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Life cycle costs for the optimized production of hydrogen and biogas from microalgae

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A B S T R A C T

Despite the known advantages of microalgae compared with other biomass providers or fossil fuels, microalgae are predominately produced for high-value products. Economic constraints might limit the commercial energetic use of microalgae. Therefore, we identify the LCCs (life cycle costs) and economic hot spots for photoautotrophic hydrogen generation from photoautotrophically grown *Chlamydomonas reinhardtii* in a novel staggered PBR (photobioreactor) and the anaerobic digestion of the residual biomass to obtain biogas. The novel PBR aims at minimizing energy consumption for mixing and aeration and at optimizing the light conditions for algal growth.

The LCCs per MJ amounted to 12.17 Euro for hydrogen and 0.99 Euro for biogas in 2011 for Germany. Market prices per MJ of 0.02 Euro for biogas and 0.04 Euro for hydrogen are considerably exceeded. Major contributors to operating costs, about 70% of total LCCs, are personnel and overhead costs. The investment costs consist to about 92% of those for the PBR with a share of 61% membrane costs. The choice of Madrid as another production location with higher incident solar irradiation and lower personnel costs reduces LCCs by about 40%. Projecting LCCs to 2030 with experience curves, the LCCs still exceed future market prices.

1. Introduction

Microalgae are cultivated for various purposes. These include food and feed provision, fine and bulk chemicals, wastewater treatment as well as energy production [1,2]. The energetic use of microalgae has been considered for the following reasons:

- High growth rates, when CO_2 is added
- CO_2 recycling and reuse of CO_2-containing flue gases [3]
- High energy content [4]
- No competition for fertile land with food crops [5]
- Simultaneous use of wastewater as fertilizer free of charge and use of microalgae as wastewater treatment [6]
- Large potential for genetic modifications for yield optimization or adaptation to environmental conditions [7,8]

Energy production has been investigated to a large extent with a focus on biomass, biodiesel, biogas or hydrogen production [9]. An advantage of hydrogen is that it can be produced photoautotrophically by direct biophotolysis from the algal biomass [10,11] so that energy-intensive downstream processing such as purification becomes obsolete [12]. Direct biophotolysis under sulfur deprivation is also more economically favorable than washing the algal culture with acetate addition [13]. The remaining biomass may be used to produce biogas in order to enhance the energetic output and save cost [14]. Ni et al. [15] argue that hydrogen from living algal biomass may be economically competitive with other technologies for hydrogen production such as electrolysis fed by wind power. Other combined production options such as hydrogen and biodiesel are not promising. Differing preferable cultivation conditions such as nutrient deprivation for a high lipid content for biodiesel [16] or sulfur deprivation for direct biophotolysis of hydrogen [11] are contradictory. In addition,

Abbreviations: C/N, carbon-to-nitrogen ratio; DW, dry weight; LCI, economic life cycle inventory; HVP, high-value product; LCC, life cycle cost; PMMA, poly(methyl methacrylate); PBR, photobioreactor; PCE, photon conversion efficiency; PET, poly(ethylene terephthalate); TS, total solids; VS, volatile solids; FTE, full-time equivalent.

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photobiological hydrogen requires closed PBRs (photobioreactors), which are more expensive than other options for algal species for oil production [17].

The combined photobiological hydrogen production and the use of the residuals for anaerobic digestion have not been investigated in other economic studies [18]. More important, the existing studies on photobiological hydrogen do not consider all input cost. For example, they did not include cost for utilities such as nutrients or water [19], the anaerobic hydrogen production phase [20] or investment costs for gas handling [21–24]. For other biofuels from microalgae, several economic studies exist, e.g. focusing on algal oil for biodiesel [25] or assessing the costs of microalgal production systems combining biodiesel and biogas as final or at least intermediate products [26,27].

The cost of all utilities and supplies including investment costs can be assessed with the method of life cycle costing. This study identifies the LCCs (life cycle costs) and economic hot spots for hydrogen and biogas production from microalgae, species *Chlamydomonas reinhardtii*.

2. Material and methods

2.1. Life cycle costing

2.1.1. Goal and scope definition

We assess the LCCs of exclusive biogas production (in the following abbreviated as "biogas") and of coupled hydrogen and biogas production (in the following abbreviated as "H_2 + biogas") for a German production location. The functional unit is one MJ of the produced fuel. Scenarios are calculated to investigate the production system in different environmental and economic contexts and for different points in time. In that way, this study answers the question under which conditions hydrogen and biogas could be produced at (or below) market prices and how production costs can be reduced.

2.1.2. System boundaries and processes

For the calculation of the LCCs, the following general assumptions were made:

- All input factors (water, nutrients, cleaning utilities, electric power, heat, land) are bought and not generated within the system.
- Byproducts and waste are either recycled or disposal costs are considered.

Biogas is produced as follows: First, *C. reinhardtii* species are cultivated in PBRs. The biomass is then harvested and converted to biogas by anaerobic digestion in a biogas reactor with the digestate as a byproduct.

H_2 + biogas are produced as follows: *C. reinhardtii* species are again cultivated in the PBR. The culture is then turned into anaerobic conditions so that the green algae starts to produce hydrogen. The hydrogen is then compressed for storage and transport. The residual biomass is harvested and digested to generate biogas [28] analog to above. The processes are outlined in Fig. 1.

Purification of hydrogen or biogas is not included. Photobiologically produced hydrogen has typically a purity of 98% and does not need to be purified [12]. Biogas is assumed to be sold without further purification [29] and thus at a lower market price than purified biogas.

2.1.3. Cost calculation methods

2.1.3.1. Investment cost estimation. Based on major processes and equipment, we estimate the investment costs with the factor method [30]. Specifically, we determine major equipment investment costs and apply installation subfactors, obtained from several other literature studies for algal biomass production in PBRs [31–33] and biogas production [34,35]. We do not estimate costs at a more detailed level as the intended production system is not marketable yet. Some production equipment such as the PBR is only available for laboratory applications and the final set up at production scale cannot be realized yet. The investment costs are annualized to create a common basis within the different lifetimes of production and supporting equipment. Annualizing costs is also necessary to set them in relation to the use-related costs and yields, which are both calculated on an annual basis.

2.1.3.2. Scaling of major equipment. The costs for the equipment are related to a capacity and must be adjusted to the capacity required in this study. This can be done with equation (1) using an exponential scaling factor *n* [36].

$$\text{Investment costs}_{\text{scaled}} = \text{Investment costs}_{\text{original}} * \left(\frac{\text{Size}_{\text{scaled}}}{\text{Size}_{\text{original}}}\right)^{n} \quad (1)$$

For PBR-related production equipment, *n* is 0.85 [31], for hydrogen recovery, compression and storage *n* is 0.8 [37].

2.1.3.3. Cost allocation for H_2 + biogas production. H_2 + biogas production requires a method to allocate the costs to each product. Biomass growth is necessary for both biogas and hydrogen production. We assume that hydrogen is the main product. Biogas is a byproduct that uses the residual biomass. Investment and operating costs were hence attributed to hydrogen production in a first step. We only exclude those costs that can be directly related to biogas such as the costs for the biogas plant. The costs for algal biomass from the case biogas are allocated to the hydrogen production costs. The costs are separately allocated for the construction and the use phase.

2.1.3.4. Temporal and regional adjustments. All prices are harmonized with prices of 2011. We primarily focus on Germany and therefore adjust the cost items with inflation rates from the Federal Statistical Office of Germany. Personnel, utility and PBR costs are taken from German data sources or are estimated for a German setting. Investment costs were not locally adjusted to Germany as the data are mainly taken from other studies in the EU without major market price differences. We adjust producer-related cost items such as equipment with the producer price indices [38]. For labor costs, we use the labor cost index [39]. The average annual exchange rate [40] is used to convert data denoted in US Dollar into Euro.

3. Economic life cycle inventory

The LCI (economic life cycle inventory) describes the production processes included in the system boundaries, see chapter 2.1.1. The LCI is typically divided into the four life cycle phases: development, construction, use and decommissioning. We assess data for the construction and the use phase which are the major cost-producing phases. Costs for research and development were not included. Costs of the dismantling phase of the production facilities after 10 or 20 years respectively are not considered since the respective costs are expectedly negligible compared with the costs of other life cycle phases analog to another microalgal biomass production system [41].