WINTER SCHOOL | 2nd EDITION

Carbon capture, utilization and storage

CO_2 and syngas utilization for bioenergy and biochemicals

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Matosinhos, 15 Oct 2025

Renewables Energy Directive RED III (UE 2023/2413)

- ❑ **Advanced Biofuels** – means biofuels that are produced from the feedstock listed in part A of Annex IX

- ❑ **Biogas** – means gaseous fuels produced form biomass

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syngas

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- **Renewable liquid and gaseous transport fuels of non-biological origin** – means liquid or gaseous fuels which are used in the transport sector other than biofuels or biogas, the energy content of which is derived from renewable sources other than biomass

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Biogenic CO2 (+green H2)

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Biogenic CO_2 (+green H_2)

❑ **Recyclable carbon fuels** - means liquid and gaseous fuels that are produced from liquid or solid waste streams of non- renewable origin which are not suitable for material recovery in accordance with Article 4 of Directive 2008/98/EC, or from waste processing gas and exhaust gas of non-renewable origin which are produced as an unavoidable and unintentional consequence of the production process in industrial installations

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flue CO2 (+green H2)

Main value chains for biochemical/thermochemical utilization of CO2, CO, H2 gases

Value Chain	Maturity
Biomass → Anaerobic Digestion + Biological Methanation → bioCH4	TRL 5-8
CO2/CO streams + Fermentation + HEFA → e-SAF **CO2/CO streams + Fermentation + ATJ → e-SAF**	TRL 5-8
Biomass → Gasification → syngas → FT + Hydrocracking → bioSAF/e-SAF	TRL 5-8
CO2/CO streams + H2 → e-MeOH	TRL 5-8
CO2/CO streams + H2 → syngas → FT → e-fuels	TRL 5-8

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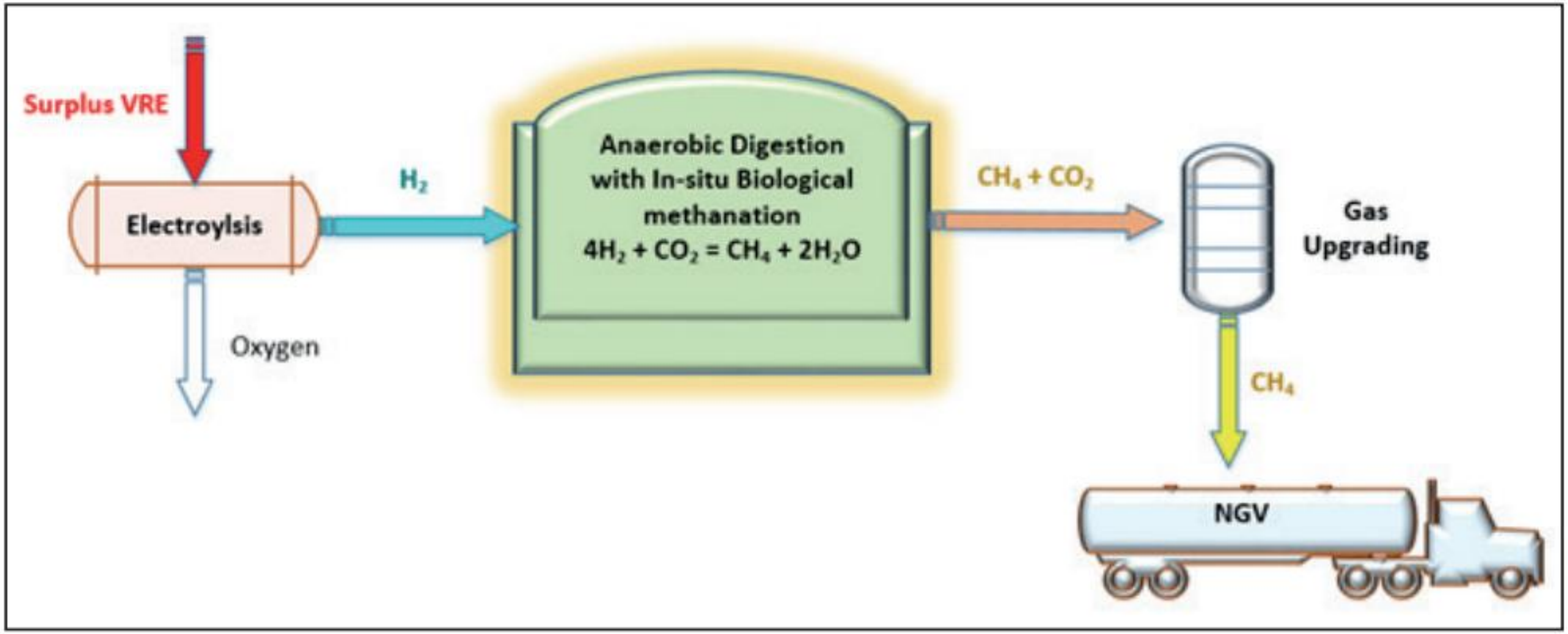
Anaerobic Digestion + Biological Methanation → bioCH4

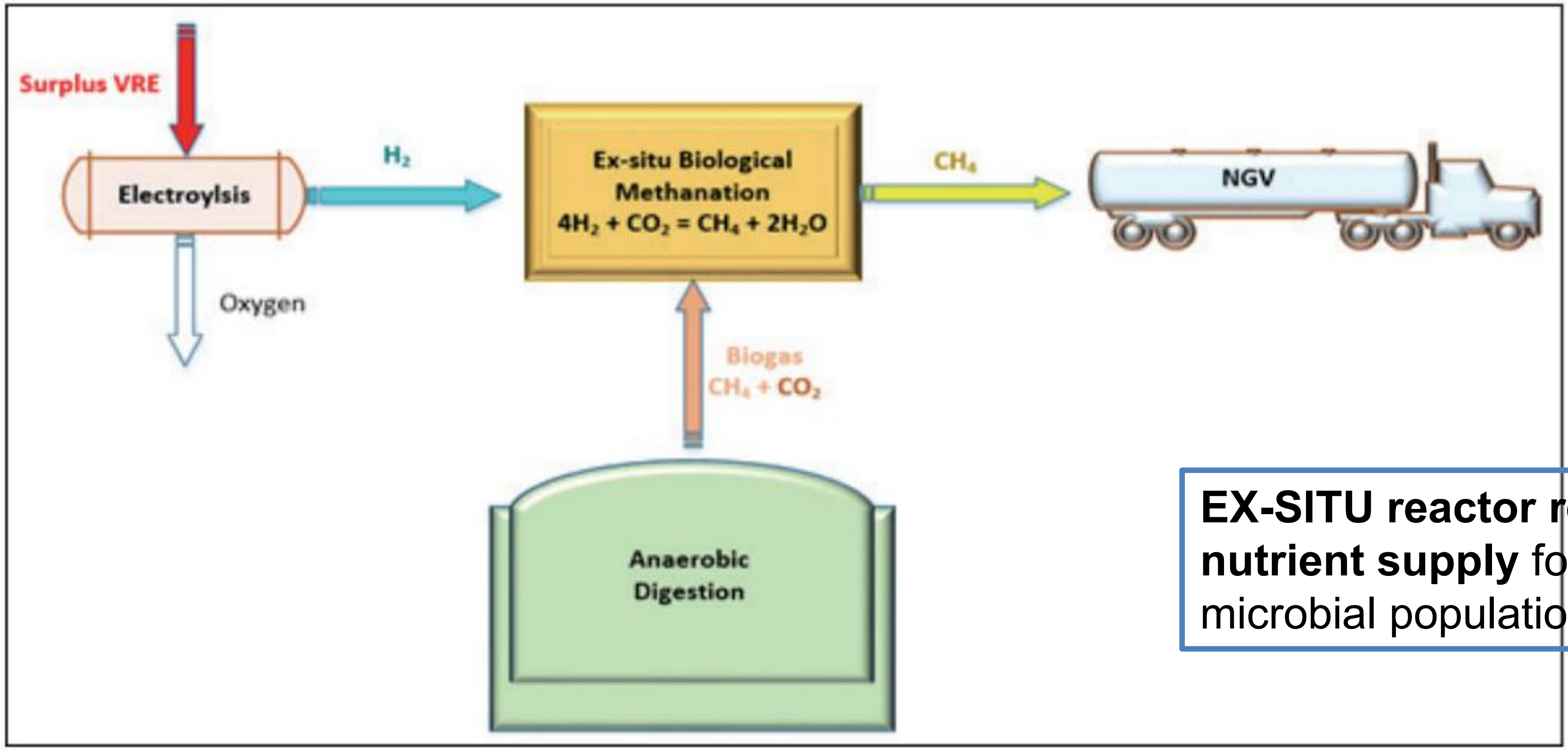
Green H2 is directly added to the AD to increase the methane production (**IN-SITU Biological Methanation**)



In: IEA Bioenergy Task 37 (2020)

Anaerobic Digestion + Biological Methanation → bioCH4

Green H2 and Carbon Dioxide (from biogas) are added to an external biomethanation reactor which can be located adjacent to the biogas system (**EX-SITU Biological Methanation**)



EX-SITU reactor requires nutrient supply for the microbial population to thrive..

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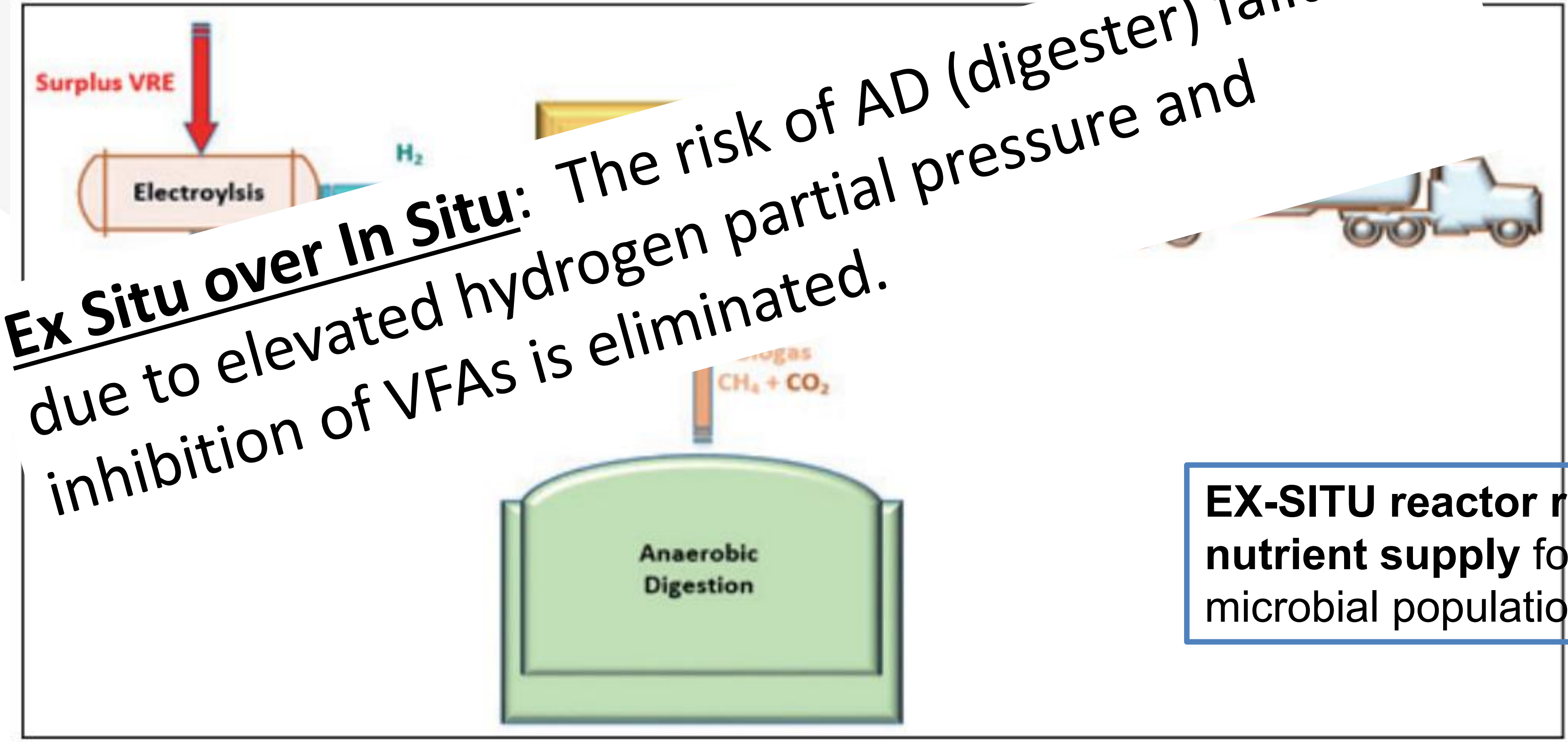
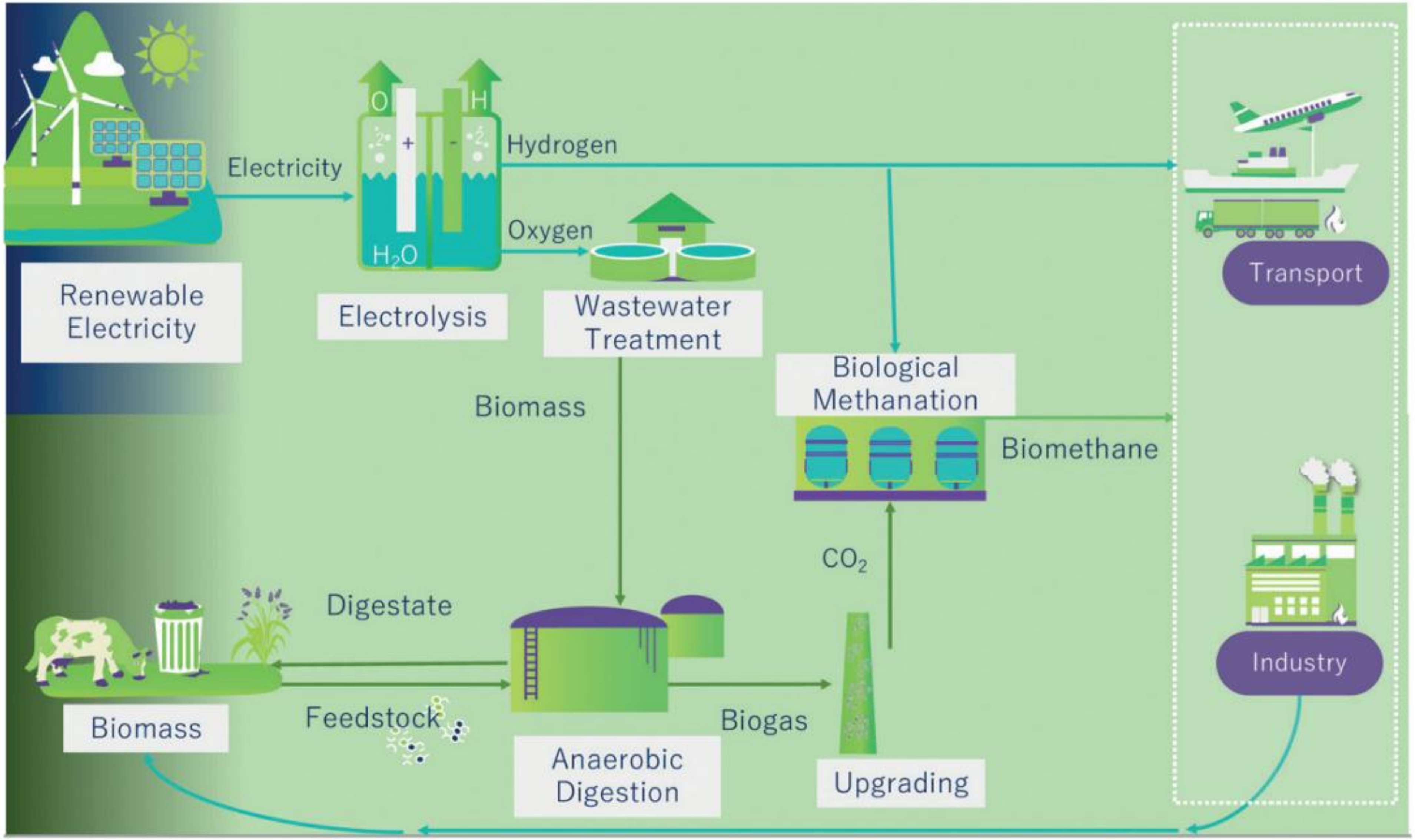


Ex Situ over In Situ: The risk of AD (digester) failure due to elevated hydrogen partial pressure and inhibition of VFAs is eliminated.

EX-SITU reactor requires nutrient supply for the microbial population to thrive..

In: IEA Bioenergy Task 37 (2020)

Integrated Biorefinery for bioSAF/e-SAF



Source: IEA Bioenergy: Task 37 (2021)

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CO2/CO streams + H2 → syngas → FT → e-fuels	TRL 5-8

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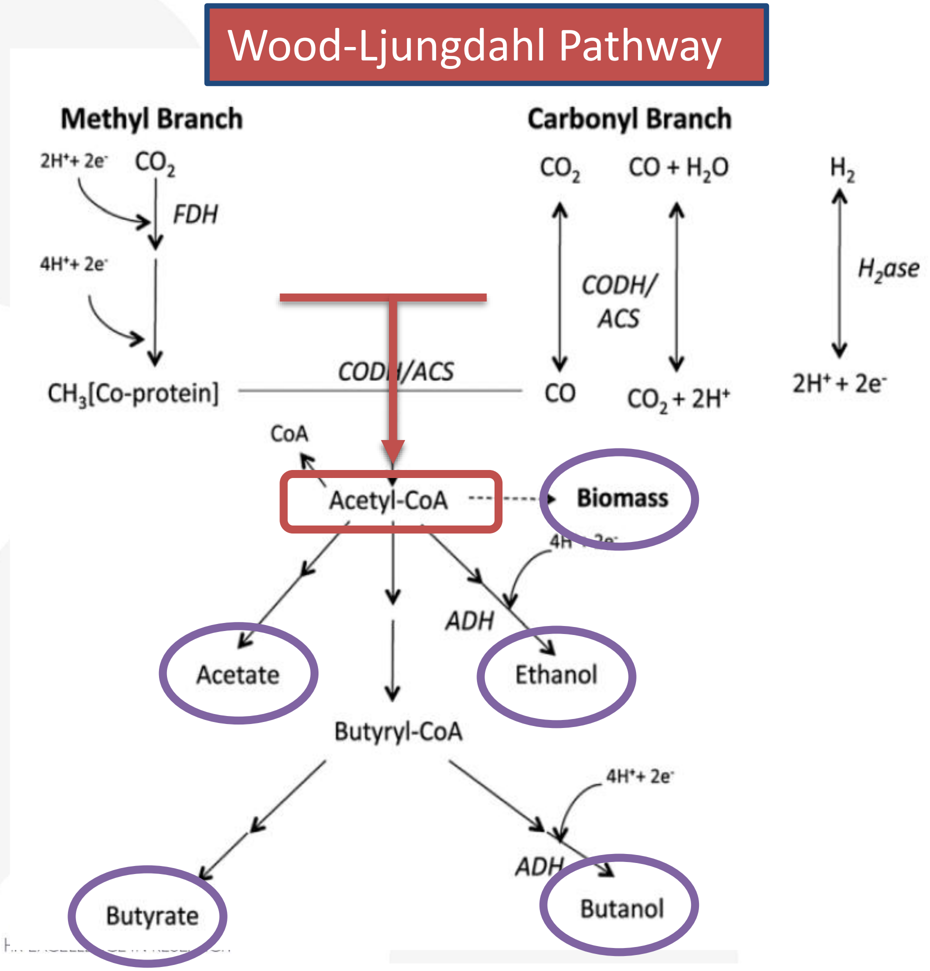
CO_2/CO + H2 streams + Fermentation + HEFA → SAF
Or CO_2/CO + H2 streams + Fermentation + ATJ → SAF

- Biological conversion of CO, CO_2 and H_2:



Adapted Ukpong *et al.* 2012 *(Biotechnol. Bioeng., 109, pp. 2721)*

- Carboxydotrophic acetogens are microorganisms that can reduce carbon monoxide (CO) and/or carbon dioxide (CO_2) using hydrogen (H_2) as energy source via the Wood-Ljungdahl pathway.

- Acetyl-CoA can then be used for the synthesis of cell carbon or can serve as intermediate to produce acids and alcohols, *e.g.,* acetate, ethanol, butyrate, butanol.

Syngas fermentation: Fundaments

- ❑Thermochemical transformation of recalcitrant carbon sources into syngas (*Gasification, Pyrolysis, Hydrothermal Liquefaction*)
- ❑Flue gases rich in CO, CO_2 and H_2
  - Examples: steel and cement industrial off-gases
- ❑Biological process
- ❑Fixation of gaseous carbon into liquid products and biomass
- ❑Contributes for carbon circularity
- ❑Produces substitutes for fossil-based chemicals

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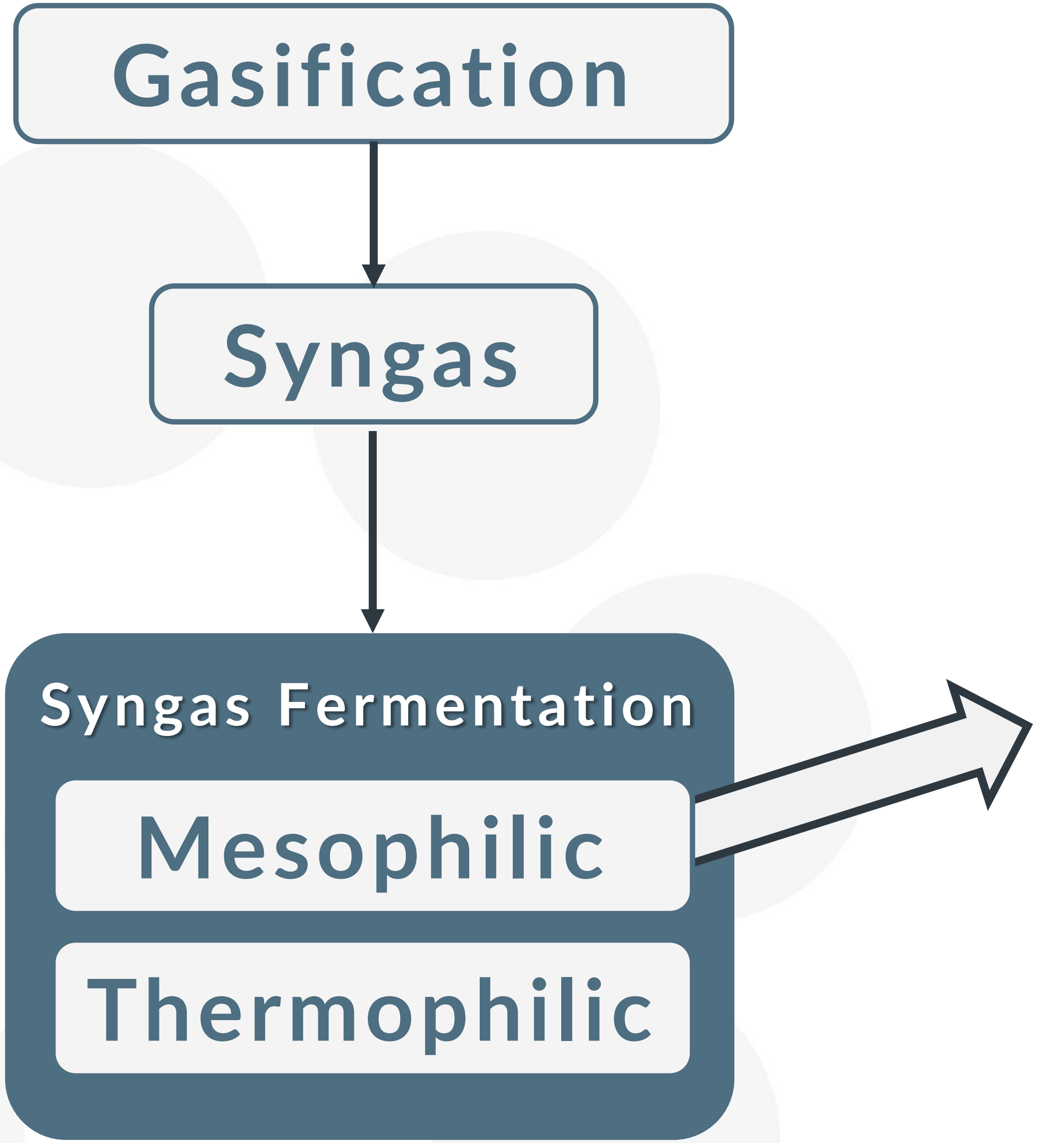
Syngas fermentation



Gasification

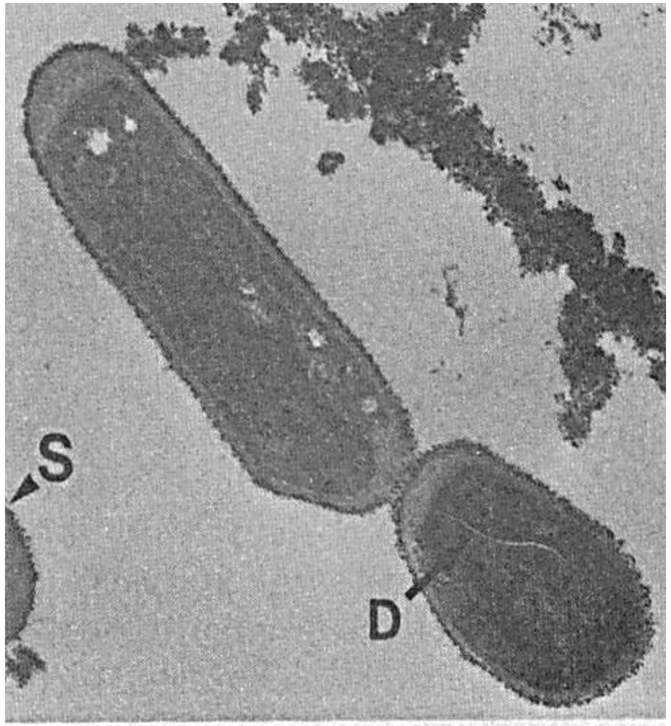
Syngas

Syngas Fermentation

Mesophilic

Thermophilic

Butyribacterium methylotrophicum (BBM)



Adapted from Lowe et al. 1993 (DOI: 10.1128/MMBR.57.2.451-509.1993)

- Gram-positive, non-motile, sporulating bacteria.
- Uses single carbon compounds, such as CO, CO_2 and methanol, as carbon and energy sources
- Main fermentation product:
  - **Butyric acid**
- But also produces:
  - **Acetic acid**
  - **Ethanol**

Source: Pacheco, Silva and Moura (2024), Biotechniques, July.

Influence of Syngas composition on Final Products

	CO	CO_2	H_2	N_2	H_2/CO	$CO:CO_2:H_2$
Commercial Syngas I	30	20	30	20	1.0	1:0.7:1
Commercial Syngas II	26	19	18	37	0.7	1:0.7:0.7

In: Pinto, F., et al. 2019. https://doi.org/10.3303/CET1976234

$$4CO + 2H_2O \rightarrow CH_3COOH + 2CO_2$$

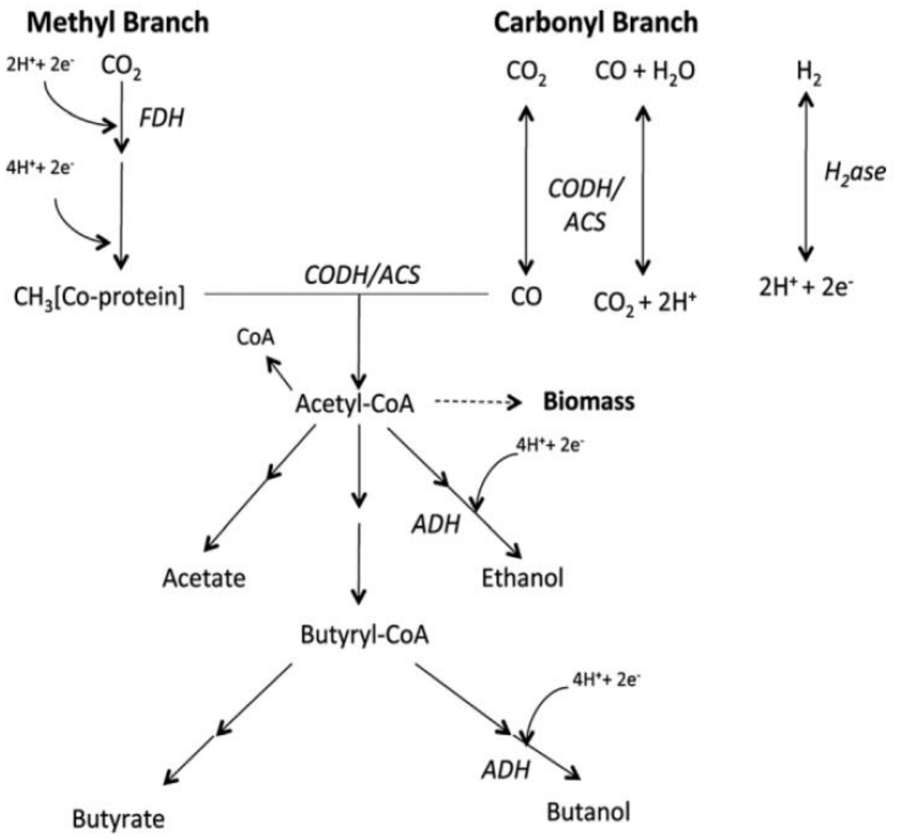
$$2CO_2 + 4H_2 \rightarrow CH_3COOH + 2H_2O$$

Product: Acetate

$$6CO + 3H_2O \rightarrow C_2H_5OH + 4CO_2$$

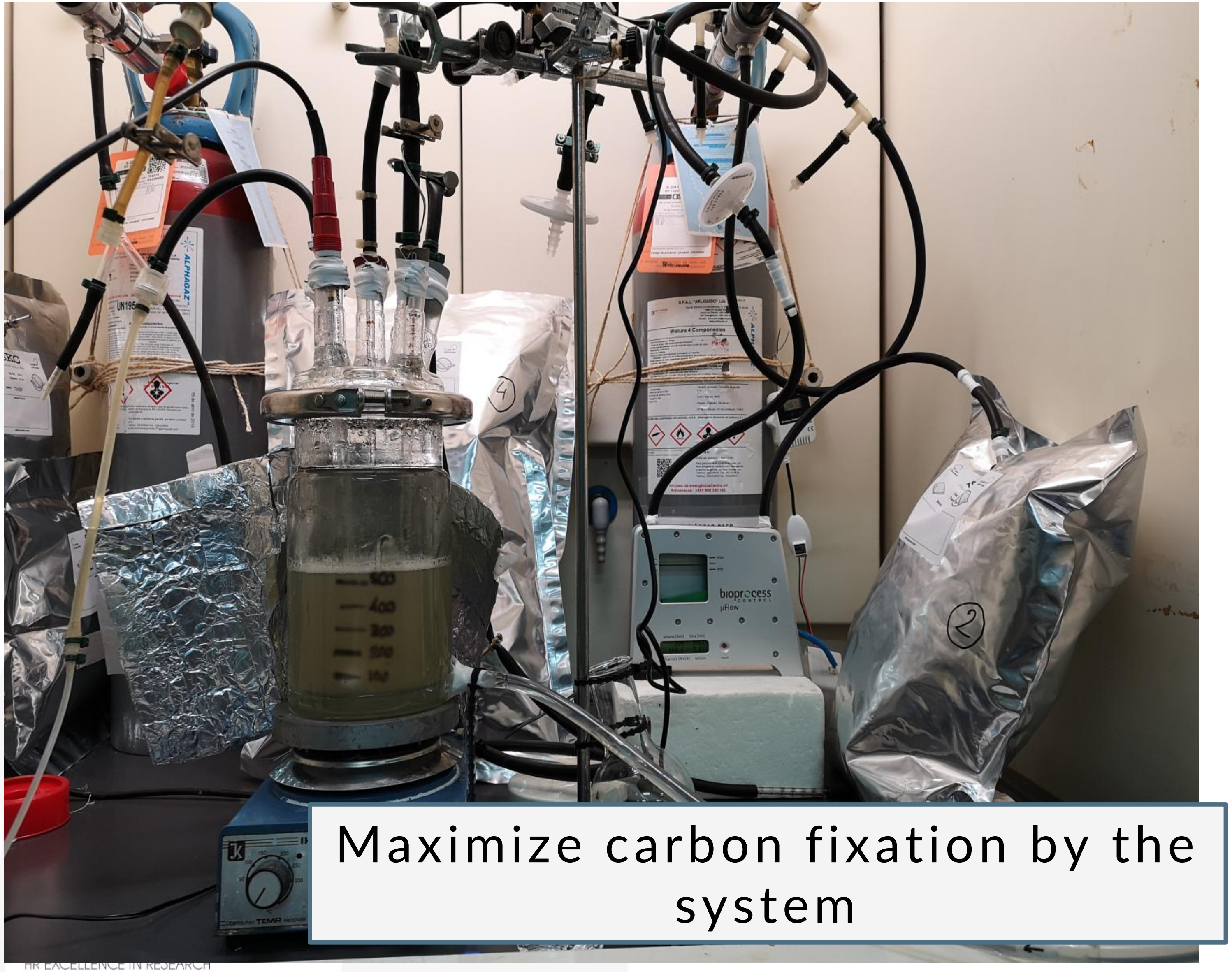
$$2CO_2 + 6H_2 \rightarrow C_2H_5OH + 3H_2O$$

Product: Ethanol



Adapted Ukpong *et al*. 2012 *(Biotechnol. Bioeng., 109, pp. 2721)*

Syngas fermentation (on-demand)



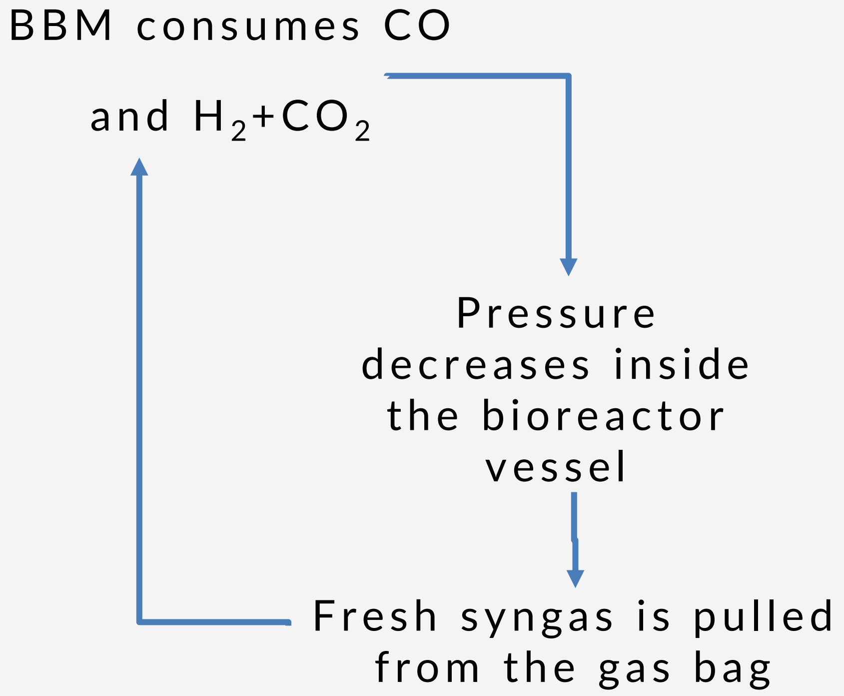
Maximize carbon fixation by the system

Source: Pacheco, Silva and Moura (2024), Biotechniques, July.

Syngas composition:

29%vol. CO, 31%vol. H_2, 23%vol. CO_2, 16%vol. CH_4

Syngas feeding mode:



BBM consumes CO and H_2+CO_2

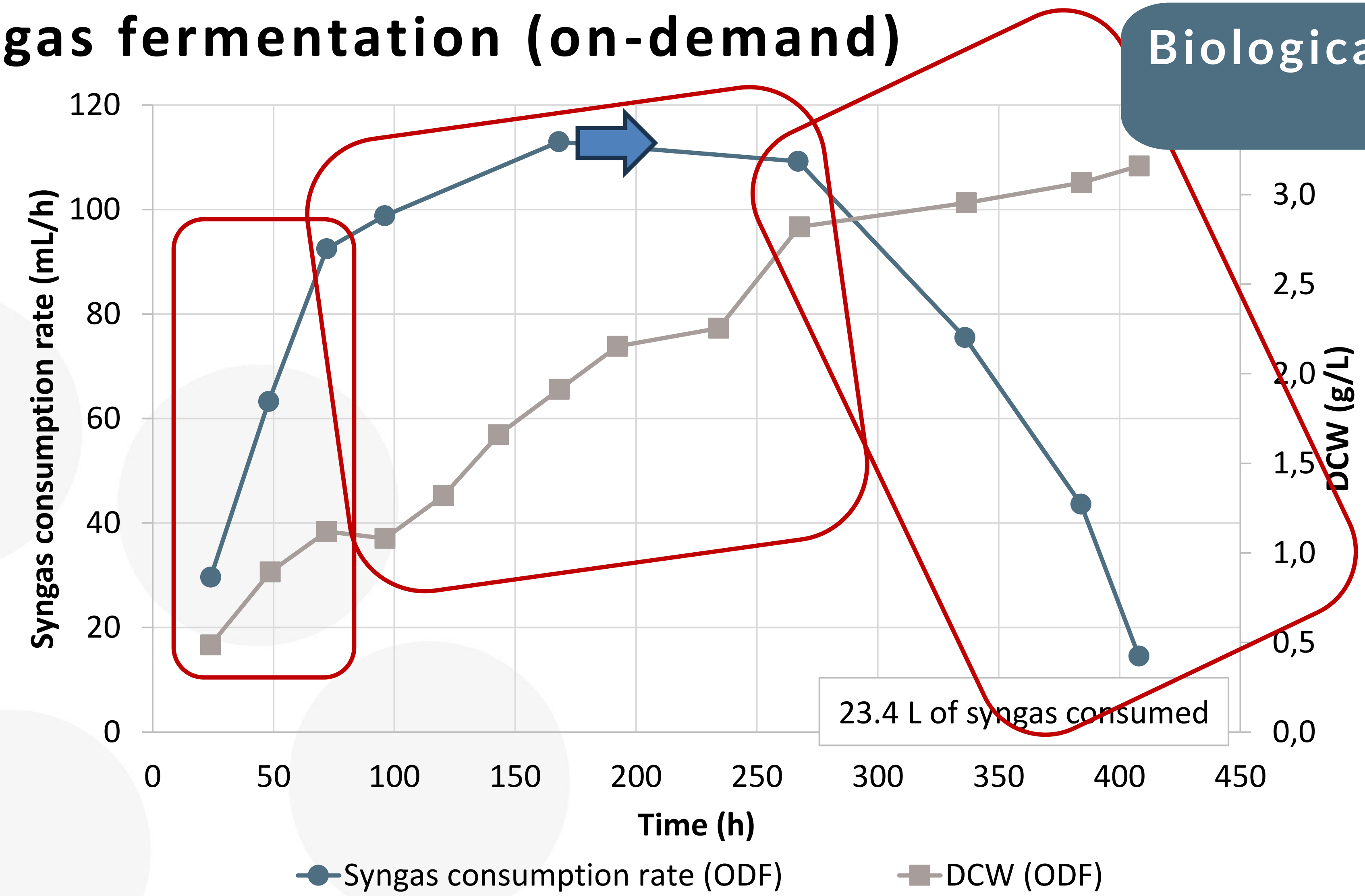
Pressure decreases inside the bioreactor vessel

Fresh syngas is pulled from the gas bag

The reactor headspace was cleansed with fresh syngas every 24 hours, to avoid accumulation of CH_4 and unused CO_2

Syngas fermentation (on-demand)

Biological consumption rate: 112 mL/h



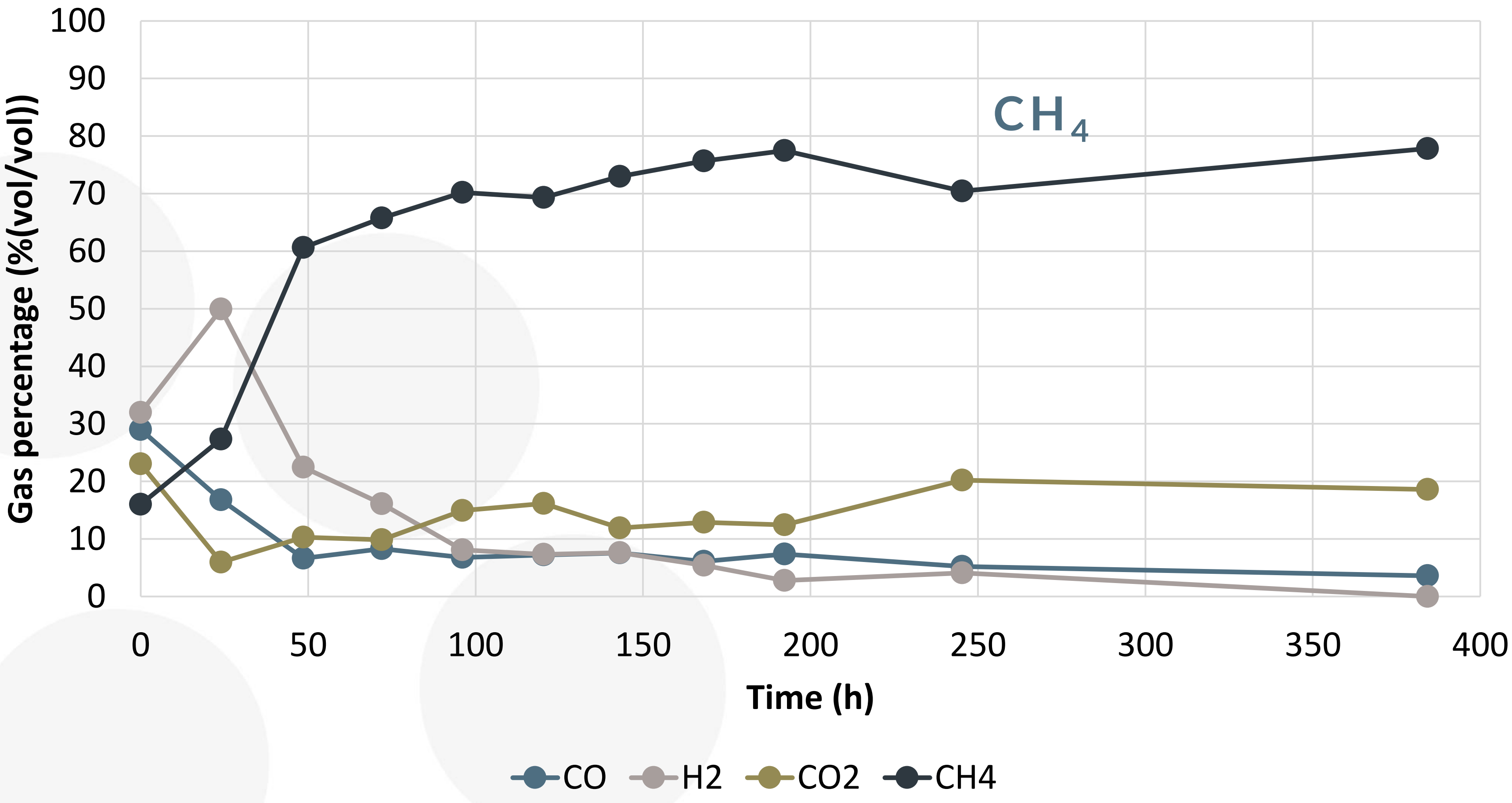
Source: Pacheco, Silva and Moura (2024), Biotechniques, July.

1st stage – Syngas consumption rate increases rapidly with biomass increase

2nd stage – Syngas consumption rate is decoupled from biomass increase – probably limited by gas mass transference

3rd stage – Syngas consumption rate starts decreasing even though biomass is still increasing

Syngas fermentation (on-demand)



CO_2 – 0.47 mmol/g$_{DCW}$/h

CO – 1.14 mmol/g$_{DCW}$/h

H_2 – 1.01 mmol/g$_{DCW}$/h

Carbon consumption:
68 %

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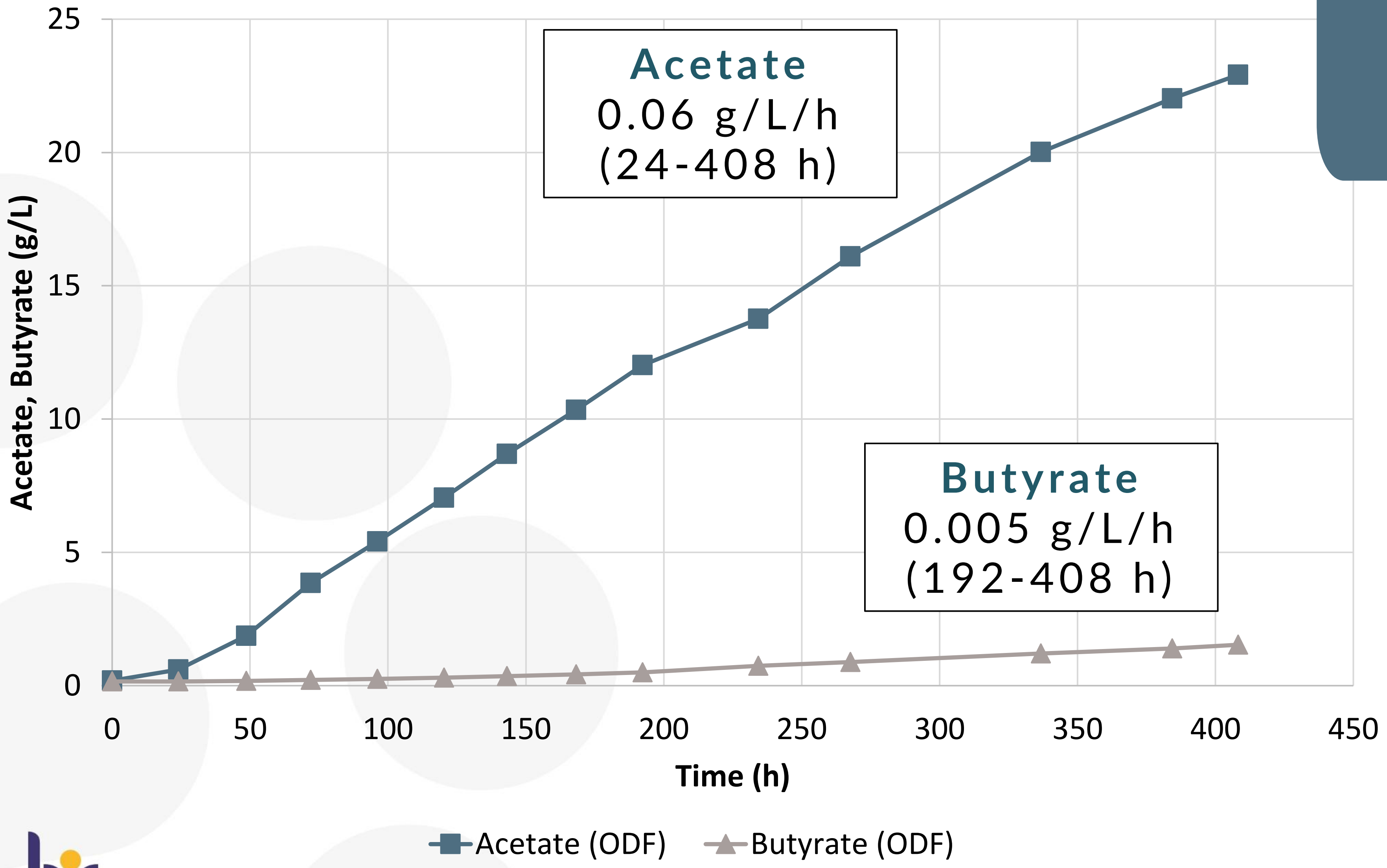
Syngas fermentation (on-demand)



Acetate
0.06 g/L/h
(24-408 h)

Butyrate
0.005 g/L/h
(192-408 h)

Total Acetate produced:

24.4 g/L

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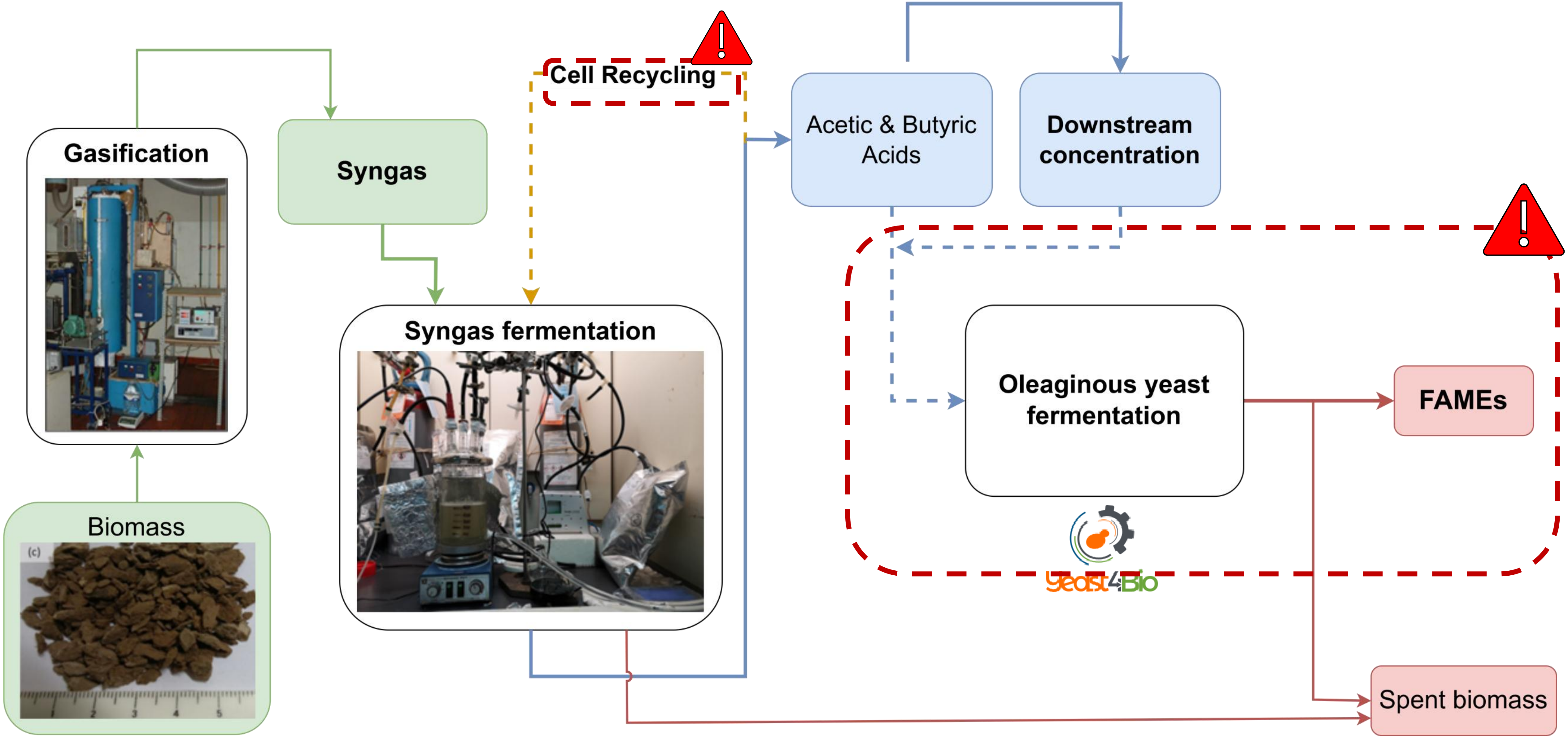
CO_2/CO + H2 streams + Fermentation + HEFA → SAF



Gasification

Syngas

Cell Recycling

Syngas fermentation

Biomass

Acetic & Butyric Acids

Downstream concentration

Oleaginous yeast fermentation

FAMEs

Spent biomass

Yeast4Bio

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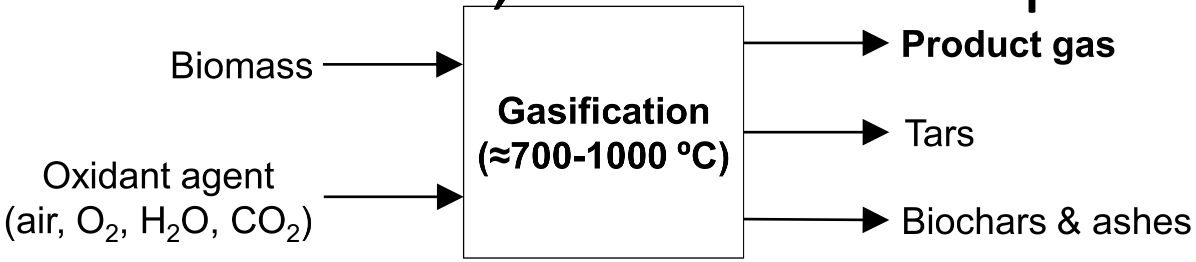
Gasification → syngas → FT + Hydrocracking → SAF

Thermochemical utilization of gases

- Definition: **thermochemical conversion of biomass** using oxidant agents for partial oxidation at high temperature, generating a **product gas for energy applications**.

- General schematic, reactions and products:



Reactions	
Oxidation	**Reduction**
$C + O_2 \rightarrow CO_2$ $2C + O_2 \rightarrow 2CO$	$C + 2H_2 \leftrightarrow CH_4$ (hydrogasification) $CO + H_2O \leftrightarrow CO_2 + H_2$ (water-gas shift) $C + CO_2 \leftrightarrow 2CO$ (Boudouard)

Tar

Char & ash

Gasification concepts and relevance (cont.)

- Product properties and applications:

Product	Properties	Applications
Product gas	• High CO content (5-26 vol.%). • High H_2 content (13-27 vol.%). • Significant lower heating value (7-16 MJ/m^3).	• Energy generation (thermal and electric). • Renewable gases (biomethane and hydrogen). • Liquid biofuels (methanol, ethanol, dimethyl ether, Fischer-Tropsch diesel and gasoline).
(Bio)chars	• High carbon and ash contents.	• Catalysts. • Construction materials. • Remediation of effluents.
Tar	• Mixture of liquid hydrocarbons (e.g., naphtalene, benzene, toluene).	• Recovery of chemical products. • Liquid fuels (through regeneration). • Recirculation to the gasifier.

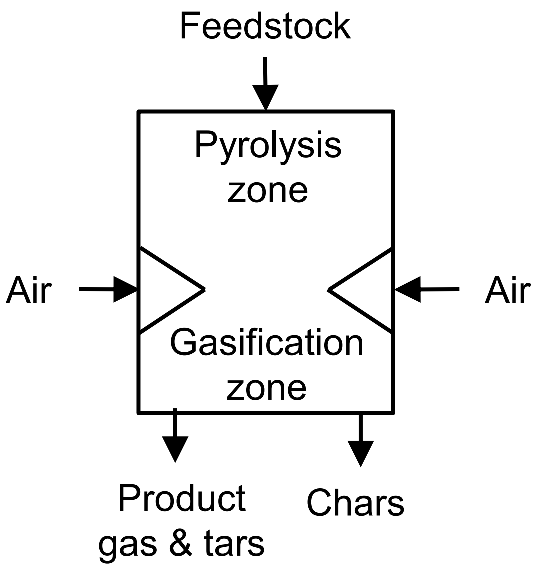
(Basu, 2013; Molino et al., 2018)

Gasification concepts and relevance (cont.)

- Reactor configurations:

Fixed-bed downdraft

(10 kW - 1 MW)



Feedstock

Pyrolysis zone

Air

Air

Gasification zone

Product gas & tars

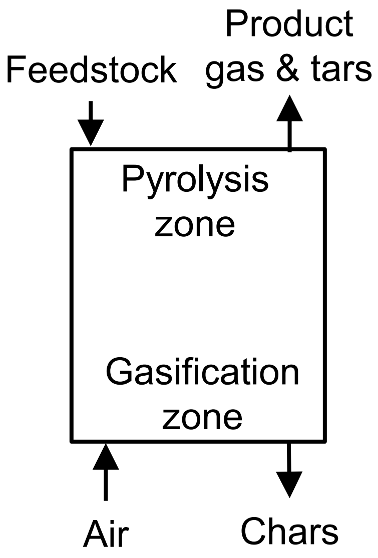
Chars

Characteristics:

- less tars;
- lower startup time;
- small-scale implementation;
- demanding requirements for feedstocks.

Fixed-bed updraft

(1 MW - 30 MW)



Feedstock

Product gas & tars

Pyrolysis zone

Gasification zone

Air

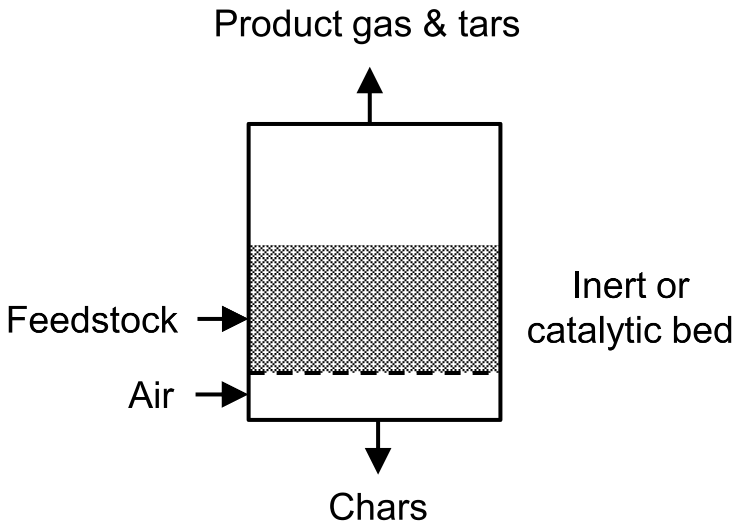
Chars

Characteristics:

- admits wetter feedstocks;
- high tar amounts;
- reduced process flexibility.

Bubbling fluidised-bed

(3 MW - 200 MW)



Product gas & tars

Feedstock

Inert or catalytic bed

Air

Chars

Characteristics:

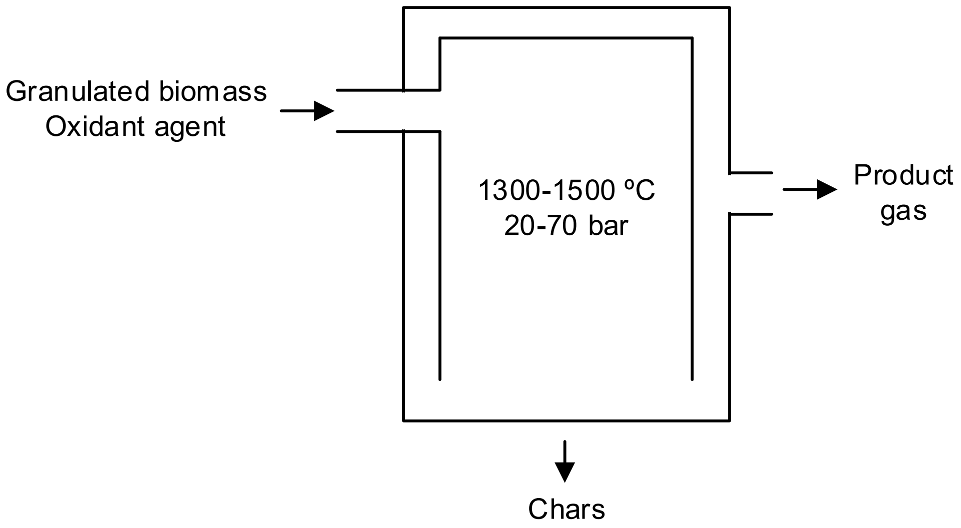
- greater tolerance to feedstock variability;
- constant temperature;
- implementation at larger scales.

Gasification concepts and relevance (cont.)

- Reactor configurations (cont.):

Entrained flow

(100 MW - 5000 MW)

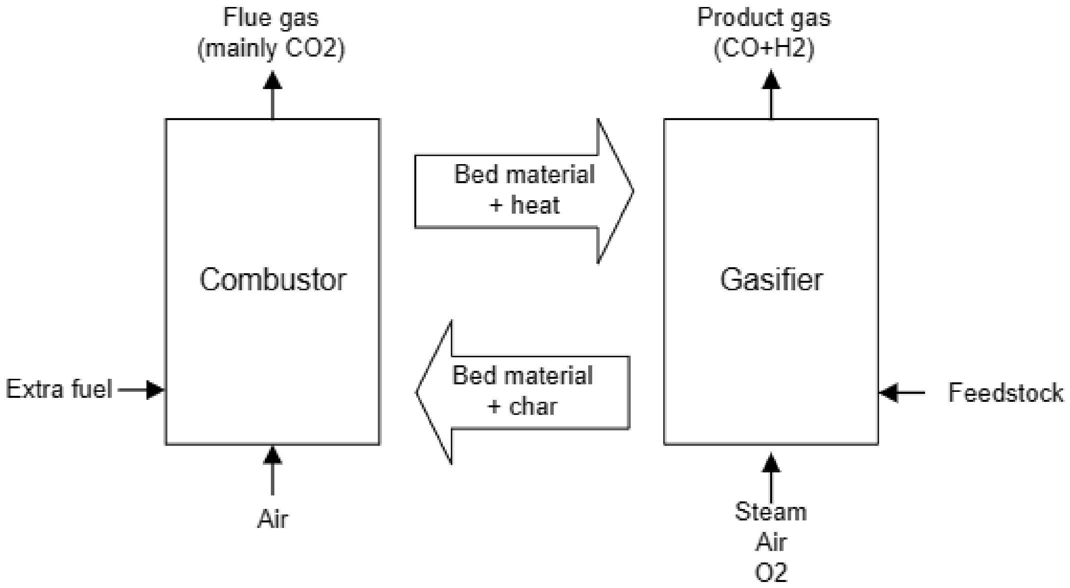


Characteristics:

- minimal tar production;
- high feedstock conversion rates;
- demanding feedstock pre-treatment (grains/powder, ≈250-1000 µm).

Dual fluidised-bed

(200 kW - 200 MW)



Characteristics:

- large-scale implementation;
- separation of CO_2-rich flue gas;
- high H_2 and CO contents in product gas;
- high calorific value (12-20 MJ/Nm^3).

Gasification concepts and relevance (cont.)

- Product gas characteristics:

Reactor	Conditions	Syngas composition (vol.%)				LHV (MJ/m³)
		H_2	CO	CO_2	CH_4	
Fluidised bed	• Pine sawdust. • 700-900 ºC. • Air-steam.	21-39	35-43	18-20	6-10	7.4-8.6
Updraft	• Woodchips. • 900 ºC. • Air.	18	14	14	2	4,4
Downdraft	• Wooden cubes. • 800-850 ºC. • Air	11-20	17-24	7-11	1-2	4-5
Dual fluidised bed	• Bark. • 850ºC. • Steam.	45	23	18	8	10.6
Entrained flow	• Corn cobs. • Oxygen.	25-28	34-36	26-35	2-5	7.7-9.4

(Molino et al., 2018; Hanchate et al., 2021; Kremling et al., 2017; Hsi et al., 2008; Dogru & Erdem, 2020)

Gasification concepts and relevance (cont.)

Gasification pros and cons (compared to combustion)	
Pros	**Cons**
• Lower emissions of pollutants (NO_x, SO_2, dioxins and furans). • Implementation at smaller scales (<100 kW). • Higher energy efficiency during syngas combustion. • Flexibility of gas applications (energy and fuels). • Autothermal operation is possible. • Possible valorisation of by-products (chars and tars).	• Pre-treatment of feedstocks may be demanding. • Lower technological maturity. • Higher precision of oxidant agent injection. • Instability of temperature. • Less silent and odorless process.

(Grande et al., 2021)

TECHNOECONOMIC ASPECTS OF GASIFICATION FOR ENERGY AND FUEL PRODUCTION

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Laboratório Colaborativo para as Biorrefinarias

RESEARCH OBJECTIVES

- ○ **Understanding Economic Parameters**: Gain insights into capital expenditures (CAPEX) and operational expenditures (OPEX) associated with gasification technologies.
- ○ **Trend Analysis**: Examine historical data to identify trends that influence technology selection and investment decisions.
- ○ **Strategic Planning**: Leverage trend knowledge for strategic planning and future forecasting in energy technology investments

recycling
MDPI

Article

Costs of Gasification Technologies for Energy and Fuel Production: Overview, Analysis, and Numerical Estimation

Gonçalo Lourinho [1,2], Octávio Alves [1,2], Bruno Garcia [1], Bruna Rijo [1], Paulo Brito [2] and Catarina Nobre [2,*]

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Abstract: During recent years, gasification technology has gained a high potential and attractiveness to convert biomass and other solid wastes into a valuable syngas for energy production or synthesis of new biofuels. The implementation of real gasification facilities implies a good insight of all expenses that are involved, namely investments required in equipment during the project and construction phases (capital expenditures, CapEx) and costs linked to the operation of the plant, or periodic maintenance interventions (operational expenditures, OpEx) or costs related to operations required for an efficient and sustainable performance of a gasification plant (e.g., feedstock pre-treatment and management of by-products). Knowledge of these economic parameters and their corresponding trends over time may help decision-makers to make adequate choices regarding the eligible technologies and to perform comparisons with other conventional scenarios. The present work aims to provide an overview on CapEx associated with gasification technologies devoted to convert biomass or solid waste sources, with a view of reducing the carbon footprint during energy generation or production of new energy carriers. In addition, an analysis of technology cost trends over time using regression methods is also presented, as well as an evaluation of specific capital investments according to the amount of output products generated for different gasification facilities. The novelty of this work is focused on an analysis of CapEx of existing gasification technologies to obtain distinct products (energy and fuels), and to determine mathematical correlations relating technology costs with time and product output. For these purposes, a survey of data and categorization of gasification plants based on the final products was made, and mathematical regression methods were used to obtain the correlations, with a statistical analysis (coefficient of determination) for validation. Specific investments on liquid biofuel production plants exhibited the highest decreasing trend over time, while electricity production became the least attractive solution. Linear correlations of specific investment versus time fitted better for electricity production plants ($R^2 = 0.67$), while those relating the product output were better for liquid biofuel plants through exponential regressions ($R^2 = 0.65$).

Keywords: gasification; cost; investment; evolutionary investment trend

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Citation: Lourinho, G.; Alves, O.; Garcia, B.; Rijo, B.; Brito, P.; Nobre, C. Costs of Gasification Technologies for Energy and Fuel Production: Overview, Analysis, and Numerical Estimation. *Recycling* 2023, *8*, 49. https://doi.org/10.3390/recycling8030049

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1. Introduction

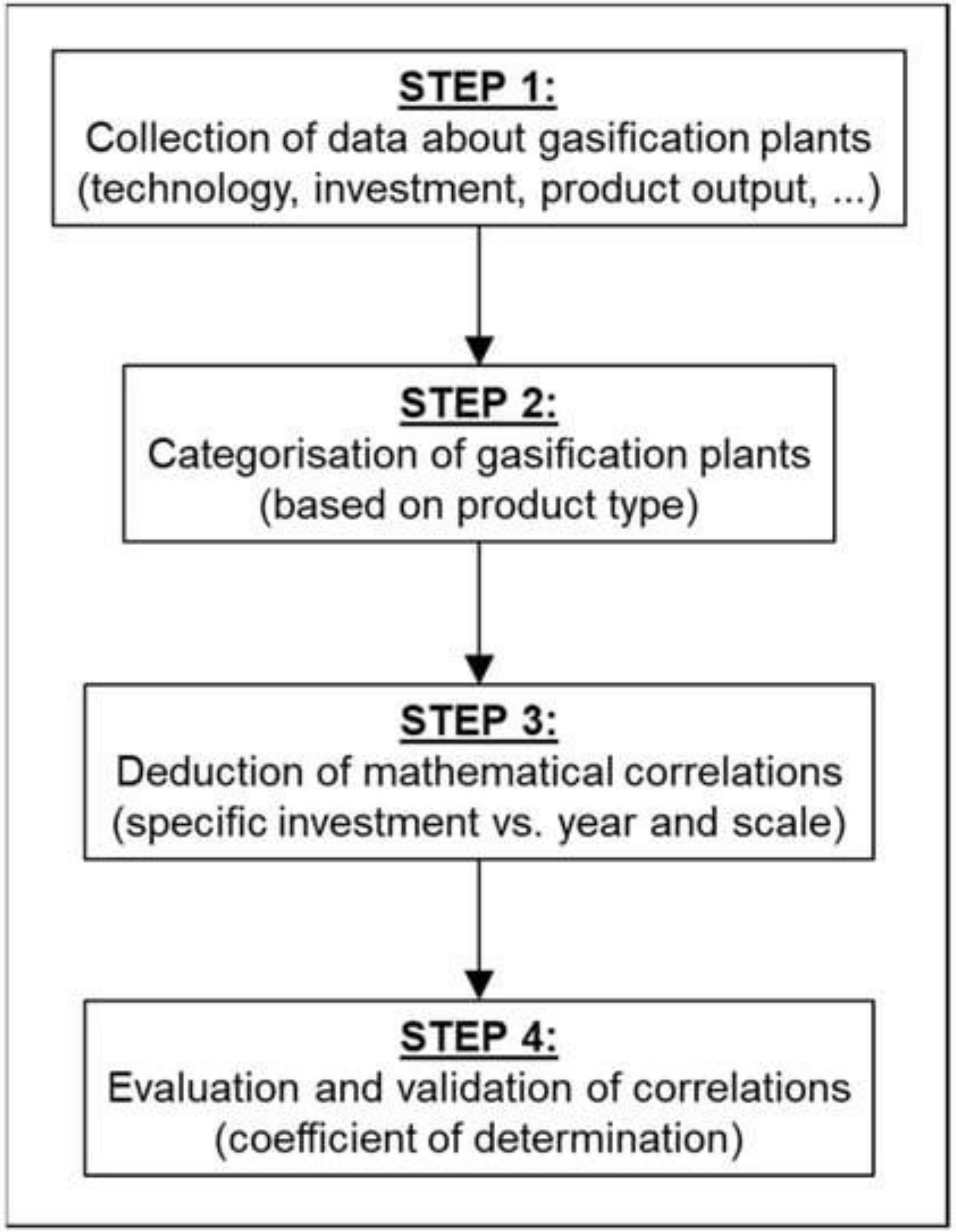
There is a significant and growing need to develop clean and renewable energy sources to achieve carbon neutrality by 2050 [1]. Biomass gasification is the only method that uses completely renewable resources and offers a range of advantages in terms of its associated environmental impact and carbon neutral characteristics [2]. Thus, it is critical to increase the production capacity of renewable gases from gasification processes. Various innovative gasification technologies are being developed, which offer improved efficiency and cost-effectiveness. These technologies include plasma gasification [3], entrained flow gasification [4,5], dual fluidized bed gasification [6,7], and sorption enhanced gasification [8–10], while other recent developments have been a resurgence in research into oxidizing agents, using air, steam, oxygen, carbon dioxide, or a combination of them [11–15]. It is expected that the hydrogen

doi:10.3390/recycling8030049

METHODOLOGY

DATA COLLECTION

- Several sources were considered for data collection including **institutional reports, databases, and scientific articles** and the temporal period considered for this survey was between 1996 and 2021.
- The **specific investment** of each plant were calculated considering the ratio of **total CAPEX and the output capacity** (expressed in mass or energy units, as appropriate) and updated through to EUR 2020.



STEP 1:
Collection of data about gasification plants (technology, investment, product output, ...)

STEP 2:
Categorisation of gasification plants (based on product type)

STEP 3:
Deduction of mathematical correlations (specific investment vs. year and scale)

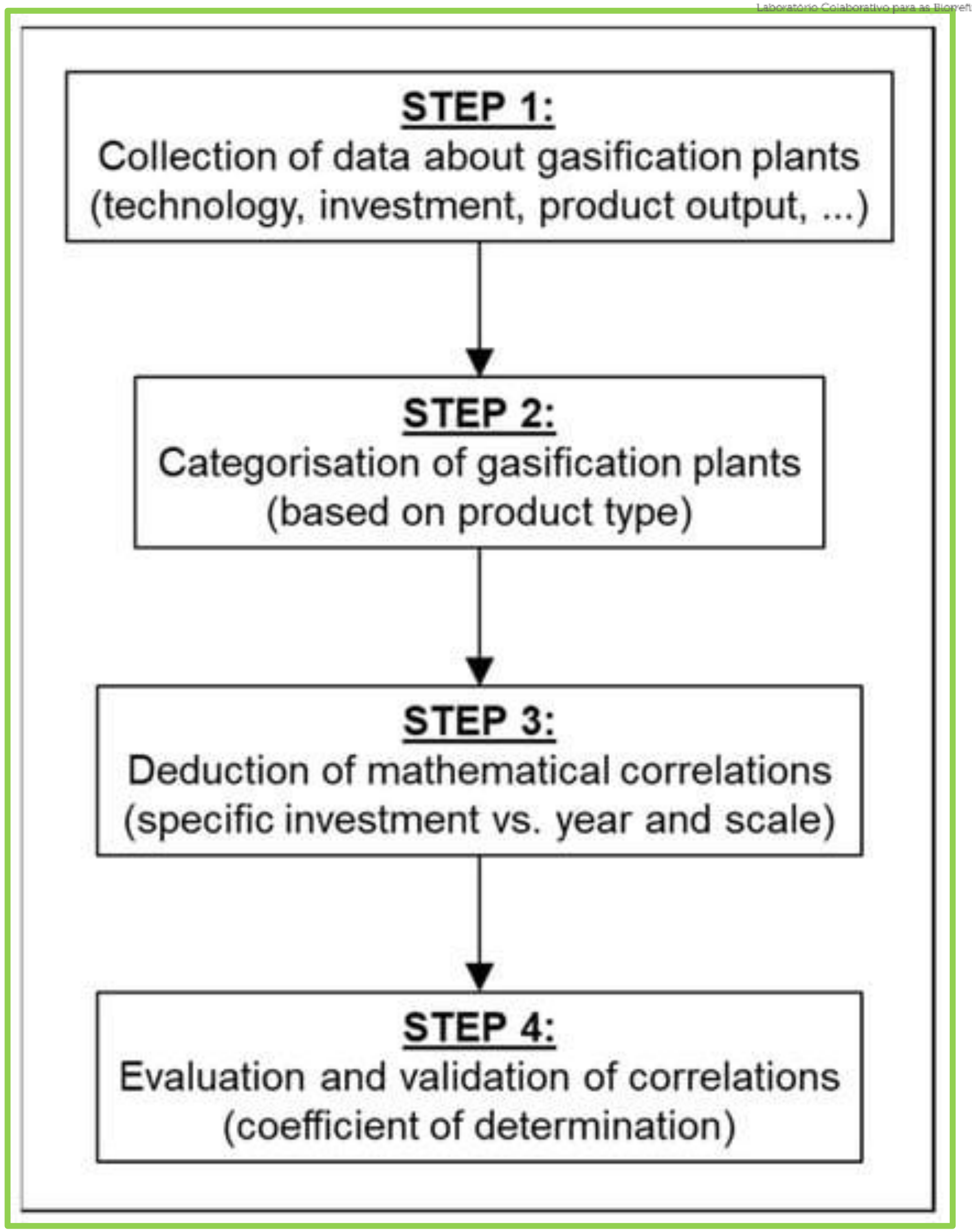
STEP 4:
Evaluation and validation of correlations (coefficient of determination)

doi:10.3390/recycling8030049

METHODOLOGY

PLANT CLASSIFICATION

- A **classification for the different gasification plants** based on the final product to differentiate between production technologies according to process complexities, and capital investments required.
- The list of gasification plants was classified in **three product classes** and **eight product subclasses**.
- Products obtained from energy generation (**electricity, heat, and CHP**), from renewable gases generation (**SNG**), and from liquid fuels generation (**ethanol, methanol, gasoline, and FT fuels**).



STEP 1:
Collection of data about gasification plants (technology, investment, product output, ...)

STEP 2:
Categorisation of gasification plants (based on product type)

STEP 3:
Deduction of mathematical correlations (specific investment vs. year and scale)

STEP 4:
Evaluation and validation of correlations (coefficient of determination)

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EVOLUTIONARY TRENDS - TIME

- **Feedstock Analysis**: Plants processing **diverse feedstocks** like forestry and wood wastes, municipal solid wastes (MSW), sewage sludge, and others.
- **Investment Trends**: A demonstrated **decrease in specific investments over time**, especially for electricity, CHP, and liquid biofuel production plants

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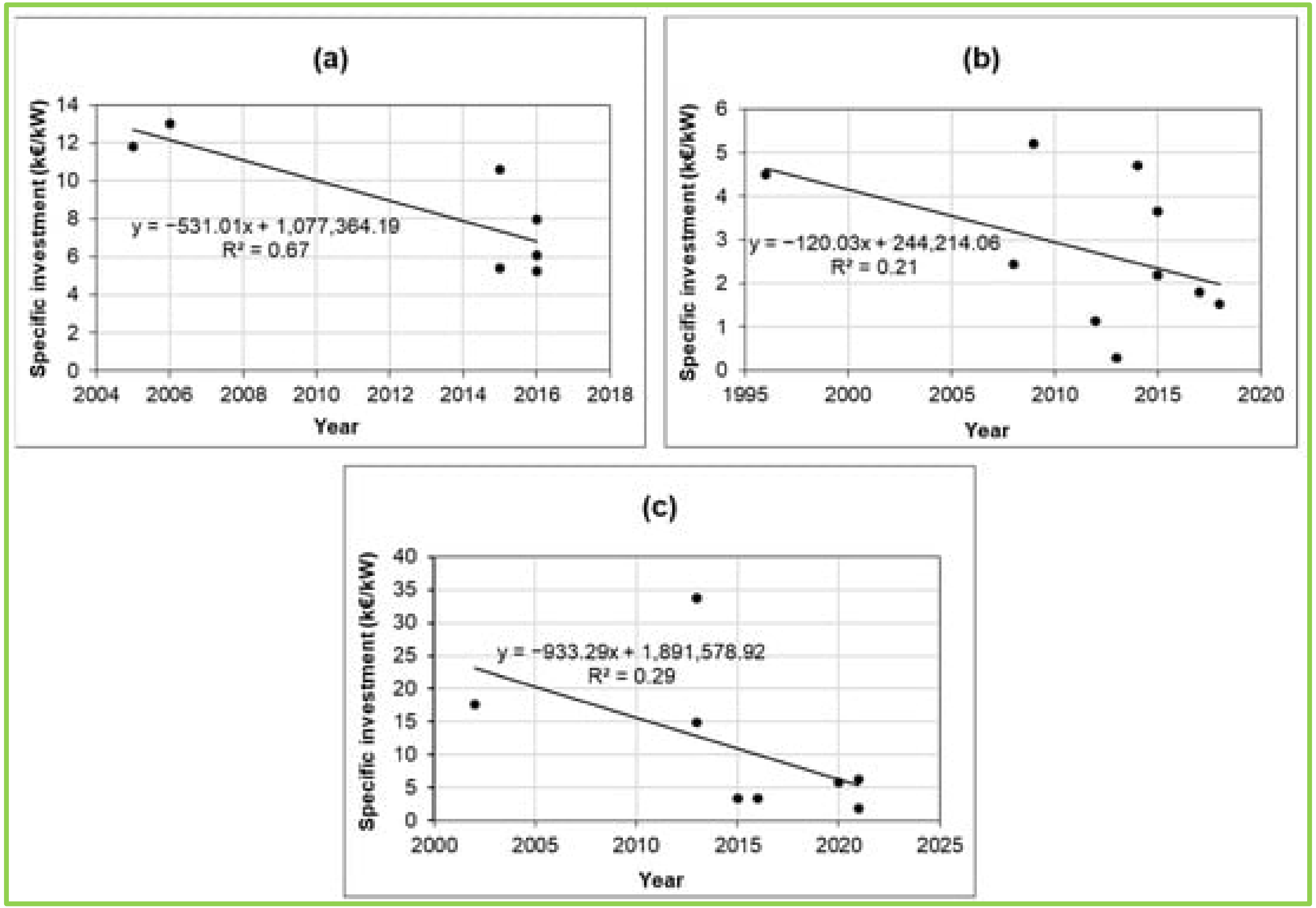
ELECTRICITY

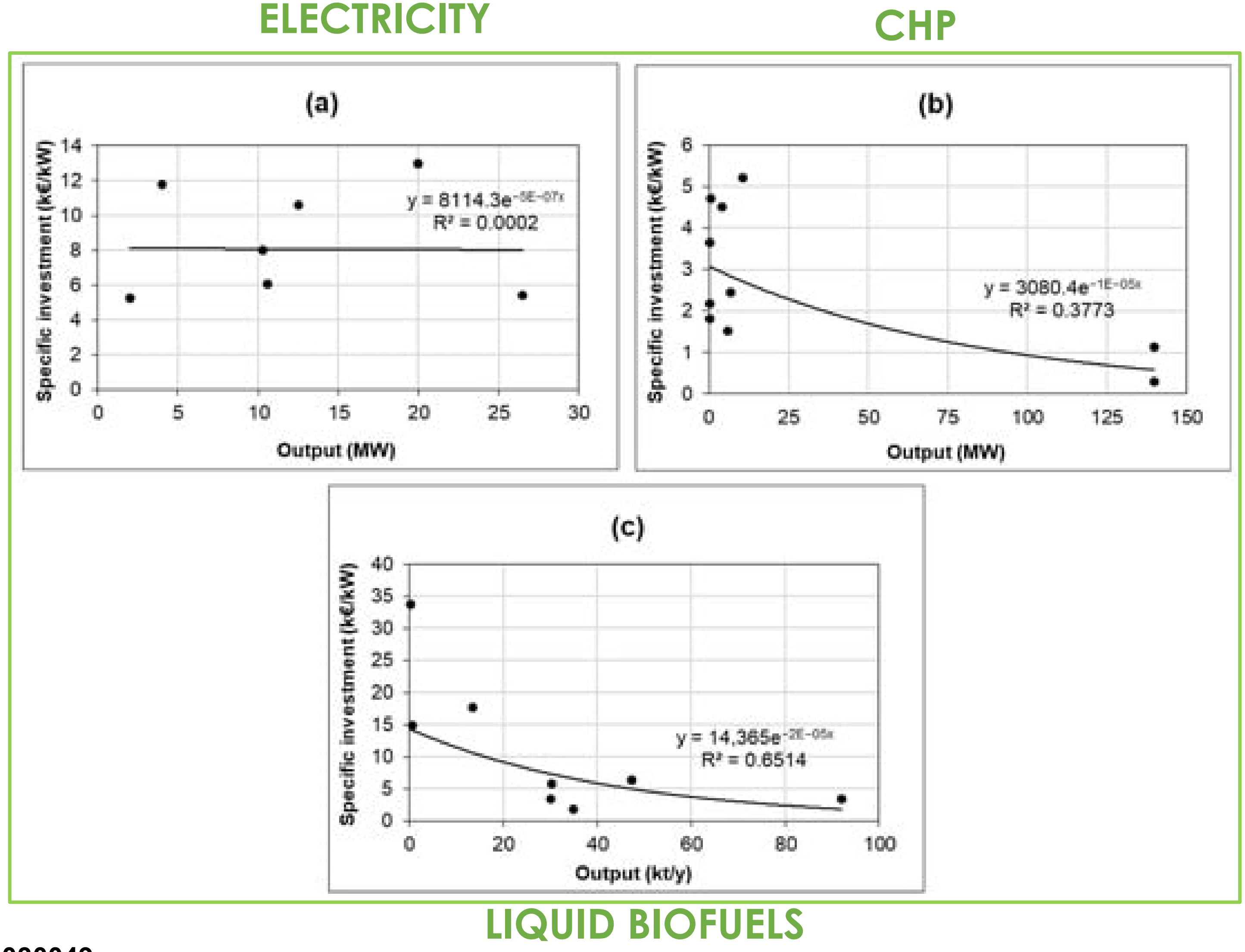
CHP



LIQUID BIOFUELS

EVOLUTIONARY TRENDS - OUTPUT

- Specific Investment Costs: **High specific costs for liquid or gaseous fuel plants**, ranging from €1,800 to €34,000 per t/year, reflecting the complexity of production processes and technological development.
- Liquid Fuel Plant Flexibility: A **wide product range** including ethanol, methanol, gasoline, and various Fischer-Tropsch (FT) fuels, with plant scales from 140 kW to 190 MW for energy production and 250 to **92,000 tons/year for fuel production**
- Economies of Scale: More **pronounced for CHP and liquid biofuel plants**, showing a downward exponential pattern in investment costs as output increases.



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HR EXCELLENCE IN RESEARCH

Thank you!

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