High Rate Biomethanation Delivered by Mixed Microbial Cultures: Pathways and Performance

AERIOGEN® Technology

AD Network Research Colloquium - Beyond Biogas
25th January 2019, University of Manchester

Prof. Sandra Esteves
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Wales Centre of Excellence for Anaerobic Digestion

• Established in 2008 with financial support from WG and ERDF
• Expand knowledge and expertise for a rapid and successful deployment of anaerobic technologies
• The Centre acts as a process development platform and delivers:
  – Industrial focus R&D
  – feasibility studies; feedstock and digestate analysis
  – system monitoring, diagnostics and optimisation
  – analytical method development
  – development of new of improved processes and products
  – regulatory and policy development support
  – awareness raising and training events
  – Engaged with over 150 companies

www.walesadcentre.org.uk
USW Team’s Expertise & Facilities

- Team has decades of experience in bioreactors design, integration, monitoring and control
- Novel process development in the lab (1-100 l), pilot (200 l -30 m³) and full scale experience (50-7000 m³)
- Pure and mixed culture reactor facility
- C1 Gas fermenters
C1 Gases Fermentation Lab
Facilities
USW Team’s Expertise & Facilities

- Expertise in bioreactors, biochemistry, biotechnology, microbiology, engineering, monitoring, modelling and control, economic and environmental appraisals
- 450 m² lab space, 13 labs, an extensive suite of analytical equipment - headspace GC/FID, ion chromatography, ICP-AES, CHNSO, TOC, TKN analysers, GC/TCD, GC/FPD, GC/MS/MS, SEM, NMR, SFE, GC-MIS, on-line FT-NIR, rheometer, zeta potential analyser, particle sizer, Ion Torrent Sequencer, RT-PCR and DGGE
- ADM1 model, AI tools, LCA software/databases and CFD software
Storage of Renewable Electricity

- Batteries – expensive, not environ. friendly & short life
- Pumped hydro & underground compressed air storage are limited by geographical factors
- Super capacitors, superconducting coils & flywheels – short discharge period – suitable only as emergency UPS units

Discharge time (h)
- Batteries <10 hrs
- Pumped hydro 10-600 hrs
- Synthetic methane 1 – 10,000 hrs

Storage Capacity
- Batteries 1 kWh - 60 MWh
- Pumped hydro 100 MWh - 60 GWh
- Synthetic methane 60 GWh – 30 TWh

- Power to green gas
  - Sabbatier conversion using metal catalysts – expensive, high temp requirement, low selectivity, low yields and deactivation
  - Biomethanation – low cost, low temp., high throughput & conversion efficiency and resistant to contaminants

(Source: Specht et al. 2009)
Variable Output Renewable Electricity

Demand > Supply

Export to Grid

Power to Gas PEM Electrolyser (H₂)

Industrial gases Industrial Processes (H₂, CO, CO₂)

Biological Process e.g. AD (CO₂)

Biomethanation

Gas Grid Injection/Storage

Fuel/Chemical End Use
AERIOGEN® Technology

- Increased productivity of RE assets
- Increase deployment of RE generation
- Reduce elec. grid constraints
- Grid scale energy storage
- Integration of elec. & gas grids
- Decarbonise gas grid
- Decarbonise domestic, industrial heat and transport fuel sectors
- Energy, chemical and food security
- Valorise industrial CO₂ emissions

Integration of power to gas in the energy infrastructure (DENA, 2015)
Unlocking new potential with R&D

<table>
<thead>
<tr>
<th>Feedstock type</th>
<th>TWh useable energy (after 10% parasitic)</th>
<th>Useable energy after R&amp;D (after 10% parasitic)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household food waste</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>C&amp;I food waste</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Farm animal wastes and bedding</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Crops</td>
<td>12</td>
<td>17</td>
</tr>
<tr>
<td>Sewage sludge</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Other potential sources</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Nature conservation managed</td>
<td>0.4</td>
<td></td>
</tr>
<tr>
<td>Straw</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Uncontaminated organic street sweepings (e.g. leaves) and park waste (e.g. grass cuttings and leaves). Pretreatment, dry AD.</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Household garden waste (e.g. grass cuttings and leaves). Pretreatment, dry AD.</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Orchard waste (e.g. apple pomace)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>AD integrated into greenhouse horticulture with waste heat, CO2 use</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Glycerol - dependant on biodiesel industry</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Fish processing waste - conventional sources</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>Higher value food production integration such as hydroponics, aquaponics and aquaculture (overlap with greenhouses)</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Microalgae (e.g. using nutrients from sewage sludge, digestate etc. and waste heat, co2 and water from AD plants). Also potential to use excess grid electricity.</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Macroalgae (e.g. seaweed etc.)</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Power-to-gas via hydrogen with AD</td>
<td>31.8</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>35.4</strong></td>
<td><strong>95.3</strong></td>
</tr>
<tr>
<td>Domestic gas demand</td>
<td>300</td>
<td>270</td>
</tr>
<tr>
<td>Percent of domestic gas demand</td>
<td><strong>12%</strong></td>
<td><strong>35%</strong></td>
</tr>
</tbody>
</table>

ADBA 2025 "high" potential scenario
AERIOGEN® Technology
Potential Integrations

Current distribution of energy generation in the UK (sources of CO₂ can be identified for coal, gas and biomass energy generation sites; renewable energy sites are also indicated)

AD infrastructure (outside Water sector); CO₂ is available at all these locations and can easily be used, in the BtG (biomethane to grid) plants in green colour the CO₂ has already been separated and is ready to use (Source: AD portal biogas map, March, 2017)
Biomethanation
P2M & Biogas Upgrading

Electrolysis

\[ e^- \rightarrow O_2 \rightarrow CO_2 \rightarrow CH_4 \]

Thermal & Aerobic Processes

Intermittent Renewable Energies

AERIOGEN®

Anaerobic Digestion

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Existing Commercial Technologies for Biogas Upgrading vs. Biomethanation

- PSA
- Water scrubbing
- Organic scrubbing
- Amine scrubbing
- Membrane separation

Biogas → 60% CH₄ → PSA → 40% CO₂ → >99% CH₄

Biomethanation AERIOGEN®
AERIOGEN®
(P2G & Biogas Upgrading)

- **High conversion efficiencies** for lab scale >99% CH₄ at a throughput of >300 vvd
- **Stable pH** by controlling the CO₂ – H₂CO₃ buffering system
- **Nutrient quasi closed system.** Syntrophic relation between hydrogenotrophic species and bacterial background responsible for biomass recycling
- **Dewatering system** under optimisation with sporadic top-up of certain elements and reduced dilution of biomass
- **Fast recovery** after long fasting periods / Fast recovery after oxygenation
- **Potential for zero methane slip**
- **Improvements in reactor design** eliminates the need of intense mixing, reducing energy input while increasing gas throughputs
High Rate Gas Transfer Reactors

Savvas et al., 2017a, 2017b

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Liquid Recirculation Reactor Design

Recovery after 45 days of fasting

Closed nutrient recycling via microbial catabolism in an eco-engineered self-regenerating mixed anaerobic microbiome for hydrogenotrophic methanogenesis

Savvas Savvas \textsuperscript{a,b,*}, Joanne Donnelly \textsuperscript{a,b}, Tim Patterson \textsuperscript{a,b}, Richard Dinsdale \textsuperscript{b}, Sandra R. Esteves \textsuperscript{a,b}

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HIGHLIGHTS
- A methanisation biocatalyst was observed to be capable of self-regeneration.
- Self-regeneration was accomplished by creating a closed nutrient ecosystem.
- pH of the media was controlled solely by the amount of CO₂ entering the reactor.

GRAPHICAL ABSTRACT
Input gases control allow >99% quality output and help maintain appropriate pH

Savvas et al. (2017)
Temperature and Support Media Evaluations

Methanogenic capacity and robustness of hydrogenotrophic cultures based on closed nutrient recycling via microbial catabolism: Impact of temperature and microbial attachment

Savvas Savvaid, Joanne Donnelly, Tim Patterson, Zyh Siong Chong, Sandra R. Estover

Abstract

A biological methanation system based on nutrient recycling via mixed culture microbial catabolism was investigated at mesophilic (37 °C) and thermophilic (55 °C) temperatures. At mesophilic temperatures, the formation of biofilms on two different types of material was assessed. Results showed that the system using the biofilm reactors presented methanogenic capacities (per working volume) 50% higher than the ones operated with suspended cultures. Gas production rates of 200 L dm⁻³ were achieved at a H₂/CO₂ ratio of 0.8. Conversion efficiency of above 90% by linking two reactors in series. Furthermore, the robustness of the cultures was assessed under a series of inhibitory conditions that simulated possible process interferences at full scale operation. Full recovery after separate intense oxygenation and long starvation periods was observed within 2–5 days.

Oxygenation

% Recovery after 2 days
Homoacetogenesis Pathway in Suspended Anaerobic Mixed Cultures

Reactor 1 – mesophilic temperature
Reactor 2 – thermophilic temperature

45 days starvation

Savvas et al., 2018
Integration of Power to Methane in a waste water treatment plant – A feasibility study

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\textbf{ABSTRACT}

The integration of a biomethanation system within a wastewater treatment plant for conversion of CO\textsubscript{2} and H\textsubscript{2} to CH\textsubscript{4} has been studied. Results indicate that the CO\textsubscript{2} could be utilized to produce an additional 13,420 m\textsuperscript{3}/day of CH\textsubscript{4}, equivalent to approximately 133,825 kWh of energy. The whole conversion process including electrolysis was found to have an energetic efficiency of 68.2%. The energy output of the biomethanation system of the process had a parasitic load of 19.9% of produced energy and strategies to reduce this to < 5% are identified. The system could provide strategic benefits such as integrated management of electricity and gas networks, energy storage and maximising the deployment and efficiency of renewable energy assets. However, no policy or financial frameworks exist to attribute value to these increasingly important functions.
Biofilm Based Reactor Design

Plug flow of gases and liquid through a tube replaces intense agitation
Power-to-Green Methane Feasibility to Scale Up

- Feasibility study: Production of ‘synthetic methane’ using biological methanation and electrolytic hydrogen
- CO₂ sourced from existing biogas to biomethane upgrade facility operating at waste water treatment plant
- H₂ from rapid-response PEM electrolysis providing grid-balancing services
- Biomethanation process AERIOGEN®
- Funded by Innovate UK (3 months in 2015)
- Project partners:
AERIOGEN® Technology Development

IUK / BBSRC Industrial Biotechnology Catalyst Jan 2016 – March 2017

Feasibility of an Innovative reactor for enhanced C1 gas bioconversion for energy production and storage

Evaluate potential for improvement of gas / liquid transfer in novel reactor

• Production of green methane

• Production of carboxylic acids
Flexible Methane Production to Meet Demand

• Points of entry to the gas grid are limited by capacity on a daily basis as well as due to seasons
  – summer up to 1/1000 of that in winter
  – AD plants not being able to connect to the gas grid

• Current configurations of AD/biomethane plants:
  – are not flexible in terms of gas output
  – have long conversion periods and cannot vary output suddenly
  – lead to a mismatch between supply/demand
Flexible Methane Production

Current
Fairly Constant Output
Supporting base load

Future
Variable Output to Meet Gas Needs
(Daily/Seasonal)

- Daily and seasonal production to match demand
- AD Plant(s) as the only gas supplier(s) or part of a gas supply mix
- Production and supply of methane from organics and inorganic gases
- Production based on predictive gas demand refined with gas grid feedback control <1 hr response
Production of high chain alkane gases (C2-C4) from anaerobic biological processes

- Production of C2-C4 bioalkanes gases for adjusting methane gas quality for natural gas grid injection (Wobbe index and CV)
- Reducing propane costs, additional installations and site footprint and even avoid planning refusal
- Reduce the H&S requirements and risks associated with large propane gas storage on sites by having production match demand
- Increase the gaseous stream sustainability by utilizing renewably produced alkane gases C2-C4, which would help further with the decarbonisation of the gas grid
SMART CIRCLE: Technical Research and Development Areas

- Biomethanation / CO₂ Utilisation
- Heat Recovery
- Nutrient / Metals recovery
- Advanced Process Monitoring
- High Value molecule recovery

Utilisation of CO₂ and Industrial Gases (WP2)
Design & Optimise Industrial Bio Processes (WP3)
Value Molecules & heat from Industrial Residues, Waste and BioProcesses (WP4)

Impact Assessment

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BioGrid Project Overview

Start: April 2018     End: Sept 2020

The project is seeking to improve the commercial viability of the USW Biomethanation process by:

1. Increasing gas throughput, therefore minimising process footprint, capital costs and process economics
2. Lowering parasitic energy demand of the biomethanation process
3. Moving from TRL3 (Laboratory Proof of Concept) to TRL6 (Prototype demonstration)
4. Demonstrating production of organic acids as chemical feedstock / energy storage medium as an alternative to the direct production of methane
5. Engaging with industry and making relevant R&D approaches to facilitate process integration at full scale

Project part Funded by:

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Methane Conversions

Plus Methanotrophs!! To Multiple Products
Polyhydroxyalkanoates

- PHAs are polyesters that can be produced from organic molecules, CH₄, CO₂/CO and H₂
- PHA can accumulate as granules within bacterial cell cytoplasm (excess carbon + nutrient deficiency)
- Low, medium and long chain PHAs (brittle, foam, rubber) over 150 types
- Useful properties
  - UV stable, high melting point, low permeation of water and good barrier properties
- Good prospects for biodegradability!!
- PHAs are high value biopolymers (~£4/kg) with growing uses in the medical, packaging, furniture, chemical, textile and aquaculture food production
Animal Feed: Single Cell Protein from CH$_4$

- Sales of protein between US$1300-2500/tonne
- Values of 0.8 kg of protein / kg of CH$_4$

![Diagram of Calysta's Natural Proprietary Fermentation Process](image-url)
Acknowledgments

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