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From Waste Treatment to Fuel Production: Ensuring Energy Circularity

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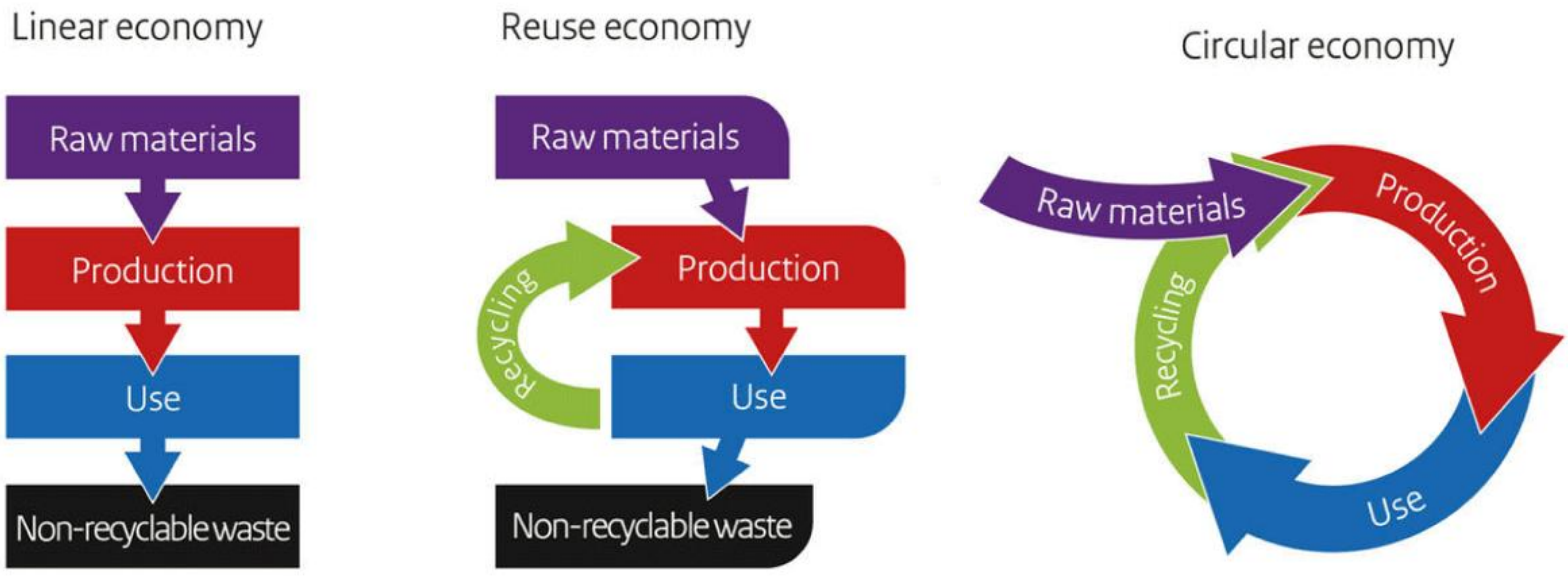
from a linear to a circular economy



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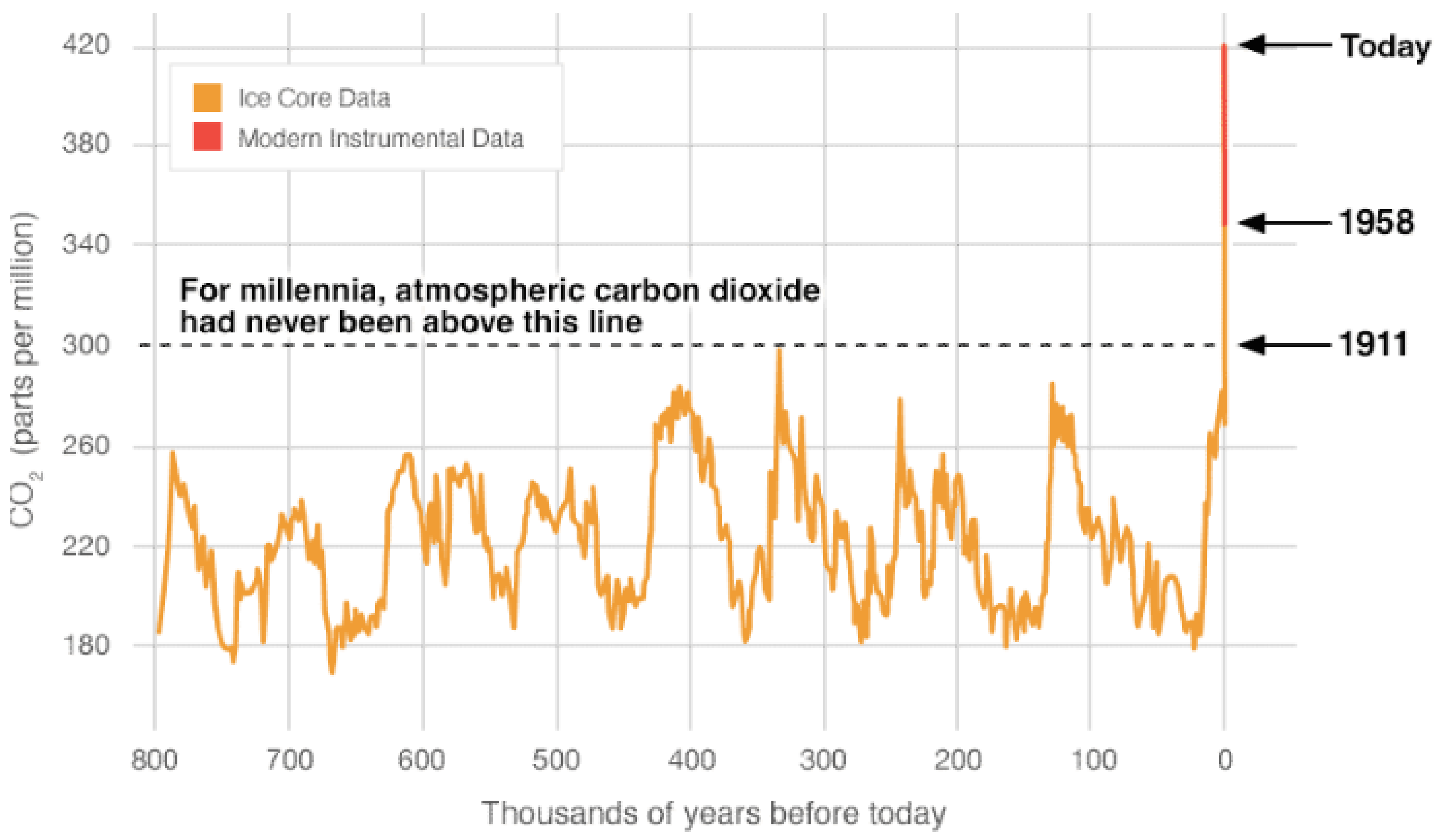
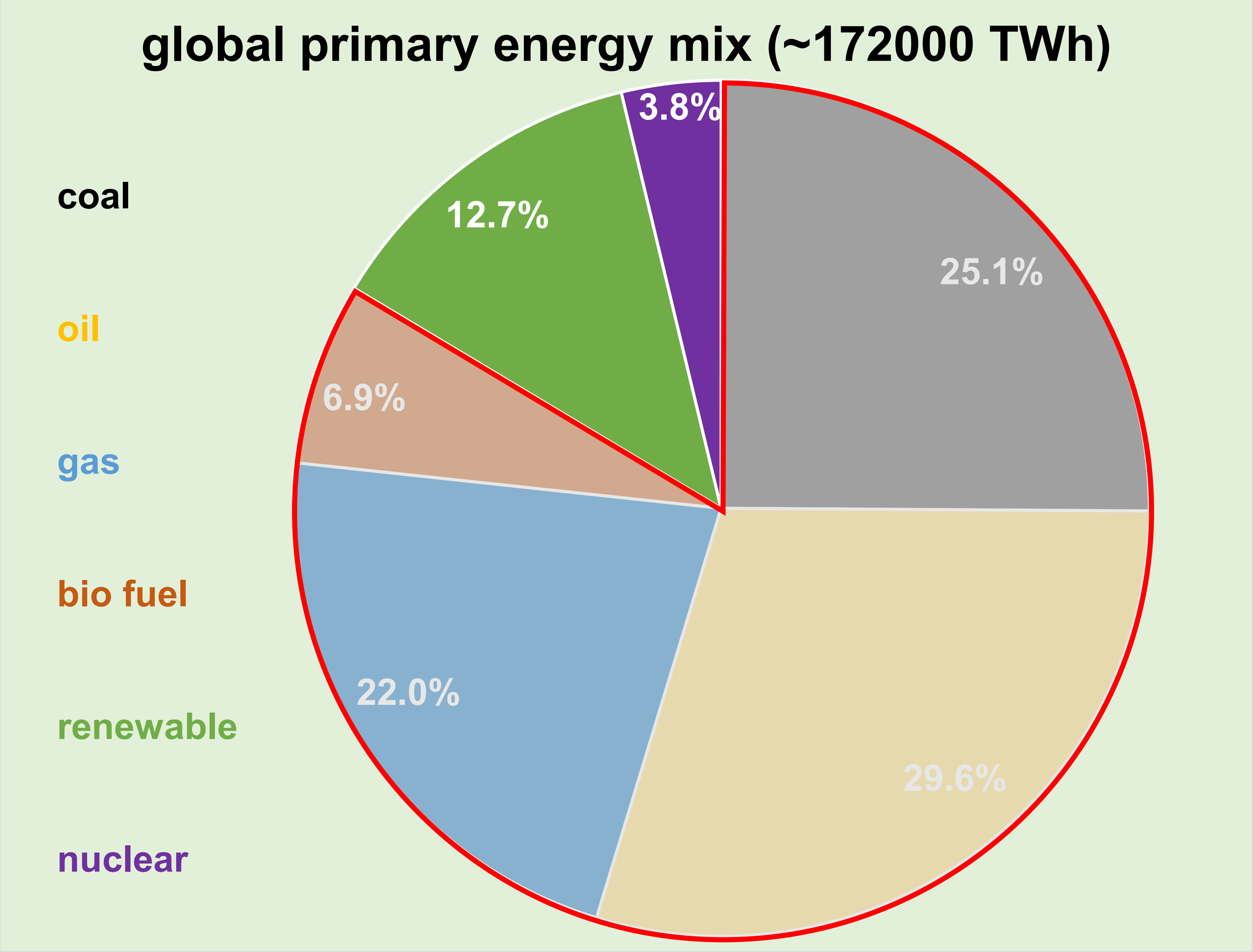
CO_2 challenge and energy transition





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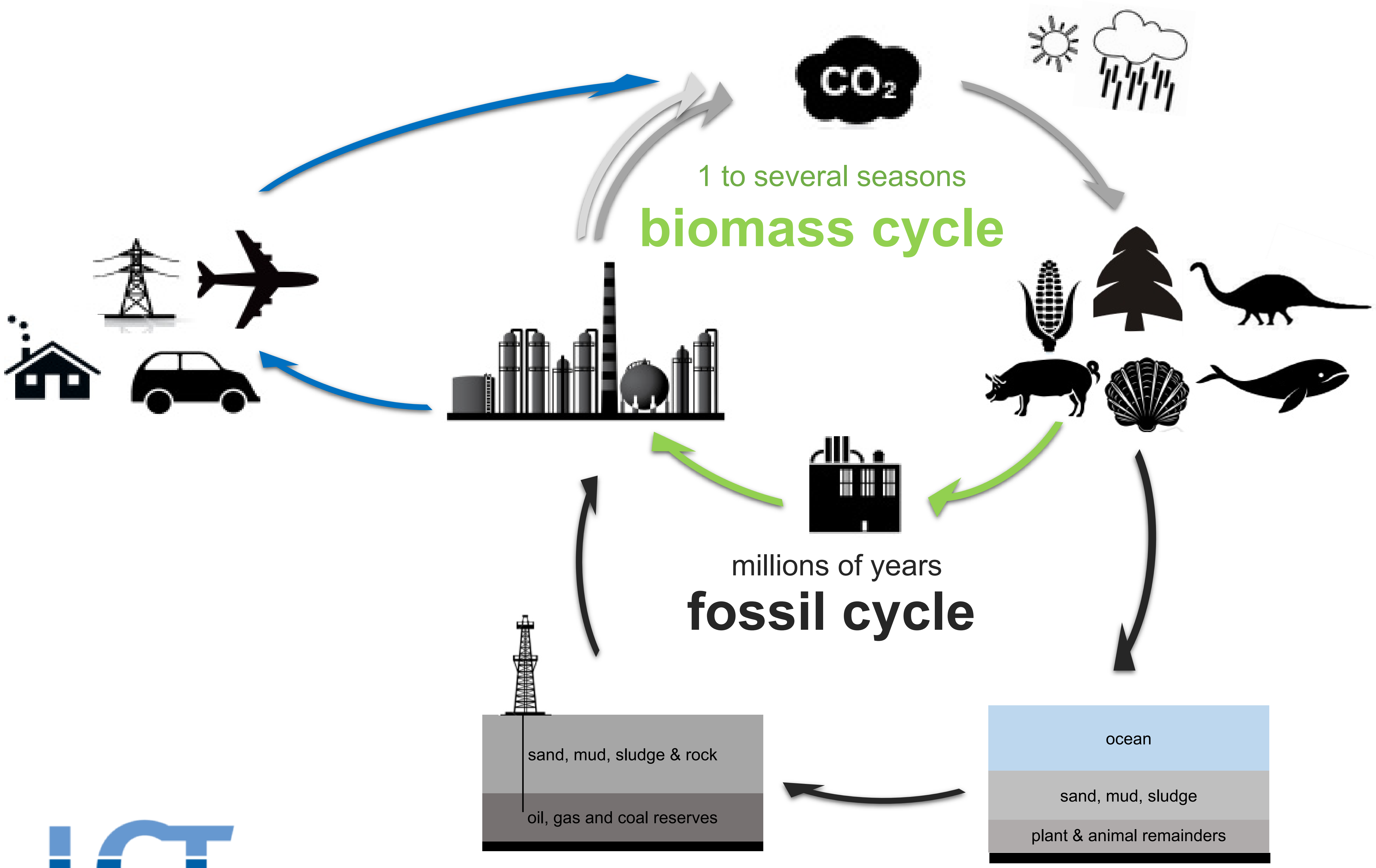
https://www.iea.org/reports/global-energy-review-2025/global-trends

https://ourworldindata.org/energy-mix

energy context



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biomass cycle

- thermochemical methods
  - gasification ($CO + H_2$)
  - pyrolysis (complex liquid oil)
  - hydrothermal liquefaction (complex liquid oil)
- biochemical methods
  - fermentation ($CH_4 + CO_2$)

outline

- introduction
- energy circularity
  - OBIWAN
  - STEROPE
- ElectroThermal Fluidized Bed reactor (ETFB)
  - electrification principles
  - reactor modeling
- conclusions & perspectives

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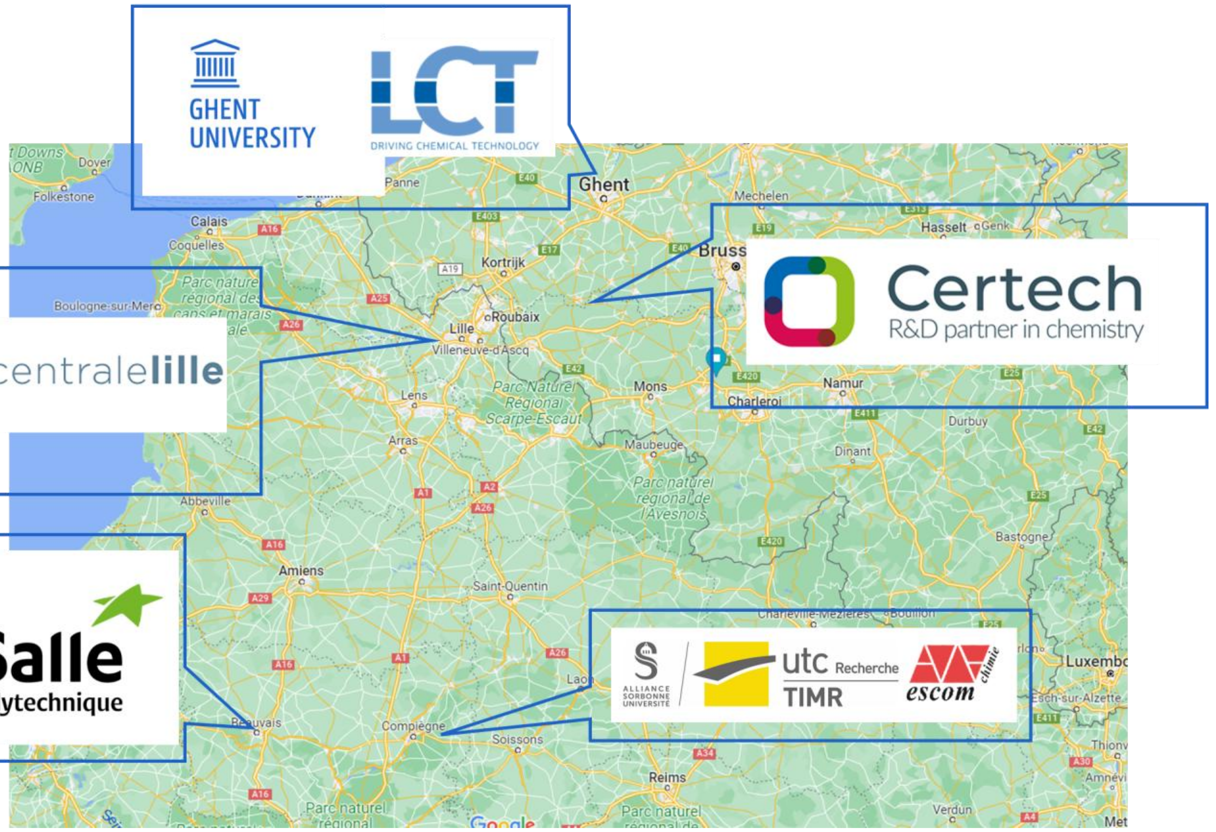
OBIWAN: context

- biogas (CH_4 + CO_2) valorization
  - calorific
  - to chemicals/(sustainable aviation fuels)



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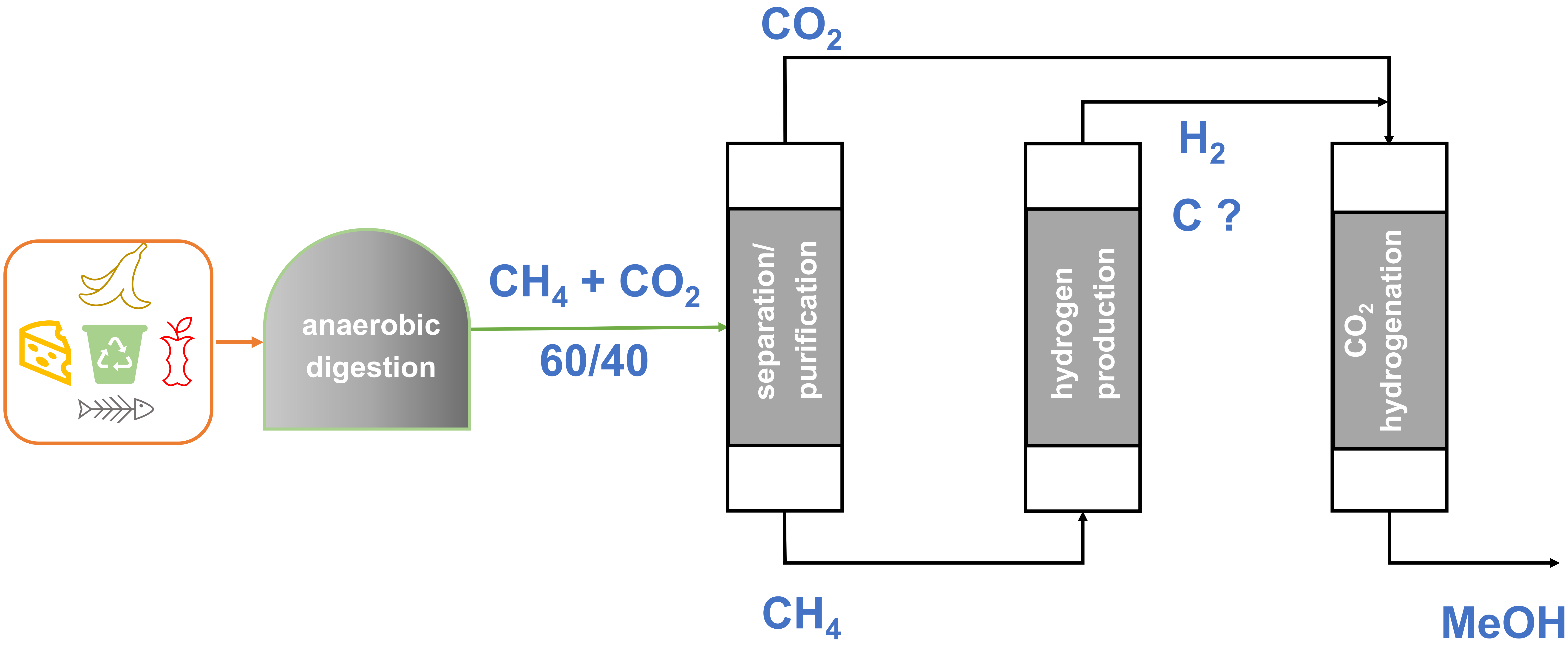
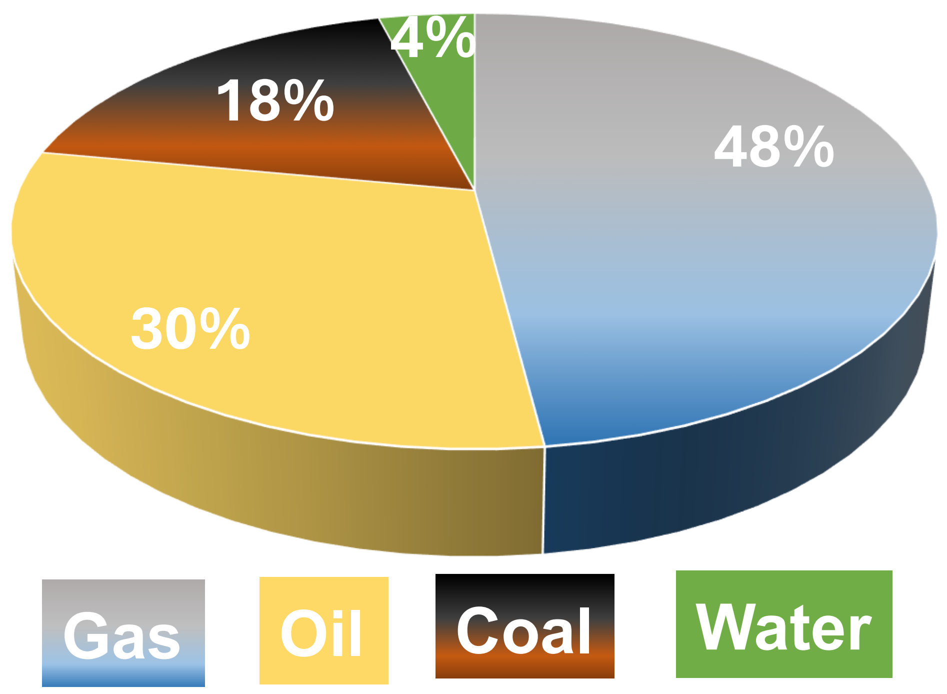
OBIWAN: process lay-out



H_2 production technologies



Technology	reaction	ΔH kJ/mol	cost ($/kg)	GWP (kg CO_2 eq)
Steam Methane Reforming	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	206	2.08	11.9
SMR + CCS			2.27	3.7
Coal Gasification	$C + H_2O \leftrightarrow CO + H_2$	-130	1. 34	22.9
CG + CCS			1. 63	4.8
Electrolysis	$2H_2O \leftrightarrow 2H_2 + O_2$	285	>3	>0.7

Catalytic Methane Decomposition:

$$CH_4 \rightarrow C(s) + 2H_2(g) \qquad \Delta H = \mathbf{74}\ \text{kJ/mol}$$

CDM on carbonaceous catalyst:

- less energy-intensive
- Less greenhouse gas emission
- Produces H_2 with high purity
- Cheap catalyst
- Sulfur-resistive catalyst

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Gholami, Z., Gholami, F., Šimek, J., Svobodová, K. & Vakili, M *Journal of Industrial and Engineering Chemistry*

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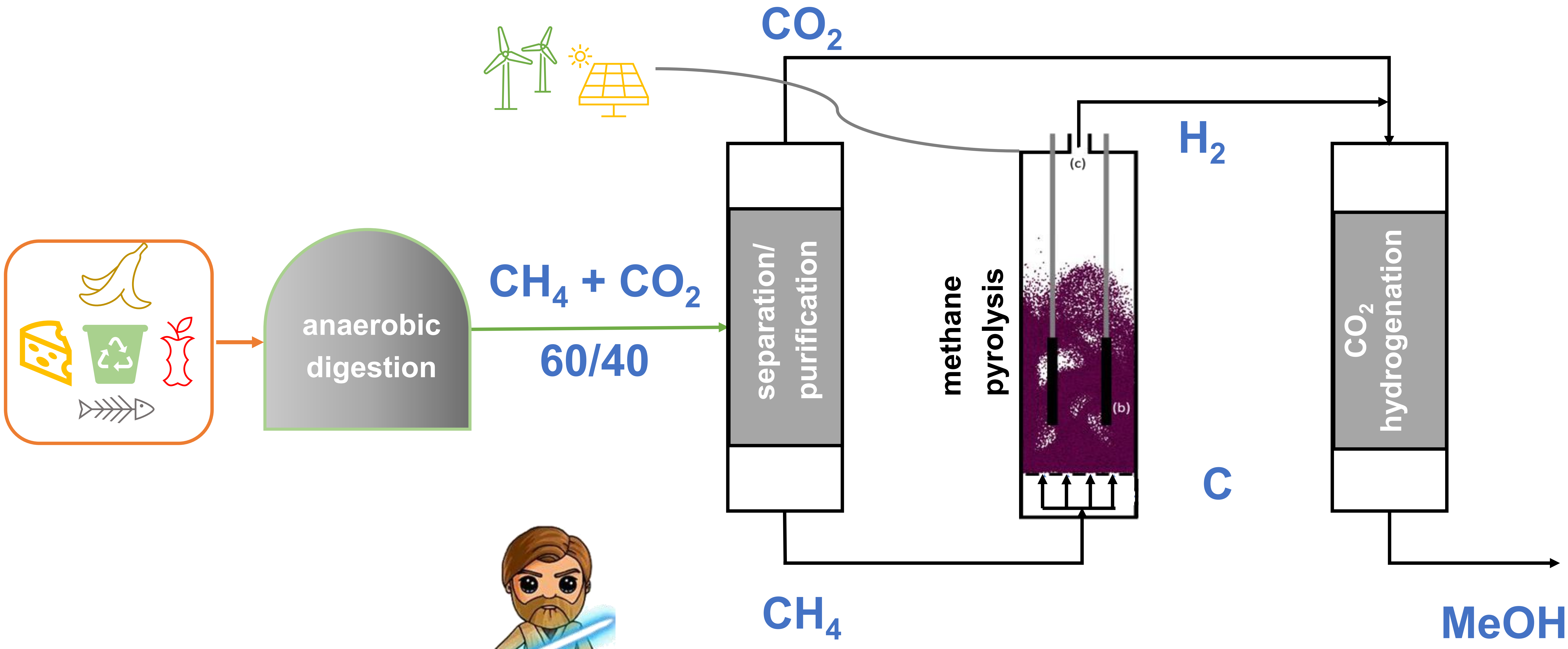

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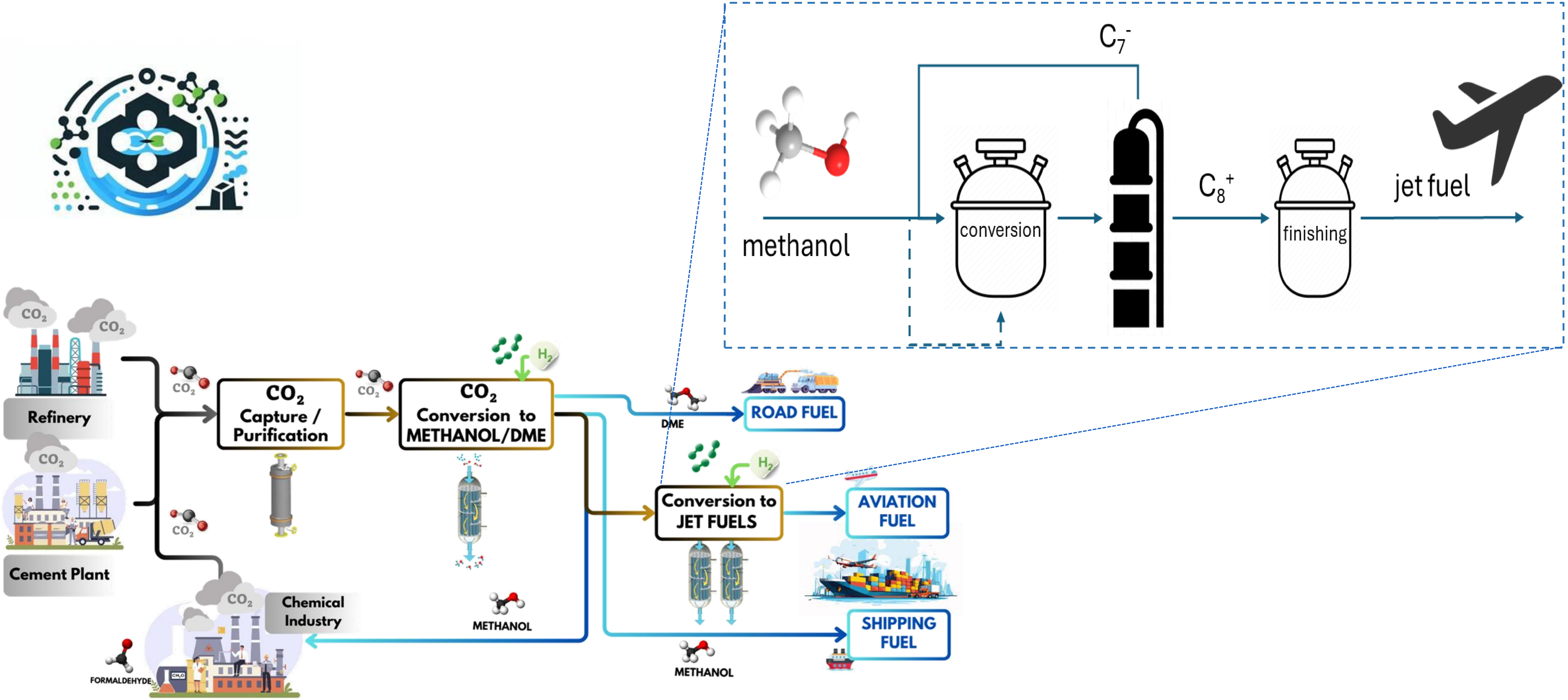
OBIWAN: October 2024 – September 2028

STEROPE



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October 2025 – September 2029

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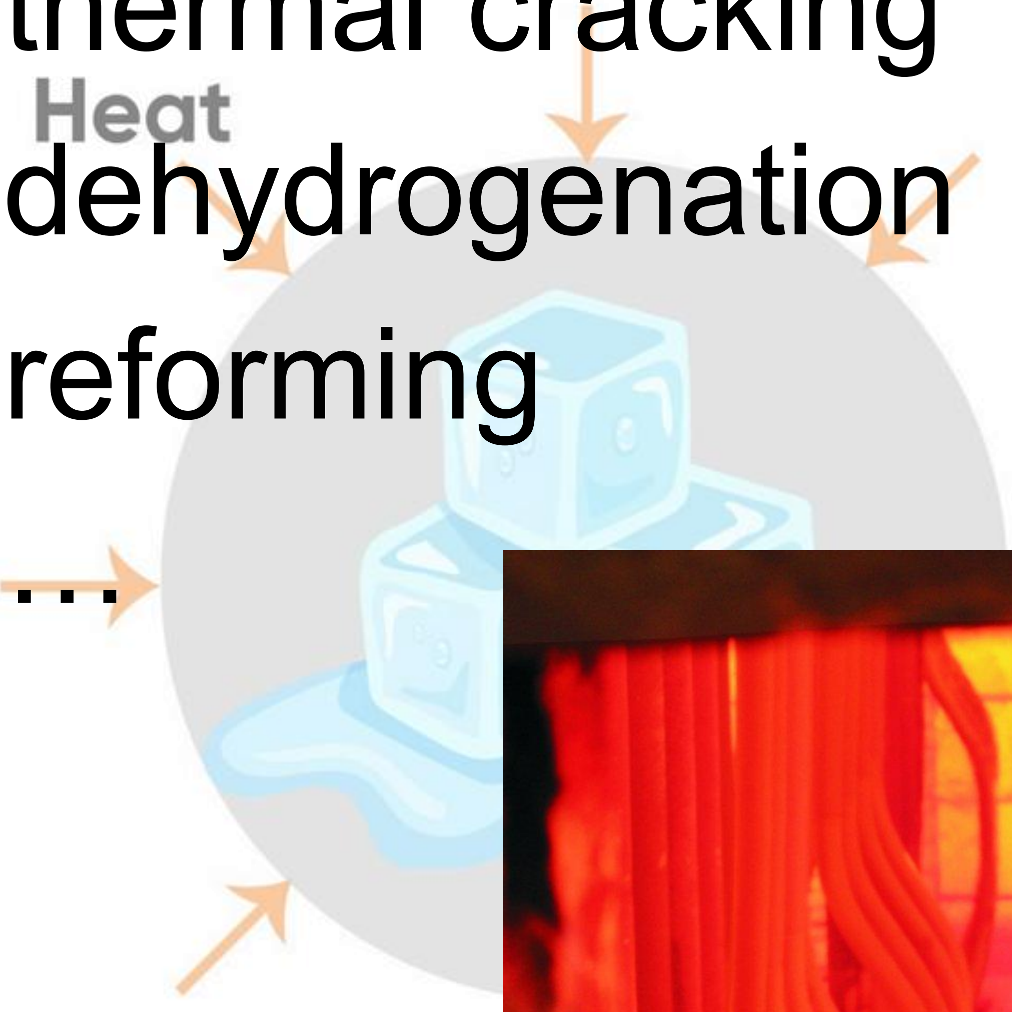
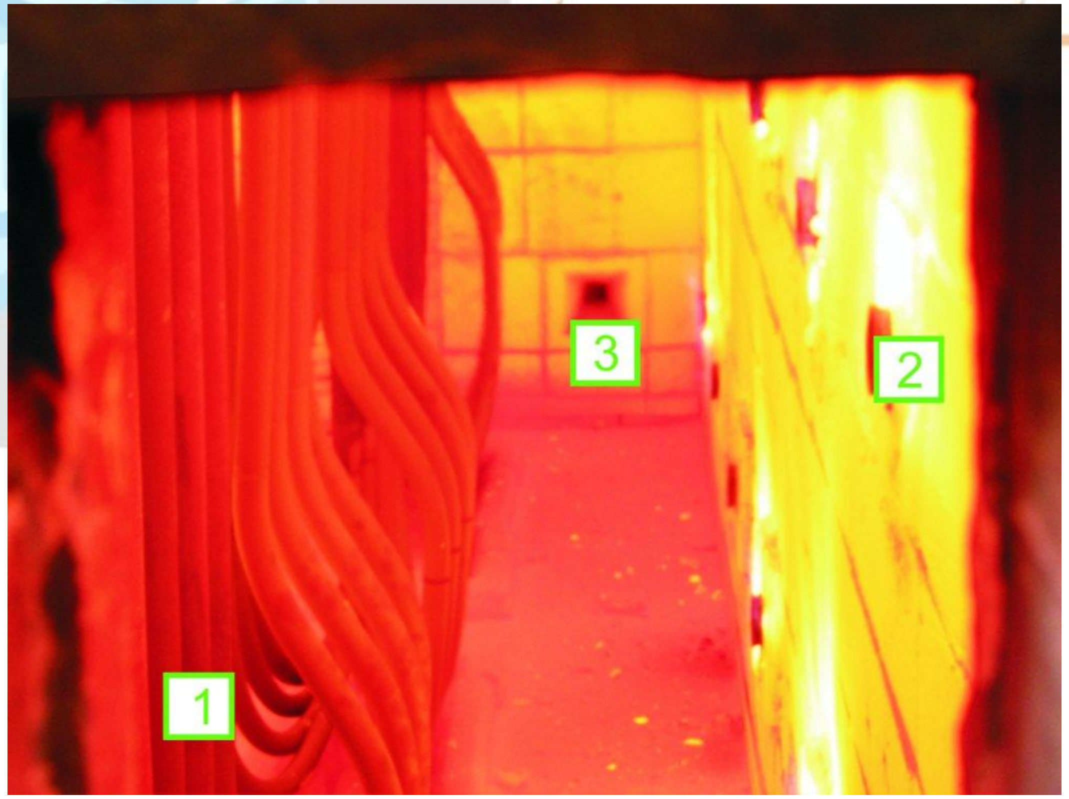
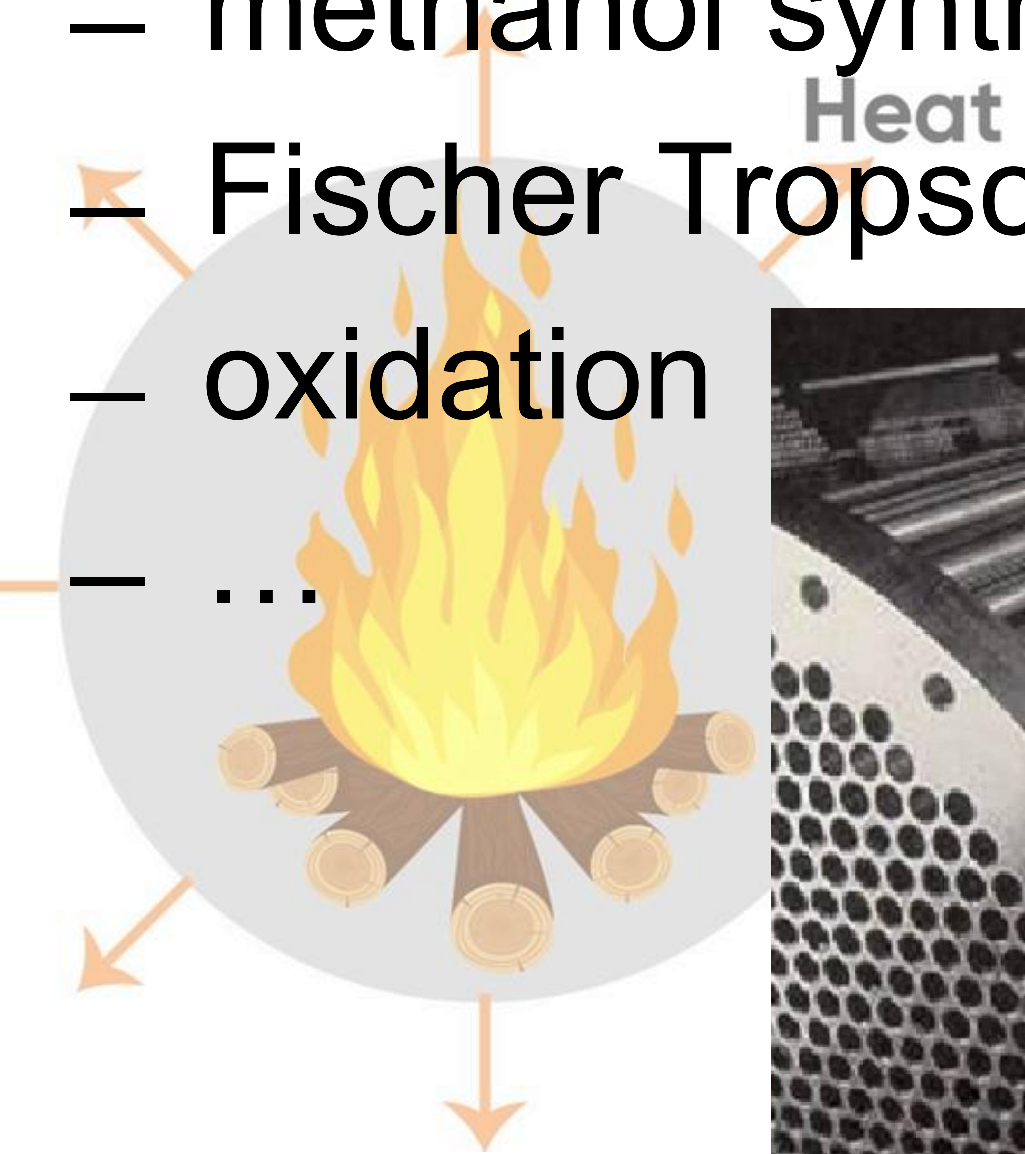
heat requirements in chemical reactions

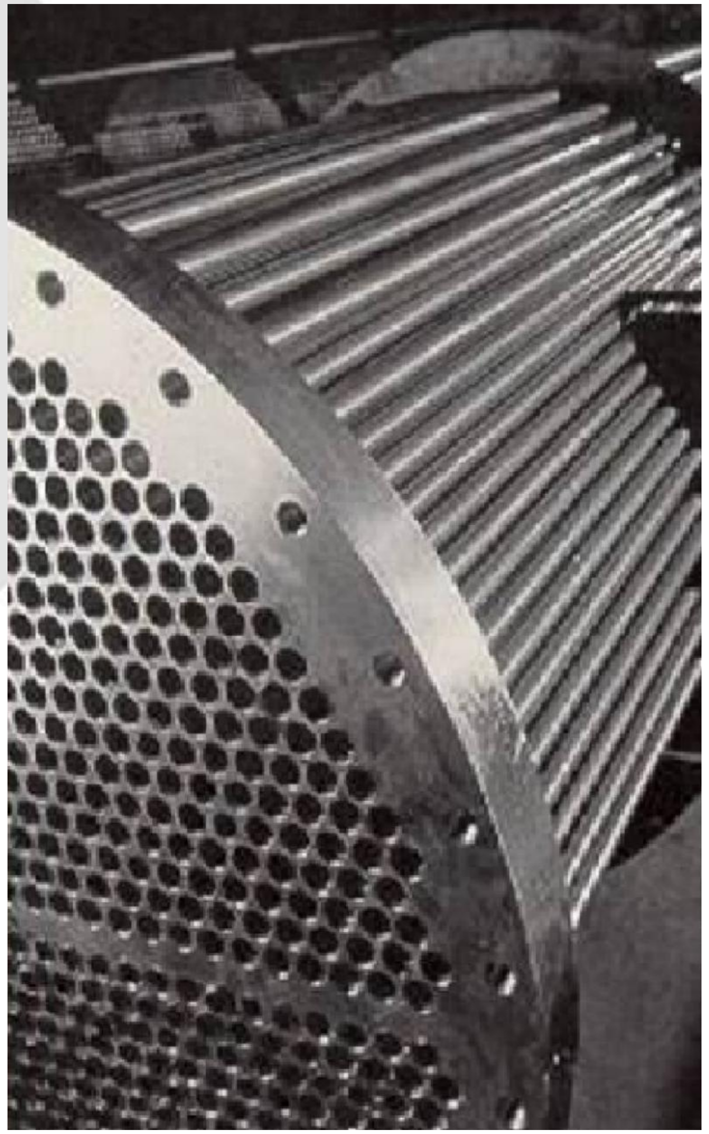
- endothermic reactions
  - thermal cracking
  - dehydrogenation
  - reforming
  - …





- exothermic reactions
  - methanol synthesis
  - Fischer Tropsch
  - oxidation
  - …





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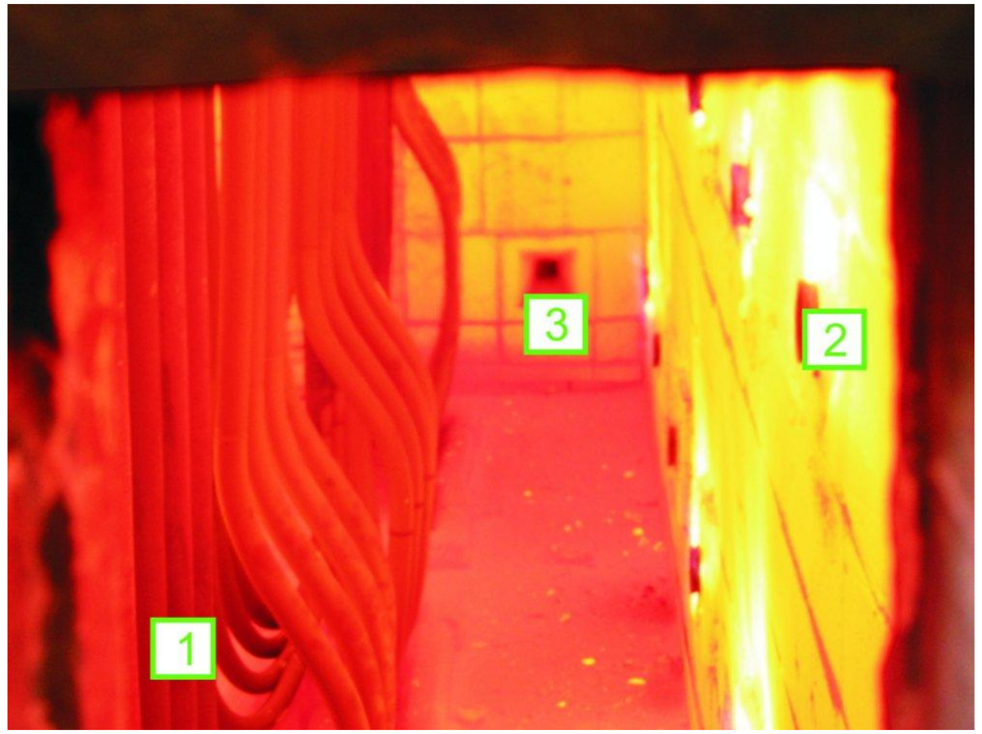
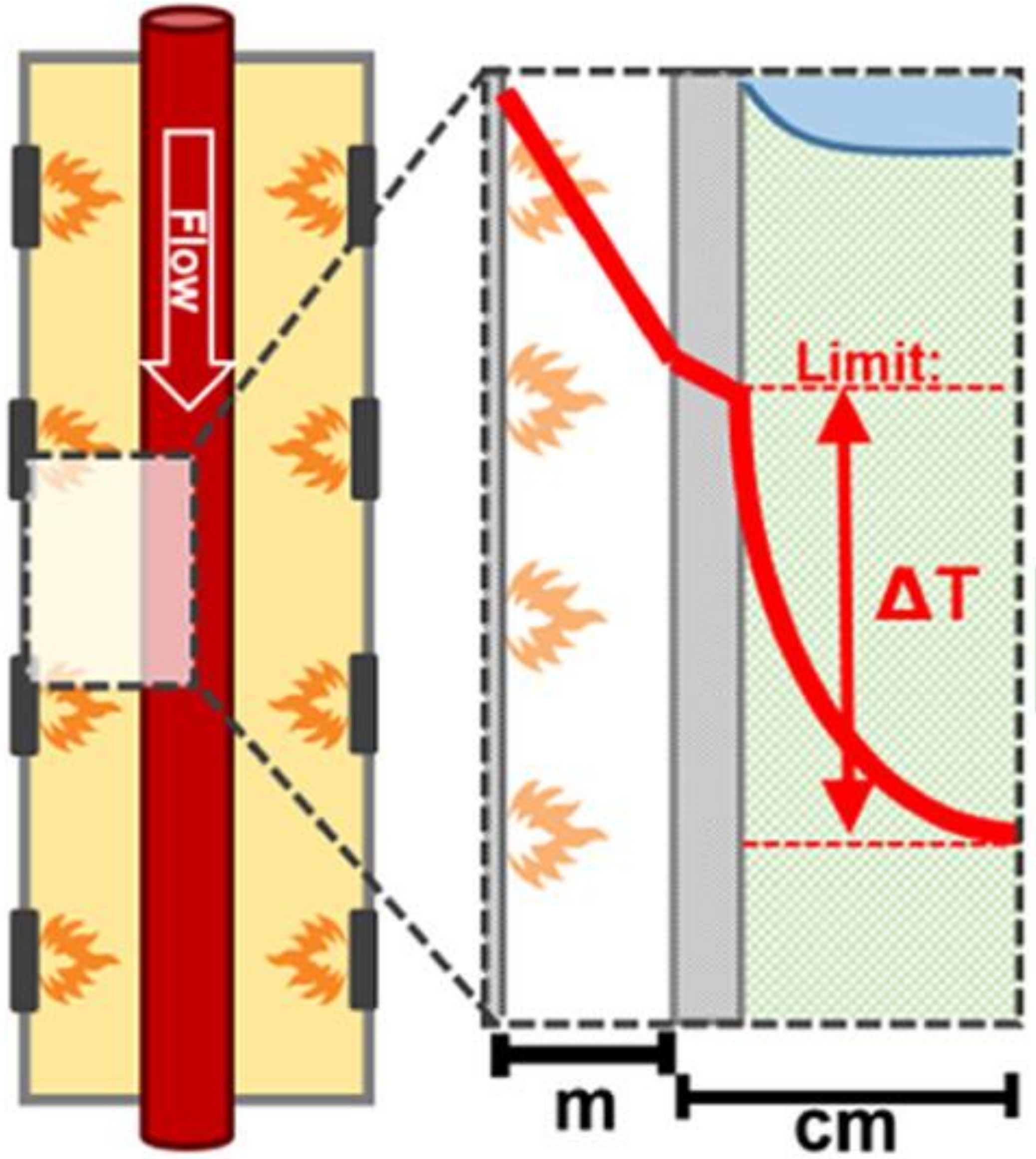
Westerterp, et al. *Chemical Reactor Design and Operation* Wiley (1991)

(strongly) endothermic reactions

- heat transport focused reactor design
  - narrow tubes
  - fired furnace
- pronounced temperature gradients





Wismann, et al. *Ind. Eng. Chem. Res.* 58 (2019) 23380

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how can we enhance heat transfer?

heat containment

electrification

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how can we do even better?

microwave

induction

heating from the inside

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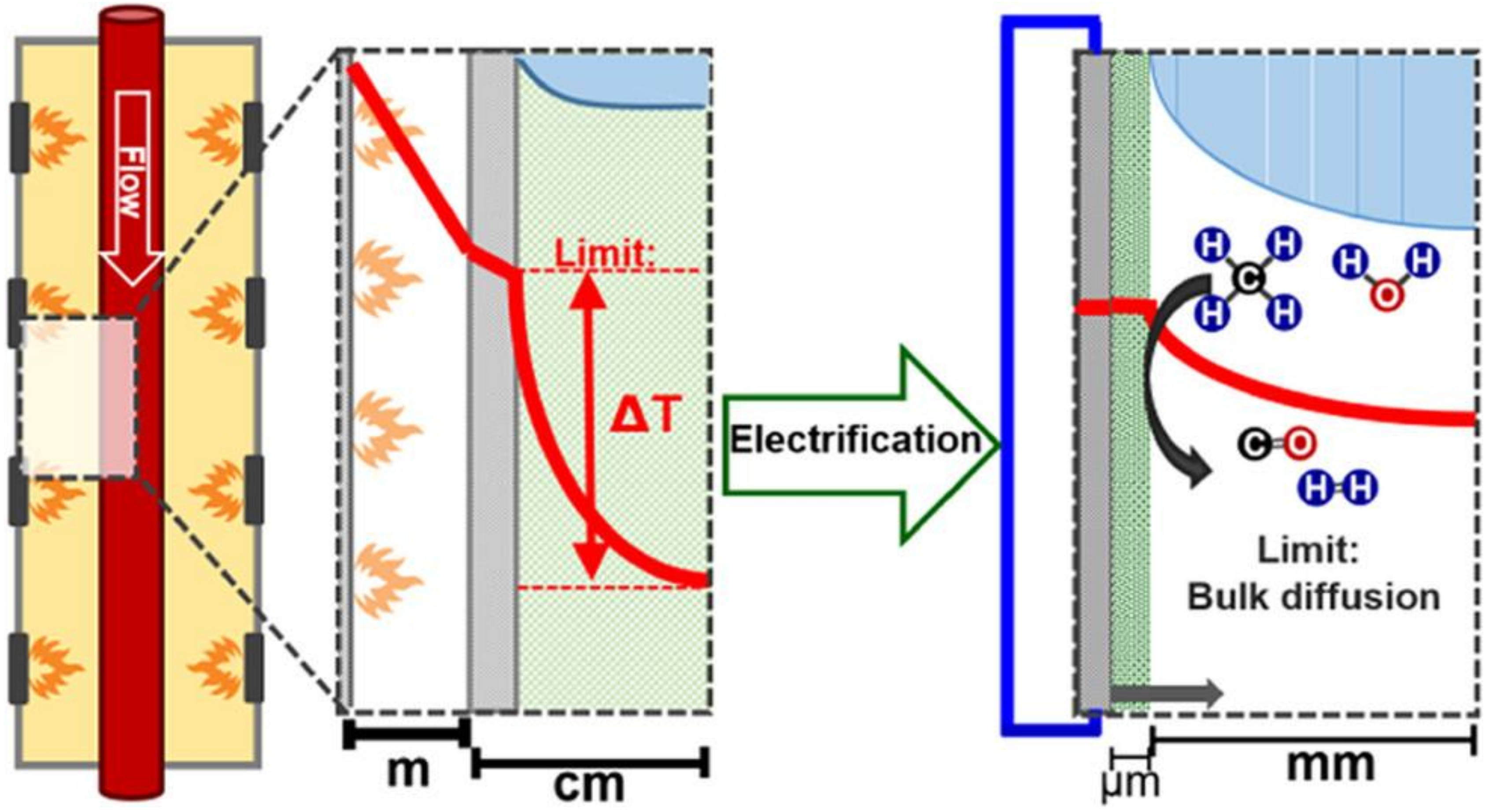
reactor electrification

electrical heating -> overcoming limitations of combustion in furnaces

advantageous in terms of:

- energy efficiency
- process control
- safety and maintenance
- rapid heating
- …



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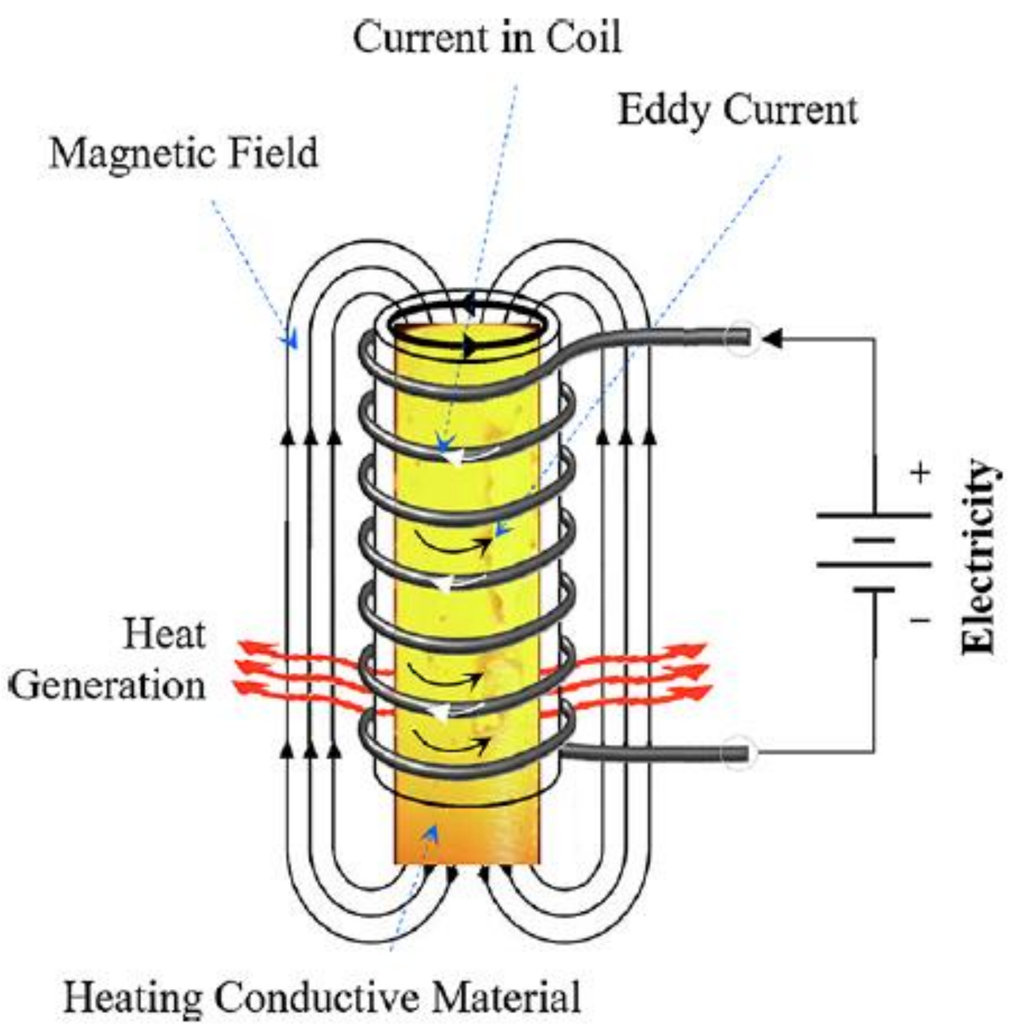
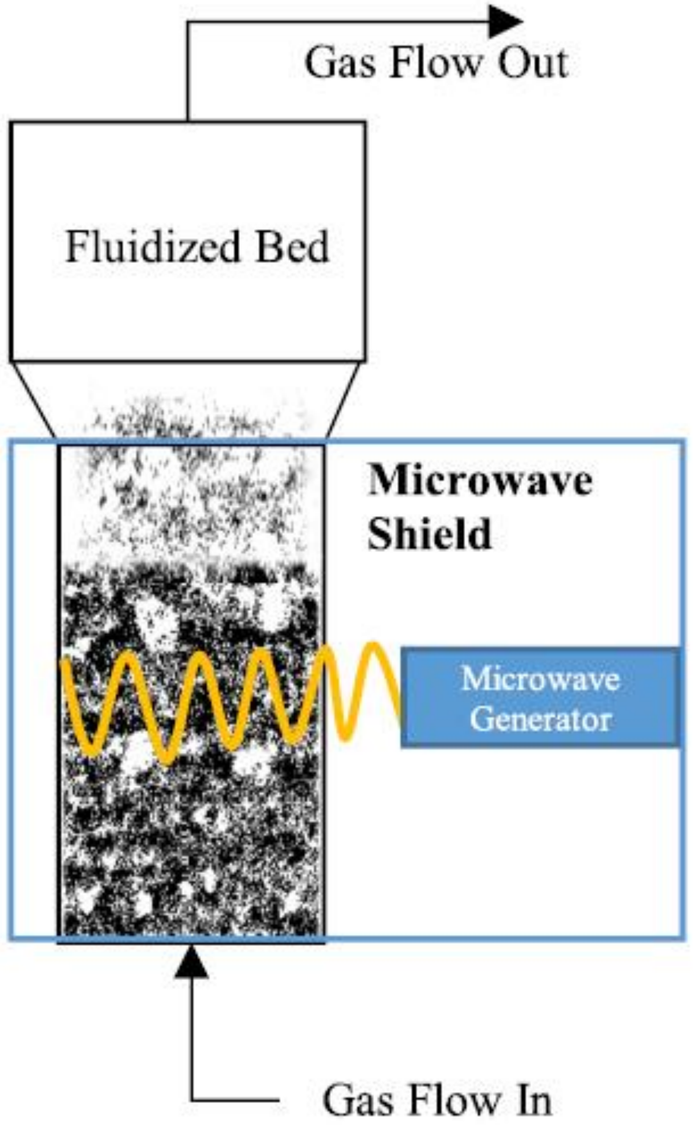
electrical heating

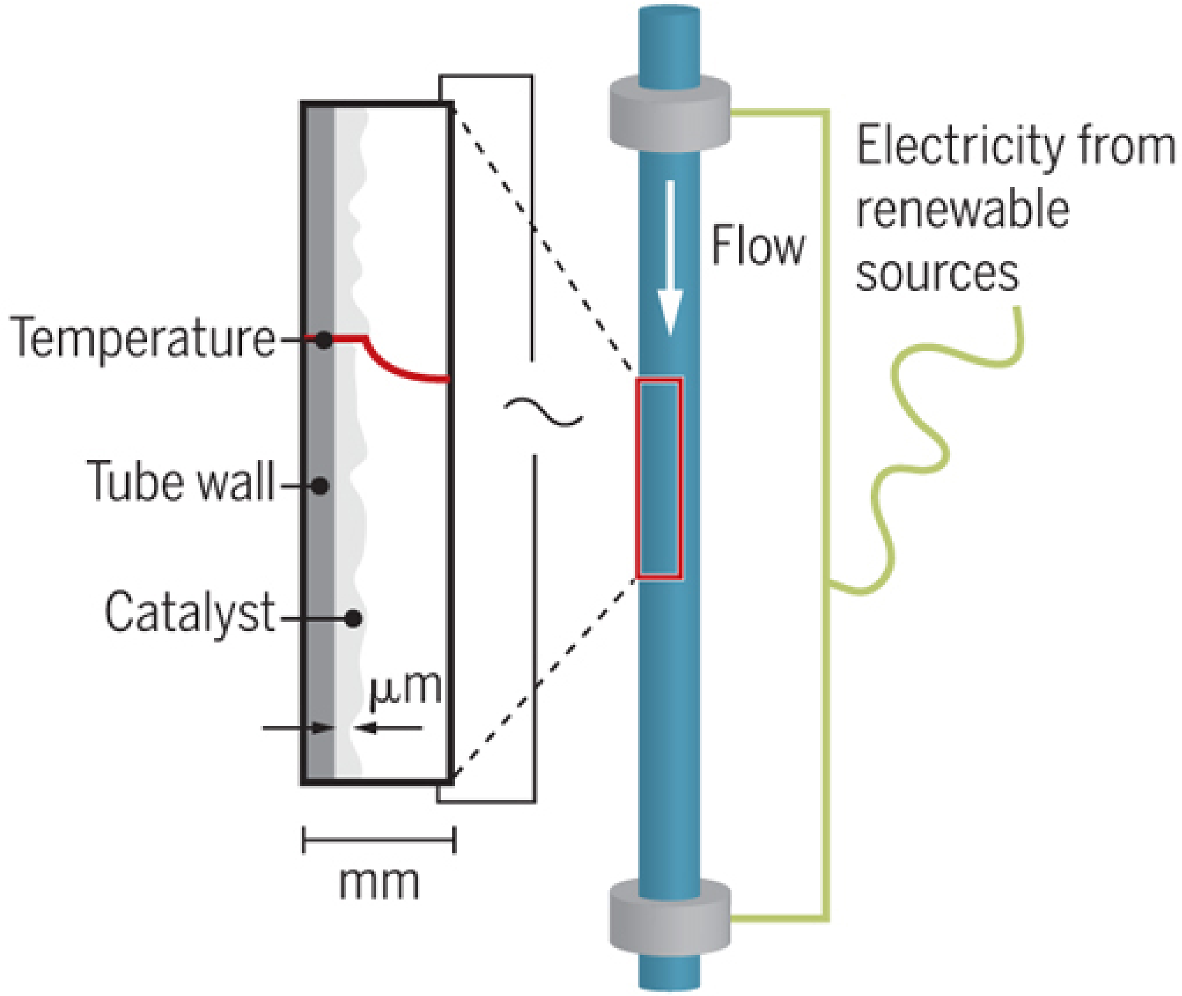
induction



microwave



Joule

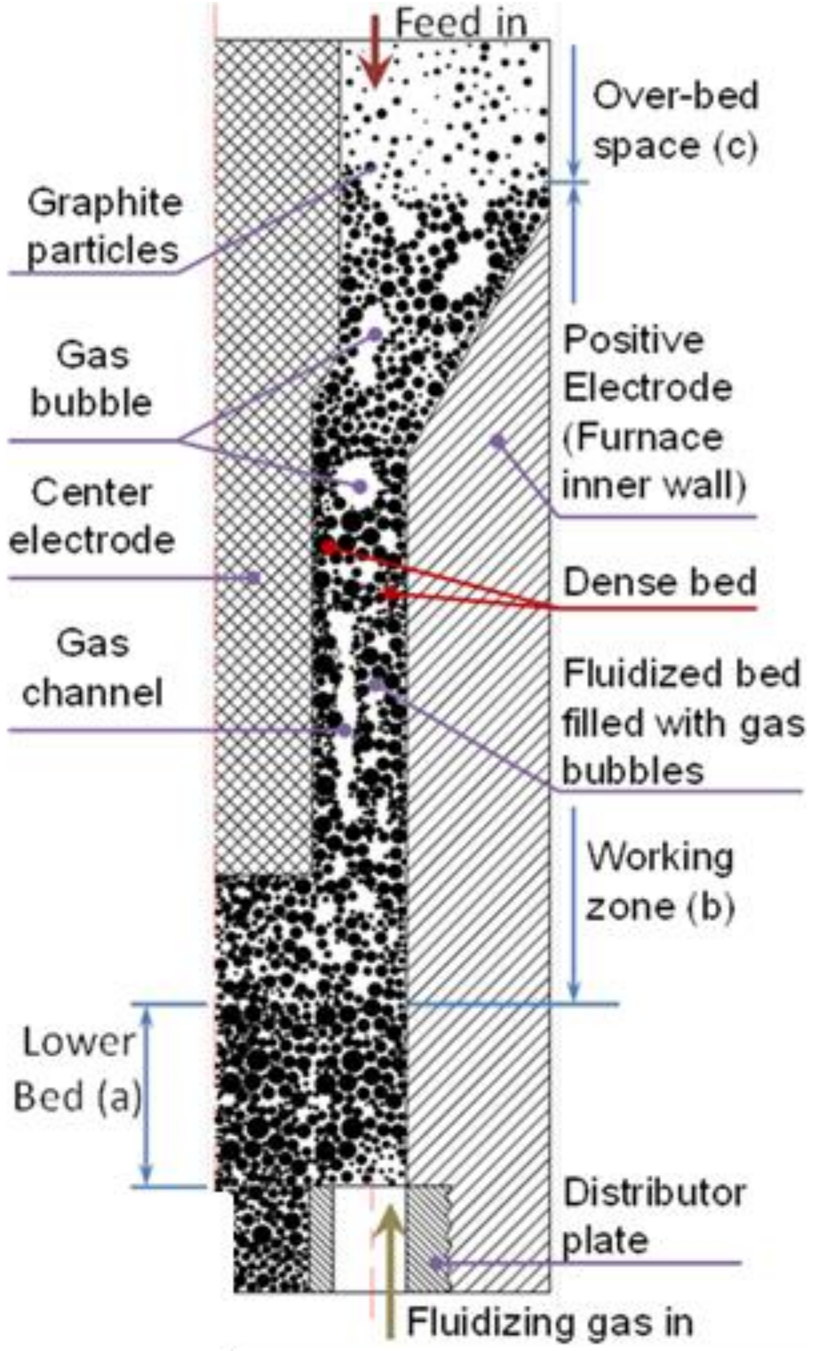


Imtiaz, et al. *Ind. Eng. Chem. Res.* 63 (2024) 4205

sonication
plasma

ElectroThermal Fluidized Bed reactor (ETFB)

- combination:
  - fluidization
  - Joule heating
- compared to conventional fluidized beds
  - better control over bed temperature
  - highly energy efficient
  - rapid and uniform heating



Fedorov *J. Fluids Eng.* 138 (2016) 044502

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TMEC

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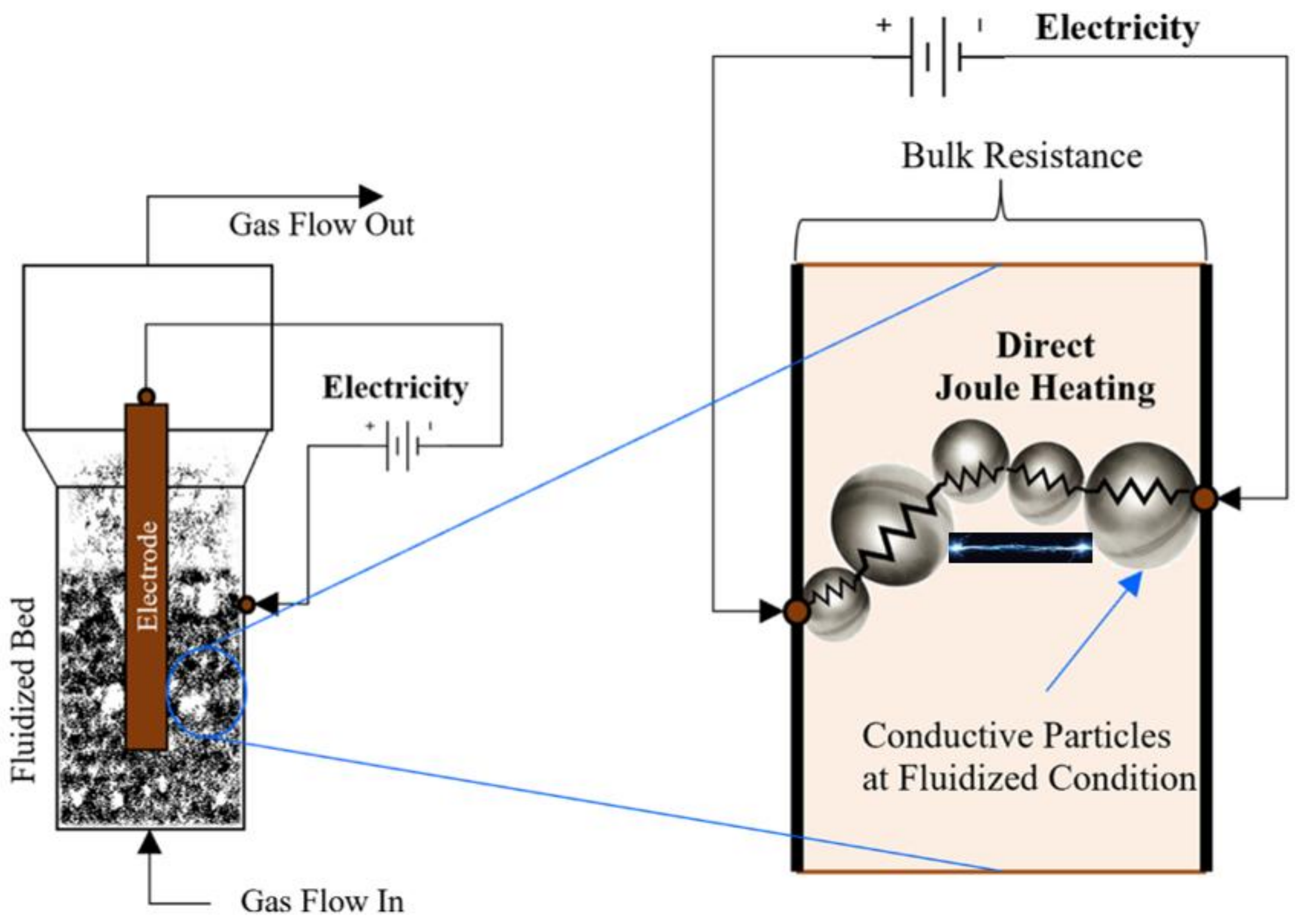
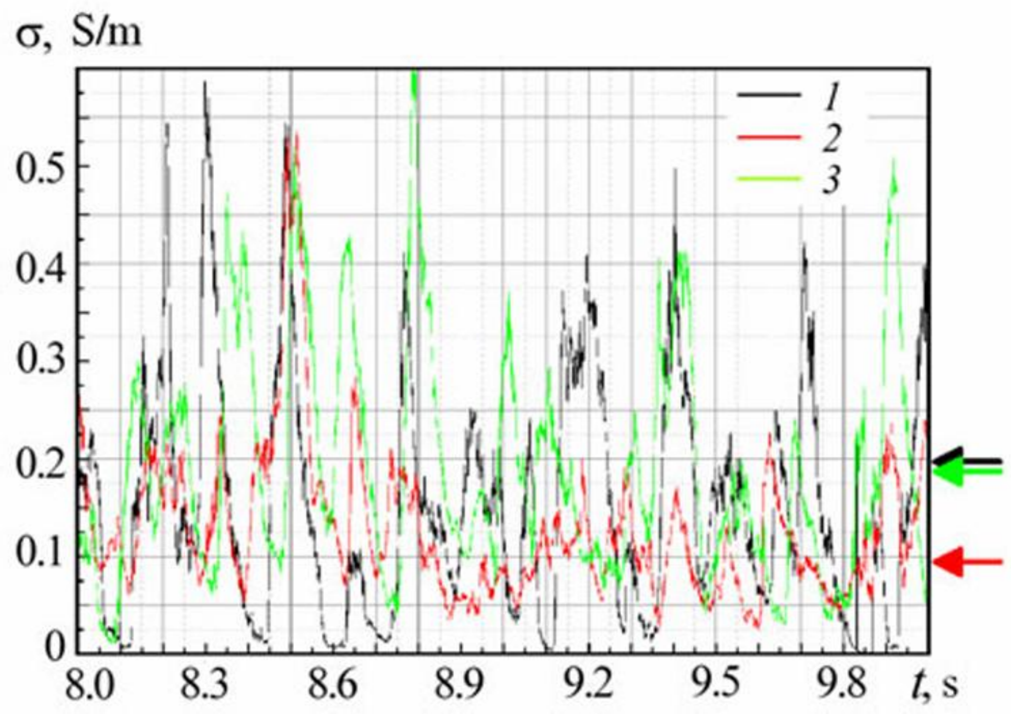
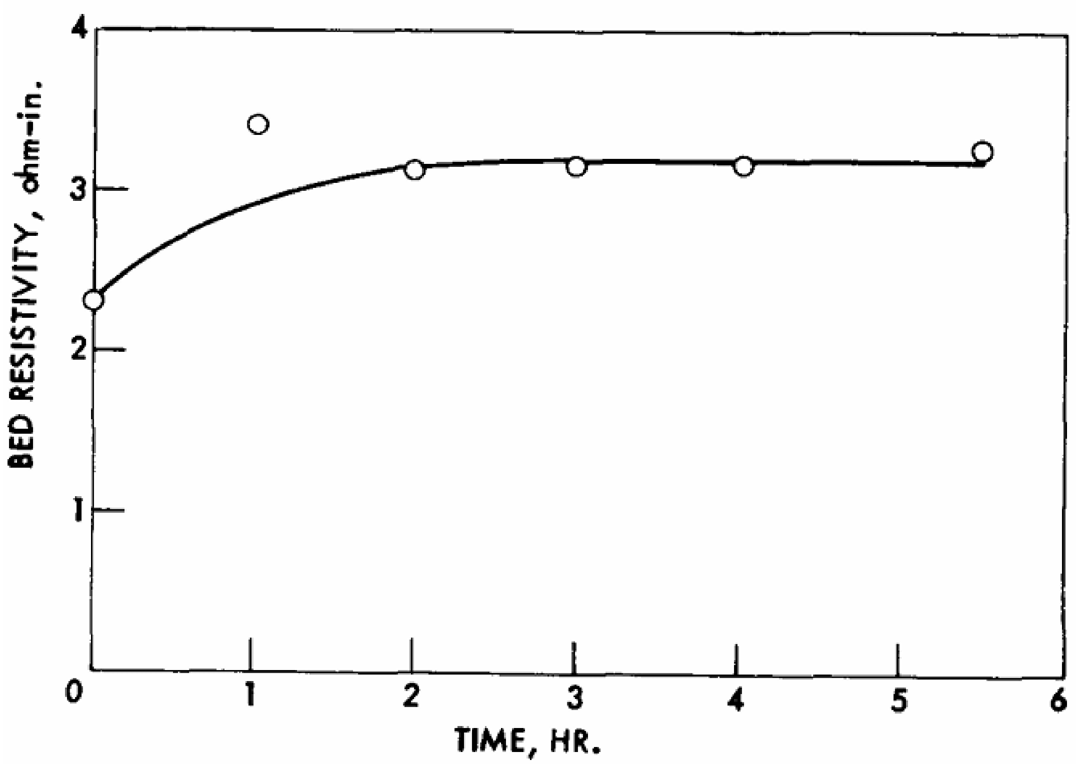
Joule heating in a fluidized bed







Ind. Eng. Chem. Res. 2024 https://pubs.acs.org/doi/10.1021/acs.iecr.3c04232
Malinovskii et al., J. Eng. Physics Therm, 85(2), 251–258, 2012
Pulsifer and Wheelock, Interim Report No. 3, Iowa State University, Ames, 1974.

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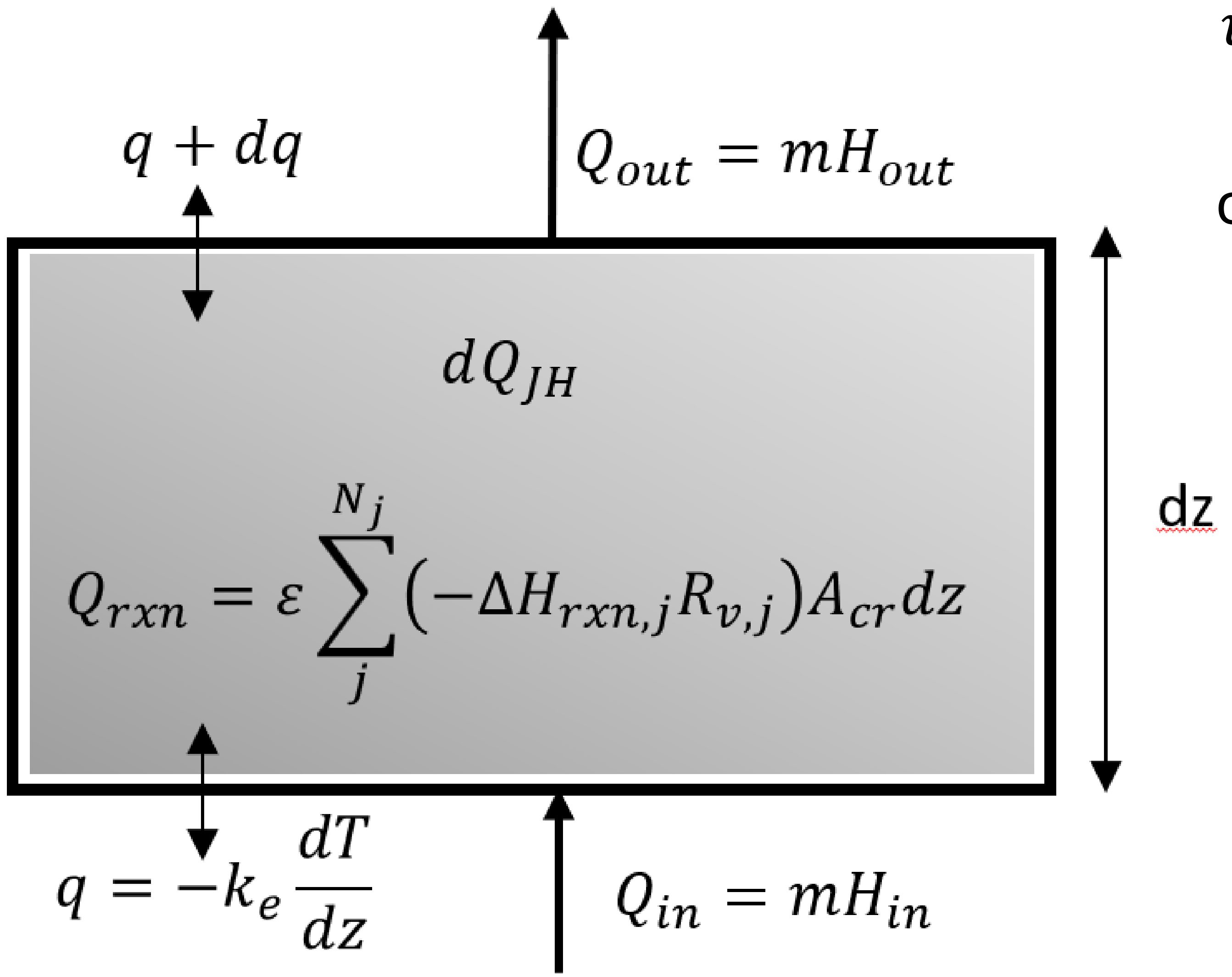
ETFB reactor heat balance



$$u\rho_g Cp_g \frac{dT}{dz} - k_e \frac{d^2T}{dz^2} - \varepsilon \sum_{j}^{N_j} (-\Delta H_{rxn} R_{v,j}) - \frac{\boldsymbol{dQ_{JH}}}{\boldsymbol{dzAc_{reactor}}} = 0$$

convection conduction heat of reaction heat generation
→ Joule heating term

assumptions

- bubbling fluidization regime
- low- and high-density phases are at the same temperature
- no radial profiles
- constant effective conductivity at average temperature and composition
- adiabatic operation
- steady state operation

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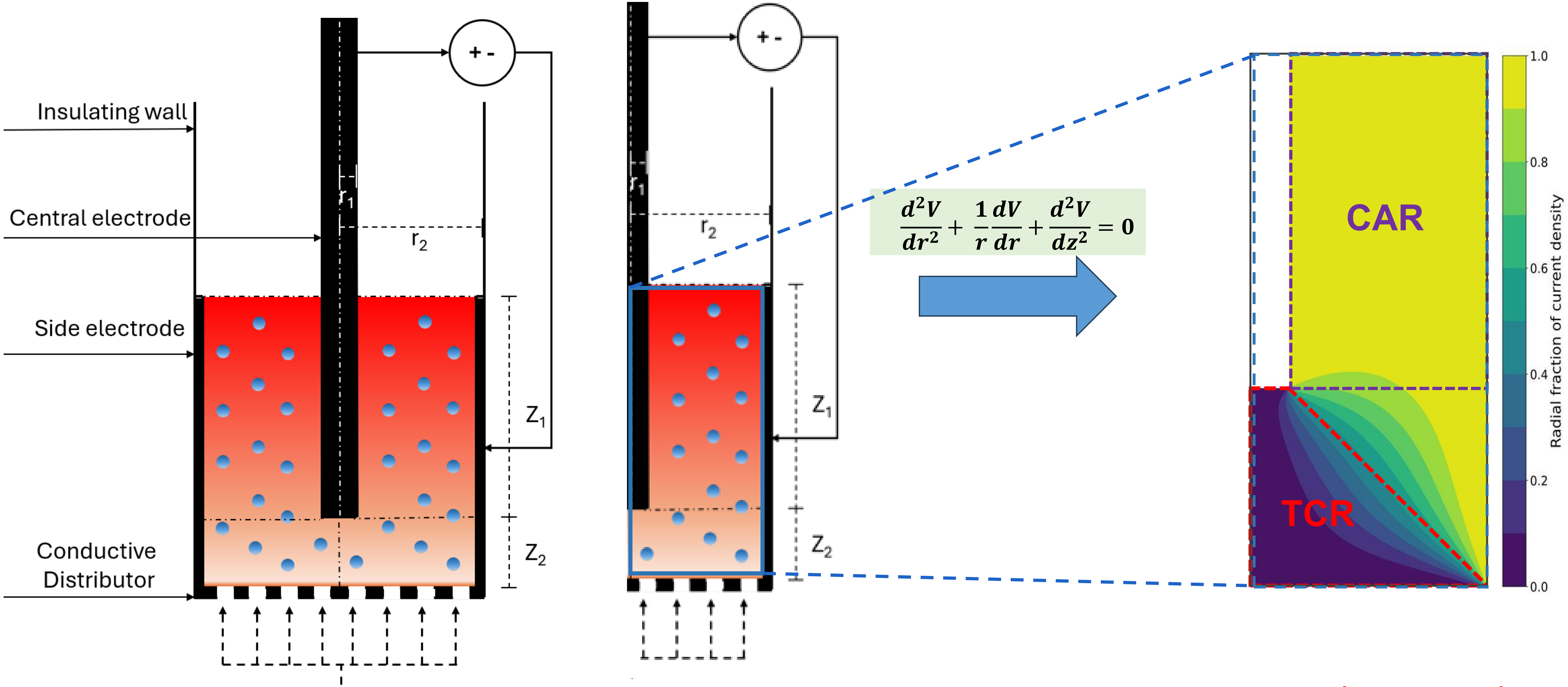
ETFB electrical field

coaxial resistor



$$\frac{d^2V}{dr^2} + \frac{1}{r}\frac{dV}{dr} + \frac{d^2V}{dz^2} = 0$$

truncated cone resistor

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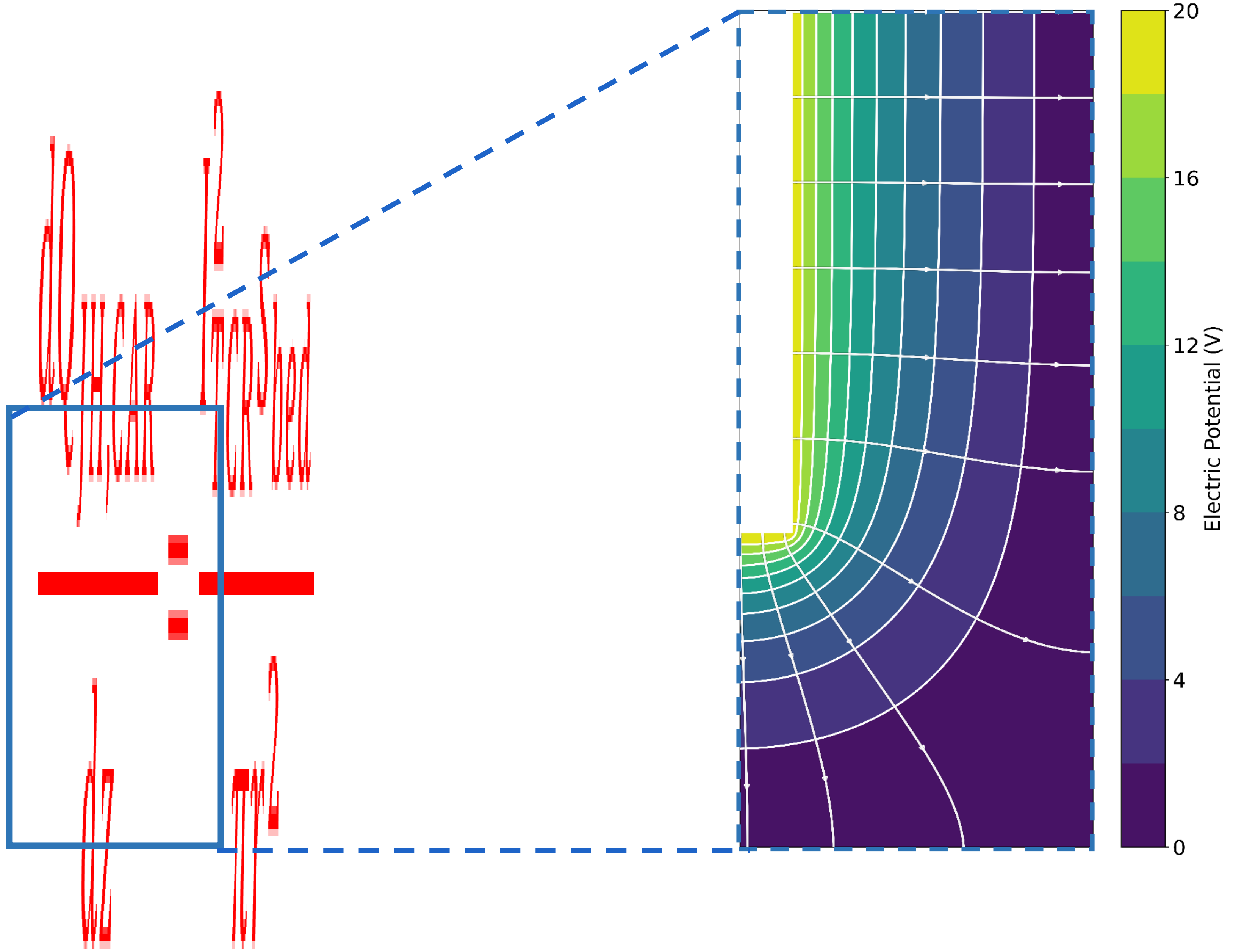
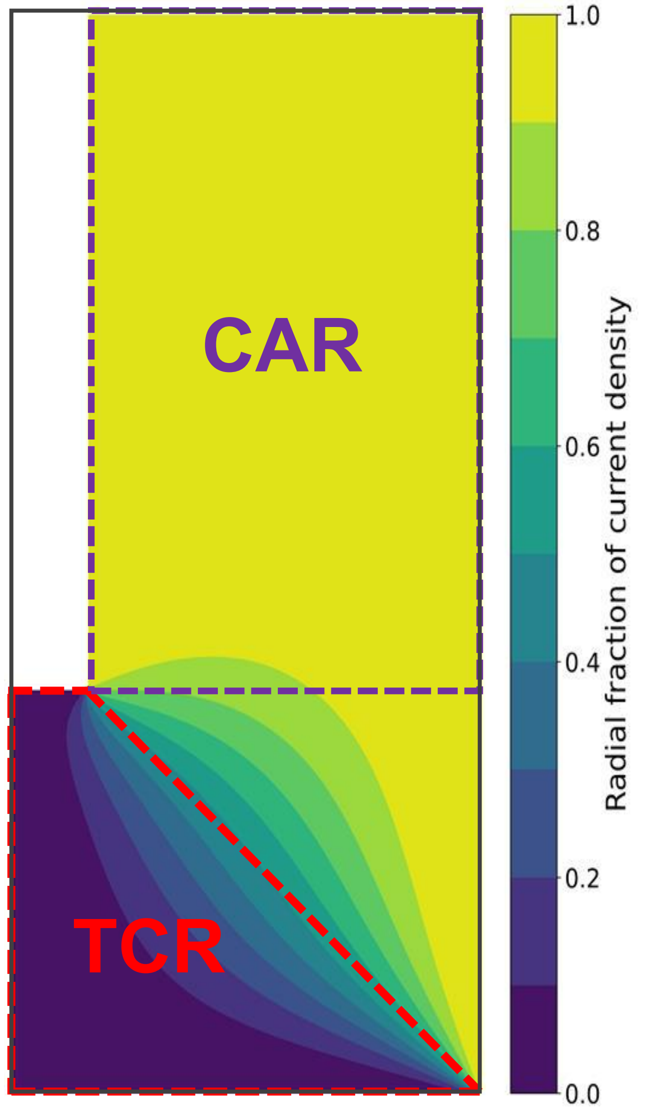
ETFB electrical field modeling

Laplacian Field (LF)



$$\frac{dQ_{JH}}{dz} = \int_0^R -\frac{2\pi}{s_{bed}}\left(\left(\frac{d\triangle V}{dr}\right)^2 + \left(\frac{d\triangle V}{dz}\right)^2\right) rdr$$

Current Partitioning (CP)



$$\frac{dQ_{JH,CAR}}{dz} = \frac{V^2 2\pi}{s_{bed} ln\left(\frac{r_2}{r_1}\right)}$$

$$\frac{dQ_{JH,CAR}}{dz} = \frac{I_{TCR}^2 s_{bed}}{\pi r^2}$$

CH_4 pyrolysis in ETFB reactor

power density profile

CH_4 = 0.72 kg hr^{-1}

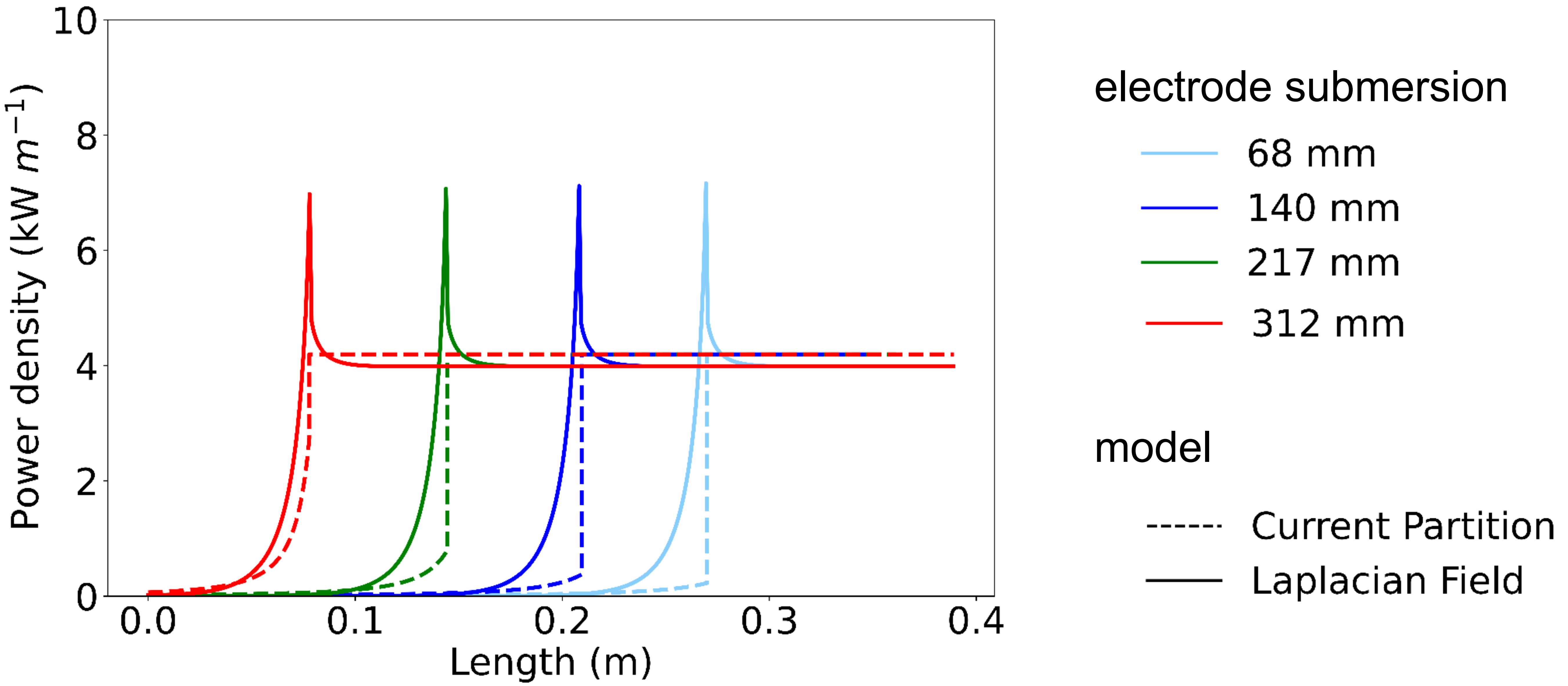
T_{in} = 600°C

P = 1atm

ST = 1 kg h m^{-3}

$\sigma = 50\ \Omega\,.\,\mathrm{cm}$

$\Delta V = 20\mathrm{V}$



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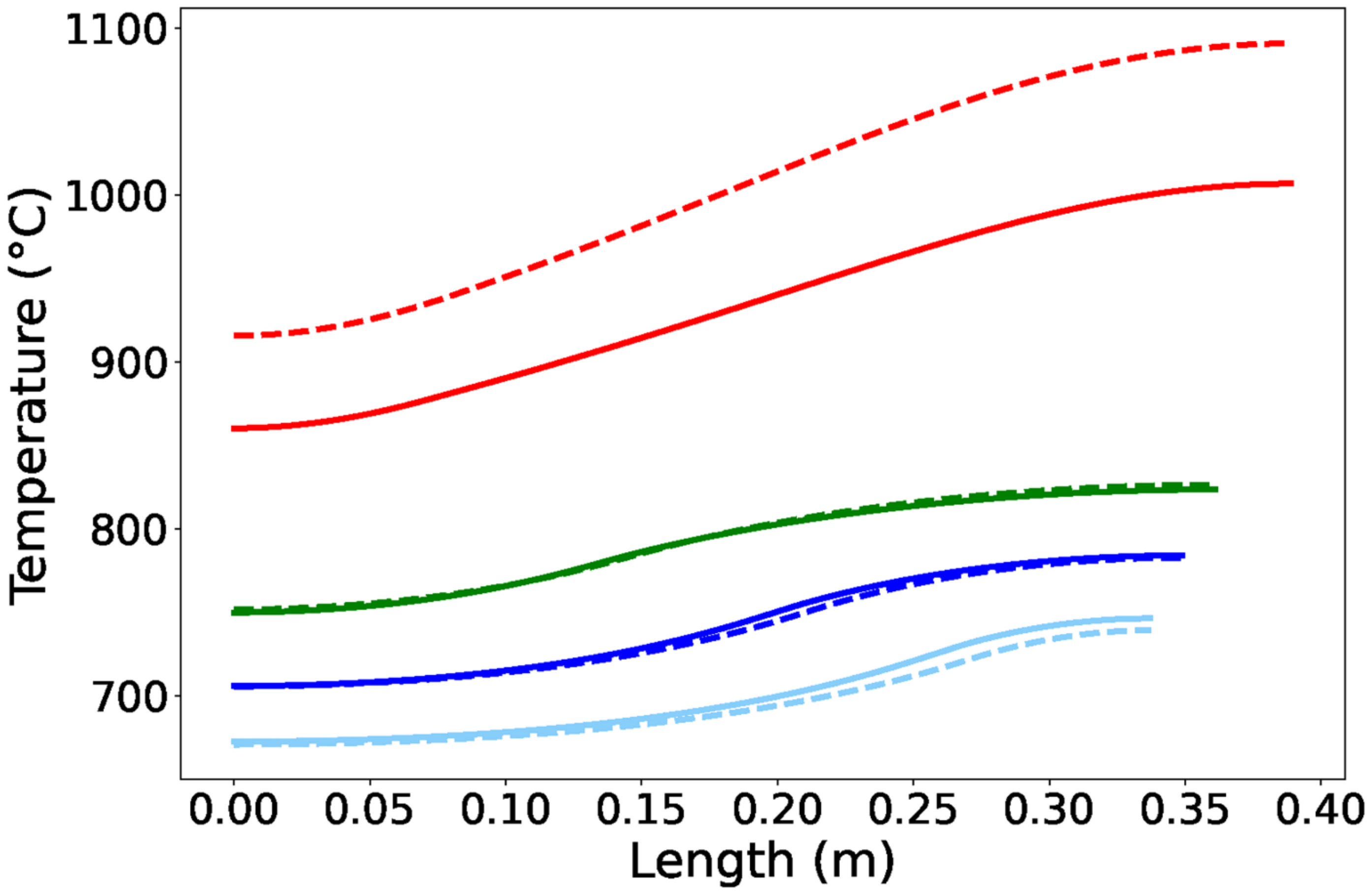
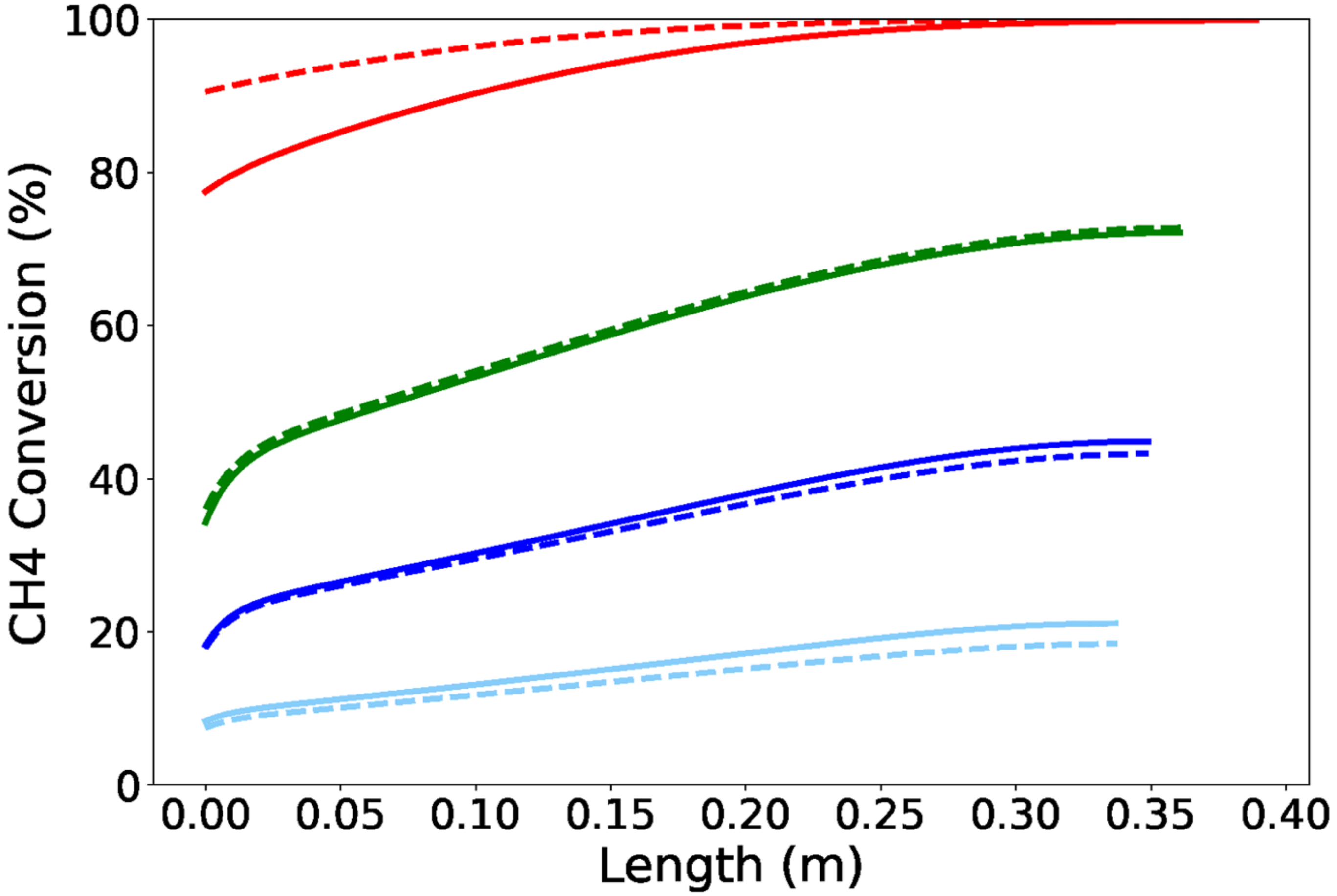
temperature profile



CH_4 conversion profile



electrode submersion

- 68 mm
- 140 mm
- 217 mm
- 312 mm

model

- ------ Current Partition
- —— Laplacian Field

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conclusions

From Waste Treatment to Fuel Production: Ensuring Energy Circularity

- waste
  - biomass
    - forestry & agricultural residues
    - excess sludge from waste water treatment

- treatment via biogas production
  - CO_2 hydrogenation
  - H_2 obtained from CH_4 pyrolysis
  - reactor electrification:
    - heating from inside: “electricity is in the catalyst”
    - ElectroThermal Fluidized Bed (ETFB) reactor

- fuel production (for endothermic reactions):
  - Sustainable Aviation Fuels (SAF) …

Interreg
Cofinancé par l’Union Européenne
Medegefinancierd door de Europese Unie
France – Wallonie – Vlaanderen

OBIWAN

Sterope

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perspectives and challenges

- other waste
  - plastics
    - pyrolysis
    - hydrotreatment
  - treatment adapted to type of waste

- global treatment scenarios
  - distributed production
  - centralized processing
  - where to transition between both?

- challenges
  - few large-scale vs many small-scale applications
  - (renewable) electricity availability
  - impact on chemistry
  - …

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OBIWAN

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Laura Pirro
Loïc Eloi
Lucas Ivan Garbarino
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