



**SISTEMA INTEGRADO DE PRODUÇÃO DE HIDROGÊNIO VERDE, OXICOMBUSTÃO DE
BIOGÁS E CAPTURA DE CARBONO**
**INTEGRATED SYSTEM FOR GREEN HYDROGEN PRODUCTION, BIOGAS
OXY-COMBUSTION AND CARBON CAPTURE**

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RESUMO

Propõe-se e avalia-se um sistema integrado que associa: (i) eletrólise alcalina/PEM movida por eletricidade eólica, (ii) uma unidade termelétrica de oxidação de biogás tratado com captura de CO₂ e (iii) a recirculação do vapor d'água condensado para prover parte da água de eletrólise. O objetivo é estabelecer um modelo simples, transparente e escalável que relacione a razão de potências do sistema (x = potência de eletrólise/potência elétrica da oxidação) aos balanços de água e oxigênio, e, a partir disso, identificar o ponto de menor custo nivelado do hidrogênio (LCOH). Desenvolveu-se um modelo analítico de duas razões: $y_w(x) = K_e/x$ (água ofertada/demandada) e $y_{O_2}(x) = C \cdot x$ (oxigênio ofertado/demandado), cujos parâmetros são função da eficiência elétrica da termelétrica, estequiometria de CH₄, excesso de O₂, recuperação de condensado e consumo específico da eletrólise. Os resultados mostram três zonas operacionais e dois pontos notáveis: autossuficiência hídrica ($x = K_e$) e autossuficiência de O₂ ($x = 1/C$). Para premissas realistas (água barata e O₂ caro), o LCOH mínimo ocorre em $x = 1/C$. No ponto ótimo, com biogás comprado a preço comercial representativo, estimam-se: LCOH $\approx$ US\$ 3,90/kg H₂, VPL@8% $\approx$ US\$ 59 M, TIR $\approx$ 29% e payback descontado $\approx$ 4,2 anos. Conclui-se que a integração proposta é tecnicamente consistente e economicamente promissora, sujeita a sensibilidade aos preços de biogás e eletricidade.

Palavras-chave: hidrogênio verde; biogás; oxidação; captura de carbono; análise técnico-econômica.

ABSTRACT

We propose and evaluate an integrated system combining: (i) wind-powered alkaline/PEM electrolysis, (ii) a treated biogas oxy-combustion power unit with CO₂ capture, and (iii) condensate recycling to supply part of the electrolyzer's water demand. The aim is to derive a compact, transparent and scalable model linking the system's power ratio (x =electrolyzer power/oxy-power output) to water and oxygen balances, and then locate the minimum levelized cost of hydrogen (LCOH). We formulate two analytic ratios: $y_w(x) = K_e/x$ (water offered/demanded) and $y_{O_2}(x) = C \cdot x$ (oxygen offered/demanded), where the constants depend on oxy-unit electrical efficiency, CH₄ stoichiometry, O₂ excess, condensate recovery and electrolyzer specific consumption. Results reveal three operating zones and two landmarks: water self-sufficiency ($x = K_e$) and oxygen self-sufficiency ($x = 1/C$). Under realistic assumptions (cheap water, costly O₂), the minimum LCOH occurs at $x = 1/C$. At the optimum, buying biogas at representative market price, we estimate LCOH $\approx$ US\$ 3.90/kg H₂, NPV@8% $\approx$ US\$ 59 M, IRR $\approx$ 29%, and discounted payback $\approx$ 4.2 years. We conclude the proposed integration is technically sound and economically promising, with sensitivity to biogas and electricity prices.

Keywords: green hydrogen; biogas; oxy-combustion; carbon capture; techno-economic analysis.

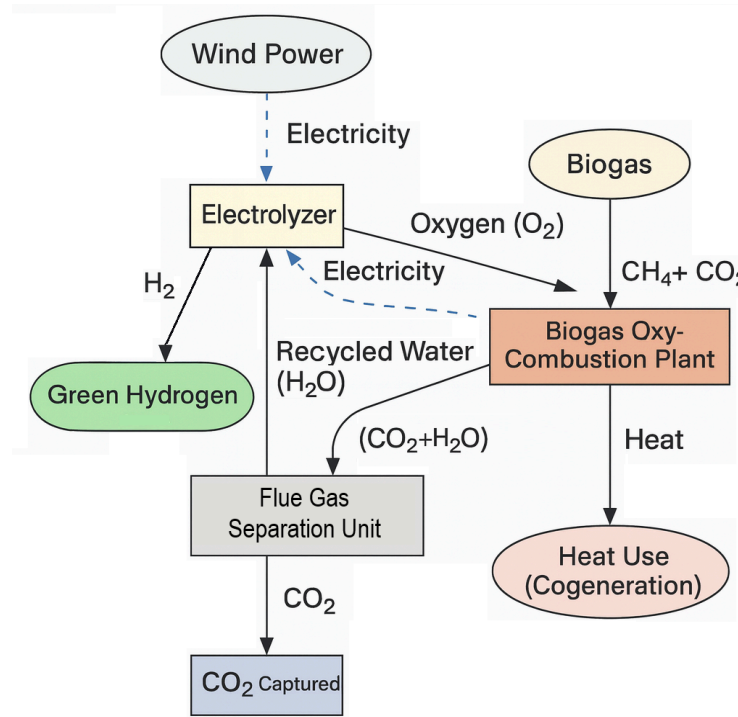


1 INTRODUCTION

Low-carbon hydrogen hinges on affordable renewable electricity and reliable water supply. Coupling electrolysis with biogenic oxy-combustion and carbon capture (Power-to-X + BECCS) can simultaneously (i) supply high-purity O_2 to the boiler, (ii) return condensed water to the electrolyzer, and (iii) generate negative-emission credits by capturing biogenic CO_2 . This paper develops a minimal analytical framework that explains how sizing the electrolyzer relative to the oxy-unit dictates water and O_2 “bottlenecks”.

Figure 1 summarizes the concept: wind and thermal power feed electrolysis to produce H_2 and O_2 ; the O_2 is routed to a biogas oxy-combustion plant; flue gas (CO_2+H_2O) is sent to a separation unit; CO_2 is captured while the condensed H_2O is recycled to the electrolyzer; useful heat can be cogenerated. The flowsheet underpins the mass–energy coupling and supports the derivation of the water and oxygen ratio models presented in Section 2.

Figure 1 - Integrated flowsheet for hybrid green hydrogen production coupled to biogas oxy-combustion and CO_2 capture with water recycling.



2 METHODOLOGY

2.1 Water ratio model

Let $x = P_{el}/P_{e,ox}$, where P_{el} is electrolyzer power and $P_{e,ox}$ is the electric output of the oxy-combustion unit. The water offered/demanded ratio is



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$$y_w(x) = \frac{\dot{m}_{w,offer}}{\dot{m}_{w,demand}} = \frac{K_e}{x},$$

with

$$K_e = \frac{\eta_{rec} \nu_{H_2O} e_{H_2}}{r_w LHV_{CH_4} \eta}.$$

Here, η_{rec} is condensate recovery, ν_{H_2O} the stoichiometric H_2O per kg CH_4 burned (kg/kg_{CH_4}), e_{H_2} the electrolyzer specific energy ($kWh/kg H_2$), r_w the electrolyzer water need (kg_{H_2O}/kg_{H_2}), LHV_{CH_4} methane lower heating value (kWh/kg), and η the oxy-unit electrical efficiency. Water self-sufficiency occurs at $y_w=1 \Rightarrow x=K_e$.

2.2 Oxygen ratio model

The oxygen offered/demanded ratio reads

$$y_{O_2}(x) = \frac{\dot{m}_{O_2,offer}}{\dot{m}_{O_2,demand}} = C x,$$

with

$$C = \frac{2 \eta LHV_{CH_4}}{\lambda e_{H_2}},$$

where λ is the O_2 excess factor (≈ 1.00). Oxygen self-sufficiency occurs at $y_{O_2}=1 \Rightarrow x=1/C$.

2.3 Locating the minimum LCOH

The total LCOH is modeled as $LCOH(x) = LCOH_0 + \Delta LCOH_{O_2}(x) + \Delta LCOH_w(x)$, where $\Delta LCOH_{O_2}$ and $\Delta LCOH_w$ are non-negative penalty terms proportional to the external O_2 and water make-up required when $y_{O_2} < 1$ or $y_w < 1$. Because make-up O_2 is typically far more expensive per $kg-H_2$ than water, $LCOH(x)$ decreases with x until oxygen becomes self-sufficient, and increases only mildly thereafter due to water make-up; hence the minimum at $x=1/C$.



2.4 Economic assessment at the optimum

At $x=1/C$ we compute annual H_2 output, power purchases, CO_2 captured, OPEX (biogas, electricity, O&M, water) and CAPEX (electrolyzers, oxy-boiler+CCUS, BOP). We then evaluate NPV (8% discount, 20 years), IRR and discounted payback.

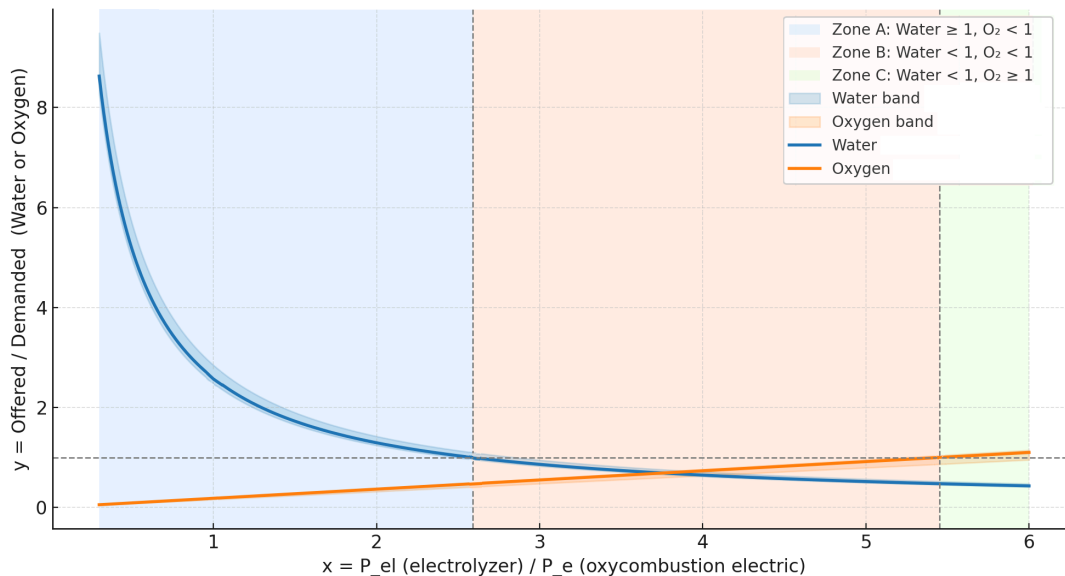
3 RESULTS AND DISCUSSION

3.1 Ratio model behavior

To numerically apply the ratio models, we adopted the following parameters: oxy-combustion electrical efficiency $\eta=0.33$; methane lower heating value $LHV_{CH_4}=13.9 \text{ kWh/kg}$; electrolyzer specific energy $e_{H_2}=50.0 \text{ kWh/kg}_{H_2}$; oxygen excess factor $\lambda=1.00$ (stoichiometric); condensate recovery $\eta_{rec}=0.95$; water formed per kilogram of CH_4 burned $v_{H_2O}=2.25 \text{ kg/kg}_{CH_4}$; and electrolyzer water requirement $r_w=9.0 \text{ kg}_{H_2O}/\text{kg}_{H_2}$. Using these values in the equations of K_e and C yields the constants $K_e \approx 2.589$ and $C \approx 0.183$ (dimensionless), which are used in the plots and subsequent discussion. Graph 1 plots $y_w(x)=K_e/x$ (blue) and $y_{O_2}(x)=C \cdot x$ (orange). Three colored regions emerge:

- Zone A (blue): $y_w \geq 1$ and $y_{O_2} < 1$ — water is sufficient (condensate covers electrolysis), oxygen is the bottleneck.
- Zone B (peach): $y_w < 1$ and $y_{O_2} < 1$ — both water and O_2 require make-up.
- Zone C (green): $y_w < 1$ and $y_{O_2} \geq 1$ — oxygen is sufficient; only water needs make-up.

Graph 1 - Offered-to-demanded ratios for water and oxygen as a function of $x=P_{el}/P_{e,ox}$. Shaded zones indicate which input is limiting.



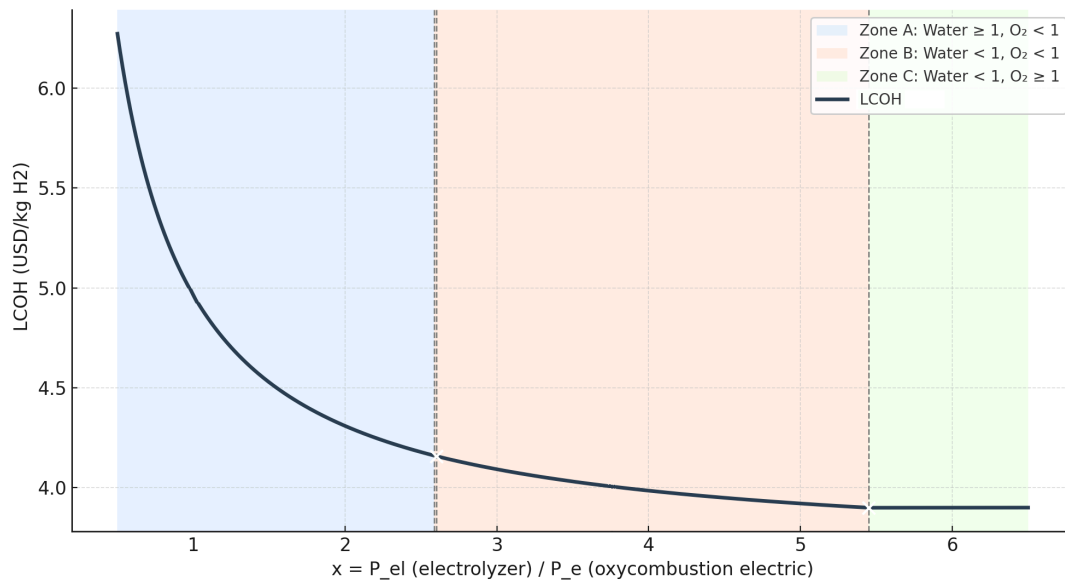


Two landmarks are visible: water self-sufficiency at $x=K_e \approx 2.59$ (left dashed line) and oxygen self-sufficiency at $x=1/C \approx 5.45$ (right dashed line). Between them lies Zone B, where both deficits coexist. The crossing of the curves ($x=3.76, y=0.69$) marks equal relative coverage of water and O_2 ; below it O_2 dominates the deficit; above it water does.

3.2 Cost behavior and optimum

Graph 2 shows total LCOH vs. x . The curve declines steeply from the base point (small x) because external O_2 purchases shrink as more electrolyzer power is installed. After reaching oxygen self-sufficiency at $x=1/C$, the curve flattens — the remaining increase in x would only add water make-up cost, which is comparatively minor — so the minimum LCOH ($\approx$ US\$ 3.90/kg H_2) occurs at $x=1/C \approx 5.45$.

Graph 2 – Total LCOH vs. x with operating zones. The minimum occurs at oxygen self-sufficiency ($x \approx 5.45$).



3.3 Economic performance at the optimum ($x=1/C$)

Using consolidated datasets, the optimal configuration features an electrolysis plant of ≈ 27.2 MW coupled to a 5 MW_e biogas (60% CH_4 + 40% CO_2) oxy-unit, yielding ≈ 4.53 kt H_2 yr⁻¹, ≈ 44 kt CO_2 yr⁻¹ captured, and ≈ 185 GWh yr⁻¹ of purchased wind electricity. The annual economics (H_2 price US\$ 5/kg; CO_2 credit US\$ 40/t) give total revenue $\approx$ US\$ 23.7 M yr⁻¹ and OPEX $\approx$ US\$ 14.4 M yr⁻¹, with the two largest items being biogas ($\approx$ US\$ 6.94 M yr⁻¹ at $\approx$ US\$ 0.52 per Nm³, a representative market parity value) and purchased electricity ($\approx$ US\$ 6.66 M yr⁻¹). EBITDA is $\approx$ US\$ 9.28 M yr⁻¹ and all-in LCOH $\approx$ US\$ 3.90/kg H_2 . Total CAPEX is $\approx$ US\$ 31.8 M ($\approx$ US\$ 21.8 M electrolyzers, US\$ 8.0 M oxy+CCUS, US\$ 2.0 M BOP). Over 20 years at 8%, we obtain NPV $\approx$ US\$ 59.3 M, IRR $\approx$ 29% and discounted payback $\approx$ 4.2 years.

The system is economically attractive at the optimum, provided (i) H_2 off-take $\approx$ US\$ 5/kg, (ii) competitive wind PPA ($\approx$



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US\$ 36/MWh), and (iii) biomethane (upgraded biogas) around US\$ 0.52/Nm³ CH₄. The biomethane price assumption (~US\$ 0.52/Nm³ CH₄) is based on a public Argus parity range of R\$ 2.43–2.79/Nm³; using BRL/USD≈5 gives ~US\$ 0.49–0.56 per Nm³. We applied the mid-value in this study. The LCOH and NPV are most sensitive to the gas and electricity prices; each +US\$ 0.10/Nm³ in biomethane raises LCOH by ~US\$ 0.29/kg and reduces NPV by ~US\$ 12–13 M (20 y, 8%). Credits for captured biogenic CO₂ add ≈ US\$ 0.23/kg-H₂ to revenue and strengthen the business case, but do not alone guarantee viability if energy inputs worsen. Finally, the sizing rule $x=I/C$ is robust: unless external O₂ becomes extremely cheap relative to water, the LCOH minimum remains at oxygen self-sufficiency.

4 CONCLUSIONS

We presented a compact, physics-based framework that couples electrolysis with biogas oxy-combustion and CCUS (Power-to-X + BECCS). Two analytic ratios, $y_w=K_e/x$ and $y_{O_2}=C.x$, explain the operating regions and identify water and O₂ bottlenecks. Cost-wise, the minimum LCOH occurs at $x=I/C \approx 5.45$, where oxygen becomes self-sufficient and only small water make-up is needed. For a 5 MW_e oxy-unit with ≈ 27 MW electrolysis and commercial biogas at ~US\$ 0.52/Nm³ CH₄, we estimate: LCOH ≈ US\$ 3.90/kg, NPV@8% ≈ US\$ 59 M, IRR ≈ 29%, discounted payback ≈ 4.2 years.

Improvement levers include long-term gas and power contracts, hybrid wind/solar to increase electrolyzer utilization, electrolyzer CAPEX compression, heat-integration to cut auxiliaries and premium certification of negative-emission hydrogen to enhance revenue.

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