

ENERGY AND ENVIRONMENTAL PERFORMANCE OF A BIOGAS- POWERED SOLID OXIDE FUEL CELL (SOFC): A NUMERICAL MODELING APPROACH

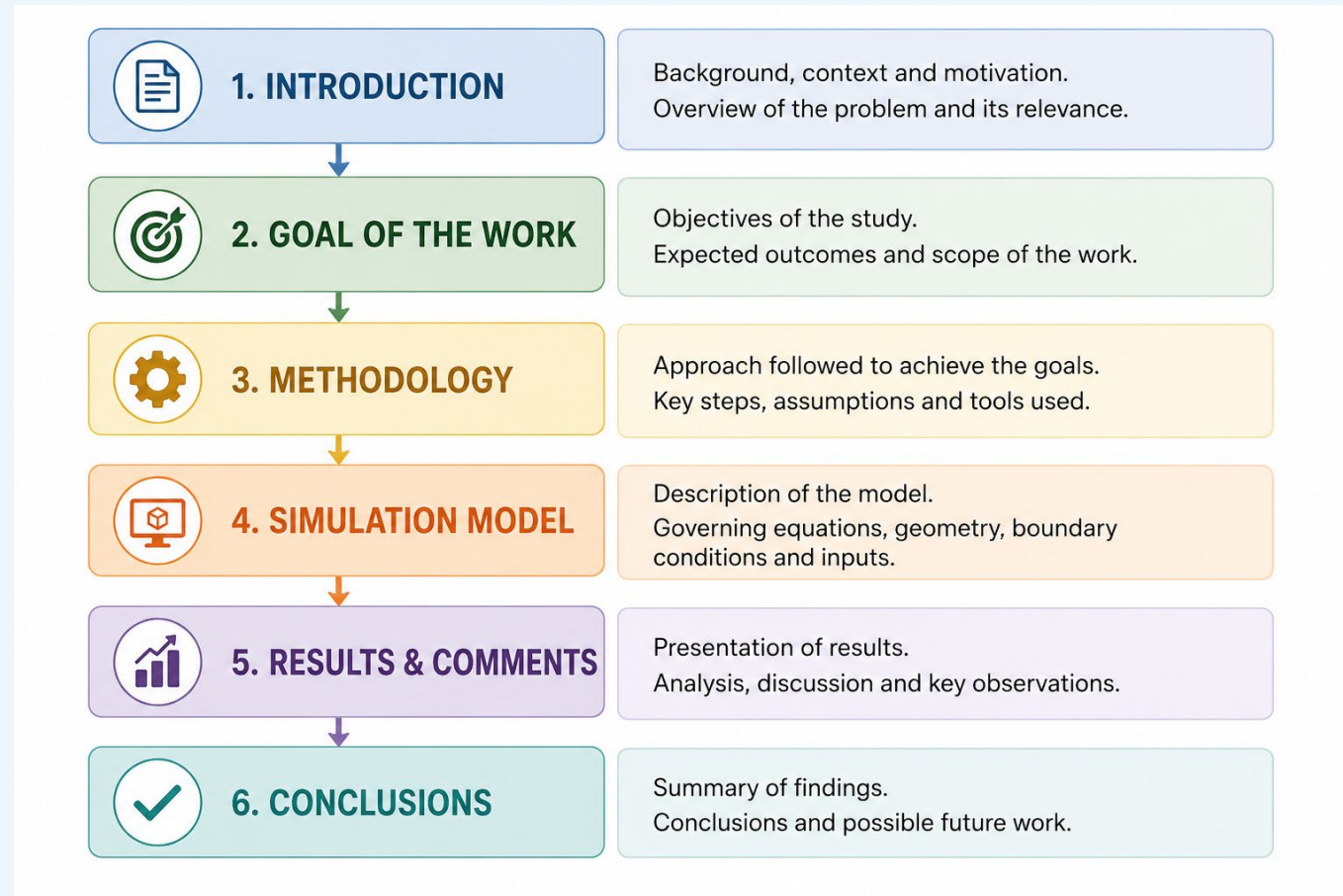
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DIPARTIMENTO DI
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Outline:



Internal Combustion Engines (ICEs) and Microturbines (MTs) current performance and limitations to overcome

Conventional cogeneration technologies like ICEs/MTs have a low electrical efficiency compared to Fuel Cells (FCs).

Electrical efficiency:

- **ICEs: 30-42%.**
- **MTs: 25-33%.**

Strongly dependent on fuel quality and loads.

Mechanical wear and maintenance.

Moving parts → Mechanical degradation.

- **High maintenance frequency.**
- **Oil Change.**
- **Overhaul.**
- **Spare parts.**

MTs:

- **High-speed rotating components.**
- **Specialised maintenance.**

CO₂ dilution vs concentration

ICE/MTs:

- CO₂ diluted in large exhaust streams (N₂ from air).
- Capture or valorization is:
 - Technically complex.
 - Economically unattractive.

SOFC:

- CO₂ exits mainly in the anode exhaust.
- More concentrated CO₂ stream.
- Easier integration with:
 - CO₂ capture, storage, and usage.
 - CO₂ utilization concepts.

Criterion	ICEs (Biogas)	MTs (Biogas)	SOFCs (Biogas)
Electrical efficiency	30-42%	25-33%	50-60%
Thermal efficiency (recoverable heat)	40-50%	45-55%	30-40% but high-grade thermal output
Total CHP efficiency	75-85%	70-80%	80-90%
Heat temperature level	Medium (90-400°C)	Medium-high (250-500°C)	High (400-800°C)
Heat quality for process integration	Good	Good	Excellent
Heat-to-power ratio	High	High	Moderate and flexible
CO ₂ emissions (specific)	Medium-high	Medium	Low
NO _x / SO _x / PM emissions	Present (after-treatment often needed)	Low but non-zero	Negligible
Noise and vibrations	High	Medium	Very low
Fuel flexibility (biogas quality)	High	Medium	High (with internal reforming)

How could Solid Oxide Fuel Cells (SOFCs) be a game-changer?

- High-temperature electrochemical conversion:
 - High-temperature operation (650-900°C) enables recovery of *high-temperature thermal energy*, not accessible in ICEs/MTs.

- Thermal energy at multiple temperature levels:
 - High-temperature heat for internal reforming and conditioning of fuel.
 - Medium-to-low-temperature heat for digester and auxiliary processes.

- Direct coupling enables:
 - Internal biogas reforming.
 - Reduced external heat generation.

SOFCs capabilities vs. conventional CHP technologies

Benchmarking	ICEs	MTs	SOFCs
Electrical efficiency	30-42 %	25-33 %	50-60 %
Recoverable heat quality	Low/medium (jacket water)	Medium (exhaust heat recovery)	High (650-900°C) for process integration
Mechanical wear	High moving parts (frequent oil change/overhaul)	Extreme speed moving parts but less than ICEs	Minimal (solid state)
Moving parts in core	Many	Few but rotating at very high speed	None in stack
Exhaust & carbon capture, storage, and usage readiness	N ₂ diluted exhaust	N ₂ diluted exhaust	Concentrated CO ₂ at anode exhaust, excellent for carbon capture, storage, and usage

Commercially Installed SOFCs Worldwide

Region	Company / Site	Installed Capacity	Electrical Efficiency	CHP / Overall Efficiency
USA	Bloom Energy Server (product fleet, >1,000 sites, 9 countries)	~1.4 GW cumulative; 200–300 kW/unit	~65% (LHV, standalone)	Up to ~90% (CHP config.)
USA	Bloom Energy – Oracle/Project Jupiter (NM) & AEP (WY), contracted	~3.7 GW contracted (ramping up)	~65% (product spec)	Not CHP
USA	FuelCell Energy SOFC pilot – UConn Storrs campus, CT	Up to ~1 MW (2 × 250 kW × 2 phases)	Vendor claims up to ~90% (HHV)*	Integrated w/ campus thermal loop
USA	Redox Power Systems – Redox Cube field trials	25 kW/unit (early-stage)	~50–60%	>80% in CHP mode
South Korea	Bloom Energy – Bundang, Hwaseong, Paju, KOMIPO, Chungcheong ecopark (incl. 80 MW single site)	>400 MW cumulative (SK ecoplant)	~52–53% (typical NG fleet)	Mostly power-only
South Korea	Doosan Fuel Cell (Ceres-licensed tech) – Jeollabuk-do	50 MW/yr mfg capacity; ~9 MW 1st order	>60% (platform spec)	>85% (platform spec)
Japan	ENE-FARM Type S – Kyocera/Aisin/Osaka Gas/Toyota (residential, nationwide)	0.7 kW/unit; >80,000 units cumulative	46.5% → 55% (2012→2020 models)	~87–90% total
Japan	Kyocera 3 kW institutional SOFC (schools, offices)	3 kW/unit	52%	90%
Japan	Mitsubishi Power SOFC–MGT hybrid demonstrator, Nagasaki (R&D)	229 kW (demo scale)	52.1% (2007 record)	Not CHP-focused
Italy	DEMOSOFC – Convion modules, SMAT wastewater plant, Turin	175 kW elec. / 90 kW thermal	53% (peaks to 56%)	100% site thermal + ~30% elec. need
Italy	SOLIDpower EnGen-2500 field trial, N. Italy	46 units deployed	Not published	Not published
Germany & wider EU	SOLIDpower / EnergyPlus BlueGEN (Germany, Benelux, UK)	1.5 kW/unit; >500 units (+2,650 via PACE)	60%	Up to 89% total
Germany, CH & EU	Hexis Galileo 1000N (12 European countries)	1 kW/unit; >250 units installed	35–40% (AC net)	~95% total
Germany	Bosch (Ceres tech) – Deutsche Telekom pilot, Berlin	2 × ~10 kW elec. / ~3 kW heat	60% (product spec)	>85% (product spec)
Germany	Sunfire – Callux field units & 50 kW marine demo (historical)	1.7 kW residential; 50 kW marine	~50%	~90%
Finland	Convion C60 – LEMENE smart micro-grid, Lempäälä	116 kW (2 × 58 kW units)	60% (best-in-class 50–300 kW)	Capable; not maximized here
China	Weichai Power (Ceres-licensed tech) – Weifang, Shandong	120 kW/unit, modular toward MW-scale	>60%	92.55% (record claim)
Taiwan	Bloom Energy – Unimicron plant (Phase 1)	10 MW	~52–53% (typical NG fleet)	Not confirmed
Taiwan	Ceres Power / Delta Electronics mfg. license (pre-deployment)	Production targeted 2026	>60% (platform spec)	>85% (platform spec)

Goal of the Work

- Development of a simulation model to evaluate **SOFC integration with biogas for CHP.**
- **Focus Areas**
 - Effect of CH_4 content in the biogas.
 - Thermal integration.
 - Sensitivity analysis for Steam/Carbon (S/C) ratios from 0.5 to 2.5.
- Provides practical insights for SOFC operations.

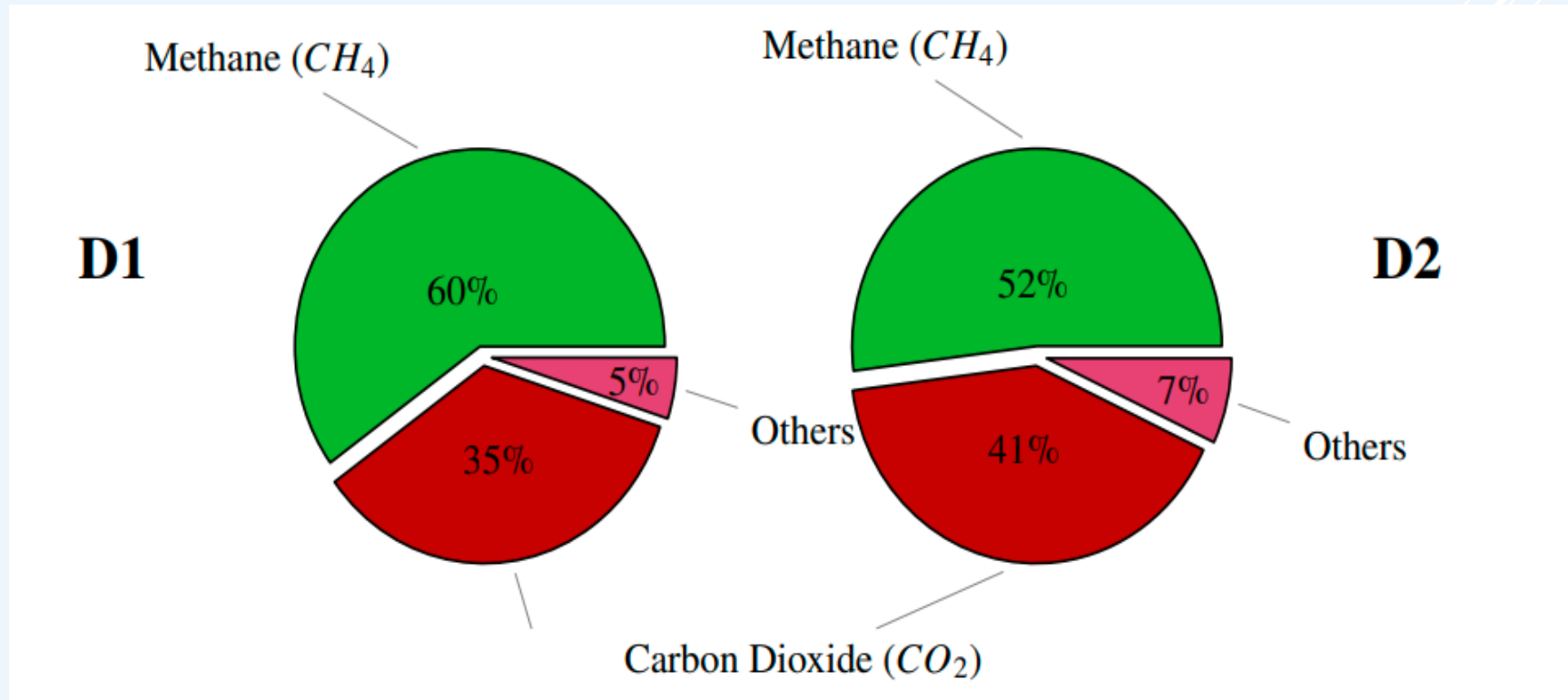
INGENIA Technology & Performance



- **Thermochemical Hydrolysis:** Strips ammonia and highly solubilises complex organic matter to optimise anaerobic digestion.
- **Zero-Emission Upgrading:** Captures CO₂ as calcium bicarbonate at atmospheric pressure, avoiding gas compression costs.
- **Process Efficiency:** Drastically reduces sludge viscosity and minimises required digester volumes.
- **Full-Scale Plant Case Study:** At a specific operating plant, feeding **Digester D1 (with INGENIA pretreatment)** and **Digester D2 (standard conditions)** in parallel with an exact 50/50 split allows for a direct performance evaluation. Under these identical conditions, **D1 delivers a >20% increase in methane production and boosts methane concentration from 54% to 65% and achieves a >50% reduction in total nitrogen (TN) in the digestate.**

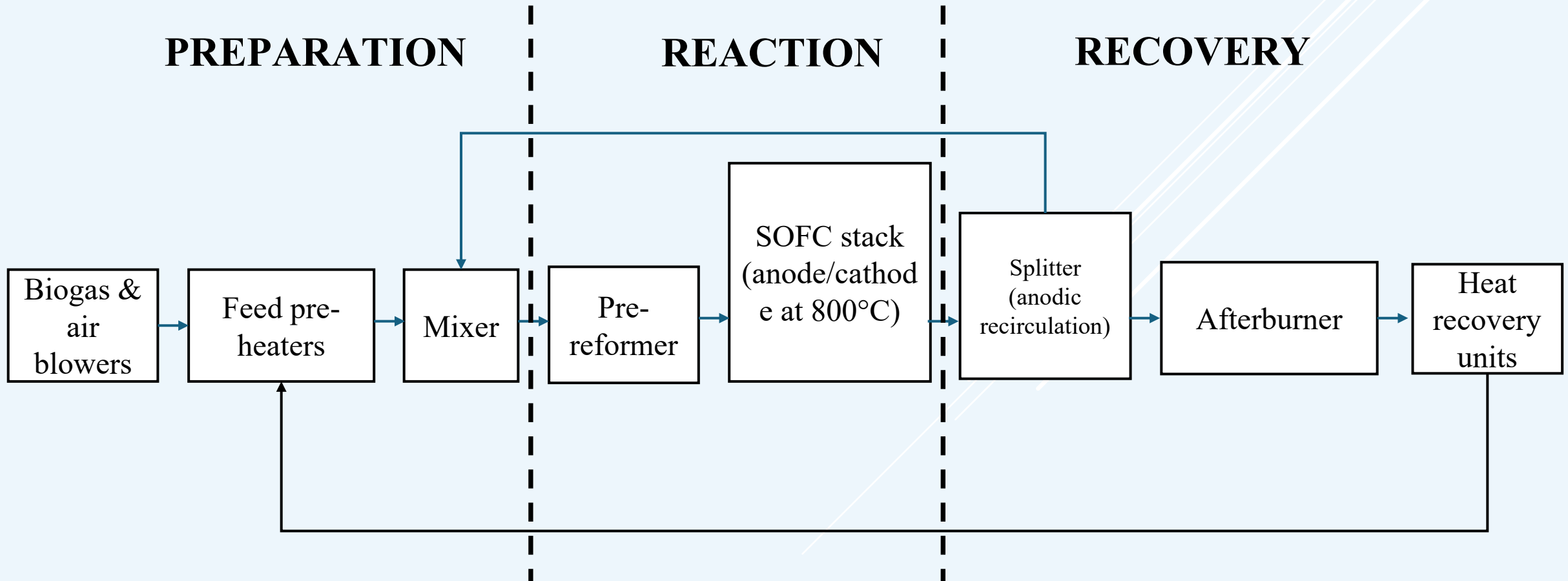
For energy conversion, considering fuel quality as a prerequisite

Patented
Upgrading
Technology,
Configuration
D1, optimized
Feedstock to
the anaerobic
digestion

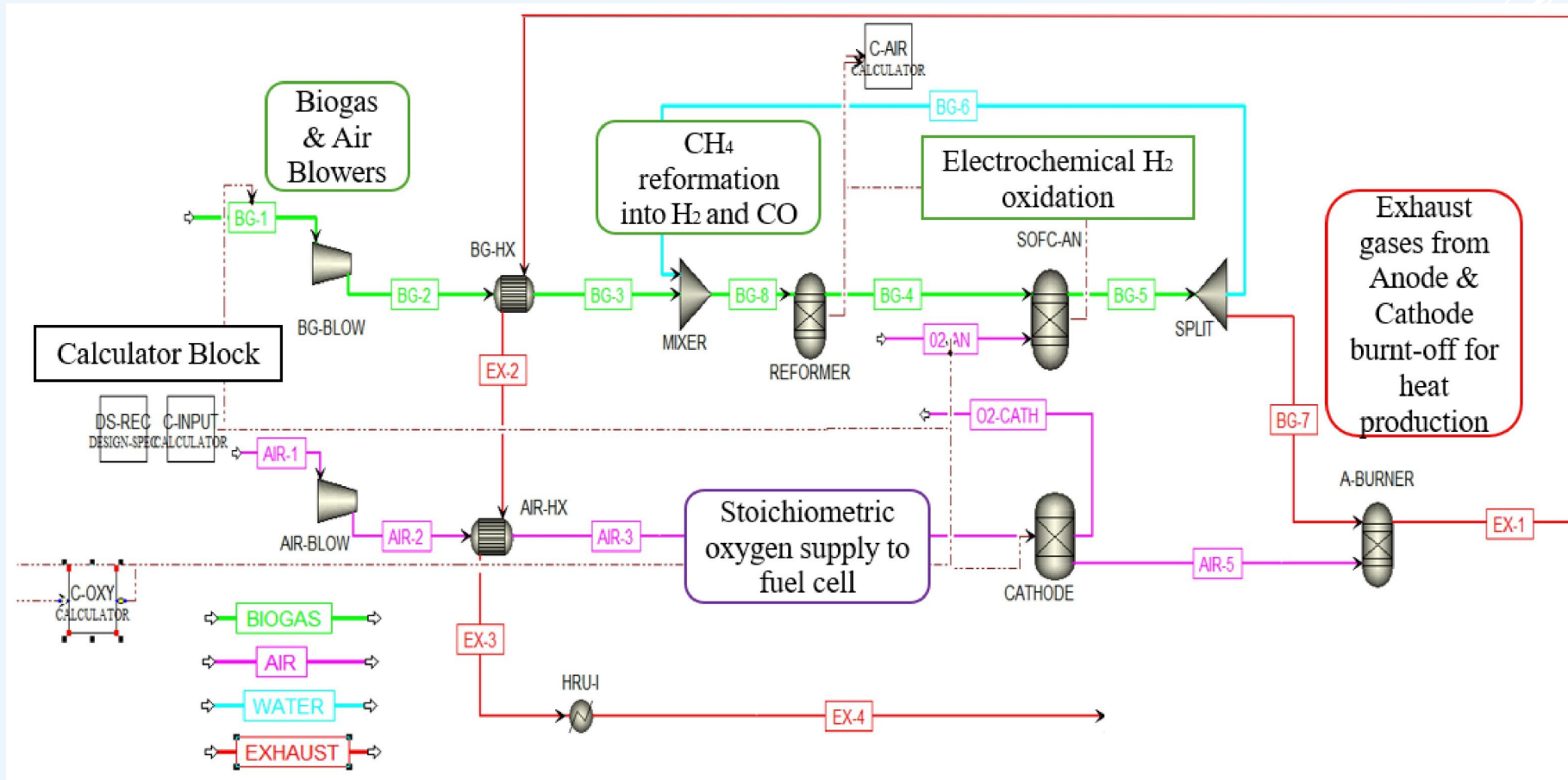


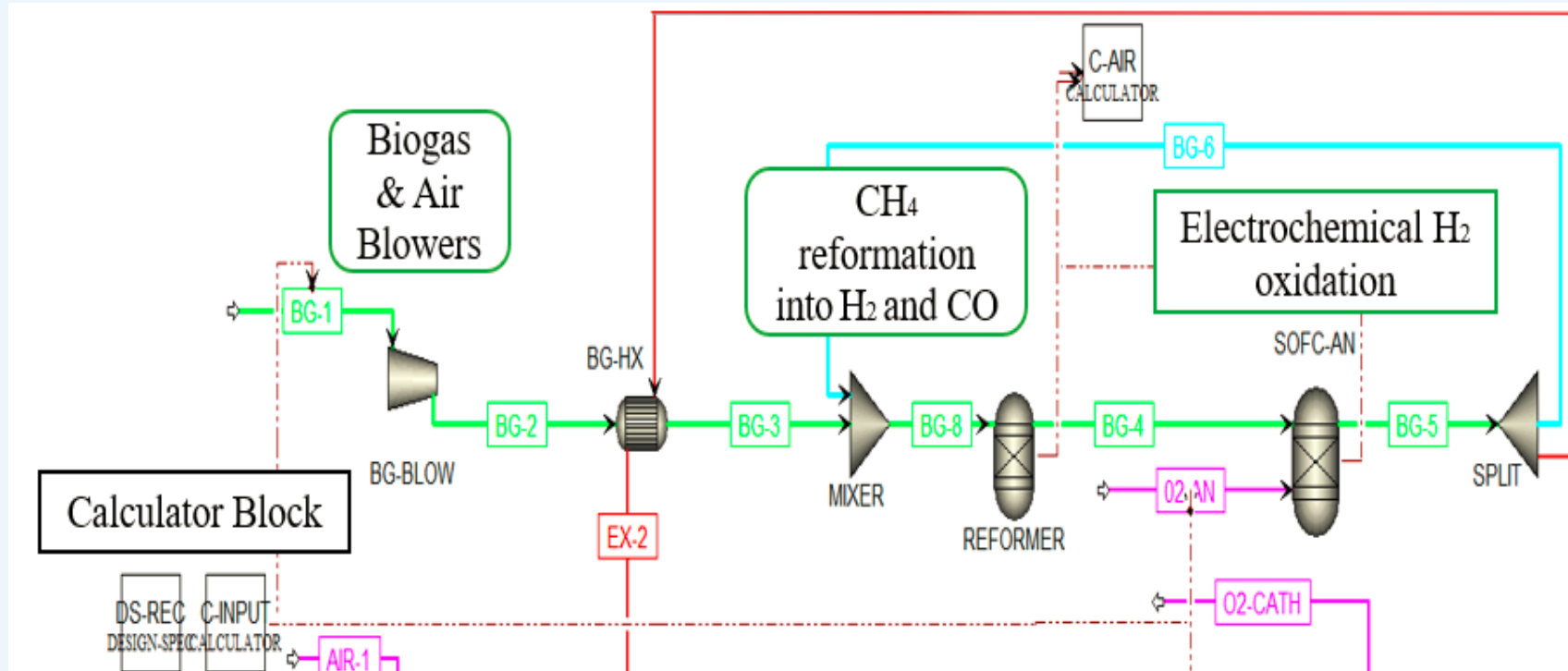
Conventional
feedstock,
configuration
D2, to the
anaerobic
digestion

Methodology of integrated three stage Aspen® model



Methodology – Overall Simulation Model

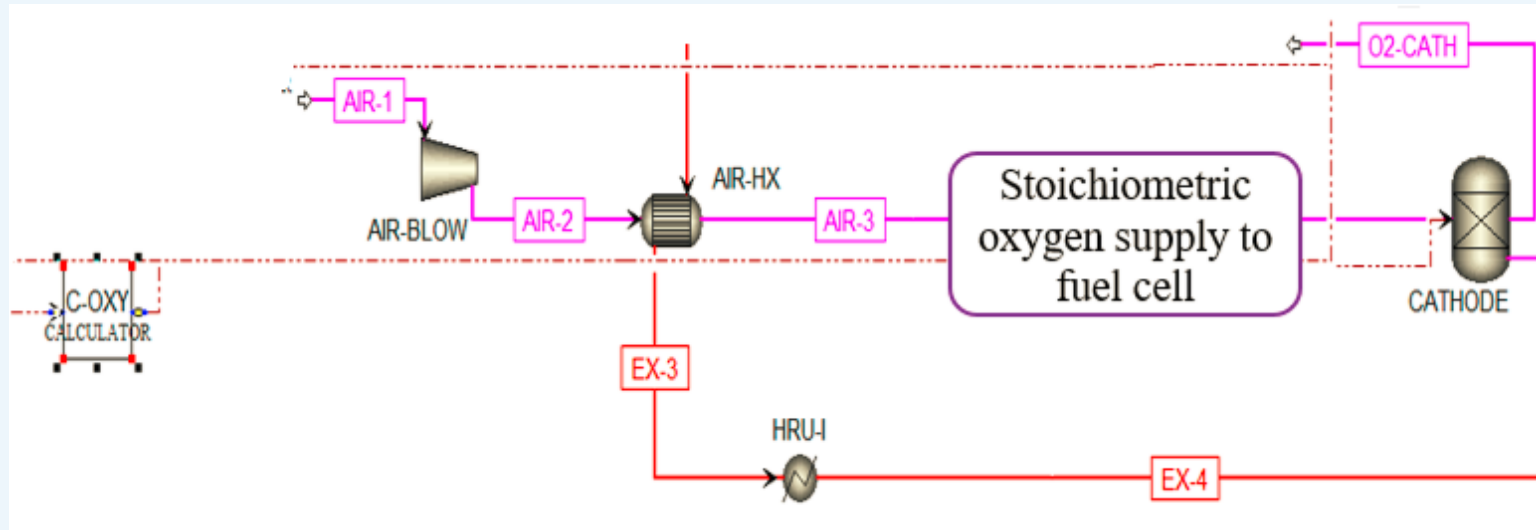




“SOFC-AN” Gibbs
Equilibrium Reactor
operating at **800°C** where
the electrochemical
oxidation of fuel occurs.

The use of RGibbs
throughout avoids hard-
coding reaction extents,
letting thermodynamic
equilibrium drive product
compositions at each
stage.

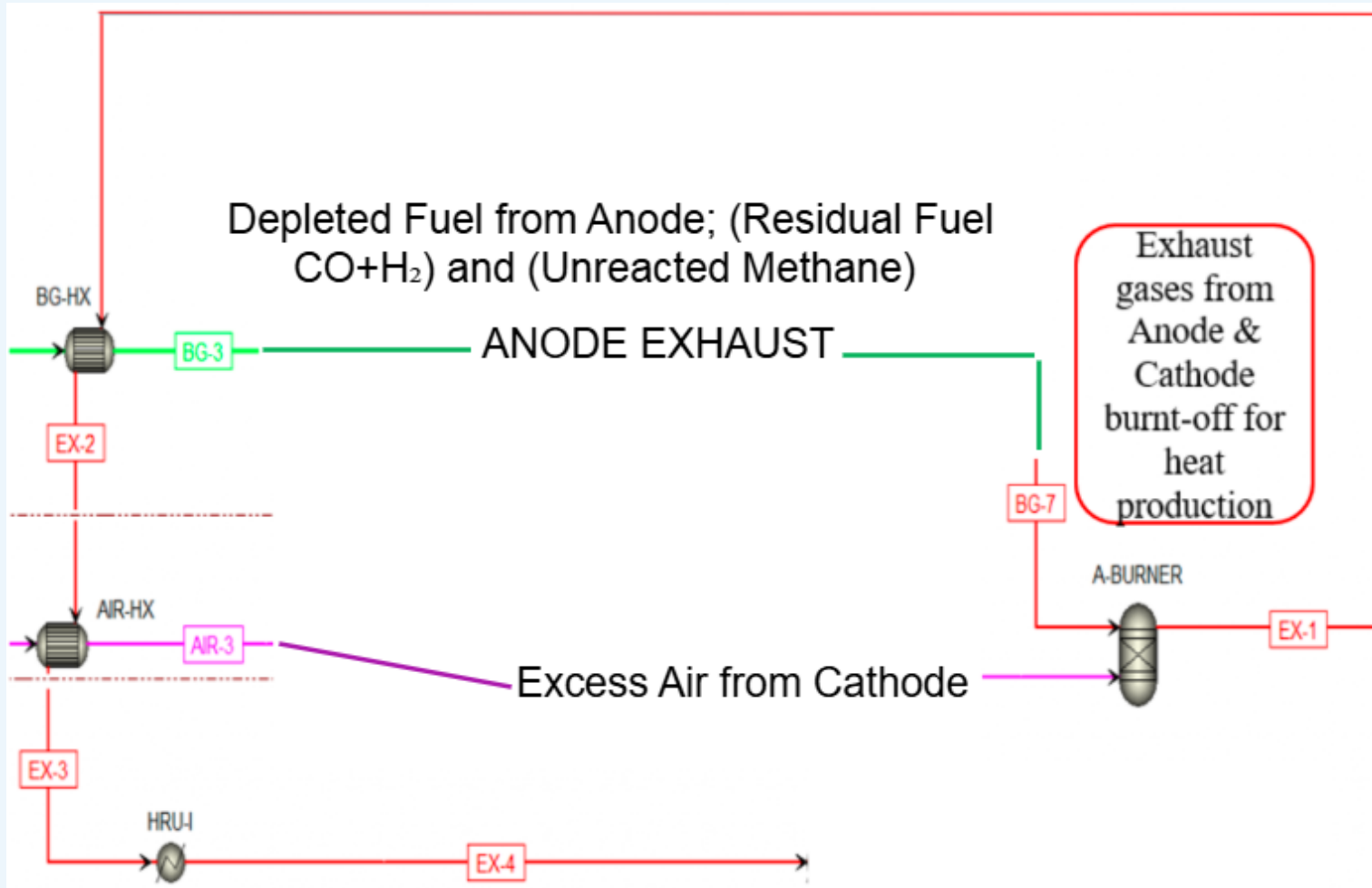
“REFORMER” (Gibbs Equilibrium Reactor): This component facilitates the endothermic conversion of CH_4 and H_2O into H_2 and CO . By minimising Gibbs free energy at 750°C , the reactor predicts the equilibrium composition of the synthesis gas entering the stack.



“C-OXY” - Oxygen Flow Synchroniser.

Passes the O_2 demand calculated by C-INPUT into the CATHODE separator block, ensuring the correct amount of O_2 is extracted from the air stream.

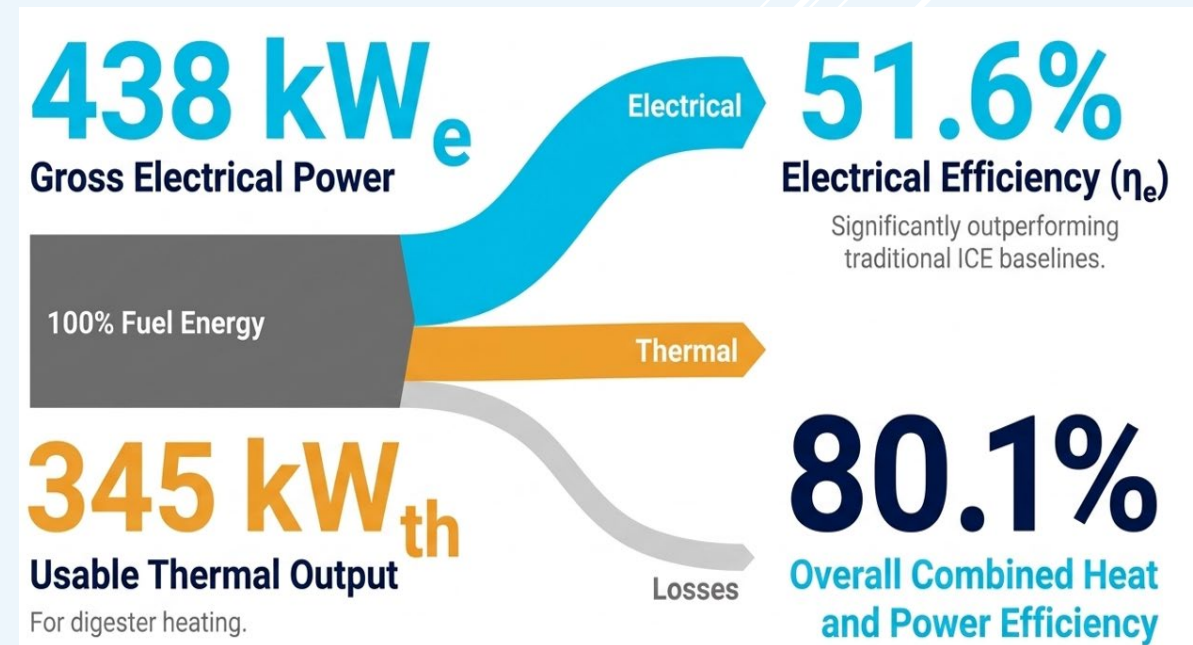
- Variables read: NO2AN (mole-flow of O_2 in stream 02-AN [mol/s]).
- Variables written: NO2CAT (FLOW/FRAC spec on CATHODE block, O2-CATH outlet, O_2 component [mol/s]).
- **Thermodynamic role:** this enforces stoichiometric oxygen balance between anode and cathode, which is the defining constraint of an SOFC: exactly the amount of O^{2-} transported through the electrolyte must be supplied by the cathode air stream. Without this synchronisation, the Gibbs minimisation in SOFC-AN would have an inconsistent O_2 supply.



- The adiabatic flame temperature is at complete equilibrium; products are primarily CO_2 , H_2O , N_2 , and any unreacted O_2 .
- Exhaust EX-1 is the hot stream driving both heat exchangers.

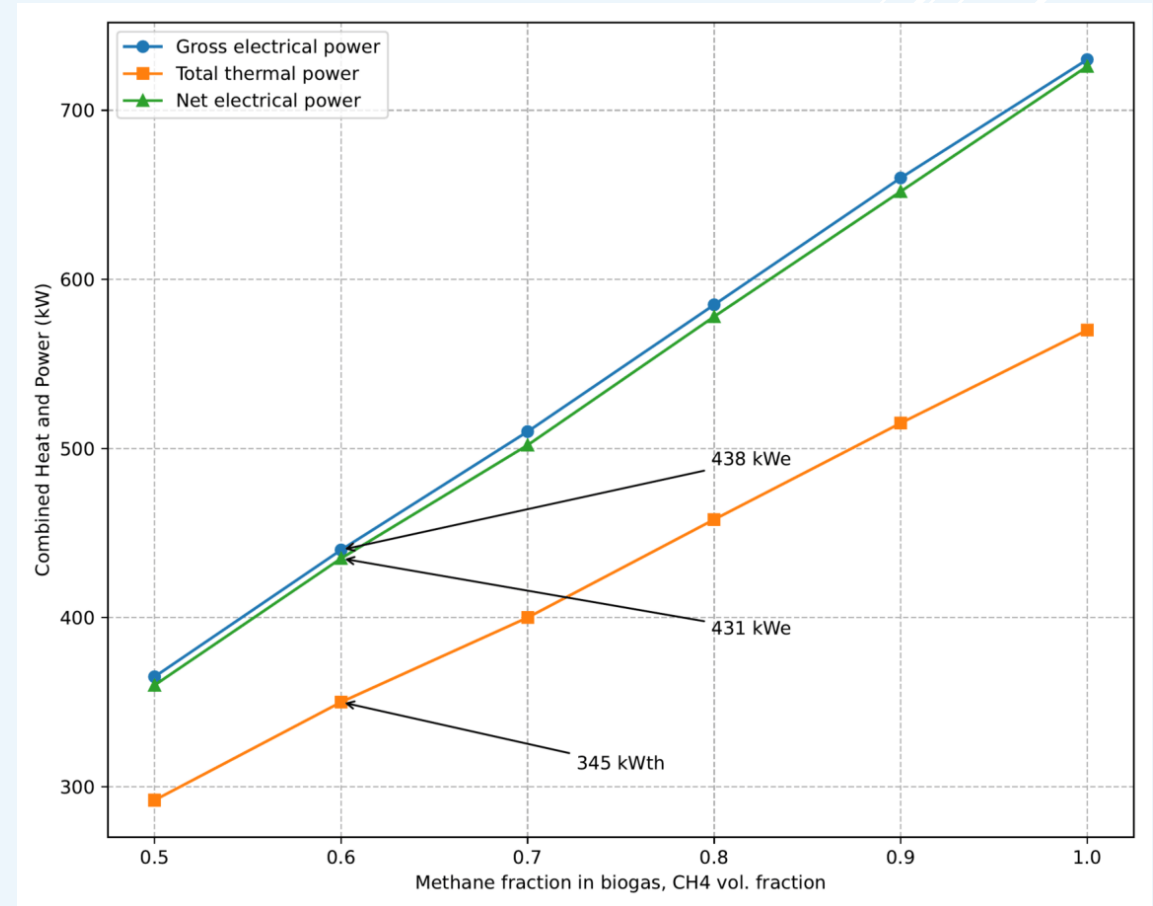
Results and Comments:

- This signifies that **over half of the chemical energy in the fuel is converted directly into electricity**. Hence, this performance **significantly outperforms traditional ICE baseline technologies**, which typically operate at lower electrical efficiencies.
- Captured heat is utilised to **heat the digester**, making it an ideal setup for biogas plants where maintaining digester temperature is critical.



Results and Comments:

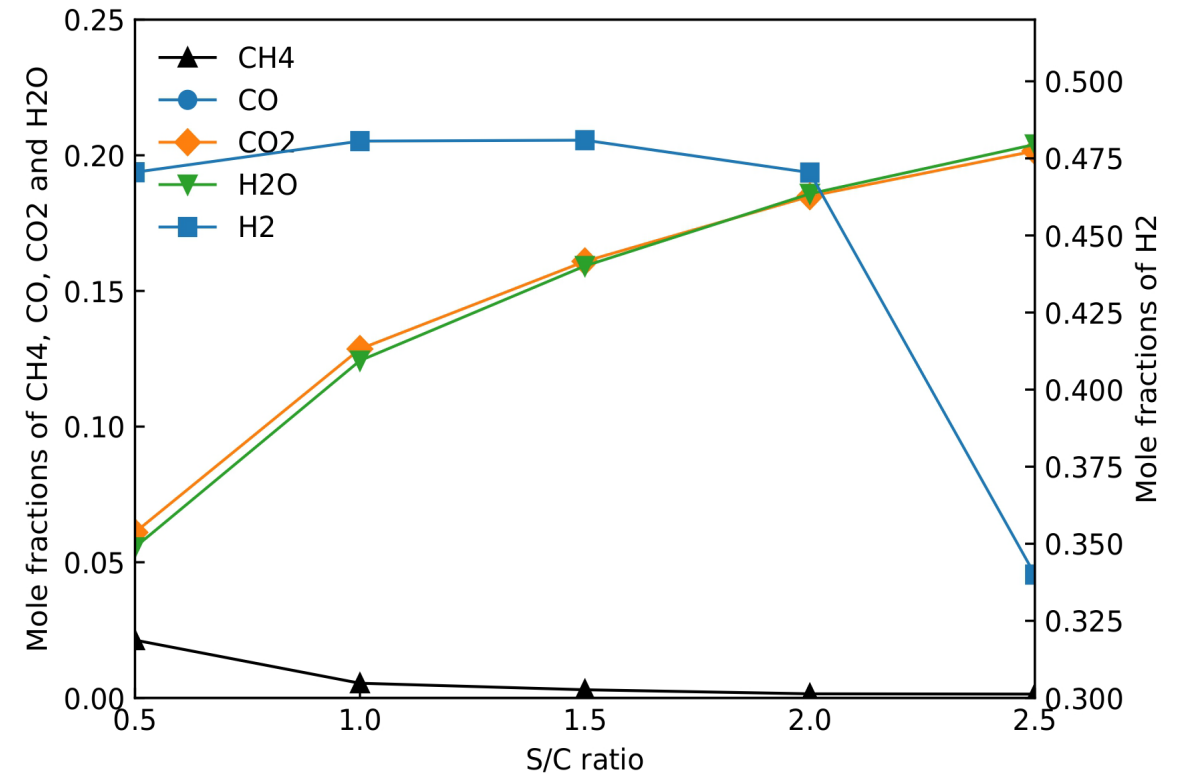
- The operating condition with 60% CH_4 content demonstrates the power generations. **Enhanced results can be drawn with higher CH_4 content in the biogas.**
- **Power values are derived under idealised modeling conditions** and should be interpreted with caution, as the simplifying assumptions inherent to the simulation such as steady-state operation, idealised heat integration, and fixed fuel utilisation.



Results and Comments:

Steam-to-Carbon (S/C) Ratios Evaluation

- Testing the S/C ratios from 0.5 to 2.5 confirmed that an **S/C ratio of 2.0 is the best value in terms of CH₄ conversion into H₂.**
- **Mechanism:** It maximises both **CH₄ conversion** and **H₂ production** at the pre-reformer outlet **without flooding the system or degrading downstream efficiency.**



Conclusions

- **SOFCs operate at elevated temperatures (650-900°C), enabling highly efficient conversion of H_2 into H_2O and CO_2 .**
- **SOFCs produce more electrical energy by efficiently converting chemical energy into electricity, without using any prime mover, through direct conversion of chemical energy into electricity.**
- **Higher $CH_4 \rightarrow$ better conversion into H_2 and higher voltage.**
- **Enhanced H_2 production & efficiency at 60% of CH_4 and more.**
- **Future work: Integration of electrochemical losses and kinetic models into numerical simulations and numerical model validation at CNH2 in Spain.**

Acknowledgements

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References

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CELL (SOFC): A NUMERICAL MODELING APPROACH**

THANK YOU FOR YOUR ATTENTION!

Q&A



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