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Economic Assessments of Hydrogen Production Processes Based on Natural Gas Reforming with Carbon Capture

Ana-Maria Cormos, Szabolcs Szima, Szabolcs Fogarasi, Calin-Cristian Cormos*

Babes – Bolyai University, Faculty of Chemistry and Chemical Engineering, 11 Arany Janos, Postal code: RO-400028, Cluj – Napoca, Romania
cormos@chem.ubbcluj.ro

Hydrogen is a promising energy carrier for future low carbon economy as fuel or chemical for various industrial applications (e.g. heat and power, petro-chemical, metallurgy etc.) as well as for transport sector. In order to decarbonise the energy sector as well as the transportation sector, the fossil fuels need to be efficiently converted to hydrogen and the resulted CO_2 to be captured and then used / stored. The Carbon Capture, Utilisation and Storage (CCUS) technologies are promising options of efficiently combating climate change (by significantly reducing the greenhouse gas emissions) as well as continuing of using the fossil fuels.
This paper is assessing the key updated technical and economical performances of hydrogen production based on natural gas reforming with and without carbon capture. As illustrative examples, conventional steam reforming and autothermal reforming (using both oxygen and air) of natural gas were evaluated. The CO_2 capture technology was based on pre-combustion capture configuration using gas-liquid absorption. As illustrative cases, Methyl-DiEthanol-Amine (MDEA) as a chemical solvent and Selexol^{TM} as a physical solvent were assessed for their performances. The evaluated hydrogen production concepts have a capacity of 100,000 Nm^3/h (corresponding to 300 MW_{th} based on lower heating value) with a purity higher than 99.95 % (vol.). The paper presents in details the evaluated hydrogen production concepts based on natural gas reforming, modelling and simulation aspects, model validation, mass and energy integration issues as well as proposing an integrated methodology for quantification of key economic aspects. As the results show, the conventional steam reforming has higher energy utilisation factor (about 5 net percentage points) than the autothermal reforming cases. The carbon capture rate is about 65 - 70 % for the conventional steam reforming considered as an illustrative case. The economic indicators show better performances for conventional steam reforming in comparison to autothermal reforming in term of specific capital investment cost (about 12 - 24 % lower), operational and maintenance costs (about 7 % lower), hydrogen costs (about 5 - 10 % lower). Physical absorption is more energy and cost effective than chemical absorption as pre-combustion capture method.

1. Introduction

The usage of hydrogen as an energy carrier looks very promising for developing low carbon applications for energy-intensive industrial sectors such as energy, chemistry, metallurgy etc. (European Commission, 2007). Hydrogen can be obtained by various methods, the most important involving the usage of fossil fuels (e.g. catalytic reforming, coal gasification). In order to decarbonise heat and power sector as well as transportation sector, the fossil fuels need to be efficiently converted to hydrogen and resulted CO_2 to be captured and then used / stored. Along this line, Carbon Capture, Utilisation and Storage (CCUS) technologies are promising solutions for combined reduction of CO_2 emissions and continuation of fossil fuel usage (Metz et al., 2005).
This paper is evaluating the main techno-economic and environmental performance indicators (updated values vs. reported literature data) of hydrogen production based on natural gas reforming with and without CO_2 capture. As illustrative example, conventional steam methane reforming was evaluated with and without carbon capture step (Aasberg-Petersen et al., 2011). The natural gas reforming designs without carbon capture were evaluated as benchmark cases to assess the energy and cost penalties for CO_2 capture. The commercially and technologically mature gas-liquid absorption technology was assessed as pre-combustion CO_2 capture method using either chemical (MDEA) or physical (Selexol^{TM}) solvents (Voldsund et al., 2016).

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The evaluated hydrogen production concepts have a capacity of 100,000 Nm^3/h (corresponding to 300 MW_{th} based on hydrogen lower heating value - 10.795 MJ/Nm^3) with a purity higher than 99.95 % (vol.), suitable to be used both in petro-chemical applications as well as for Proton Exchange Membrane (PEM) fuel cells for transport applications (Sengodan et al., 2018). The carbon capture rate is maximised considering the usage of hydrogen purification unit (PSA) tail gas as fuel for the reforming island. The paper presents the evaluated hydrogen production concepts based on natural gas reforming, modelling and simulation aspects, model validation, mass and energy integration issues as well as proposing an integrated methodology for quantification of key economic aspects (e.g. capital costs, operational and maintenance costs, hydrogen production costs, CO_2 capture costs, sensitivity analysis of hydrogen cost, cumulative cash flow analysis etc.).

2. Plant configurations, modelling assumptions and process integration

Three natural gas reforming technologies were assessed for the hydrogen production concepts: the conventional steam methane reforming (Case 1); the oxygen authothermal reforming (Case 2) and the air autothermal reforming (Case 3). The conventional steam methane reforming concepts were evaluated in no carbon capture scenario (Case 1a), MDEA-based pre-combustion CO_2 capture (Case 1b) and Selexol^{TM}-based pre-combustion CO_2 capture (Case 1c). The conceptual design of conventional steam reforming with pre-combustion carbon capture (Cases 1b and 1c) is presented in Figure 1 (Cormos et al., 2014).

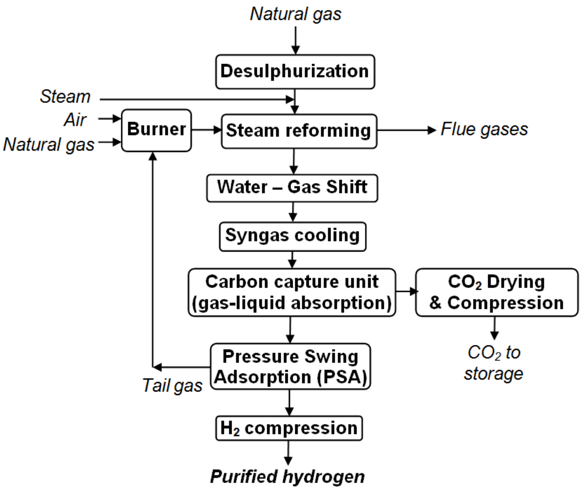

Figure 1: Design of conventional steam reforming for hydrogen production with pre-combustion CO_2 capture

The natural gas stream is first desulphurised and then catalytically reformed using steam. The produced syngas is subject to shift conversion to increase the hydrogen ratio and to concentrate the carbon species as CO_2 which then is captured by gas-liquid absorption. The hydrogen-rich gas is purified by a PSA unit to desired quality specification (>99.95 % vol.) and the tail gas is used to fire the reformer. The main design assumptions of reforming-based hydrogen production processes are presented in Table 1 (IEAGHG, 2017).

The evaluated hydrogen production processes based on natural gas reforming with and without CCS were simulated using ChemCAD (SRK was used as thermodynamic package). The concepts were subject of thermal integration using Pinch method (Smith, 2016). Figure 2 presents hot and cold Composite Curves for the conventional steam reforming design (Case 1). One can notice the tight thermal integration of the plant.

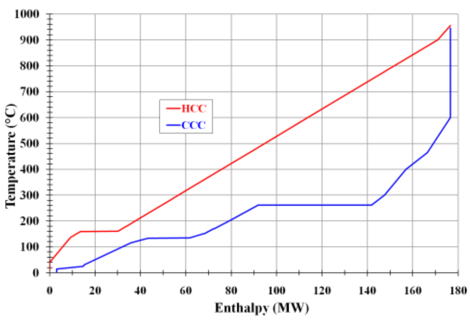

Figure 2: Composite Curves for the conventional steam methane reforming concept (Case 1)

Table 1: Design assumptions

Plant sub-system	Specifications
Fuel (natural gas) characteristics	Composition: 89 % CH_4, 7 % C_2H_6, 1 % C_3H_8, 0.1 % C_4H_{10}, 0.01 % C_5H_{12}, 0.001 % C_6H_{14}, 2 % CO_2, 0.89 % N_2, 10 ppm mercaptan Lower heating value (LHV): 46.73 MJ/kg
Air Separation Unit (ASU)	Oxygen purity (% vol.): 95 % O_2, 2 % N_2, 3 % Ar ASU power consumption: 200 kWh/t O_2
Reformer reactor	Operating pressure: 30 bar Outlet temperature: 900 ^oC Burner configuration: Cases 1 Autothermal configurations: oxygen (Case 2), air (Case 3)
Pre-combustion CO_2 capture	Chemical solvent: Methyl-diethanol-amine (MDEA) 50% wt. Physical solvent: Selexol^{TM} Absorption - desorption cycle Solvent regeneration: thermal (MDEA) / pressure flash (Selexol^{TM})
CO_2 compression and drying	Delivery pressure: 120 bar Compressor efficiency: 85 % Solvent used for CO_2 drying: TEG (Tri-ethylene-glycol) Captured CO_2 specification (vol. %): >95 % CO_2, <2,000 ppm CO, <250 ppm H_2O, <100 ppm H_2S, <4 % non-condensable gases
Hydrogen purification and compression	Pressure Swing Adsorption (PSA) for purification (>99.95 % vol.) Hydrogen delivery pressure: 60 bar
Heat recovery steam generation, steam cycle and power block	Steam pressure levels: 48 bar / 3 bar Steam turbine isentropic efficiency: 85 % Steam wetness ex. steam turbine: max. 10 % Minimum approach temperature: $\Delta T_{min.}$ = 10 ^oC

3. Techno-economic and environmental assessment

The mass and energy balances generated by process simulation of natural gas reforming-based hydrogen production concepts with or without carbon capture were compared to industrial data (IEAGHG, 2017) for model validation (no significant differences being recorded) and then used for quantification of main techno-economic performances. The main technical and environmental performances are presented in Table 2.

Table 2: Main technical and environmental performance indicators

Main plant data	Units	Case 1a	Case 2	Case 3	Case 1b	Case 1c
Natural gas flowrate	t/h	31.37	34.12	32.98	31.37	31.37
Natural gas LHV	MJ/kg			46.73		
Natural gas thermal energy (A)	MW_{th}	407.26	442.93	428.24	407.26	407.26
Steam turbine output	MW_e	16.03	31.45	28.69	11.32	15.92
Expander output	MW_e	0.99	1.26	2.94	0.37	0.52
Gross power output (B)	MW_e	17.02	32.71	31.63	11.69	16.44
Hydrogen output (C)	MW_{th}	300.00	300.00	300.00	300.00	300.00
Air separation unit / Air compression	MW_e	-	8.62	17.90	-	-
CO_2 capture and compression	MW_e	-	-	-	4.23	4.81
Hydrogen compression	MW_e	4.18	4.18	4.18	4.18	4.18
Power island	MW_e	2.08	2.36	2.29	2.08	2.12
Ancillary consumption (D)	MW_e	6.26	15.16	24.37	10.49	11.11
Net power output (E = B - D)	MW_e	10.76	17.55	7.26	1.20	5.33
Net power efficiency (E/A * 100)	%	2.64	3.96	1.69	0.29	1.30
Hydrogen efficiency (C/A * 100)	%	73.66	67.73	70.05	73.66	73.66
Energy utilisation factor (C+E/A * 100)	%	76.30	71.69	71.74	73.95	74.96
Carbon capture rate	%	0.00	0.00	0.00	70.00	65.00
CO_2 specific emissions (H_2+power)	kg/MWh	267.39	284.59	284.37	82.78	95.58

As can be observed from Table 2 among various natural gas reforming concepts without carbon capture, the conventional steam reforming design has the highest energy utilisation factor (76.3 % vs. 71.7 %) due to lower ancillary power consumption compared to oxygen and air autothermal reforming cases. When pre-combustion carbon capture step is introduced, one can notice a reduction of overall plant energy utilisation factor by about 1.34 to 2.35 percentage points with an advantage for the Selexol^{TM} process (Case 1c) compared to the MDEA process (Case 1b) due to lower thermal duty for solvent regeneration (about 0.76 MJ/kg CO_2 for MDEA vs. 0.08 MJ/kg CO_2 for Selexol^{TM}). The carbon capture rate is about 65 - 70 % with a higher value for MDEA process (Case 1b) due to higher CO_2 capture selectivity of chemical solvents vs. physical solvents.

The economic assessment of hydrogen production processes based on natural gas reforming technologies with and without carbon capture was based on International Energy Agency - Greenhouse Gas R&D Programme methodology (IEAGHG, 2017) as well as the own work of authors (Cormos et al., 2014). For estimation of capital costs and specific capital investment costs (defined as capital cost divided to net energy production), the cost correlation method was used. Figure 3 presents the specific capital investment costs per kW net equivalent (LHV-based hydrogen thermal output plus net power output) for all evaluated designs.

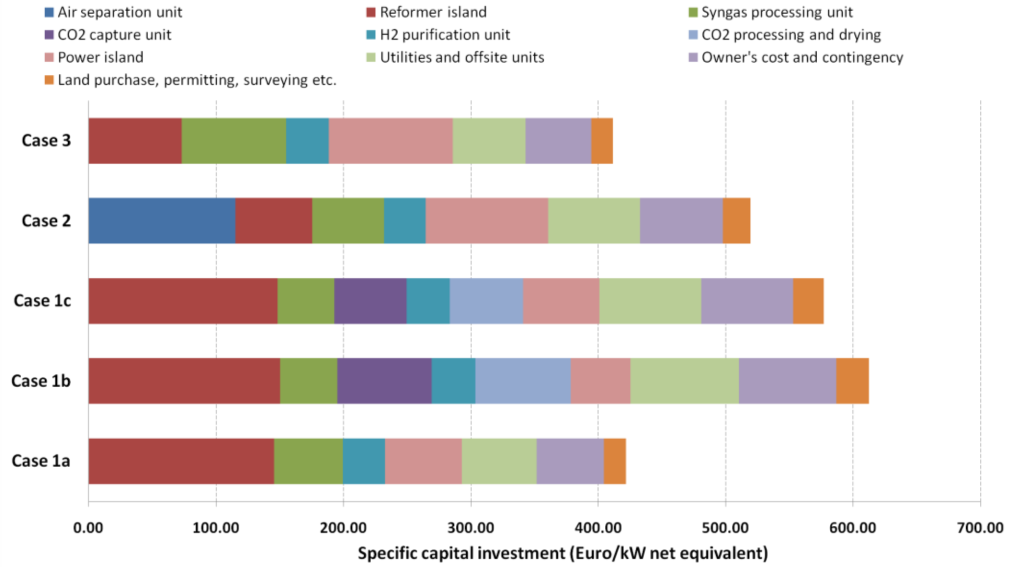

Figure 3: Specific capital investment costs for natural gas reforming-based hydrogen production concepts

As can be observed, the conventional steam reforming without CCS has a specific investment cost of about 422 Euro/kW net equivalent. The autothermal reforming cases have higher specific investment costs (by about 12 - 24 %) mainly due to the contribution of air separation unit / air compressor. If pre-combustion CO_2 capture is applied for conventional steam reforming, the specific capital investment cost increases by 45 % for MDEA process (Case 1b) and 37 % for Selexol^{TM} process (Case 1c) compared to the case without CCS.

For calculation of operational and maintenance (O&M) costs, hydrogen and power production costs and CO_2 capture costs, the main economic assumptions used in the assessment are presented in Table 3.

Table 3: Economic assumptions

Natural gas price	6 € / GJ
BFW water price	0.10 € / t
Cooling water price	0.01 € / t
MDEA price	4,000 € / t
Selexol price	6,500 € / t
Catalyst price	250,000 € / y
Cooling water treatment chemicals	0.0025 € / t
BFW treatment chemicals	45,000 € / month
Direct labour cost	50,000 € / y / person
Administration cost as percentage of labour cost	30 %
Discount rate	8 %
CO_2 price	5 € / t
Operational plant life	25 y

The operational and maintenance (O&M) costs are composed by two main components: the fixed costs which are not varying with the generated energy output (e.g. capital depreciation, labour cost, taxes, insurances, administration etc.) and the variable costs which are proportional with the generated energy output (e.g. fuel, chemicals, catalysts, solvent, waste disposal, unscheduled repairs). Figure 4 presents the fixed and variable O&M costs for all evaluated hydrogen production processes based on natural gas catalytic reforming.

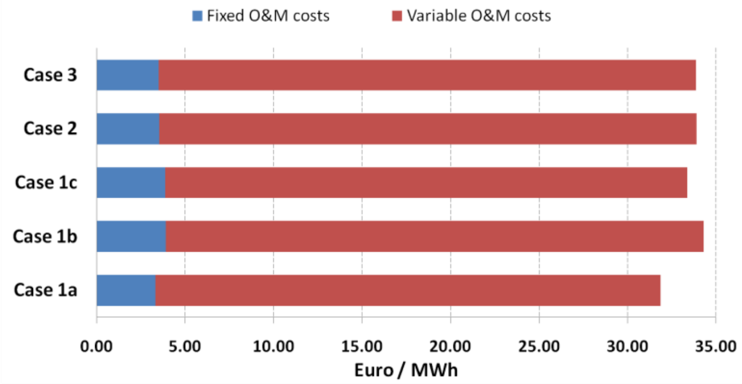

Figure 4: Fixed and variable O&M costs for natural gas reforming-based hydrogen production concepts

It can be observed that the variable cost component is significantly higher than the fixed one; this is because the fuel (natural gas) cost is having a major cost influence. The levelised cost of hydrogen (LCOH) & levelised cost of electricity (LCOE) were calculated using the net present value (NPV) method (Smith, 2016). Once the levelised cost of hydrogen (LCOH) was calculated for non-CCS and CCS concepts, the CO_2 capture costs were calculated based on the following mathematical equations and Table 4 presents the calculated values:

$$CO_2 \ removal \ cost = \frac{LCOH_{Capture} - LCOH_{No \ capture}}{CO_2 \ removed} \qquad (1)$$

$$CO_2 \ avoided \ cost = \frac{LCOH_{Capture} - LCOH_{No \ capture}}{Specific \ CO_2 \ emissions_{No \ capture} - Specific \ CO_2 \ emissions_{Capture}} \qquad (2)$$

Table 4: Costs of hydrogen & electricity and CO_2 capture costs

Main plant data	Units	Case 1a	Case 2	Case 3	Case 1b	Case 1c
Levelised cost of hydrogen (LCOH)	€ / MWh	37.72	41.10	39.63	43.03	41.64
Levelised cost of electricity (LCOE)	€ / MWh	38.15	40.90	38.55	43.20	41.77
CO_2 removal cost	€ / t	-	-	-	27.40	30.59
CO_2 avoided cost	€ / t	-	-	-	29.85	21.86

One can notice that the hydrogen production cost has the lowest value for conventional steam reforming design (Case 1a) than air autothermal reforming (Case 3) then oxygen autothermal reforming (Case 2) - all cases without carbon capture. For conventional steam reforming design, the introduction of pre-combustion CO_2 capture implies an increase of hydrogen production cost by about 14 % for MDEA process (Case 1b) and 10 % for Selexol^{TM} process (Case 1c). The CO_2 avoidance cost is lower for the Selexol^{TM} case than for the MDEA case by about 36 %. The sensitivity analysis of the hydrogen cost vs. various economic parameters for the conventional steam reforming with Selexol^{TM}-based pre-combustion CO_2 capture is presented in Figure 5.

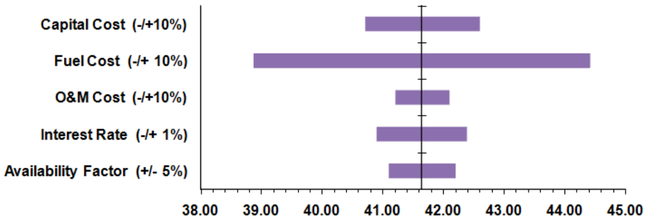

Figure 5: Hydrogen production cost sensitivity analysis

One can notice that the fuel (natural gas) cost is having the major influence on the hydrogen production cost. Cumulative cash flow analysis is an important evaluation aspect to be considered when evaluating the plant economics over it's entirely life. Figure 6 presents the cumulative cash flow analysis for the evaluated cases. As can be noticed, the cases with carbon capture (Cases 1b and 1c) have the highest cumulative cash flows.

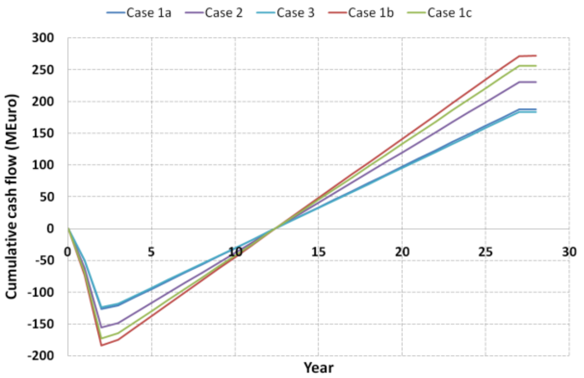

Figure 6: Cumulative cash flow analysis

4. Conclusions

This work is evaluating the updated techno-economics and environmental performances of hydrogen production based on different natural gas reforming technologies with and without carbon capture. Two pre-combustion gas-liquid absorption processes using chemical and physical solvents were assessed. As the techno-economical results show, the conventional steam reforming has higher overall energy utilisation factor than the oxygen and air autothermal reforming cases (about 76.3 % vs. 71.7 %). The carbon capture rate is not higher than 70 % due to unconverted methane and carbon monoxide. The economic indicators show better performances for conventional steam reforming in comparison to autothermal reforming technologies in term of specific capital investment cost (422 vs. 474 - 520 Euro/kW), operational and maintenance costs (31.9 vs. 33.9 Euro/MWh) and hydrogen production costs (37.7 vs. 39.6 - 41.1 Euro/MWh). As main conclusion, the conventional steam reforming technology (coupled with physical gas-liquid absorption for CO_2 capture) is more energy and cost effective than the autothermal reforming technology as hydrogen production method.

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