Optimization of CO_2 feeding strategy for synthetic biogas upgrading in a three-cell electromethanogenesis stack

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Background

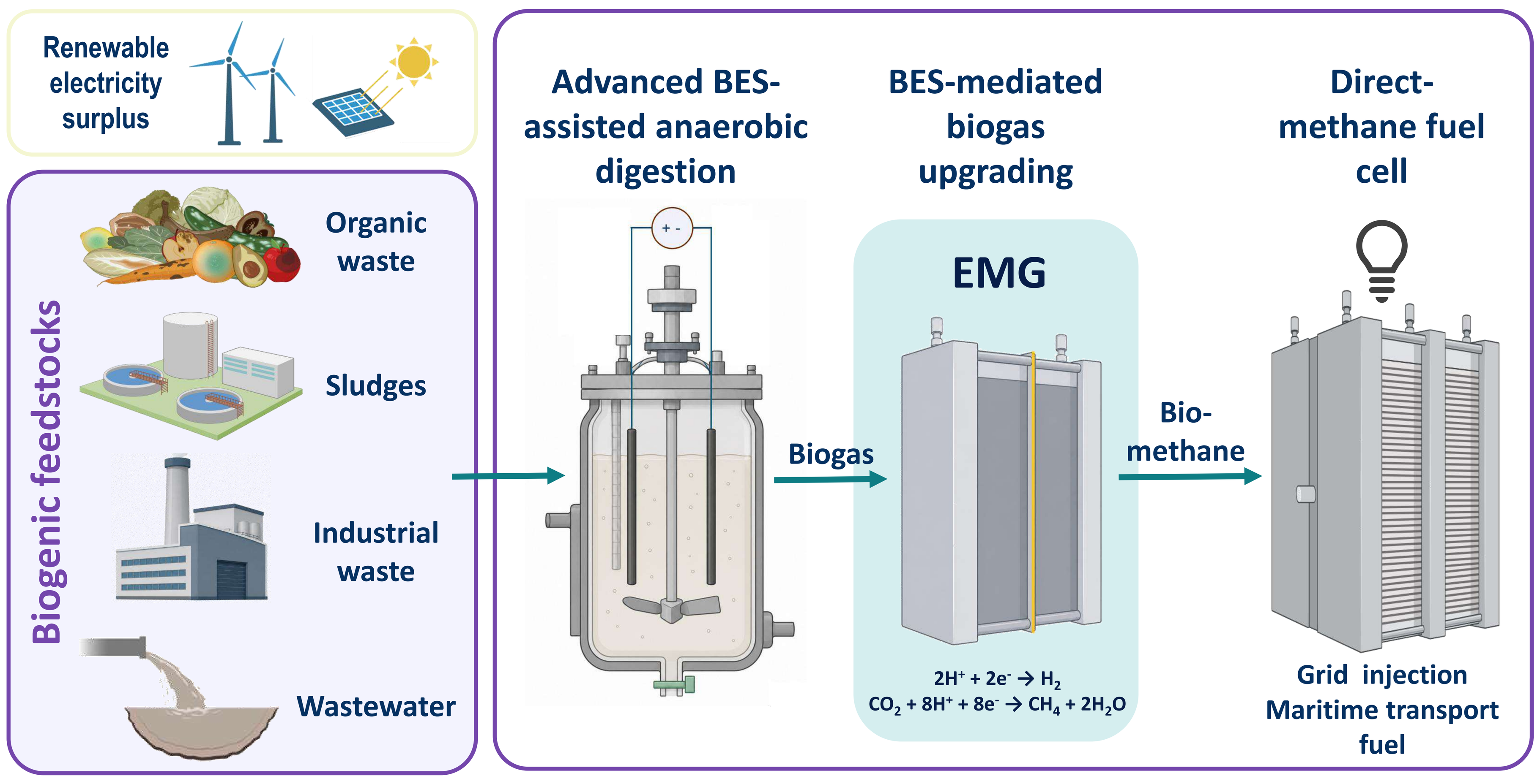


Figure 1: Maritime transport fuel production route for biomethane.

Research gap. Most **electromethanogenesis (EMG)** studies focus on:

- Electrodes materials
- Electrochemical conditions
- Cathodic microbial enrichment

However, **CO_2 feeding strategy remains poorly studied.**

Objective. To **optimize and progressively automate the CO_2 injection strategy into an EMG reactor** when no direct, continuous measurement of dissolved CO_2 is available.

System optimization is therefore based exclusively on methane production rate and gas composition measurements.

Technical KPIs of Fuels-C

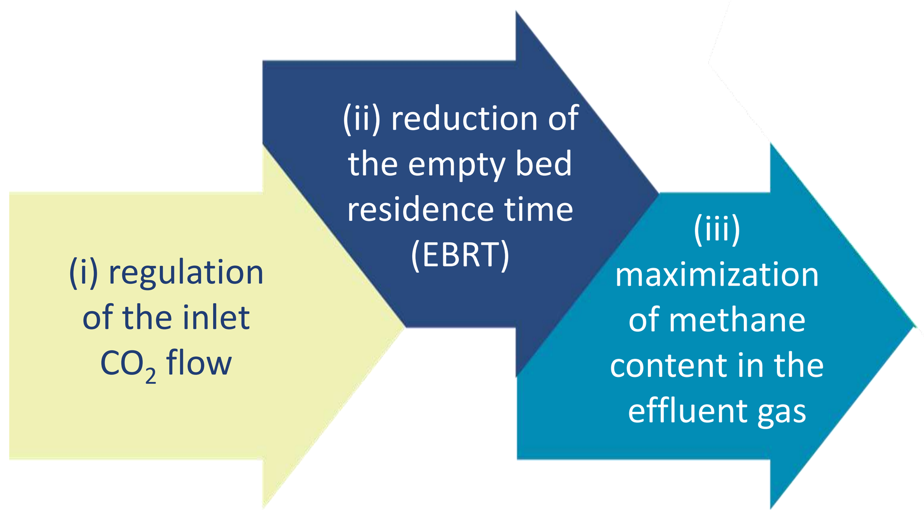
- ➢ Biogas upgrading to biomethane (>95% CH_4)
- ➢ Specific energy consumption 0.2 kW Nm^{-3} biogas
- ➢ CO_2 conversion efficiency of 95%
- ➢ Production rate of 2 L CH_4 L_{cat}^{-1} d^{-1}
- ➢ Cathodic Coulombic efficiency >90%

Materials & Methods

- **Bioanode** of stainless-steel wool (total specific surface; 255 cm^2) → organic matter oxidation at a poised potential of -0.100 V vs Ag/AgCl.
- **Biocathode** of stainless-steel wool (total specific surface; 255 cm^2) → **reduction of CO_2 to CH_4**, operating at 35°C and 200 mbarg.

CO_2 feeding	Flow	EBRT
Manual pulses	2 mL min^{-1} (on demand)	Not determined
Continuous	2 mL min^{-1}	1 h
Automated pulses	0.2 mL min^{-1}	14 d

Optimization of CO_2 strategy. Pure CO_2 was supplied (manual, continuous or automated pulses) and the operating conditions were adjusted following a stepwise approach:



Once the optimal operating point was achieved, an **upgrading biogas test** with a **synthetic biogas mixture** was performed and evaluated.

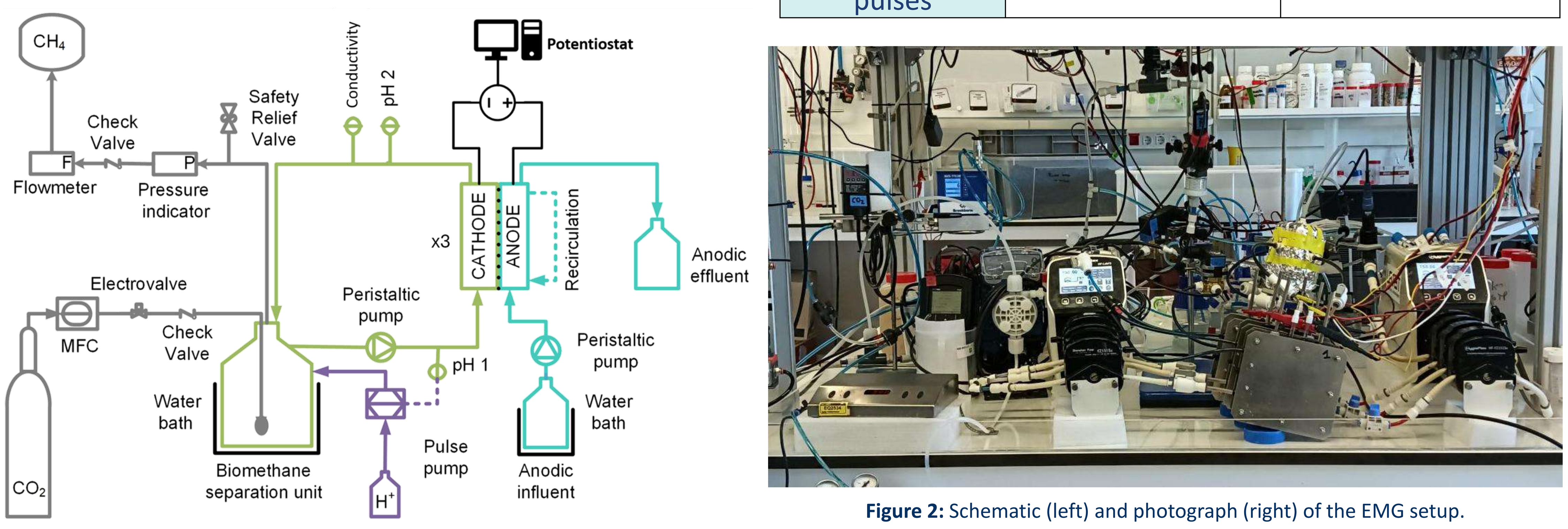


Figure 2: Schematic (left) and photograph (right) of the EMG setup.

Results & Discussion

Optimization of CO_2 feeding

Automated flow (low and semi-continuous feeding) enhanced gas quality without compromising any performance parameters.

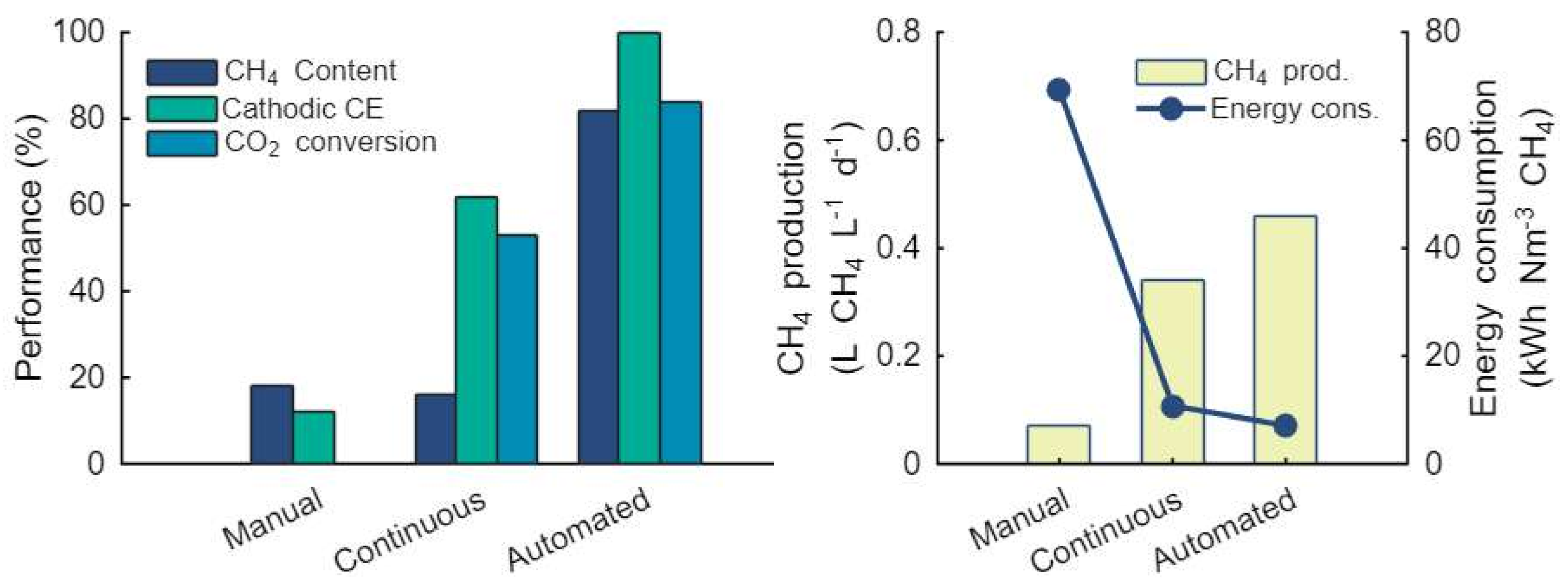


Figure 3: Performance comparison of the CO_2 optimization conditions tested: Manual, Continuous and Automated. CO_2 conversion efficiency could not be determined for the Manual pulses feeding.

Synthetic biogas upgrading

The EMG stack effectively converted residual CO_2 and upgraded methane quality from a synthetic biogas mixture.

Technology	TRL	CH_4 Content (%)	Specific Energy Consumption (kWh Nm^{-3} biogas)	CO_2 valorisation
Electromethanogenesis	4-5	87-90	1.3-6 (influenced by the bioanode)	✓
Biological Methanation	6-8	95-99	4.5-5.5	✓
Water Scrubbing	9	95-98	0.25-0.30	✗
Pressure Swing Adsorption	9	96-99	0.25-0.35	✗
Membrane Separation	8-9	90-99	0.18-0.35	✗

Cathodic biofilm characterization

Microbial community

Taxonomic composition analysis, based on 16S rRNA gene sequencing, revealed a **highly significant difference** in Shannon diversity between **bulk** and **cathode biofilm** samples.

The bulk community was dominated by *Methanobacterium* (~50%) and *Propionicimonas* (~35%), whereas electrode-associated biofilms were consistently enriched in *Mesotoga* (>80%).

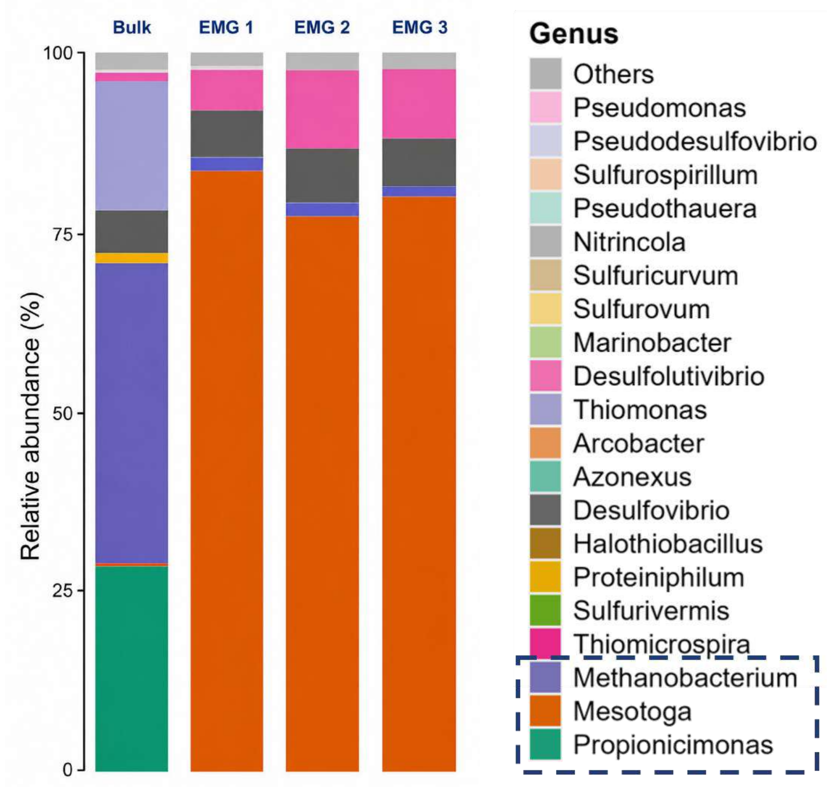


Figure 4: Relative abundance (%) of the microbial community in the three EMG cells.

Conclusions

- → **CO_2 feeding strategy** is a critical operational parameter in **EMG**.
- → **Semi-continuous low-flow CO_2 injection** improved **biomethane quality**.
- → The **3-cell EMG stack** were able to **upgrade synthetic biogas**.
- → The results highlight the **potential of optimized CO_2 feeding strategies** for **biomethane upgrading** applications and support further validation under **real biogas conditions**.
- → The transition from **pure CO_2** to **synthetic biogas** operation revealed the need for a deeper understanding of **microbial responses, including microbial community shifts** and **methanogenic-related functional genes**.

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