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Synergistic integration of direct air capture in bioenergy systems

Nor Syuriaty Jaafar[a], Norhuda Abdul Manaf[ab*], Noor Fatina Emelin Nor Fadzil[a], and Nilay Shah[b*],

[a] Department of Chemical and Environmental Engineering, Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia, Kuala Lumpur, Malaysia
[b] Department of Chemical Engineering, Imperial College London, SW7 2AZ, United Kingdom
* Corresponding Author: norhuda.kl@utm.my, n.shah@imperial.ac.uk

ABSTRACT

The present work aims to demonstrate the synergy achieved through the integration of biomass gasification with a direct air capture (DAC) system to maximize overall CO_2 removal capacity, while simultaneously converting waste into value-added products (hydrogen) and supplying the energy required for DAC operation (BG-H_2P-DAC). The proposed configuration is modeled using Aspen Plus to investigate the synergistic interactions and key performance indicators of the BG-H_2P-DAC system. Parametric analyses are conducted by varying gasification temperature, air inlet flow rate, and amine concentration and flow rate. The results indicate that increasing the monoethanolamine (MEA) concentration from 10% to 40% leads to a gradual decline in CO_2 capture efficiency, accompanied by a reduction in CO_2 slip. The system achieves a net specific electricity consumption of 0.0293 MWh/t CO_2, confirming that the electricity generated from the integrated steam power cycle is sufficient to fully offset the electrical requirements of the DAC process. The regeneration heat requirement at a steam temperature of 150 °C is 1.32 MWh/t CO_2, which represents the total net thermal demand of the DAC unit.

Keywords: Carbon Capture, Aspen Plus, Energy, Hydrogen, Environment

INTRODUCTION

Deep decarbonization pathways aimed at limiting the world's surface temperature increases to no more than 1.5°C have placed significant pressure on the global energy system. One promising avenue to achieve this target is by deploying the renewable sources for clean energy alongside negative emission technologies (NETs).

Sustainable biomass plays a vital role towards the transition to decarbonized economy with broad applications [1]. Gasification of biomass features an effective technology to enhance thermochemical efficiency and curtailing environmental impact. The benefits result from the syngas production composes of hydrogen that serves as the primary fuel in the combustion process. Which render vital potential for multiple products such as methanol, hydrogen, power, and freshwater production[2].

Direct Air Capture (DAC) has emerged as a game changing NET due to its ability to capture CO_2 directly from the atmosphere (demand-side) [3], in contrast to other carbon capture technologies that primarily focus on the supply-side. DAC operates by removing CO_2 directly from ambient air through chemical processes using liquid solvents or solid sorbents usually requiring high and low regeneration temperatures.

Few studies have explored the potential of integrating biomass gasification, DAC couple/hybrid with other technologies. A novel integrated sustainable aviation fuel (SAF) production system combining DAC, CO_2 electrolysis, and biomass gasification was proposed and evaluated by [3]. The system achieved an overall energy efficiency of 54.7 % and a negative global warming potential estimated at -339.7 g CO_2-e/MJ SAF. In another study, [4] designed a high-temperature direct air capture (HTDAC) system integrated with Fischer-Tropsch synthesis (FTS) for renewable jet fuel production. The proposed configuration resulted in a fuel specific energy consumption about 122 MJ/kg jet fuel with DAC accounting for about 16 % of the total energy demand. From a thermodynamic perspective, the theoretical minimum energy required to separate CO_2 from air using a DAC

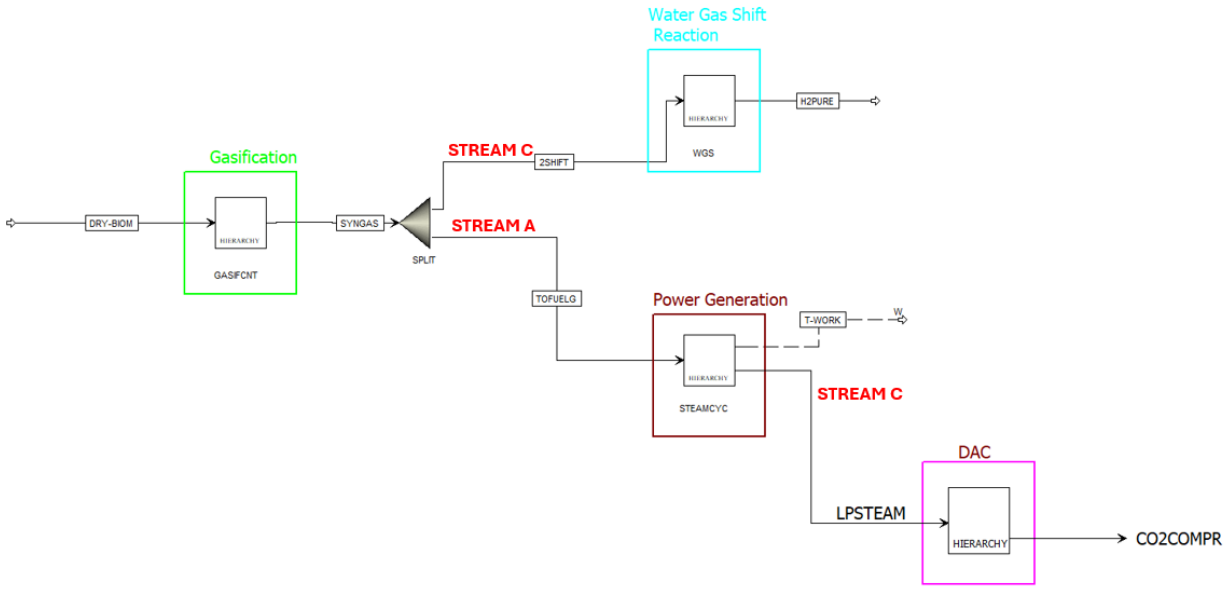

Figure 1: Hierarchies block in the Aspen Plus interface for BG-PH2-DAC system.

system and deliver it in pure form at 1 atm has been reported to be approximately 0.5 GJ per tonne of CO_2 [5]. The integration of nuclear small modular reactor (SMR) with a low-temperature solid sorbent DAC system was evaluated by [6]. Based on the DAC plant's output and energy requirement, a thermal input of 51.25 MW was required necessitating the SMR to supply 100°C steam at this capacity. Utilizing this amount corresponds to an estimated 15% reduction in electricity generation. An innovative low-CO_2 emission system that integrates biomass gasification, monoethanolamine (MEA)-based CO_2 capture, and methanol synthesis for waste-to-energy and power-to-fuel applications was proposed by [7]. This system generates 75 MW of electricity with the capture unit exhibits a capture efficiency of 59.24 % requiring 1.92 MW of power per kilogram of CO_2 captured. While extensive research has been conducted on various technology integration configurations, limited research has focused on integrated application of biomass gasification combined cycle systems for simultaneous power and hydrogen production coupled with DAC (BG-PH_2-DAC).

Research contribution

Biomass gasification has been evident to make a significant contribution to achieve net-zero/negative emissions [8, 9]. Synergizing biomass gasification with a combine cycle system has been proven to enhance power generation efficiency and environmental performance compared to a conventional coal fired power plant [10].

A major challenges associate with DAC lies in its high CO_2 capture cost [11] and substantial demand of low carbon thermal and electrical energy [6]. Where, electricity is required to operate fans and auxiliary equipment, while a considerable amount of heat to regenerate the capture medium and release the captured CO_2. Despite its considerable mitigation potential, the large-scale commercialisation and deploying DAC of systems remain challenging. Although recent improvements have brought DAC closer to commercial feasibility, high regeneration energy and substantial energy requirement continue to represent a critical barrier to widespread adoption [5, 12].

The ability of biomass gasification to generate power in its downstream processes offer a significant advantage for integrated industrial ecosystem that include DAC. Present work demonstrates this synergy at a computational level (technology readiness level 2) serving as a preliminary contribution toward the development of a smart industrial ecosystem. Furthermore, this work highlights how the low-carbon energy required for DAC can be accommodated by the power produce from gasification system. The high-purity hydrogen produced via the water-gas shift reaction in biomass gasification enhances the efficiency of industrial ecosystems by enabling multiple energy vectors from renewable biomass sources.

METHODOLOGY

Process description

A simplified diagram of BG-PH_2-DAC system proposed in this study is illustrated in Figure 1. The diagram shows the hierarchical blocks used in Aspen Plus simulation consisting of biomass gasification, water gas shift (WGS), steam cycle and DAC processes. In this work, enriched air is employed as the gasification agent to produce syngas. A study has confirmed that using air as a gasification agent can produce high-purity H_2 [13], demonstrating the technical feasibility of this approach. Based on Figure 1, the syngas is controlled and divided into multiple streams for the co-production of electricity (Stream A), low pressure steam (Stream B) and hydrogen (Stream C). For Stream A, the syngas is cooled before entering the combustion unit, where it is burned with compressed air. The hot combustion gases drive a gas turbine and waste heat is recovered through a series of heat exchangers to generate power in combine cycle. At the down-stream process, energy required by the DAC is accommodated by generated power (assume as a pseudo stream/connection) and bleed steam is used for solvent regeneration at stripper. For Stream C, the syngas undergoes a water-gas shift reaction to increase its hydrogen content.

Model development

Biomass integrated gasification combine cycle coupled with water gas shift (BG-PH_2) process

A simplified biomass integrated gasification combine cycle model is adapted from a study conducted by [14], while WGS process is based on the simplified model developed in [15, 16]. Biomass gasification is modelled in Aspen Plus using a non-conventional solid approach combined with equilibrium-based reactors. The process consists of biomass decomposition, gasification, particulate removal, and syngas cleaning prior to its use in a combined cycle gas turbine. In gasification model, woodchip is used as fuel with their proximate and ultimate composition is based on [13, 17]. Based on the experimental study conducted by [13], utilization of woodchips as fuel source can produce almost H_2 purity of ≥ 99.977 vol.%

The WGS reactor converts CO and steam into H_2 and CO_2 through the reversible chemical reaction: $CO + H_2O \rightleftarrows CO_2 + H_2$. During this process, raw syngas is mixed with steam to achieve high purity H_2. The cooled syngas mixer then enters the RStoic reactor containing iron-based catalyst where perfect mixing is assumed for modelling purposes. For simplification, a single-stage WGS reactor is employed in this study following the process suggested by [16]. This process involves high temperature stage between 300 – 500°C. Finally, the tail gas stream (CO_2 + unconverted gases) is removed by the scrubber and high purity H_2 is released on the top scrubber column. Details of the model development and Aspen Plus unit operations involved is presented in Appendixes S1 and S2.

Direct air capture with CO_2 compression

The DAC model is developed and adapted from [5, 11, 18] utilizing the mature MEA absorption process modified to suit DAC environmental conditions. This technology is deployed as it holds a promise as a low-cost and scalable solution for DAC [19]. Details of the model development and Aspen Plus unit operations involved is presented in Appendixes S1 and S2.

Hybrid BG-PH2-DAC

The individual models are interconnected as illustrated in Figure 1. A splitter unit operation is used to divide the syngas between H_2 production and power generation at 50% ratio. For steam supply to the reboiler, a MHeatX unit operation is employed. In the stripper column (Radfrac), reboiler option is disable as steam is supplied externally from a low-pressure steam. The individual models are validated independently before being integrated to ease the convergence process.

RESULT AND DISCUSSION

Synergistic analysis of BG-PH2-DAC

Synergistic analysis through sensitivity evaluation is conducted by manipulating several operating variables such as gasification temperature, air inlet (at DAC), and amine solvent concentration and flowrate. The analysis is conducted based on nominal operating condition of BG-PH_2-DAC plant as tabulated in Appendix S2.

Figures 2(a)-(b) show the strong influence of gasifier temperature on syngas composition and the subsequent enhancement of hydrogen yield through the WGS reaction during biomass gasification. In Figure (a), increasing the gasifier temperature from 300 °C to around 700 °C markedly increases the H_2 and CO mole fractions, indicating enhanced devolatilization, char gasification, and endothermic reactions such as steam reforming [20] and the Boudouard reaction [21]. The H_2 mole fraction reaches a maximum at approximately 700 °C, beyond which it slightly declines, suggesting the increasing dominance of competing high-temperature reactions and which shift the equilibrium[20]. In contrast, [20] obtained the highest H_2 fraction at 800 °C, suggesting the existence of optimal condition for efficient H_2 production. The CO_2 shows a decreasing trend with temperature, reflecting its consumption in gasification and affect of the endothermic character of Boudouard reaction [22].

After the WGS reactor (Figure 2(b)), H_2 started to produce at 300 °C and increased drastically until 700 °C, with H_2 mole fraction significantly increasing and stabilizing at around 34–35% for temperatures above 700 °C, while CO_2 correspondingly increases due to CO conversion. This plateau indicates that the WGS reaction approaches equilibrium and all methane had been converted into hydrogen. Similar trend was observed in the

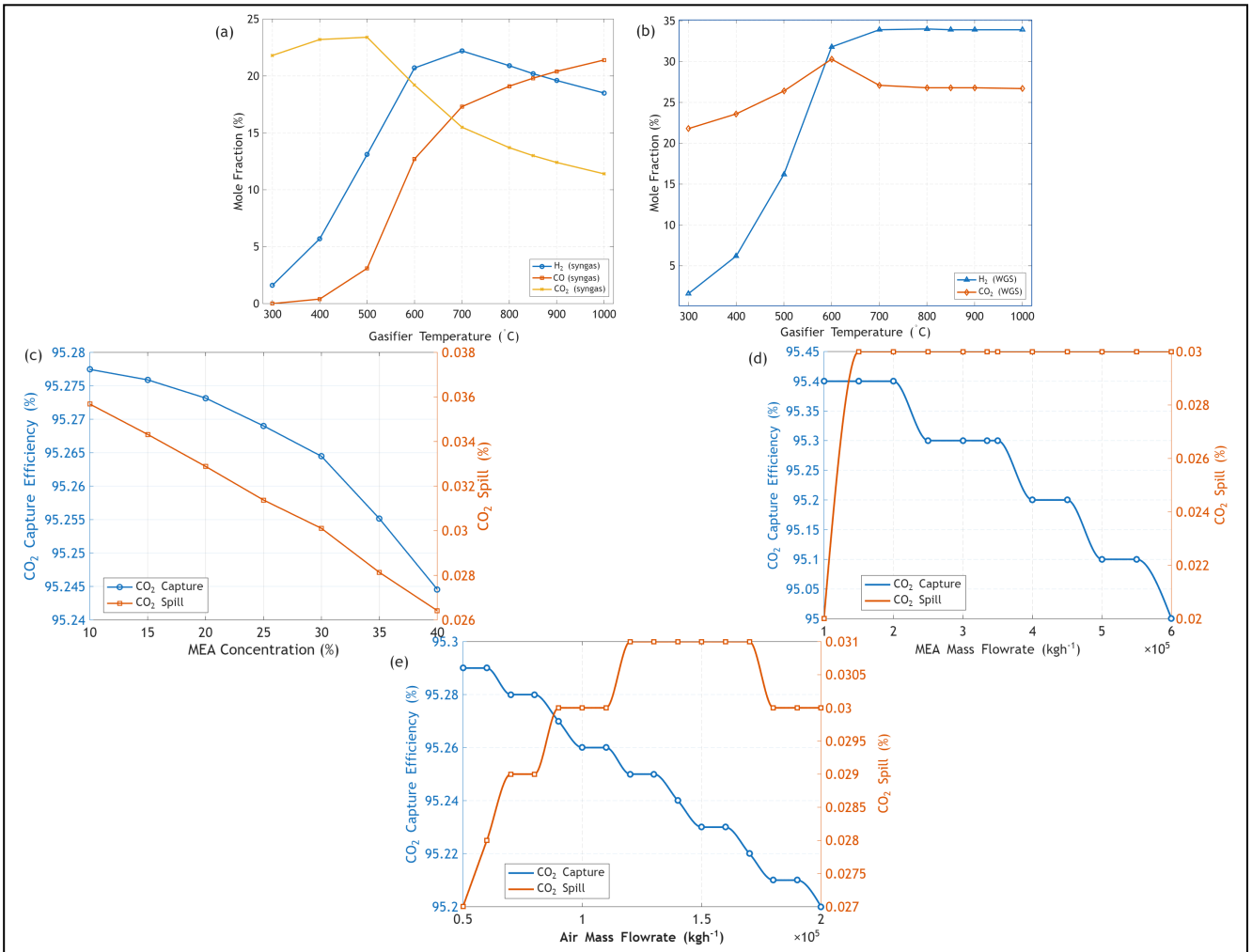

Figure 2. Synergisitc effect of BG-PH₂-DAC BG at nominal operating condition, in which a single parameter is varied (x-axis) while all other operating conditions are maintained constant. (a) Variation of gasification temperatue with syngas composition, (b) Variation of gasification temperature with gas composition after WGS, (c) Variation of MEA concentration with CO_2 capture rate and CO_2 spill (top absorber), (d) Variation of MEA mass flowrate with CO_2 capture rate and CO_2 spill (top absorber), (e) Variation of air mass flowrate with CO_2 capture rate and CO_2 spill.

study conducted by [15].

Figures 2 (c)–(e) present a synergistic analysis of the downstream process (DAC), highlighting the sensitivity of CO_2 capture efficiency and CO_2 slip (off-gas at absorber column) to key operating variables. In Figure 2(c), increasing the MEA concentration from 10% to 40% results in a gradual decline in CO_2 capture efficiency, accompanied by a reduction in CO_2 slip. This trend suggests that while higher MEA concentrations enhance the solvent's CO_2 absorption capacity, mass transfer limitations and high liquid-to-gas volumetric flow ratio may hinder overall capture efficiency under DAC conditions [23]. Additionally, higher lean loading (i.e. higher MEA concentration) can lead to low productivity (low capture efficiency) due to increased pressure drop within the column [11]. Figure 2(d) shows the effect of MEA mass flow rate, where an increase initially sustains high capture efficiency within the range of 95.0 – 95.4%. This behavior indicates that, within this specific range of MEA flowrate, the flowrate ensures complete wetting of the packing and effective gas–liquid contact for reaction and capture [23]. Meanwhile, CO_2 slip remains relatively stable, implying that solvent availability is no longer the limiting factor. As illustrated in Figure 2(e), increasing air mass flow rate exhibits minimal impact on capture efficiency, exhibiting a slight decreasing trend accompanied by a corresponding increase in CO_2 slip. This trend indicates that higher air flow rates may minimize the required contactor inlet area [23], though this may subsequently diminish the capture efficiency. This interpretation is based on the qualitative trend rather than a quantitative approach.

Key performance analysis of BG-PH2-DAC

Table 1 summarizes the key performance indicators of the integrated BG-PH_2-DAC system operating under nominal conditions (Appendix 2). The system demonstrates marginal hydrogen production, achieving a specific H_2 yield of 0.0292 kg H_2/biomass with an almost complete hydrogen purity (~100%). This indicates efficient syngas conversion and effective downstream purification. Simultaneously, the process generates 66.25 kgCO_2/biomass, of which approximately 98% is successfully captured, highlighting the strong integration between biomass gasification, hydrogen production, and DAC subsystem.

The specific CO_2 capture energy requirement is quantified at 4.74 MJ/kg CO_2, indicating a moderate thermal energy intensity for solvent regeneration. This result is consistent with the findings of [24] who reported a regeneration duty of approximately 4.0 MJ/kg CO_2 when increasing the reboiler temperature from 123 to 150 °C. This minor deviation can be attributed to differences in solvent operating conditions and process integration strategies. In terms of power generation, the system delivers a gross electrical output of approximately 6.5 MWe, corresponding to a specific gross power output of 0.302 MWh/t CO_2.

As the present work employed a simplified BG-PH_2-DAC plant design, the electricity consumption for the air contactor is adopted from [6] at 0.232 MWh/t CO_2. Electricity consumption for CO_2 compression is calculated at 0.04 MWh/t CO_2 with auxiliary pumping at 0.0007 MWh/t CO_2. This results in a total DAC electricity demand of 0.2727 MWh/t CO_2. It can be observed that the pumping energy requirement in this study is slightly lower than the 0.007 MWh/t CO_2 reported in [24], as only a single pump is considered in the present configuration. Larger discrepancies are noted in CO_2 compression work, where other studies reported higher values of 0.0944 MWh/t CO_2 (0.34 MJ/kg CO_2) [25] and 0.132 MWh/t CO_2 (0.475 MJ/kg CO_2) [26].These differences are primarily attributed to variations in compressor design assumptions and isentropic efficiencies. Overall, the electrical energy demand (for DAC) reported here is comparable with the value reported by [27] with a difference of 0.0327 MWh/t CO_2. As a benchmark, a standalone DAC system typically requires about 1.4 MWh/t CO_2 under the external supply of power and heat sources [24].

The resulting net specific electricity of 0.0293 MWh/t CO_2 confirms that the electricity generated from the integrated combined power cycle is sufficient to fully offset the electrical requirements of the DAC process. This internal energy integration substantially enhances overall system efficiency and reinforces the feasibility of the BG-PH_2-DAC configuration. In this work, net specific electricity is defined as the gross power generated from the steam cycle minus the total electrical demand of the DAC unit. On the thermal side, the desorption heat requirement at a steam temperature of 150 °C is 1.32 MWh/t CO_2, which constitutes the total net thermal demand of the DAC unit. This value is slightly higher than the 1.14 MWh/t CO_2 reported in the literature [27], reflecting differences in solvent regeneration conditions and heat integration assumptions. Overall, the combination of high CO_2 capture efficiency, high-purity H_2 production, and effective internal energy utilization underscores the technical viability and energetic coherence of the BG-PH_2-DAC system.

CONCLUSION

This study provides a preliminary insight for the BG-PH_2-DAC system that aim to anchor the decarbonization effort while producing multiple energy vectors. A simplified configuration proposed in this work evident the feasibility of integrated system to sufficiently accommodate electricity and thermal energy within the system. Existing work can be enhanced by considering comprehensive plant design with the integration of pressure swing adsorption and detailed combined cycle system to reflect actual operation design.

DIGITAL SUPPLEMENTARY MATERIAL

Digital supplementary is available in Living Archive for Process Systems Engineering at http://PSEcommunity.org/LAPSE:2026.0037

Table 1: Key performance analysis of BG-PH_2-DAC at nominal operating condition (extracted and derived from Aspen stream summary).

Key Performance	Value	Unit
Specific H_2 production	0.0292	kg H_2/biomass
H_2 purity	~100	%
Specific CO_2 production	66.25	kg CO_2/biomass
CO_2 capture rate	~98	%
Specific CO_2 capture	4.74	MJ/kg CO_2
Gross power output	~6.5	MW_e
Energy requirement		
Electrical		
Specific power output	0.302	MWh/tCO_2
Air contactor (DAC)	0.232 [6]	MWh/tCO_2
CO_2 compressor (DAC)	0.04	MWh/tCO_2
Pump (DAC)	0.0007	MWh/tCO_2
Thermal		
Desorption heat (at steam 150°C)	1.32	MWh/tCO_2
Net specific (thermal)	1.32	MWh/tCO_2
Net specific (electricity)	0.0293	MWh/tCO_2

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AUTHOR IDENTIFIERS

Abdul Manaf N: 0000-0002-4548-6425
Shah N: 0000-0002-8906-6844

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