



Techno-economic assessment of hydrogen production based on dual fluidized bed biomass steam gasification, biogas steam reforming, and alkaline water electrolysis processes



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ABSTRACT

In this paper, three CO₂-neutral H₂ production processes were investigated. The three employed technologies were dual fluidized bed (DFB) biomass steam gasification, biogas steam reforming (BSR), and alkaline electrolysis (AEL) powered by renewable electricity with their necessary downstream separation and purification process steps. Aspen Plus process simulations were carried out in order to calculate the mass and energy balances of the three processes. In addition, a techno-economic assessment was carried out for a fictitious business producing H₂ at a rate of 90 kg h⁻¹ in Austria in 2016. This assumption was used so that the economic feasibility of these investigated processes could be directly compared.

The simulation results show that the DFB biomass steam gasification process has a higher H₂ conversion rate (51.4%) but a lower fuel based H₂ production efficiency (38.9%) than the BSR process (27.2% and 47.0%, respectively). Moreover, the alkaline electrolysis process shows the highest energy based H₂ conversion efficiency at about 66%.

The results of the economic assessment show that the DFB biomass steam gasification process has investment costs of 12.1 MEUR followed by the biogas steam reforming process with investment costs of 9.9 MEUR. The alkaline electrolysis process has investment costs of 4.4 MEUR. However, the after tax H₂ break-even price of the DFB process is the lowest with 0.148 EUR kWh⁻¹. The BSR process has an after tax H₂ break-even price of 0.152 EUR kWh⁻¹ and the AEL process has an after tax H₂ break-even price of 0.191 EUR kWh⁻¹. The net present value (NPV) calculations reveal that the BSR process has the highest NPV, followed by the AEL process and the DFB biomass steam gasification process. However, the NPV of all three processes are very similar. In general, all three H₂ production processes perform at the same level based on the results of the process simulation and the chosen economic assumptions.

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1. Introduction

Today most H₂ used in industry is produced by steam reforming of natural gas or other hydrocarbons [1]. These large scale steam reformer plants mainly cover the H₂ demand of refineries and ammonia plants. However, other industries, like the glass, food, metal, and petrochemicals also need H₂ but in significantly smaller amounts. Consequently, small-scale natural gas steam reformer plants have been established throughout these markets because

in most cases on-site supply of H₂ offers greater economy when compared to delivery by truck [2].

In light of climate change, small scale CO₂-neutral H₂ production processes should be established. Hence, this work investigates the following three CO₂-neutral H₂ production routes: biomass steam gasification, steam reforming of biogas, and alkaline electrolysis powered by renewable electricity together with its necessary downstream separation and purification steps.

In the case of biomass steam gasification, the dual fluidized bed (DFB) steam gasification technology was chosen because it has proven its feasibility for several years in multiple commercial plants. In addition, the product gas generated is practically free of N₂ and already contains a high volumetric H₂ fraction of about 40% [3,4]. Anaerobic digestion (AD) is an established technology for

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Nomenclature

Abbreviations and acronyms

AD	anaerobic digestion
AEL	alkaline electrolysis
AT	after tax
BSR	biogas steam reforming
BT	before tax
CHP	combined heat and power
DFB	dual fluidized bed
PSA	pressure swing adsorption
RME	rapeseed methyl ester
SG	steam generator
SR	steam reformer
WGS	water gas shift

Symbols

φ_j	volumetric fraction of component j in $\text{m}^3 \text{m}^{-3}$
ρ	density in kg m^{-3}

AT cash flow	after tax cash flow in EUR a^{-1}
BEP	break-even price in EUR kg^{-1} or EUR kWh^{-1}
BT cash flow	before tax cash flow in EUR a^{-1}
Capital	required capital for the plant in EUR
CEPI	chemical engineering plant index in –
Depreciation	linear depreciation in EUR a^{-1}
Expenses	in EUR a^{-1}
i	discount/interest rate in –
LHV	lower heating value in MJ kg^{-1}
m	exponent for order of magnitude capital estimation in –
\dot{m}_j	mass flow of component j in kg h^{-1}
n	plant lifetime in a
NPV	net present value in EUR
Revenues	in EUR a^{-1}
Tax rate	in –
ω_j	mass fraction of component j in kg kg^{-1}

the generation of biogas, which mainly consists of CH_4 and CO_2 . Furthermore, the separation of CH_4 from biogas and its injection in the natural gas grid is commercially employed at different locations. Moreover, CH_4 in the biogas can also be used as feed stock in a steam reforming process in order to generate H_2 [5]. Alkaline water electrolysis (AEL) is a well established and commercially used route for production of H_2 from electricity. It is mainly used to generate small scale H_2 supplies on-site [6,7]. If powered by renewable electricity, the generated H_2 is CO_2 -neutral.

The three CO_2 -neutral H_2 production routes were evaluated via process simulation in Aspen Plus in order to acquire mass and energy balances and, consequently, to deliver the data necessary for a techno-economic assessment. Based on this assessment, a decision about which kind of plant offers the greatest economic benefit can be made.

The work presented here is based on the following fictitious business case located in Austria in 2016: A company needs about 90 kg h^{-1} ($1000 \text{ m}^3 \text{ h}^{-1}$) H_2 with a volumetric purity greater than 99.9% for its process. They want to erect a H_2 production plant which needs to be available for 8000 h per year. Heat is not a required product. Company policy demands that the H_2 production plant be CO_2 -neutral. Based on the results of this study, a decision should be possible, which of the three investigated CO_2 -neutral H_2 production routes offers the highest economy feasibility.

2. Materials and methods

This section introduces the three processes for production of CO_2 -neutral H_2 . Furthermore, assumptions made for the simulation of each of the three processes are shown. In addition, the approach for the techno-economic assessment is presented.

2.1. Investigated processes

This section describes the three routes for production of CO_2 -neutral H_2 : DFB biomass steam gasification, steam reforming of biogas, and alkaline electrolysis. The presented principles are the basis for Aspen Plus process simulations and, further on, for the techno-economic assessment. The described processes were simulated using Aspen Plus 8.6. All volumetric flow rates are given at standard temperature and pressure (273.15 K and 101,325 Pa).

Table 1 shows the technical boundary conditions and assumptions used for all three process designs.

Table 1

Assumptions for simulations of the DFB, BSR, and AEL processes.

	Values	Units
\dot{m}_{H_2}	90	kg h^{-1}
φ_{H_2}	99.9%	$\text{m}^3 \text{m}^{-3}$
p_{H_2}	1.0	MPa
T_{H_2}	25	$^\circ\text{C}$

Based on these assumptions, the mass and energy balances from all three processes were calculated. No district heat generation within the DFB and BSR design was considered. Therefore, all heat was used within the processes, mainly for steam generation.

2.1.1. Dual fluidized bed biomass steam gasification

Fig. 1 shows the simplified process layout for H_2 production by DFB biomass steam gasification.

Wet wood chips are fed into the biomass dryer (not depicted), which is operated with low temperature waste heat from the process. In the dryer, the H_2O mass fraction of the feedstock is reduced from about 32% to about 16%, which is a typical value for dryers within commercial DFB biomass steam gasification plants [8]. Dried wood chips are fed into the gasifier where they devolatilize and react with H_2O . According to the endothermic gasification reactions, at about $850 \text{ }^\circ\text{C}$ the product gas with the main gas components H_2 , CO , CO_2 , and CH_4 is formed. Olivine is used as bed material and heat carrier. It exhibits catalytic activity that enhances gasification reactions and, therefore, reduces the tar content of the product gas [9–12]. Subsequently, the product gas is cooled, filtered (mainly by particle separation), and fed into a fixed bed water gas shift (WGS) reactor employing a Fe/Cr-based catalyst where CO and H_2O are converted into additional H_2 and CO_2 according to the exothermic WGS reaction. The gas inlet temperature is about $350 \text{ }^\circ\text{C}$, and a molar steam to dry gas ratio of 1.5 avoids coking and carbon deposition on the catalyst surface. During past investigations, the Fe/Cr-based catalyst has proven its stability in processing tar-rich product gas [13,14]. In the next steps, the product gas is cooled and fed into a rapeseed methyl ester (RME, $\rho = 880 \text{ kg m}^{-3}$, $\text{LHV} = 36.9 \text{ MJ kg}^{-1}$) scrubber, where the gas is further cooled from about $150 \text{ }^\circ\text{C}$ to about $50 \text{ }^\circ\text{C}$. Consequently, tar and steam are removed and condensed. The condensed steam is recycled and used to generate more steam for the process. The RME scrubber has proven to be sufficient for removing tar and steam from the product gas stream when employed at commercial

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