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Techno-economics of "Teal" Hydrogen Production via Combined Steam Methane Reforming and Biomass Gasification

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The global transition towards net-zero greenhouse gas emissions establishes a need for cleaner energy technologies. Hydrogen is a promising energy carrier whose global demand is steadily increasing and is conventionally produced through steam-methane reforming with carbon capture, or blue H_2. Hydrogen production supplied by renewable energy (green H_2) is an emerging process, but developing countries are not yet ready for a full transition. Augmenting blue H_2 with green H_2 production will allow a smoother transition until green H_2 costs significantly decrease by 2050. In this work, a novel, low-cost teal hydrogen (teal H_2) plant, a mixture of blue and green H_2 technologies, located in the Philippines which combines steam-methane reforming, rice husk gasification, and carbon capture by monoethanolamine absorption, is proposed. Setting a production rate of 9,000 kg H_2/h, the techno-economic potential of five cases with varying natural gas to rice husk contribution ratios were evaluated using AspenPlus. The levelized cost of the 25:75 teal H_2 case at 1.06 USD/kg is cheaper than blue H_2 and green H_2 by 4.37 and 2.34 USD/kg, respectively. Moreover, the CO_2-equivalent emissions of the 25:75 teal H_2 case at 0.002 t CO_2 -eq/1,000 Nm^3 H_2 is 57.10 % and 39.25 % lower than those from blue H_2 and green H_2. As green H_2 becomes more economical, rice husk feed to the gasification process can be gradually increased to favor biomass- over petroleum-derived H_2. This case study is a successful proof of concept that teal H_2 may help transition the energy sector to carbon neutrality.

1. Introduction

The Paris Agreement is a global mandate that legally binds countries to reduce greenhouse gas emissions and achieve a climate neutral world by the mid-21st century, driving the development of renewable and green technology and industrial processes (United Nations, 2015). Hydrogen is a clean-energy carrier that has the potential to reduce reliance on coal- and gas-generated electricity. Its demand in the chemical industry is expected to increase by 31 % by 2030 (International Energy Agency, 2019). Hydrogen is conventionally produced from the reforming of natural gas (i.e., steam-methane reforming, SMR) or gasification of coal. To reduce emissions, two production pathways are at the center of research trends: (i) blue hydrogen and (ii) green hydrogen production. Blue hydrogen is produced when conventional hydrogen plants are simply augmented with carbon capture technologies to store and utilize the carbon dioxide by-product. On the other hand, green hydrogen relies on water electrolysis, biomass gasification (BG), and renewable technologies (Noussan et al., 2020).

With around 98 % of current hydrogen production derived from fossil-fuels, blue H_2 is the more accessible technology with hundreds of commercial and pilot plants across the globe (Global CCS Institute, n.d.). Blue H_2 is the more mature production pathway with costs ranging from 1.40 to 2.40 USD/kg, which is lower than the cost of green H_2 at 2.30 to 7.70 USD/kg. However, green H_2 is capable of becoming a carbon-neutral or carbon-negative pathway, provided that it is powered by renewable energy (Ibrahim et al., 2021).

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Developing countries have difficulties in a full transition to either H_2 production pathway, because they lack the infrastructure for commercial blue H_2 and emerging green H_2 technologies. However, international and intergovernmental reports project an 80 % reduction in green H_2 costs by 2050; whereas blue H_2 costs are forecasted to stagnate (Newborough and Cooley, 2020). In addition, increasing reliance on renewable feedstock is expected due to concerns such as decreasing fossil fuel supply, price uncertainty, and environmental effects (Peres et al., 2013). In line with the ongoing global discussion, blue H_2 is seen as a short-term solution to reduce emissions, while green H_2 is regarded as the long-term solution to cleaner hydrogen production once its techno-economic challenges have been addressed (Newborough and Cooley, 2020). As such, this paper proposes a novel "teal" hydrogen plant, which augments the conventional steam-methane reforming plus carbon capture (SMR+CC, blue H_2) process with biomass gasification (BG, green H_2). Its techno-economic potential is assessed through process simulations with varying feed ratios for blue and green H_2 production and evaluations of the levelized cost of hydrogen (LCOH) for each scenario. The proposed teal H_2 plant may serve as a guide for developing countries to start investing in existing commercial hydrogen production and transitioning to greener technologies as costs drop in the long term.

2. Methodology

The methodology is divided into five parts. First, the modeling scenarios and plant location were introduced. Second, an overview of the hydrogen production process was discussed. Third, the techno-economic values and assumptions were shown. Fourth, the different scenarios were simulated in Aspen Plus (2017) and presented. Lastly, the profitability metrics to assess the H_2 plants were presented.

2.1 Case studies

Setting the production capacity to 9,000 kg H_2/h, five case studies were compared to determine the sensitivity of the LCOH to changes in feed. Three cases of the teal H_2 plant were considered with varying natural gas (NG) and rice husk (RH) feed flow rates, adjusted based on their set contributions to the H_2 production capacity. The breakdown of the three variations are as follows: 1) 25 % of H_2 produced is made from NG & 75 % made from RH; 2) 50 % NG & 50 % RH; and, 3) 75 % NG & 25 % RH. Two other cases, namely the blue H_2 plant (SMR + CC; 100 % NG) and green H_2 plant (BG + CC; 100 % RH), were considered for comparison.
The chosen plant location is in Batangas, Philippines given its proximity to liquefied NG import terminals targeted to be in place by 2022-2025 (Reynolds, 2021) and the opportunities for CO_2 storage in Malampaya, Palawan with the anticipated shutdown of the Malampaya Gas Fields (Asian Development Bank, 2013).

2.2 Process description

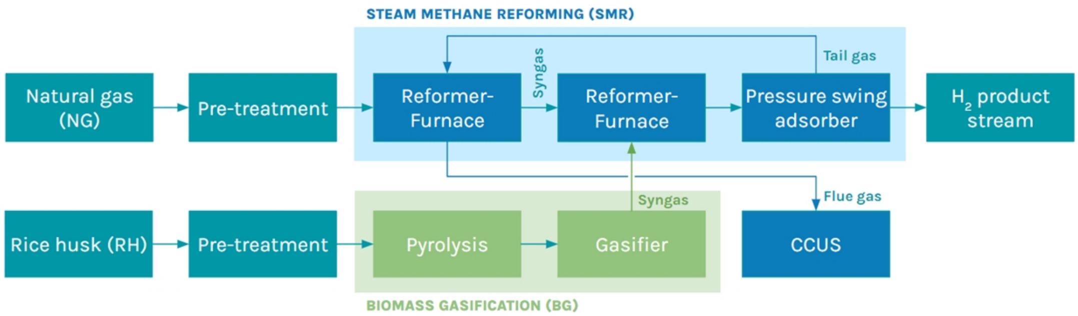

Figure 1: Block-flow diagram of proposed novel teal hydrogen production plant

The process, simulated using AspenONE Suite (Aspen Plus (2017), Aspen Adsorption (2017), & Aspen Energy Analyzer (2017)), can be divided into three units: the steam methane reforming unit (blue H_2), the biomass gasification unit (green H_2), and the carbon capture (CC) unit, as shown in Figure 1. The reactions involved in the main process units (SMR and BG) are summarized in Table 1.
In the Steam Methane Reforming unit, the fed natural gas is split into two streams: (1) feedstock for the reformer process, and (2) supplementary fuel for the steam reformer furnace. The feedstock NG undergoes 6 units: desulfurization (Eq(1) & Eq(2)), sulfur adsorption (Eq(3)), pre-reformer (Eq(4), Eq(5), Eq(6)), main reformer (Eq(7) & Eq(8)), water-gas shift (WGS) reactor (Eq(9)), and pressure swing adsorber (PSA). Streams before the pre-reformer and the main reformer are mixed with an excess amount of steam to achieve a steam-to-carbon ratio of 3.0 and 5.0, respectively. The heat of the reaction in the main reformer is supplied by the furnace where the combustion of fuel natural gas and air occurs. The flue gas resulting from the combustion proceeds to the carbon capture unit. Meanwhile, syngas from BG is mixed with the reformer syngas before entering the WGS

reactor. Afterward, the PSA tail gas is recycled back to the furnace as fuel for combustion. The high-purity hydrogen stream is further compressed based on the product requirements.

Furthermore, the overall process of biomass gasification can be modelled in three stages, which include drying (Eq(10)), pyrolysis, and gasification (Eq(11)). It is hypothesized that any phase transition in the gasification process is stable and, thus, the equilibrium model may be based on the Gibbs free energy minimization principle. Some other important assumptions include: (i) O, H, N, and S are in the gaseous phase while C undergoes incomplete transformation to gas, (ii) rice husk ash is inert, (iii) the gasifier remains stable and parameters are time-independent, (iv) all gas-phase reactions in the biomass gasifier are instantaneous and will reach equilibrium, (v) biomass particles are at a uniform temperature, and (vi) the reactions are isobaric (Vassilev et al., 2010). The syngas produced is then mixed with that from SMR and sent to the water-gas shift reactor.

After cooling to 40 °C, the reformer flue gas is sent to the bottom stage of the absorber column where lean MEA (30 wt%, 0.25 mol CO_2/mol MEA) absorbs CO_2 by reactive distillation. The decarbonized flue gas is then washed with water to remove excess MEA before it is sent to the stack to be released into the air. The now rich MEA solvent is regenerated by a stripper (114 °C, 1.8 bar) with a partial condenser and partial reboiler. The captured CO_2 in the stripper is then compressed for storage. The condensate of the partial condenser is recycled to the absorber's water-wash section, whose bottoms stream is mixed with MEA makeup. A purge stream is added to prevent the accumulation of H_2O.

From these simulations, the required feed (NG, RH, and MEA), H_2 product flow rate and purity, and CO_2-eq emissions are obtained for the five cases.

Table 1: Summary of reactions in the SMR and BG facilities of the proposed Teal H_2 plant

Reaction	Eq	Operating Conditions	Ref.
Desulfurization Unit: Hydrogenolysis and H_2S Removal			
C_4H_8S (tetrahydrothiophene) + $2H_2 \rightarrow$ n-C_4H_{10} + H_2S	(1)		[a]
C_4H_4S (thiophene) + $4H_2 \rightarrow$ n-C_4H_{10} + H_2S	(2)	380.2 °C, 36.28 bar	
$ZnO + H_2S \rightarrow ZnS + H_2O$	(3)		
Pre-Reformer			
$C_nH_m + nH_2O \rightarrow nCO + (n + ½m)H_2$	(4)		[a]
$CO + 3H_2 \leftrightarrow CH_4 + H_2O$	(5)	450 °C, 24 bar	
$CO + H_2O \leftrightarrow CO_2 + H_2$	(6)		
Main Reformer			
$CH_4 + H_2O \leftrightarrow 3H_2 + CO$	(7)	450 °C, 24 bar	[b]
$CH_4 + 2H_2O \leftrightarrow 4H_2 + CO_2$	(8)		
Water Gas Shift Reactor			
$CO + H_2O \rightarrow CO_2 + H_2$	(9)	313 °C, 28 bar	[a]
Biomass Gasification			
Rice husk $\rightarrow$ 0.0556 H_2O	(10)	610 °C, 1 bar (Pyrolysis)	[c]
Dry rice husk $\rightarrow$ ash + gases (e.g., CO, CH_4, CO_2, H_2, H_2O) + carbon	(11)	850 °C, 1 bar (Gasification)	

[a] (Twigg, 2018), [b] (Sharma et al., 2019), [c] (Liu et al., 2016)

2.3 Techno-economic data

The feasibility of the teal H_2 plant was assessed by investment analysis. Fixed capital investments (FCI), operating costs, and other important assumptions are listed in Table 2 for a total plant life of N = 27 years, which includes 2 years in construction, and a 24-h operation with 30 days downtime per year. The plant was assumed to be funded at 40 % equity with the balance coming from a 6 % interest rate bank loan. During operation, the sales were simulated to gradually increase from a 50 % turnover to a 100 % turnover by the 16^{th} year of operation.

Table 2: Techno-economic modelling parameters to determine the LCOH of cases 1 to 5.

Production ratio (Blue H_2:Green H_2)	Case 1 (100:0)	Case 2 (75:25)	Case 3 (50:50)	Case 4 (25:75)	Case 5 (0:100)	Ref
Capital costs (mil USD)	287.820	495.673	791.013	1,070.098	1,137.899	[a],
Operating costs (mil USD/y)	643.476	542.850	454.105	365.037	490.131	[b]
Plant capacity (MW)	174.075	290.060	290.027	304.967	258.036	

[a] (Wittholz et al., 2008), [b] (Sinnott and Towler, 2020). Other costs adapted from Aspen Plus (2017) and Aspen Energy Analyzer (2017). Operating costs at 100 % plant loading.

2.4 Scenario modeling

The simulation for the whole teal H_2 plant is shown in Figure 2, which represents the five cases. For case 1 (blue H_2), the biomass gasification facility of the plant is deactivated. For case 5 (green H_2), the steam-methane reforming facility is deactivated, syngas from gasification is redirected to the low- and high-temperature water-gas shift reactor, and PSA tail gas is directed to the CC unit.

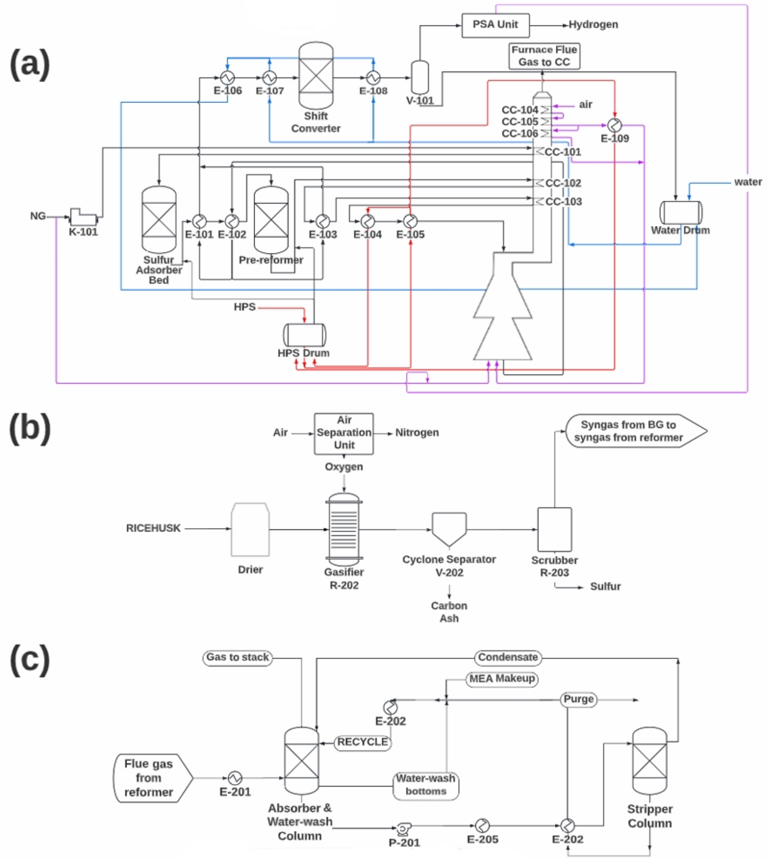

Figure 2: Process flow diagrams of the proposed teal H_2 plant, (a) steam-methane reforming facility and its utilities, (b) biomass gasification, and (c) carbon capture. The blue lines represent the cold utility stream, the red lines represent the hot utility stream, and the purple lines represent the furnace feed

2.5 Techno-econometric metrics

The techno-economic potential of the five cases in the teal H_2 simulation were assessed based on the following parameters: CO_2 capture rate, net present value (NPV), payback period (PBP), internal return rate (IRR), and LCOH. The last four parameters were obtained using the built-in spreadsheet functions. Note that the LCOH was calculated by finding the IRR that would result to a zero NPV, at which point the selling price of hydrogen equates to its production cost. Furthermore, plant revenue included sales projection of the produced H_2 and captured CO_2 based on market prices.

3. Results and discussion

The techno-economic metrics of the optimized simulations are presented below to assess whether teal H_2 is a feasible and profitable alternative to blue H_2 production (case 1).

3.1 Techno-economic metrics

The results of the techno-economic analysis for each case are presented in Table 3. With each case, the NG feed decreases as more RH feed was introduced to attain a constant production rate of 9,000 kg H_2/h. It has been found that the decrease in NG feed is not proportional to the increase of RH from one case to the other. This demonstrates that given equal amounts of feed, SMR can produce more H_2 than BG. However, the cheaper price of RH makes BG more attractive. Therefore, intermediate cases that combine SMR and BG were simulated to reduce total feed costs while maintaining high conversion.

Table 3: Techno-economic metrics describing each simulation

	Case 1 (100:0)	Case 2 (75:25)	Case 3 (50:50)	Case 4 (25:75)	Case 5 (0:100)
NG feed (kg/h)	29,951.00	22,463.25	14,977.00	7,487.75	-
RH feed (kg/h)	-	13,470.00	45,795.00	86,600.00	99,700.00
CO_2 captured (kg/h)	80,237.44	70,545.16	88,813.50	103,797.80	98,633.23
Carbon capture rate (%)	97.78	97.59	97.96	98.34	97.47
CO_2-eq emissions (t/1,000 Nm^3 H_2)	0.004765358	0.003062251	0.002461588	0.002044461	0.003365320
LCOH (USD/kg)	5.43	4.83	2.86	1.06	3.40

Case 1 exhibits the highest LCOH value. This is higher than the LCOH values of SMR processes found in literature (Global CCS Institute, 2021), which stems from higher NG import price and lower amount of CO_2 captured. As the NG feed share decreases across cases, LCOH also decreases, with case 4 exhibiting the lowest value. This trend can be attributed to two factors: first, the decrease of high-cost NG combined with the increased share of low-cost RH to H_2 production; and second, the increase in CO_2 captured contributing to a rise in revenue. The abrupt increase seen in Case 5 can be attributed to the higher capital and operating costs required, especially when compared to cases 3 and 4, given that full reliance on green H_2 costs significantly more at present. Moreover, the CO_2-eq emissions exhibit the same trend as that of LCOH values, with the CO_2-eq emissions of case 4 being 57.10 % and 39.25 % lower than that of case 1 and 5, respectively. Notably, the PSA tail gas of case 5 is methane-rich, which could both be a source of fuel gas because of its higher heating value and an additional hydrogen source (Thomson et al., 2020).Therefore, a reformer-furnace was added to utilize this stream.

3.2 Profitability and sensitivity analysis

The NPV, PBP, and IRR of the five cases for varying H_2 selling prices (USD/kg) are shown in *Figure 3*. When priced between 2 to 6 USD/kg, Case 4 is profitable since it exhibited positive NPV, PBP as low as 6.9 years, and an IRR as high as 22.6 %. Considering current average market prices for blue H_2 at 2 USD/kg and green H_2 at 5 USD/kg (Global CCS Institute, 2021), cases 3 and 4 present competitive pricing and high returns.

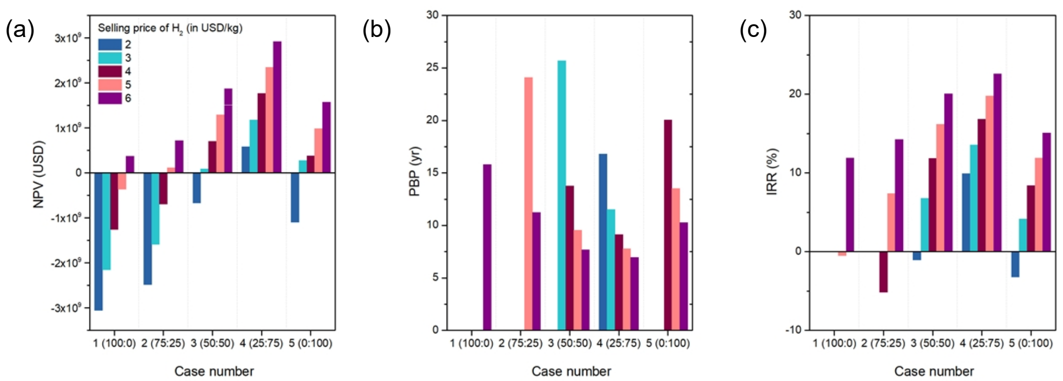

Figure 3: NPV (a), PBP (b), and IRR (c) of the five cases of hydrogen production (blue H2:green H2) at selling prices from 2 to 6 USD/kg H2. Absence of PBP means 'no payback' and absence of IRR denotes a negative return rate

4. Conclusions

In this work, techno-economic case studies and profitability analyses were conducted on five cases of hydrogen production plants to determine if the proposed teal H_2 plant is suitable and practical, specifically for developing countries. The techno-economic metrics suggest that a 25:75 teal H_2 plant has the lowest LCOH of 1.06 USD/kg H_2 and emissions of 0.002 t CO_2-eq/1,000 Nm^3 H_2 for a capacity of 9,000 kg/H_2, when compared to a fully blue or green H_2 plant. Moreover, the profitability analysis also suggests that a 25:75 teal H_2 plant is profitable at prices comparable to current blue and green H_2 prices. Its sound economic parameters (IRR, PBP, NPV) indicate that teal H_2 is an attractive investment for companies and governments as it considers available commercial infrastructures and future trends in hydrogen demand and prices.

This study serves as proof of concept that teal H_2 is future-fit, market competitive, and economically feasible as a transition into green hydrogen technologies. This is also a call to sustain research and development in green production and to achieve global environmental commitments. Future work will involve simulating other NG to biomass ratios not considered in this study, adding range of values around the input parameters (e.g., raw material, utility, and product prices), testing the synergies of other forms of blue (chemical-looping combustion, auto-thermal reforming, etc.) and green (electrolyzers) H_2 production, and pilot testing of the proposed teal H_2 plant.

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