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Life Cycle Analysis of Hydrogen Production from Biomass Fermentation

Dominik Ochs*, Werner Ahrer
PROFACTOR GmbH, Dept. Innovative Energy Systems, Im Stadtgut A2
4407 Steyr/Gleink, Austria
dominik.ochs@profactor.at

The environmental impact of hydrogen production from potato steam peels was identified. Based on the ISO 14040, ISO 14044, ecoinvent data base and SimaPro 7.1 software, a life cycle inventory analysis was performed. Reflecting the current state of process development, the LCA shows an impact of 4.3 points (pts) which is at least 5.7 times higher than the selected reference technologies regarded as state-of-the-art. Over half (53.5%) of the environmental impact is generated by the use of phosphate in fermentation processes. A sensitivity analysis shows a potential impact reduction of 65.8% due to recirculation of sewage or reduction of buffer concentration. The analysis also demonstrates that the production of the process ingredients cause 98.3% of the environmental impact. The impact of the process itself is 0.07 pts which is up to 10 times lower than the reference technologies.

1. Introduction

The non-thermal production of hydrogen from biomass is currently under investigation within the EU FP6 project: HYVOLUTION. The HYVOLUTION process starts with the conversion of biomass to make a suitable feedstock for the following bioprocess, which consists of a thermophilic fermentation and a consecutive photo-heterotrophic fermentation. The selected biomasses are by-products from food industry, molasses and potato steam peels, and the specifically grown substrate Miscanthus. A dedicated gas upgrading is also developed (Claassen and de Vrije, 2006).

The present paper is aimed at evaluating the environmental impact of the non thermal hydrogen production of HYVOLUTION compared to the environmental impact of fossil and renewable methane based hydrogen generation.

2. Methodology

The Life Cycle Assessment (LCA) methodology was chosen to evaluate the environmental impact of the biological hydrogen production. The environmental burdens and benefits of the entire production chain are identified and quantified. The whole LCA was based on the ISO 14040 (International Organization for Standardization, 1997) and 14044 (International Organization for Standardization, 2006) which foresee four steps:

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(i) Definition of goal and scopes, (ii) Inventory analysis (LCI), (iii) Impact assessment (LCIA) and (iv) Interpretation of the results. The LCIA is conducted with the help of the SimaPro 7.1 software (PRé Consultants). As an impact assessment methodology Eco-indicator 99 (H) V2.06/ Europe EI 99 H/A was used. The method uses an average weighting set to the three damage categories human health, ecosystem quality and resources. The database used to run the evaluations is ecoinvent (Swiss Centre for Life Cycle Inventories, 2008).

3. Goal And Scope

The final product of HYVOLUTION is to establish a technology for decentralized production of hydrogen based on locally available biomass. The HYVOLUTION technology itself has the function to produce a widely applicable energy source – H_2.

The LCA is deliberately carried out in parallel to the project development in order to identify and foresee environmental high loaded in- and outputs. It can be regarded as a consulting tool for process development and optimization. As a consequence, the intended audience of this LCA is firstly the partners of the project, especially scientists and engineers involved in process development.

3.1 System boundaries

The system boundaries include the entire process chain of the non-thermal hydrogen production. It starts with the transport of the feedstock (organic residues from agriculture and food processing) from a limited distance (maximum 15 km) to the plant and ends with the upgraded hydrogen gas. The process steps in between are feedstock pre-treatment, thermophilic fermentation, photo fermentation and gas upgrading. The biological and chemical inputs (e.g. enzymes, phosphate and nutrients) as well as heat, electricity and water demand of the process steps are included in the system boundaries. The storage and transport of the produced hydrogen are out of the system boundaries and hence are not considered in the LCA.

3.2 Functional unit

The functional unit set for the entire process is 1 kg H_2, due to its easy convertibility to other units and the fact that all data in the database are related to mass units.

3.3 Reference system

The purpose of the reference system is to compare the burden and benefit of the newly developed process to a state-of-the-art technology of producing hydrogen. Hence, the HYVOLUTION process is compared to fossil fuel based hydrogen generation and also to hydrogen production from biogas. Both reference systems are based on the steam methane reforming (SMR) which is a widely used, well established and documented process for centralized industrial plants. The steam methane reforming process is the basis for both reference systems. It changes the source from natural gas to biogas which has been cleaned from CO_2.

4. Life Cycle Inventory

The present analysis is based on potato steam peels (PSP) as a substrate for the HYVOLUTION process. According to the sensitivity analysis in the simulation activities, a number of data sets for the non-thermal hydrogen production using PSP as feedstock are available (Wukovits et al., 2007). The base case data set only connects the different process steps without consideration of any process improvements due to process and heat integration. For this base case, the production of 1 kg H_2 needs 249.3 kg PSP and a total water amount of 2,390 kg. The other data sets vary from the base case by the recirculation of sewage and the reduction of buffer concentration in the photo fermentation. Recirculation of sewage refers to the use of process effluents in the thermophilic and photo fermentation stages.

For the following three cases LCAs were conducted:

HYVOLUTION PSP 1 (Base case): Simple balance, no recirculation, 20 mM buffer.

HYVOLUTION PSP 2: Simple balance, replacement of 90% of tap water by process effluents, 20 mM buffer.

HYVOLUTION PSP 3: Simple balance, no recirculation, 4 mM buffer.

In some process steps impacts were disregarded, such as the impact of the enzyme production for the pre-treatment and the land demand of the fermenters in the photo fermentation. Furthermore the gas upgrading step was the only process step which is currently not considered in the simulation. Therefore an assumption of 10 % losses of hydrogen caused by gas purification was applied to charge an impact to that process step.

5. Environmental Impact Assessment

5.1 HYVOLUTION PSP 1 (Base case)

The total environmental impact of the case HYVOLUTION PSP 1 (Base case) is 4.3 pts. The impact can be allocated to the four process steps: 0.5 pts from the pre-treatment, 0.8 pts from dark fermentation, 2.6 pts from the photo fermentation and 0.4 pts from the gas upgrading. The highest impact categories for the overall process are carcinogens (1.38 pts), fossil fuels (1.07 pts), respiratory inorganics (1.04 pts) and climate change (0.21 pts). Figure 1 shows further details. The biggest impact on carcinogens and respiratory inorganics is caused by the use of phosphate in the photo fermentation. In the dark fermentation, the highest impact is on fossil fuels due to the use of potassium hydroxide. In the pre-treatment the highest impact is also caused by fossil fuels due to steam consumption. In case of gas upgrading it is not verified what impacts are caused, since detailed balance data for this process are not available yet from process simulation. The assumed loss of 10% of hydrogen leads to environmental impact increase of 0.4 pts.

Allocating the impact to the inputs and outputs, three process ingredients are identified causing a high environmental load (see Figure 2). The highest environmental impact is caused by phosphate with 2.3 pts. It corresponds to 53.5 % of the total environmental impact of the HYVOLUTION process. The phosphate is used in the photo fermentation as a buffer and again in the dark fermentation in a lower concentration, but also causes a measurable impact of 0.23 pts. The second highest impact of 0.47 pts is created by the use of a base (i.e. potassium hydroxide) in the dark fermentation process. The use of steam for pre-treating the substrate causes the third highest impact. It can be seen that the inputs to the HYVOLUTION process are mainly responsible for its high environmental load. The outputs directly caused by the HYVOLUTION process are CO2 and sewage. Their cumulative environmental load is only 0.07 pts, which corresponds to 1.7 % of the total impact.

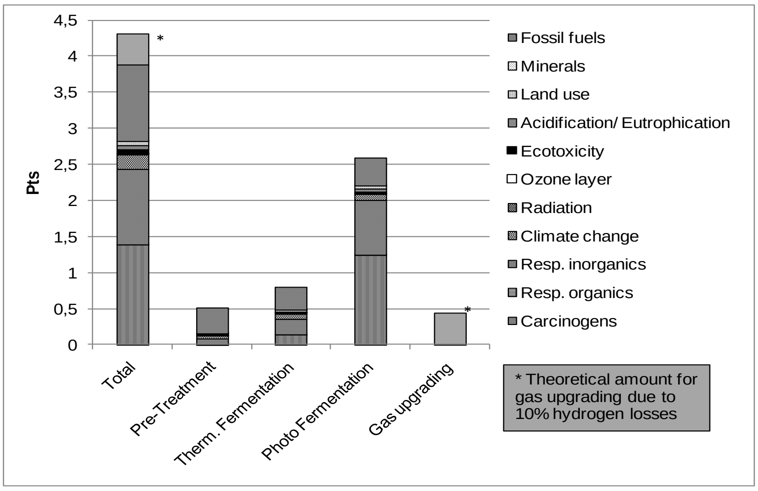

Figure 1: Environmental impact of HYVOLUTION PSP 1 (Base case), displaying the total environmental impact allocated to the impact categories and the single processes.

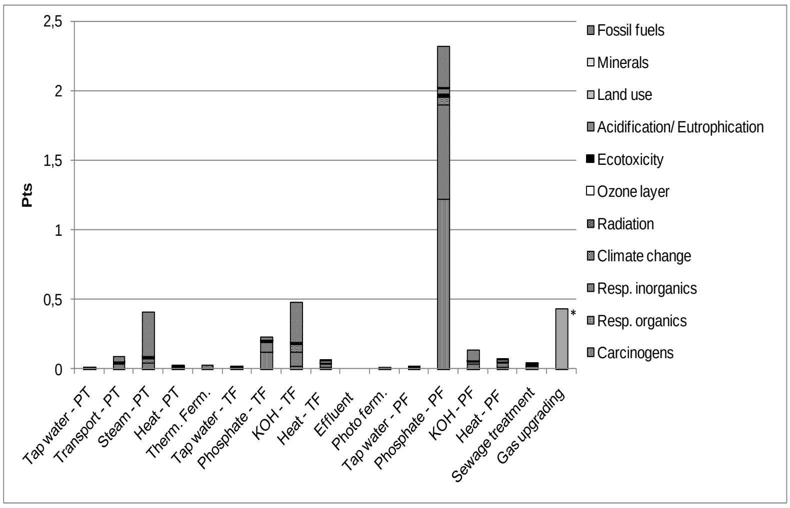

Figure 2: Allocation of the environmental impact to the inputs and outputs of the single processes in HYVOLUTION PSP 1 (Base case).

5.2 HYVOLUTION PSP 2

In HYVOLUTION PSP 2 it is foreseen to recirculate the major part (90 %) of the sewage from the whole process to the dark and photo fermentation. As a positive consequence the fresh water and buffer demand would be reduced, leading to an environmental impact reduction of 65.8 % to 1.47 pts. The process step giving the highest impact remains the photo fermentation, but its amount is reduced by 78.5 % to 0.56 pts. Pre-treatment creates the second highest impact with 0.5 pts while the dark fermentation decreases its environmental impact by 67.5 % to 0.26 pts. The highest impact categories in this process step are still fossil fuel (0.58 pts), respiratory inorganics (0.35 pts) and carcinogens (0.31 pts) with a change in order in significance.

5.3 HYVOLUTION PSP 3

In HYVOLUTION PSP 3 the buffer concentration used in the photo fermentation is reduced from 20 mM to 4 mM without any recirculation of sewage applied. Photo fermentation and the gas upgrading are the only process steps changing their environmental impact in comparison to HYVOLUTION PSP 1. The total impact is reduced by 52.1 % to 2.06 pts. The impact is allocated to the process steps as follows: 0.79 pts from dark fermentation, 0.5 pts from pre-treatment, 0.49 pts from photo fermentation and 0.26 pts from gas upgrading. The highest impact categories generally stay the same as in HYVOLUTION PSP 1, but their order changes: fossil fuel (0.88 pts), respiratory inorganics (0.49 pts) and carcinogens (0.37 pts).

5.4 Comparison

The reference systems generally show a lower environmental impact than the three HYVOLUTION PSP cases (see Figure 3) at the current stage of development. The steam methane reforming of purified methane from biogas has the lowest impact of all the processes exhibiting only 0.17 pts. The steam methane reforming of natural gas has an environmental impact of 0.75 pts. Its main impact is caused by the extraction and use of natural gas.

A comparison of HYVOLUTION PSP 1 (Base case) to the centralized steam methane reforming shows that the HYVOLUTION process in the current development stage has an impact 5.7 times higher. The recirculation of sewage, as set out in HYVOLUTION PSP 2, leads to a HYVOLUTION process with twice the impact of steam reforming of fossil methane. A comparison of the HYOLUTION processes to the steam methane reforming of a CO2 cleaned biogas shows an impact 252 time higher for HYVOLUTION-PSP 1 and 86 times higher for HYVOLUITION PSP 2.

6. Discussion And Conclusion

At the current state of development, the non-thermal small-scale decentralized hydrogen production shows a 5.7 times higher environmental impact than the large scale centralized SMR. A possible process improvement (recirculation of sewage) would lead to an environmental impact that is only twice high as large scale SMR of natural gas. In HYVOLUTION PSP 1 (base case) 98.3% of the environmental impact is caused by the

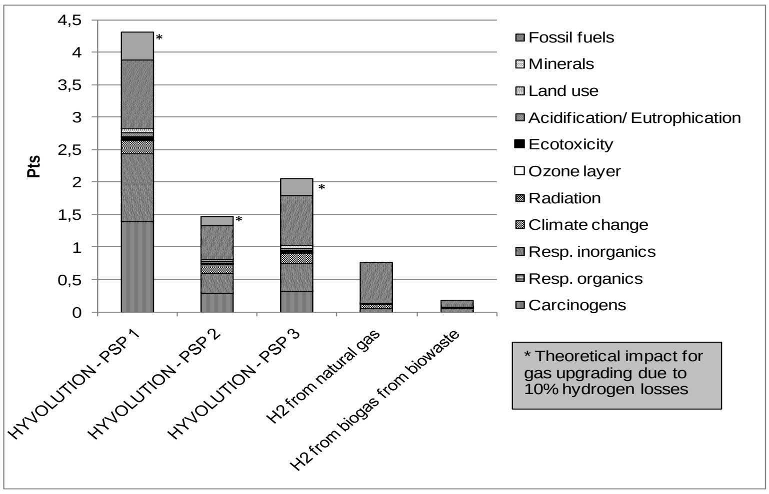

Figure 3: Comparison of HYVOLUTION PSP 1, 2 and 3 to the reference systems, showing a generally higher environmental impact of the new developed HYVOLUTION technology in contrast to the state of the art technologies.

inputs (mainly phosphate, base and steam). In contrast, the process emissions or solid outputs only cause 1.7 % of the impact. This corresponds to 0.07 pts of the LCA evaluation. The backpack the process ingredients are wearing is extremely high in the non-thermal hydrogen production and therefore their consumption needs to be decreased.

Compared to the SMR or biogas technology, non-thermal hydrogen production is a new development, which needs to be improved in future. During the HYVOLUTION project much basic research was undertaken which established the process as a whole; this needs to be adapted by engineering activities (heat integration). Furthermore a replacement of high loaded inputs (phosphate or potassium) with ecologically produced inputs needs to be realized in order to lower the environmental impact.

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