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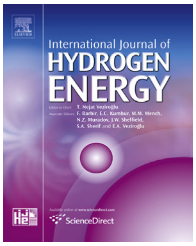

Life cycle assessment of wind-based hydrogen production in Western Canada

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ABSTRACT

Hydrogen is a key input to industrial processes. In western Canada, there is a significant demand for hydrogen for industrial purposes, both to upgrade bitumen and as a chemical agent. The key driver for this research is the need to assess options for the energy industry to lower its carbon footprint by using hydrogen produced from renewable sources. The environmental impacts associated with hydrogen production through water electrolysis using the electricity generated from a wind power plant are evaluated in this paper. A life cycle assessment was done to determine the greenhouse gas (GHG) emissions per unit mass of produced hydrogen by considering the emissions starting from the extraction of wind energy to the production of hydrogen. An uncertainty analysis was conducted to assess the effects of variations of different input parameters on the GHG footprint of hydrogen produced from wind. The total GHG emissions of a wind-based hydrogen production plant are estimated to be 0.68 ± 0.05 kg CO_2 eq./kg H_2, 65% of which are from the construction of the wind power system. The results are compared with those of conventional fossil fuel-based systems. The overall GHG emissions from wind-based hydrogen production are about 94% lower than those associated with hydrogen production through steam methane reforming (SMR). Natural gas-based hydrogen production emissions are mainly found in the plant operation stage. For wind-to-hydrogen systems, the manufacturing and installation of the systems have significant environmental impacts. However, the hydrogen produced from wind energy can significantly reduce the GHG footprint of the energy industry.

Introduction

Global energy consumption is predicted to increase by 56% from 553 EJ in 2010 to 865 EJ in 2040 [1]. Renewable energy is the fastest-growing source of energy in the world. Its share of total energy consumption is expected to increase from 11% in 2010 to 15% in 2040. However, fossil fuels continue to supply most of the world's energy demand. In 2040, liquid fuels, natural gas, and coal will supply over 75% of the world's total energy use. Liquid fuel consumption is expected to increase from 87 million barrels per day (bbl/d) in 2010 to 115 million bbl/d in 2040 [1]. Canada has shown strong growth in its liquids production with an average increase of 1.8% per year until recently.

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Liquids are produced from three major sources: oil sands in Alberta; crude oil in the Western Canada Sedimentary Basin (WCSB), which includes Alberta, Saskatchewan, and parts of British Columbia and Manitoba; and offshore oil fields in eastern Canada. Liquids production from the oil sands has increased steadily in recent decades. It represented over 50% of oil production in 2011, with Alberta, one of the key energy-producing provinces in western Canada, being responsible for more than 75% [1]. This industry has a large greenhouse gas (GHG) emissions footprint and is looking for options to reduce it.

In 2012, about 1.9 million bbl/d of crude bitumen were produced from three oil sands regions in Alberta: Athabasca, Cold Lake, and Peace River. About 1.0 million bbl/d of crude bitumen was sent for upgrading in 2012. The upgrading of bitumen to synthetic crude oil (SCO) requires vast amounts of hydrogen. Each barrel of bitumen requires 3–4.5 kg of hydrogen for upgrading [2]. There are currently five operating bitumen upgraders in Alberta, and they have a total capacity of 1.3 million bbl/d [3]. Bitumen upgrading volumes are forecast to rise to 1.5 million bbl/d by 2030 [4]. At present, most of the upgrading operations rely on hydrogen production through steam methane reforming (SMR) [5].

Alberta has the highest GHG emissions in Canada. Its total GHG emissions in 2011 were 246 Mt CO_2 eq., which represented 35% of the national total [6]. The oil sands operations sector was reported as having the largest share of Alberta's 2011 GHG emissions, emitting 39.8% of total reported emissions [7]. GHG emissions from hydrogen production through SMR are estimated to be 11.89 kg CO_2 eq./kg H_2 [8]. The emissions associated with bitumen upgrading are expected to rise from 18 Mt CO_2 eq. in 2011 to 29 Mt CO_2 eq by 2030 [9]. As GHG emissions associated with hydrogen production are significant, the development of cleaner, more sustainable methods of hydrogen generation are essential for Alberta's oil sands industry.

Various methods of hydrogen production from renewable energy resources have been studied [1,10–18]. Acar and Dincer [19] did a comparative environmental impact assessment of possible hydrogen production methods from renewable and non-renewable sources. A hybrid-based renewable energy (including wind and solar) hydrogen and electricity production system was investigated by Caliskan et al. [20]. The challenges associated with production of H_2 from renewable sources derived from agricultural or other waste streams were presented in a study conducted by Levin and Chahine [21]. Another study done by Cormos [22] assesses hydrogen production from bioethanol reforming with carbon capture. Suleman et al. [23] investigated the case of hydrogen production by electrolysis of sodium chloride cycles. In this paper, electrolytic hydrogen productions was also compared using different types of cells, such as the membrane, diaphragm and mercury. Dufour et al. [24], in their study, determined the critical aspects that need to be addressed to ensure feasibility of hydrogen production form renewables sources. A novel system for continuous hydrogen production from waste plastic by fluidized-bed gasification combined sorption-enhanced steam reforming process was proposed by Dou et al. [25]. Li et al. [26] investigated the case of hydrogen production by steam reforming of tar from biomass pyrolysis over supported Co catalysts. The study of hydrogen production from fossil and renewable sources using an oxygen transport membrane was carried out by Park et al. [27]. A new light-based photoelectrochemical hydrogen production system was designed and developed by Ghosh and Dincer [28]. Chaubey et al. [12] reviewed the recent developments in industrial techniques for hydrogen production. Among the different methods, water electrolysis is a proven and mature technology in which electricity is used to split water into oxygen and hydrogen. Patyk et al. evaluated the environmental performance of different hydrogen production systems through high temperature electrolysis [29]. A life cycle assessment (LCA) for a high temperature water vapour electrolysis for hydrogen production through a nuclear plant was studied by Utgikar and Thiesen [30]. Thermal-to-electric efficiency of the nuclear plant was assumed to be 45%. The plant's GHG emissions were reported to be 2 kg CO_2 eq./kg H_2.

Wind energy is one of the most cost-effective forms of renewable energy with current technology. Alberta has an abundant wind energy resource that can be used to produce the electricity and hydrogen required for bitumen upgrading [31]. As of July 2013, there were 1088 MW of wind capacity connected to the Alberta grid, which represented about 7% of Alberta's total generation capacity of 14,422 MW [31]. There could be approximately 2200 MW of wind power connected to the grid by 2022 [4]. Table 1 presents the wind farms in Alberta that are currently connected to the grid [32].

Olateju and Kumar [33] developed a techno-economic model to determine the cost of hydrogen production from wind energy. The Summerview wind farm in Pincher Creek, Alberta was considered in their study. An electrolyser size of 50 Nm^3/h was shown to be the optimal size for a constant flow rate electrolyser.

Large-scale hydrogen production from wind energy was also studied by Olateju et al. [34]. It was shown that the optimal plant configuration would consist of 80 units of 760 Nm^3/h electrolyzers with a hydrogen production cost of \$8.43/kg H_2.

A life cycle assessment of wind-based hydrogen production was conducted by Spath and Mann [35]. Three 50 kW wind turbines with a 30 Nm^3/h electrolyser were considered. The electricity-to-hydrogen efficiency of the electrolyser was 85%, on a higher heating value basis. Transmission losses of 7.03% were also considered. The produced hydrogen was compressed to a pressure of 20 MPa and stored. The overall GHG emissions were reported as 0.970 kg CO_2 eq./kg H_2 [35]. No publication has been found on an LCA of wind-based hydrogen production specific to western Canada.

The overall objective of this paper is to assess the GHG emissions associated with the full life cycle of hydrogen production through water electrolysis using the electricity generated from a wind power plant in western Canada. The specific objectives are to:

- Conduct an LCA for the production of hydrogen from wind energy in western Canada considering all the unit operations.
- Compare the LCA results with fossil fuel-based hydrogen production.

Table 1 – Alberta's wind farms.[a]

Wind farm	Year installed	Turbines	Total installed capacity (MW)
Ardenville	2010	23XVestas V90-3 MW	69
Blue Trail	2009	22XVestas 3 MW	66
Castle River	2000	15XVestas V47-660 kW	39
	2001	44XVestas V47-660 kW	
Castle Rock	2012	33 X Enercon	75.9
Cowley Ridge	1993	57 X Kenetech 375 kW	40.9
	2001	15 X Nordex 1.3 MW	
Taber	2007	37XEnercon E70 2.2 MW	81.4
Ghost Pine	2010	51X GE 1.6	81.6
Halkirk	2012	83XVestas V90–1.8 MW	149.4
Kettles Hill	2006	5XVestas V80–1.8 MW	63
	2007	30XVestas V80–1.8 MW	
McBride Lake	2003	114XVestas 660 kW	75.2
Soderglen	2006	47XGE 1.5 MW	70.5
Summerview 1	2004	39XVestas 1.8 MW	70.2
Summerview 2	2010	22XVestas 3 MW	66
Chin Chute	2006	20X1.5 MW GE	30
Magrath	2004	20X1.5 MW GE Wind	30
Wintering Hills	2011	General Electric x 55	88

[a] Data presented in Ref. [34] are updated based on [32].

- Conduct an uncertainty analysis to assess the impact of input data on the results.
- Develop information to better understand hydrogen production using wind energy and make decisions on alternative energy pathways for hydrogen production from wind.

Approach and methodology

Life cycle assessment

A LCA evaluates the environmental aspects of a product system from raw material acquisition to final disposal. It consists of four phases, as follows [36]:

- The goal and scope definition, including the reasons for performing the study, the functional unit, and the system boundary.
- Inventory analysis, including data collection and the quantifying inputs and outputs of each unit operation.
- Impact assessment, in which the significance of potential environmental impacts is evaluated.
- Interpretation, that is, the findings from the inventory analysis and the impact assessment phases are considered together to present consistent results based on the goal and scope definition phase of the study.

The main life cycle stages and system boundary examined in this study are shown in Fig. 1. The main unit operations studied are wind power generation, hydrogen production through water electrolysis, hydrogen compressions, and

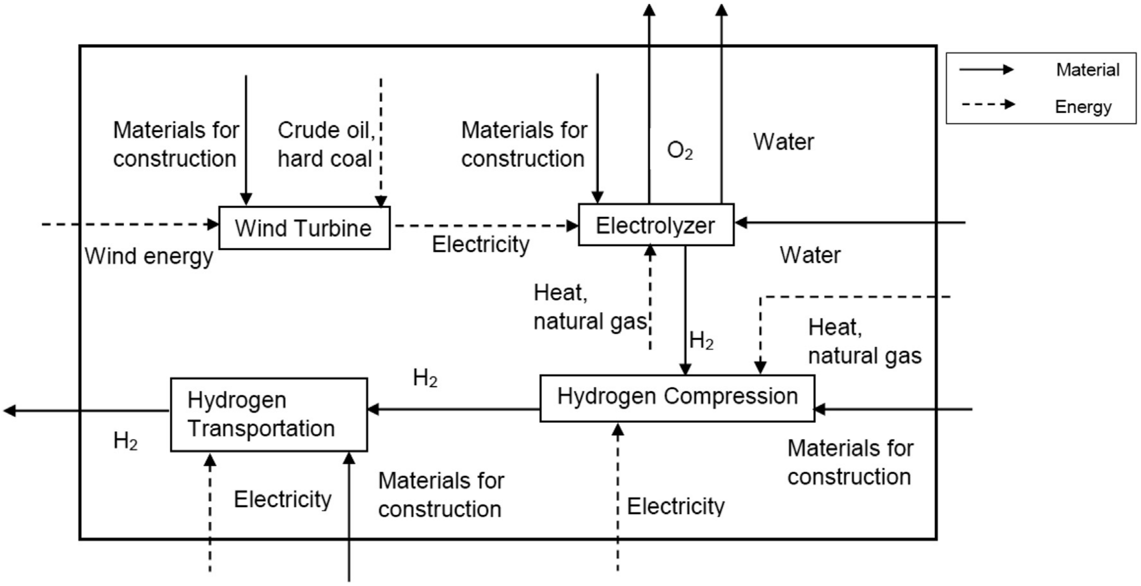

Fig. 1 – Life cycle stages for hydrogen production from wind-based electricity.

hydrogen transportation. Each stage includes manufacturing, transport and erection, operation and maintenance, dismantling, and scrapping. The functional unit is 1 kg of hydrogen delivered to the bitumen upgrader.

Uncertainty analysis

A major problem regarding LCA is the uncertainty of the data used in the inventory analysis. Different techniques are available to estimate uncertainties in the LCA. A framework for data uncertainty analysis in an LCA was presented by Huijbregts et al. [37]. Data uncertainty is divided into two categories: (1) absence of data, and (2) the inaccuracy of data. Applying uncertainty factors, using input–output modelling, and stochastic modelling are potential options to deal with data inaccuracy for an uncertainty analysis [37]. Stochastic modelling done through a Monte Carlo simulation is a favourable technique to deal with data uncertainty in an LCA [37]. Among various available Monte Carlo simulation risk analysis add-ins, ModelRisk is selected and used in this paper [38].

Input data and assumptions

Wind power generation

The Summerview 2 Wind Facility was selected for this study. The facility is located northeast of Pincher Creek, Alberta and is comprised of 22 Vestas V90-3 MW turbines on 80 m towers with a total capacity of 66 MW [39]. The technical specifications of a Vestas V90-3 MW wind turbine are presented in Table 2 [40]. With an average capacity factor of 30% [41], the total electric power generation of the plant is about 173 GWh/y.

Table 2 – Technical specifications of a Vestas V90-3 MW turbine.[a]

Number of blades	3
Hub height (m)	80
Cut-in wind speed (m/s)	4
Nominal wind speed (m/s)	15
Cut-out wind speed (m/s)	25
Rated output (MW)	3
Nacelle weight (t)	70
Rotor weight (t)	41
Tower weight (t)	160

[a] Derived from Ref. [40].

Table 3 shows the material breakdown for a wind power plant of V90-3.0 MW turbines. The electricity grid factor for Alberta, 0.65 t CO_2 eq./MWh, was used for the manufacturing stage [42].

Water electrolysis

The production of hydrogen through water electrolysis is a critical part of the integrated wind-to-hydrogen system. There are three types of electrolyzers available: alkaline, polymer electrolyte membrane (PEM), and high temperature solid oxide electrolyzers (SOE) [43].

Alkaline water electrolysis is a mature technology. Since these electrolyzers are reliable and safe, they are considered the most extended electrolysis technology at the commercial level in the world [43].

An alkaline electrolyser was selected for hydrogen production in this study [33]. The main parameters of this electrolyser are presented in Table 4. With an electricity-to-hydrogen efficiency of 74% on a higher heating value basis, the rate of hydrogen production is 6.5 t/d. The data presented in Ref. [44] are used to evaluate the material and energy consumption for the production of electrolysis.

Hydrogen compression

The material and energy consumption for the hydrogen compression is presented in Table 5. The energy consumption is calculated based on the exit pressure of the compressor which is considered to be 60 bar [34]. The compressor has an efficiency of 70% and lifetime of 22 years [44].

Table 4 – Main parameters of the electrolyser studied.[a]

Electricity consumption (kWh/kgH_2)	53
Water consumption (m^3/kgH_2)	0.01
Electricity-to-hydrogen efficiency (%)	74
Temperature (°C)	70
Pressure (bar)	15
Maximum hydrogen production rate (Nm^3/h)	60
Lifetime (y)	15

[a] Derived from Ref. [44].

Table 3 – Material consumption of the wind power plant studied.[a]

Material (kg/kgH_2)	Turbine	Foundations	Cables	Transformer
Steel and iron materials	5.82×10^{-2}	1.41×10^{-2}	0	1.68×10^{-4}
Aluminium and aluminium alloys	4.49×10^{-4}	0	1.80×10^{-3}	2.25×10^{-4}
Copper	7.30×10^{-4}	0	8.99×10^{-4}	5.62×10^{-5}
Polymer materials	2.25×10^{-3}	5.62×10^{-5}	1.40×10^{-3}	0
Process polymers	3.37×10^{-4}	0	0	0
Ceramic/glass	2.92×10^{-3}	0	0	0
Concrete	0	2.55×10^{-1}	0	0
Electronics/electrics	5.06×10^{-4}	0	0	0
Lubricants	2.25×10^{-4}	0	0	1.68×10^{-4}

[a] Derived from Ref. [47] using capacity factor of 30%.

Table 5 – Material and energy consumption for hydrogen compression.[a]

Material/Energy	Unit	
Compressor		
Chromium steel 18/8	kg/kgH$_2$	1.34×10^{-3}
Cast iron	kg/kgH$_2$	4.23×10^{-4}
Ethylene glycol	kg/kgH$_2$	4.94×10^{-6}
Lubricating oil	kg/kgH$_2$	1.27×10^{-5}
Aluminium	kg/kgH$_2$	4.23×10^{-5}
Tube insulation	kg/kgH$_2$	1.06×10^{-5}
Copper	kg/kgH$_2$	3.17×10^{-5}
Electricity	kWh/kgH$_2$	7.05×10^{-4}

[a] Derived from Ref. [44] using the energy consumption calculated in Section 3.3.

Hydrogen transportation

Hydrogen is transported from the integrated wind-to-hydrogen plant to the bitumen upgrader through pipeline [44]. The length of the pipeline is estimated as 400 km. The pipeline diameter was calculated by a model developed by Ogden [45]. The lifetime of hydrogen pipeline was assumed to be 22 years [46].

Results and discussions

Fig. 2 shows the GHG emissions associated with the various stages of wind power generation. The results are presented per unit mass of hydrogen produced by wind-based electricity. GHG emissions of a wind power plant are calculated to be 0.44 kg CO$_2$ eq./kg H$_2$. It is observed that the manufacturing stage contributes significantly to the life cycle GHG emissions. The production of the tower, nacelle, and foundations are the principal constituents contributing to GHG emissions. Plant operation contributes about 7% of the total GHG emissions. The end-of-life stage provides an environmental credit of 52% due to avoided metal production of aluminium, iron, copper, and steel.

Fig. 3 shows the overall emissions associated with the integrated wind-to-hydrogen system and a breakdown of emissions. The plant's total GHG emissions are 0.68 kg CO$_2$ eq./kg H$_2$. About 65% of the total integrated plant emissions come from the wind power plant. This is due to the steel and iron materials required for its manufacturing stage. Hydrogen compression, water electrolysis, and hydrogen transportation account for 22%, 7%, and 6% of the total GHG emissions of the plant, respectively.

Life cycle emissions from wind-based hydrogen production may be compared with those associated with hydrogen production through steam reforming of natural gas. Overall GHG emissions of the natural gas steam reforming system (SMR) were reported to be 11.89 kg CO$_2$ eq./kg H$_2$ [8]. As expected, the GHG emissions associated with fossil fuel-based hydrogen production are mainly in the plant operation stage. The operation stage of a SMR hydrogen production plant contributes to about 75% of the total emissions of the plant. However, GHG emissions of hydrogen production through wind-based electrolysis are 0.68 kg CO$_2$ eq./kg H$_2$, which are 94% lower than those of an SMR.

Uncertainty analysis

An uncertainty analysis was performed by building a Monte Carlo simulation model through ModelRisk. Table 6 shows the variations in key input parameters. The results for the overall GHG emissions are presented in Fig. 4. As can be seen, with a 95% level of confidence, GHG emissions of the plant range between 0.66 and 0.77 kg CO$_2$ eq./kg H$_2$.

A sensitivity analysis was conducted to better understand the importance and scale of uncertainties in data for a wind-to-hydrogen plant. The lifetime of the plant is 20 years; however, this value may change depending on operating

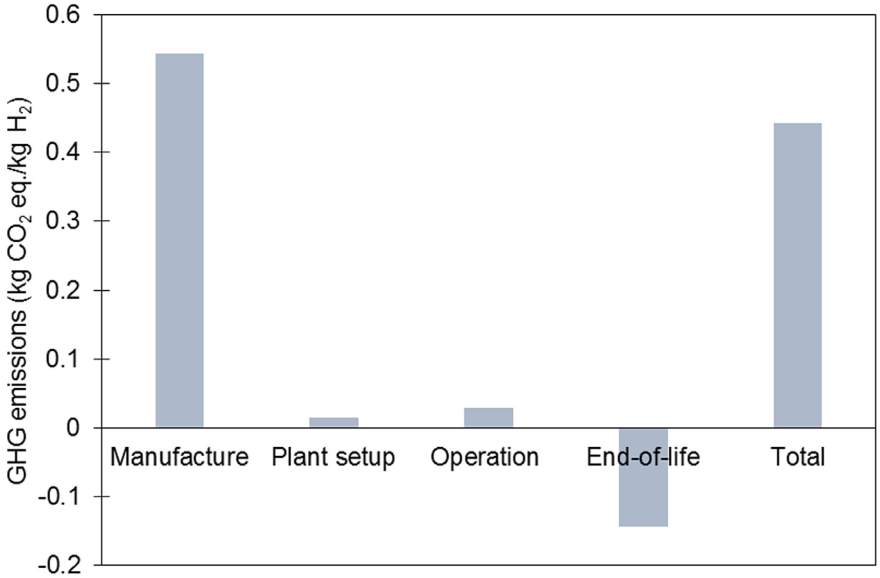

Fig. 2 – GHG emissions associated with the various stages of a wind power plant.

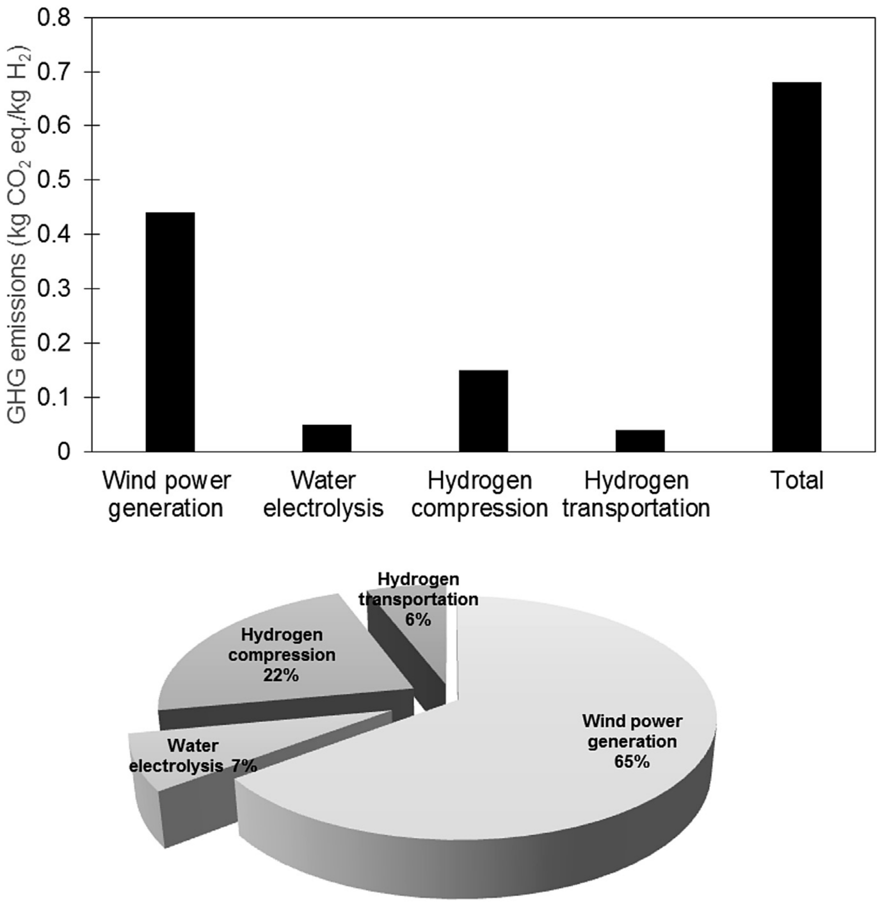

Fig. 3 – GHG emissions of an integrated wind-to-hydrogen system.

Table 6 – Variation in key input parameters used in uncertainty analysis.

Parameter	Unit	Range
Power plant lifetime	y	16–24
Wind speed	m/s	7.5–10
Electrolyser efficiency	%	70–80
Compressor efficiency	%	70–80
Hydrogen pipeline length	km	100–400

conditions. A sensitivity analysis was conducted to study the impact of variations in plant lifetime on the GHG emissions. The results show that GHG emissions increase by about 26% for a reduced lifetime of 4 years and decrease by 16% for an increased lifetime of 4 years.

High wind condition is considered as the baseline case for the LCA. The output electricity is reduced by about 20% if the wind turbine is operated under medium wind conditions. A sensitivity analysis was performed to investigate the changes in construction of the foundation and the tower when moving from high wind conditions to medium wind conditions. The results indicate a substantial increase of 26% in GHG emissions.

As stated earlier, the total GHG emissions of the plant range from 0.66 to 0.77 kg CO_2 eq./kg H_2. It is important to know which of the unit operations causes this uncertainty. The tornado chart in Fig. 5 shows the degree that the mean of the total emissions is affected by each unit operation distribution. It is observed that the wind power plant's emissions drive the total emissions uncertainty the most. The total GHG emissions range from 0.66 to 0.77 kg CO_2 eq./kg H_2 depending on the emissions from the wind power plant. This range is 0.70–0.72 kg CO_2 eq./kg H_2 for hydrogen compression and 0.70–0.71 kg CO_2 eq./kg H_2 for hydrogen production and hydrogen transportation. The total GHG emissions of the integrated wind-to-hydrogen plant are estimated to be 0.68 ± 0.05 kg CO_2 eq./kg H_2.

Conclusions

The environmental aspects of hydrogen production using wind energy were studied in this paper. An life cycle assessment (LCA) was conducted to evaluate GHG emissions per unit mass of produced hydrogen considering the various stages of wind-to-hydrogen plants. An uncertainty analysis of the results was also performed. The results show that wind power generation has the most significant effect on the total GHG emissions uncertainty. Therefore, it is worth investigating the possibility of reducing the uncertainty on wind power plant's emissions.

The results for life cycle emissions were compared with those of conventional fossil fuel-based systems. The total GHG emissions of a wind-based hydrogen production plant

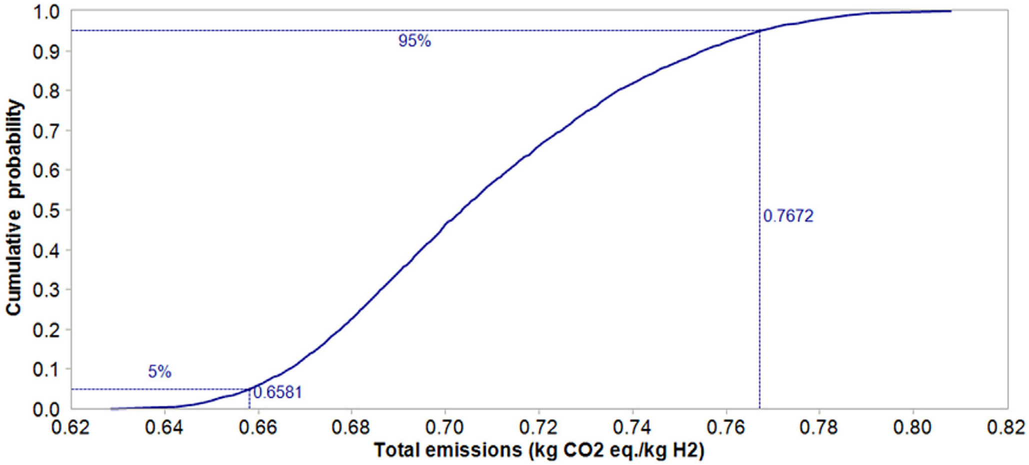

Fig. 4 – Uncertainty analysis with Monte Carlo simulation.

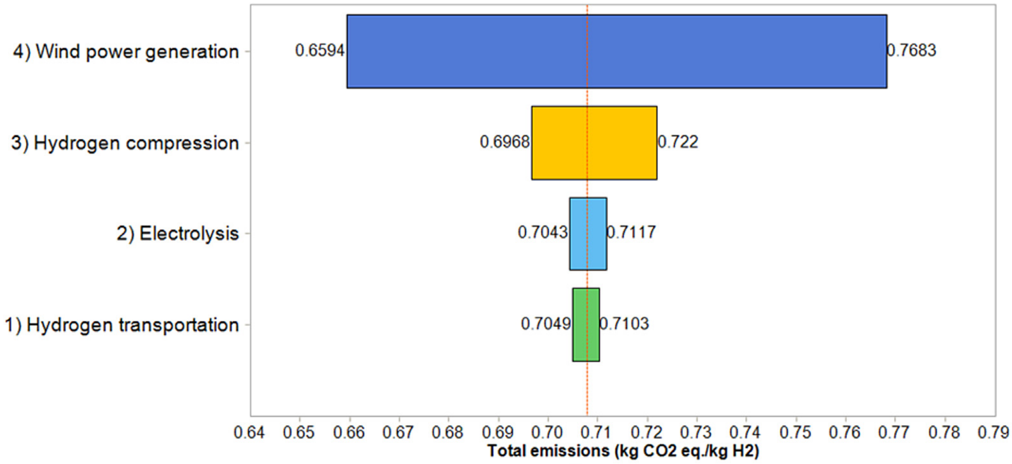

Fig. 5 – Tornado plot for total GHG emissions of an integrated plant.

are estimated as 0.68 ± 0.05 kg CO_2 eq./kg H_2, which are about 94% lower than those of a natural gas steam reforming system for hydrogen production. The environmental impacts associated with fossil fuel-based hydrogen production are mainly in the plant operation stage. However, for wind-to-hydrogen systems, while there are almost no direct emissions during operation, manufacturing and installation have significant environmental impacts. 65% of the total GHG emissions of the integrated wind-to-hydrogen plant come from the wind power generation unit.

The results presented in this paper contribute to a better understanding of wind-based hydrogen production processes and provide information that assists in decision-making on alternative energy pathways.

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