

Hydrogen Production via Natural Gas Reforming Process – A Life Cycle Assessment Approach

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Abstract

The use of hydrogen as a sustainable alternative fuel and energy carrier is gaining more acceptance as the environmental impact of hydrocarbons becomes more significant. Hydrogen can be produced from various energy sources, such as steam reforming of natural gas, coal gasification, water electrolysis and thermo-chemical water splitting. Hydrogen production is accomplished by steam reforming of natural gas and other fossil primary energy at approximately 97% of total and less than 3% is based on renewable energy sources, such as solar, wind, biomass, geothermal, etc. Today, steam reforming of natural gas is the most important and economic ways of the hydrogen production. The environmental performance of products or processes has become a key issue, which is why ways to minimize the effects on the environment are investigated. One of the effective ways for this purpose is life cycle assessment (LCA). In this paper, LCA of hydrogen production by natural gas reforming (NGR) process are investigated for environmental affect. The investigation uses LCA, which is an analytical tool to identify and quantify environmentally critical phases during the life cycle of a system or a product and/or to evaluate and decrease the overall environmental impact of the system or product.

Keywords: Environmental effects, hydrogen production, LCA, natural gas reforming

1. INTRODUCTION

The energy carrier hydrogen can help solve some energy challenges. Since, its oxidation does not emit greenhouse gases; its use does not contribute climate change, provided it is derived from clean energy sources. Moreover, conversion to electricity via fuel cells is efficient and environmental benign (Solli 2004). There are several ways to produce hydrogen including steam reforming of natural gas, coal gasification, water electrolysis and thermo-chemical cycles. The most commonly used method for hydrogen production is natural gas reforming (Dufour et. al 2009). Natural gas is one of the most important energetic resources. Its importance is growing in the economic world. The methane reforming process is therefore widely studied because of its importance in the petrochemical industry (Gresser and et. al 1998).

In addition, due to the increase in hydrogen demand and the importance of synthesis gas as a major feedstock for carbon chemistry and fuel cells, methane reforming reactions have become more important. Notably, the one site hydrogen production has received considerable attention (Armor and et. al 1999; Roch and et. al 2003; Matsumura and et. al 2004; Kusakabe and et. al 2004). The steam reforming of methane (SRM) is currently the most cost-effective and highly developed method for production of hydrogen at relatively low cost and high hydrogen to carbon ratios are desired for hydrogen production (Sharma and et. al 2007; Profeti and et. al 2008; Xu and et. al 2008; Maluf and et. al 2009). However carbon formation is always the main drawback of the reaction. Some recent works pointed out the basicity role of the support and of the reduction conditions in the carbon formation. In fact, two other factors seem to be important to decrease the carbon deposition: size of metal particles and interactions between the metal particles and the support.

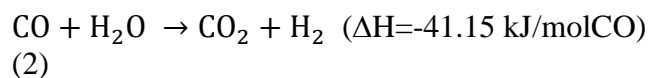
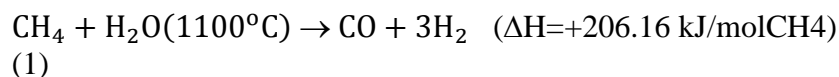
In order to evaluate potential options for the future energy strategy it is of interest to evaluate hydrogen energy system. It has become of great interest to evaluate power system using different criteria. In this respect there are a number of methods, which are used with respective procedure in presenting quantitative merits for the rating of different power system designs (Afgan and Carvalho 2000). Among popular methods applied in the evaluation of power system are: thermodynamic method, energy cost evaluation method and LCA method. Each of the methods is based on the optimization function reflecting a single indicator in evaluation of individual options of power plant design. It has been noted that the energy system complexity requires multivariable assessment taking into a consideration different aspect of power system. It is obvious that beside the economic valorization of the power system the modern approach has to take into a consideration other aspect of the individual design of power system. Since energy production in the power system is based on different physical principles each power system option will reflect the importance of different optimization parameter. Also, each power system option will use different energy source, which conversion in the finale energy will impose different interaction with its environment (Afgan and et. al 2000). In this paper LCA is used to compute life cycle emissions and material use of hydrogen production via natural gas reforming process (without CO₂ capture), and the results are compared using process criteria and value scaling for a similar plant.

2. Analysis of Life Cycle Assessment

The concept of a LCA simply means that the inputs to the cycle (energy, materials, etc.) and outputs (energy waste materials, products, etc.) are evaluated for each step of a product or process life (Ciambrone 1997). LCA analysis can have a positive impact on human health, the ecosystem and natural resources. Specially, LCA is a systematic technique that uses four steps to assess the potential impacts associated with a product, process or service: i-) Goal definition and scoping, ii-) life cycle inventory, iii-) life cycle impact assessment, iv-) life cycle interpretation. It establishes the context in which the assessment is to be made and identifies the boundaries and environmental effects to be reviewed for the assessment. Inventory Analysis identifies and quantifies energy, water and materials usage and environmental releases (e.g., air emissions, solid waste disposal, and wastewater discharge). Impact Assessment assesses the human and ecological effects of energy, water, and material usage and the environmental releases identified in the inventory analysis. Interpretation evaluates the results of the inventory analysis and impact assessment to select the preferred product, process or service with a clear understanding of the uncertainty and the assumptions used to generate the results.

3. Natural Gas Reforming Process

A simplified basic diagram of a conventional steam reforming process of natural gas is shown in Figure 1. The process basically consists of three main steps: I-) Synthesis gas generation, II-) water-gas shift reaction, and III-) gas purification. Natural gas feedstock is mixed with process steam and reacted over a nickel based catalyst contained inside a system of alloyed steel tubes (Steinberg and Cheng 1988). To protect the catalyst, natural gas has to be desulphurized before being fed to the reformer. The following reactions take place in the reformer (Veziroglu and Barbir 1998).



The reforming reaction is strongly endothermic and energy is supplied by combustion of natural gas. The metallurgy of the tubes usually limits the reaction temperature to 700-925°C. The synthesis gas leaving a catalytic reformer is typically a mixture of H₂, CO, CO₂ and CH₄. After the reformer the gas mixture passes through gas purification units to remove CO₂, the remaining CO and other impurities in order to deliver purified hydrogen. Several commercial processes can be used for removing CO₂ (and CO), such as wet scrubbing, pressure swing adsorption, and recently membrane processes.

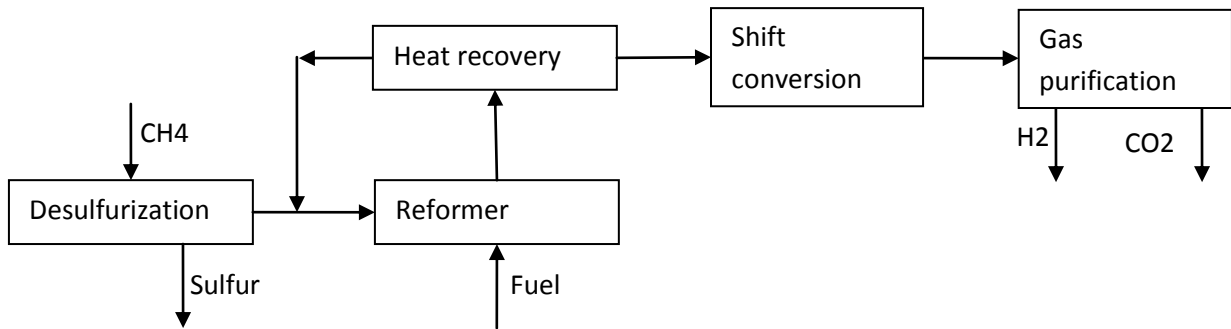


Figure 1. Block diagram of hydrogen production via NGR process

4. Environmental Assessment of Hydrogen Production via NGR Process

LCA analysis is carried out by the National Renewable Energy Laboratory (NREL) for renewable-based (wind electrolysis) and fossil-based (NGR process) system in order to compare the two different types of systems currently seen as feasible near-term hydrogen generation options (Spath and Mann 2001). The natural gas system considered in NREL study was assumed to be sized as 1:5 millionNm³/day. This reflects the typical size of the current systems found in oil refineries. In this study, unlike the literature (Spath and Mann 2001), impact values of material use and environment are scaled and also it is determined that which impact values should be improved.

4.1. Material Use and Environmental Impacts

Regional Air Impacts; The main air pollutions and the quantities emitted to the air during the life cycle of NGR process are given in Table 1. Most of the air emissions in the hydrogen production process originate from the natural gas production and distribution process steps. NGR process plant itself produces a small amount of the listed air emissions during its operation. The regional air emissions from the life-cycle of the process result in a total of 47.7 g/kgH₂ of air emissions.

Table 1. Air emission of NGR process

Pollutant	Emission (g/kgH ₂)	Pollutant	Emission (g/kgH ₂)
Benzene (C ₆ H ₆)	1.4	Non-methane hydrocarbons	16.8

Carbon monoxide (CO)	5.7	Particulates matter	2.0
Nitrogen oxide (N ₂ O)	12.3	Sulfur oxide (S ₂ O)	9.5
Total emission			47.7

Global Warming; The greenhouse gases carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) are considered as contributing factors for the global warming potential (GWP) of the system, which is expressed as the amount equivalent to CO₂ emissions. GWP of CH₄ and N₂O are 21 and 310 times that of CO₂, respectively. Therefore, the GWP of the NGR process is found to be 11,888 gCO₂-equivalent/kgH₂, with contributions of 89.3%, 10.6% and 0.1% from CO₂, CH₄ and N₂O, respectively. The distributions of the greenhouse gas emissions are as follows: 25% from natural gas production and distribution, 2.3% from electricity generation, 0.4% from construction and decommissioning, 78.4% from hydrogen plant operation and -2.5% (credit) from avoided operations.

Water Impacts; The total amount of water emission from NGR process plant is 0.2 g/kgH₂, with the primary pollutant being oils (60%) followed by dissolved matter (29%). The water pollutants come primarily from the material manufacturing steps required for pipeline and plant construction.

Solid Wastes; The total amount of solid waste generated by the NGR process is 202 g/kgH₂, a majority of which comes from the natural gas production and distribution steps. The compressor stations and the natural gas reforming plant have electricity requirements that are significant (80% of solid waste generation is due to these power requirements). The electricity required to operate the pumps and compressors in the system are provided from the national grid.

Land Use; The engineering, procurement and construction company (CB&I), involved in projects for natural resource industries such as oil and gas, is annoyed about the land use of natural gas reforming facility. An approximation of 37.5x45 m (0.17 ha) of land area for a 0.5 milNm³/day facility is given. This land area is scaled to a 1.5 milNm³/day facility size (to match the assumed facility size given in the literature (Spath and Mann 2001)), giving a land area of 0.5 ha/MW.

Water Use; A total amount of 19.8 L/kgH₂ of water is used in the NGR process. The majority of the water is consumed at the hydrogen plant. The smaller percentage (24.0%) is the amount that is consumed during the conversion of natural gas to hydrogen while the higher percentage (71.2%) is a result of the excess steam production.

Energy Use; The total energy consumption (on LHV basis) of NGR process is 183.2 MJ/kgH₂, which is mainly from the natural gas extraction and transport steps of the process.

Materials Use; The non-feedstock resources (fossil fuels, minerals and metals) utilized within the boundaries for NGR process are given in Table 2. The most resource used is natural gas. Iron and limestone are made use of in the construction of the pipeline that transports the natural gas to the NGR plant, as well as the construction of the NGR plant itself most of the oil is consumed while producing and distributing the natural gas and coal is the main sources of

electricity (which is used by the plant). A total amount of 3855 g/kgH₂ of materials is used by the system.

Table 2. Resources consumption of NGR plant

Resources	Consumption (g/kgH ₂)	Resources	Consumption (g/kgH ₂)
Coal	159.2	Limestone	16.0
Iron (ore)	10.3	Natural gas	3642.3
Iron (scrap)	11.1	Oil	16.4
Total Consumption			3855

4.2. Life Cycle Assessment of the Processes

The information gained on the performance of NGR process on all of the criteria is initially entered in Table 3. The best and worst cases is the noted (based on the maximization or minimization of the criterion from literature), and the range between the best and worst case is indicated as seen in Table 4.

Table 3. Environmental impact, resource use and cost data for NGR process

Impacts	Value	Unit	Impacts	Value	Unit
Regional Air Impacts (RAI)	47.7	g/kgH ₂	Water (W)	19.8	L/kgH ₂
Global Warming (GW)	11888	gCO ₂ /kgH ₂	Energy (E)	183.3	MJ/kgH ₂
Water Impacts (WI)	0.2	g/kgH ₂	Materials (M)	3855	g/kgH ₂
Solid Wastes (SW)	202	g/kgH ₂	Cost (C)	1.38	\$/kgH ₂
Land (L)	0.5	ha/MW	Cost (C)	5.60	\$/GJ

The data is then scaled according to these ranges, to result in values ranging from zero (the worst) to one (the best). This calculation is done by using the following formulation.

$$\text{Value} = (X - X_w)/(X_b - X_w) \quad (3)$$

where, X is scaled data, X_w and X_b is the worst and best value assumed for data, respectively.

Table 4. Example data on the performance of the NGR process on the criteria and value scaling

Criteria (Raw Data)

RAI	GW	WI	SW	L	W	E	M	C
47.7	11888	0.2	202	0.5	19.8	183.3	3855	1.38
Best	Best	Best	Best	Best	Best	Best	Best	Best
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Worst	Worst	Worst	Worst	Worst	Worst	Worst	Worst	Worst
80.0	30000	10.0	3000	3	130	500	30000	8.0

Criteria (Scaled Data)

RAI	GW	WI	SW	L	W	E	M	C
0.40	0.60	0.98	0.93	0.85	0.84	0.63	0.87	0.82

Table 4 demonstrates a portion of the raw data, best/worst cases, ranges and value scaled data to illustrate the explanations above.

5. CONCLUSION

Environmental effects normally are not revealed in market prices. By assigning monetary values to these effects, they will be enabled to have a place in the market, thus providing grounds for more effective decision-making. Since the market is deficient in representing the external costs resulting from the environmental impacts, there is no incentive to incorporate this cost in the decision-making process. However, if the market takes the externalities into account, then a final decision will also have to include both the private and external costs, thus providing a fairer system. In this study, LCA of hydrogen production via natural gas

reforming is presented. Obtained impact values of material use and environment are scaled from 0 (worst) to 1 (best). Accordingly, water impacts (WI) and solid wastes (SW) impacts values of this process are good. In addition, land (L), water (W), materials (M) and cost (C) values are average, meaning neither good nor bad. However, it is emphasized that values of regional air impacts (RAI), global warming (GW) and energy (E) should be improved in terms of environment.

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