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Economic Assessment of Green Hydrogen Production from Biomass Gasification with Chemical Absorption and Membrane-based CO_2 Capture

Calin-Cristian Cormos [a,*], Mihaela Dragan [b], Cristian Dinca [c], Ana-Maria Cormos [a], Simion Dragan [a], Ionela-Dorina Dumbrava [a], Flavia Ilea [a], Stefan Galusnyak [a]

[a] Babes - Bolyai University, Faculty of Chemistry and Chemical Engineering, 11 Arany Janos, Postal code: RO-400028, Cluj – Napoca, Romania
[b] Babes - Bolyai University, Faculty of Economics and Business Administration, 58-60 Teodor Mihali, Postal code: RO-400028, Cluj-Napoca, Romania
[c] University Politehnica of Bucharest, Faculty of Power Engineering, 313 Splaiul Independentei, Postal code: RO-060042, Bucharest, Romania
calin.cormos@ubbcluj.ro

Development of environmentally friendly energy carriers is of great importance today in the attempt to reduce the global warming and climate change. Hydrogen is seen as a promising energy carrier for the future low carbon economy on condition that it is produced in an environmentally friendly fashion as well as in energy and cost-effective ways. This work is evaluating the techno-economic implications of green hydrogen production from biomass gasification with CO_2 capture using various chemical gas-liquid absorption and membrane systems (including hybrid ones). The evaluated concepts have a capacity of 50,000 Nm^3/h high purity hydrogen (> 99.95 % vol.) with a minimum 90 % CO_2 capture rate. As the results show, the biomass gasification integrated with chemical absorption and membrane systems for CO_2 removal has promising potential to give a high overall energy efficiency (about 57 - 59 %), low specific CO_2 emissions (about 55 - 60 kg/t hydrogen) and better environmental indicators (e.g., specific CO_2 emissions) than current fossil-based hydrogen production concepts.

1. Introduction

The development of low carbon economy requires innovative solutions for instance to increase the share of renewable energy sources (e.g., solar, wind, biomass) within the overall energy system, deployment of new energy conversion and storage technologies as well as introducing energy carriers having negligible carbon footprint. In this respect, hydrogen is seen as a promising energy carrier for both energy and transport applications which not implies CO_2 emission at the point of usage. Currently, most of the hydrogen is produced from fossil fuels with high CO_2 emissions (the so-called grey hydrogen). Renewable sources (e.g., solar, wind, biomass) can be utilised (as illustrated in this paper) for green hydrogen production with low environmental burden. Coupling usage of renewables and CO_2 capture technologies will result in a negative carbon emission energy conversion system with positive environmental consequences (removal of CO_2 from atmosphere).

This work evaluates from a techno-economic perspective the green hydrogen production from biomass gasification coupled with CO_2 capture features (done individually either by chemical gas-liquid absorption, membrane and hybrid solvent - membrane system). The size of investigated concepts is 50,000 Nm^3/h high purity hydrogen (> 99.95 % vol.) with 90 % CO_2 capture rate. Detailed process flow modelling, simulation and thermal integration analysis were performed to cover the following aspects: conceptual designs, characterisation of mass and energy balances, evaluation of mass and energy integration issues, detailed calculation of techno-economic and environmental performance indicators, future development issues etc. The key novelty element of this analysis, in respect to current state-of-the-art literature, represents the detailed techno-economic evaluation of an industrial-relevant green hydrogen production facility with negative CO_2 emissions. These results can form the base of a business case for an environmentally friendly hydrogen production facility.

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2. Conceptual design, main design assumptions and thermal integration analysis

The conceptual design of decarbonised biomass gasification for hydrogen production is presented in Figure 1. As can be noticed, biomass (sawdust) is gasified with oxygen and steam to produce syngas, then CO is catalytically converted to CO_2 and H_2 followed by Acid Gas Removal (AGR) unit to capture separately CO_2 and H_2S. The H_2S-rich gas is sent to a Claus plant and the captured CO_2 stream is dried and compress prior storage / utilisation. The hydrogen-rich syngas is then purified in a Pressure Swing Adsorption (PSA) unit to a purity of at least 99.95 % vol. The PSA tail gas is further used for energy recovery purposes (power generation to cover plant ancillary consumption eventually for power export to the grid).

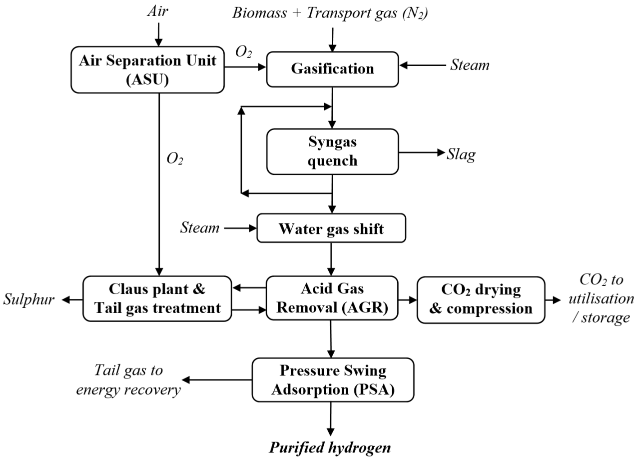

Figure 1: Conceptual design of biomass gasification with CO_2 capture feature for hydrogen production

Three options were evaluated for the pre-combustion CO_2 capture: (i) chemical gas-liquid absorption using Methyl-Di-Ethanol-Amine (MDEA) as illustrative solvent; (ii) 2-stage membrane unit and (iii) hybrid solvent - membrane unit with membrane located at the top of CO_2 absorption column. The first two options are based on conventional designs e.g., Koronaki et al. (2015) for the chemical gas-liquid absorption and Giordano et al. (2019) for the membrane systems. The conceptual design of the hybrid system is presented in Figure 2.

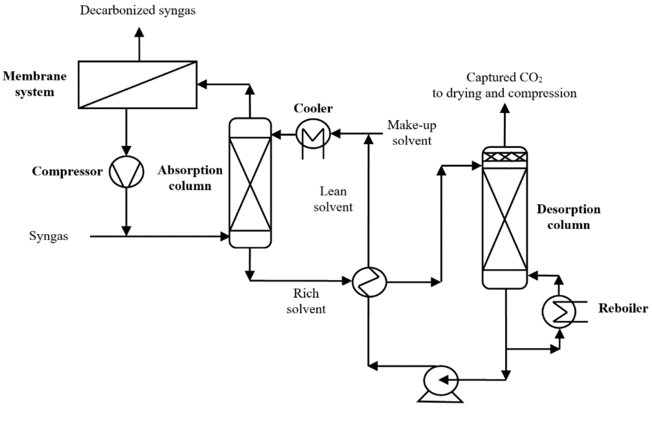

Figure 2: Conceptual design of hybrid solvent - membrane system for pre-combustion CO_2 capture

The decarbonised biomass gasification systems were mathematically modelled and simulated using ChemCAD software (version 7.1.8). The most important design assumptions are presented in Table 1 (Cormos et al., 2022). The developed models were validated against experimental / industrial data e.g., Higman and van der Burgt (2008) for gasification systems, IEAGHG (2003) for chemical scrubbing. No significant differences are observed in term of key performance indicators (e.g., fuel conversion rate, CO_2 capture yield, syngas composition in various points of the plant etc.). The investigated concepts were thermally integrated using Pinch methodology (Klemeš, 2013). To illustrate the thermal integration, Figure 3 presents the Composite Curves for gasification island, syngas conditioning train and water gas shift reactors (common to all investigated cases). Following simulation, the overall mass and energy balances were used for estimation of performance indicators.

Table 1: Main design assumptions

Plant sub-system	Design specifications
Biomass (sawdust, residual wood) composition and thermal properties	Composition (% wt. dry): 49.20 % carbon, 5.99 % hydrogen, 0.82 % nitrogen, 42.98 % oxygen, 0.03 % sulphur, 0.98 % ash; Moisture: 10 %; Lower heating value: 18.11 MJ/kg
Air separation unit (IEAGHG, 2003)	Product purity (% vol.): 95 % O_2, 2 % N_2, 3 % Ar Ancillary consumption: 200 kWh/t O_2
Gasification island (IEAGHG, 2003)	Dry feed syngas quench gasification reactor type Temperature & pressure: 1,400 °C & 40 bar Syngas quench temperature: 800 °C
Water gas shift conversion (IEAGHG, 2003)	Sour (sulphur tolerant) catalyst, 3 adiabatically operated reactors CO conversion rate: 97 - 98 %
Chemical absorption (MDEA) for CO_2 capture (Cormos et al., 2022)	MDEA 50 % wt. aqueous solution CO_2 capture rate: 90 %
Membrane unit for CO_2 capture (Giordano et al., 2019)	H_2-selective membrane, 2 stage unit Permeance data (GPU): H_2 - 300, CO_2 - 10, CO - 4, N_2 - 2, Ar - 2, CH_4 - 2 CO_2 capture rate: 90 %
PSA hydrogen purification unit (IEAGHG, 2003)	H_2 recovery yield: 85 % Product purity (% vol.): 99.95 % H_2 Final delivery pressure: 60 bar, compressor efficiency: 85 %
CO_2 drying and compressing unit (Cormos et al., 2022)	Drying unit: TEG (Tri-ethylene-glycol) CO_2 composition (vol. %): > 95 % CO_2, < 2,000 ppm CO, < 250 ppm H_2O, < 100 ppm H_2S, < 4 % non-condensable gases Final delivery pressure: 120 bar Compressor efficiency: 85 %
Energy recovery (Cormos et al., 2022)	Steam (Rankine) unit, turbine efficiency: 85 % Steam conditions: 580 °C & 120 bar / 200 °C & 3 bar PSA tail gas used for energy recovery, overall efficiency: 50 % Minimum temperature difference: $\Delta T_{min.}$ = 10 °C

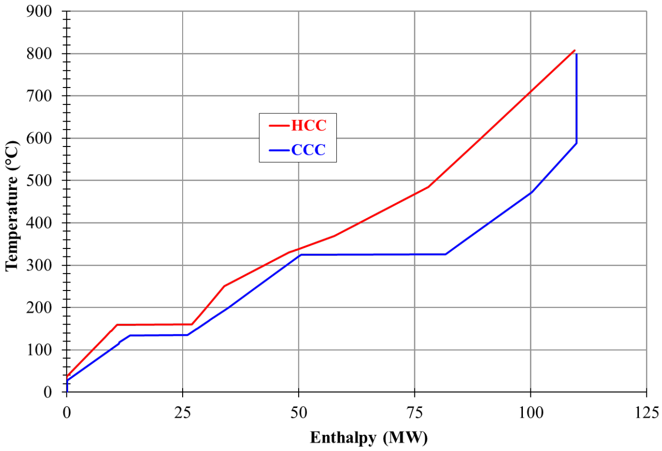

Figure 3: Composite Curves for gasification island, syngas conditioning train and water gas shift reactors

3. Techno-economic assessment methodology

The following hydrogen production concepts were evaluated:

Case 1: Biomass (sawdust) gasification without CO_2 capture;
Case 2: Biomass (sawdust) gasification with CO_2 capture by MDEA-based gas-liquid absorption;
Case 3: Biomass (sawdust) gasification with CO_2 capture by membrane technology;
Case 4: Biomass (sawdust) gasification with CO_2 capture by hybrid solvent (MDEA) - membrane.

The hydrogen production systems based on biomass gasification with CO_2 capture were modelled and simulated using ChemCAD process flow modelling software (Chemstations, 2022). The Soave-Redlich-Kwong (SRK) model was used as thermodynamic package. The developed models were validated by comparison of the simulation results with available experimental data. The key performance indicators used for validation purposes were: biomass conversion rate, gasification cold gas efficiency gasification, water gas shift CO conversion rate, CO_2 capture rate. For instance, the fuel (biomass) conversion rate within the gasifier is almost total (> 99 %) in accordance to the relevant literature references in the field (Higman and van der Burgt, 2008). The simulated CO conversion rate and CO_2 capture yield are also in line with literature sources (e.g., IEAGHG reports from 2003 and 2008). Considering the available heat sources within the plant (e.g., gasification island, syngas treatment line, water gas shift conversion reactors etc.) as well as energy of the PSA tail gas, the steam generation was considered which was further expanded in a steam turbine to produce power. The generated power was used to cover completely the ancillary consumption, the remaining being considered for grid export. Based on the mass and energy balances produced from modelling and simulation of assessed hydrogen production concepts, the key techno-economic and environmental plant performance indicators were calculated. For techno-economic assessment, the overall methodology proposed by International Energy Agency - Greenhouse Gas R&D Programme (IEAGHG) was followed with the calculation of following indicators: hydrogen thermal efficiency, net power efficiency and cumulative energy efficiency to show the overall energy conversion yields of biomass to hydrogen and power; CO_2 capture rate to show the overall plant decarbonisation yield; specific CO_2 emissions per energy produced (hydrogen and power); specific investment cost to illustrate the investment required per each kW of energy produced (in form of hydrogen and power); operational & maintenance (O&M) cost; levelized cost of hydrogen and electricity; CO_2 removal and avoidance costs etc. An in-depth characterization of calculated key performance indicators as well as the main economic assumptions are provided by the IEAGHG report (2008) for the gasification, syngas treatment and chemical scrubbing-based CO_2 capture. For the only membrane CO_2 capture system (Case 3) as well as for the hybrid solvent – membrane system (Case 4), the overall assumptions are presented by Cormos et al. (2022).

4. Results and discussions

The key technical and environmental performance indicators for evaluated hydrogen production systems based on biomass (sawdust) gasification with / without CO_2 capture are presented in Table 2.

Table 2: Key performance technical indicators for biomass gasification systems for hydrogen production

Plant indicator	Units	Case 1	Case 2	Case 3	Case 4
Sawdust flowrate	t/h	58.66	58.66	58.66	58.66
Sawdust lower calorific value	MJ/kg	18.11			
Input sawdust thermal energy	MW_{th}	295.17	295.17	295.17	295.17
PSA tail gas energy recovery unit	MW_e	15.75	14.82	15.05	14.90
Steam turbine output	MW_e	25.94	24.75	25.60	25.05
Gross power output	MW_e	41.69	39.57	41.10	39.95
Ancillary power consumption	MW_e	11.70	19.74	17.44	18.85
Hydrogen thermal output	MW_{th}	150.00	150.00	150.00	150.00
Net power output	MW_e	29.99	19.83	23.66	21.10
Hydrogen thermal efficiency	%	50.81	50.81	50.81	50.81
Net electrical efficiency	%	10.16	6.71	8.01	7.14
Cumulative energy efficiency	%	60.97	57.52	58.82	57.95
CO_2 capture rate	%	0.00	90.00	90.00	90.00
Solvent regeneration duty	MJ/kg	-	0.56	-	0.45
Specific CO_2 emissions	kg/MWh	528.03	59.07	56.58	57.43

It can be observed that introduction of CO_2 capture feature induces a reduction of overall plant energy efficiency. The CO_2 capture energy penalty is in the range of about 3 - 3.4 net cumulative percentage points for Case 2 (chemical gas-liquid absorption) and Case 4 (hybrid chemical absorption - membrane). The lowest decarbonisation energy penalty is for Case 3 (only membrane system) with about 2 net cumulative percentage points. All decarbonisation systems have the same CO_2 capture rate (90 %) with specific CO_2 emissions in the range of 56 to 60 kg/MWh. Considering that the used fuel (sawdust) is a renewable energy source, the Case 1 can be considered with overall zero CO_2 emissions which means that the decarbonisation systems (Cases 2 to 4) have negative specific CO_2 emissions of about - 472 to - 469 kg/MWh. The evaluated biomass gasification systems are perfect examples how renewable energy sources can be efficiently converted (overall cumulative energy efficiencies of about 57 - 59 %) to hydrogen as promising energy carrier for the future. In addition, they contribute to the removal of CO_2 from atmosphere (CO_2 was capture from atmosphere during the process of photosynthesis when biomass grew and then captured and geologically stored from the evaluated concepts).

After technical and environmental evaluation of hydrogen production systems based on biomass gasification, the main economic indicators were also evaluated. The capital cost was calculated based on cost correlation method as described by Smith (2016). The time updated reference data for capital cost calculation were reported by Cormos et al. (2022). Figure 4 presents the specific capital cost investment for all evaluated concepts.

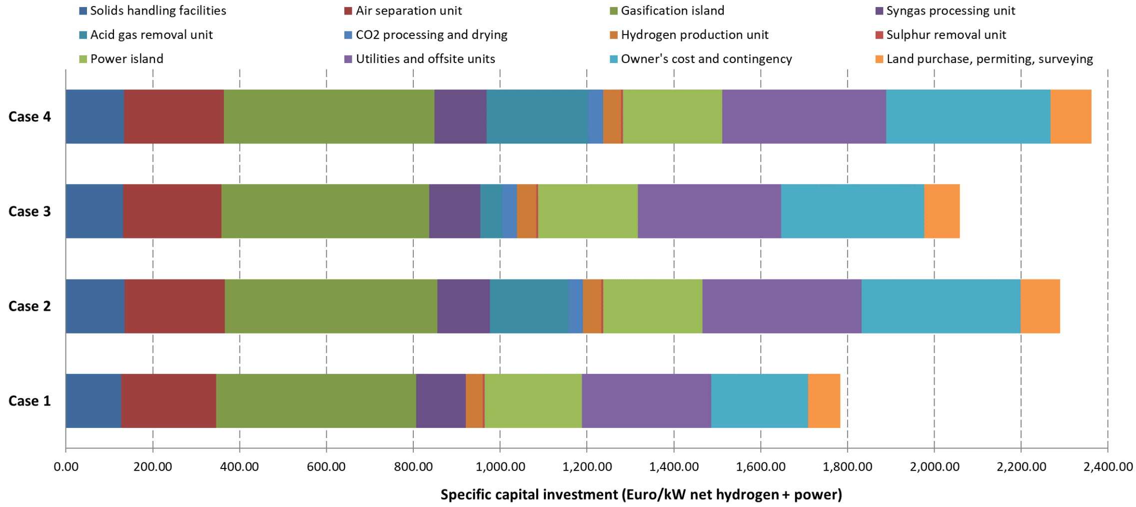

Figure 4: Specific capital cost investment for evaluated hydrogen production concepts

It can be observed that the introduction of pre-combustion CO_2 capture feature induces a significant increase of specific capital cost investment (about 15 - 32 % compared to the similar case without carbon capture). The lowest increase of the investment cost is reported for Case 3 (membrane only CO_2 capture) due to design simplicity. The chemical gas-liquid absorption concepts (either alone or in a hybrid combination with membrane) have higher specific investment costs (about 11 -15 %) than the membrane-only case due to a more complex design as well as higher ancillary energy consumptions. The next evaluated economic indicator was the Operational & Maintenance (O&M) costs. Figure 5 presents the O&M costs for all evaluated concepts.

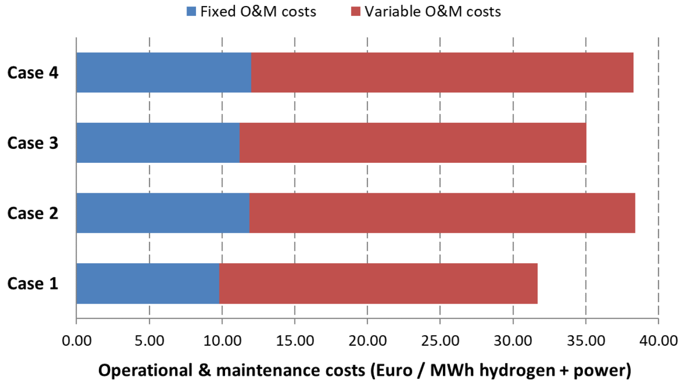

Figure 5: Operational & maintenance (O&M) costs for evaluated hydrogen production concepts

The levelized cost of hydrogen (LCOH) was calculated based on the Net Present Value (NPV) method (Smith, 2016). The CO_2 capture costs (CO_2 removal and avoided costs) were calculated considering the hydrogen production costs and the specific CO_2 emissions for both concepts with and without carbon capture. Table 3 presents these indicators for all evaluated hydrogen production concepts.

Table 3: Levelized cost of hydrogen and CO_2 capture costs

Plant indicator	Units	Case 1	Case 2	Case 3	Case 4
Levelized cost of hydrogen	€/MWh	58.80	71.03	64.42	72.06
CO_2 removal cost	€/t	-	14.32	6.59	15.56
CO_2 avoided cost	€/t	-	26.07	11.92	28.17

In can be observed that the membrane only concept (Case 3) has the lowest O&M costs as well as hydrogen production and CO_2 capture costs. Between chemical scrubbing and hybrid solvent – membrane concepts, the system with only gas-liquid absorption performs better than hybrid one. Comparing to conventional fossil-based systems, the hydrogen cost of this analysis is about 30 - 45 % higher. Sensitivity analysis was done to assess the variation of hydrogen production costs vs. upper and lower values of several key economic indicators (e.g., investment cost, fuel cost, O&M cost, interest rate, plant availability factor). Figure 6 shows the variation of hydrogen production cost for one illustrative concept (Case 3). It can be noticed that the most important influence on hydrogen production cost is observed for the capital cost followed by the interest rate, plant availability factor and biomass (sawdust) price. The operational & maintenance (O&M) cost has the smallest influence on LCOH.

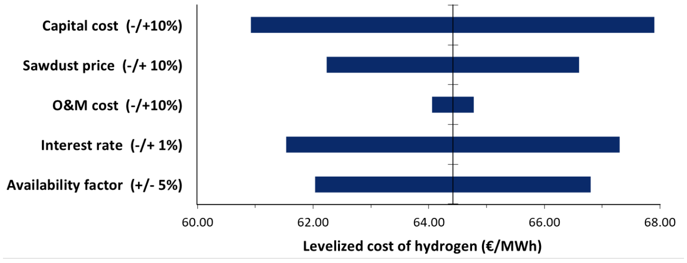

Figure 6: Sensitivity analysis for hydrogen production cost (Case 3)

5. Conclusions

This analysis evaluates the techno-economic and environmental aspects of hydrogen production concepts based on biomass (sawdust) gasification with pre-combustion CO_2 capture. As decarbonisation options, there pre-combustion capture technologies were assessed: the chemical gas-liquid absorption concept using MDEA as illustrative solvent, only membrane concept and a hybrid solvent – membrane concept with membrane unit located at the top of the absorber. The membrane only concept has the best performances from all decarbonised biomass gasification designs in term of highest cumulative energy efficiency (about 58.8 vs. 57.5 - 57.9 %), lowest CO_2 capture energy penalty (about 2 net cumulative energy efficiency percentage points), reduced specific investment costs (about 2,059 vs. 2,290 - 2,361 €/kW), O&M costs (about 35 vs. 38 €/MWh) and hydrogen production cost (about 64.4 vs. 71 - 72 €/MWh). The negative CO_2 emission feature of investigated biomass-based hydrogen production systems is very promising for developing innovative low carbon solutions.

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