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COMPARATIVE ECONOMIC AND ENVIRONMENTAL PERFORMANCE ASSESSMENT OF BIOMASS GASIFICATION PATHWAY FOR GREEN H_2 PRODUCTION

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ABSTRACT

The transition to low-carbon energy sources is essential to limit the temperature rise due to global warming. Biomass is a carbon-neutral source of energy that could aid in the energy transition and decarbonisation goals. This work compares the economic and environmental performances of small-scale (100 kg/h output) green hydrogen [biomass gasification (BG) and water electrolysis (WE)] pathways, using commercial-scale (20 tph output) conventional hydrogen [steam methane reforming (SMR)] as reference. The source of the electricity supply for BG system operations is a major determinant of the life-cycle emissions. It could be sourced externally (grid) or generated in-situ through an auxiliary gasification system. Capture of CO_2 from the syngas stream is feasible through a vacuum pressure swing adsorption (VPSA) unit. The assessment reveals negative specific carbon emissions (up to -19 kg CO_2/kg H_2) when electricity is generated in-situ and carbon capture is carried out in BG systems. The hydrogen costs from the BG pathway are in the range of INR 307-352/kg ($3.71-4.27/kg), competitive with water electrolysis using solar power. The study also suggests the introduction of emission reduction incentive (ERI) as a combined economic-environmental performance indicator. Among the green pathways, BG-H_2 with in-situ electricity generation and carbon capture has the best combined performance, requiring an incentive of $127/tonne CO_2. While commercial-scale SMR has a low hydrogen production cost due to economies of scale, the increasing natural gas prices could make the BG-H_2 pathway lucrative in the future.

1. INTRODUCTION

The increase in greenhouse gas (GHG) emissions over the years have driven the transition from fossil fuels to renewable energy. To achieve climate targets, a 20-50% reduction in fossil fuels is required by 2050, with hydrogen and its derivates playing a big role in the decarbonisation of industries and transportation. About 10-20% of the global final energy consumption is expected to be supplied from low-carbon hydrogen. Hydrogen is an important commodity used in oil refining, steel reduction, ammonia and methanol production, and transportation (BP p.l.c, 2023). It could also be used as an energy carrier to store renewable energy (Narayana Sarma et al., 2024).

The global hydrogen production amounted to 97 million tonnes (MT) in 2023, with low-carbon hydrogen production accounting for only about 1.03%. This comprises mostly of fossil-hydrogen with carbon capture, utilisation, and storage (CCUS) and water electrolysis through renewable energy. Around 15 fossil-hydrogen facilities are equipped with CCUS globally, with a cumulative hydrogen production of 0.6 MT. The electrolyser capacity reached 1.4 GW in 2023, with another 6.5 GW in advanced stages of planning and execution. Green hydrogen is expected to reach 49 MT by 2030, driven mostly by the announced electrolysis projects (International Energy Agency & Clean Energy Ministerial Hydrogen Initiative, 2024). Hydrogen could also be produced from solid biomass through thermochemical, biochemical or electrochemical conversion. Thermochemical processes like gasification could achieve high yields of hydrogen, lower production costs, and high technology readiness levels (TRL). Biomass is a carbon-neutral fuel, which could result in low life-cycle emissions. Carbon capture during hydrogen production could also lead to net CO_2 removal from the atmosphere (International Energy Agency & Clean Energy Ministerial Hydrogen Initiative, 2024).

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The green hydrogen and ammonia policy in India envisages production of 5 MT of hydrogen by 2030 (Ministry of Power Notifies Green Hydrogen/ Green Ammonia Policy, 2022). The abundance of agricultural residues makes the biomass-hydrogen pathway a lucrative option (Technology Information & ICAR - Indian Agricultural Research Institute, 2018). The declining local and industrial demands, uneconomical in-situ management techniques, and meagre returns often prompt the farmers to resort to open field burning, resulting in the loss of agricultural residues (Bhattacharyya et al., 2021). Therefore, diverting these residues for hydrogen production could enhance their value and provide an additional local income source, thereby also reducing air emissions by preventing their open burning and integrating circular economy principles. On the other hand, the increasing renewable power in the Indian electricity system makes water electrolysis a forerunner in fulfilling the green hydrogen demands and the policy objectives (Narayana Sarma et al., 2024). The selection of the appropriate pathways for hydrogen production is influenced by the economic and environmental performance metrics. Hence, the comparison of these pathways on important indicators such as production costs and life-cycle GHG emissions must be investigated.

The performance evaluation of hydrogen pathways is well represented in literature (Arcos & Santos, 2023; Arfan et al., 2023; Ganesh et al., 2024; Garcia G. & Oliva H., 2023; Helf et al., 2022; Lepage et al., 2021; Longden et al., 2022; Materazzi et al., 2023; Narayana Sarma et al., 2024; Salkuyeh et al., 2018). (Longden et al., 2022) estimated that achieving high carbon capture rates from fossil-hydrogen through CCUS requires high CO_2 avoidance costs (> $80/tonne), increasing the hydrogen costs. Water electrolysis could achieve hydrogen costs competitive with steam methane reforming (SMR) at low tariffs. (Salkuyeh et al., 2018) estimated that the direct emissions from biomass-hydrogen pathway could be negative even without carbon capture. Large-scale (18.9 tph output capacity) biomass gasification (BG) systems could compete with natural gas-based hydrogen at biomass costs of $100/tonne, natural gas costs of $5/GJ, or a carbon price of $115/tonne. (Ji & Wang, 2021) reported hydrogen costs of $1.77-2.77/kg from BG, which is much lower compared to water electrolysis from renewable energy ($5.27-5.78/kg). The GWP of renewable electrolysis is 50-70% lower than SMR with carbon capture. (Narayana Sarma et al., 2024) estimated green hydrogen costs of about INR 400/kg ($4.84/kg) through alkaline and PEM electrolysis. (Materazzi et al., 2023) compared the environmental emissions of biomass and waste gasification systems with those of natural gas-to-hydrogen and water electrolysis (WE). They reported that the gasification pathway with carbon capture could achieve negative emissions. (Ganesh et al., 2024) assessed the economics of distributed-scale BG systems and reported that the cost of bio-hydrogen is competitive with that of green hydrogen from electrolysis. The BG pathway could achieve economic parity with fossil-hydrogen pathways for biomass costs of about $30/tonne.

From the brief review of literature, it is clear that SMR is the most inexpensive pathway, as it uses mature technology. BG and WE pathways are comparable in terms of cost, but the BG pathway could achieve much lower emissions compared to WE. It must, however, be noted that most studies in literature have focused on large-scale systems. The unorganised residue supply chain still remains challenging, leading to uncertainties in the biomass availability for conversion. These uncertainties could be minimised through distributed-scale systems focusing on smaller radii of procurement, thereby reducing the costs of transporting the bulky residues (Ganesh et al., 2024; Rosburg et al., 2016). Hence, a performance evaluation of small-scale BG systems and its comparison with other green hydrogen pathways is essential. While the individual economic and environmental performances of various hydrogen pathways are abundantly covered in literature, joint performance assessments and comparison of the distributed-scale green hydrogen pathways are seldom reported.

Considering the above gaps in literature, this study evaluates the costs and emissions associated with hydrogen production from small-scale fixed-bed downdraft gasification systems. Four scenarios are considered in the assessment – BG with purchased electricity (BG1 - with and without carbon capture) and BG with an auxiliary gasification system for in-situ electricity generation (BG2 - with and without carbon capture). The individual economic and environmental performances of these scenarios are compared with the SMR and WE pathways for each kg of hydrogen produced. The Emissions Reduction Incentive (ERI) is introduced as a combined performance assessment indicator and is measured in terms of $/kg of CO_2 emissions saved. The detailed methodology is discussed in the next section.

1.1 Highlights

- Comparison of three hydrogen pathways based on cost and global warming potential;
- Emission reduction incentive introduced as a combined indicator for comparison;
- Negative GHG emissions are feasible with carbon capture in the BG pathway;
- BG pathway displays better combined performance compared to water electrolysis;
- Rise in natural gas prices could make the BG pathway lucrative in the future.

2. METHODOLOGY

2.1 BG pathway description

Biomass is utilised in a fixed-bed downdraft system with dual air entry capabilities, ensuring sufficient oxygen supply for tar cracking within the reactor. This ensures relatively tar-free gas, circumventing the issues faced by other fixed-bed systems. The ash contained in the biomass is extracted from the bottom of the reactor through a screw conveyor. The rate of extraction could be defined based on the biomass properties, making this system suitable for a wide range of biomass. The gas is further cleaned in a series of wet scrubbers to obtain very low impurities, suitable for multiple downstream applications. The system uses pre-processed biomass with a particle size of 50 mm (Ganesh et al., 2024). It could be operated in two modes, depending on the oxidizer used – air gasification for the production of producer gas and oxy-steam gasification for the production of hydrogen-rich syngas (Kumar, 2016). The hydrogen from the gas could be separated through a Vacuum Pressure Swing Adsorption (VPSA) unit with a hydrogen recovery of 70% and purity of over 99.97% (Singh et al., 2023). The off gas from the VPSA unit could be used for the complete fulfilment of the heat demand and partial fulfilment of the electricity demand of the system (Ganesh et al., 2024). Two scenarios are evaluated for the source of the balance electricity demand. The BG1 scenario considers purchased electricity from the grid. The BG2 scenario considers an auxiliary air gasification (AG) unit along with the main gasification unit. This unit consumes additional biomass to generate producer gas, which could be used to produce electricity. The internal electricity requirement for the AG unit operation is assumed to be supplied from the gross power generated by the unit itself. Hence, the system requires no external energy supply and is entirely self-sufficient. BG1 and BG2 are evaluated under two conditions – without carbon capture and with carbon capture – giving rise to four scenarios. The gasification system for hydrogen production and the air gasification unit are depicted in Figure 1 and Figure 2, respectively.

2.2 Economic assessment

The economics of the BG pathway are established by estimating the minimum selling price (MSP) of hydrogen. The MSP is the lowest price at which the project is still profitable. This is evaluated through a discounted cash flow analysis and setting the Net Present Value (NPV) to zero, as described in the below equation (Ganesh et al., 2024).

$$\sum_{i=1}^{N} \frac{(P_i \times MSP) - (CC_i + SOC_i)}{(1+r)^i} = 0 \quad (1)$$

Where P_i, CC_i, SOC_i, r, and N are the annual production, carrying charges, system operating costs in the 'i'th year, the discount rate, and the system lifetime, respectively. The SOC includes the annual expenditure on fuel, utilities, wages, and maintenance. The carrying charges include the Total Capital Recovery (TCR) and cost of capital (interest on debt and returns on equity) (Bejan et al., 1996; Ganesh et al., 2024). The key inputs and assumptions for the economic assessment are provided in Table 1.

2.3 Environmental assessment

While carbon emissions from the direct conversion of biomass are considered biogenic, the other activities such as agriculture, biomass collection, transportation, and pre-processing contribute to the overall emissions. The emissions from hydrogen production depend on the emissions from each stage of the life cycle. The emissions during agriculture phase include N_2O-N emissions from nitrogenous fertilisers and CH_4 emissions from flooded rice fields. The average biomass mix of Karnataka majorly

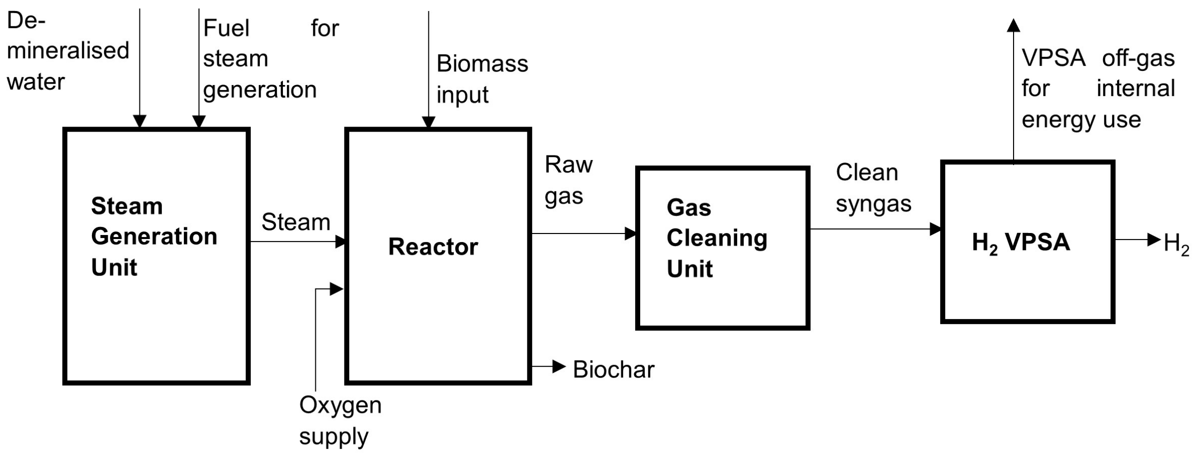

FIGURE 1: Biomass gasification pathway for hydrogen production (Ganesh et al., 2024).

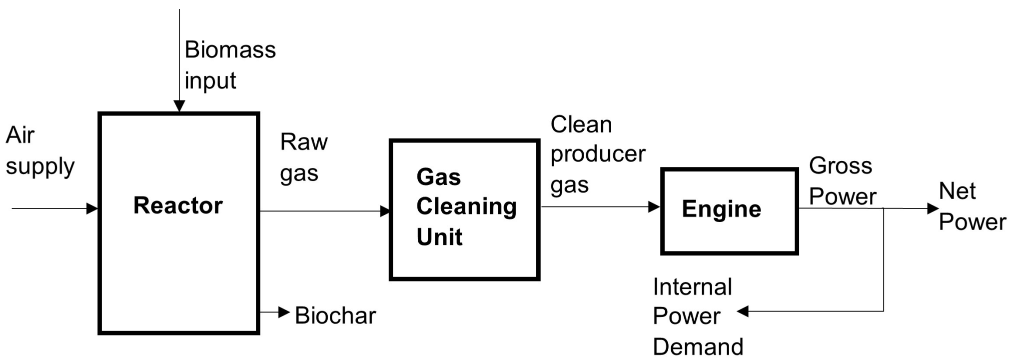

FIGURE 2: Auxiliary air gasification unit (Ganesh et al., 2024).

TABLE 1: Key inputs for economic assessment of BG pathway.

Parameter	Value	Reference
Discount rate	12%	(Union Bank of India, n.d.)
Debt repayment period	10 years	Assumption
System lifetime	25 years	Assumption
Inflation rate	6%	(RI, n.d.)
Annual operation	7500 hours	Assumption
Total capital investment (for 100 kg/h BG-H_2 plant)	INR 863-1177 million ($10.45-14.25 million)	Quotations
Annual maintenance costs	2% of Fixed Capital Investment	(Wang et al., 2019)
Electricity tariff	INR 8/kWh ($0.10/kWh)	(Karnataka Electricity Regulatory Commission, 2024)
Feedstock cost	INR 6/kg ($0.07/kg)	Average cost of biomass as per correspondences with local suppliers
Labour costs	INR 40,000/day ($484/day)	Obtained through expert opinions and considering three 8-hour-shifts per day

includes sugarcane tops and trash (24%), coconut fronds (22%), maize stalk (22%), maize cobs (10%), rice straw (8%), and others (pigeon pea stalk, sunflower stalk, cotton stalk etc.) (Punjab Renewable Energy Systems Pvt. Ltd., 2017). The agricultural emission factors are obtained from (Jain et al., 2016) and (Rathnayake & Mizunoya, 2023). Economic allocation methodology is followed for emission allocation to the crop residues. The life cycle of the BG pathway and the system boundary considered in this assessment are described in Figure 3. The functional unit is 1 kg of hydrogen produced. GREET® 2023 tool is used for the environmental assessment, considering the case of Karnataka State, India.

The prevalence of machinery for the harvest of agricultural biomass influences the biomass collection efficiency. Residue collection without suitable machinery (balers) becomes labour-intensive. The specific diesel consumption for straw baling operations is 7.59 litres/hectare, with a biomass collection efficiency of 74.6% (All India Coordinated Research Project on Farm Implements and Machinery, 2008). The residues are assumed to be procured from up to a radius of 20 km, and the pre-processed biomass is transported by about 100 km before reaching the BG plant. The power demand for the pre-processing plants is adopted from the literature (Tripathi et al., 1998). The indirect emissions from the purchased electricity (for scenario BG1) are estimated through the electricity mix of Karnataka state for 2023 (Central Electricity Authority: Operation Performance Monitoring Division, 2023; Central Electricity Authority: Renewable Energy Project Monitoring Division, 2023). About 2% of the biomass input remains unconverted and comes out from the screw conveyor in the form of biochar, which

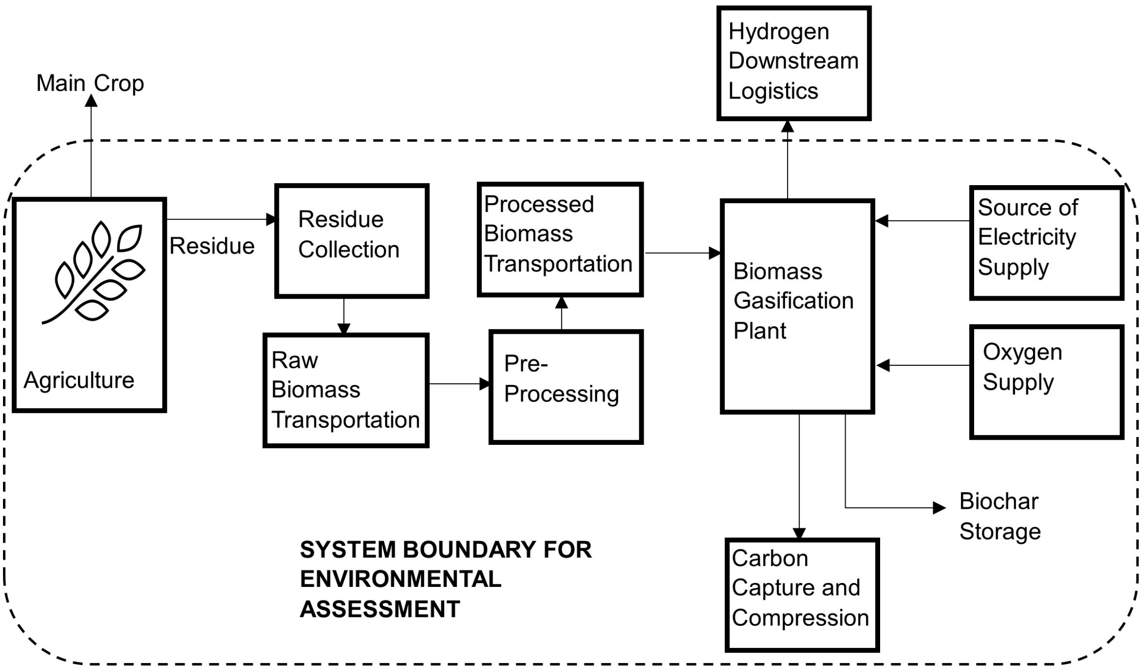

FIGURE 3: Life-cycle of BG-H_2 pathway and system boundary for assessment.

TABLE 2: Key inputs for SMR and WE pathways.

Parameter	Steam methane reforming (Katebah et al., 2022)	Water electrolysis
System output capacity	20830 kg/h	100 kg/h
Total capital investment	$0.15/kg H_2	$519/kW (Ahmad Mayyas et al., 2018)
Maintenance costs	7% of fixed capital investment	4.6% of Fixed Capital Investment (T. Ramsden; D. Steward; J. Zuboy, 2009)
Primary fuel demand	3.2-3.4 kg natural gas/kg H_2	12.5 litres (water)/kg H_2 (Ahmad Mayyas et al., 2018)
Electricity demand	Generated internally	55-60 kWh/kg H_2 (Ahmad Mayyas et al., 2018)
Cost of natural gas	$3.7/GJ	-
Grid electricity tariff	-	INR 8/kWh ($0.10/kWh) (Karnataka Electricity Regulatory Commission, 2024)
Electricity tariff from remote open-access renewable power plant	-	INR 5.50/kWh ($0.06/kWh)
Required captive solar plant capacity	-	27 MW (for 100 kg/h H_2 plant)
Solar plant capital costs	-	INR 40 million/MW ($0.48 million/MW) (Karnataka Electricity Regulatory Commission, 2023)
Levelised cost of electricity from captive plant	-	INR 3.08/kWh ($0.04/kWh) (estimated)

could be sequestered to reduce the life cycle emissions further. The carbon dioxide in the syngas or off-gas could be separated through a VPSA unit with sodium zeolites (Singh et al., 2022).

2.4 Comparison with other hydrogen pathways and emission reduction incentive

The biomass gasification pathway is compared with steam methane reforming (SMR) and water electrolysis (WE). The costs and emissions of the SMR with and without carbon capture scenarios are obtained from literature (Katebah et al., 2022). Proton Exchange Membrane (PEM) electrolysis is considered in this study, as described by (Ahmad Mayyas et al., 2018). The electricity demand for the electrolysis pathway is assumed to be procured from one of three sources: grid electricity (scenario WE-grid, which is a non-green scenario), captive ground mounted solar PV plant with power banking facilities (WE-Captive), and remote renewable power plants (WE-Remote) at INR 5.50/kWh ($0.06/kWh - $1 = INR 82.57, as of December 31, 2023 (Open Financial Exchange (OFX), n.d.), obtained through correspondences with local companies procuring power from open-access remote plants. The key inputs and assumptions for SMR and WE pathways are provided in Table 2. The economic and environmental performances of the four BG scenarios are compared with two SMR scenarios and three WE scenarios.

The captive solar PV plant is evaluated using PVSYST V6.74 to estimate the daily and annual electricity produced. The capacity utilisation factor of a solar plant installed near Bengaluru is assessed to be about 0.193. Wheeling and banking of power is feasible in Karnataka state, which ensures steady availability of solar power (Karnataka Electricity Regulatory Commission, 2023). With the electricity demand for electrolysis at about 55-60 kWh/ kg (Ahmad Mayyas et al., 2018), it is estimated that a 27 MW solar plant (with power banking) could sufficiently provide the annual electricity demand of a 100 kg/h output system.

The economic and environmental dimensions are reconciled by introducing the Emission Reduction Incentive (ERI). It is estimated as the incentive required for each scenario per tonne of CO_2 saved with reference to the scenario with the lowest cost, to achieve economic viability. Scenarios with lower ERIs are considered to have better combined economic and environmental performance.

3. RESULTS AND DISCUSSION

3.1 Minimum selling price of H_2 through BG pathway

The minimum selling price is a function of the fixed operating costs (maintenance), variable operating costs (fuel, labour, and utilities), and carrying charges (capital costs and interest payments). BG2 has higher carrying charges and fuel costs due to the requirement of an auxiliary air gasification unit and additional biomass for in-situ electricity generation. Carbon Capture (CC) from the off-gas or the syngas requires an additional VPSA unit and compressor, increasing the overall hydrogen MSP. Hence, BG1 without CC has the lowest MSP of INR 307/kg ($3.71/kg). BG2 with CC has the highest hydrogen MSP of INR 352/kg ($4.26/kg), with close to a half being contributed the fuel costs alone. This is caused due to the additional electricity demand for CO_2 compression, requiring biomass input to the auxiliary gasification unit. The breakdown of the MSP for the four scenarios are provided in Figure 4.

3.2 100-year Global Warming Potential (GWP-100) of BG-H_2 pathway scenarios

Under conditions of no carbon capture, the indirect emissions contribute majorly to the GWP (7.39 kg CO_2-e/kg H_2) due to grid electricity use in the gasification plant. This can be attributed to the high share (54%) of coal in the electricity mix of Karnataka. There is a significant reduction in the GWP with the introduction of in-situ power generation. It is possible to achieve negative emissions with the capture and compression of CO_2 through the VPSA system. The breakdown of the GWP-100 of the four BG scenarios are provided in Figure 5.

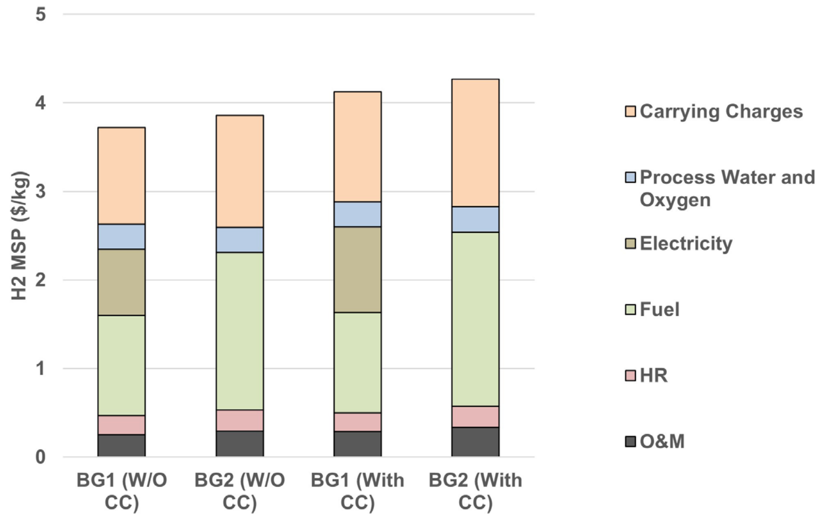

FIGURE 4: Breakdown of hydrogen MSP for BG pathway scenarios.

FIGURE 5: Breakdown of GWP-100 for BG-H_2 scenarios.

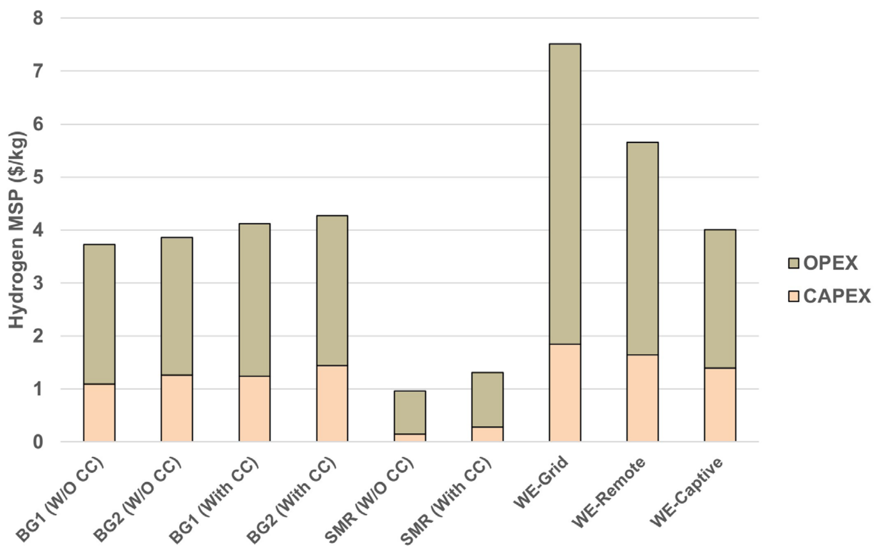

FIGURE 6: Comparison of hydrogen MSPs for BG, SMR, and WE systems.

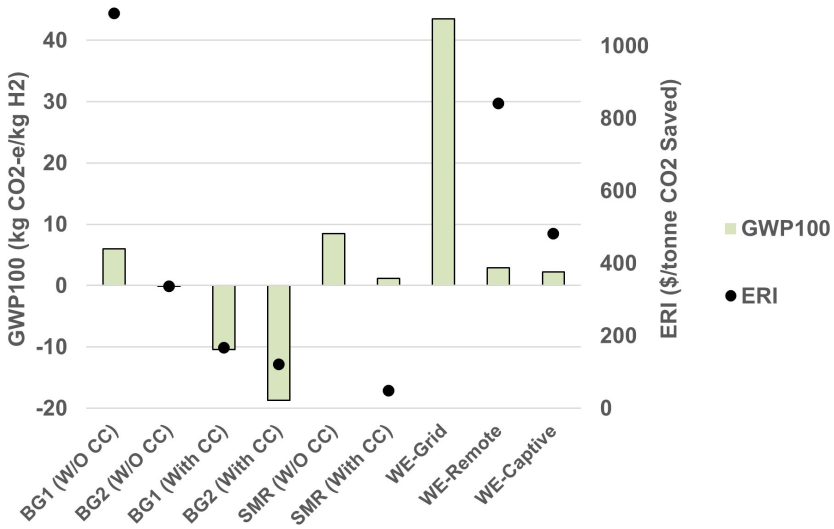

FIGURE 7: Comparison of GWP100 for BG, SMR, and WE systems.

3.3 Scenario comparison and emission reduction incentives

The comparison of BG, SMR, and WE scenarios based on hydrogen cost and GWP100 with the ERIs are provided in Figure 6 and Figure 7, respectively. The lowest hydrogen cost ($0.96/kg) could be obtained through commercial-scale steam methane reforming. However, this pathway has a high GWP of about 8.5 kg CO_2-e/kg H_2. Carbon capture from the SMR process increases the hydrogen cost by 36%, while reducing the emissions by about 86% (Katebah et al., 2022). On the other hand, hydrogen through PEM electrolysis is power-intensive, resulting in very high share of Operational Expenditure (OPEX) in the hydrogen MSP. The highly coal-reliant power grid of Karnataka leads to high emissions in the WE-Grid scenario. Procuring electricity from remote renewable power plants at INR 5.50/kWh ($0.06/kWh) reduces the costs by 25% and emissions by 93%. Installing a captive solar PV plant with a capacity of about 27 MW with power banking facilities improves the economic and environmental performances further. With a 25-35% contribution of the Capital Expenditure (CAPEX) to the hydrogen costs, reduction in the electrolyser stack costs in the future could lead to significant gains. It is evident from Figure 6 that the hydrogen MSP of $3.71-4.26/kg from biomass gasification is comparable to the WE-captive scenario ($4/kg), making it economically attractive compared to the WE pathway. The SMR with carbon capture scenario fares better than the two renewable power scenarios of electrolysis from both cost and emissions perspective. Among all the reviewed scenarios, BG-2 (with CC) displays the best environmental performance.

Individually, SMR without CC has the best economic performance, while BG-2 with CC has the best environmental performance. The combined economic and environmental performance of the hydrogen production pathways are measured through the emissions reduction incentive. Due to its high cost and emissions, BG-1 without CC requires the highest incentives ($1090/tonne of CO_2 saved) to achieve hydrogen cost parity with the reference scenario (SMR without CC). Among the BG scenarios, BG-2 with CC requires the lowest incentive of about $127/tonne of CO_2 saved. Water electrolysis, on the other hand, requires a minimum incentive of $482/tonne of CO_2 saved. Hence, among the green pathways, BG has the best combined performance. The overall best combined performance is displayed by SMR with CC, requiring an incentive of only $48/tonne of CO_2 saved, owing to subsidised feedstock, technology maturity, and economies of scale.

4. CONCLUSIONS AND FUTURE WORK

It is evident from this analysis that the BG pathway to hydrogen has the best environmental potential, while SMR has the best economic potential. The BG pathway is affected by uncertainties in the biomass supply chain. Higher offered biomass prices would increase the participation rates and reduce the procurement radius, leading to higher plant availability and lower feedstock transportation costs. On the other hand, increasing the offered biomass price would increase the variable operating costs. From a purely monetary perspective, the BG system costs could be reduced through suitable policy initiatives. The ERI provides the combined economic-environmental comparison of the alternatives. Among the green hydrogen pathways, the BG pathway has a better combined performance, with an incentive requirement of $127-336/tonne, compared to $482-842/tonne for water electrolysis using solar power. On the other hand, the fossil-hydrogen pathways have better economic metrics due to better technology maturity, feedstock subsidies, and economies of scale. With a heavy reliance on imported natural gas in India (Sukalp Sharma, 2024) and the increasing fuel prices, the extensive development of the biofuel value chain through the BG pathway would provide monetary savings through reduced imports, compared to the SMR pathway. The BG pathway would also pave way for the complete utilisation of the available waste biomass (residues), generating additional income for small and marginal farmers and helping the local economy. The extent of social benefits from the large-scale integration of the biofuel value chain remains to be evaluated. Hence, a rigorous, indicator-based approach for the quantification of the performance of the biofuel value chain is essential in addition to the economic and environmental assessments.

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