Chair of Energy Systems
TUM School of Engineering and Design
Technical University of Munich

Development of sewage sludge to methanol pathways

Process design, simulation and techno-economic analysis of alternative conversion routes

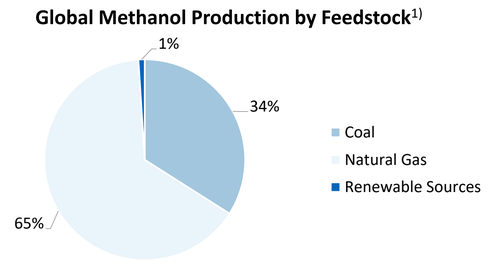
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Motivation and Background

Sewage sludge is a biogenic waste product of wastewater treatment that is contaminated with substances such as heavy metals and pharmaceutical residues. Apart from that it contains valuable resources such as phosphorus. In Germany, the **Klärschlammverordnung** (AbfKlärV) promotes its recovery and **requires** the **highest-quality disposal** option of the sewage sludge. In 2024, Germany incinerated 82 % of the total sewage sludge quantity, making it the most common elimination pathway.

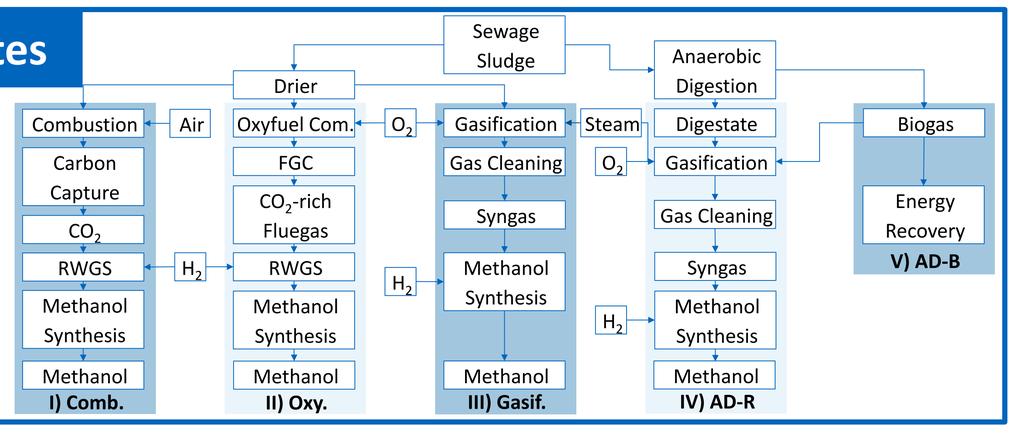
Global Methanol Production by Feedstock[1)]



Methanol (CH_3OH) is the simplest monohydric alcohol and a key **platform chemical** used for numerous syntheses. It is utilized to produce acetic acid, formaldehyde, methyl tert-butyl ether (MTBE), dimethyl ether (DME), and olefins, that serve as intermediates in large scale production processes for paints, resins, pharmaceuticals, cosmetics, and packaging material [2]. In 2021 the global methanol output amounted to 107 Mt a^{-1} [2]. Its production remains **dependent on fossil feedstocks**, with 65 % derived from natural gas, 35 % from coal, and less than 1 % from renewable sources [1].

Conversion Process Routes

A total of **five pathways** are investigated: conventional combustion **(I)**, oxyfuel combustion **(II)**, entrained-flow gasification **(III)**, anaerobic digestion with biogas co-gasification **(IV)**, and anaerobic digestion with energetic biogas recovery **(V)**. PEM electrolysis supplies the required H_2 and O_2 across all routes.



Multi-stage Methodological Framework

Technical Analysis

Feedstock Preparation
- Conversion of elemental analysis data into compatible input
- Decomposition into macromolecules for anaerobic digestion via MATLAB

Process Simulation
- Simulation of five process routes in Aspen Plus
- Energy and mass balances calculation
- Technical performance indicators

Economic Analysis

Equipment and Utility Mapping
- Equipment listing and sizing
- Determination of utility and material requirements

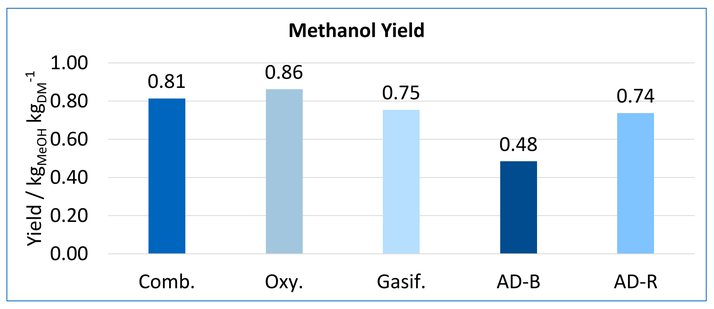
Economic Assessment
- Levelized Cost of Methanol production (LCOM)
- Brownfield approach for combustion routes
- Greenfield approach for gasification routes

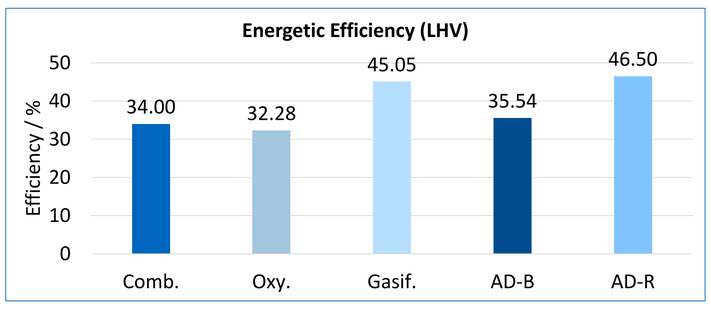
Results

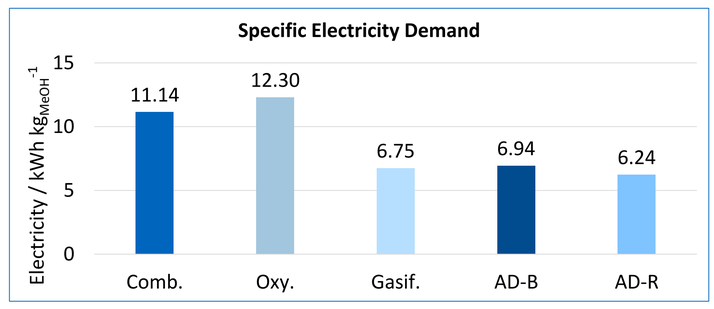
Comparison and Sensitivity
- Evaluation of technical and economic KPI's
- Sensitivity analysis of key cost drivers

Process Development
Heat & mass integration potential

Technical Results

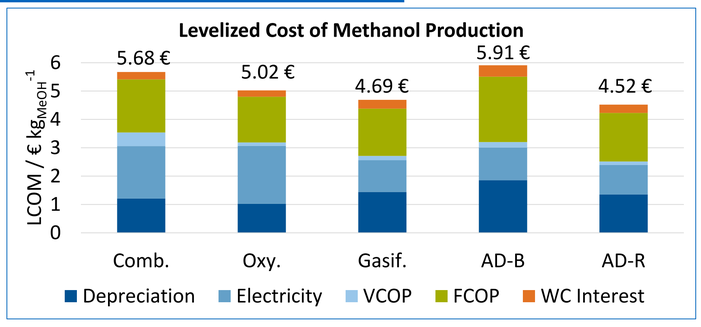


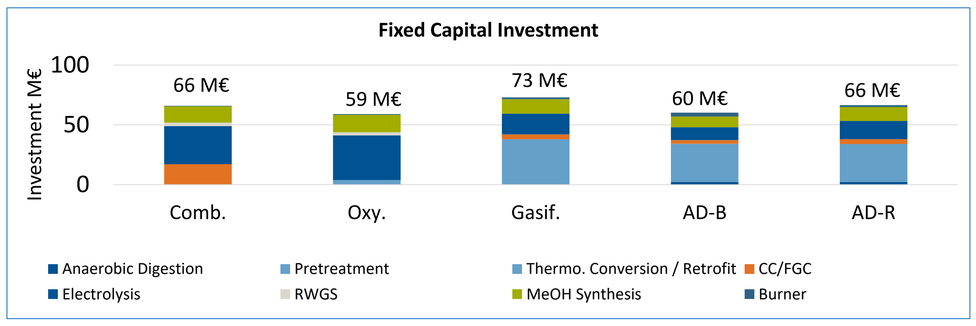




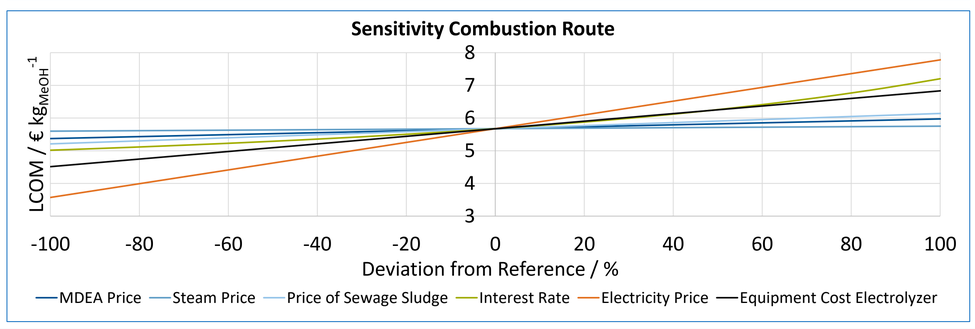
Oxyfuel maximizes methanol yield, whereas **gasification**-based routes achieve **higher energetic efficiency** at **lower electricity demand**. Carbon efficiency follows methanol yield and ranges from 95 % (Oxy.) to 53 % (AD-B). Gasification routes require less additional H_2 to achieve SN = 2.05 due to a higher CO content in the synthesis gas. This results in a lower power requirement for electrolysis and hence a higher energy efficiency.

Economic Results



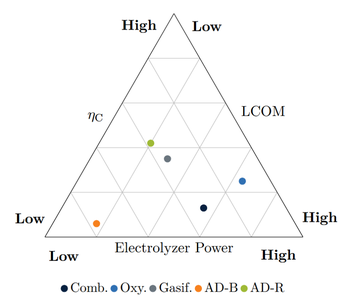


AD-R achieves the **lowest LCOM at 4.52 € kg_{MeOH}^{-1}**, despite higher investment costs than the oxyfuel route. **Electricity accounts** for more than **20 % and 33 % of the LCOM** in the gasification- and combustion-based routes, respectively. More than **48 % of the fixed capital investment** is attributed to **PEM electrolysis** in the combustion routes **and** to **thermochemical conversion** in the gasification pathways. As a consequence, **electricity prices and electrolyzer costs are key drivers of the LCOM**.



Outlook

The production of methanol from sewage sludge is **technically feasible**. At 4.52 € kg_{MeOH}^{-1}, **AD-R** achieves the **lowest LCOM**, but **surpasses** the cost of natural **gas-based methanol** at 0.27 € kg_{MeOH}^{-1} [3]. The key **trade-off** exists **between LCOM**, η_C, and **electrolyzer power**. Further **cost reductions** require **lower electrolysis demand**, thereby reducing electricity consumption and capital costs.



[1] IRENA, METHANOL INSTITUTE; Innovation Outlook: Renewable Methanol. International Renewable Energy Agency. Abu Dhabi. 2021.

[2] Mahdi Fasihi, Christian Breyer; Global production potential of green methanol based on variable renewable electricity. *Energy Environ. Sci.* 2024; 17 (10): 3503–3522. https://doi.org/10.1039/d3ee02951d.

[3] Carlos Arnaiz del Pozo, Schalk Cloete, Ángel Jiménez Álvaro; Techno-economic assessment of long-term methanol production from natural gas and renewables. *Energy Conversion and Management.* 2022; 266 (115785): https://doi.org/10.1016/j.enconman.2022.115785.

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