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Milestone Report

Life Cycle Assessment of Renewable Hydrogen Production via Wind/Electrolysis

Milestone Completion Report

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INTRODUCTION

Although hydrogen is generally considered to be a clean fuel, it is important to recognize that its production may have negative impacts on the environment. Examining the resource consumption, energy requirements, and emissions from a life cycle point of view gives a complete picture of the environmental burdens associated with hydrogen production. Life cycle assessment (LCA) is a systematic analytical method that helps identify and evaluate the environmental impacts of a specific process or competing processes. The National Renewable Energy Laboratory has performed a life cycle assessment on a renewable hydrogen production process which employs wind/electrolysis. In order to quantify the emissions, resource consumption, and energy use, collectively known as environmental stressors, material and energy balances are performed in a cradle-to-grave manner on the operations required to transform raw materials into useful products. For the wind/electrolysis system, the material production processes required to construct the wind turbines, electrolyzer, and hydrogen storage tanks were taken into account. All resources, emissions, and energy flows were inventoried within the boundaries of the system so that the total environmental picture of each system could be determined.

SYSTEM DESCRIPTION/BOUNDARIES

The wind/electrolysis system examined in this study is shown in Figure 1. Material requirements and design data for this system were taken from electrolyzer and wind turbine manufacturers. The system incorporates three 50 kW Atlantic Orient Corporation (AOC) wind turbines with a 30 Nm^3/hr Stuart Energy electrolyzer. The size of the electrolyzer determines that multiple wind turbines are required because they come in discreet sizes, generally classified as small, industrial, or utility. Additionally, it is usually better to operate with several wind turbines to allow for more consistency in the wind distribution, and having multiple wind turbines will also allow the system to operate at a reduced capacity if one of the turbines is shut down. The turbine blades, which are currently manufactured in Europe, were assumed to be transported across the Atlantic Ocean to a major coastal port in the U.S. and then transported by rail to the upper Midwest. To operate at a higher point on its efficiency curve for a greater number of hours during the year, the electrolyzer was sized for 75% of the maximum wind speed. For the wind data used in this analysis, the wind turbines operate at greater than 75% of the maximum wind speed for only 1% of the year. The amount of hydrogen that is not generated during this time is very small, 2.6 kg/yr of H_2, and is equal to 0.05% of the total amount of hydrogen produced by the system per year.

The system operation was determined using class 5 wind data from the upper Midwest region of the United States. The electricity is wheeled from this remote location to a fueling station where the electrolyzer converts the electricity to hydrogen with an efficiency of 85% (higher heating value basis). The product hydrogen is compressed to a pressure of 20 MPa, stored, and dispensed at the fueling station. Several electrical losses were subtracted from the gross amount of electricity produced by the wind turbines. First, there are the transmission losses, which are 7.03%. Next, there is a small amount of electricity needed to pump the deionized water. Finally, there is the electrical requirement for compression of the product hydrogen. The amount of hydrogen produced by this system is enough to fuel 36 vehicles at 3 kg of H_2/week.

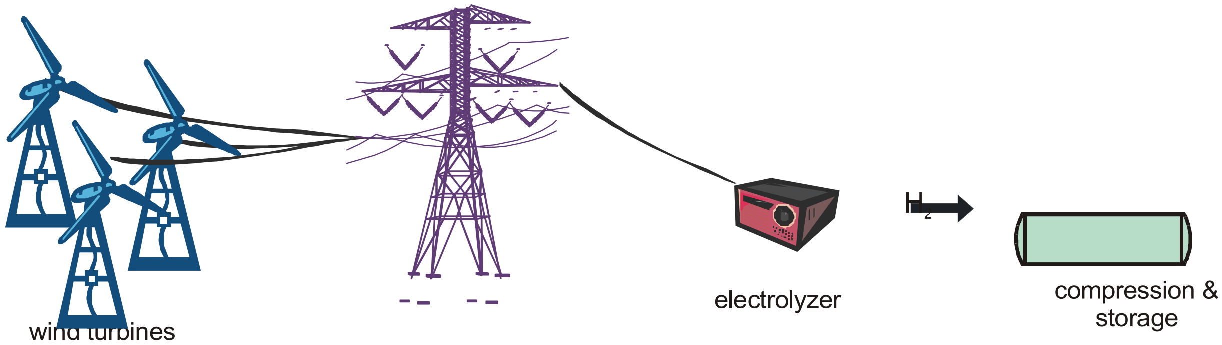

Figure 1: Wind/electrolysis System

RESOURCE REQUIREMENTS

Fossil fuels, metals, and minerals are used to produce hydrogen in this process. Table 1 shows the major resource requirements for this system, excluding water. The resources that are consumed at the highest rate are iron (ore plus scrap) and limestone. The iron, which is mostly used in manufacturing the wind turbines and hydrogen storage vessels, accounts for 37.4% of the resources shown in Table 1. The large amount of limestone, 35.5% of the major resources, is used for the turbines' concrete foundations. Coal, which is consumed primarily to produce the steel, iron, and concrete, accounts for 20.8% of the remaining resources. This is followed by oil at 4.7%, and natural gas at 1.6% which are primarily used in manufacturing the wind turbines. The wind turbine foundation used in the analysis is a standard design by AOC and depending on the site specific soil conditions, it is quite possible that less concrete and steel could be used, thus reducing the required resources. A sensitivity analysis was performed to determine how changes in this parameter would affect the results (see section labeled Sensitivity Analysis - Wind Turbine Foundation Requirements).

Table 1: Average Resource Consumption

Resource	total ($g/kg\ H_2$)	% of total in this table	from wind turbines	from electrolysis	from storage
Coal (in ground)	214.7	20.8%	67.6%	5.6%	26.7%
Iron (Fe, ore)	212.2	20.6%	64.2%	5.9%	30.0%
Iron scrap	174.2	16.9%	52.7%	7.7%	39.6%
Limestone ($CaCO_3$, in ground)	366.6	35.5%	96.4%	0.3%	3.3%
Natural gas (in ground)	16.2	1.6%	72.0%	15.4%	12.6%
Oil (in ground)	48.3	4.7%	76.2%	13.1%	10.7%

Water is consumed not only in the electrolysis operation, but also in upstream processes. For each kg of hydrogen produced, 26.7 liters of water are consumed by the system. Nearly 45% is used by the electrolyzer, while 38% and 17% is used in manufacturing the wind turbines and the hydrogen storage vessels, respectively.

GLOBAL WARMING POTENTIAL & GREENHOUSE GASES

The global warming potential (GWP) of the system is a combination of CO_2, CH_4, and N_2O emissions expressed as CO_2-equivalence. For a 100 year time frame, the capacity of CH_4 and N_2O to contribute to the warming of the atmosphere is 21 and 310 times higher than CO_2, respectively (Houghton, *et al*, 1996). The GWP and the contribution from each compound is given in Table 3.

Table 3: GWP (g CO_2-equivalent/kg of H_2)

GWP (g CO_2-equivalent/kg of H_2)	% contribution to GWP		
	CO_2	CH_4	N_2O
970	97.9%	0.6%	1.5%

Figure 2: Life Cycle GWP (CO_2-equivalent)

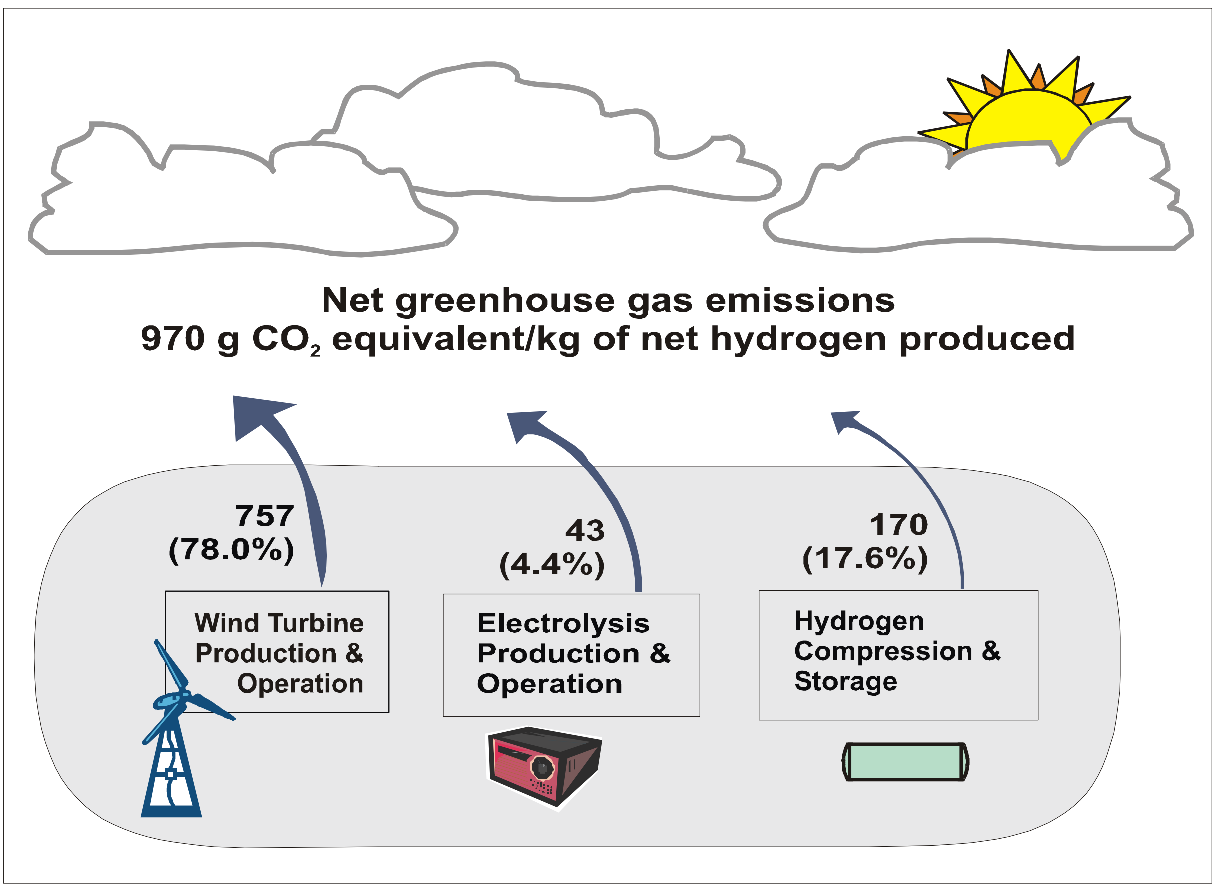

Figure 2 shows how the CO_2-equivalent emissions are divided among the different process blocks for the wind/electrolysis system. Because of the steel and concrete requirements, the construction and operation of the wind turbines account for 78% of the total GWP. Hydrogen storage and compression accounts for 18% of the GWP. This is due primarily to the production of the steel used in the storage tanks.

OTHER AIR EMISSIONS

Table 4 is a list of the major air emissions. In terms of total air emissions, CO_2 is emitted at the highest rate, accounting for greater than 95 wt%. Producing concrete and steel for the wind turbines and hydrogen storage accounts for 77% of the system's CO_2. After CO_2, the next highest air emission is particulates. These come primarily from quarrying the sand and limestone needed for concrete production. Concrete production for the wind turbines accounts for 85% of the system's particulate emissions. For the electrolysis step, the largest air emissions are SO_X at 26% of the system total and NO_X at 47%. These come from producing benzene, which is used to make Ryton© for the electrolyzer. However, in general, the majority of the air emissions come from the process steps in manufacturing the wind turbines.

Table 4: Average Air Emissions

Air Emission	System Total (g/kg of H_2)	% of total in this table	% of total excluding CO_2	from wind turbines	from electrolysis	from storage
Carbon dioxide	950.0	95.5%		78.1%	4.4%	17.5%
Carbon monoxide	0.9	0.1%	1.9%	80.3%	3.5%	16.2%
Methane	0.3	<0.0%	0.6%	92.4%	2.8%	4.8%
Nitrogen oxides	4.7	0.5%	10.3%	45.9%	47.1%	7.0%
Nitrous oxide	0.05	<0.0%	0.1%	67.1%	5.6%	27.3%
Non-methane hydrocarbons	4.4	0.4%	9.9%	62.5%	7.3%	30.1%
Particulates	28.7	2.9%	63.7%	94.2%	0.7%	5.0%
Sulfur oxides	6.1	0.6%	13.5%	61.8%	26.1%	12.1%

ENERGY BALANCE

There are several ways of looking at the energy balance of the system. The first is to examine the total energy consumption of the system as shown in Table 5. The majority of the energy consumption, 72.6%, comes from manufacturing the materials required for the wind turbines.

Table 5: Average Energy Requirement (LHV basis)

System total energy consumption (MJ/kg H_2)	from wind turbines	from electrolysis	from storage
9.1	72.6%	4.8%	31.6%

The net energy ratio, defined in Table 6, provides another means of examining the system's energy balance. It illustrates how much energy is produced for each unit of fossil fuel energy consumed. Because of the nature of the wind/electrolysis system, the net energy ratio is greater than one indicating that the energy in the product hydrogen is greater than the fossil energy consumed. For every 13.2 MJ of hydrogen produced, 1 MJ of fossil energy must be consumed (LHV basis).

Table 6: Net Energy Ratio (LHV)

Net Energy Ratio	
Definition	Result
E_{H2}/Eff	13.2
where: E_{H2} = energy in the hydrogen Eff = fossil fuel energy consumed within the system	

SOLID WASTES

The solid waste produced from the system can be classified as miscellaneous non-hazardous waste. The total quantity of waste is 223 g/kg of H_2. The majority of the solid waste (79%) comes from manufacturing the wind turbines. Concrete production results in 47% of the total solid waste for this system and steel production results in 22% of the total waste. In the concrete manufacturing step, the two major sources of solid waste are grid electricity (42%) and limestone production (30%). In the steel production step, 61% of the solid waste comes from converting iron ore to steel and 31% comes from grid electricity. The total amount of solid waste that is a result of grid electricity is 27% of the system total. Because most of the electricity in the U.S. is generated from coal-fired power plants, this waste will be in the form of coal ash and flue gas clean-up waste. After grid electricity, limestone production accounts for 14% of the total system waste and converting iron ore to steel accounts for another 14% of the system's total solid waste.

SENSITIVITY ANALYSIS - WIND TURBINE FOUNDATION REQUIREMENTS

The wind turbine foundation used in the analysis is a standard design by AOC and, depending on the site specific soil conditions, it is quite possible that less concrete and steel could be used, thus reducing the resources, emissions, and energy consumption per kg of hydrogen produced. To test the effect of reducing the material requirements, the concrete and steel needed for the foundation were decreased by 25% and 50%. The following table, Table 7, summarizes the results of these reductions compared to the base case.

Table 7: Results from Sensitivity Analysis on Wind Turbine Foundation Requirements

	Base case value	25% material reduction		50% material reduction	
		value	change from base case	value	change from base case
RESOURCES					
Coal	214.7	201.3	-6.2%	187.9	-12.5%
Iron ore	212.2	205.3	-3.3%	198.3	-6.5%
Iron scrap	174.2	166.6	-4.3%	159.1	-8.6%
Limestone	366.6	281.8	-23.1%	197.0	-46.3%
Natural gas	16.2	15.6	-4.0%	14.9	-8.1%
Oil	48.3	46.4	-3.8%	44.6	-7.6%
AIR EMISSIONS					
Benzene	0.0012	0.0011	-12.8%	0.0009	-25.6%
Carbon dioxide	950.0	845.3	-11.0%	740.6	-22.0%
Carbon monoxide	0.86	0.75	-12.4%	0.64	-24.7%
Methane	0.29	0.25	-13.7%	0.21	-27.3%
Nitrogen oxides	4.7	4.4	-5.5%	4.1	-10.9%
Nitrous oxide	0.046	0.043	-6.1%	0.041	-12.1%
Non-methane hydrocarbons	4.4	4.3	-3.5%	4.1	-7.0%
Particulates	28.7	22.5	-21.6%	16.3	-43.1%
Sulfur oxides	6.1	5.8	-4.6%	5.5	-9.3%
OTHER					
GWP	970	864	-11.0%	758	-21.9%
System energy consumption (MJ/kg of H_2)	9.1	8.6	-5.9%	8.0	-11.8%
Net energy ratio	13.2	14.0	6.2%	15.0	13.3%
Total solid waste generated (g/kg of H_2)	223.8	193.6	-13.5%	163.4	-27.0%

Reducing the amount of concrete and steel results in a decrease in the resource requirements, most notably the amount of limestone used. Several air emissions decrease by significant amounts primarily due to the reduction in limestone. The particulates decrease by 21.6% and 43.1% for the 25% and 50% material reduction case, respectively. The reduction in the amount of CO_2 caused by reducing the foundation material requirements, results in a 11.0% and 21.9% decrease in the GWP for the 25% and 50% material reduction case, respectively. Additionally, because material manufacturing steps are energy-intensive, reducing the foundation material requirements lowers the system's energy consumption and increases the net energy ratio.

Finally, the amount of solid waste generated is decreased by 13.5% and 27.0% for the 25% and 50% material reduction case, respectively.

SUMMARY

This study examined the resource consumption, energy requirements, and emissions of a wind/electrolysis system from a life cycle point of view, giving a complete picture of the environmental burdens associated with hydrogen production from wind/electrolysis. On a system basis, CO_2 is emitted in the largest quantity, accounting for over 95 wt% of the total air emissions. The resources required, energy consumed, pollutants emitted, and waste generated are mostly due to plant construction. The majority of the stressors come from manufacturing and constructing the wind turbines. Because of the nature of the process, almost no emissions result from plant operation. The energy balance of each system shows that considerably more hydrogen energy is produced than the amount of fossil energy consumed. Any increase in wind turbine or electrolyzer efficiency will result a reduced amount of resource consumption, emissions, and energy use per kg of hydrogen produced.

FUTURE WORK

This study is being compared to a separate LCA previously performed on a fossil based system, steam methane reforming (Spath and Mann, 2000). Future work will involve comparisons of these studies to hydrogen production via other routes such as biomass and photovoltaics. Additionally, long-term technologies (e.g., photobiological hydrogen production, plasma reforming/oxidation, and carbon nanotube hydrogen storage) can be examined using life cycle assessment to explore the possibility of improved environmental consequences.

RELATED LCA STUDIES

Prior to conducting this LCA, a literature search was performed to see what life cycle work had been done on systems involving wind and/or electrolysis. No publications were found related to LCAs of systems using electrolysis. However, several papers were found containing information about LCAs for wind generated power production. The following list is a brief summary of these documents.

Bates, J.; Watkiss, P.; Thorpe. T. (1997).
This article gives the results of LCAs for three renewable technologies: wind turbines, photovoltaic systems, and small, stand-alone solar thermal systems. They state that the material manufacturing steps result in the largest amount of emissions therefore, they look at only these steps. While their statement is true this does not give the total environmental picture of each renewable. Specific material requirements are not given. They list only air emission results obtained from using German and UK data. They do not say if the material requirements were from specific wind turbines.

Kato, S.; Widiyanto, A. (1999).
They examined net energy, resource consumption, and emissions of various electricity generation systems using an evaluation method called NETS (Numerical Environmental Total Standard). This method calculates a value which indicates the impact on the environment.

Proops, J.L.R.; Gay, P.W., Speck, S.; Schröder, T. (1996).
This paper examines only CO_2, SO_X, and NO_X for eight forms of electricity generation: 2 coal technologies, methane, tide, wave, wind, and solar. They use the input-output approach which deals with economic activity. Their data sources come from the UK.

Schleisner, L. (1999).
This study examined life cycle energy and emissions for electricity production from both offshore and land-based wind farms. The offshore wind farm consists of ten 500 kW turbines and the onshore farm consists of eighteen 500 kW units. The total amount of electricity produced over a 20 year life was assumed to be the same for both systems at 250 GWh. Danish energy data is assumed for all materials manufacturing steps. A breakdown of total material requirements for each system is given. Only CO_2, SO_2, and NO_X emissions are given in g/kWh.

Uchiyama, Y. (1997).
This paper presents the net energy and CO_2 emissions for photovoltaic cell and wind power generation plants. The only material requirements listed are cement, steel, and sand and stone for four different Japanese wind machines. They state that higher performance advanced wind turbines can improve the energy ratio and reduce the CO_2 emissions by 1/5 to 1/3 of that from today's turbines.

Van De Vate, J.F. (1996).
They examined the greenhouse gases for the full energy chain of the following energy sources: coal, oil, natural gas, hydro, nuclear, wind, solar PV, and biomass. The article talks about the methodologies and databases for making comparative assessments. Very little data is given.

Wiese, A.; Kaltschmitt, M. (1996).
They perform an LCA on electricity production from wind examining three system sizes: 100 kW, 500 kW, and 1,000 kW and three different annual mean wind velocities (4.5, 5.5, and 6.5 m/s). They used hourly wind data from several locations in Germany. Ranges of material requirements for steel cement, non-ferrous metals, and plastic are listed. The only results given are air emissions for SO_2, NO_X, and CO_2.

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13. ABSTRACT *(Maximum 200 words)*

This report summarizes the results of a lifecycle assessment of a renewable hydrogen production process employing wind/electrolysis. Resource consumption, energy requirements, and emissions were determined in a cradle-to-grave manner on the operations required to transform raw materials into useful products, including the material production processes required to construct the wind turbines, electrolyzer, and hydrogen storage tanks.

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