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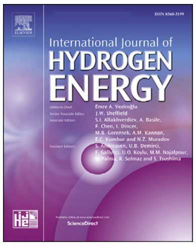

A comparative analysis of hydrogen production from the thermochemical conversion of algal biomass

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ABSTRACT

Gasification has the potential to convert biomass into gaseous mixtures that can be used for hydrogen production. Thermal gasification and supercritical water gasification are commonly used thermochemical methods for conversion of biomass to hydrogen. Supercritical water gasification handles wet biomass, thus eliminating the capital cost-intensive drying step. Thermal gasification is considered as an alternative means of producing hydrogen from microalgae where biomass has to be dried before gasification. The authors developed techno-economic models for assessment of the production of hydrogen through supercritical gasification and thermal gasification processes. Techno-economic assessment was based on developed process models. Equipment was sized and costs were estimated using the developed process models, and the product value was determined assuming 20 years of plant life. The economic assessment of supercritical water and thermal gasification show that 2000 dry tonnes/day plant requires total capital investments of 277.8 M$ and 215.3 M$ for hydrogen product values of $4.59 ± 0.10/kg and $5.66 ± 0.10/kg, respectively. The relatively higher yield obtained in supercritical water gasification compared to thermal gasification results in lower product value of hydrogen for supercritical water gasification, thereby making it more desirable. This cost of hydrogen is about 4 times the cost of hydrogen from natural gas. The sensitivity analysis indicates that biomass cost and yield are the most sensitive parameters in the economics of the supercritical or thermal gasification process; this signifies the importance of algal biomass availability. The techno-economic assessment helps to identify options for the production of hydrogen fuel through these novel technologies.

Introduction

Hydrogen is considered a potential energy resource, and biomass, because it is renewable, is emerging as a vital energy source [1,2]. Western Canada has the largest hydrocarbon reserves in North America. Canada produced about 438 million barrels of bitumen and synthetic crude oil in 2007. Canadian oil sands operations process bitumen into synthetic crude oil. However, the process requires upgrading, which depends

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heavily on hydrogen. Most of the hydrogen for upgrading is met by the use of natural gas, which undergoes reforming to produce 59% hydrogen; however, this reforming leads to significant greenhouse gas (GHG) emissions (~30 million t/year) [3]. Canada's expected hydrogen demand is estimated to reach 5.9–6.9 Mt/year by 2020, while the current production rate is 7970 t/year [3]. Hence, there is a great need to identify alternative sources of hydrogen that are competitive with known conventional approaches. Alternative methods include obtaining hydrogen from biomass, which is the focus of this paper. Biomass is a renewable resource and over the life cycle of its utilization it is considered nearly carbon neutral.

Biomass is widely used for different processes such as pyrolysis, anaerobic digestion, and gasification to produce gaseous fuels [4–9]. Microalgae has gained considerable attention owing to its application as a renewable energy source and in the production of high value chemicals for the pharmaceutical industry and of protein supplements [10,11]. Though commercial algae cultivation is limited to regions with abundant sunlight, there has been recent interest in cultivating it in northern climates [12]. Microalgae, a renewable feedstock characterized by high protein, lipid, and carbohydrates, is an interesting candidate for biofuels because of its ability to grow in variety of climatic conditions. Algae allow CO_2 fixation through photosynthesis, which produces several cellular components and energy [13]. Microalgae do not contain lignin and have low density and viscosity. Other key features that make it a more suitable candidate than lignocellulosics include faster growth potential, less fresh water requirement, and the ability to grow on low or marginal lands including in wastewater, saline water, etc. [14–16].

The known energy conversion pathways using algae include biochemical and thermochemical conversion approaches. Thermochemical conversion pathways such as thermal gasification and supercritical water gasification show high energy conversion and efficiency [17–23]. Thermal gasification allows biomass conversion into gaseous products in the presence of gasifying agents such as steam, air, oxygen, etc. This technology is based on the partial oxidation of biomass into syngas comprising H_2, CO_2, CH_4, and CO, the amount and quality of which are a function of the nature of the biomass, the type of gasifier, and various technical parameters. However, high moisture biomass must be dried to achieve efficient energy conversion during the gasification process. On the other hand, supercritical water gasification (SCWG) produces gases and can convert high moisture biomass such as algae, wastewater sludge, and even wastes from food processing. Because SCWG can handle wet biomass feedstocks directly, there is no energy-intensive drying step [24]. SCWG increases the gasification efficiency rate and hydrogen molar fraction and decreases tar and coke formation [25]. However, a typical SCWG in a continuous flow process requires a high-pressure reactor system and pumping, which is cost-intensive [26,27].

Research efforts have focused largely on the economic, environmental, and energetic feasibility of biodiesel obtained from microalgae [28–30]. There has also been a considerable interest in the life cycle water analysis of the thermochemical processing pathways using microalgae as a biomass feedstock [31]. Yet there have been no significant improvements in thermochemical conversion technologies for algal biomass, nor has the economic potential in the processing of such biomass into hydrogen received much attention. As algal gasification is yet to be developed commercially, a study is needed on its technical and economic aspects to determine its future market potential. Hence, the aim of the present study is to perform a techno-economic assessment of large-scale hydrogen production from algal biomass. The specific objectives are:

- To develop a detailed techno-economic model to evaluate the product value ($/kg) of hydrogen derived from microalgae using thermal gasification and supercritical gasification;
- To determine the hydrogen product value with respect to plant capacity;
- To conduct sensitivity and uncertainty analyses of several cost parameters that influences the product value.

The results will provide key insights into the techno-economic feasibility of producing hydrogen from high moisture containing feedstocks such as microalgae.

Thermal gasification

Microalgal biomass is seen as a promising candidate for biofuel production as a future energy source. Thermal gasification, a known thermochemical method, occurs at a temperature of 800–1000 °C and involves partial oxidation of biomass in the presence of gasifying agents such as steam, oxygen, and air [32,33]. The syngas thus produced is a mixture of H_2, CH_4, CO_2 and CO. In general, gasification is suitable for biomass with a moisture content <15%. There has been several studies on gasification of biomass [34–38] but limited focus has been on microalgae [39,40]. Microalgae require drying because high moisture content materials reduce gasifier efficiency and syngas energy content. A study based on biomass-based integrated gasification combined cycle showed that a moisture content of less than 10 wt% is required to achieve high temperatures during gasification, thus improving energy efficiency [41]. The gasifier used for microalgal conversion is a vertical fluidized bed. However, such reactors pose challenges in terms of scalability and ensuing carbon loss, so they are commercially infeasible [42,43]. A horizontal bed reactor improves heat transfer by allowing significant contact time, which can reduce the char formation. This reactor design is simple and easy to operate and can improve carbon conversion [44]. Using air as a gasifying agent is more advantageous than other known gasifying agents such as pure oxygen and steam that make the process long, expensive, and complex.

There are very few studies on algal thermal gasification for biofuel production. Hirano et al. [45] studied the gasification of *Spirulina* at 850–1000 °C into syngas that consisted of H_2, CO_2, CO, and CH_4. Their study showed that temperature has a key role in increasing hydrogen and carbon conversion efficiency. A study by Minowa et al. [46] involving the gasification of *C. vulgaris* at 350 °C in the presence of a Ni-catalyst was aimed at producing higher levels of CH_4 than H_2; the study showed the significance of catalysts for higher carbon conversion efficiency. Raheem et al. [47] studied air gasification of *C. vulgaris* in a horizontal tube configuration and reported 950 °C as an optimal temperature. Adnan et al. [48] studied gasification potential a microalgae and concluded that oxygen at ER of 0.3 showed maximum H_2/CO ratio. Ripoll et al. [49] investigated hydrogen production from algal biomass in natural gas-air filtration system and reported highest hydrogen concentrations in the range from 8.15 to 9.56% and mole fraction of hydrogen improved slightly with increasing algae content. Dascomb et al. [50] employed thermal conversion of hydrogen enriched syngas production from biomass steam gasification and reported highest yield at 51%. They concluded that the energy conversion increases with bed temperature but has inverse proportionality to steam to biomass ratio. Nipattummakul et al. [51] studied hydrogen yield from oil palm tree using steam gasification and reported reduction in reaction rate at temperatures lower than 700 °C as high amount of steam is used per unit sample mass. Yan et al. [52] investigated steam gasification of char obtained from cyanobacterial blooms in a fixed-bed reactor and reported that residence time greatly influenced steam gasification, whereas particle size had less influence on gasification. High temperature decreased impact of particle size on gasification process, and small particle size needed low residence time, with highest dry gas yield at 1.84 $Nm^3\ kg^{-1}$ at 850 °C and particle size of 0.45–0.9 mm. Zaini et al. [53] investigated cogeneration system to produce H_2 using steam gasification, attaining H_2 production efficiency at 57.25%. Duman et al. [54] performed steam gasification via algal biomass in the presence of 10% Fe_2O_3-90% CeO2 and red mud. The catalysts improved reforming of tar and enhanced WGSR, with highest hydrogen yields varying from 413 to 1036 cc/g for a range of algal feedstocks. Díaz-Rey et al. [35] employed low temperature catalytic gasification using algal biomass in the presence of different gasifying agents. They found that the reactions involving reforming and water gas shift reaction improved H_2 and the use of a Ni-based catalyst was effective in reforming of biomass volatiles and tars, with Pt–Ni/Al_2O_3 producing 0.3 Nm^3 of hydrogen. Soreanu et al. [55] studied CO_2 gasification process performance for microalgae using high-pressure thermogravimetric analyzer at an industrial scale and showed the impact of temperature, pressure and gasifying agents wherein reactivity and gasification rate were positively impacted by operating conditions.

Supercritical water gasification

The unique properties of supercritical water are the basis of supercritical water gasification technology [23,56,57]. Beyond the critical point (374 °C, 22.1 MPa), water shows different properties than at ambient conditions [58]. Supercritical water has a smaller dielectric constant than water at ambient conditions. Consequently, supercritical water behaves like an organic solvent, thereby improving the solubility of organics and preventing the formation of by-products such as tar and char. In addition, the chemical reactions occur in a single fluid medium that would otherwise happen in a multiphase environment under normal conditions [59]. Supercritical water has high reactivity, which further increases the hydrogen yield. Some of the advantages of the SCWG process are: Biomass does not need drying; in fact, water acts as a high reactive medium for SCWG; High hydrogen and considerably low carbon monoxide yields are achieved; The unique properties of supercritical water often result in less tar and char formation. There have been number of experimental studies on catalytic performances on SCWG using biomass as a feedstock. The activity and stability of Ni-based catalysts of phenol in supercritical water were studied using a continuous reactor and reported an increase in H_2 yield using Ni/CNT [60]. The activity of Ni/CeO_2 catalyst for phenol gasification in supercritical water was studied by Li et al. [61]. They performed characterization analyses and indicated NiCe alloy formation in Ni/CeO_2 which have the potential to improve gas yields. Xie et al. [62] studied SCWG of microalgae over nickel catalysts which is known to promote water–gas shift and steam reforming reactions. The H_2 yield increased from 2.19 to 5.61 mmol/g with increasing catalyst molar ratio. The experimental study on food waste energy conversion through SCWG for hydrogen production resulted in maximum hydrogen yield at 20.37 mol/kg with total gas yield of 38.36 mol/kg with the help of 5 wt% KOH [63]. A study using Zn doped MgO catalysts in SCWG for hydrogen production showed the highest H_2 yield and stability owing to maximum number of basic sites [64]. Cao et al. [65] studied the synergistic effect of co-gasification of black liquor and wheat straw in supercritical water and reported improvements in the H_2 yield from 12.29 mol/kg at 500 °C to 46.02 mol/kg. The detailed reaction pathway and mechanisms of gasification of guaiacol in supercritical water have been proposed by Zhu et al. [66]. They reported that phenols and arenes are not easy to gasify in supercritical water, whereas organic acids, alcohols and cyclopentanones gasifies into hydrogen-rich gas. The stability and activity of Mg promoted Ni/Al_2O_3 catalyst for SCWG of biomass led to the conclusion that the activity of catalyst is higher for water-soluble organics than real biomass [67]. The assessment of sugarcane bagasse in SCWG resulted in highest hydrogen yield (35.3 mol/kg) at 650 °C in the presence of 20 wt % Na_2CO_3 [68]. The thermodynamic study on integrated SCWG with reforming for hydrogen production improved the syngas yield to 1.51 kg/kg as compared to 1.20 kg/kg in the conventional SCWG [69]. Safari et al. [70] investigated hydrogen production via SCWG of almond shell using algal and agricultural hydrochars as bio-catalysts. The hydrogen conversion efficiency was highly impacted by inorganics in hydrochars as opposed to surface area and pore volume, with highest hydrogen yields at 10.77 and 11.63 mmol/g, for wheat straw and algal hydrochars, respectively. The study of Ce on NiCe/γAl_2O_3 for hydrogen yield improvements in SCWG of biomass concluded that Ce led to more active nickel sites for steam methane reforming [71]. Zhu et al. [72] investigated SCWG of glycerol and glucose in different reactors and found that the percentage of H_2 increased with Ni wire in the quartz reactor. The catalytic wall effect was found to promote WGSR, methanation and C–C bond cleavage. Elif et al. [73] employed SCWG of fruit pulp using Ru/C and reported highest hydrogen yield at 54.8 mol H_2/kg at 2.5% biomass ratio. Cheng et al. [74] employed semicoke gasification using supercritical water fluidized bed reactor and reported hydrogen yield at 85.90 mol/kg with 61.02% molar fraction. An earlier study provided an initial cost estimate for a typical SCWG plant system [75] and reported hydrogen production costs using sewage sludge at both 20 and 40 wt% at a throughput of 5625 kg/h. Their costs included the feed supply line, and gas cleaning was done through a membrane separation method and a pressure swing adsorption unit. Their experimental setup had a liquefaction step to precipitate the insoluble organics to prevent problems in the feed line. Amos [76] estimated the costs of hydrogen production for starch waste (15 wt% dry matter) at a throughput of 7500 kg/h (wet basis). The costs did not include the feed supply lines, and the gas cleaning was done through membrane technology, which made up >35% of the purchased equipment costs. Another study performed a similar cost estimate for water hyacinths (5 wt% dry matter) at a throughput of 42.67 kg/h [77]. The gas cleaning approach involved a CO_2 absorber with water as scrubbing medium. The investment costs consisted mainly of bulk plant components, and costs related to engineering, assembly, etc., were not incorporated. Gasafi et al. [27] studied the economics of SCWG of sewage sludge (20 wt% dry matter) for hydrogen production at a throughput of 5 t/h and found that SCWG could be competitive if the revenues associated with the sewage sludge disposal as a waste product were considered. The study lacked the information on what scale the plant could be commercially built to produce hydrogen via supercritical water gasification. Recently, Mosuli et al. [78] studied the economics of producing renewable hydrogen from glucose (15 and 25 wt%) and sewage sludge (15 wt%). These studies show the potential of SCWG for hydrogen production from a range of high moisture feedstocks. However, the techno-economics of algae processing through SCWG have not been studied.

Methods

An understanding of the techno-economics of hydrogen production from algal biomass requires an analysis of the mass and energy flows of the different unit operations in the plant design. The techno-economic assessment was done through development of process models using Aspen Plus Simulator [79] to estimate the product value of hydrogen. The analysis considers a base plant capacity of 2000 t/day of dry algal biomass feedstock for hydrogen production through thermochemical technologies, based on studies at large scale. The thermochemical plants have the infrastructure to intake biomass as it is produced and the production and conversion facilities are co-located [31].

Process model description

The development of a process model for producing hydrogen via thermal gasification and supercritical gasification is discussed in this section.

Gasification

Algal thermal gasification consists of drying, pyrolysis, and gas cleanup, as shown in Fig. 1. Drying occurs at a temperature range of 0–150 °C which is aimed at improving the product's calorific value. The dried biomass is subjected to a temperature of 500 °C; this produces syngas comprising H_2, CH_4, and CO. For the purpose of gasification, a fluidized bed gasifier is suitable as it provides enhanced mass and heat transfer and a high heating value, resulting in high efficiency [80]. Following syngas production, the sulphur is removed to avoid equipment fouling and catalyst poisoning [81]. Hence, the syngas undergoes gas treatment, that is, the gas is cleaned using Selexol and sulphur is removed. During this process, a ~99% H_2S removal efficiency was achieved [82,83]. The sulphur-free gas is passed through set of reactors including steam reforming reactor and high and low temperature water-gas shift reactors (WGSRs). The water-gas shift reaction enriches H_2 yield by using CO and H_2O to form H_2 and CO_2. The conversion of microalgae to syngas involves gasification reactions, that is, the water-gas shift reaction, methanation, and the Boudouard reaction [80]. The resulting gas is subjected to CO_2 removal using Selexol which is the next step in gas purification [84]. Following CO_2 removal, the gas mixture is passed through a pressure swing adsorption (PSA) to produce high purity hydrogen [83,85,86].

Supercritical water gasification (SCWG)

The simplified flowsheet (shown in Fig. 2) includes the following major unit operations: feed preparation, supercritical water gasification of wet biomass to syngas, and purification of syngas into hydrogen. The modeled reactor system has a pre-hydrolysis reactor, a pseudo-critical minerals separator, and a supercritical water gasification reactor. The pressurized feed initially passes through the pre-hydrolysis reactor where the non-conventional components of biomass are broken down. This is followed by a minerals separator step at the pseudo-critical point of ~380 °C to remove salts, whose presence would cause plugging and clogging downstream. The resulting stream is directed to the supercritical water reactor, which operates at 600 °C. For gas processing applications, physical absorption is performed with the help of solvents such as Selexol, Rectisol and Purisol [87]. Such solvents work by dehydrating the feed and are known to have moderate consumption of energy [88,89]. The Sulphur removal from stream of product gas through SCWG is required to prevent equipment and catalyst poisoning downstream in water-gas shift reactors [81]. The sulphur in the biomass is captured in the form of H_2S in an absorption column by using Selexol (dimethyl ether of polyethylene glycol) [83,86,90]. A ~99% H_2S removal efficiency was attained as also reported elsewhere [82,83]. The sulphur-free gas is allowed to pass through reactors, i.e., a steam reforming reactor with high and low temperature water-gas shift reactors (WGSRs). A steam-carbon ratio of 3 was considered to enhance H_2 production from syngas, wherein carbon flow is based on molar rate of CH_4 and CO in syngas [91]. CO_2 is further removed through its absorption with Selexol downstream of WGSRs. CO_2 removal acts as the second step in gas purification which is absorbed using Selexol as it is known to consume lower energy than other solvents such as methyl diethanolamine [84]. Once the CO_2 has been removed, the H_2-rich product gas passes through a pressure swing adsorption (PSA). The PSA employs the principle of regenerative solid adsorbents and is selective to hydrogen at ambient conditions [83,85,86]. The process model has been described in detail by the authors in an earlier paper [92].

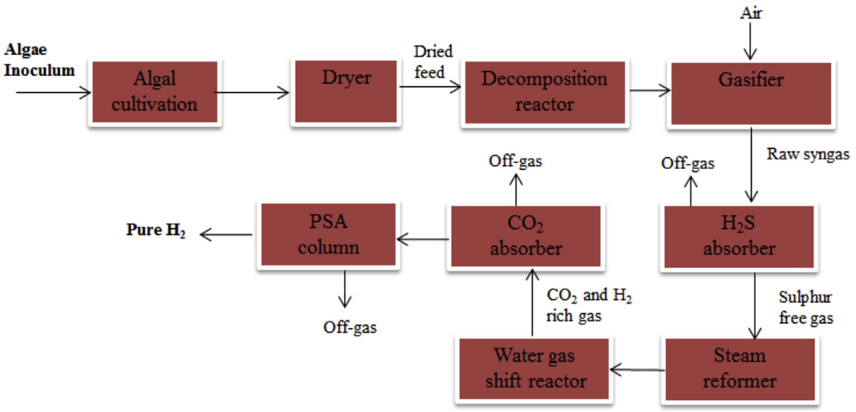


Fig. 1 – **Block diagram for thermal gasification pathway for hydrogen production.**

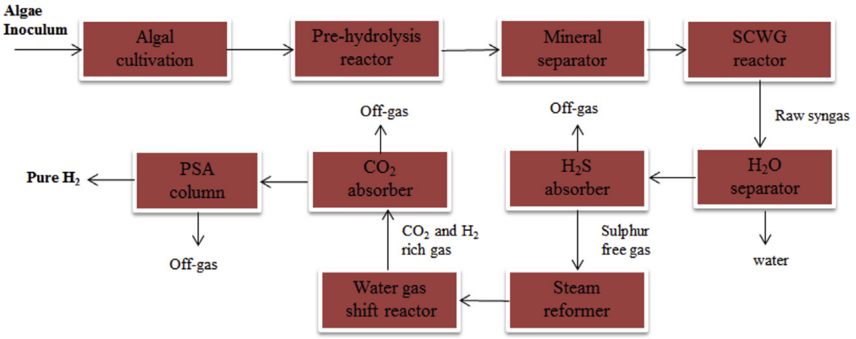


Fig. 2 – **Block diagram for supercritical water gasification pathway for hydrogen production.**

Techno-economic assessment

The techno-economic assessment determines the product value (PV) using the plant's capital and operating costs. In this analysis, the life of the plant is assumed to be 20 years. The Aspen Icarus Process Evaluator is used to calculate the total purchased equipment costs, which are used to determine the product value through a discounted cash flow rate of return (DCFROR) analysis. Following process model development, the unit equipment is mapped and capital costs are obtained. Based on total project capital investment, the fuel product value at a net present value of zero is determined.

Capital cost estimate

The total capital cost is obtained by combining individual purchased equipment costs with installation factors and indirect costs. The indirect costs include engineering, construction, and contingency costs. The simulation results are used for economic analysis. The process model is used to map unit operations, which are sized to determine overall costs. An installation factor, which includes electrical, piping, and other installations, is needed for the total purchased equipment costs. The installation factors obtained from the process model are usually lower than those suggested by Peters et al. [93]. Hence, an installation factor of 3.02 is considered more suitable for solid-liquid chemical plants and is used to calculate the total installed cost (TIC), as shown in Table 1. The indirect costs (IC), as a percentage of the total purchased equipment cost (TPEC), include engineering and supervision costs (32%), legal and contractors' fees (23%), and project construction expenses (34%) [36]. The total direct and indirect costs (TDIC) are the sum of the total installed costs and indirect costs (IC). A project contingency of 15% of the total direct and indirect costs (TDIC) is applied. A location factor of 10% was added to calculate the total project investment (TPI) [94]. The present analysis assumes that there are no special financing requirements resulting from the project's working capital and longer startup times.

Operating cost estimate

Annual operating costs are made up of fixed and variable costs. The fixed costs include operating labor, maintenance,

Table 1 – Capital cost factors for capital cost estimate for a thermochemical plant [93].

Estimates for total project investment cost factors (in 2016 dollars)	
Installation factor	3.02
Total installed cost (TIC)	302% of TPEC
Indirect cost (IC)	89% of TPEC
Total direct and indirect costs (TDIC)	TIC + IC
Contingency	15% of TDIC
Fixed capital investment (FCI)	TDIC + Contingency
Location cost	10% of FCI
Total project investment (TPI)	FCI + location cost

Table 2 – Economic assumptions during the development of the techno-economic model.

Parameters	Values	References
Plant life (year)	20	[104]
Cost year basis	2016	
Capital cost distribution		
Year 1 (%)	20	[106,107]
Year 2 (%)	35	
Year 3 (%)	45	
Production plant capacity factor		
Year 1	0.7	[106,107]
Year 2	0.8	
Year 3 and beyond	0.85	
Internal rate of return (%)	10	[104]
Maintenance cost ($)	3% of TPI	[79]
Operating charges ($)	25% of operating labor cost	[79]
Plant overhead ($)	50% of total operating labor and maintenance cost	[79]
Subtotal operating cost, SOC ($)	Sum of all operating costs including raw material and utility cost	[79]
G & A cost ($)	8% of SOC	[79]
Solid waste revenues ($/t Nitrogen)	500	[108]
Wastewater disposal cost ($/t)	1.16	[109]

and administrative expenses. The variable costs are the operating supply costs such as feedstock, chemicals, and utilities. The biomass feedstock cost of 392 $/t (dry) was obtained from a study by Davis et al. [95]. The cost of microalgae is dependent on growth, cultivation, and harvesting costs, hence, the cost of raw algal biomass may attain 3000 $ t^{-1} [96]. Thilakaratne et al. [97] suggests that algal biomass costs could even vary from 0.35 to 7.32 $ kg^{-1} owing to the differences in cultivation systems, nature of strain, extraction methods, as well as geographic location. The cost of selexol for gas cleaning operations in supercritical water gasification and thermal gasification is 1.8 $/kg based on an economic study on gas capture technology [98]. The price of catalyst is based on an earlier study on supercritical water gasification by Mosuli et al. [78]. The labor cost is the salaries of operators and supervisors. Hourly wages in Alberta, a western province in Canada, were 26.11 $/h and 33.57 $/h for operators and supervisors, respectively [99]. A total of 8 staff (7 operators and 1 supervisor) are required per shift for the operation of a 2000 t day^{-1} supercritical water gasification plant [79] and three shifts per day are considered [100–102]. The plant utility costs, such as electricity cost, are taken to be 0.067 $/kWh based on the average electricity price in Alberta [103]. Other costs that are crucial for plant operation include maintenance and overhead costs. The maintenance cost is usually considered to be 2–10% of the total project investment cost; the present economic analysis considers this cost to be 3% of the TPI [79,104,105]. Operating charges are 25% of operating labor costs [105]. Plant overhead is assumed to be 50% of operating labor and maintenance costs [105]. Plant overhead mainly re [88]fers to the facilities, payroll, overhead, services, etc. General and administrative (G&A) expenses, specified as 8% of operating costs, refer to general administrative expenses, research and development, product distribution, etc. [79,105]. The construction of the thermochemical plant is considered to make up 20%, 35%, and 45% of the total capital cost during the first, second, and third years, respectively [106,107]. Other costs pertaining to the plant's overall techno-economic analysis were obtained from the literature [108,109]. Table 2 shows the economic assumptions used in the development of the techno-economic model for thermochemical technologies for hydrogen production.

Product cost estimate

The product value of hydrogen ($/kg) is determined using a discounted cash flow rate of return (DCFROR) analysis at a discounted internal rate of return (IRR) of 10% over a 20-year plant life [104]. For currency conversion, a US$/CAD$ exchange rate of 1:0.77 (Bank of Canada exchange rate, March 2016) was used. All cost numbers in this study are in US$ 2016. An inflation rate of 2% was considered for the present economic analysis [107,110,111].

Results and discussion

The results obtained from the techno-economic process model developed for hydrogen production from two thermochemical technologies are discussed, followed by sensitivity and uncertainty analyses.

Process modeling results

The process model results show that from an algal biomass SCWG plant with a capacity of 2000 t/day, approximately 209 t/day of hydrogen is produced, corresponding to a percentage yield of 10.5%. This is in agreement with values reported in other studies (8.4–11.2%) [27,78,112,113]. Gasafi et al.

Table 3 – Cost estimates for hydrogen production using thermochemical technologies (in 2016 US dollars).

Parameters	SCWG	Thermal Gasification
Installed capital cost (M$)	169.6	131.48
Total capital investment (M$)	277.8	215.3
Cost of hydrogen ($/kg)	4.59	5.66

[27] studied the hydrogen production from sewage sludge via SCWG and reported a hydrogen yield of 8.39%. Lina et al. [112] estimated a hydrogen yield of 10% from the SCWG of palm oil waste. The details of the developed process simulation model results for thermochemical technologies are summarized in the appendix in the supplementary file. .

Techno-economic modeling results

The cost estimates for the hydrogen production for a plant capacity of 2000 t/day using algal feedstock via SCWG and thermal gasification are given in Table 3. The total purchased equipment cost for supercritical water gasification is 56.2 M$, which corresponds to a total capital investment of 277.8 M$. For thermal gasification, the installed capital cost is 131.48 M$, with a total capital investment of 215.3 M$. The purchased equipment cost obtained in this study for supercritical water gasification is in good agreement with that found by an earlier study [78], who studied the SCWG of 15 wt% glucose for renewable hydrogen production and reported total purchased equipment cost of around 62 M$ for a 2000 t/day plant.

The supercritical water gasification unit and water gas shift reactor together incur the highest total purchased equipment cost (30.2 M$), followed by the gas purification unit (25.9 M$). Spath et al. [114] studied the process model and economics for hydrogen produced through biomass gasification at a plant capacity of 2000 dry tonnes/day and reported total purchased equipment costs for processing and gas purification at approximately 39–41 M$ (2016 US dollars). For thermal gasification, feed handling and drying contributed 10.1 M$ whereas gas cleanup, compression, sulphur removal, and steam methane reforming unit contributed 24.5 M$. The cost parameter contributions to the product value of hydrogen for supercritical water gasification and thermal gasification are shown in Fig. 3. It is clear that the raw material cost contributes highest to the overall product value of hydrogen from biomass for both thermochemical processes. Similar results were reported in a study on synthetic natural gas (SNG) production via SCWG, which found >94% of algal biomass production to be attributed to production cost [115].

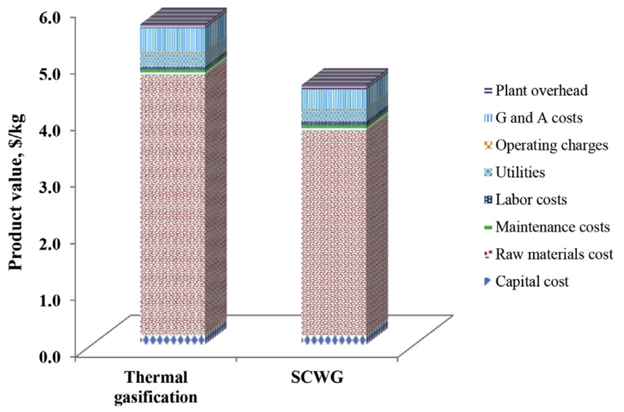


Fig. 3 – Breakdown of product values of hydrogen for SCWG and thermal gasification of biomass.

Plant capacity profile

The plant capacity profile versus the product value of hydrogen is shown in Fig. 4. As the plant capacity increases, the product value decreases and then flattens out. This trend is the result of the trade-off between capital, raw materials, and labor cost. The flat trend shown in the graph indicates that the product value of hydrogen is unaltered with any further increase in plant capacity beyond a capacity size of 2000 dry tonnes/day, signifying the economies of scale. The optimum plant capacity is found in the trade-off between the biomass transportation cost and plant capital cost.

Comparison of hydrogen costs with those from the literature

To the best of the authors' knowledge, there are no studies on the production of hydrogen through supercritical water gasification in Western Canada. Some authors have done studies on the supercritical water gasification of different feedstocks. Mosuli et al. [78] showed that no profit can be realized with a glucose feed concentration of 15% until the hydrogen price is more than $5/kg. Matsumura [77] reported hydrogen production costs of $58.89/GJ (based on currency conversion and 2% inflation). The current study found a product value of $4.59/kg ($38.16/GJ) assuming the LHV of hydrogen to be 120.21 MJ/kg,

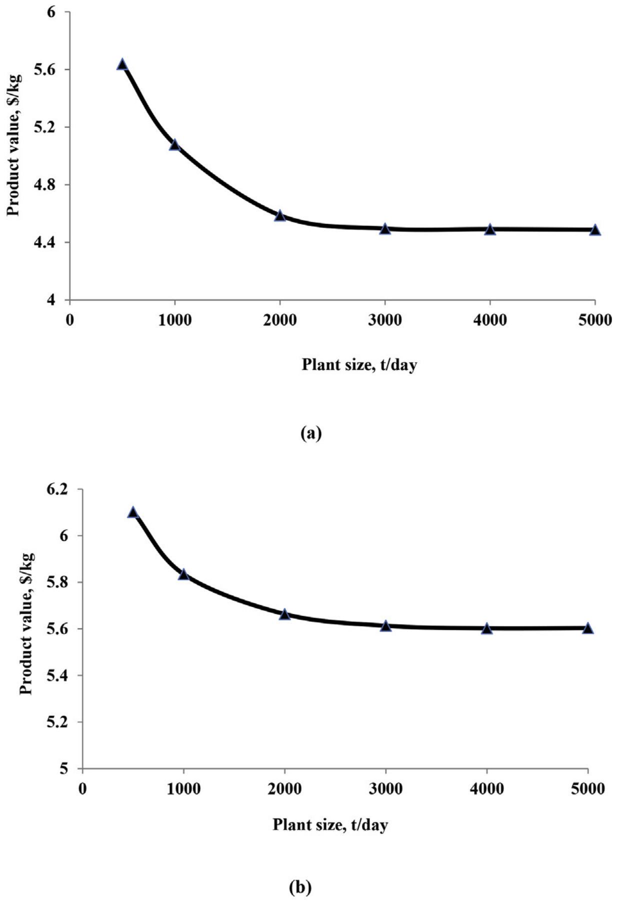


Fig. 4 – Effect of plant scale factor on product value of hydrogen for (a) supercritical water gasification (b) thermal gasification.

which is in good agreement with the values reported in the literature [77,115]. The differences in product value arise due to the location-specific nature of the plant design. Sarkar et al. [8] studied a gasifier for biohydrogen production using forest residues and straw and reported $1.17/kg and $1.29/kg of H_2 at a plant capacity of 2000 dry tonnes/day. Brandenberger et al. [115] studied the economics of synthetic natural gas (SNG) using microalgae from SCWG from raceway ponds (RP) and tubular and flat-panel (FP) photobioreactors through a process named SunCHem. For the most optimistic cases, this study estimated SNG production costs of approximately $37–127/GJ based on different algal production costs. The main downsides to large-scale implementation of microalgae-based biofuels are the high costs of investment and high energy requirement during cultivation and harvesting [28,30]. Brandenberger et al. [115] analyzed the base case scenario for SNG production from microalgae, with an algal production cost of $ 2.84–7.33/kg, and found it to be economically not viable. Different cost estimates for microalgae biomass production have been reported in the literature. van Beilen [30] estimated $5–15/kg for algal biomass production in raceway ponds. Williams and Laurens reported large-scale production costs of $0.41/kg under optimized conditions [10]. In Western Canada, most hydrogen is obtained from natural gas with a cost of $0.78/kg [7]. The thermochemical plant using 2000 dry tonnes/day algae as a feedstock is not economical. However, the algae's carbon neutrality and its ability to take up CO_2 make it potentially an attractive option.

Drying using hydrogen gas

The chemical reactions in the gasification of microalgal biomass require moisture removal or dewatering, as high moisture in biomass such as algae reduces the efficiency of the gasifier. Hydrogen gas can also be used for purposes of drying algae. A European refinery used high purity hydrogen for drying purposes for certain unit operations [116]. Another study on industrial processes employed gaseous hydrogen for drying as an efficient energy efficiency alternative [117]. In this study, the potential of using hydrogen as an energy source for drying was investigated for gasification. The product value of hydrogen increased to $5.90/kg when hydrogen was partly used as a drying energy resource. The increase in the product value occurred through the decrease in the overall yield of hydrogen produced. This suggests that the use of hydrogen as a drying source reduces the profitability of the process.

Sensitivity analysis

Because the technology is still developing, an understanding is needed on how economic parameters influence product value in order to improve process efficacy. A sensitivity analysis was done by selecting cost variables that impact the product value estimate. The influence of cost variables on the product value of hydrogen is important in view of the uncertainties. The chosen parameters are those associated with biomass, utility, labor, maintenance, and plant overhead, and G&A costs including IRR, hydrogen yield, and plant capital costs. Sensitivity analysis is done by varying cost parameters by ± 20% while the other parameters remain fixed. The key sensitive parameter is the hydrogen yield obtained during the process. A 20% increase in product yield reduces the product value by $0.76/kg and $1.30/kg for SCWG and thermal gasification, respectively. Thilakaratne et al. [97] also found product yield to be the most sensitive parameter in the techno-economic assessment of microalgae for both thermal drying and partial mechanical dewatering processes. The other significant parameter is biomass feedstock cost. A ±20% variation in biomass cost changes the product value by > 20% for both processes. The cost of algal biomass depends on the availability of biomass, which relies on optimized design and performance of algal production methods that improve biomass productivity. Also, there are uncertainties in the cultivation and harvesting of microalgae for biofuel production [118]. Thus, algal production methods vary with location and capital costs, and algal production costs range from $30–70/kg for photobioreactors [119] and $0.24–15/kg for raceway ponds [30]. Manganaro et al. [120] studied the doubling time with respect to the techno-economic assessment of algae production and found that a 10% decrease in doubling time reduced the price of algae by ~ $0.92/gal and thus requires research into the inhibiting impacts on microalgae doubling time.

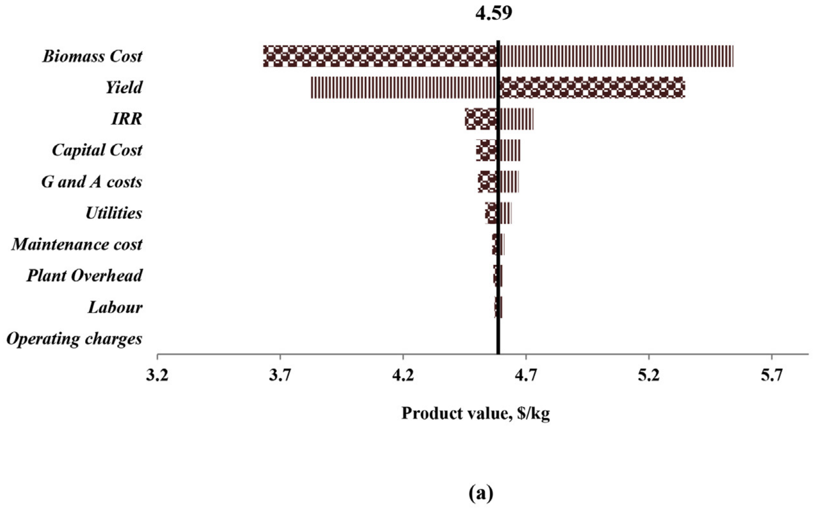
The other important sensitivity parameter is internal rate of return (IRR), followed by the plant capital cost. The product value of hydrogen through thermal gasification ranges from $5.54-$5.79/kg with a ±20% variation in IRR. The product value shows an increasing trend with increasing IRR. Another key factor is the capital cost; it influences the capital investment of the plant, which in turn affects return on investment. Within a ±20% variation in capital costs, the product value for thermal gasification is in the range $5.59-$5.73/kg. However, other cost variables such as utility, labor, maintenance, G&A, and plant overhead have little or no impact on product value. The influence of key parameters on the product value of hydrogen is provided in Fig. 5. The analysis shows that the product value of hydrogen can be significantly reduced either by increasing product yield or reducing microalgae biomass cost, as also reported in another study [97].

Uncertainty analysis

The lack of accurate data and relative uncertainty in techno-economic parameters constrains accurate data prediction and modeling and thus production cost estimates. In order to address these uncertainties, a Monte Carlo simulation was performed based on relative volatilities in the estimation of economic parameters. For this purpose, a Model Risk software was used to run the simulation [121]. The simulation was performed for 10,000 iterations to obtain accurate data. The Monte Carlo simulation results for the cost of hydrogen at a plant capacity of 2000 t/day are $4.59 ± 0.10/kg and $5.66 ± 0.10/kg at an assumed 95% confidence level for supercritical water gasification and thermal gasification, as shown in Fig. 6.

Impact of industrial CO_2 on product value of hydrogen

To mitigate problems with rising atmospheric CO_2 levels, biological CO_2 utilization has gained industrial attention. The



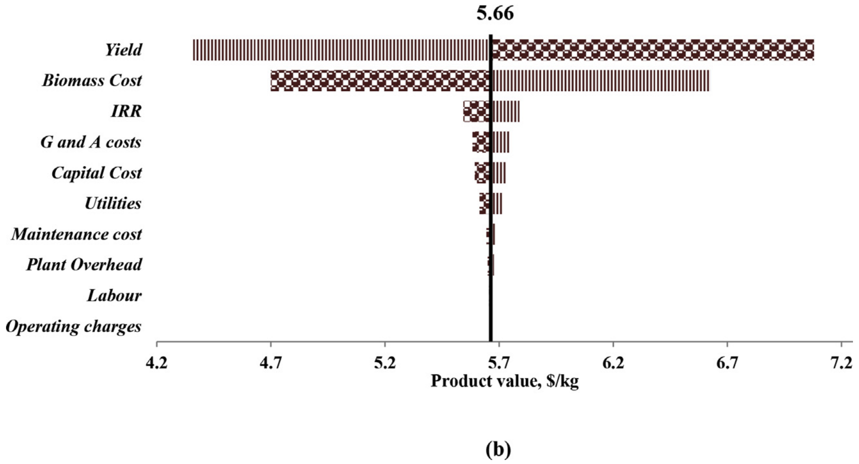
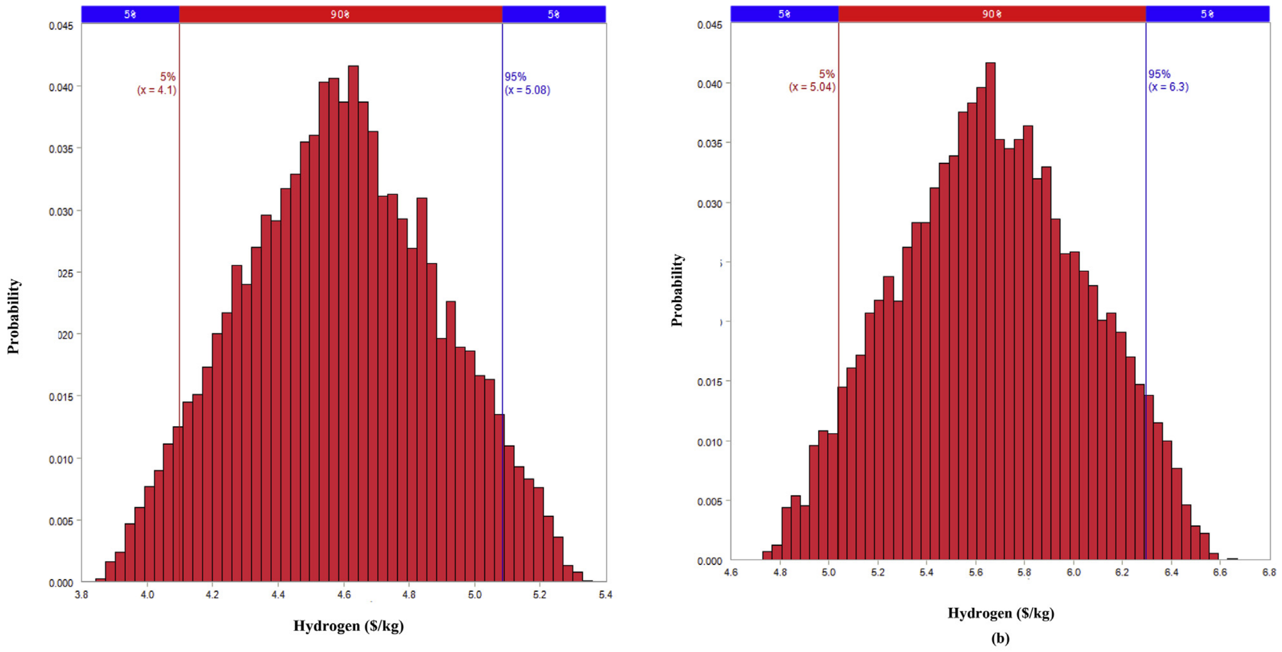


Fig. 5 – Sensitivity analysis on the product value of hydrogen for (a) supercritical water gasification (b) thermal gasification.

photosynthetic microalgae has the ability to use flue gas CO_2 in the form of a carbon source [122]. This inherent feature of algae can be employed to produce biomass with high growth rates. This means that the algal cultivation can rely on CO_2 from a number of industrial sources. This may transform future hydrogen industry as algae are known to have high fixation efficiencies [123]. This could be desirable for industrial sector in the jurisdictions where there is a carbon tax associated with the release of CO_2 in the environment. In jurisdictions like Alberta, a Western Province in Canada, the effective levy on CO_2 emissions have been in the range from $10/tonne to $30/tonne of $CO_{2\text{-eq}}$ [124]. The companies which are paying these levies might be willing to dispose of their CO_2 if there is an opportunity to do this at a lower cost than the carbon levy. The algae conversion facility might benefit from these companies which are willing to pay for taking up the industrial CO_2. Every tonne of algal biomass takes away 1.8 tonnes of CO_2 [12]. The impact of using industrial CO_2 on the product value of hydrogen is further assessed in this study. The payment for CO_2 ($/tonne) to the algae conversion facility was varied from $0–40/tonne and its impact on the product value of hydrogen was studied for both thermochemical routes. Fig. 7 shows the influence of payment for CO_2 utilization on the product value of hydrogen. The assumption in this analysis is that the industrial CO_2 is directly utilized by the algae conversion facility and do not need any purification. Also, it is assumed that the industrial facility is located near the algae conversion facility so there is no transportation cost. For supercritical water gasification plant and thermal gasification, the product value of hydrogen can be reduced to $2.60/kg H_2 and $3.65/kg H_2, respectively, when payment for CO_2 utilization is increased to $40/tonne. Hence, relying on industrial CO_2 for algal biomass growth reduces the product value of hydrogen for both thermochemical technologies.

Future perspectives

As discussed in this paper, algal gasification for hydrogen production can occur through two gasification technologies, thermal gasification and supercritical water gasification. SCWG has limitations with respect to the use of high pressure equipment including continuous pumping, plugging, etc. [125–127]. The availability of algal biomass is a major concern as its cultivation and growth depends on several factors such as nutrients, water, CO_2, temperature, sunlight, etc., as well as



(a)

(b)

Fig. 6 – Uncertainty costs in the product value of hydrogen produced through (a) supercritical water gasification and (b) thermal gasification.

doubling time. Manganaro et al. [120] studied the techno-economics of microalgae production and reported doubling time to be the most sensitive parameter on the sale price of algae; it can be lowered by improving mixing or increasing pond velocity. Also, co-locating an algal plant near industry would make use of industrial CO_2 emissions in algal biomass cultivation [128]. Moreover, the presence of NOx and SOx in industrial emissions does not negatively impact algal growth as NOx is converted to NO_2, which acts as a nitrogen source, and SOx has no influence on algal growth below concentration levels of 400 ppm [129,130]. Thus, flue gas components can be used as nutrients for algal cultivation. Algae are characterized by high moisture containing feedstocks (70–90 wt%) that require drying for thermal gasification. Thermochemical pathways are high-energy processes. During the process run, energy can be lost due to limitations in heat exchanger design [131,132]. The CO_2-rich gas obtained after gas cleanup can be recycled for algal cultivation. Algal companies claim lower costs of microalgae and biofuels production, though this assertion has not been proven in published literature [10,11,30,133].

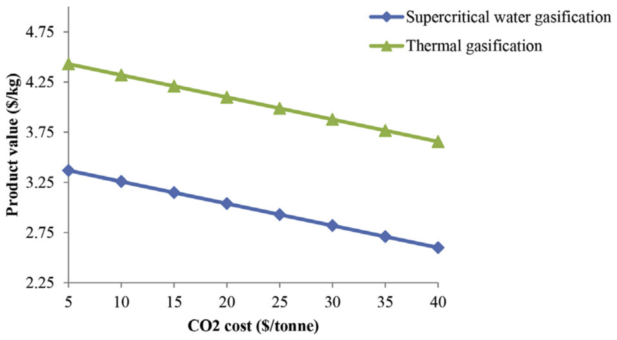


Fig. 7 – Effect of payment for utilization of industrial CO_2 on product value of hydrogen.

Conclusions

Algae is a promising biomass feedstock for energy. Hydrogen production from algae is considered to be an option for obtaining energy as the process is believed to offer highly energy efficient operation, use, and storage. Moreover, the use of CO_2 from industrial source and obtaining a tipping fee for using the CO_2 for algae cultivation reduces the cost of hydrogen production in the thermochemical plant. The harvesting of energy from algae via a thermochemical approach results in a high conversion rate and efficiency. A system was developed to produce hydrogen based on two different gasification technologies. A techno-economic assessment of supercritical water gasification and thermal gasification shows that a 2000 dry tonnes/day plant needs total capital investments of 277.8 M$ and 215.3 M$ with hydrogen product values of $4.59 ± 0.10/kg and $5.66 ± 0.10/kg, respectively. These costs are higher than the natural gas based hydrogen. The sensitivity analysis indicates that cost of algae feedstock and yield are the key sensitive parameters in the economics of the process, which highlights the importance of algal biomass availability. Supercritical water gasification holds tremendous potential because of its ability to handle wet biomass, thereby avoiding the cost-intensive drying step. The economic assessment suggests that the feasibility of the technology depends heavily on the cost of algal biomass and the yield obtained. Increasing algal biomass yield requires developing novel algal biomass production and cultivation systems including new reactor designs, harvesting approaches, and highly productive algal species. Hence, further process optimization research is essential to increase fuel production. If there is a payment from the producer of CO_2 to the algae conversion facility, the cost of hydrogen production comes down significantly.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.ijhydene.2019.02.220.

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