen due the location change, but it can be assume that this is valid for both hydrogen and biomass production. The relevant parameters for biomass production – solar irradiation and air temperature – are also of major importance for hydrogen production. An increase of the annual solar irradiation and the number of hours with sufficiently high temperatures raise the hydrogen yield as well (Tsygankov et al. 2006).

and algae strains with similar PCEs (Franz et al. 2011)[43]. A major increase of the production costs can be expected currently in terms of a higher installed cooling capacity. In detail, this is associated with scaling of the heat exchanger and the pump for cooling water. A higher water consumption due to more days requiring cooling need to be considered as a result of more days with higher temperatures and a higher solar irradiation. The calculation method for heat exchanger capacity and water consumption is similar to the one described for Stuttgart in chapter 2.3.1, but the value for solar irradiation is 950 W/m² (Kerdoncuff 2008) instead of 640 W/m² and climate data for a similar time frame for the weather station Madrid – identification number 3195 – is taken from the state meteorological agency of Spain (AEMET 2012).

Due to higher temperatures, the heat consumption for anaerobic digestion in Spain has been estimated to be minimal that it can be omitted in calculations (Hospido et al. 2005). A higher accuracy is not decisive for the overall costs due to the low share of heat on total and operating costs (Deublein and Steinhauser 2010). Price adjustments on personnel costs, prices for CO_2, water and electricity are made. The price data is taken for 2011 from a Spanish study for PBR-based algal biomass production by Acién et al. (2012)[44]. The data deviating from Table 8 of the base case is indicated in Table 12.

Table 12: Operating costs items (use phase) – Location change

Labor	Price per unit	Currency	Year	Unit	Source
Gross labor costs	37,500	EUR	N/A (2011)	FTE	Acién et al., 2012
Utilities	**Price per unit**	**Currency**	**Year**	**Unit**	**Source**
Water	0.10	EUR	N/A (2011)	m³	Acién et al., 2012
Electricity	0.10	EUR	N/A (2011)	kWh	Acién et al., 2012
CO_2	300	EUR	N/A (2011)	t	Acién et al., 2012

The prices for production equipment are expected to bear comparable costs as already demonstrated by Norsker et al. (2011), who assumed that cost data from Spain for these items is comparable to those in the Netherlands. This can be justi-

[43] The study by Franz et al. (2011) similarly assumes for both Karlsruhe and Madrid 250 days of production per year, which is comparable to the 252 annual production days in this study.

[44] Lacking representative and comparable data for Germany and Spain for fertilizer, similar prices in Spain are assumed. But as both nutrients only have a minor share on total operating costs (Acién et al. 2012), a missing adjustment will not deteriorate the significance of the results.

fied by the fact that it is highly specialized equipment and cost differences should be marginal on a common European market.

2.3.3 Hydrogen as a byproduct

In the base case, biogas is considered as a byproduct of the photobiologically produced hydrogen to use the residual algal biomass. Nevertheless, if economic viability is not achievable at the current development stage and for the given energy prices, another option will be the joint production with a subsidizing high-value product (HVP), which is likely to be profitable (Brennan and Owende 2010) and possible with *C. reinhardtii* (Landgraf 2012). Depending on the HVP, some residual biomass might be available for anaerobic digestion or other energy processing options (Melis 2002) – as described in chapter 1.5.6. Lacking data on HVP options from *C. reinhardtii*, further processing steps of the residual biomass are disregarded and the harvested biomass is assumed to be sold without further processing. The total market volume is estimated with 1.25 billion Euros and an average dry weight price for algal biomass of 250 Euro/kg (Pulz and Gross 2004).

Another option for a larger target market could be the use as animal feed. Freshwater algae could be a major contributor of proteins with a content of more than 50 percent of the algal dry weight, which is higher than the one of soybeans – 44 percent of the dry weight. The latter are used as soybean meal to a large extent for livestock production (Lupatsch 2012). The current price of soybean meal is between 400 and 500 Euro/t at different German commodity exchanges (SWB 2012a, 2012b), which is the upper price level to be observed.

2.3.4 Break-even scenario

To derive the extent to which production costs might need to be reduced, the yield is increased first. Secondly, current life cycle costs are reduced to meet with biogas and hydrogen from algal biomass the projected energy prices for 2030. Nevertheless, this should not exceed the biologically realizable future maximum of the photon conversion efficiency of five percent for biomass production (Tredici 2010) and one percent for hydrogen production (Lehr et al. 2011; Kruse, Rupprecht, Mussgnug, et al. 2005).

3 Results

The results are separately displayed for the construction phase – investment costs – and for the use phase – operating costs – in the first two subchapters. In the third subchapter, the LCC results for the functional unit MJ of hydrogen and methane[45] are obtained by allocating costs and yields of the foregone subchapters. The robustness of the results is tested by a sensitivity analysis in the second to last chapter. The last subchapter shows the results of the different scenarios.

3.1 Construction phase

To use the investment costs in the LCC model, the annualized investment costs for biogas production – displayed in the left column in Figure 6 are taken. They consist of the installed production equipment and buildings as well as other supporting facilities. Other investment costs also consider the installation and capital services necessary for setting up the production facility. Annualized investment costs are calculated to create a common basis within the different lifetimes of production and supporting equipment. Annualizing ofcosts is also necessary to set them in relation to the use-related costs and yields, which are both calculated on an annual basis as shown in the following chapters. For the case of exclusive biogas production, the total investment costs and the respective scaling factors of the equipment can be found in Table 24 and the annualized investment costs in further detail in Table 25 in Appendix I: Investment costs. Scaling factors of the production equipment, which show the size or number of equipment units respectively in relation to the basic capacity or volume Table 7 in chapter 2.2.6, are named. For example, 10,000 PBR units of one m² and their associated costs would be required to

[45] The energy content from biogas is indicated as methane as justified in chapter 2.1.1.

set up the biomass production facility with a total volume of 250 m³ per ha, which is the aim of this study.

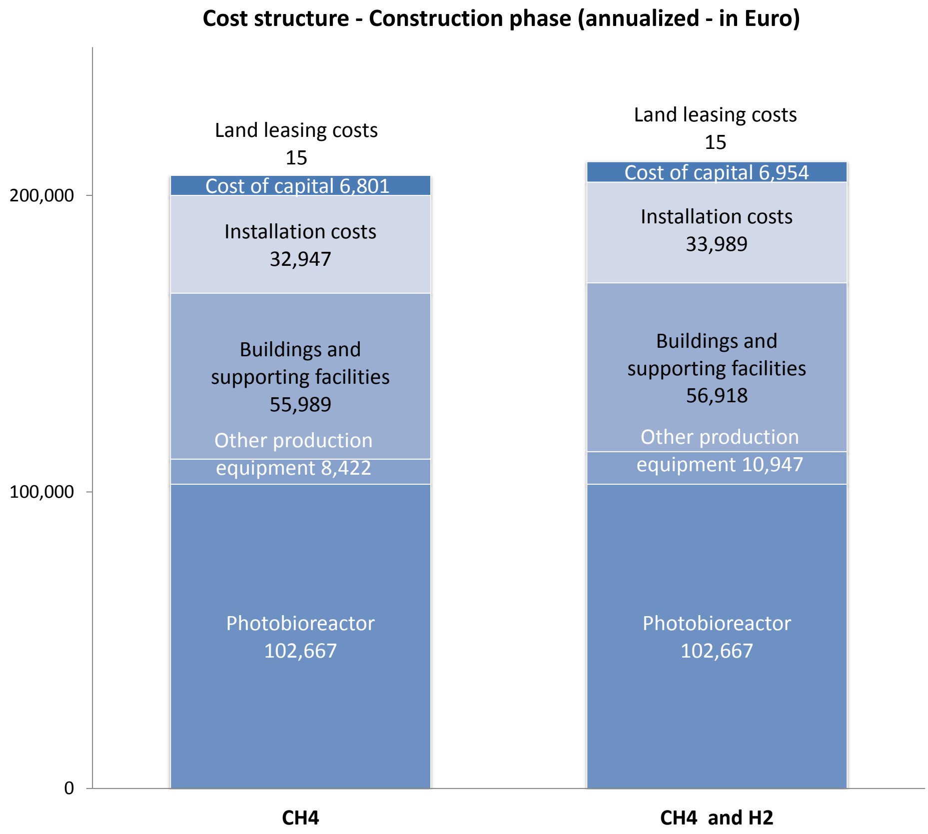

Figure 6: Cost structure – Annualized investment costs

Figure 6 shows that about 49.6 percent of the annualized investment costs are caused by the PBR itself, 27.1 percent for buildings and supporting facilities and further 15.9 percent for the installation costs of the production facilities. The PBR costs consist to 80 percent of material costs and 20 percent are manufacturing costs. The material costs are dominated by the membrane costs, which amount to 76 percent and the remaining 24 percent equal the costs for the remaining material – ten percentage points PET and 14 percentage points PMMA.

The total annualized investment costs for the coupled production of hydrogen and biogas in the right column of Figure 6 are lower than for exclusive biogas production. Directly biogas-related investment costs are lower for coupled production of hydrogen and biogas as the algal biomass yield is only 25 percent of the case of exclusive biogas production. This can be inferred by comparing Table 25 and Table 29 in Appendix I: Investment costs. This percentage reflects the biomass yield decrease. 50 percent decline is attributable to the 50 percent reduction of production cycles. Another 50 percent of the produced biomass is respired during the hydrogen production phase. Additionally, the size of the harvesting equipment – centrifuge and centrifuge feed pump – has a smaller scale due to the longer harvesting interval of 14 instead of seven days. The costs for the major production equipment apart from the biogas plant increase as additional hydrogen recovery and storage equipment is required – see Table 26 in Appendix I: Investment costs. This increase of major production equipment costs results in higher installation costs, which do not consider those for the biogas plant, which are treated separately in Table 28.[46]

To allocate the annualized investment costs in Figure 6 to the products hydrogen and biogas, a separate computation of the investment costs for hydrogen production excluding all investment costs related to biogas production, of the investment costs which are exclusively related to biogas production and the costs for biomass production with the production parameters for the case of exclusive biogas production[47] is performed. An explanation for this approach is given in chapter 2.2.5. The costs necessary for hydrogen production are displayed in Table 27, those for biogas production in Table 29 and those for biomass production in Table 31. The annualized investment costs for hydrogen production in Table 27 overestimate the actual hydrogen-related investment costs as the use of residual biomass is not considered. Some of the annualized investment costs in Table 27 that are related to hydrogen should be allocated to biogas production to reflect the use of residual biomass. Therefore, 25 percent of the annualized investment costs for biomass production – shown in Table 31 – are deduced from those for hydrogen production and added to the biogas production costs. For this reason, the annual-

[46] The investment cost data for the biogas plant comprises installation costs, but does not indicate the actual share of installation costs (Deublein and Steinhauser 2010).

[47] The investment costs for biomass production only differ from those for the case of exclusive biogas production due to the missing costs for the biogas plant and the related other investment costs – buildings and costs of capital.

ized investment costs for hydrogen production decrease by about 51,000 Euro and those for biogas increase by the same amount.

3.2 Use phase

This chapter contains three subchapters, of which the first one shows the cost structure of the operating costs. The second one deals with the energy balance of the use phase. The material flow analysis for the production system is given in the last one.

3.2.1 Cost structure

The costs structure of operating costs for the case of exclusive biogas production is shown in the left column of Figure 7. Utilities amount to about eight percent and other operating costs to about 92 percent of annual operating costs. The personnel – labor and overhead costs – have the major share with about 74 percent of total operating costs. Three of the FTE of 3.1 – see. Table 32 in Appendix II: Operating costs – are attributable to algal biomass production and harvesting and 0.1 FTE to biogas production.

The right column in Figure 7 shows the case of coupled hydrogen and biogas production. It can be seen that this case consumes fewer utilities than exclusive biogas production. During the hydrogen production phase neither tap water for filling the PBR nor nutrients for generating additional biomass are required so that the overall consumption decreases by 50 percent. The reduced water consumption is associated with lower wastewater discharge fees. Other operating costs remain largely unchanged as both coupled hydrogen and biogas production as well as exclusive biogas production require continuous operation of the production facilities.

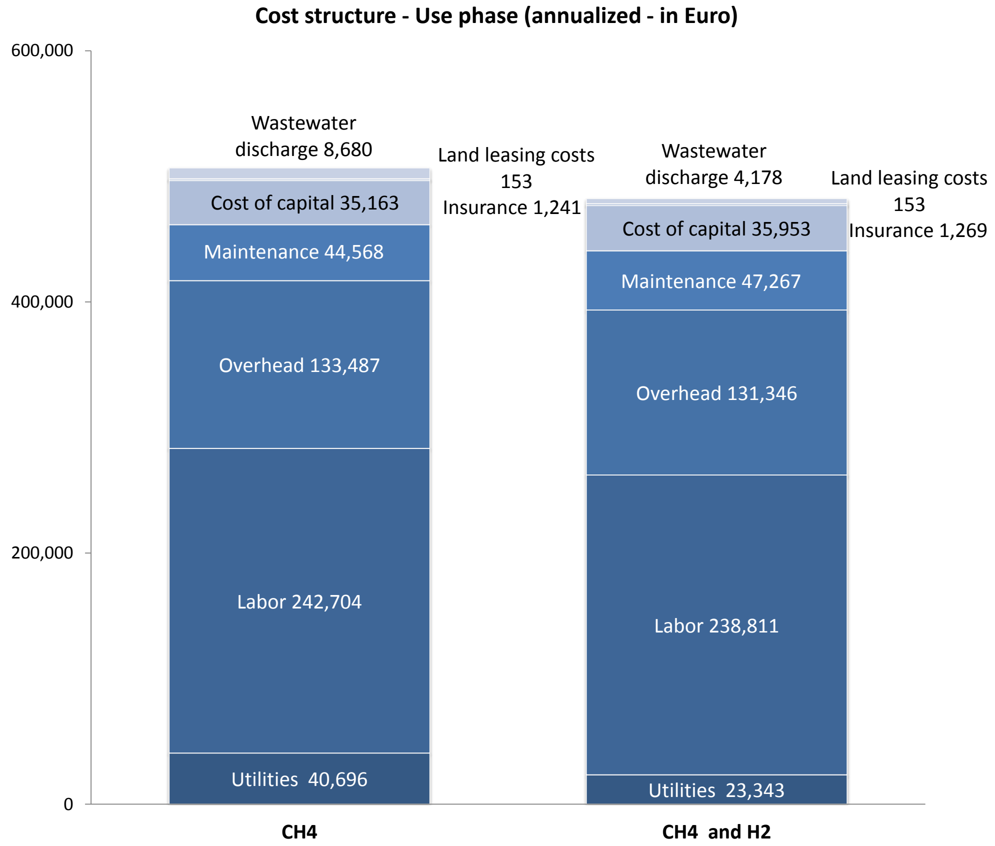

Figure 7: Cost structure – Annual operating costs

Operating costs for biogas production are lower for coupled hydrogen and biogas production due to the lower biomass yield as already described for the investment costs. This is valid for heat and electricity, which are allocated by the biomass processed, and other operating costs such as personnel – 0.02 FTE for coupled hydrogen and biogas production in Table 32 instead of 0.1 FTE for exclusive biogas production in Table 34 – or costs of capital, which are allocated by the required size of the biogas reactor for algal biomass digestion.

The allocation of operating costs for the residual biomass from the hydrogen- to the biogas-related operating costs is similarly done as for the investment costs. 25 percent of the operating costs for biomass production[48] in Table 35 are deduced from the operating costs for hydrogen and added to those for biogas production – i.e. approximately Euro 125,000.

[48] Operating costs for biomass only differ – as already explained for the investment costs – from the biogas production costs by the excluded operating costs for the biogas production facility.

3.2.2 Energy balance

The energy balance for exclusive biogas production – only for the use phase[49] – is shown in Figure 8. Apart from heating, the energy used by the production equipment is power. The usable solar irradiation equals a PCE of twelve percent. This share of solar irradiation is the one that can be used to convert CO_2 into biomass – the maximum theoretical efficiency of photosynthesis – (Tredici 2010). The energy conversion efficiency of biomass provision is about 28 percent. The energy loss is attributable to about 90 percent to the fact that only a PCE of 3.65 percent can be realized for the strain of *C. reinhardtii* used[50]. Concerning the biomass provision, centrifugation as the chosen harvesting technology has the major share of more than 63 percent of the power demand.

The energy conversion efficiency for biogas production from algal biomass is about 57 percent. The major energy consumer is heat with a share of 62 percent of the energy input for anaerobic digestion, which equals about 17 percent of the energy, i.e. biogas, produced.

[49] Other phases are disregarded as they do not affect the costs in this model. Energy consumed in the construction phase is included in the investment costs and the lump sums used such as for installation costs.

[50] In particular, the losses can be attributed to photoinhibition and -respiration, respiration and reflection (Tredici 2010).

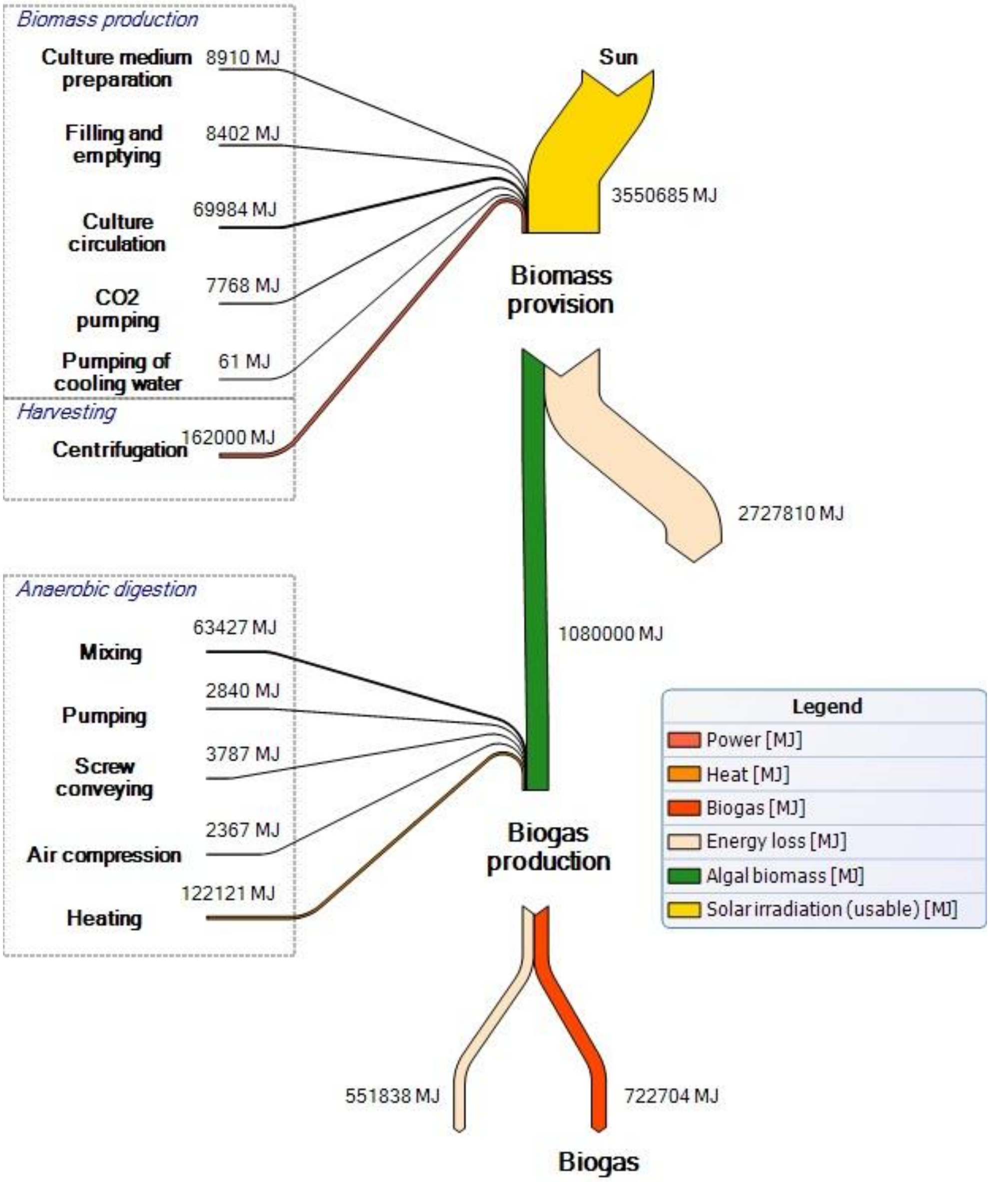

Figure 8: Energy balance (biogas)

The energy produced of the coupled hydrogen and biogas production is about 37 percent of those for the exclusive biogas production – shown in Figure 9. The energy conversion efficiency of biomass provision and hydrogen production is about ten percent.

The significantly lower energy conversion efficiency is attributable to the fact that 50 percent of the algal biomass is respired during hydrogen production. Additionally, the PCE for hydrogen production amounts to 0.3 percent instead of 3.65 percent for biomass production for 50 percent of the production period, in which hydrogen and no biomass is produced. A small share is explainable by the fact that the major electricity consumption for culture processing, i.e. culture circulation, is slightly larger and additional energy is required for hydrogen recovery and compression.

The energy conversion efficiency from biomass to biogas is about 58 percent. It is one percentage point higher than for the case of exclusive biogas production. Hence, the hydrogen production phase results in a higher accumulation of starch and lipids so that the biomass has a larger energy content[51], which yields 23 percent more biogas per unit biomass. Per unit biogas less biomass is required, which also lowers the relative share per unit biogas on the biogas reactor required for algal biomass since the energy consumption is attributed by biogas reactor volume. Heat equally has the major share with 54 percent on total energy consumption, but the heat requirement amounts only to 14 percent of the energy produced due the higher biogas yield per unit algal biomass.

[51] Lacking of data on the energy content of algal biomass after hydrogen production, it is assumed that the energy content of the biomass is larger proportionally to the biogas yield increase.

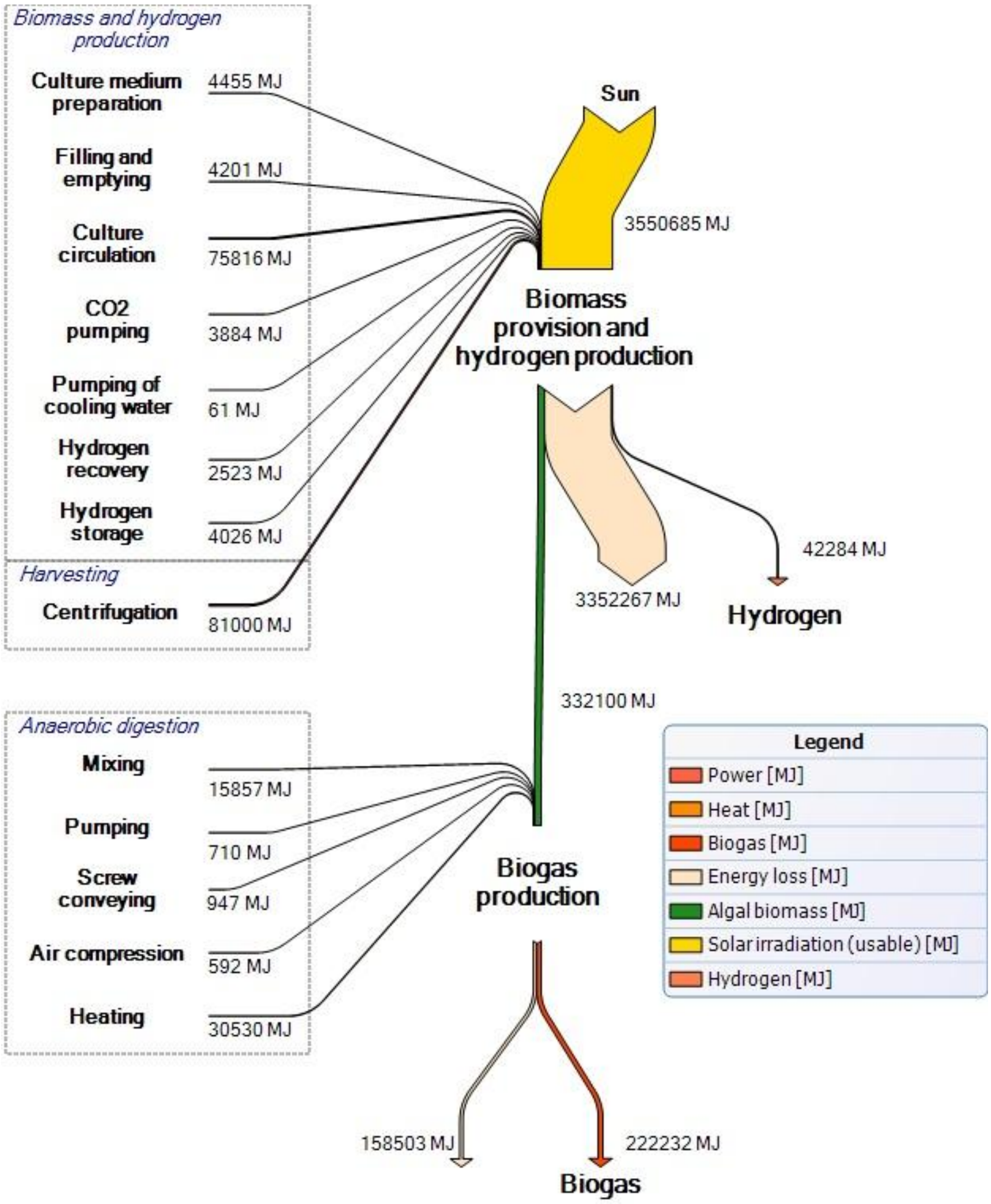

Figure 9: Energy balance (hydrogen and biogas)

3.2.3 Material flow analysis

The material flow analysis for the use phase in Figure 10 shows that the major water loss occurs in the harvesting step as the recovered water from centrifugation is only reused twice and algal biomass ingestate contains water to about 94 percent of the wet weight (Mussgnug et al. 2010). The water consumption for cooling is minimal compared with the consumption for biomass production.

The anaerobic digestion of algal biomass allows N and P recovery by reuse of the digestate as fertilizer. To some extent N and P are reused in the recycled culture medium, but this share cannot be determined exactly due to the lack of experimental data. Therefore, a reuse rate is not considered in the nutrient application in batches with recycled culture medium. Most of the CO_2 applied is dissolved in the culture medium and used during the photosynthesis. The amount of excess is not displayed due to the lack of experimental data. For the same reason, the resulting amount of oxygen is not modeled, but both are assumed to be mostly dissolved in the culture medium and the wastewater. A marginal amount of excess wastewater is likely to be gaseous CO_2 and oxygen. Concerning the fertilizer, it has to be noted that the mineralization of N and P during the anaerobic digestion process allows recovering of about 71 percent of the initial N, of which the inorganic share of 77 percent is considered to calculate the economic fertilizer value of the digestate, and about 86 percent of the initial P application, which is totally considered for the economic fertilizer value of the digestate. The cooling water is heated up to 27 °C and afterwards discharged as further reuse is not possible.

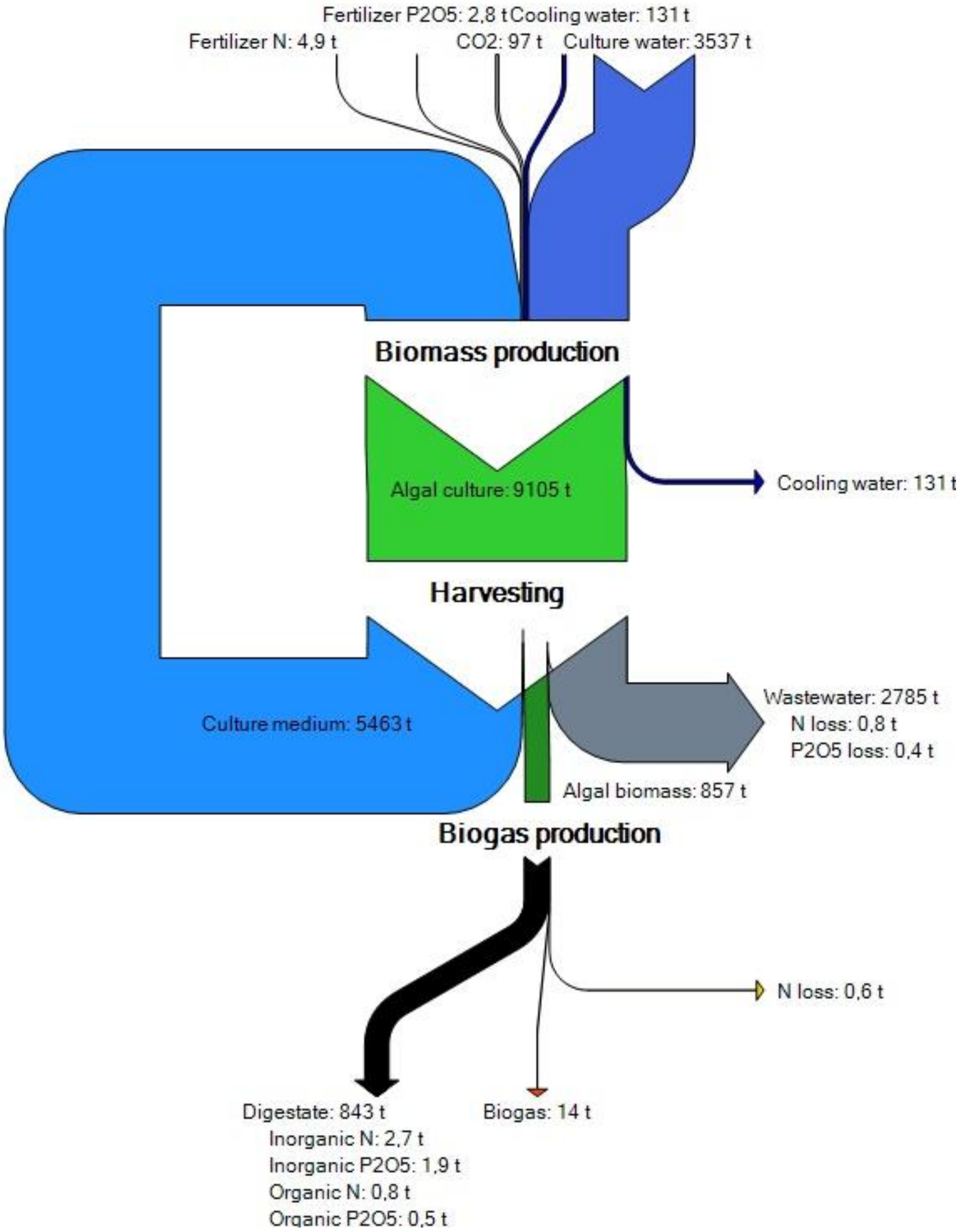

Figure 10: Material flow analysis (biogas)[52]

[52] The indicated values for the different N and P_2O_5 forms are included in the mass of wastewater and digestate respectively. The mass of P used is indicated in P_2O_5, which is the common unit for P fertilizer in agriculture. The mass of biogas is obtained by dividing the energetic yield from biogas – indicated in chapter 3.2.3 – by the LHV of 50 MJ/kg (EU 2009).

The material flow analysis for the coupled hydrogen and biogas production shows that the wastewater in relation to the harvested biomass and the energy produced as shown in the foregone chapter is significantly higher. It is significantly higher in comparison with algal biomass produced due to the respiration of biomass during the hydrogen production phase. This also results in less digestate and lower nutrient recovery rates in the digestate of about 28 percent for N, of which the inorganic share of 71 percent has an economic fertilizer value, and 29 percent for P, which completely has an economic fertilizer value.

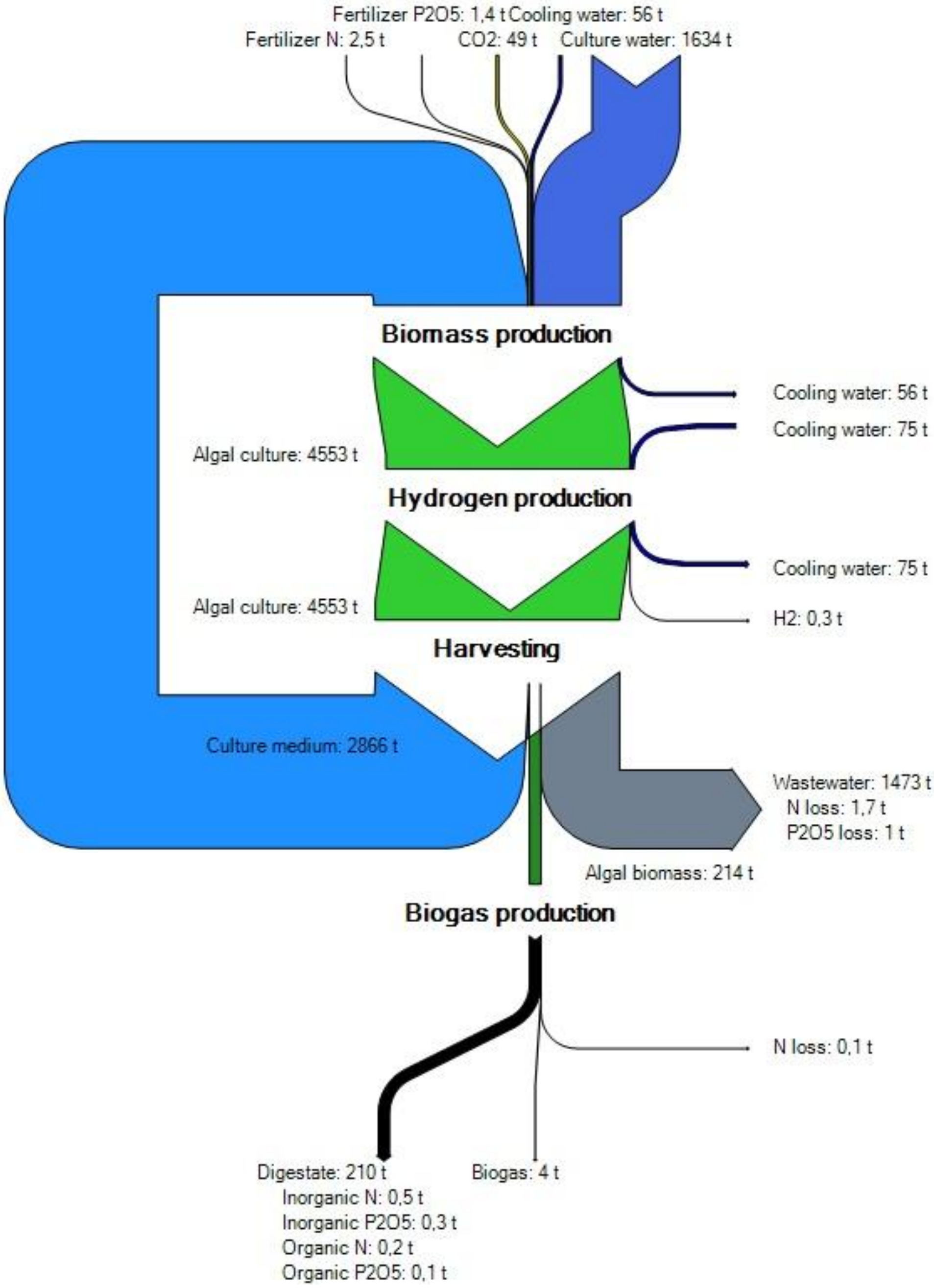

Figure 11: Material flow analysis (hydrogen and biogas) [53]

[53] The indicated values for the different N and P_2O_5 forms are included in the mass of wastewater and digestate respectively. The mass of P used is indicated in P_2O_5, which is the common unit for P fertilizer in agriculture. The mass of hydrogen is obtained by dividing the energetic yield from hydrogen – indicated in chapter 3.2.3 – by the LHV indicated in Table 10 in chapter 2.2.8. The mass

3.3 Environmental life cycle costs

The life cycle costs of exclusive biogas production consist to about 30 percent of investment costs (construction phase) and to about 70 percent of operating costs (use phase) as shown in Table 13. For coupled hydrogen and biogas production, this distribution of investment and operating costs is unchanged, but the total life cycle costs decrease due to the higher methane yield per unit algal biomass after hydrogen production. Economically viable biogas production from microalgae is with the given life cycle costs not possible as the average selling price in Germany for biogas – including a discount for purification to natural gas quality – of 0.02 Euro/MJ in 2010 (Volk 2011)[54] is significantly exceeded. In addition, the produced biogas is not expected to have natural gas quality and is likely to require further processing to reach this state, i.e. the selling price would be even lower.

The total life cycle costs for hydrogen consist to one third of investment costs and to two thirds of operating costs. Hydrogen production with microalgae is – more strongly than biogas – not economically viable as the targeted market price by 2015 is 0.04 Euro/MJ (LHV)[55]. The life cycle costs of hydrogen amount to about twelve to 15 times the costs of biogas production for the same amount of energy.

Table 13: LCC results for biogas and coupled hydrogen and biogas production

Production system	Unit	Construction phase	Use phase	Total
Biogas	EUR per MJ CH_4	0.29	0.70	0.99
Hydrogen and biogas	EUR per MJ CH_4	0.23	0.57	0.81
Hydrogen and biogas	EUR per MJ H_2	3.78	8.40	12.17

3.4 Sensitivity analysis

To determine the robustness of the results, the major contributors to total life cycle costs and the determining parameters were subject to a sensitivity analysis such as

of biogas is obtained by dividing the energetic yield from biogas – indicated in chapter 3.2.3 – by the LHV of 50 MJ/kg (EU 2009).

[54] In this source, it was not indicated, whether the given price is applicable for the LHV or the HHV.

[55] No reliable market price for hydrogen was found and therefore this projection was taken. Nevertheless, it was not investigated further as the production costs do not meet the projected market price for 2015 by far. This value is obtained by dividing the price of five Euro/kg (Jackow 2007) with the LHV of hydrogen of 121 MJ/kg (Linstrom and Mallard 2011) .

the biomass and hydrogen yield. The biomass and hydrogen yield have been estimated by Weiss et al. (2011) and the results still require laboratory and field test. Concerning the investment costs, the major contributor is the PBR. Concerning the operating costs, the personnel costs are of major influence. The PBR assemblage is additionally subject to estimates due to lack of data on the exact membrane price and the manufacturing costs. Several studies agree on the number of FTEs – for smaller or larger PBR volumes (Acién et al. 2012; Molina Grima et al. 2003; Norsker et al. 2011) – as described in chapter 2.1.1. Norsker et al. (2011) also propose this FTE number for a production area of one ha, but for a larger PBR volume. Consequently, the input costs of the PBR and the personnel are the major source of uncertainty in addition to the fact that both are the major cost contributors.

The sensitivity is tested by altering the gross labor costs, PBR costs and the total biomass and hydrogen yield by ten percent to observe the changes on the LCC results given in Table 13.

Table 14: Sensitivity analysis – Change of gross labor costs by ten percent[56]

	Production system	Unit	Construction phase	Use phase	Total
+10%	Biogas	EUR per MJ CH_4	0.0%	7.4%	5.3%
	Hydrogen and biogas	EUR per MJ CH_4	0.0%	7.4%	5.3%
	Hydrogen and biogas	EUR per MJ H_2	0.0%	7.8%	5.4%
-10%	Biogas	EUR per MJ CH_4	0.0%	-7.4%	-5.3%
	Hydrogen and biogas	EUR per MJ CH_4	0.0%	-7.4%	-5.3%
	Hydrogen and biogas	EUR per MJ H_2	0.0%	-7.8%	-5.4%

Table 14 shows that the life cycle costs – total – and the operating costs – use phase – are highly sensitive to changes in personnel costs. This can be explained by the fact that personnel costs have a major share on total costs. Therefore, it is crucial to have reliable data for this cost item, which is given by the data source – the federal statistical office, and detailed information on the required qualification of the staff, which is not given at the current development stage of the production. The production processes at field conditions are not defined in detail so that a qualification scheme for the personnel could not be set up. The sensitivity of

[56] The change of the LCC results due to an increase of gross labor costs is denoted in the upper part and the decrease in the lower part of the table.

hydrogen production costs to gross labor costs is slightly higher due to the larger share of personnel costs on operating and life cycle costs compared with biogas production.

Table 15: Sensitivity analysis – Change of PBR costs by ten percent[57]

	Production system	Unit	Construction phase	Use phase	Total
+10%	Biogas	EUR per MJ CH_4	9.2%	1.5%	3.7%
	Hydrogen and biogas	EUR per MJ CH_4	9.2%	1.5%	3.7%
	Hydrogen and biogas	EUR per MJ H_2	9.0%	1.6%	3.9%
-10%	Biogas	EUR per MJ CH_4	-9.2%	-1.5%	-3.7%
	Hydrogen and biogas	EUR per MJ CH_4	-9.2%	-1.5%	-3.7%
	Hydrogen and biogas	EUR per MJ H_2	-9.0%	-1.6%	-3.9%

Table 15 shows that the total costs are less sensitive to changes in PBR costs than to changes in personnel costs. Nevertheless, the investment costs are even more sensitive to the PBR costs than the operating costs to the personnel costs. The operating costs also change as some costs items such as costs of capital and insurance costs are also affected by the change of investment costs, i.e. the PBR costs.

Table 16: Sensitivity analysis – Change of the biomass and hydrogen yield by ten percent[58]

	Production system	Unit	Construction phase	Use phase	Total
+10%	Biogas	EUR per MJ CH_4	-9.0%	-8.3%	-8.5%
	Hydrogen and biogas	EUR per MJ CH_4	-9.0%	-8.4%	-8.6%
	Hydrogen and biogas	EUR per MJ H_2	-16.7%	-17.0%	-16.9%
-10%	Biogas	EUR per MJ CH_4	11.0%	10.2%	10.4%
	Hydrogen and biogas	EUR per MJ CH_4	11.0%	10.1%	10.3%
	Hydrogen and biogas	EUR per MJ H_2	22.6%	22.9%	22.8%

Table 16 shows that the costs per unit energy do not change linearly proportional to a yield variation due to economies of scale – decreasing fixed costs per

[57] The change of the LCC results due to an increase of PBR costs is denoted in the upper part and the decrease in the lower part of the table.

[58] The change of the LCC results due to a yield increase is denoted in the upper part and the decrease in the lower part of the table.

energetic unit. The hydrogen yield is more significantly altered as the changes of the biomass yield and the hydrogen yield per unit biomass by ten percent each accumulate. The increase of investment costs, which are mainly fixed costs, is disproportionately large to the yield change – slightly for biogas production and significantly for hydrogen production – due to the economies of scale. The operating costs decline is disproportionately small as only some variable costs – e.g. fertilizer, CO_2, hydrogen recovery and storage – decline linearly with the yield decline. Personnel costs and other fixed costs stay mainly constant. The same holds for a yield increase. The results show that hydrogen production is more sensitive to changes of the yield parameters than biomass production, which can be also explained by the fact that the total hydrogen yield is significantly smaller than the biogas yield in the base case.

3.5 Scenario analysis

3.5.1 Scenario 2030 – Technology learning

Based on the results of the base case in chapter 3.3, the LCC results are projected to the year 2030 with experience curves. The cost share of the different technologies is indicated in Table 17, according to which the weighting of the cost reductions in Table 18 is determined. It can be observed that the highest costs reduction can be obtained for the PBR due to the expected significant increase of production facilities. The biogas plant cost reductions are the lowest due to the expected lower increase of production facilities as well as the regional limitation of technology learning – i.e. Europe. This reflects that biogas plants are at a mature development stage compared to the PBR and the hydrogen recovery technology.

Table 17: Cost share of technologies

Production system	Product	PBR	Hydrogen recovery	Biogas plant	Total costs
Biogas	MJ CH_4	98.9%	0.0%	1.1%	100%
Hydrogen and biogas	MJ CH_4	98.9%	0.0%	1.1%	100%
Hydrogen and biogas	MJ H_2	98.3%	1.7%	0.0%	100%

Table 18: Experience related cost reductions for the different technologies

Production system	PBR	Hydrogen recovery	Biogas plant
Cost reduction	-77.0%	-98.5%	-44.0%

To obtain the results of the LCC in Figure 12, the cost reductions as in Table 18 are first multiplied with the share on total LCC of the different technologies from Table 17. Secondly, the weighted cost reductions are subtracted from the results of the base case and adjusted by the yield increase described in 0. The projected market price for hydrogen in 2030 is ten to 15 US Dollar/GJ HHV (IEA 2007). The one for natural gas[59], which is taken due to the lack of projected market prices for biogas, is 11.6 US Dollar/GJ HHV – prices of 2009 – (IEA 2011). Both are about 0.01 Euro/MJ HHV each. The production costs of biogas from microalgae are about to exceed the market price for natural gas for biogas production by 13 to 16 times. The projected hydrogen production costs are the eightyfold of the projected market price.

[59] The price for biogas would be lower due to the fact that the HHV per volume biogas is lower. To obtain the quality of natural gas, cleaning of the biogas would be necessary, for example.

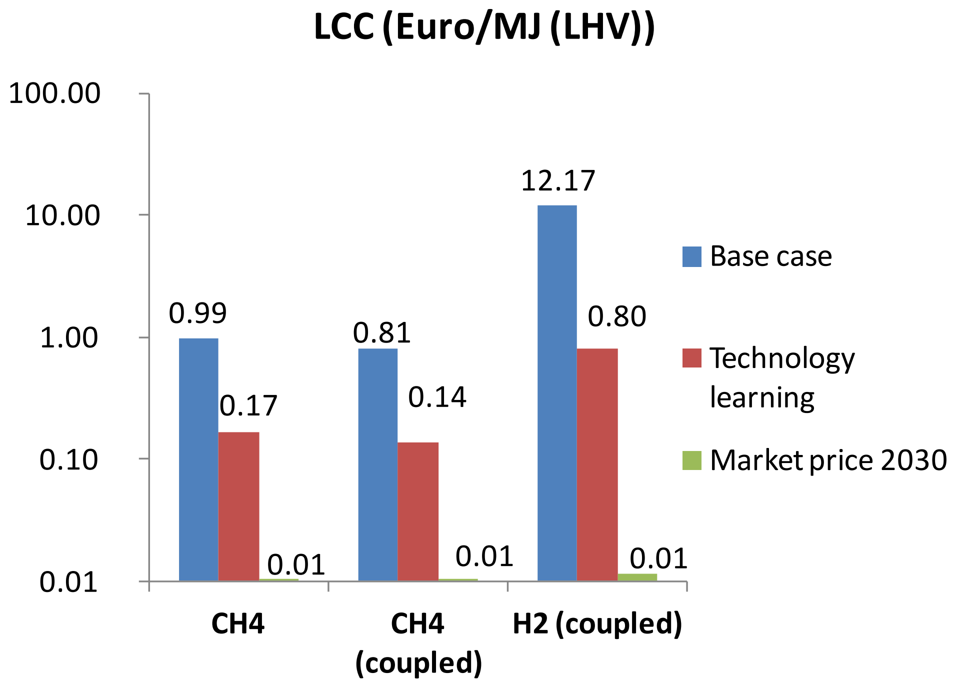

Figure 12: LCC results – Scenario 2030 – Technology learning[60]

Additionally, the impact of possible explanations for cost reductions described in chapter 2.3.1 is given. Here, the personnel costs, the yield increase due to an improved PCE bears the major quantifiable potential for cost reductions – see Table 19. The bundle of energy consumption reduction measures has the least cost reduction potential. Table 19 shows the potential of each measure if only one is applied. Such approach does not consider interactions between the measures. Therefore, these numbers are not cumulative. For example, the total yield increase after a cost reduction by a given percentage – e.g. a PCE increase from 3.65 to five percent for algal biomass production – is nominal less due to the lower cost basis used for calculation. Table 20 indicates the cumulative cost reductions, which are iteratively calculated from the top to the bottom line. The basis to calculate the cost reduction of one measure is the base case reduced by the above listed cost reduction positions. Due to the lower cost calculation basis, the yield increase cost reduction potential appears significantly lower than in the stand-alone case.

Nevertheless, named cost reduction categories could only be seen as possible explanations to allow an easier understanding of the concept of technology

[60] The market prices are given for the HHV as they are not available for the LHV in this study.

learning, but are not exhaustive – as seen in the category further reductions with a major share. In addition, this position is not to be seen as completely quantified. The named measures are only examples and either do not need to be realized or are realizable, but to a different extent. The concept of technology learning as a generic approach is not aiming at quantifying selected aspects and has the advantage to include unforeseeable improvements as well.

Table 19: Stand-alone cost reduction potential of single measures

Production system	**Biogas**	**Hydrogen and biogas**	**Hydrogen and biogas**
Unit	EUR per MJ CH_4	EUR per MJ CH_4	EUR per MJ H_2
Base case	**0.99**	**0.81**	**12.17**
Personnel	-0.20	-0.28	-2.90
No CO_2 cost	-0.02	-0.02	-0.11
CO_2 certificates	-0.06	-0.01	-
Energy consumption	-0.01	-0.02	-0.20
Yield increase	-0.12	-0.10	-9.44

Table 20: Cumulative cost reduction potential of measures

Production system	Biogas	Hydrogen and biogas	Hydrogen and biogas
Unit	EUR per MJ CH_4	EUR per MJ CH_4	EUR per MJ H_2
Base case	**0.99**	**0.81**	**12.17**
Personnel	-0.20	-0.28	-2.90
No CO_2 cost	-0.02	-0.02	-0.11
CO_2 certificates	-0.06	-0.01	0.00
Energy consumption	-0.01	-0.02	-0.20
Yield increase	-0.09	-0.06	-6.95
Further reductions	-0.61	-0.29	-1.22
Technology learning (LHV)	**0.17**	**0.14**	**0.80**
Technology learning (HHV)	**0.15**	**0.12**	**0.68**

3.5.2 Location change

First, the location change to Spain – precisely, Madrid – results due to higher incoming solar irradiation and more days with sufficiently warm temperatures in a yield increase by one third – compared with the base case in chapter 3.2.2 – and are displayed in Table 21.

Table 21: Energetic yields of hydrogen and biogas (location change)

Product system	Unit	Production cycle	Year
Biogas	MJ CH_4	26,700	961,197
Hydrogen and biogas	MJ CH_4	16,420	295,568
Hydrogen and biogas	MJ H_2	4,155	74,796

The yield increase is combined with adjusted prices for personnel and utilities, a newly scaled heat exchanger and pump as well as an increased cooling water and pumping energy requirement. Considering the named changes, the results in Table

22 are obtained. It shows an operating costs decline from the base case by about 51 and 53 percent for biogas respectively and by 64 percent for hydrogen – comparing Table 22 with Table 13. This decline is mainly attributable to the sharp decline of the personnel costs of about 50 percent and the additional yield increase of one third. Further important cost reductions arise from omitted wastewater discharge fees. The decline is even higher for hydrogen production as no costs for biogas production are included, which undergo a proportional increase of investment and operating costs with increasing biomass production. The yield increase does not directly result in a decline of the life cycle costs with a comparable percentage since investment costs only decline by 24 percent for exclusive biogas production and for coupled production, by 22 percent for biogas and by 42 percent for hydrogen production. The decline is attributable to the yield increase, but is also counteracted by the fact that some production equipment becomes more expensive due to a larger required capacity for equipment such as the pump for cooling or the biogas plant. Additionally, the share of variable costs, which rises with an increasing biomass yield, such as fertilizer and CO_2 counteract the cost reductions. The location change does not result in profitable hydrogen and biogas production from *C. reinhardtii* today if compared with the market prices in. Nevertheless, it allows for a cost reduction by about 50 percent of life cycle costs for both hydrogen and biogas production without any processing optimization, technological improvements or further genetic modification of *C. reinhardtii*.

Table 22: LCC results – Location change – construction and use phase

Production system	Unit	Construction phase	Use phase	Total
Biogas	EUR per MJ CH_4	0.22	0.34	0.56
Hydrogen and biogas	EUR per MJ CH_4	0.18	0.27	0.44
Hydrogen and biogas	EUR per MJ H_2	2.20	2.99	5.18

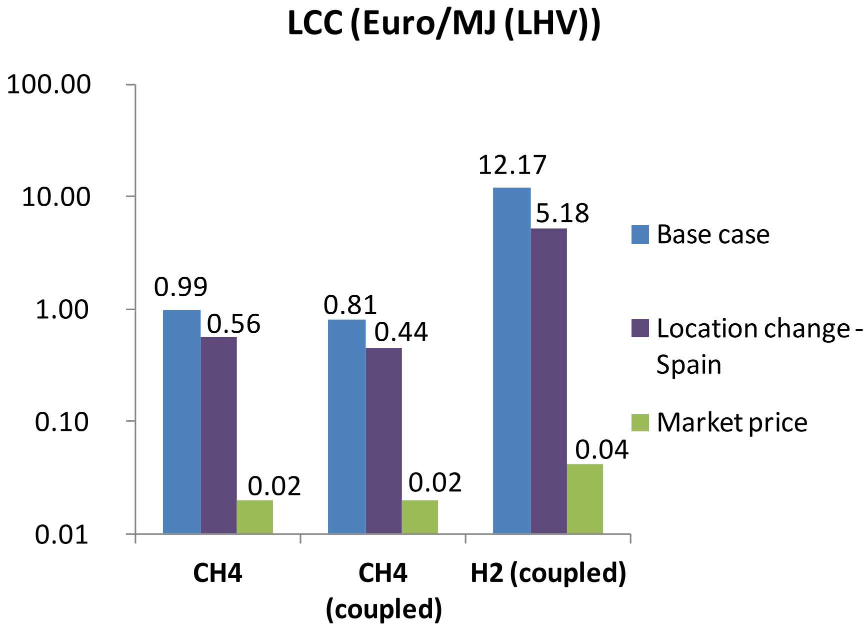

Figure 13: LCC results – Location change[61]

3.5.3 Hydrogen as a byproduct

The combined production of hydrogen and a HVP with an average price of 250 Euro is economically viable with possible additional costs – shown in Table 23. The indicated numbers show the possible additional hydrogen production costs that would be possible if the HVP and hydrogen together only need to be economically viable. The life cycle costs are obtained by subtracting the sales from a HVP and the current hydrogen price as indicated in chapter 3.3 from the hydrogen production costs.

Table 23: Additional max. life cycle costs for hydrogen production as byproduct of a HVP

Production system	Unit	Construction phase	Use phase	Total
Hydrogen	EUR per MJ H_2	41.54	101.76	143.30

The break-even point is a price of 25.58 Euro/kg DW algal biomass for the given hydrogen production system – described in chapter 2.2.3. This is the minimum

[61] The market prices are taken from the source already indicated in Table 13 in chapter 3.3. For the market price of biogas, the source does not indicate, whether the price is given for the HHV or the LHV. Additionally, this price is only valid for Germany, but no Spanish price is necessary as it is significantly exceeded.

price to be incurred from algal biomass for possible products associated to hydrogen production. It determines the product options for the subsidizing product. The option to use algae as animal feed is not economically viable as the price of algal biomass needs to meet 0.50 Euro/kg – explained in chapter 2.3.3, which is about two percent of the break-even price.

3.5.4 Break-even scenario

To determine necessary costs reductions for a *Break-even scenario*, a yield increase has been modeled. Figure 14 shows in the red column the life cycle costs per MJ (LHV) including an increase of the PCE from 3.65 percent to five percent for biomass production and from 0.29 to one percent for hydrogen production derived from the costs given for the base case – blue bar in Figure 14. The break-even point is met through a cost reduction of about 98.8 percent for biogas production and 99.6 percent for hydrogen production after considering the yield increase. The break-even points are the projected market prices for hydrogen and biogas in 2030 as indicated in chapter 2.3.1.

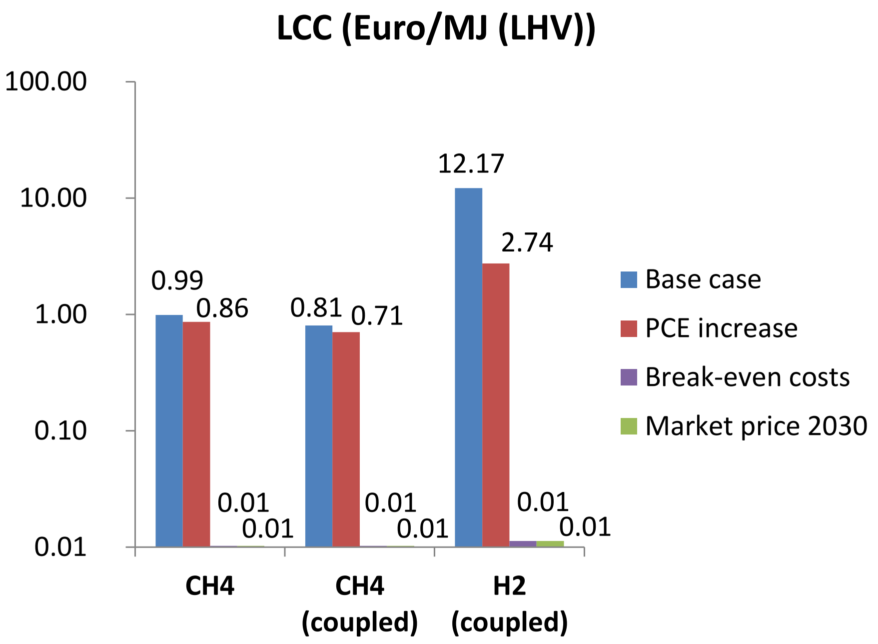

Figure 14: LCC results – Break-even scenario[62]

[62] The market prices are given for the HHV as data on the LHV were not available.

4 Discussion

4.1 General

The base case and the scenarios show that economic viability for exclusive energy production from *C. reinhardtii* – i.e. biogas and hydrogen – cannot be achieved under contemporaneous production circumstances in Germany. Future projections until 2030 show that for the German production setting the most favorable *Scenario 2030 – Technology learning* the break-even point is still exceeded for biogas production by about 15 times. The production costs for hydrogen would be still required to decline by about 80 times. Even if estimation errors[63] turned energy production more favorable and market prices for the LHV instead of the HHV were available, it would be very unlikely that this would result in the required decline of the life cycle costs per MJ – especially for hydrogen. This is especially attributable to the low photon conversion efficiency of hydrogen production compared with biomass production. This could also be seen if the energy conversion efficiencies for biomass production of 28 percent and for the coupled hydrogen and biomass production of ten percent are compared.

Concerning the results of the *Scenario 2030 – Technology learning*, it should be noted that the applied experience curves assume that five percent of total worldwide biofuels are derived from microalgae. Moreover, PBRs have a large share on total microalgae production facilities and an optimistic share of PBRs on total algal biofuels production was applied for the projection by 2030. The first assumption implies that microalgae undergo a breakthrough and the latter that PBR are at least equally competitive to open ponds for microalgae production. Both assumptions will not necessarily hold. Additionally, possible investment costs of the development phase as well as the decommissioning phase and possible

[63] For example, the typical error for estimating the investment costs with the factor method is – as indicated in chapter 1.4.2 – about 15 percent.

price changes have not been considered – e.g. an increase of utility prices and wages – that are likely to counteract the cost reduction due to technology learning.

The break-even scenario shows – after an increase of the PCE to the imaginable maximum – that a cost decline of biogas production costs to 1.1 and 1.3 percent respectively and for hydrogen to 0.4 percent of those in the base case is required, which is not realistic today and in the projection for 2030, but probably later.

Currently, the only viable way to produce hydrogen from an economic point of view is to produce it as a byproduct of a HVP, but not for products with a large market such as animal feed due to the too high production costs. Animal feed as a major product is unlikely to be economically successful in the modeled time frame until 2030 as under consideration of technology learning results a cost reduction below the required two percent of current costs by 2030 is unlikely to be achieved. For the suitable HVPs, it has to be considered that it is limited to the respective primary market, which is estimated to have an annual market volume for the whole range of products between 5,000 to 8,000 tons (Spolaore et al. 2006; Wijffels and Barbosa 2010). In addition, one has to consider that it is more favorable to produce biomass without hydrogen as both 50 percent of the biomass is respired during hydrogen production and only 50 percent of the production period can be used for biomass generation. Additionally, already the additional annual costs for the hydrogen recovery and storage equipment of about 44,000 EURO – see Table 27 – significantly outrun the additional sales from hydrogen of about 1,700 Euro[64]. A producer would prefer to produce a HVP or animal feed without hydrogen for costs of 13.07 Euro/kg algal biomass[65] instead of 106.70 Euro/kg[66]. Therefore, this option is unlikely to be set into practice without government intervention in favor of hydrogen production with a subsidizing product. As long as other options for sustainable hydrogen production are more profitable and associated with sufficiently large capacities such as alkaline

[64] The hydrogen sales are obtained by multiplying the hydrogen price of 0.04 Euro/MJ (LHV) – see chapter 3.3 – with the annual hydrogen production of 42,284 MJ – see Figure 9.

[65] This value obtained by dividing the annualized investment and operating costs for biomass production costs without hydrogen production equipment, which are indicated in Table 31 in Appendix I: Investment costs and in Table 35 in Appendix II: Operating costs , by the annual biomass production of 54 t DW algal biomass. 54 t DW algal biomass will result if the PBR volume of 250 m³ is multiplied with six production days per batch and a algal biomass production of one g DW /(l PBR*d). The parameters are indicated in chapter 2.2.8.

[66] This can be obtained by calculating the sum the market price of algal biomass for HVPs of 250 Euro/kg (Wijffels and Barbosa 2010) and the maximum additional possible life cycle costs for hydrogen production in Table 23.

electrolysis (Mansilla et al. 2012), hydrogen from algal biomass through direct biophotolysis is unlikely to be supported by the government.

The most important parameters to be considered to reduce production costs are the personnel costs, the PBR costs and the geographic location determining the yield. This could be seen for the scenario *Location change* to Spain with a costs reduction of about 50 percent. A similar production system and similar algae strains – i.e. similar PCE – would have biomass and hydrogen yields by about one third higher due to a higher solar irradiation as well as personnel costs of about 50 percent of those in Germany.

The unfavorable outcome of this study in relation to the economic viability is to some extent attributable to the novel PBR. Apart from the ideal light provision, the aim of the PBR design is to reduce energy consumption rather than to minimize production costs (Posten et al. 2011). The PBR in this study has a large material to culture volume ratio and is covered by a membrane on 50 percent of the lower surface. The increased material requirement, the dependent manufacturing costs and the use of expensive membranes instead of other materials turn the PBR of this project much more expensive than other designs.[67] The increased PBR costs outrun the reduced energy consumption for aeration by far.[68] Nevertheless, this does not change the fact that biogas and hydrogen from microalgae grown in PBRs is not economically viable as can be seen in the comparison with other studies in the next subchapter, which either have comparable results or are nearly economically viable due to very favorable assumptions. This PBR design might rather result in the fact that the break-even point with this PBR design is less likely to be met than with low-cost PBR options.

Within this study, only the economic perspective of sustainability is considered. Whether environmental sustainability is given would require a comparison with other biofuel sources by a LCA for the specific products – i.e. hydrogen and

[67] This is supported by the fact that the membrane covers only 50 percent of the lower surface of the PBR, but amounts to 76 percent of the material costs, whereas the remaining 75 percent of culture medium containing walls from PET amount to only ten percent of material costs. Additionally, membranes are expected to require more maintenance than PBR walls from PET.

[68] Norsker at al. (2011) estimate costs for power consumption for algal biomass production in a tubular PBR – PBR production technology with the highest power consumption (Posten 2009) – of about 0.06 Euro/kg DW algal biomass and PBR costs of 0.13 Euro/kg DW algal biomass. We obtain 0.0035 Euro/kg DW algal biomass for CO_2 pumping and PBR costs of 1.90 Euro/kg DW algal biomass by dividing the cost items, which are indicated in Table 31 in Appendix I: Investment costs and in Table 35 in Appendix II: Operating costs, by the annual biomass production of 54 t DW algal biomass. 54 t DW algal biomass will result if the PBR volume of 250 m³ is multiplied with six production days per batch and an algal biomass production of one g DW/(l PBR*d). The parameters are indicated in chapter 2.2.8.

biogas from microalgae – in comparison to fossile fuels and other biofuels. An overall sustainability assessment through a cost-benefit analysis, which includes private – i.e. production costs in this study –, environmental and social costs, would allow to compare the outcome in the different sustainability categories. Relevant social costs might arise from other energy production options and compared to which algal biomass could be favorable. It has been shown that biodiesel production from rapeseeds is expected to lead to an increase in food prices due to the competition for arable land with food crops (Kovacevic and Wesseler 2010). Here, microalgae are advantageous as they could be grown on any kind of land if the required utilities can be provided and the terrestrial as well as environmental conditions allow production (Duffy et al. 2009).

4.2 Comparison with existing studies

The two existing economic studies for photobiological hydrogen production show significantly lower prices for hydrogen production of 15 US Dollar/GJ (Tredici, Zittelli, and Benemann 1999) and 13.53 US Dollar/kg (Wade 2004). For the former, the difference of the results of this study is to a large extent attributable to the very favorable PCE of ten percent for photobiological hydrogen production in the form of direct biophotolysis, but this PCE is more likely to be obtained, if algal biomass is grown photoautotrophically and afterwards hydrogen is produced by fermenting algal biomass – indirect biophotolysis (Hallenbeck and Benemann 2002). Optimistic studies expect a PCE of one percent for photobiological hydrogen production with *C. reinhardtii* (Kruse, Rupprecht, Mussgnug, et al. 2005). In this study it is 0.29 percent in the base case. With a PCE of ten percent – neglecting the increase of total direct costs –, this study would yield life cycle costs of about 40 Euro/GJ. The study by Wade (2004) assumes a production rate of hydrogen of about 1200 to 1300 ml H_2/(g DW algal biomass*d)[69], which is more than 50 times the currently achieved yield of 24 ml/(g DW algal biomass*d) (Kim et al. 2010). Additionally, no costs for the generation of biomass are considered and year-round production of hydrogen is assumed, with one third of the staff for 44 times the PBR volume of this study. PBR costs of ten US Dollar/m² are named, which cannot not be attained for a membrane reactor such as the one in this study. Other studies have shown that costs for a simple flat plate

[69] This is obtained by using the parameters indicated by Wade (2004): A production rate of 300 kg/d for a PBR volume of 11,000 m³ and biomass concentration of 0.2 g/l. A production period of 12 hours per day in accordance with the light-dark cycle is assumed.

PBR are about 3,000 Euro/m³ (Posten 2009), which would be about 75 Euro/m² for the 25 l/m² PBR module in this study. This value does not include any membrane costs as well as higher material requirements due to the comparably thin culture film in the PBR in this study. This shows that the estimated PBR costs of 103 Euro/m² in this study are rather optimistic.

A comparison for biogas production costs from microalgae is not possible due to the lack of another study. Nevertheless, the biomass production costs can be compared. A production site for Dutch conditions – Eindhoven – of one ha and with a mostly comparable PBR type – flat plate –, costs of 10.49 Euro/kg DW algal biomass are obtained (Norsker et al. 2011), whereas costs of algal biomass 13.07 Euro/kg DW are estimated in this study. The remaining difference can be explained to a large extent by the personnel costs, which are assumed to be about two thirds of those in this study.

4.3 Data and modeling

Most of the parameters are either identified at laboratory scale or even no experiments have been conducted. Those are especially yield parameters such as the PCE, hydrogen yield per dry weight algal biomass as well as the production days per year. All of the parameters do not need to hold for large scale production sites. Nevertheless, the *Break-even scenario*, the scenario *Location change* and the sensitivity analyses have shown that even the high sensitivity of the LCC results to yield changes will not change the fact that economic viability for hydrogen and biogas production is currently by far not achievable.

The same holds for assumptions on the PBR such as the one that 25 percent of the PBR material costs would cover the manufacturing of the PBR modules as well as the price and the required properties of membrane modules for PBR aeration. Nevertheless, the decision is not taken yet, which kind of polymer will be taken (Lehr et al. 2011) and therefore a higher accuracy will be possible only if a decision on it is taken.

Apart from the sensitivity analysis, the sensitivity of life cycle costs to gross labor costs has been shown in the scenario *Location change* with 50 percent of gross labor costs compared with the base case. Both additional analyses have demonstrated that the determination of personnel costs is of major importance for the reliability of the life cycle costs due to the high sensitivity. For current life cycle costs, it is not crucial as economic viability is not achievable by far. For future projections, it could be seen that the assumption on the personnel costs is very crucial next to the yield assumptions as exclusive biogas production could be economically viable by 2030.

A further issue of uncertainty is, whether the chosen set-up provides sufficiently sterile conditions. This could largely affect the biomass and hydrogen yield. Some studies propose to use sterilization and filtering equipment to reduce pathogens and to remove accumulated organic products generated by the algae biomass, which inhibit algal biomass growth (Williams and Laurens 2010; Pienkos and Darzins 2009; Lívanský et al. 1996). Within this study, no equipment for sterilization is considered, but a frequent renewal of the culture medium and a cleaning day per batch are included, which are expected to provide sufficiently sterile growth conditions. This assumption still requires further experimental tests at field scale. Therefore, it cannot be deduced whether the chosen proceeding provides adequate growth conditions and whether regular culture renewal or sterilization is the more cost-effective option.

The assumptions made on the biogas reactor to use only a share of the total biogas reactor is reasonable from both an economic – constant use to full capacity – and a processing perspective. Concerning the processing, only co-digestion of algal biomass with e.g. maize as commonly done for manure instead of algal biomass allows to obtain an optimal C/N ratio and a sufficiently high organic loading rate. Due to the minor share on annualized investment and annual operating costs of about one percent for both, taking the cost estimate from another study with price adjustments in this study is sufficient.

Further assumptions made on utilities include the digestate composition are less crucial as they only have a minor share of operating costs of eight percent, which is about two percent in life cycle costs. For example, the excess application of nutrients was not justifiable through laboratory experiments or the assumption that nutrient prices for Germany are also valid for Spain. Additionally, similar nutrient recovery rates per unit biomass have been assumed for different algal biomass compositions – varied in form of different fatty acid compositions. Similarly, the fluid mechanics of the PBR could not be accurately considered as the PBR design – apart from a laboratory model from different materials than assumed in this study for field application, i.e. PMMA instead of PET, and without a membrane – has not been set into practice. Instead the equipment sizing is mainly based on the characteristics of a flat plate PBR, which is the most comparable to the one in this study. Since this only affects the pump sizing and the related investment costs, which amount to less than one percent of annualized investment costs, as well as the energy consumed, which amounts to about two percent of operating costs, the related inaccuracies could only insignificantly alter the LCC results.

The choice of system boundaries always provides some potential for discussion. Nevertheless, the focus on the production site and the exclusion of any transport costs should not be seen as an important trade-off of this study. Neither the transport of the final energy carrier nor the delivery of utilities differ from other renewable energy production options and do not provide a large optimization potential as those processes are at a mature stage. The current study might need to be extended by the costs for the development and the decommissioning phase if in the future further information on the research and development costs for the manufacturers is available or reasons arise that the share of decommissioning costs on life cycle costs will become more significant than expected today.

5 Conclusions

The environmental life cycle costs of hydrogen and biogas production from the microalgae species *C. reinhardtii* for a novel PBR design from a producer perspective have been determined, which was the major goal of this study. Apart from the base case, which already reveals the major cost drivers – personnel costs and PBR costs – for the production of both biofuels, prospective and current scenarios were calculated, which allowed studying the sensitivity of production costs to different settings. Additionally, sensitivity analyses for the major cost drivers have been conducted to test the robustness of the results. Exact numbers are associated with uncertainty due to the early stage of the concept for the production facility and the resulting necessity to use investment costs estimation methods and further assumptions. Despite this uncertainty, it can be inferred from the results of this study that exclusive biogas production is not economically viable for a German setting today and by 2030. This is also to be said for coupled hydrogen and biogas production, where the economic viability for hydrogen production is significantly less likely.

Currently, the break-even point for hydrogen production can only be met for a coupled production of hydrogen and a high-value product due to the large gap to economic viability in all scenarios. But it has to be kept in mind that the economic viability for any of both subsidizing products is only obtained on the cost of a reduced return on the subsidizing products, which is unlikely to be set into practice without government intervention, which is even not very likely either.

The following conclusions drawn from this study should be taken into account in future research:

a. Highly automated production process

The major cost driver is – as mentioned above – the personnel costs. They increase the more sophisticated and the less automated a production facility is because, first, more qualified staff is needed and secondly, the number of FTE per biomass production facility increases. To avoid this, both highly automated production equipment should be used and materials such as membranes, which require regular manual cleaning, should be avoided.

b. Use of low-cost PBR material and simple manufacturing

Concerning the investment costs, the PBR could be identified as the major cost driver. Therefore, the major improvement effort apart from further automation of the production process should focus this direction as the life cycle costs are highly sensitive to this investment cost item.

c. Choice of production location

The scenario *Location change* has shown that the use of a similar production system allows in a climatic and economically more favorable surrounding for cutting production costs per energy unit by nearly 50 percent. Future research and construction projects of biomass production facilities should therefore compare different climatic conditions and factor prices of major cost drivers in different countries or regions, i.e. gross labor costs for the production system in this study, before a production location is chosen.

d. Optimization of production equipment should not solely focus on the energy balance in the use phase

The PBR design should minimize the energy consumed by culture processing, i.e. circulation and aeration (Posten et al. 2011), but does neither consider the economics nor the energy consumed for the manufacturing of the PBR, which deteriorate the more the material consumption per culture volume increases.

e. Consideration of the trade-off between economic and social sustainability

The indicated results show exclusive energy production from microalgae is not profitable, but even the environmentally LCC approach does not indicate, whether the production of hydrogen and biogas from microalgae is more sustainable than other biofuel sources from an environmental perspective. This trade-off will be further treated in an accompanying LCA that is currently developed. A simultaneous consideration of the three dimensions of sustainability is only given in one cost-benefit analysis for biodiesel production from microalgae (Kovacevic and Wesseler 2010). It should be complemented by the treated energy carriers in this study and compared with alternative production options of hydrogen and biogas.

Despite the fact that the life cycle costs of biogas and hydrogen from microalgae could be quantified, the results of this study should not be taken as the actual costs at which hydrogen or biogas from microalgae would be marketed. It is rather to be seen as an economic evaluation of a production system at an early development stage of a specific PBR and production setting with the associated uncertainties. More important is to consider from this study, which hot spots future research should target to approach economic viability of hydrogen and biogas from microalgae grown in PBRs and whether, when or under which conditions, it will be realistic to use microalgae for the named purpose.

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Appendix I: Investment costs

Table 24: Total investment costs (biogas)

	Production equipment	Costs in EUR	Scaling factor	Capacity	Unit
1	Photobioreactor	1,026,669	10,000	250	m³
2	Culture medium preparation unit	36,379	6.1	33	m³/h
3	Culture medium feed pump	6,753	1.0	13	m³/h
4	Carbon dioxide supply station	4,871	1.3	38	kg/h
5	Cooling system	879	25	25	m²
7	Pump for cooling system	2,323	0.4	4	m³/h
7	Centrifuge	19,151	0.1	1.5	m³/h
8	Centrifuge feed pump	1,207	0.2	1.7	m³/h
12	Biogas plant	12,660	94	94	m³
	Subtotal	*1,110,891*			

Other investment costs	Costs in EUR
Buildings	351,026
Control unit	164,735
Piping	219,646
Installation costs	329,469
Land leasing costs	153
Cost of capital	73,981
Subtotal	*1,139,010*
Total	**2,249,901**

Table 25: Depreciation – Annualized investment costs (biogas)

	Production equipment (in EUR)	Lifetime 10y	Lifetime 20y	Depreciation	Share
1	Photobioreactor	1,026,669	-	102,667	49.6%
2	Culture medium preparation unit	36,379	-	3,638	1.8%
3	Culture medium feed pump	6,753	-	675	0.3%
4	Carbon dioxide supply station	4,871	-	487	0.2%
5	Cooling system	879	-	88	0.0%
6	Pump for cooling system	2,323	-	232	0.1%
7	Centrifuge	19,151	-	1,915	0.9%
8	Centrifuge feed pump	1,207	-	121	0.1%
12	Biogas plant	12,660	-	1,266	0.6%
	Subtotal	*1,110,891*	-	*111,089*	*54%*

Other investment costs (in EUR)	Lifetime 10y	Lifetime 20y	Depreciation	Share
Buildings	-	351,026	17,551	8.5%
Control unit	164,735	-	16,473	8.0%
Piping	219,646	-	21,965	10.6%
Installation costs	329,469	-	32,947	15.9%
Land leasing costs	153	-	15	0.0%
Cost of capital	62,046	11,935	6,801	3.3%
Subtotal	*776,049*	*362,961*	*95,753*	*46%*
Annual depreciation			**206,842**	**100%**

Table 26: Total investment costs (hydrogen and biogas) – Hydrogen

	Production equipment	Costs in EUR	Scaling factor	Capacity	Unit
1	Photobioreactor	1,026,669	10,000	250	m^3
2	Culture medium preparation unit	36,379	6.1	33	m^3/h
3	Culture medium feed pump	6,753	1.0	13	m^3/h
4	Carbon dioxide supply station	4,871	1.3	38	kg/h
5	Cooling system	879	25	25	m^2
6	Pump for cooling system	2,323	0.4	3.8	m^3/h
7	Centrifuge	10,625	0.1	0.7	m^3/h
8	Centrifuge feed pump	588	0.1	0.7	m^3/h
9	Hydrogen recovery	3,852	0.02	0.3	kg H2/h
10	Storage compressor	15,519	0.03	2.0	Mpa
11	High-pressure storage	24,514	0.03	13	kg H_2
	Subtotal	*1,132,971*			

Other investment costs	Costs in EUR
Buildings	339,891
Control unit	169,946
Piping	226,594
Installation costs	339,891
Land leasing costs	153
Cost of capital	75,121
Subtotal	*1,151,596*
Total	**2,284,566**

Table 27: Depreciation – Annualized investment costs (hydrogen and biogas) – Hydrogen

	Production equipment (in EUR)	Lifetime 10y	Lifetime 20y	Depreciation	Share
1	Photobioreactor	1,026,669	-	102,667	48.7%
2	Culture medium preparation unit	36,379	-	3,638	1.7%
3	Culture medium feed pump	6,753	-	675	0.3%
4	Carbon dioxide supply station	4,871	-	487	0.2%
5	Cooling system	879	-	88	0.0%
6	Pump for cooling system	2,323	-	232	0.1%
7	Centrifuge	10,625	-	1,062	0.5%
8	Centrifuge feed pump	588	-	59	0.0%
9	Hydrogen recovery	3,852	-	385	0.2%
10	Storage compressor	15,519	-	1,552	0.7%
11	High-pressure storage	24,514	-	2,451	1.2%
	Subtotal	*1,132,971*	-	*113,297*	*54%*

Other investment costs (in EUR)	Lifetime 10y	Lifetime 20y	Depreciation	Share
Buildings	-	339,891	16,995	8.1%
Control unit	169,946	-	16,995	8.1%
Piping	226,594	-	22,659	10.7%
Installation costs	339,891	-	33,989	16.1%
Land leasing costs	153	-	15	0.0%
Cost of capital	63,565	11,556	6,934	3.3%
Subtotal	*800,148*	*351,447*	*97,587*	*46%*
Annual depreciation			**210,884**	**100%**

Table 28: Total investment costs (hydrogen and biogas) – Biogas

	Production equipment	Costs in EUR	Scaling factor	Capacity	Unit
12	Biogas plant	3,165	23	23	m^3
	Subtotal	*3,165*			

Other investment costs	Costs in EUR
Buildings	5,389
Cost of capital	291
Subtotal	*5,680*
Total	**8,845**

Table 29: Depreciation – Annualized investment costs (hydrogen and biogas) – Biogas

Production equipment (in EUR)	Lifetime 10y	Lifetime 20y	Depreciation	Share
12 Biogas plant	3,165	-	317	52.2%
Subtotal	*3,165*	-	*317*	*52%*
Other investment costs (in EUR)	**Lifetime 10y**	**Lifetime 20y**	**Depreciation**	**Share**
Buildings	-	5,389	269	44.5%
Cost of capital	108	183	20	3.3%
Subtotal	*108*	*5,572*	*289*	*48%*
Annual depreciation			**606**	**100%**

Table 30: Total investment costs (biomass)

Production equipment	Costs in EUR	Scaling factor	Capacity	Unit
1 Photobioreactor	1,026,669	10,000	250	m^3
2 Culture medium preparation unit	36,379	6.1	33	m^3/h
3 Culture medium feed pump	6,753	1.0	13	m^3/h
4 Carbon dioxide supply station	4,871	1.3	38	kg/h
5 Cooling system	879	25	25	m^2
6 Pump for cooling system	2,323	0.4	4	m^3/h
7 Centrifuge	19,151	0.1	1.5	m^3/h
8 Centrifuge feed pump	1,207	0.2	1.7	m^3/h
Subtotal	*1,098,231*			

Other investment costs	Costs in EUR
Buildings	329,469
Control unit	164,735
Piping	219,646
Installation costs	329,469
Land leasing costs	153
Cost of capital	72,818
Subtotal	*1,116,290*
Total	**2,214,521**

Table 31: Depreciation – Annualized investment costs (biomass)

Production equipment (in EUR)	Lifetime 10y	Lifetime 20y	Depreciation	Share
1 Photobioreactor	1,026,669	-	102,667	50.2%
2 Culture medium preparation unit	36,379	-	3,638	1.8%
3 Culture medium feed pump	6,753	-	675	0.3%
4 Carbon dioxide supply station	4,871	-	487	0.2%
5 Cooling system	879	-	88	0.0%
6 Pump for cooling system	2,323	-	232	0.1%
7 Centrifuge	19,151	-	1,915	0.9%
8 Centrifuge feed pump	1,207	-	121	0.1%
Subtotal	*1,098,231*	-	*109,823*	*54%*

Other investment costs (in EUR)	Lifetime 10y	Lifetime 20y	Depreciation	Share
Buildings	-	329,469	16,473	8.1%
Control unit	164,735	-	16,473	8.1%
Piping	219,646	-	21,965	10.7%
Installation costs	329,469	-	32,947	16.1%
Land leasing costs	153	-	15	0.0%
Cost of capital	61,616	11,202	6,722	3.3%
Subtotal	*775,619*	*340,671*	*94,595*	*46%*
Annual depreciation			**204,419**	**100%**

Appendix II: Operating costs

Table 32: Annual operating costs (biogas)

Utilities	Costs in EUR	Share	Amount	Unit
Culture water	5,901	1.2%	3,537	m³
Cooling water	219	0.0%	131	m³
Fertilizer N	7,366	1.5%	4.9	t
Fertilizer P2O5	5,162	1.0%	2.8	t
Digestate sales N	- 4,062	-0.8%	2.7	t
Digestate sales P205	- 3,489	-0.7%	1.9	t
Electricity	10,262	2.0%	91,541	kWh
Heat	1,452	0.3%	33,922	kWh
CO2	17,885	3.5%	97	t
Subtotal	*40,696*	*8.0%*		

Other	Costs in EUR	Share	Amount	Unit
Labor	242,704	47.9%	3.1	FTE
Overhead	133,487	26.3%		
Maintenance	44,568	8.8%		
Land leasing costs	153	0.0%	1.3	ha
Insurance	1,241	0.2%		
Cost of capital	35,163	6.9%		
Wastewater discharge	8,680	1.7%	3,669	m³
Subtotal	*465,996*	*92.0%*		
Total	**506,692**	**100%**		

Table 33: Annual operating costs (hydrogen and biogas) – Hydrogen

Utilities	Costs in EUR	Share	Amount	Unit
Culture water	2,727	0.6%	1,634	m^3
Cooling water	219	0.0%	131	m^3
Fertilizer N	3,683	0.8%	2.5	t
Fertilizer P2O5	2,581	0.5%	1.4	t
Electricity	5,479	1.1%	48,879	kWh
CO2	8,942	1.9%	49	t
Subtotal	*23,632*	*4.9%*		

Other	Costs in EUR	Share	Amount	Unit
Labor	237,513	49.4%	3.0	FTE
Overhead	130,632	27.2%		
Maintenance	47,145	9.8%		
Land leasing costs	153	0.0%	1.3	ha
Insurance	1,265	0.3%		
Cost of capital	35,850	7.5%		
Wastewater discharge	4,178	0.9%	1,766	m^3
Subtotal	*456,736*	*95.1%*		
Total	**480,368**	**100%**		

Table 34: Annual operating costs (hydrogen and biogas) – Biogas

Utilities	Costs in EUR	Share	Amount	Unit
Digestate sales N	- 680	-34.8%	0.5	t
Digestate sales P205	- 536	-27.5%	0.3	t
Electricity	564	28.9%	5,029	kWh
Heat	363	18.6%	8,481	kWh
Subtotal	*- 289*	*-14.8%*		

Other	Costs in EUR	Share	Amount	Unit
Labor	1,298	66.5%	0.02	FTE
Overhead	714	36.6%		
Maintenance	122	6.2%		
Insurance	4	0.2%		
Cost of capital	103	5.3%		
Subtotal	*2,240*	*114.8%*		
Total	**1,951**	**100%**		

Table 35: Annual operating costs (biomass)

Utilities	Costs in EUR	Share	Amount	Unit
Culture water	5,901	1.2%	3,537	m^3
Cooling water	219	0.0%	131	m^3
Fertilizer N	7,366	1.5%	4.9	t
Fertilizer P2O5	5,162	1.0%	2.8	t
Electricity	8,007	1.6%	91,541	kWh
CO2	17,885	3.6%	97	t
Subtotal	*44,540*	*8.9%*		

Other	Costs in EUR	Share	Amount	Unit
Labor	237,513	47.4%	3.0	FTE
Overhead	130,632	26.0%		
Maintenance	44,081	8.8%		
Land leasing costs	153	0.0%	1.3	ha
Insurance	1,227	0.2%		
Cost of capital	34,751	6.9%		
Wastewater discharge	8,680	1.7%	3,669	m^3
Subtotal	*457,036*	*91.1%*		
Total	**501,577**	**100%**		

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