Low-carbon energy transition with the sun and forest: Solar-driven hydrogen production from biomass

AUTHOR(S):

Takeda, Shutaro; Nam, Hoseok; Chapman, Andrew

CITATION:

Takeda, Shutaro ...[et al]. Low-carbon energy transition with the sun and forest: Solar-driven hydrogen production from biomass. International Journal of Hydrogen Energy 2022, 47(58): 24651-24668

ISSUE DATE:

2022-07

URL:

http://hdl.handle.net/2433/275773

INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 47 (2022) 24651–24668

Available online at www.sciencedirect.com
ScienceDirect
journal homepage: www.elsevier.com/locate/he

Low-carbon energy transition with the sun and forest: Solar-driven hydrogen production from biomass

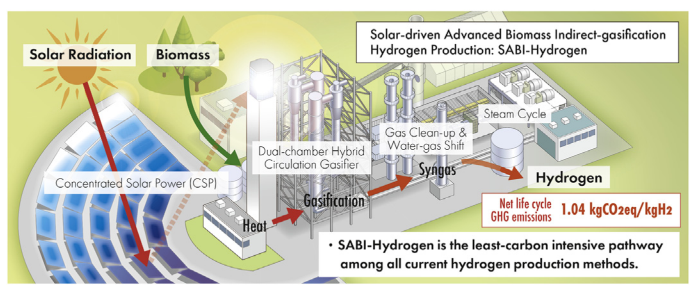
Shutaro Takeda [a,b,*], *Hoseok Nam* [c], *Andrew Chapman* [d]

[a] *Graduate School of Advanced Integrated Studies in Human Survivability (GSAIS), Kyoto University, Kyoto, Japan*
[b] *Kyoto Fusioneering: Uji, Japan*
[c] *Busan Development Institute, Busan, Republic of Korea*
[d] *International Institute for Carbon Neutral Research (I^2CNER), Kyushu University, Fukuoka, Japan*

HIGHLIGHTS

- A novel solar-driven, biomass-derived H_2 production process is proposed.
- GHG emissions of solar-driven H_2 production are 1.04 kg CO_2-eq/kg H_2.
- Solar-driven H_2 from biomass is the least-carbon intensive production method of all.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 12 July 2021
Received in revised form
27 October 2021
Accepted 26 November 2021
Available online 22 December 2021

Keywords:
Hydrogen
Biomass
Gasification
Concentrated solar
Life cycle assessment

ABSTRACT

There is a need to derive hydrogen from renewable sources, and the innovative stewardship of two natural resources, namely the Sun and forest, could provide a new pathway. This paper provides the first comparative analysis of solar-driven hydrogen production from environmental angles. A novel hydrogen production process proposed in this paper, named Solar-Driven Advanced Biomass Indirect-Gasification (SABI-Hydrogen), shows promise toward achieving continuous operation and scalability, the two key challenges to meet future energy needs. The calculated Global Warming Potential for 1 kg of solar-driven hydrogen production is 1.04 kg CO_2-eq/kg H_2, less than half of the current biomass gasification process which emits 2.67 kg CO_2-eq/kg H_2. Further, SABI-Hydrogen demonstrates the least-carbon intensive pathway among all current hydrogen production methods. Thus, solar-driven hydrogen production from biomass could lead to a sustainable supply, essential for a low-carbon energy transition.

* *Corresponding author*. Graduate School of Advanced Integrated Studies in Human Survivability (GSAIS), Kyoto University, Kyoto, Japan.
E-mail address: takeda.shutarou.55r@kyoto-u.jp (S. Takeda).
https://doi.org/10.1016/j.ijhydene.2021.11.203

Introduction

The potential for hydrogen to play a role in the future energy system

As the global energy transition shifts toward not only reducing the carbon intensity of energy generation, but also the incorporation of new technologies, the potential combination of renewable energy and hydrogen has emerged as a contender which may meet both goals. One aspect of energy transitions which will be critical to achieving sustainable, low carbon energy systems is the consideration of so called ‘niche’ technologies [1] and their ability to break through and become mainstream, competing for market share with mature technologies [2] (see Table 1).

Although still arguably a ‘niche’ technology in many markets [3], hydrogen is already recognized as a potential storage and energy generation medium for the future, low carbon energy system [4,5]. Global hydrogen demand is estimated to increase by 4–5% annually over the next five years [6]. By 2050, the annual demand for hydrogen is expected to increase to 650 million tons, or approximately 78 EJ, based on the 2 °C scenario, contributing to an annual decrease of 6 billion tons of carbon dioxide (tCO_2) compared to current emission levels, assuming the majority of the hydrogen is produced from renewable energy sources [7]. Meanwhile, hydrogen is currently still produced predominantly from fossil fuels (i.e., via steam methane reforming and coal gasification) and via electrolysis using a variety of electricity inputs and alkaline water, solid oxide or proton exchange membrane electrolysis methods [7]. As a result, hydrogen production was the source of 500 million tCO_2 in 2015 and 830 million tCO_2 in 2019 [8]. To meet this growing demand while contributing to a reduction in emissions, less carbon intensive methods of hydrogen production need to be employed. This study proposes a novel hydrogen production process from biomass and solar power, both somewhat mature technologies in their own right, in a unique, ‘niche’ combination, as a proposal toward low carbon energy generation.

Current hydrogen production pathways: biomass pyrolysis and gasification

In light of the high percentage of fossil fuel derived hydrogen, production methods which utilize biomass feedstocks are attracting attention as a carbon-free hydrogen source [9]. The three major thermochemical conversion processes for biomass are pyrolysis, gasification and combustion. Pyrolysis is the thermochemical conversion of organic substances in the absence of oxygen at a temperature of between 350 and 600 °C [10]. Gasification occurs at a higher temperature range typically above 800 °C with lower than stoichiometric levels of oxygen [11]. Unlike combustion, whose principal product is heat, both pyrolysis and gasification yield synthesis gas (syngas), a blend of hydrogen and carbon monoxide as their primary products. Syngas can be further processed into hydrogen through water-gas-shift reactions.

The life cycle environmental impacts of hydrogen production from biomass feedstocks have been thoroughly investigated, where reductions in GHG emissions are widely reported in comparison to fossil fuel-based production methods [13–16]. The resultant acidification impact is also generally estimated to be lower than conventional hydrogen production methods, to varying degrees [16–18]. However, despite the environmental advantages, cost is currently a prohibiting factor for hydrogen production from biomass. While the cost of hydrogen production with biomass gasification is estimated to be less than half of that of renewable energy based electrolysis [19], a minimum natural gas price of $5/GJ must be met for the process to be economically competitive against commercial natural gas-based steam methane reforming plants, assuming a biomass feedstock cost of $100 per ton [20,21]. A part of the higher hydrogen production cost is due to the feedstock cost [22], therefore, improving resource efficiency is essential in reducing production costs.

There are a number of hydrogen producing biomass gasification pilot plants in operation [23]. Notably, the National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy has operated a pilot plant-based research project on hydrogen production from biomass gasification over the last few decades [22,24–26]. NREL's studies are based on an indirectly heated biomass gasifier technology originally developed by the Battelle Memorial Institute [27].

Innovative pathways: solar-driven pyrolysis and gasification

One promising option to increase resource efficiency when producing hydrogen from biomass feedstocks is to utilize external heat sources to heat gasifiers, eliminating the need for partial combustion of feedstocks. If such a plant could be designed with zero-emission high-temperature heat sources, a novel hydrogen production plant with a high resource efficiency and a low environmental footprint could be achieved. Currently, the concentrated solar plant (CSP) provides a readily available heat source that could be coupled with a biomass plant as a means to reduce reliance on fossil fuels in the production of hydrogen.

Table 1 – Key technologies of biomass energy conversion [12].

Conversion	Process	Product	End-Use
Thermochemical Conversion	Combustion	Heat	Heat, Electricity
	Pyrolysis and Gasification	Synthetic Gas (H_2 + CO)	Electricity, Chemical Feedstock
		Hydrogen (H_2)	Electricity, Transport Fuel
		Liquid Fuel (Diesel)	Transport Fuel
Biological Conversion	Zymolysis	Methane	Transport Fuel
		Alcohol (Ethanol, Butanol)	Transport Fuel

There are a number of studies on solar-driven pyrolysis plants including pyrolytic reactors and kinetic analysis of biomass behavior [28]. The benefits of solar-driven pyrolysis were investigated by Ndukwu et al. [29] utilizing optical concentrating devices, in which the authors emphasized the significance of the appropriate configuration of the solar thermal system toward performance. Within existing research, simulation and experiment-based studies exist, for example, a computer simulation of cogeneration based on biomass incorporating a CSP facility was modeled for three cities in Turkey, identifying the effect of temperature on hydrogen production [30]. Further, an experiment was conducted utilizing the pyrolysis of rice husks to produce fuels and chemicals with concentrated solar radiation, indicating that reaction temperatures of 500–700 °C produce high quality bio-oils [31]. There are also several lab-scale plants in operation for solar-driven pyrolysis of biomass including a pyrolysis plant with a parabolic-trough solar concentrator by Morales et al. [32] which achieved a peak temperature of 465 °C. In addition to the production of bio-oils, CSP and biomass from multiple sources can be used to derive both solid and liquid fuels [33].

Advances in solar concentrating technologies indicate that certain configurations of solar reactors (indirectly irradiated packed-bed, directly irradiated vortex-flow and indirectly irradiated entrained-flow) can achieve temperatures exceeding 800 °C, sufficient for gasification. In assessing the potential of solar gasification using molten salts, Hathaway et al. [34] described a solar concentrator and molten alkali carbon salt-based approach, capable of molten salt temperatures between 850 and 960 °C. There are a small number of studies that propose to utilize solar energy for gasification. Results are presented at the laboratory scale and suggest that temperatures achieved improve gasification efficiency, extolling the virtues of using alkali carbon salts [35]. The dispersion of biomass particles in a molten salt medium (carbonates of potassium and sodium) transfers solar energy reaching operating temperatures of 800–915 °C for continuous syngas production [36]. A review paper on solar gasification of carbonaceous feedstocks explained the development of solar thermochemical reactors for gasification and further described the current situation of patents and relevant research papers [37]. An investigation of solar thermal-driven allothermal gasification processes provided information on economic, thermodynamic and kinetic analyses [38]. Two methods for hydrogen production using solar energy have been explored; i.e. solar thermochemical cycles from water, and from carbon sources (i.e., fossil fuels and biomass) [39]. Solar thermochemical processes, reactor technology, thermodynamics, economic and environmental analyses of CSP approaches have also been undertaken [40]. A concentrated solar radiation receiver specifically for biomass gasification where bio-fuel is produced from H_2O and CO_2 via 2-step redox cycles was designed in Ref. [41]; similarly, a solar receiver with a packed-bed gasifier was proposed in Ref. [42]. Romero and Steinfeld [43] provided an analytical review of these two solar receivers. Another solar-driven pyrolysis/gasification experiment was conducted by Arribas et al. [44] to investigate thermochemical reaction efficiencies and a comparison of yields. The results indicated that gasification produces more syngas of a higher quality than for pyrolysis. Finally, a supercritical water biomass gasification pilot plant utilizing solar energy was constructed by the State Key Laboratory of Multiphase Flow in Power Engineering in China [45], where the authors reported that the plant can achieve an annual operating time of 3000 h.

Design limitations of existing solar-driven pyrolysis and gasification approaches

Previous studies pointed to the potential feasibility of solar-driven hydrogen production through biomass gasification. However, previously proposed designs lack two of the most important elements for solar-driven hydrogen production to become a viable mainstream option for climate change mitigation: 1) scalability and, 2) the ability to operate continuously. To illustrate these limitations, previous gasifier designs outlined in Refs. [41,42,45] are cited in Fig. 1(a) and (b) and Fig. 2, respectively.

While the designs described in Refs. [41,42] achieve higher efficiencies due to optimized design, these reactors are not suitable to be scaled-up to industry-scale due to their fixed bed design. The supercritical water biomass gasifier detailed in Ref. [45] may satisfy the scale-up limitation, however, as their gasifier is directly heated by solar radiation, the capacity factor of the plant cannot exceed ~35%.

Purpose of this study

This purpose of this research is to provide the first comparative analysis on the environmental performance of a solar-driven hydrogen production pathway to determine the feasibility of this approach, cognizant of current technological readiness levels and potential future policy interventions.

Plant design methodology

Approach of this study

The literature review identified that scalability and continuous operation of CSP biomass gasification are the two major challenges that prohibit solar-driven biomass hydrogen production from becoming mainstream. In this paper, the authors propose a novel yet feasible alternative to solar-driven hydrogen production: a dual chamber solar hybrid indirect-heated gasifier which overcomes the two stated barriers. The purpose of this paper is to analyze this novel hydrogen production process from environmental perspectives to comparatively discuss if solar-driven hydrogen production could be a competitive option in the future energy system.

The approach used in this paper is illustrated in Fig. 3. The first step involves the development of process flow diagrams (PFD) for the Solar-driven Advanced Biomass Indirect-gasification Hydrogen production plant (SABI-Hydrogen). The energy and material balances were verified based on a rigorous literature review. Based on the material and energy balances, an environmental life cycle impact assessment (LCIA) was conducted using the ReCiPe 2016 impact assessment method to assess the environmental footprint of hydrogen production for the SABI-Hydrogen plant.

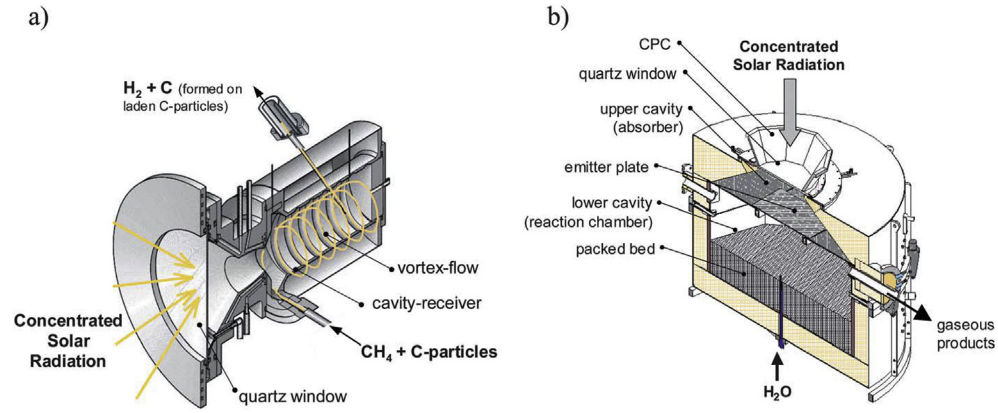


Fig. 1 – Solar Reactor for the Production of Syngas: (a) directly irradiated vortex-flow solar reactor and (b) indirectly irradiated packed-bed solar reactor [43].

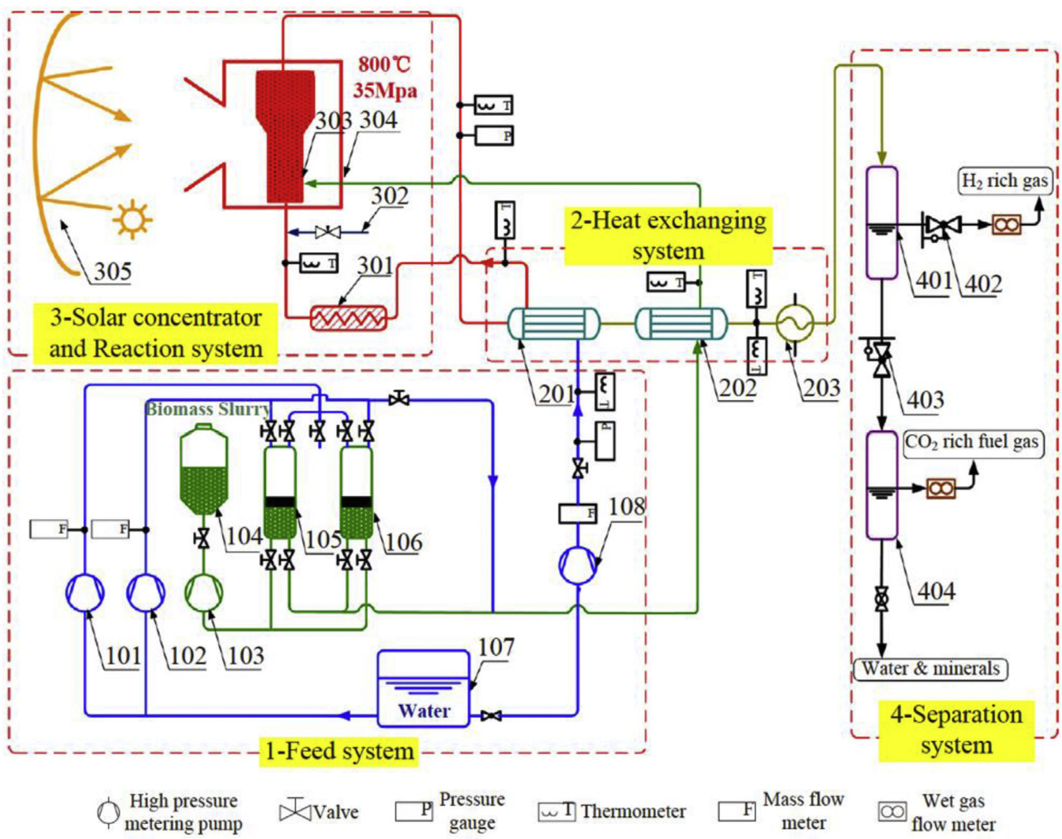


Fig. 2 – Supercritical Water Biomass Gasification Pilot Plant [45].

Design basis

The Solar-driven Advanced Biomass Indirect-gasification Hydrogen production plant (SABI-Hydrogen) was designed based on rigorous literature review of multiple approaches to biomass gasification, cognizant of their limitations as stated above. The plant capacity was fixed at 150 dry ton/day as the basis of the design. The Battelle Columbus Laboratory Indirectly-Heated Gasifier [25] was chosen as the reference gasifier for the dual chamber solar hybrid indirect-heated gasifier. The downstream processes, including gas clean-up, water-gas-shift conversion, waste heat recovery and steam cycle, were based on data from NREL [22] in order to increase the reliability of economic and environmental assessments. The proposed plant schematic is shown in Fig. 4.

The components and heating values for biomass feedstock were assumed based on [22,24] as detailed in Tables 2 and 3. In accordance with NREL assumptions, the as-received biomass (wood) was assumed to be dried to 12 wt% with a rotary dryer [22].

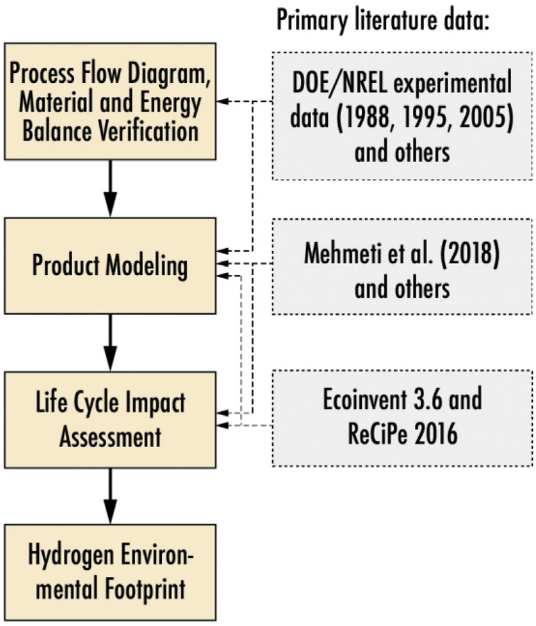


Fig. 3 – The approach of this Paper (by Authors).

Table 2 – Assumed Biomass Feedstock Components and heating values [22,24].

Component	C	H	N	S	O	Ash
[wt%, dry basis]	50.88	6.04	0.17	0.09	41.90	0.92
Heating Value	**HHV**			**LHV**		
[MJ/kg]	20.17			18.75		

Process flow diagram

Solar-driven advanced biomass indirect-gasification process

A typical gasification system is comprised of a gasifier, a gas cleanup system and an energy recovery system [46]. The three major types of gasifiers are fixed bed, entrained flow and fluidized bed. Of the three, fluidized bed gasifiers were developed to increase efficiency by injecting upward flowing gas as a gasification agent [47]. Among several types of fluidized bed gasifiers, the circulating fluidized bed (CFB) gasifier can process a wide range of biomass feedstock: they can not only gasify woody feedstocks (e.g. wood pellets and chips) but crop residues and wastes as well [48]. Typical CFB gasifiers are flexible in feed quantity and moisture between 5 and 60%, although low moisture content is desirable for high-quality syngas production. CFB gasifiers also accept a wide range of feedstock size, although feedstock of less than 20 mm in size is ideal and sieving components like metering bins, lock hoppers and screws are required for feedstock preparation. Since ash melting and sticking occur during high temperature gasification operation, using catalysts such as dolomite, potassium, sodium, and calcium is encouraged to alleviate agglomeration issues and to encourage an efficient conversion process [49]. With their lower capital costs, CFB gasifiers are also economically more suitable for the purpose of biomass hydrogen production than entrained flow gasifiers [21]. CFB gasifiers have been commercially used since the 1980s and their scale-up potential is good, as evidenced by many large projects already in operation [50].

To generate the required temperature for biomass gasification, CFB gasifiers combust either the biomass feedstock or the product synthetic gas. Currently, around 30% of the input energy from biomass feedstock is consumed for heat generation resulting in an overall exergetic efficiency of around 48% for hydrogen production [51]. This is not ideal both in terms of the efficient usage of biomass resources and for hydrogen production costs.

The usage of pure steam without oxygen instead of air as a gasification agent can increase the hydrogen production in CFB gasifiers [52]. Hydrogen purity is dependent on the gasification agent, i.e. for pure steam (53–55 vol%) > steam-O_2 (25–30 vol%) > air (8–10 vol%) [53]. To use steam as the agent,

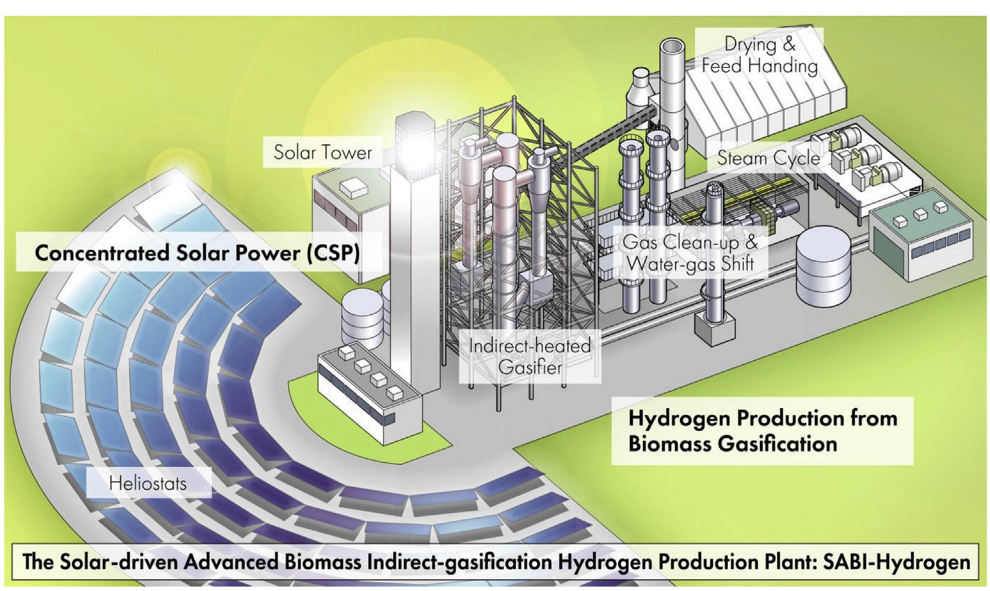


Fig. 4 – The solar-driven advanced biomass indirect-gasification hydrogen production plant: SABI-hydrogen (by authors).

Table 3 – Syngas parameters (based on [22,27]).

Operation Mode	Value
Temperature	870 °C
Pressure	1.6 bar
Gas composition	mol% (wet)
H_2	12.91
CO_2	6.93
CO	22.84
H_2O	45.87
CH_4	8.32
C_2H_2	0.22
C_2H_4	2.35
C_2H_6	0.16
C_6H_6	0.07
Tar ($C_{10}H_8$)	0.13
NH_3	0.18
H_2S	0.04
Gas heating value (Btu/lb)	Wet: 4739 HHV 4402 LHV Dry: 7984 HHV 7417 LHV
H2:CO molar ratio	0.57
Gasifier efficiency	72.1% HHV basis 71.8% LHV basis
CO_2 in Flue Gas	22.1 wt%

indirect gasifiers have been developed based on fluidized bed gasifiers. Two of the proposed indirect gasifiers are presented schematically in Fig. 5, based on [46].

Based on the analysis detailed above, this paper proposes a novel approach incorporating a dual chamber solar hybrid indirect-heated gasifier as a potential break-through solution to maximize hydrogen production while minimizing biomass resource usage. The novelty of this dual chamber solar hybrid indirect-heated gasifier is to combine solar heating with a conventional indirect-heated gasifier approach to achieve continuous operation and scalability. High-level process flow diagrams of the dual chamber solar hybrid indirect-heated gasifier are shown in Fig. 6.

In this design, the heat required for biomass gasification is normally provided by solar irradiation. While linear focusing collector technologies such as Linear Fresnel Reflector (LFR) are more mature for CSP, the Solar Tower System had to be chosen to maintain a high operating temperature. The concentrated solar plant consists of three parts: heliostats, solar tower and molten salt storage tanks. The solar irradiation is collected and then stored in the molten salt hot tank as per ordinary CSP operation. When the heat supply from hot tank is available, the sand in the gasifier will be heated through a heat exchange with molten salt in the second chamber. During this operation (Fig. 6 (a)), no air will be supplied to the second chamber, the Solar Indirect Heater, to prohibit partial combustion of biomass feedstocks. This dramatically improves the biomass resource utilization for the end product, hydrogen. When the hot tank level becomes low, air will be supplied to the indirect heater to facilitate combustion. During this operation mode (detailed in Fig. 6 (b)), the sand in the gasifier will be heated by the combustion of char. Under some climate conditions, an external heater might be needed to keep the temperature the molten salt in the cold tank above the solidification point during this operation. This hybrid design enables the plant to switch between two operational modes without affecting the downstream processes, thus, enabling the plant to operate continuously under all climatic conditions. Furthermore, as the design is based on mature CFB gasifier technology, it has proven scale-up potential. As a result, the proposed dual chamber solar hybrid indirect-heated gasifier has the potential to become an instrumental technology in overcoming the two primary barriers for solar-driven hydrogen production.

Two candidate CSP technologies, solar power tower (SPT) and parabolic dish collector (PDC), were considered for this design due to their provision of sufficient high outlet temperatures. Although PDC does not show a high compatibility with regard to thermal storage and hybridization [54], SPT, consisting of a heliostat field and a tower collector is promising because it has high hybridization flexibility to be able to select from different types of heliostats, receivers and transfer fluids [55]. The solar radiation is collected and focused by heliostats, after which the heat is transferred by varied media such as molten salts, liquid sodium, volumetric air and ceramic particles up to a temperature of 1000 °C [56,57]. Among SPT CSPs, Abengoa Solar's Planta Solar 20 (PS20) was chosen as the reference design based on its power capacity, 20-MW PS20 is an improvement over its predecessor, PS10, whereby its natural circulation receiver and increasing incident solar radiation capture increased energy output to more than 40 GW-hours of energy per annum [58]. Based on these considerations, the energy storage capacity was increased from 1 h to 15 h with an assumed capacity factor of 65%, based on [59].

The dual chamber solar hybrid indirect-heated gasifier was designed based on the low-pressure indirectly heated biomass gasifier developed by the Battelle Columbus Laboratory, which achieved greater calorific values than air blown direct gasifiers with indirect heating [25]. The Battelle indirect gasifier operates at close to atmospheric pressure (1.6 bar), enabling conveyors and hoppers to feed the feedstock. The wet wood chips are dried by a rotary dryer to a moisture content of 12 wt% before being fed to the gasifier. According to the experimental data by Battelle, the drying system can handle any reasonable moisture content for wood chips, up to at least 48.3 wt% [27]. The magnesium silicane, primarily made of Enstatite, Forsterite and Hematite were assumed as the sand medium. As this gasifier is based on commercially proven Circulating Fluidized Bed (CFB) gasifier technology, the output can be scaled up to meet larger demands [22].

Hydrogen production through syngas reforming

The syngas produced from the dual chamber solar hybrid indirect-heated gasifier can be utilized for multiple end products, including power generation, liquid fuels, urea and methanol [60]. For this paper, hydrogen was chosen as it represents an essential energy medium to engender the global energy transition as outlined in Section 1. Hydrogen production technology through reforming syngas obtained by biomass gasification has been analyzed extensively over the past decades, including by the NREL Hydrogen Analysis (H2A) team [61]. Previous studies share a commonality in the hydrogen production process from syngas, in that tar has to be recovered and transformed into lighter combustible gases by means of catalytic processes [62]. Ash produced from inorganics in biomass feedstocks are separated by cyclone

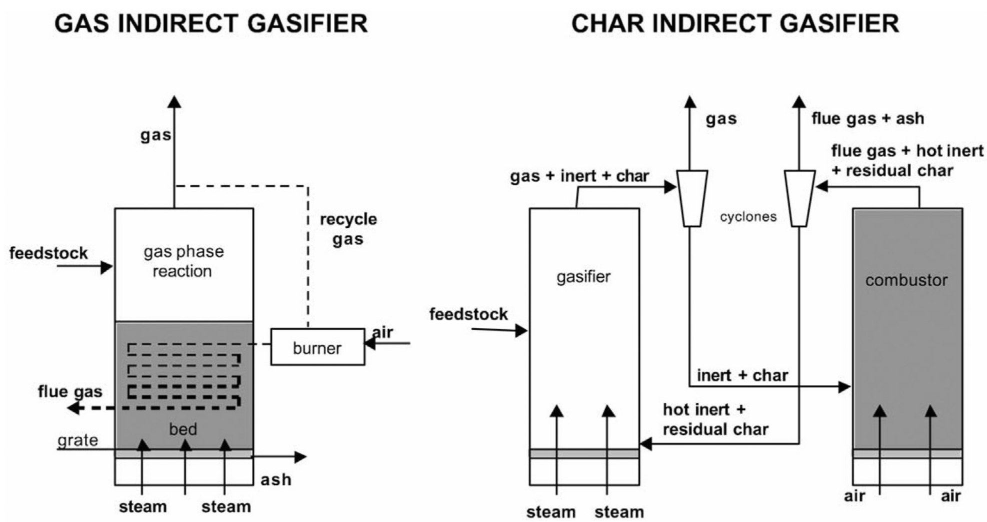


Fig. 5 — Schematic drawings of indirect gasifiers [46].

separators, which are assumed to be landfilled in this study. Following this process, the gas is cleaned, and hydrogen is produced via water-gas-shift reactions. Subsequently, hydrogen separation is performed by either pressure swing adsorption (PSA) or ceramic membranes. Since both hydrogen separation technologies produce hydrogen with a purity level of 99% at a 90% recovery rate [63,64], the appropriate technology can be chosen depending on system configuration. For this paper, downstream process from Ref. [22] were adopted as shown in Fig. 7, consisting of gas clean-up, water-gas-shift, waste heat recovery and steam cycle subsystems.

The assumed parameters for the syngas from the dual chamber solar hybrid indirect-heated gasifier are summarized in Table 3.

Evaluation and comparison methodology

Framework

To estimate the environmental impact of hydrogen production at the proposed SABI-Hydrogen plant, an environmental life cycle assessment (LCA) was conducted in conformity with ISO14040/44.

The proposed system is modeled on OpenLCA version 1.10, an open-source software tool for LCA by GreenDelta including uncertainty analysis utilizing the Monte-Carlo method [65]. Ecoinvent 3.5 with cut-off was used as the input database. The cut-off approach, also known as the 'recycled content approach', is employed when the direct relation of the products and processes of the functional unit are taken into consideration for environmental burden calculations [66].

Goal and scope definition

The system boundary for the system analysis was set to consider "cradle-to-gate" impacts, and 1 kg of hydrogen production was chosen as the functional unit. The system boundary of this assessment is illustrated in Fig. 8 in accordance with the U.S. Department of Energy's Life Cycle Stage classifications.

The Life Cycle Stage classification by the U.S. Department of Energy [67] classifies the life cycle into five stages, including raw material acquisition (RMA), raw material transport (RMT), energy conversion facilities (ECF), product transport (PT), and end use (EU). RMA and RMT are considered upstream emissions of the extraction process, while PT and EU are downstream emissions which include emissions after a product has left the plant and is consumed by end-users. The system boundary of this study included the operation and maintenance of facilities but not the replacement of major building structures, e.g., the solar tower. Since recycling could reduce the impacts of production due to reduced primary material consumption, recycled materials outside of the system boundary are not included [68].

Impact assessment method

ReCiPe2016 (Hierarchist) was utilized as the impact assessment method for this LCIA. ReCiPe2016 is an impact assessment methodology updated from ReCiPe2008 [69]. The update from the 2008 to the 2016 version enabled the characterization of factors that are "representative for the global scale, instead of the European scale, while maintaining the possibility for a number of impact categories to implement characterization factors at a country and continental scale" [70].

ReCiPe2016 has 17 midpoint impact categories and three endpoint categories and adopts Global Warming Potential (GWP) as defined in the IPCC 5th Assessment Report [71] as the climate change impact. Ecoinvent provides ReCiPe2016 indicators and parameters for OpenLCA. The default provided impact assessment parameters do not take CO_2 absorption from the atmosphere into account (in this case, from growing trees for biomass feedstock), and for this reason, the impact assessment parameters were modified from the default settings so that 1 kg of elementary flow of CO_2 from the air

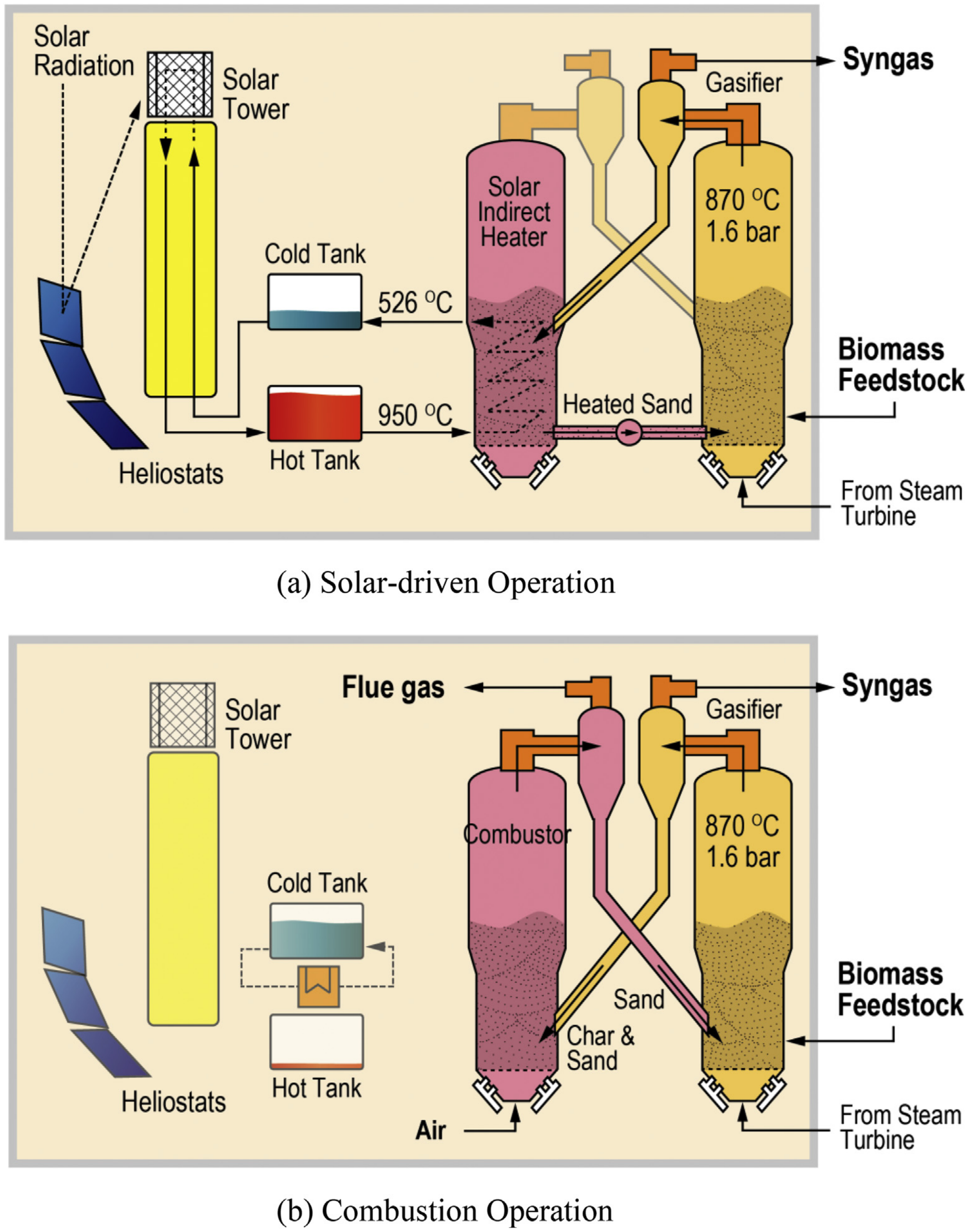


Fig. 6 – High-level process flow diagram of the dual chamber solar hybrid indirect-heated gasifier (by authors).

cancels 1 kg of elementary flow of CO_2 emissions to the air. In exchange, "carbon dioxide, biogenic" emissions were modified to be weighted as 1 kg to avoid the double counting of any carbon removal.

Comparison with competing technologies

The 17 midpoint LCIA results were compared in detail against conventional hydrogen production from biomass gasification with the Battelle indirect gasifier. Further, the 3 endpoint LCIA results and the GWP impact were compared against 12 existing hydrogen production pathways; steam reforming of natural gas, coal gasification, water electrolysis via proton exchange membrane, solid oxide electrolyzers, biomass gasification and reforming, and dark fermentation of lignocellulosic biomass, as reported in Ref. [72]. In order to enable the direct comparison of results, the system boundary and the product modeling methodology of this paper are designed to be uniform with that of [72].

Modeling

Modeling basis

The plant parameters assumed for both environmental and economic assessments are summarized in Table 4. The overall capacity factor of the SABI-Hydrogen plant was assumed to be 93% (both solar-driven and combustion operation modes combined), based on the current NREL design with the Battelle

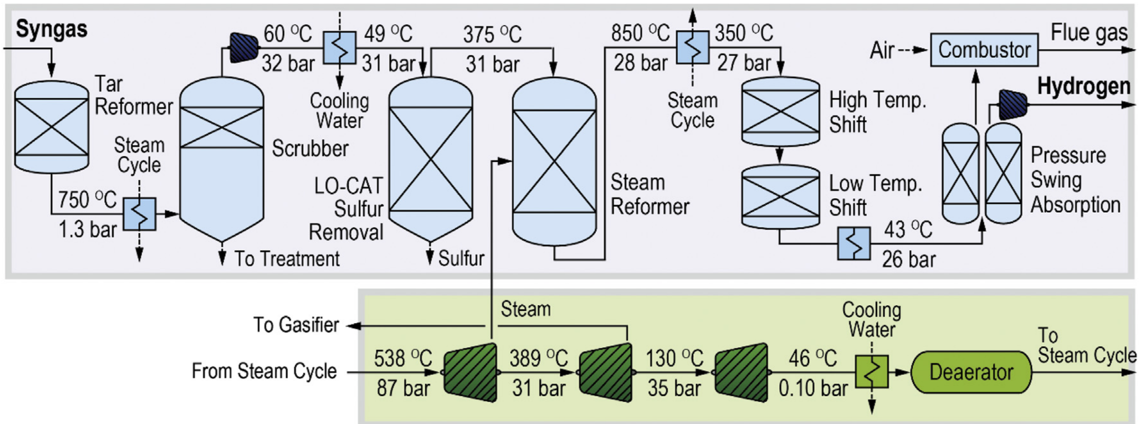


Fig. 7 – Process design for gas clean-up, water-gas-shift, waste heat recovery and steam cycle subsystems (based on [22]).

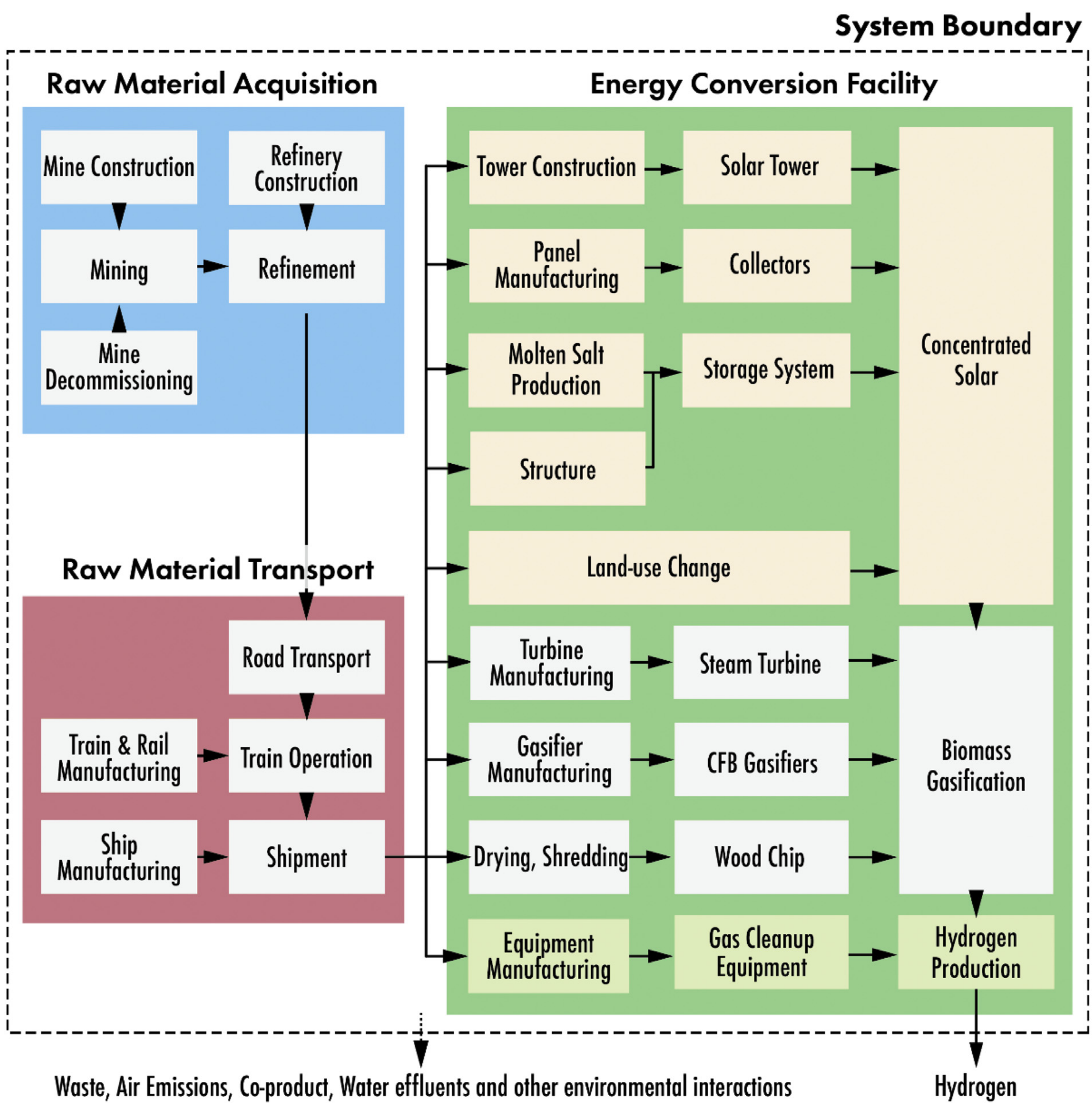


Fig. 8 – System Boundary of the Environmental Life Cycle Assessment (by authors).

Table 4 – Main plant parameters for solar-driven biomass indirect gasification plant.

Parameters	Value	Basis	Comments
Annual operating time for solar-driven operation	5694 h	Estimated based on [55]	Capacity factor of 65%, with 15-h storage.
Annual operating time for combustion operation	2453 h	Estimated based on [22]	Combined capacity factor of 93%, based on the NREL Current Design data [22].
Operation years	20 years	Assumed from [22]	
Solar resource	2012 kWh/m^2/yr	Estimated based on [58]	Measurement for Planta Solar 20. Note: the measured solar resource in Planta Solar 20 site is in range of that of the South-west U.S [73].
Biomass feedstock flow during solar-driven operation	86,200 kg/h (dried)	Calculated based on [22,27]	
Biomass feedstock flow during combustion operation	135,520 kg/h (dried)	Assumed from [22]	
Hydrogen production rate	6468 kg/h	Assumed from [22]	Constant for both solar-driven and combustion operation.
Operation pressure of the gasifier	1.6 bar	Assumed from [22]	Constant for both solar-driven and combustion operation.
Operation temperature of the gasifier	870 ^{O}C	Assumed from [22]	Constant for both solar-driven and combustion operation.
Molten salt material	$KCl-MgCl_2$	Adopted from [74]	Melting point at 426 ^{O}C and 900 °C vapor pressure at < 2 mmHg [75]
Average Transportation Distance for Biomass	27.6 km	Adopted from [76]	Assuming 10% of the land around the plant is available for crop production; 70% transported by truck and 30% by train

indirect gasifier data. The capacity factor for the solar-driven operation alone was assumed to be 65% with 15-h thermal storage based on [55], where combustion operation will supplement the remaining capacity.

The geological location of the plant was assumed to be in the South-western United States. The SABI-Hydrogen plant was designed as an extension of the NREL Battelle hydrogen production plant. As the NREL plant has already been both assessed environmentally and economically based on experimental measurements in previous studies [22,76], the SABI-Hydrogen plant was modeled according to differentials in the construction and in the operation from the NREL Battelle hydrogen production plant to increase the reliability of the assessments.

Construction

The five key additional required construction units for the SABI-Hydrogen, when compared to the NREL Battelle hydrogen production plant, are: the solar receiver system, thermal storage unit, steam generation system, power block unit and the land area required for the additional structures, primarily for the heliostats. Estimated values of these construction units are summarized in Table 5 along with estimation methods and their level of reliability.

Operation

As described in Section 2.2.1, the SABI-Hydrogen plant operates in two modes: solar-driven and combustion. Capacity factors of each operation were assumed to be 65% for solar-driven mode and 28% for combustion mode (a combined capacity factor of 93%, estimated based on [22,55]). Estimated differentials in operating parameters for solar-driven operation are summarized Table 6 along with estimation methods and their level of reliability.

Uncertainty assessment

As the modeling undertaken in this study is based on literature and not on direct measurements, reliabilities of the assumptions were appraised based on the pedigree matrix approach [77] as shown in Table 7.

Table 5 – Assumptions for additional construction units.

Construction Unit	Estimated Value	Estimation Method	Reliability
Land Area	Heliostat field area 150,000 m^2	Based on actual measurements from [58]	Non-verified data based on measurements.
Solar Tower	Single solar tower, 165 m high	Based on actual measurements from Ref. [58],	Non-verified data based on measurements.
Heliostats	1255 Heliostats	Based on actual measurements from [58]	Non-verified data based on measurements.
Storage System	15 Hrs Heat Storage	Estimated based on [55] to achieve capacity factor of 65%	Non-verified data partly based on qualified estimates

Table 6 – Differentials in operating parameters for solar-driven operation.

Parameter	Value	Estimation Method	Reliability
Feedstock consumption	−5.170 kg/kg-H2 production (Dried Mass)	Calculated based on experimental data from [27]	Non-verified data based on measurements.
Fluegas emissions from the combustor	−23.66 kg/kg-H2 production	Calculated based on experimental data from [27]	Verified data based on measurements

The SABI-Hydrogen plant operates under the same conditions as the NREL Battelle hydrogen production plant during combustion operation; as such, there are no differentials in operating parameters during this phase.

Table 7 – Uncertainty Matrix Approach [77].

Reliability Appraisal	Geometric Standard Deviation
Verified data based on measurements	1.00
Verified data partly based on assumptions or non-verified data based on measurements	1.05
Non-verified data partly based on qualified estimates	1.10
Qualified estimate (e.g. by industrial expert)	1.20
Non-qualified estimate	1.50

Under this approach, all estimated data are treated to have log-normal distributions with certain geometric standard deviations. The results of environmental assessments are calculated using the Monte-Carlo method for 10,000 iterations to quantify uncertainty.

Sensitivity analysis for solar-driven operation

Parameters that are unique to the solar-driven operation may show significant deviations from assumptions. To assess the robustness of results and their sensitivity to key parameters, sensitivity analyses were conducted both for the environmental and economic assessments on solar-driven operation specific parameters. Table 10 shows the assessed parameters and their ranges.

Results

Midpoint impact assessment

Based on the life cycle inventory results, 17 midpoint impacts were calculated for 1 kg of hydrogen production at the SABI-Hydrogen plant based on the ReCiPe2016 impact assessment method. The calculated midpoint impacts are compared against those for the NREL Battelle gasification plant in Table 9.

The uncertainties of performance indicators are also calculated using the Monte-Carlo method at a 90% Confidence Interval. The midpoint impact performance indicators for the NREL Battelle plant were cited from Ref. [72]. Please note that ref. [72] refers to the DOE H2A Production Analysis project [78], based directly on the NREL Battelle experimental results.

Among the calculated 17 midpoint performance indicators, the advantage of the SABI-Hydrogen plant is evident in the Global Warming Potential (GWP_{100}): the hydrogen production through SABI-Hydrogen only emits 39.0% of greenhouse gases (GHG) in its life cycle compared to the conventional biomass gasification hydrogen production process. This is a notable result considering the fact that conventional biomass gasification hydrogen production is considered as one of the most environmentally friendly production pathways among all currently available technologies [72]. The uncertainty of the

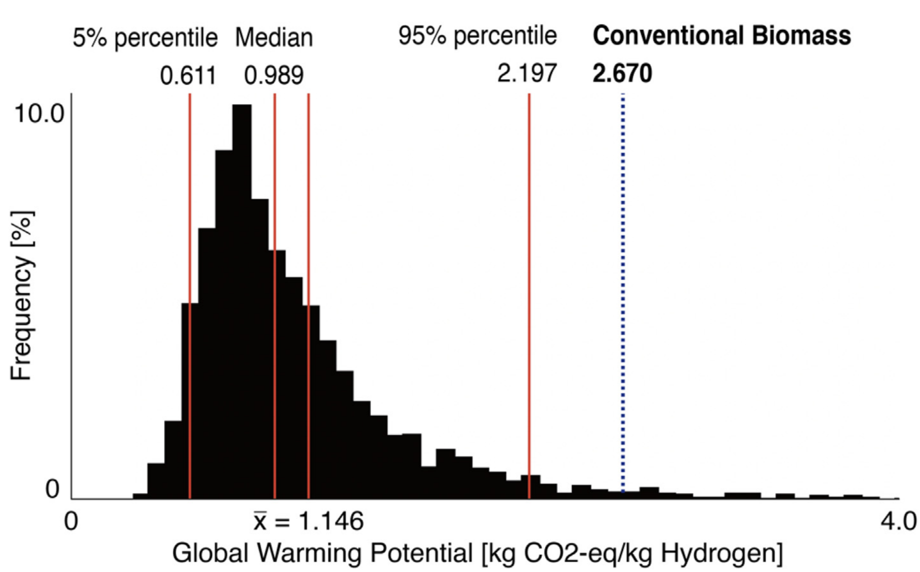


Fig. 9 – Uncertainty of the global warming protentional (GWP_{100}).

Table 8 – Parameter ranges for sensitivity analysis.

Parameters for the Solar-driven Operation	Sensitivity Analysis Range		
	Lower Value	(Baseline)	Upper Value
Capacity factor of the solar-driven operation	50%	(65%)	75%
Feedstock consumption during solar-driven operation (in relative to the combustion operation)	−4.653 kg/kg-H_2	(-5.170 kg/kg-H_2)	−5.687 kg/kg-H_2
Fluegas emissions from the combustor during solar-driven operation (in relative to the /combustion operation)	−22.15 kg/kg-H_2	(-24.61 kg/kg-H_2)	−27.07 kg/kg-H_2
Average transport distance for biomass feedstock	6.9 km	(27.6 km)	110.4 km

GWP_{100} indicator result was assessed with the Monte-Carlo method over 10,000 iterations, as shown in Fig. 9.

The 90% confidence interval for the GWP_{100} indicator was between 0.611 and 2.197 kg CO_2-eq/kg Hydrogen. This interval is lower than the GHG emissions of the conventional biomass gasification process, which is 2.670 kg CO_2-eq/kg Hydrogen. Therefore, it can be concluded that even considering the large uncertainty of the calculation result based on the lack of measurements, it is highly likely that the SABI-Hydrogen production pathway is more environmentally friendly than conventional biomass gasification hydrogen production methods.

Other midpoint impact indicators for the SABI-Hydrogen production generally show similar performance to conventional biomass gasification, with the exception of ecotoxicities. The increase in the ecotoxicity footprints were the result of additional construction of units for the SABI-Hydrogen plant: the construction of the thermal storage system alone was accountable for 0.7132 kg 1,4-DCB-eq in the Terrestrial Ecotoxicity category. A similar increase is also observed for mineral resource scarcity, where a 76% increase in the footprint is attributed to the construction of thermal energy storage and the solar tower.

Environmental sensitivity analysis

Sensitivities of the parameters specific to solar-driven operation, listed in Table 8, are analyzed for the Global Warming Potential (GWP_{100}) indicator. Results of the sensitivity analysis are shown in Fig. 10.

Parameters specific to solar-driven operation showed certain sensitivities toward the GWP_{100} indicator result. The GWP_{100} indicator decreased by 0.250 kg CO_2-eq/kg H_2 (24% of the baseline value) when the capacity factor of solar-driven operation improved to 75%; a 10% increase in consumption of biomass feedstock increased the GWP_{100} indicator by 0.380 kg CO_2-eq/kg H_2 (37% of the baseline value); and a 10% increase in the flue gas emissions from the combustor increased the GWP_{100} indicator by 0.199 kg CO_2-eq/kg H_2 (20% of the baseline value). Further, the transport distance for the biomass feedstock showed sensitivities toward results. When the average transport distance was extended from 27.6 km in the baseline case to 110.4 km, four times the baseline, the GWP_{100} indicator was commensurately increased by ~30%. These sensitivities suggest that the actual GHG emissions may differ considerably from the baseline calculation; however, the results in Fig. 12 indicate that the GHG emissions of SABI

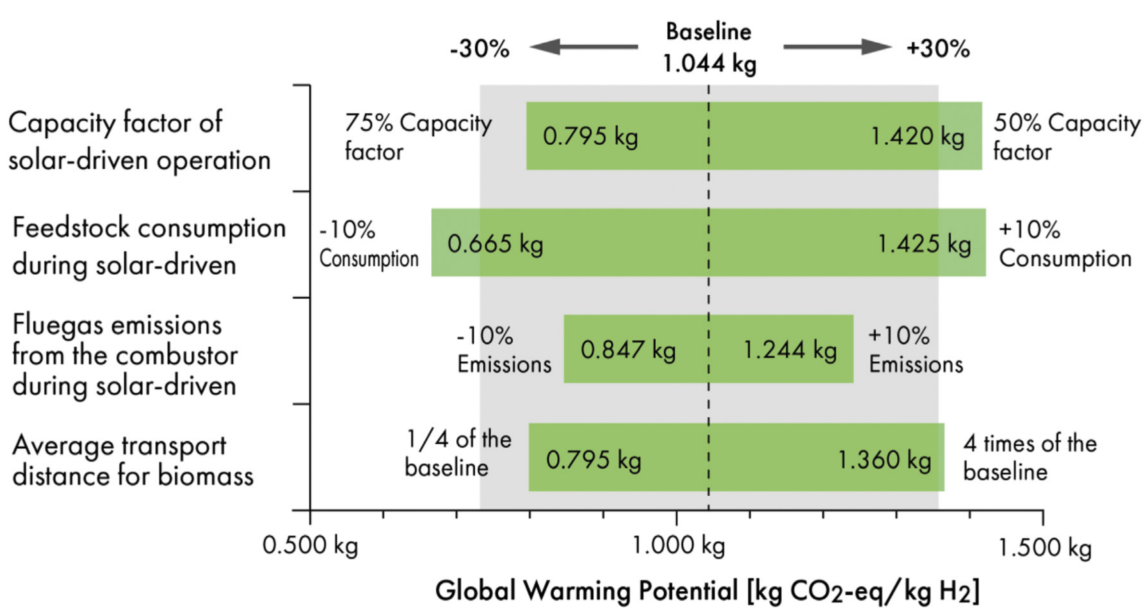


Fig. 10 – Sensitivity analysis of global warming potential for solar-driven specific parameters.

Table 9 – Environmental Impact Assessment of 1 kg of Hydrogen Production: Advanced Solar-driven vs. Conventional.

Impact Category	Unit	Hydrogen Production through Biomass Gasification		
		SABI-Hydrogen (90% Confidence Interval)		**Conventional (NREL Battelle) [72]**
Global warming potential (GWP_{100})	kg CO_2-eq	1.0436	(2.1880–0.6100)	2.6700
Stratospheric ozone depletion	kg CFC-11-eq	2.501×10^{-5}	(2.45×10^{-5}-2.38×10^{-5})	2.180×10^{-5}
Ionizing radiation	kBq Co-60-eq	0.4134	(0.4119–0.4105)	0.4060
Photochemical oxidant formation: ecosystem quality	kg NOx-eq	0.0044	(0.0043–0.0040)	0.0038
Photochemical oxidant formation: human health	kg NOx-eq	0.0045	(0.0043–0.0041)	0.0038
Fine particulate matter formation	kg $PM_{2.5}$-eq	0.0030	(0.0029–0.0028)	0.0028
Terrestrial acidification	kg SO_2-eq	0.0369	(0.0369–0.0367)	0.0371
Freshwater eutrophication potential	kg P-eq	0.0009	(0.0009–0.0009)	0.0008
Terrestrial ecotoxicity	kg 1,4-DCB-eq	1.2168	(0.9513–0.7593)	0.0003
Freshwater ecotoxicity	kg 1,4-DCB-eq	0.0377	(0.0328–0.0318)	0.0188
Marine ecotoxicity	kg 1,4-DCB-eq	0.0522	(0.0461–0.0441)	0.0271
Human toxicity potential: cancer	kg 1,4-DCB-eq	0.0748	(0.0673–0.0643)	0.0433
Human toxicity potential: non-cancer	kg 1,4-DCB-eq	20.0175	(19.9430–19.9050)	19.6900
Land use	m^2a crop-eq	0.0246	(0.0237–0.0231)	0.0206
Mineral resource scarcity	kg Cu-eq	0.0062	(0.0052–0.0047)	0.0019
Fossil resource scarcity	kg oil-eq	0.7027	(0.6930–0.6790)	0.6550
Water consumption potential	m^3 consumed	4.9425	(4.9420–4.9416)	4.9400

hydrogen production are likely to be below that of conventional biomass gasification (2.670 kg CO_2-eq/hg H_2) even taking account of these sensitivities.

Process contributions

In summary, the SABI-Hydrogen production process has 1) lower GHG emissions, 2) higher ecotoxicities and mineral resource scarcity, and 3) similar environmental footprints in other categories to the conventional biomass gasification hydrogen production pathway demonstrated by NREL. These three different patterns in the environmental footprints can be explained by the sensitivities of these indicators to the biomass feedstock resource efficiency: some performance indicators are affected significantly by the improvement of the biomass resource efficiency, while other indicators are only slightly affected by the efficiency. Fig. 11 illustrates the primary process contributions for Global Warming Potential, Freshwater Ecotoxicity, and Terrestrial Acidification.

The Global Warming Potential indicator benefited greatly from improved biomass resource efficiency, bringing down the indicator by 60.9% compared to the conventional process; on the other hand, the Freshwater Ecotoxicity is almost unaffected by improved efficiency, resulting in a 100.5% increase in the footprint. Furthermore, for the Terrestrial Acidification indicator, the decrease in footprint by the improved efficiency is canceled out by the additional constructions for heliostats and the solar tower, making the overall difference only 0.5%. These differences in sensitivity to improved efficiency explain the contrast in the midpoint impact indicator results.

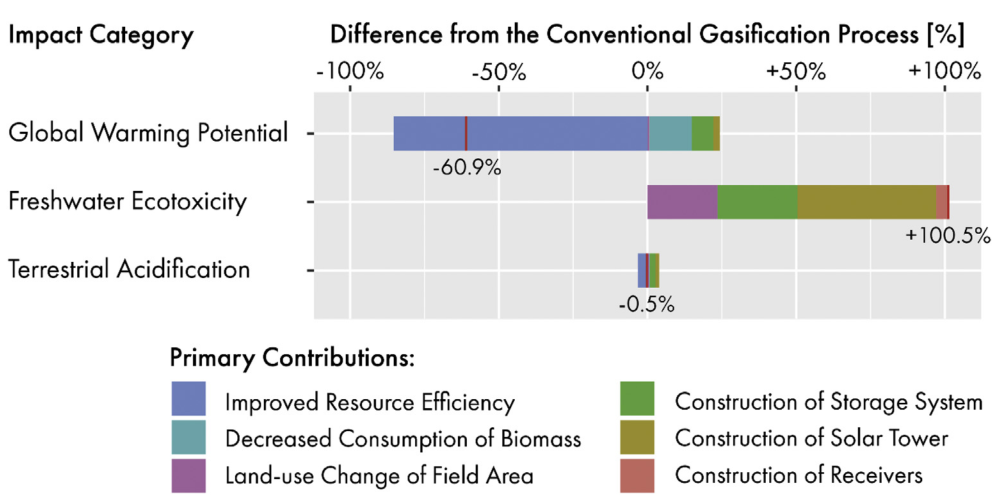


Fig. 11 – Process contributions for the midpoint impact categories.

Table 10 – Comparison of the Environmental Footprint per 1 kg Hydrogen Production from Various Production Pathways (Comparing data from Ref. [72]).

Production Pathway	Environmental Impacts [72]			
	Global Warming Potential [kg CO2-eq]	Human Health [DALY]	Ecosystems [Species year]	Resources [USD2013]
SABI-Hydrogen	1.04	1.43×10^{-5}	7.89×10^{-8}	0.175
Steam methane reforming (SMR)	12.13	2.57×10^{-5}	1.15×10^{-7}	1.560
Coal gasification (CG)	24.20	8.06×10^{-5}	2.91×10^{-7}	0.495
Biomass Gasification (BMG)	2.67	1.55×10^{-5}	8.32×10^{-8}	0.160
Biomass Reformation (BDL)-corn	9.19	3.81×10^{-5}	3.12×10^{-7}	0.899
Biomass Reformation (BDL)-wheat	14.02	2.06×10^{-5}	2.98×10^{-7}	0.587
Electrolysis with Proton exchange membrane (PEM)-Grid	29.54	5.55×10^{-5}	3.15×10^{-6}	1.514
Electrolysis with Proton exchange membrane (PEM)-Wind	2.21	4.35×10^{-5}	2.32×10^{-7}	0.219
Electrolysis with Solid oxide electrolysis cells (SOEC)-Grid	23.32	3.69×10^{-4}	2.08×10^{-6}	1.465
Electrolysis with Solid oxide electrolysis cells (SOEC)-Wind	5.10	2.78×10^{-5}	1.37×10^{-7}	0.602
Dark fermentation + microbial electrolysis cell (MEC) w/o energy recovery	16.29	2.18×10^{-4}	1.22×10^{-6}	0.971
Dark fermentation + microbial electrolysis cell (MEC) w/energy recovery	6.60	6.57×10^{-5}	3.62×10^{-7}	0.371
Dark fermentation + microbial electrolysis cell (MEC) w/H2 recovery	14.57	2.16×10^{-4}	1.21×10^{-6}	0.757

Discussion

Environmental and economic performance of SABI-Hydrogen

In order to discuss the potential competitiveness of this novel hydrogen production pathway for the future energy system, environmental performance indicators are contrasted with other hydrogen pathways in Table 10. The proposed SABI-Hydrogen plant is evaluated against its peers for Global Warming Protentional and the three endpoint impact indicators from ReCiPe2016. The environmental and economic indicators for other hydrogen production pathways were cited from Ref. [72]. These data are directly comparable to the results reported in Section 4 as these studies share the same methodologies and system boundary.

Environmental footprints

The three endpoint impact indicators for ReCiPe2016, Human Health, Ecosystems, and Resources, were compared along with Global Warming Potential in Fig. 12.

SABI-Hydrogen: Solar-driven advanced Biomass Indirect-gasification; SMR: Steam methane reforming; CG: Coal gasification; BMG: Biomass Gasification; BDL: Biomass Reformation; E-PEM: Electrolysis with Proton exchange membrane; E-SOEC: Electrolysis with Solid oxide electrolysis cells; DF-MEC: Dark fermentation with microbial electrolysis cell.

The human health indicator, measured in DALYs (disability adjusted life years), evaluates the years that are lost or that a person is disabled due to a disease or accident through the production of a product or service. The ecosystems indicator, measured in species × year, evaluates the local species loss integrated over time. Finally, the resources indicator, measured in USD2013, evaluates the extra costs involved for future mineral and fossil resource extraction [70].

SABI-Hydrogen showed the lowest Global Warming Potential among all 13 hydrogen production pathways. The GWP_{100} indicator for SABI-Hydrogen is 61% lower than conventional biomass gasification and 91% lower than steam reforming (Fig. 12 (a)). Similarly, SABI-Hydrogen obtained the lowest scores for Human Health and Species impacts: SABI-Hydrogen's indicators were 44% and 28% lower for Human Health and Species, respectively, compared to steam reforming. Finally, the Resources indicator score for SABI-Hydrogen was the second lowest behind conventional biomass gasification (Δ9.4%). On the other hand, the Resources indicator score for SABI-Hydrogen is much lower than the average of all 13 production pathways (0.752 USD2013) and indicates a reduction of 89% when compared to steam reforming. Overall, the comparison in Fig. 12 shows remarkably low environmental footprints both compared to conventional biomass gasification and existing hydrogen production pathways such as steam reforming.

Limitations

The design activities for the SABI-Hydrogen plant in this research were carried out at a conceptual-level based on data collected through a rigorous literature review. Although references were made to measurements of actual plant operation data to increase the reliability of the calculated results, some uncertainty remains. A more detailed engineering design study of the SABI-Hydrogen system, followed by a proof-of-concept experiment, is desirable to further test the feasibility of this concept. Some parameters utilized in this paper might be optimistic: e.g., a study reported lower than expected capacity factors for some CSPs [79]. For this specific example, either a

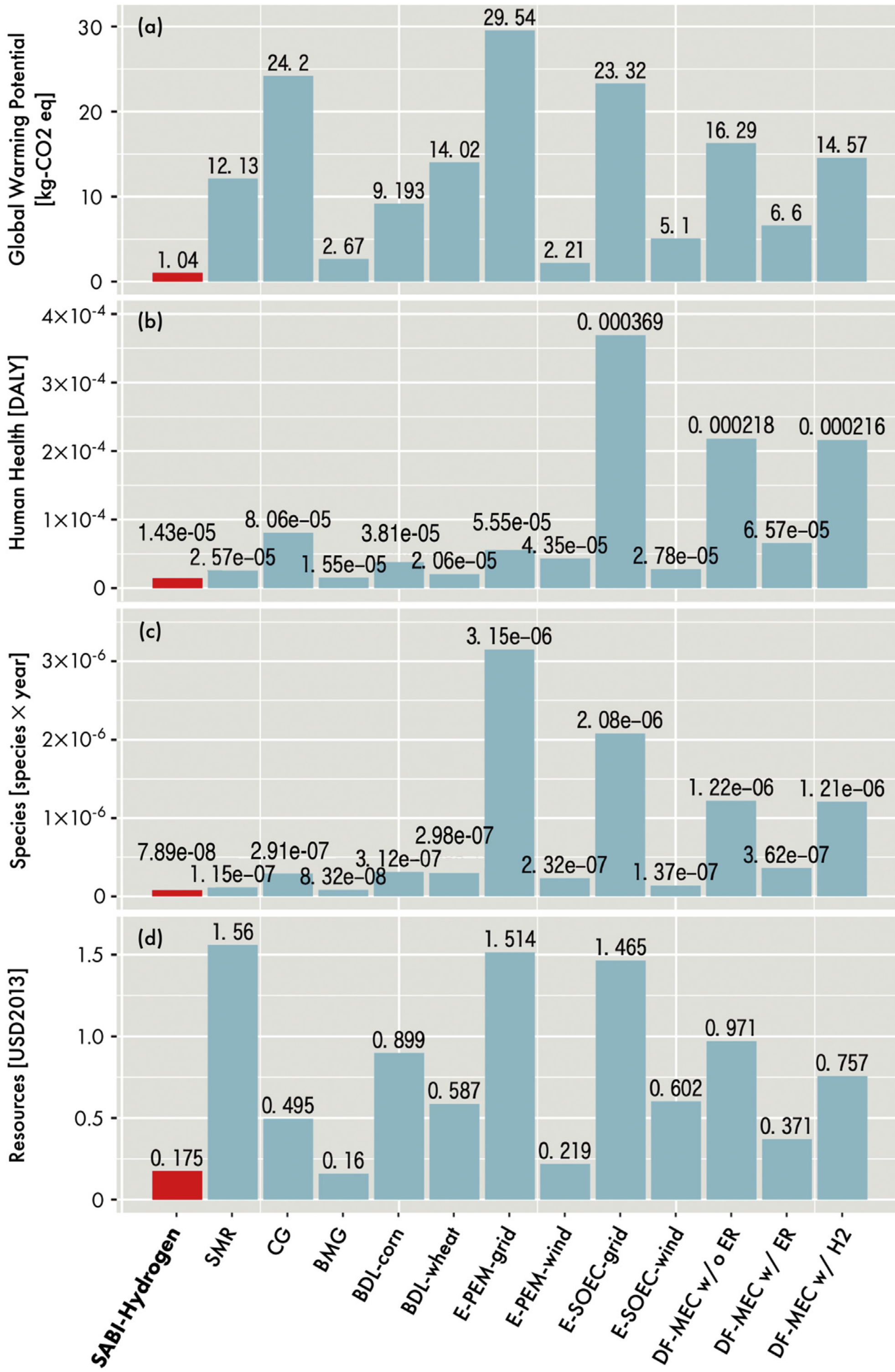


Fig. 12 – Comparison of environmental footprints: (a) Global warming potential, (b) human health, (c) species, and (d) resources.

lower capacity factor for the solar-driven operation or a larger capacity for energy storage capacity may have to be considered to attain the desired hydrogen production yield. Nevertheless, the sensitivity analyses and the uncertainty analysis should sufficiently quantify the variability of the calculation results to inform conceptual design.

Conclusions

With the adoption of a dual chamber hybrid circulation gasifier, the current limitations of solar-driven gasification systems toward continuous operation and scalability would be overcome, making solar-driven hydrogen production feasible. This finding led to the proposal of the novel Solar-driven Advanced Biomass Indirect-gasification Hydrogen Production (SABI-Hydrogen) system. Technologically, it has been demonstrated that the proposed hydrogen production methodology has a higher level of feasibility when compared to other proposed solar-driven biomass gasification plants, which cannot be stably operated nor readily scaled to meet the needs of the future energy system. The SABI-Hydrogen process is based on Circulating Fluidized Bed (CFB) gasifier technology that is commercially proven up to ~1 GW_{th} of capacity. This enabled SABI-Hydrogen's output to be scaled up to meet a greater demand with a capacity factor of greater than 90%.

The proposed SABI-Hydrogen system performs better than all current competitors including fossil fuel, biomass and crop to hydrogen processes, and fuel cell-based electrolysis methods. The low GWP of such a system makes it an appealing addition to the suite of low-carbon technologies which will drive the energy transition.

With this study illustrating the potential environmental advantages for solar-driven hydrogen production from biomass, further studies are recommended to assess the hydrogen production cost through this method. If the envisioned increase in hydrogen production cost is low enough to be offset by the decrease in GHG emissions (e.g., in the form of carbon pricing), we could propose the SABI-Hydrogen not just as an environmentally-friendly option but an economic one as well.

The analysis presented in this paper demonstrates that the innovative stewardship of two natural resources, namely the forest (i.e., woodchip feedstocks) and the sun (i.e., the heat from concentrated solar) could lead to the sustainable production of hydrogen fuel, essential for a low-carbon energy transition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

Funding from Kyoto Fusioneering is gratefully acknowledged.

REFERENCES

[1] Geels FW. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res Pol 2002;31(8–9):1257–74.

[2] Geels FW. Processes and patterns in transitions and system innovations: refining the co-evolutionary multi-level perspective. Technol Forecast Soc Change 2005;72(6):681–96.

[3] Espegren K, Damman S, Pisciella P, Graabak I, Tomasgard A. The role of hydrogen in the transition from a petroleum economy to a low-carbon society. Int J Hydrogen Energy 1 July 2021;46(45):23125–38.

[4] Chapman A, Itaoka K, Farabi-Asl H, Fujii Y, Nakahara M. Societal penetration of hydrogen into the future energy system: impacts of policy, technology and carbon targets. Int J Hydrogen Energy 2020;45(7):3883–98.

[5] Iribarren D, Martín-Gamboa M, Manzano J, Dufour J. Assessing the social acceptance of hydrogen for transportation in Spain: an unintentional focus on target population for a potential hydrogen economy. Int J Hydrogen Energy 2016;41(10):5203–8.

[6] Sazali N. Emerging technologies by hydrogen: a review. Int J Hydrogen Energy 2020;45(38):18753–71.

[7] Hydrogen Council. Hydrogen scaling up, A sustainable pathway for the global energy transition. Brussels, Belgium: Hydrogen Council; 2017.

[8] International Energy Agency. The future of hydrogen. Paris, France: International Energy Agency (IEA); 2019.

[9] Ni M, Leung DY, Leung MK, Sumathy K. An overview of hydrogen production from biomass. Fuel Process Technol 2006;87(5):461–72.

[10] Basu P. Biomass gasification and pyrolysis: practical design and theory. Academic press; 2010.

[11] Ranzi E, Faravelli T, Manenti F. Pyrolysis, gasification, and combustion of solid fuels. In: Advances in chemical engineering, vol. 49. Elsevier; 2016. p. 1–94.

[12] Kumar A, Jones DD, Hanna MA. Thermochemical biomass gasification: a review of the current status of the technology. Energies 2009;2(3):556–81. https://doi.org/10.3390/en20300556.

[13] Moreno J, Dufour J. Life cycle assessment of hydrogen production from biomass gasification. Evaluation of different Spanish feedstocks. Int J Hydrogen Energy 2013;38(18):7616–22.

[14] Hajjaji N, Martinez S, Trably E, Steyer J-P, Helias A. Life cycle assessment of hydrogen production from biogas reforming. Int J Hydrogen Energy 2016;41(14):6064–75.

[15] Kalinci Y, Hepbasli A, Dincer I. Life cycle assessment of hydrogen production from biomass gasification systems. Int J Hydrogen Energy 2012;37(19):14026–39.

[16] Koroneos C, Dompros A, Roumbas G. Hydrogen production via biomass gasification—a life cycle assessment approach. Chem Eng Process: Process Intensification 2008;47(8):1261–8.

[17] Valente A, Iribarren D, Dufour J. Life cycle sustainability assessment of hydrogen from biomass gasification: a comparison with conventional hydrogen. Int J Hydrogen Energy 2019;44(38):21193–203.

[18] Dincer I, Acar C. Review and evaluation of hydrogen production methods for better sustainability. Int J Hydrogen Energy 2015;40(34):11094–111.

[19] Nikolaidis P, Poullikkas A. A comparative overview of hydrogen production processes. Renew Sustain Energy Rev 2017;67:597–611.

[20] Salkuyeh YK, Saville BA, MacLean HL. Techno-economic analysis and life cycle assessment of hydrogen production from natural gas using current and emerging technologies. Int J Hydrogen Energy 2017;42(30):18894–909.

[21] Salkuyeh YK, Saville BA, MacLean HL. Techno-economic analysis and life cycle assessment of hydrogen production from different biomass gasification processes. Int J Hydrogen Energy 2018;43(20):9514–28.

[22] Spath AAP, Eggeman T, Ringer M, Wallace B, Jechura J. Biomass to hydrogen production detailed design and economics utilizing the Battelle Columbus laboratory indirectly-heated gasifier. In: Technical Report. Colorado: DOE/NREL; 2005. NERL/TP-510-37408.

[23] Farzad S, Mandegari MA, Görgens JF. A critical review on biomass gasification, co-gasification, and their

environmental assessments. Biofuel Research Journal 2016;3(4):483–95.

[24] Craig KR, Mann MK. Cost and performance analysis of biomass-based integrated gasification combined-cycle (BIGCC) power systems. Golden, CO (United States): National Renewable Energy Lab.; 1996.

[25] Mann MK. Technical and economic assessment of producing hydrogen by reforming syngas from the Battelle indirectly heated biomass gasifier. National Renewable Energy Lab.; 1995.

[26] Bain RL. Material and energy balances for methanol from biomass using biomass gasifiers. Golden, CO (US): National Renewable Energy Lab.; 1992.

[27] Feldmann H, Paisley M, Appelbaum H, Taylor D. Conversion of forest residues to a methane-rich gas in a high-throughput gasifier. OH (USA): Battelle Columbus Div.; 1988.

[28] Sobek S, Werle S. Solar pyrolysis of waste biomass: Part 1 reactor design. Renew Energy 2019;143:1939–48.

[29] Ndukwu M, Horsfall I, Ubouh E, Francis O, Ekop I, Ezejiofor N. Review of solar-biomass pyrolysis systems: focus on the configuration of Thermal-solar systems and reactor orientation. Journal of King Saud University-Engineering Sciences; 2020.

[30] Omar MA, Altinişik K. Simulation of hydrogen production system with hybrid solar collector. Int J Hydrogen Energy 2016;41(30):12836–41.

[31] Weldekidan H, Strezov V, Town G, Kan T. Production and analysis of fuels and chemicals obtained from rice husk pyrolysis with concentrated solar radiation. Fuel 2018;233:396–403.

[32] Morales S, Miranda R, Bustos D, Cazares T, Tran H. Solar biomass pyrolysis for the production of bio-fuels and chemical commodities. J Anal Appl Pyrol 2014;109:65–78.

[33] Li R, et al. Product distribution from solar pyrolysis of agricultural and forestry biomass residues. Renew Energy 2016;89:27–35.

[34] Hathaway BJ, Davidson JH, Kittelson DB. Solar gasification of biomass: kinetics of pyrolysis and steam gasification in molten salt. J Sol Energy Eng 2011;133(2):21011.

[35] Piatkowski N, Wieckert C, Weimerc AW, Steinfeld A. Solar-driven gasification of carbonaceous feedstock—a review. Energy Environ Sci 2011;4(1):73–82.

[36] Adinberg R, Epstein M, Karni J. Solar gasification of biomass: a molten salt pyrolysis study. J Sol Energy Eng 2004;126(3):850–7.

[37] Puig-Arnavat M, Tora E, Bruno J, Coronas A. State of the art on reactor designs for solar gasification of carbonaceous feedstock. Sol Energy 2013;97:67–84.

[38] Loutzenhiser PG, Muroyama AP. A review of the state-of-the-art in solar-driven gasification processes with carbonaceous materials. Sol Energy 2017;156:93–100.

[39] Steinfeld A. Solar thermochemical production of hydrogen––a review. Sol Energy 2005;78(5):603–15.

[40] Yadav D, Banerjee R. A review of solar thermochemical processes. Renew Sustain Energy Rev 2016;54:497–532.

[41] Z'Graggen A, Haueter P, Maag G, Romero M, Steinfeld A. Hydrogen production by steam-gasification of carbonaceous materials using concentrated solar energy—IV. Reactor experimentation with vacuum residue. Int J Hydrogen Energy 2008;33(2):679–84.

[42] Piatkowski N, Wieckert C, Steinfeld A. Experimental investigation of a packed-bed solar reactor for the steam-gasification of carbonaceous feedstocks. Fuel Process Technol 2009;90(3):360–6.

[43] Romero M, Steinfeld A. Concentrating solar thermal power and thermochemical fuels. Energy Environ Sci 2012;5(11):9234–45.

[44] Arribas L, et al. Solar-driven pyrolysis and gasification of low-grade carbonaceous materials. Int J Hydrogen Energy 2017;42(19):13598–606.

[45] Chen J, et al. System development and environmental performance analysis of a solar-driven supercritical water gasification pilot plant for hydrogen production using life cycle assessment approach. Energy Convers Manag 2019;184:60–73.

[46] Belgiorno V, De Feo G, Della Rocca C, Napoli dR. Energy from gasification of solid wastes. Waste Manag 2003;23(1):1–15.

[47] Quaak P, Knoef H, Stassen H. Energy from biomass: a review of combustion and gasification technologies. The World Bank; 1999.

[48] Olofsson I, Nordin A, Söderlind U. Initial review and evaluation of process technologies and systems suitable for cost-efficient medium-scale gasification for biomass to liquid fuels. Umeå Universitet; 2005.

[49] Arnold R, Hill J. Catalysts for gasification: a review. Sustainable energy & fuels 2019;3(3):656–72.

[50] E4tech. Review of technologies for gasification of biomass and wastes. York: NNFCC; 2009.

[51] Iribarren D, Susmozas A, Petrakopoulou F, Dufour J. Environmental and exergetic evaluation of hydrogen production via lignocellulosic biomass gasification. J Clean Prod 2014;69:165–75.

[52] Inayat A, Ahmad MM, Yusup S, Mutalib MA, Khan Z. Biomass steam gasification for hydrogen production: a systematic review. In: Biomass and bioenergy. Springer; 2014. p. 329–43.

[53] Gil J, Corella J, Aznar MaP, Caballero MA. Biomass gasification in atmospheric and bubbling fluidized bed: effect of the type of gasifying agent on the product distribution. Biomass Bioenergy 1999;17(5):389–403.

[54] Barlev D, Vidu R, Stroeve P. Innovation in concentrated solar power. Sol Energy Mater Sol Cells 2011;95(10):2703–25.

[55] Zhang H, Baeyens J, Degrève J, Cacères G. Concentrated solar power plants: review and design methodology. Renew Sustain Energy Rev 2013;22:466–81.

[56] Tetreault-Friend M, Gray LA, Berdibek S, McKrell T, Slocum AH. Optical properties of high temperature molten salt mixtures for volumetrically absorbing solar thermal receiver applications. Sol Energy 2017;153:238–48.

[57] Ho CK. Advances in central receivers for concentrating solar applications. Sol Energy 2017;152:38–56.

[58] National Renewable Energy Laboratory. Planta solar 20 - PS20 CSP project: concentrating solar power projects. US Department of Energy; 2021. https://solarpaces.nrel.gov/project/planta-solar-20-ps20. [Accessed 10 August 2021].

[59] IRENA. Renewable energy cost analysis -concentrating solar power. International Renewable Energy Agency Abu Dhabi; 2012.

[60] AlNouss A, McKay G, Al-Ansari T. A techno-economic-environmental study evaluating the potential of oxygen-steam biomass gasification for the generation of value-added products. Energy Convers Manag 2019;196:664–76.

[61] Ramsden T, Steward D, Zuboy J. Analyzing the levelized cost of centralized and distributed hydrogen production using the H2A production model, version 2. Golden, CO (United States): National Renewable Energy Lab.(NREL); 2009.

[62] de Caprariis B, De Filippis P, Scarsella M, Petrullo A, Palma V. Biomass gasification and tar reforming in a two-stage reactor. Energy Procedia 2014;61:1071–4.

[63] Hamelinck CN, Faaij AP. Future prospects for production of methanol and hydrogen from biomass. J Power Sources 2002;111(1):1–22.

[64] Fakhroleslam M, Fatemi S, Boozarjomehry RB, De Santis E, Di Benedetto MD, Pola G. Maximal safe set computation for pressure swing adsorption processes. Comput Chem Eng 2018;109:179–90.

[65] Ciroth A. ICT for environment in life cycle applications openLCA—a new open source software for life cycle assessment. Int J Life Cycle Assess 2007;12(4):209.
[66] Ekvall T, Tillman A-M. Open-loop recycling: criteria for allocation procedures. Int J Life Cycle Assess 1997;2(3):155.
[67] Skone TJ. Understanding the life cycle environmental footprint of the natural gas value chain. Bruceton: U.S. Department of Energy National Energy Technology Laboratory; 2014.
[68] Schrijvers DL, Loubet P, Sonnemann G. Developing a systematic framework for consistent allocation in LCA. Int J Life Cycle Assess 2016;21(7):976–93.
[69] Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, Van Zelm R. ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level 2009;1:1–126.
[70] Huijbregts M, et al. ReCiPe 2016: a harmonized life cycle impact assessment method at midpoint and endpoint level report I: characterization. 2016.
[71] Stocker T. Climate change 2013: the physical science basis: working group I contribution to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press; 2014.
[72] Mehmeti A, Angelis-Dimakis A, Arampatzis G, McPhail SJ, Ulgiati S. Life cycle assessment and water footprint of hydrogen production methods: from conventional to emerging technologies. Environments 2018;5(2):24.
[73] Sengupta M, Xie Y, Lopez A, Habte A, Maclaurin G, Shelby J. The national solar radiation data base (NSRDB). Renew Sustain Energy Rev 2018;89:51–60.
[74] Xu X, et al. Experimental test of properties of KCl–MgCl2 eutectic molten salt for heat transfer and thermal storage fluid in concentrated solar power systems. J Sol Energy Eng 2018;140(5).
[75] Williams D. Assessment of candidate molten salt coolants for the NGNP/NHI heat-transfer loop. Oak Ridge, TN (United States): Oak Ridge National Lab.(ORNL); 2006.
[76] Mann MK, Spath PL. Life cycle assessment of a biomass gasification combined-cycle power system. Golden, CO (US): National Renewable Energy Lab.; 1997.
[77] Frischknecht R, et al. The ecoinvent database: overview and methodological framework (7 pp). Int J Life Cycle Assess 2005;10(1):3–9.
[78] National Renewable Energy Laboratory. H2A: hydrogen analysis production models. https://www.nrel.gov/hydrogen/h2a-production-models.html. [Accessed 10 August 2021].
[79] Boretti A. A realistic expectation of electricity production from current design concentrated solar power solar tower with thermal energy storage. Energy Storage 2019;1(3):e57.

Glossary

BDL: Biomass reformation
BMG: Biomass gasification
CFB: Circulating fluidized bed
CG: Coal gasification
CSP: Concentrated solar plant
DF-MEC: Dark fermentation with microbial electrolysis cell
E-PEM: Electrolysis with proton exchange membrane
E-SOEC: Electrolysis with Solid oxide electrolysis cells
ECF: Energy conversion facility
EU: End use
GHG: Greenhouse gases
GWP: Global Warming Potential
LCA: Life cycle assessment
LCIA: Life cycle impact assessment
NREL: National Renewable Energy Laboratory
PDC: Parabolic dish collector
PFD: Process flow diagrams
PS20: Abengoa Solar's Planta Solar 20 concentrated solar plant
PT: Product transport
RMA: Raw material acquisition
RMT: Raw material transport
SABI-Hydrogen: Solar-driven advanced biomass indirect-gasification hydrogen production
SMR: Steam methane reforming
SPT: Solar power tower