INTERNATIONAL CONFERENCE ON GREEN CARBON (ICGC), SEPTEMBER, 2025

Electrothermal Fluidized Bed Reactor for Methane Pyrolysis: Toward Zero-Emission Hydrogen Production

Soroush Zareghorbaei, Klaus Jacobs, Sébastien Siradze, Jeroen Lauwaert, Joris Thybaut

Laboratory for Chemical Technology (LCT), Ghent University, Technologiepark 125, 9052, Ghent , Belgium

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e-CODUCT

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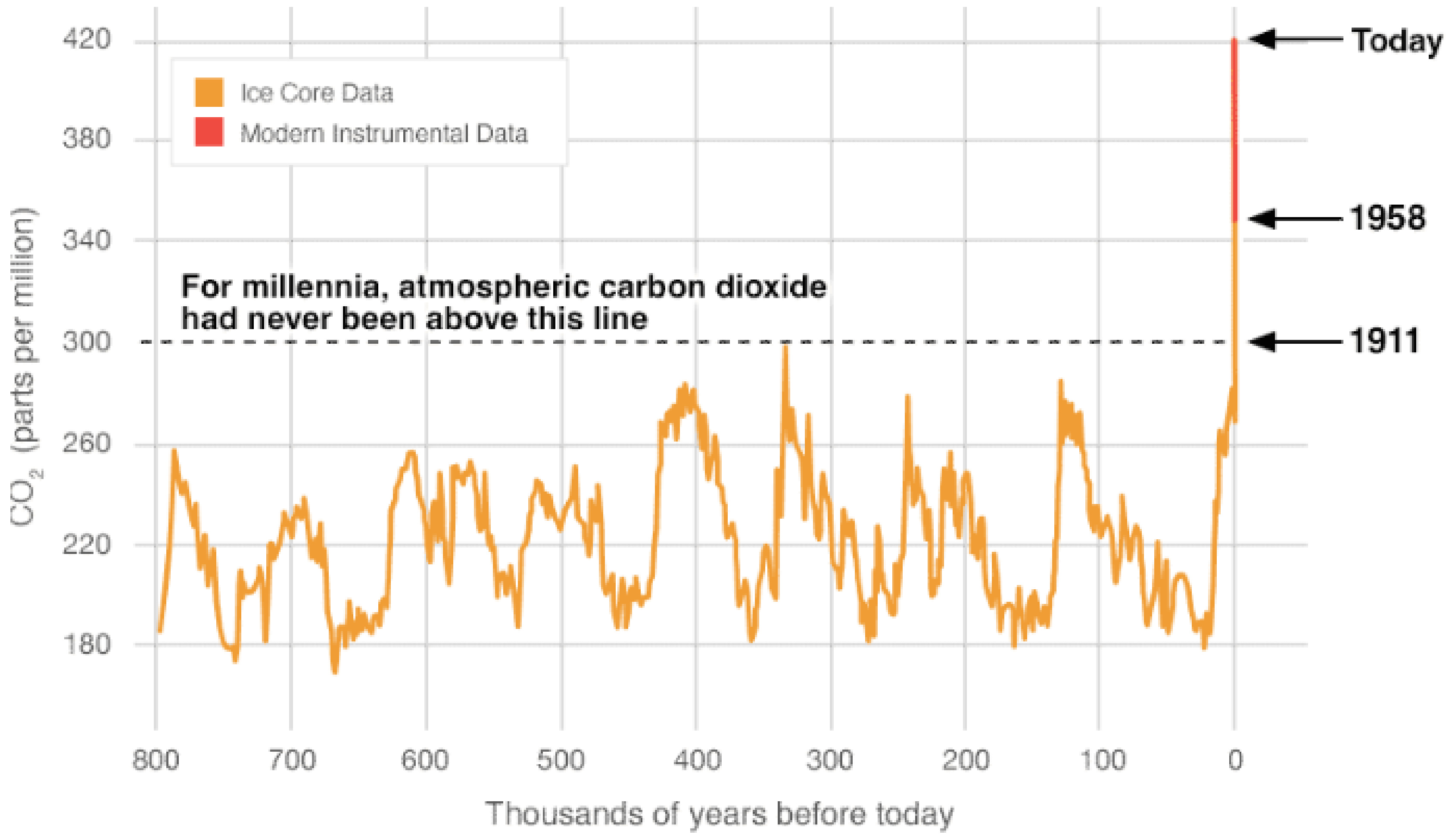
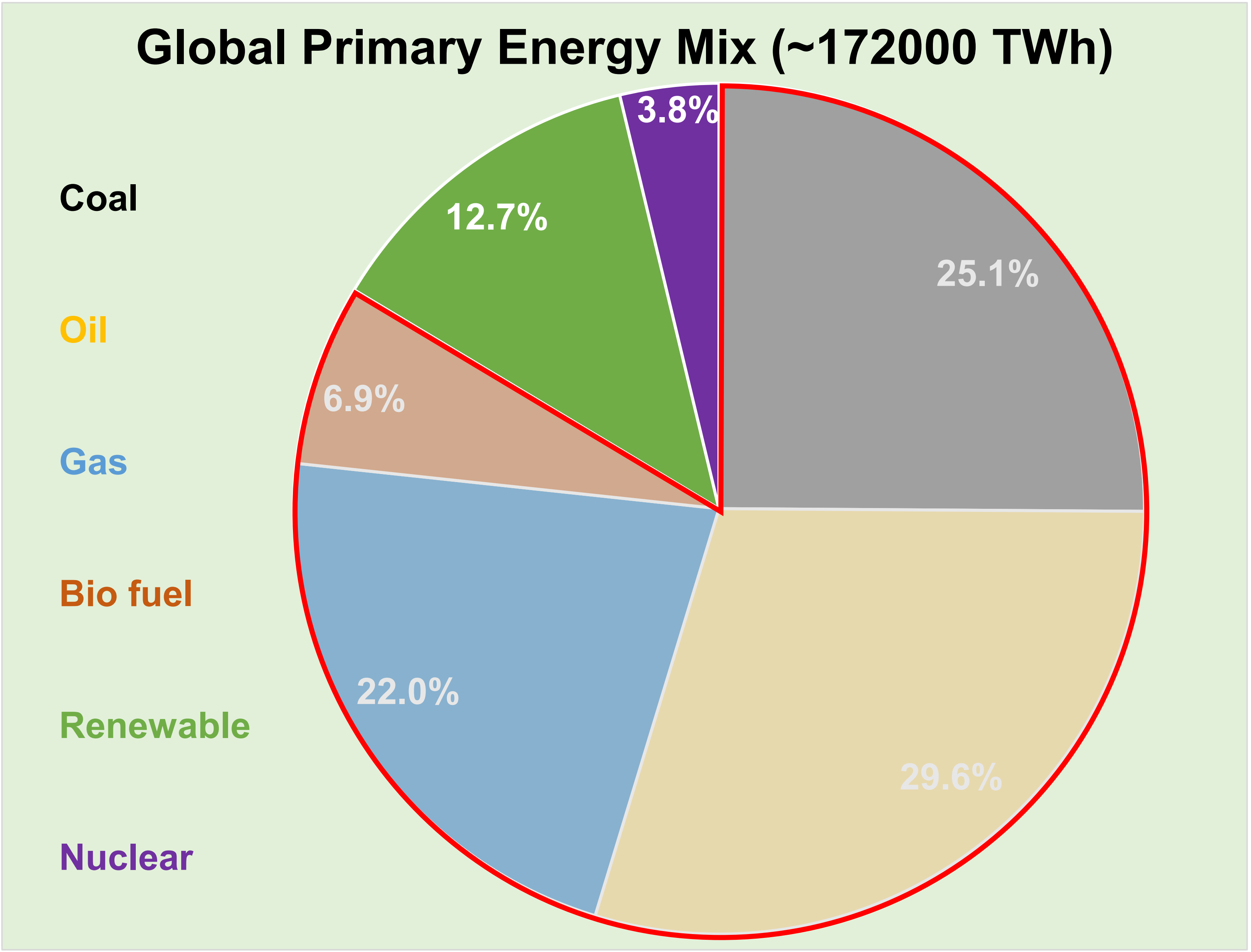
France – Wallonie – Vlaanderen
OBIWAN

CO_2 challenge and energy transition





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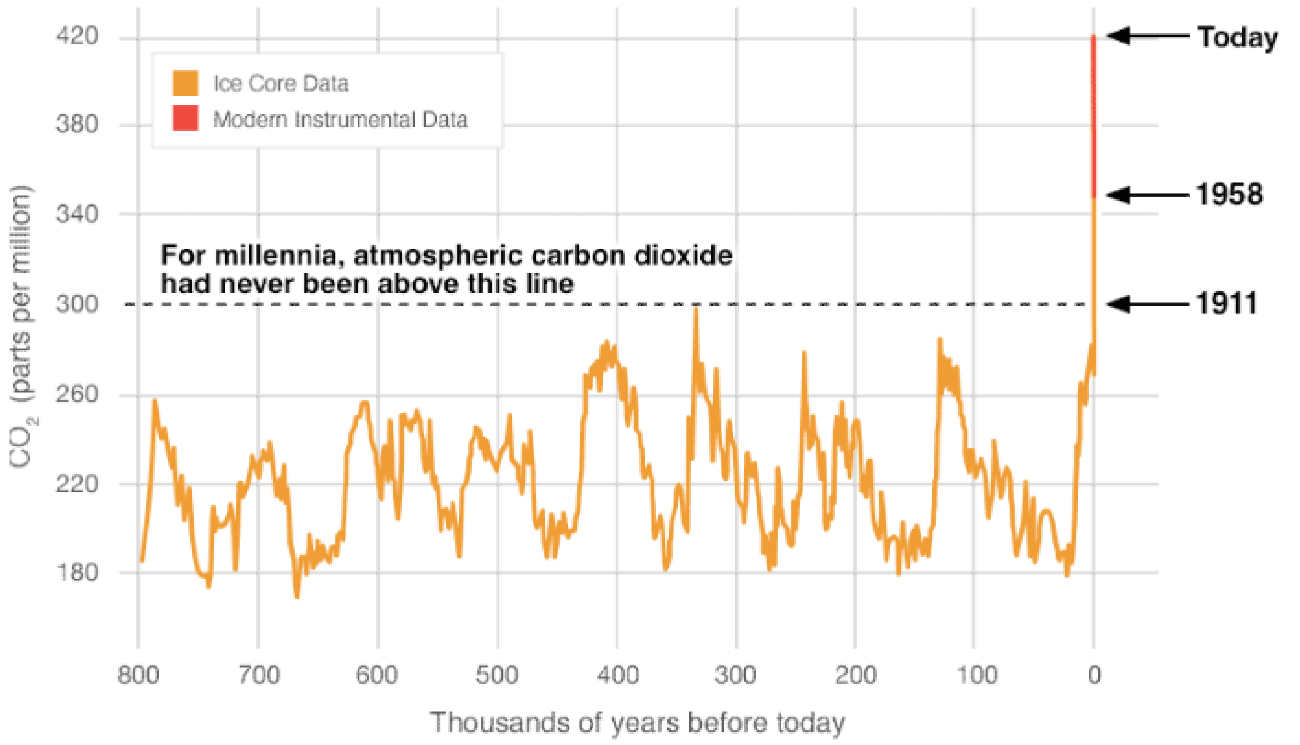
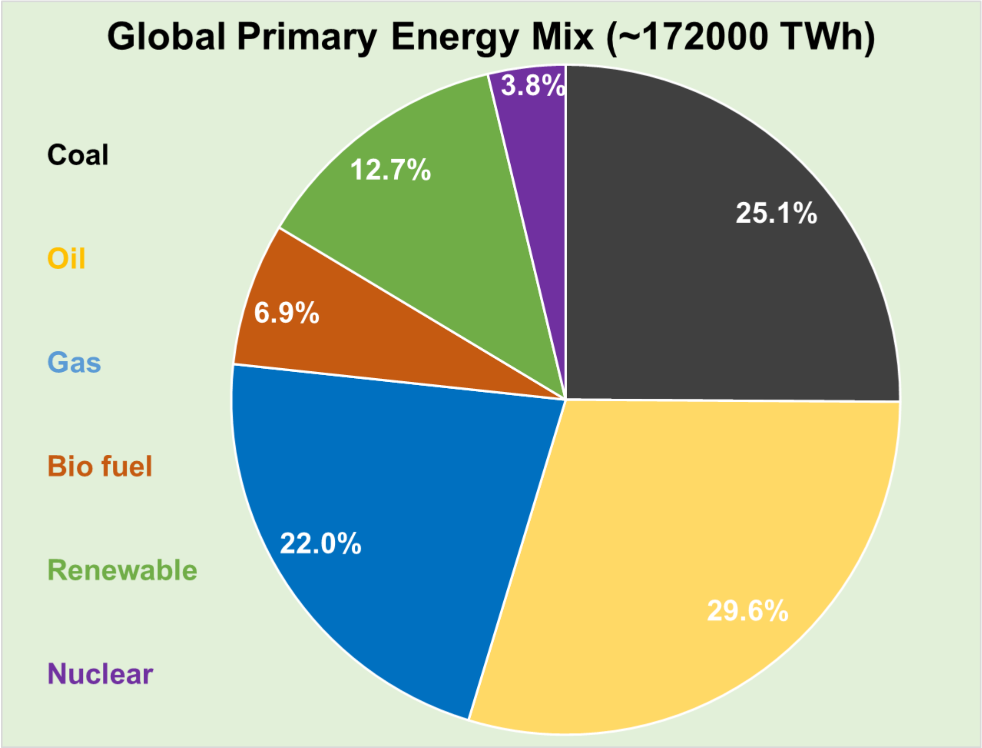
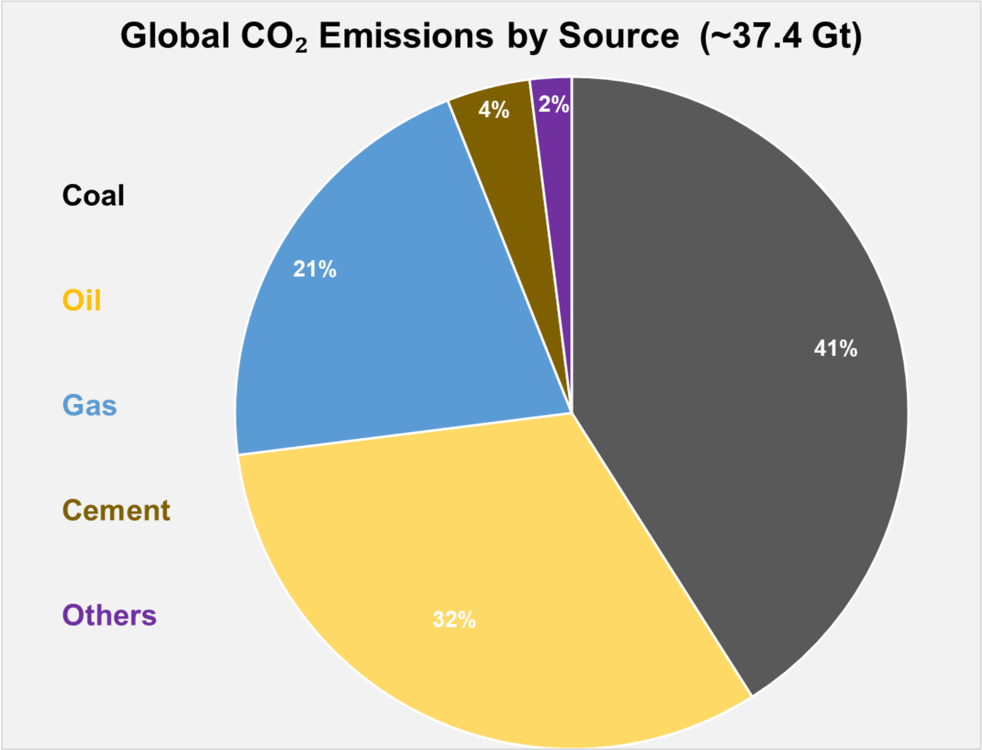
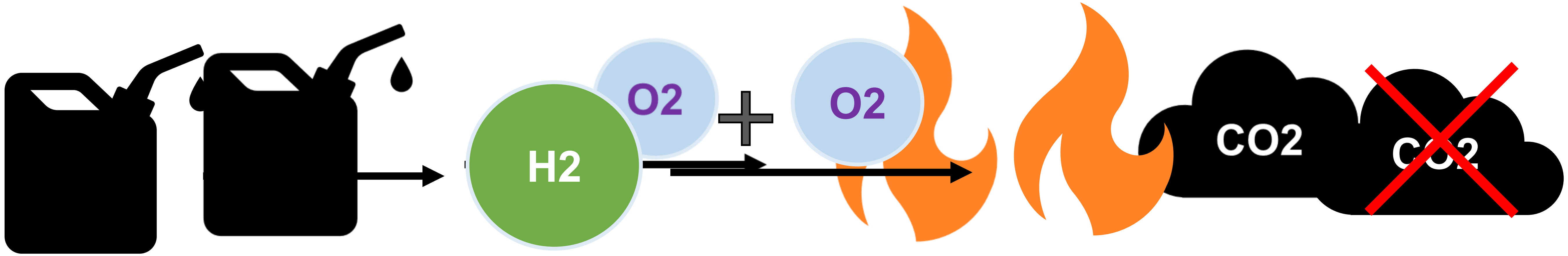
CO_2 challenge and energy transition

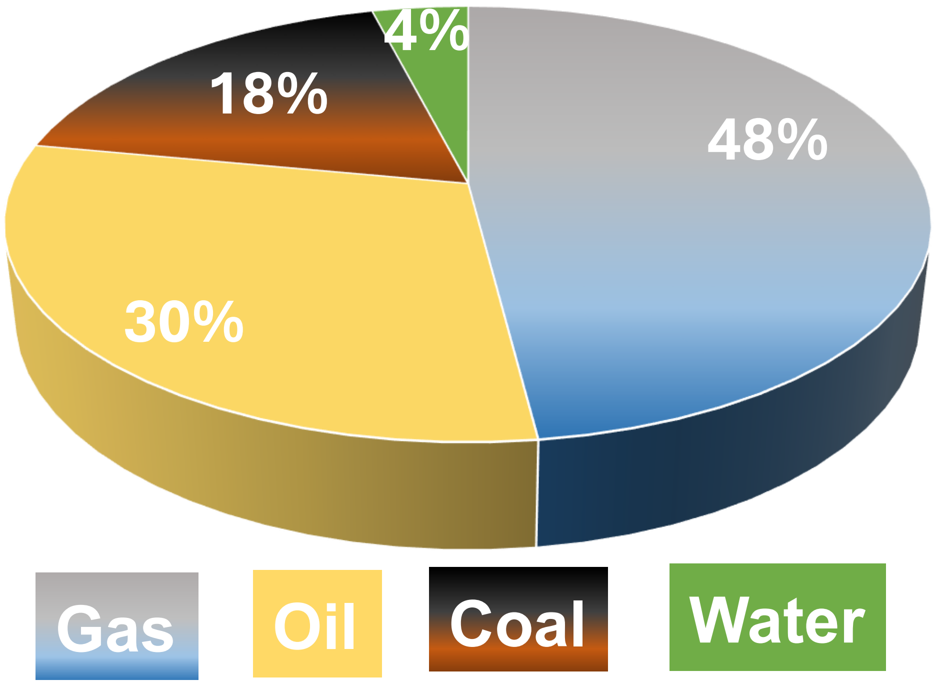



Global Primary Energy Mix (~172000 TWh)


Global CO_2 Emissions by Source (~37.4 Gt)



H_2 production technologies


H_2 production feedstocks

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:

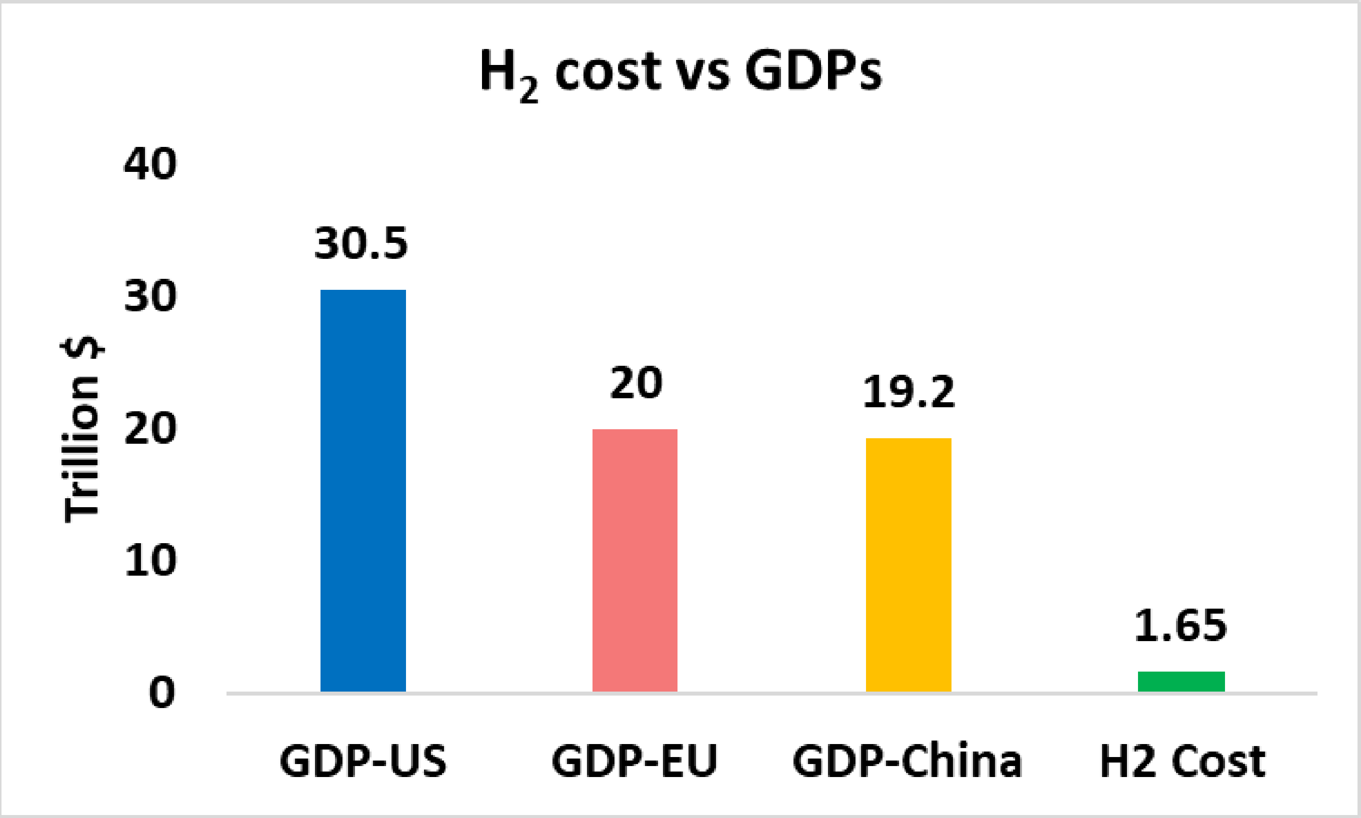
- ☐ less energy-intensive
- ☐ Less greenhouse gas emission
- ☐ Produces H_2 with high purity
- ☐ Cheap catalyst
- ☐ Sulfur-resistive catalyst

Gholami et al., *Journal of Industrial and Engineering Chemistry , 2025*

can H_2 replace methane affordably?

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

- CH_4 consumption in 2024: ~2.9 Gt
- **H_2 route needs ~50% more CH_4**
- H_2 production ~1.1 Gt
- **CO_2 avoided ~9 Gt/yr**
- H_2 production cost ~ 1.5 $/kg
- **Annual H_2 cost ~$1.65 trillion**



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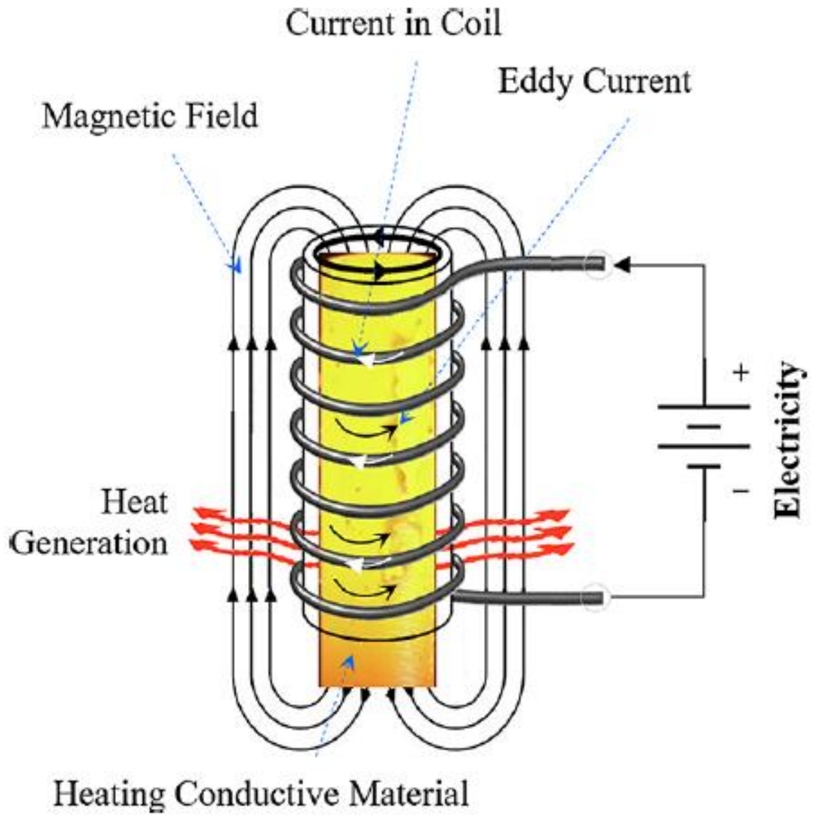
outline

- introduction
- model development
  - ElectroThermal Fluidized Bed reactor (ETFB)
- processes
  - e-CODUCT: simultaneous CO_2 and H_2S abatement
  - OBIWAN: biogas upcycling via H_2 production
- conclusions & perspectives

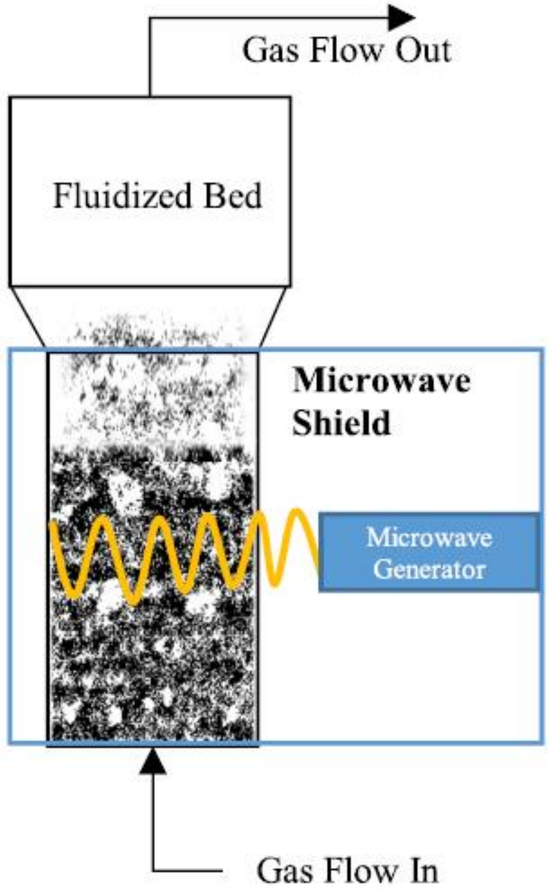
advantages of electrical heating

$\boldsymbol{CH_4} \rightarrow \boldsymbol{C} + \boldsymbol{2H_2}$ ΔH = **74** kJ/mol

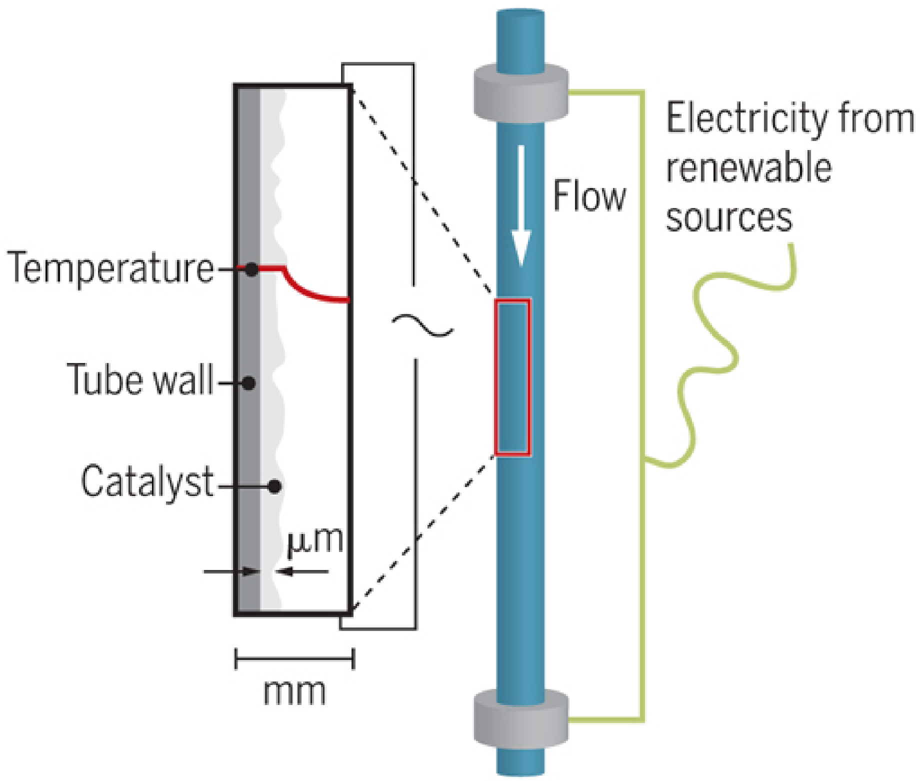
induction



microwave



Joule

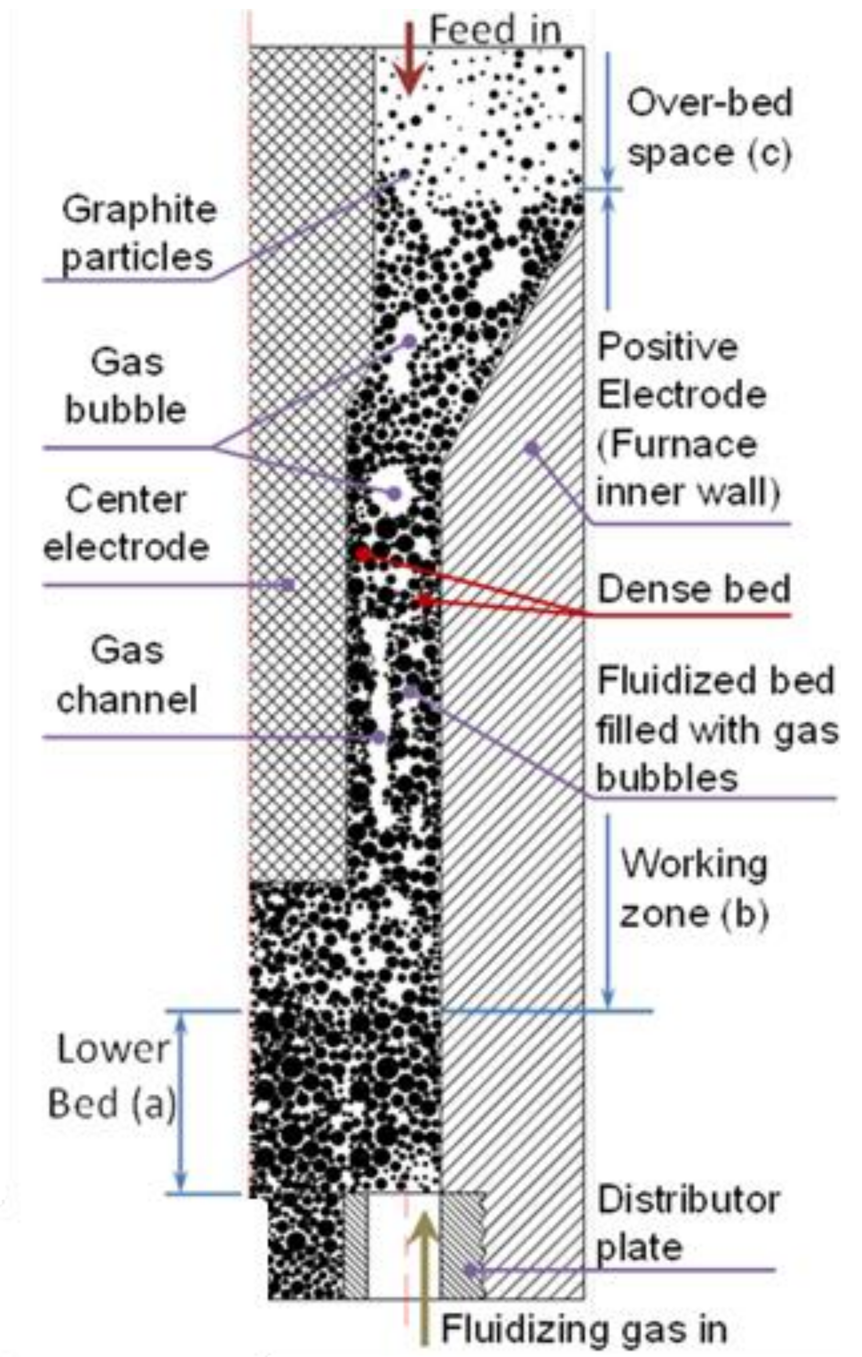


- zero emission
- energy efficient
- better T control
- rapid heating

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

ElectroThermal Fluidized Bed reactor (ETFB)

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



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

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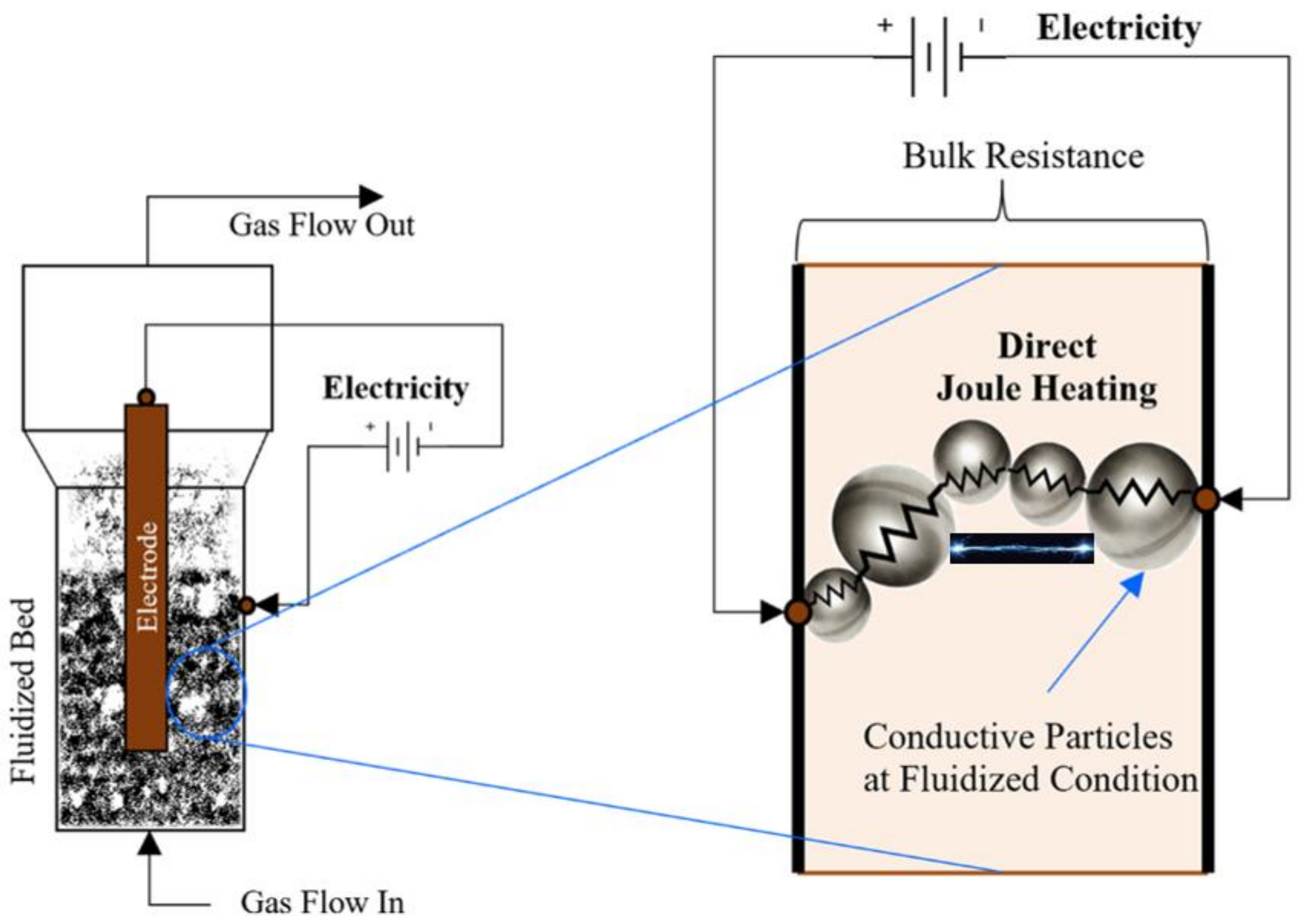
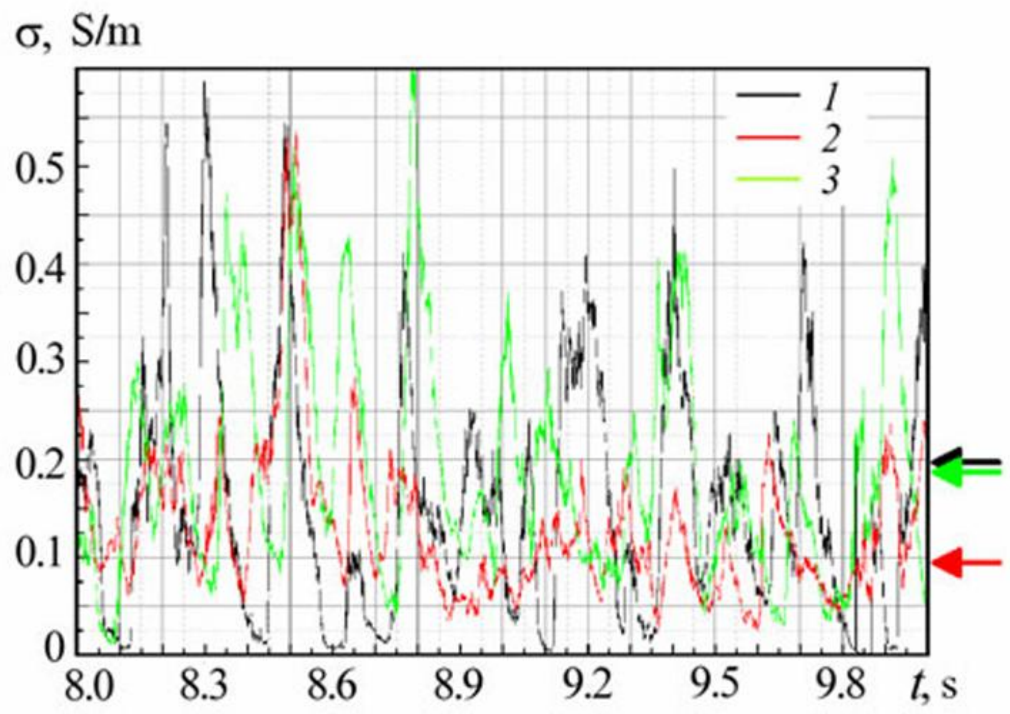
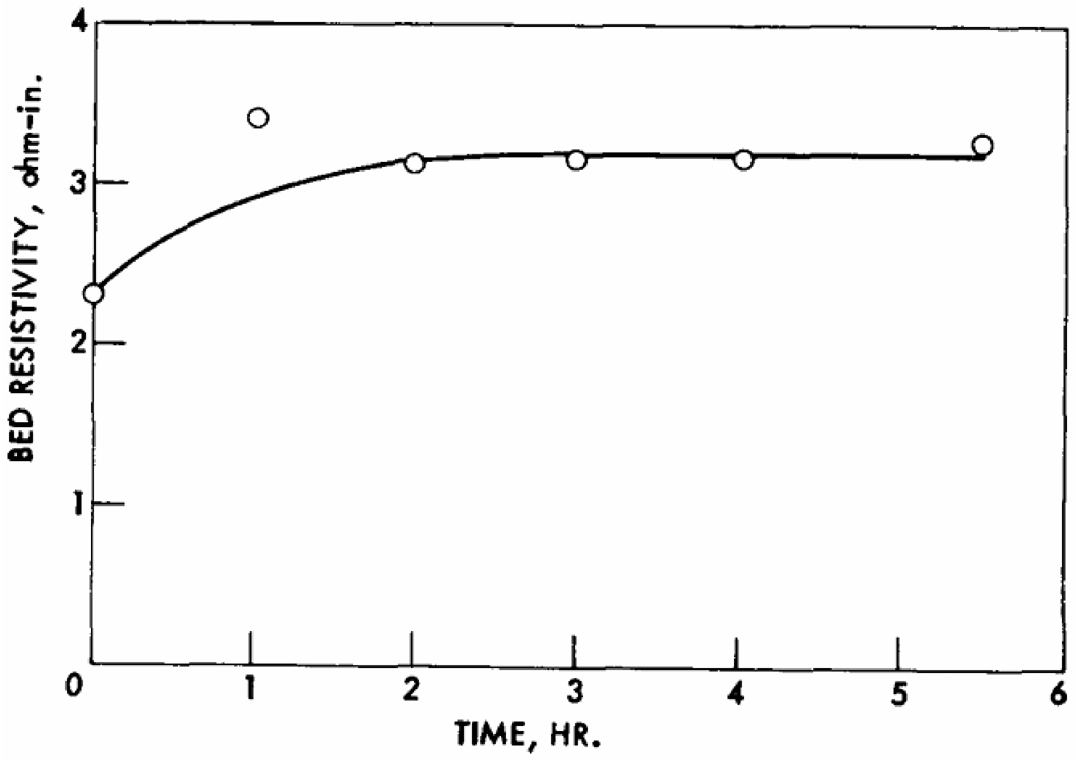
TMEC

Joule heating in a fluidized bed





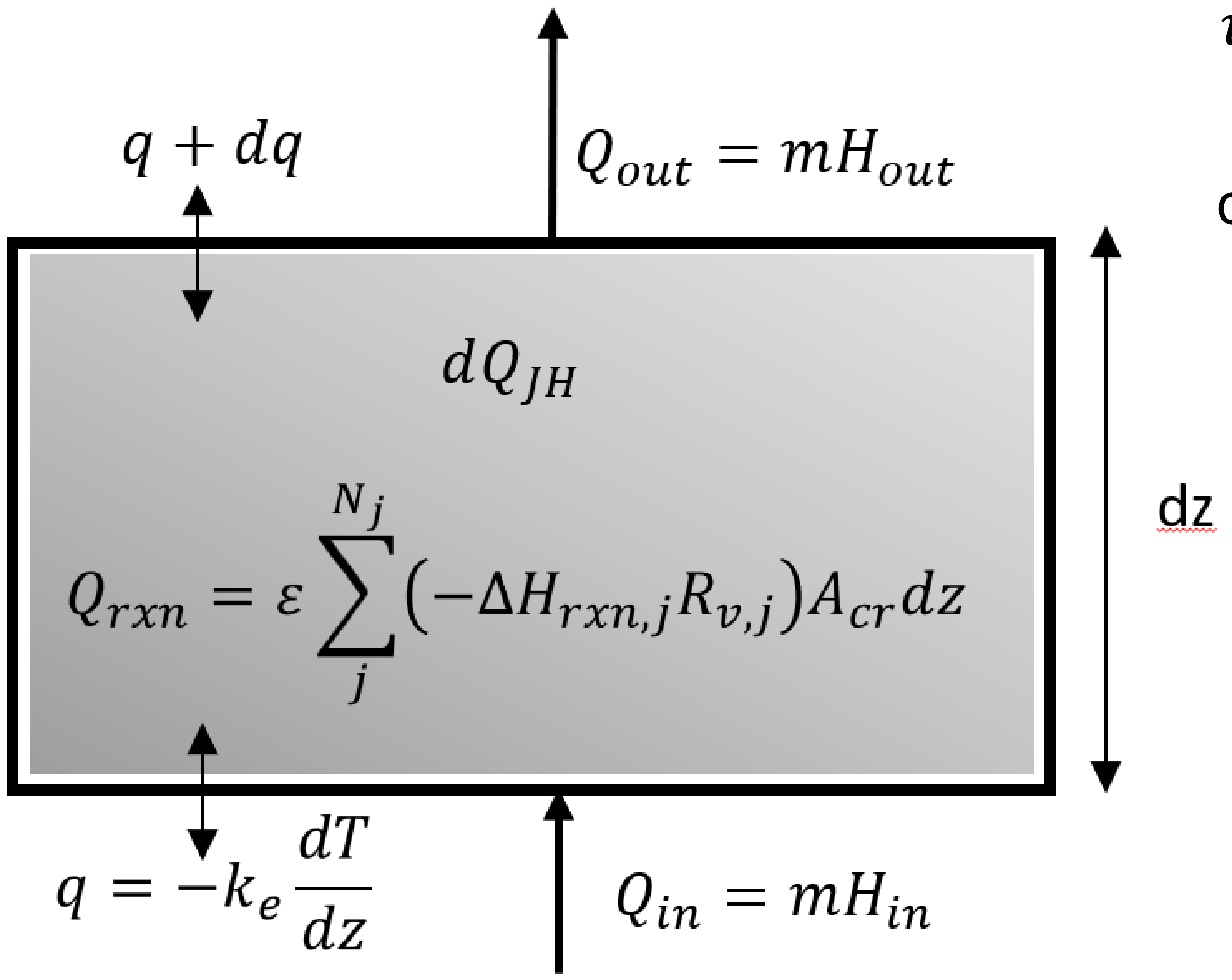


Ind. Eng. Chem. Res. 2024 https://pubs.acs.org/doi/10.1021/acs.iecr.3c04232

Malinovskii et al., J. Eng. Physics Therm, 85(2), 251–258, 2012

Pulsifer and Wheelock, Interim Report No. 3, Iowa State University, Ames, 1974.

ETFB reactor heat balance



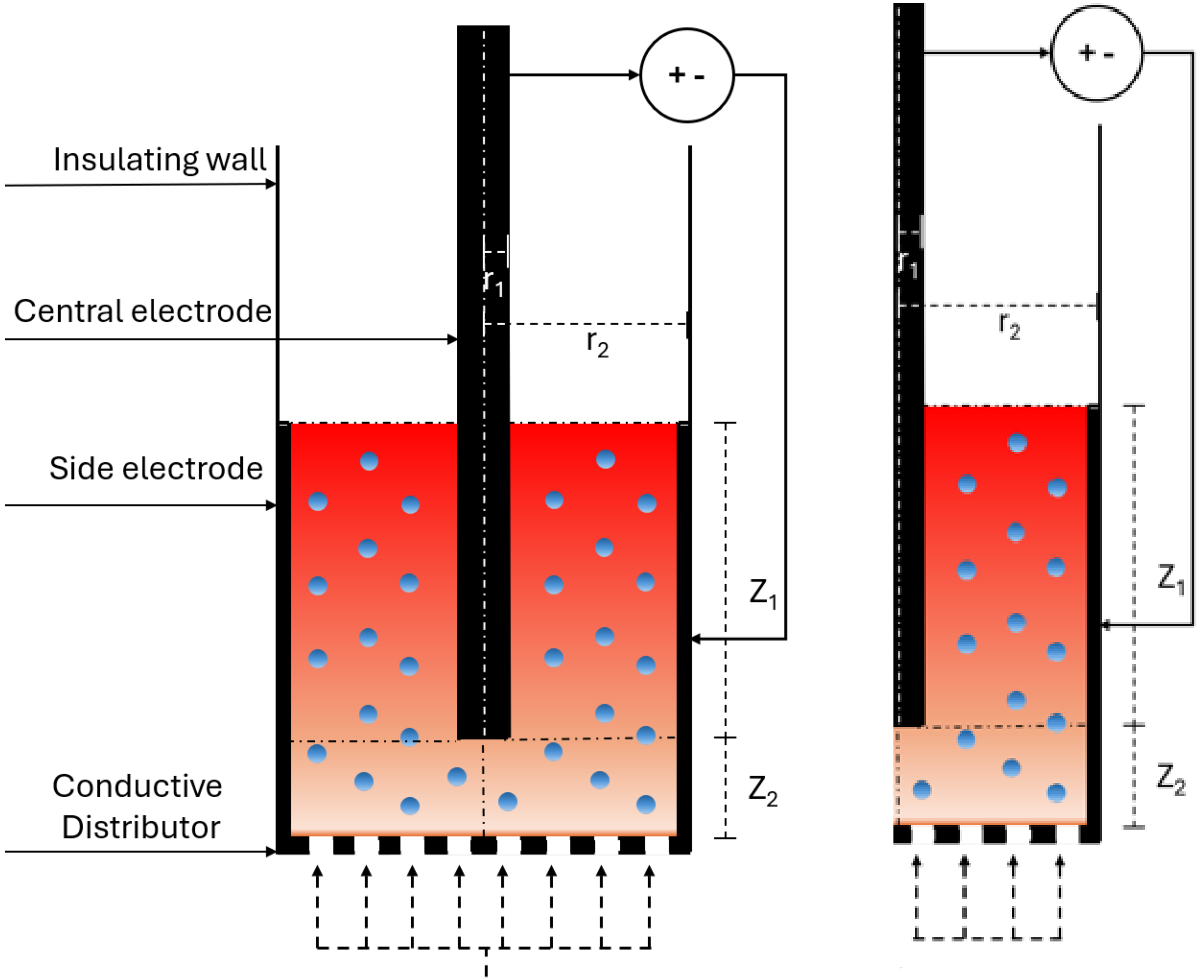
$$u\rho_g Cp_g \frac{dT}{dz} - k_e \frac{d^2T}{dz^2} - \varepsilon \sum_{j}^{N_j} (-\Delta H_{rxn} R_{v,j}) - \frac{\boldsymbol{dQ_{JH}}}{\boldsymbol{dzAc_{reactor}}} = 0$$

convection conduction heat of reaction heat generation
→ Joule heating term

assumptions

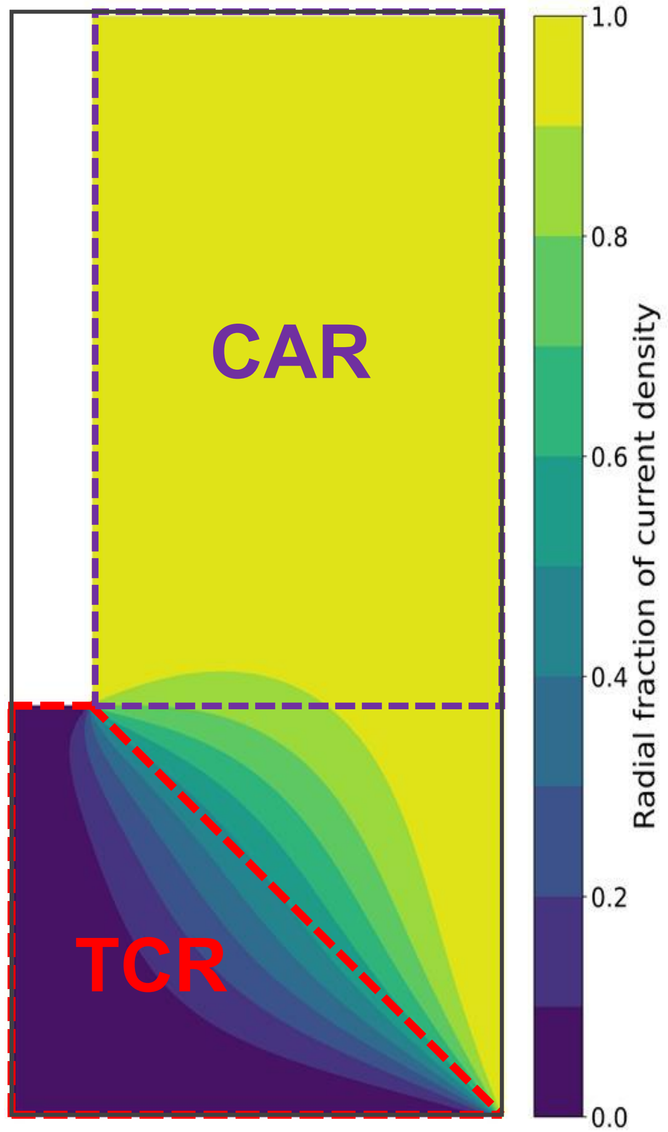
- bubbling fluidization regime
- low- and high-density phases are at the same temperature
- no radial profiles
- constant effective conductivity at average temperature and composition
- adiabatic operation
- steady state operation

ETFB electrical field



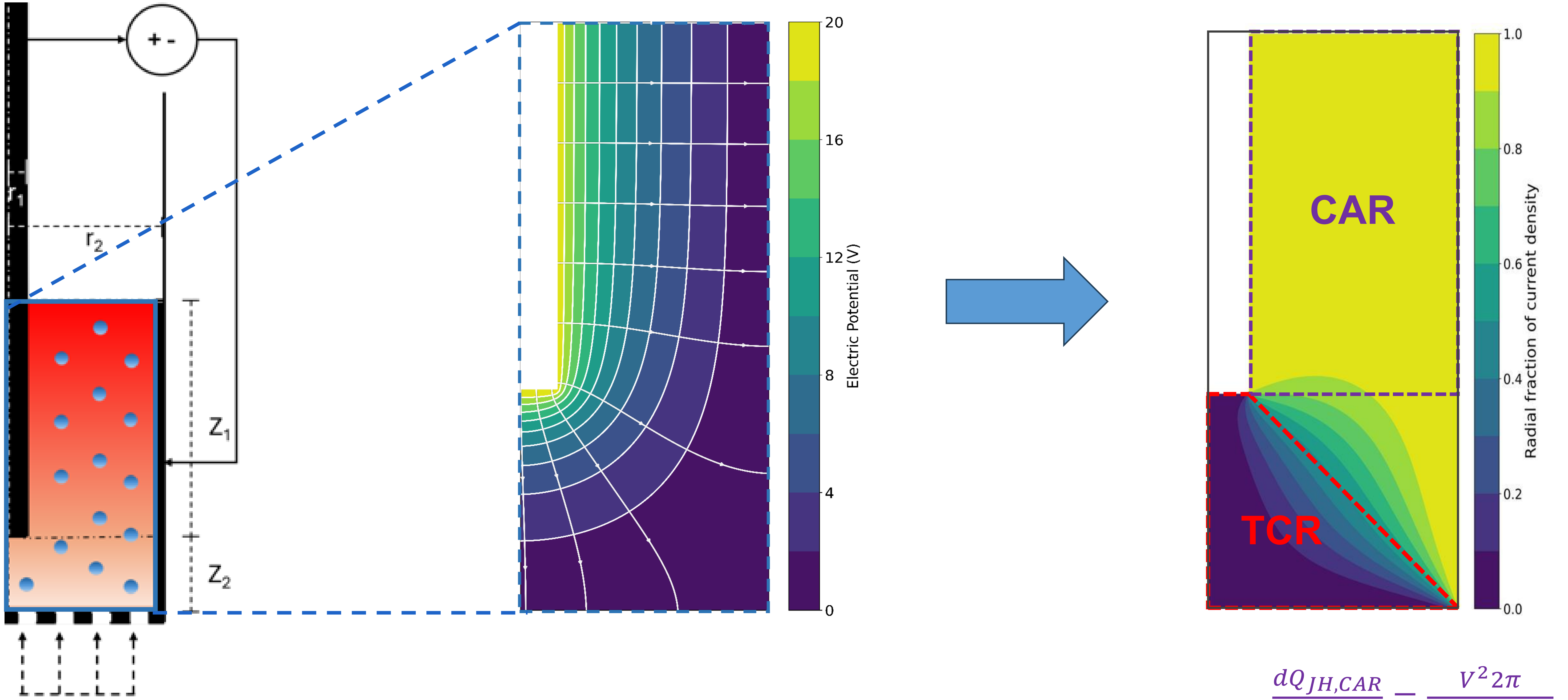
$$\frac{d^2V}{dr^2} + \frac{1}{r}\frac{dV}{dr} + \frac{d^2V}{dz^2} = 0$$

coaxial resistor



truncated cone resistor

Laplacian Filed Model vs Current Partition Model



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

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

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

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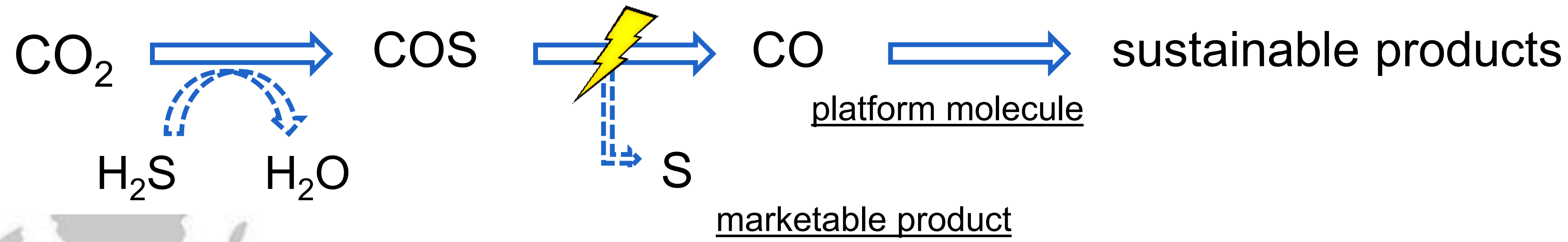
e-CODUCT: process lay-out



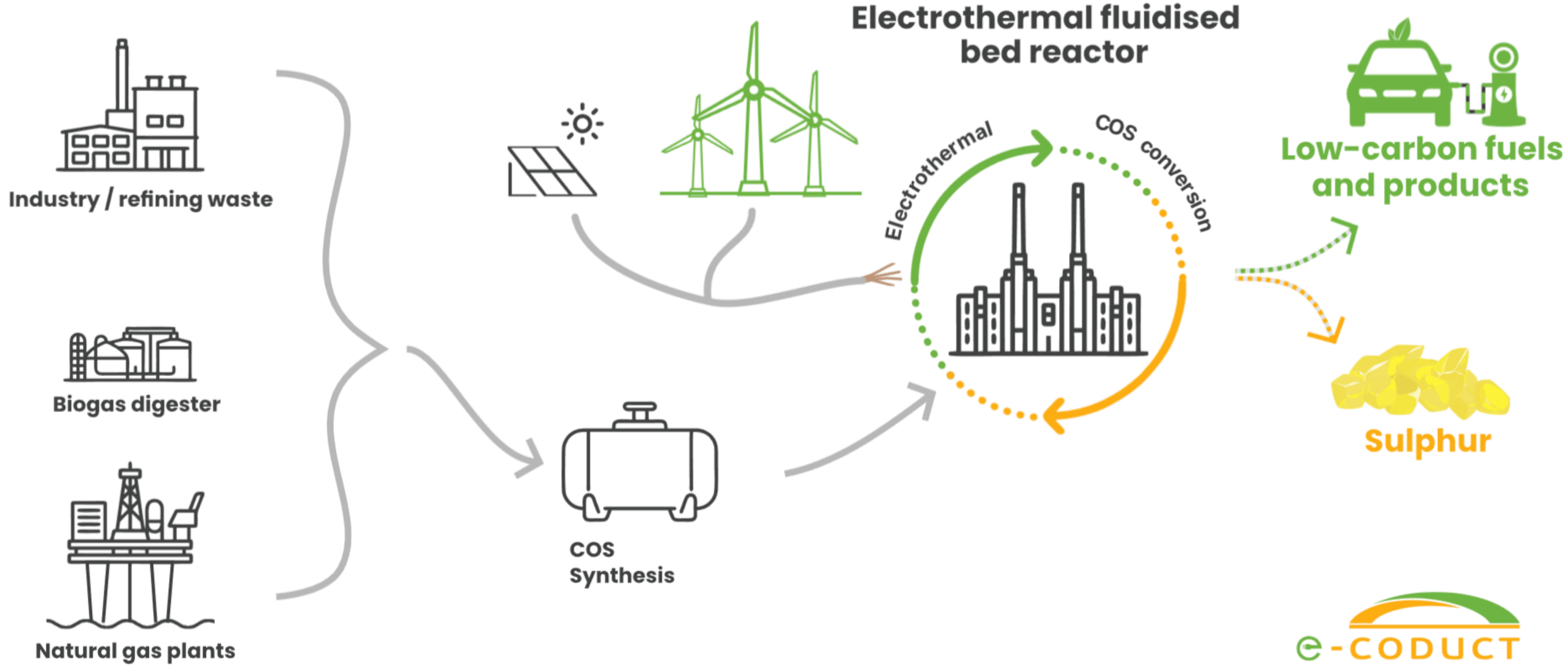
CO_2 → COS → CO → sustainable products

H_2S H_2O

S

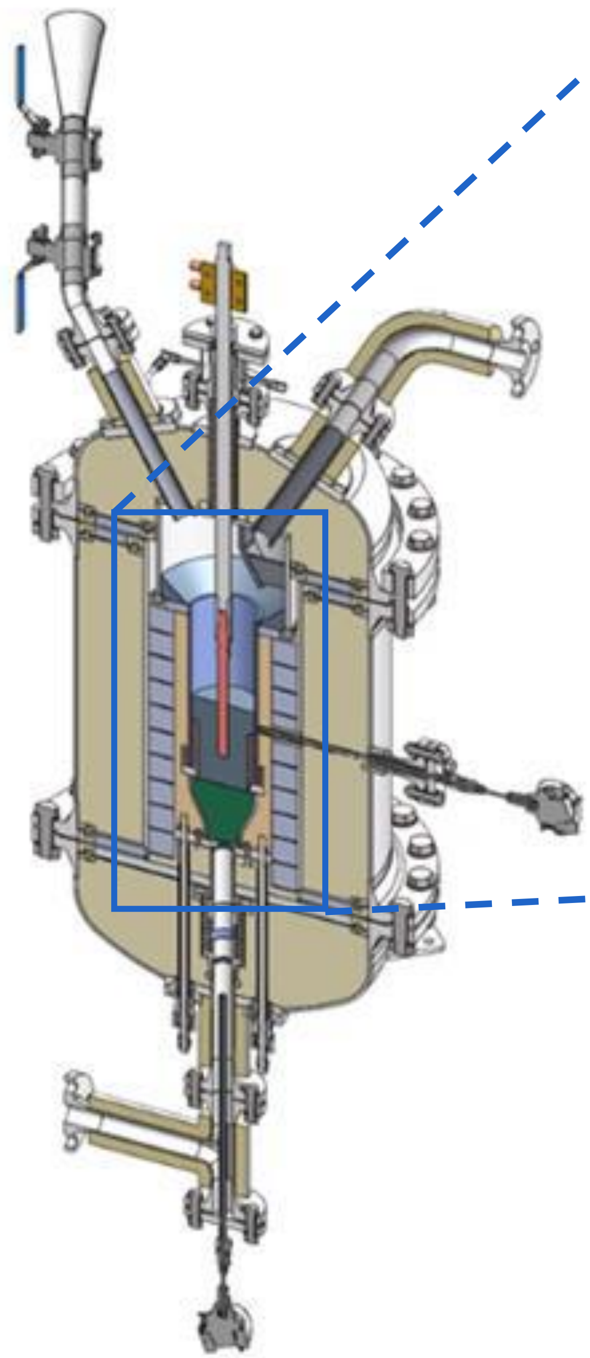
platform molecule

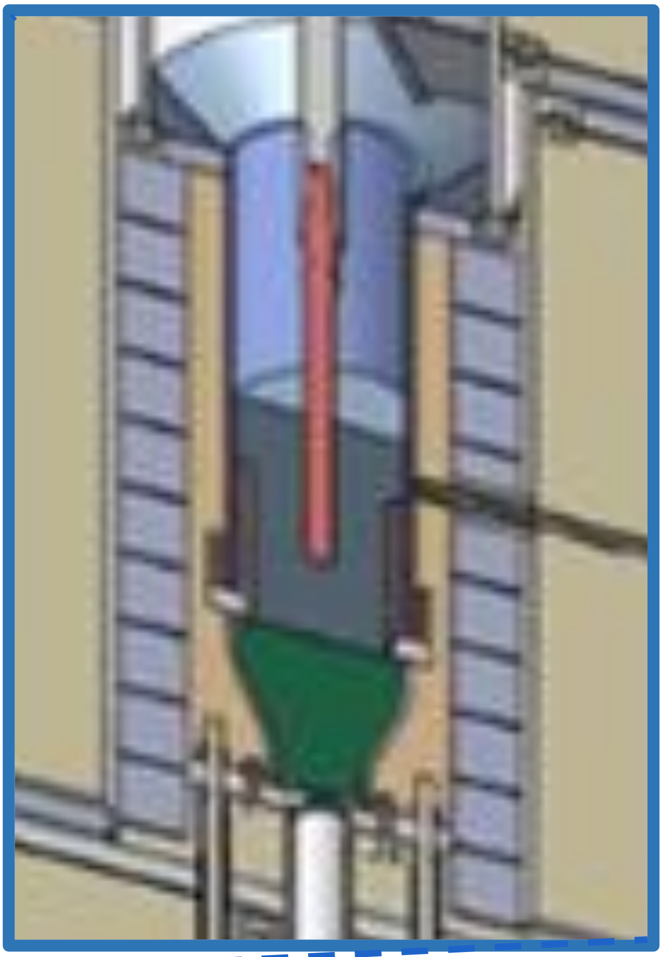
marketable product



http://www.ecoduct.eu 2022-2025 GA 101058100

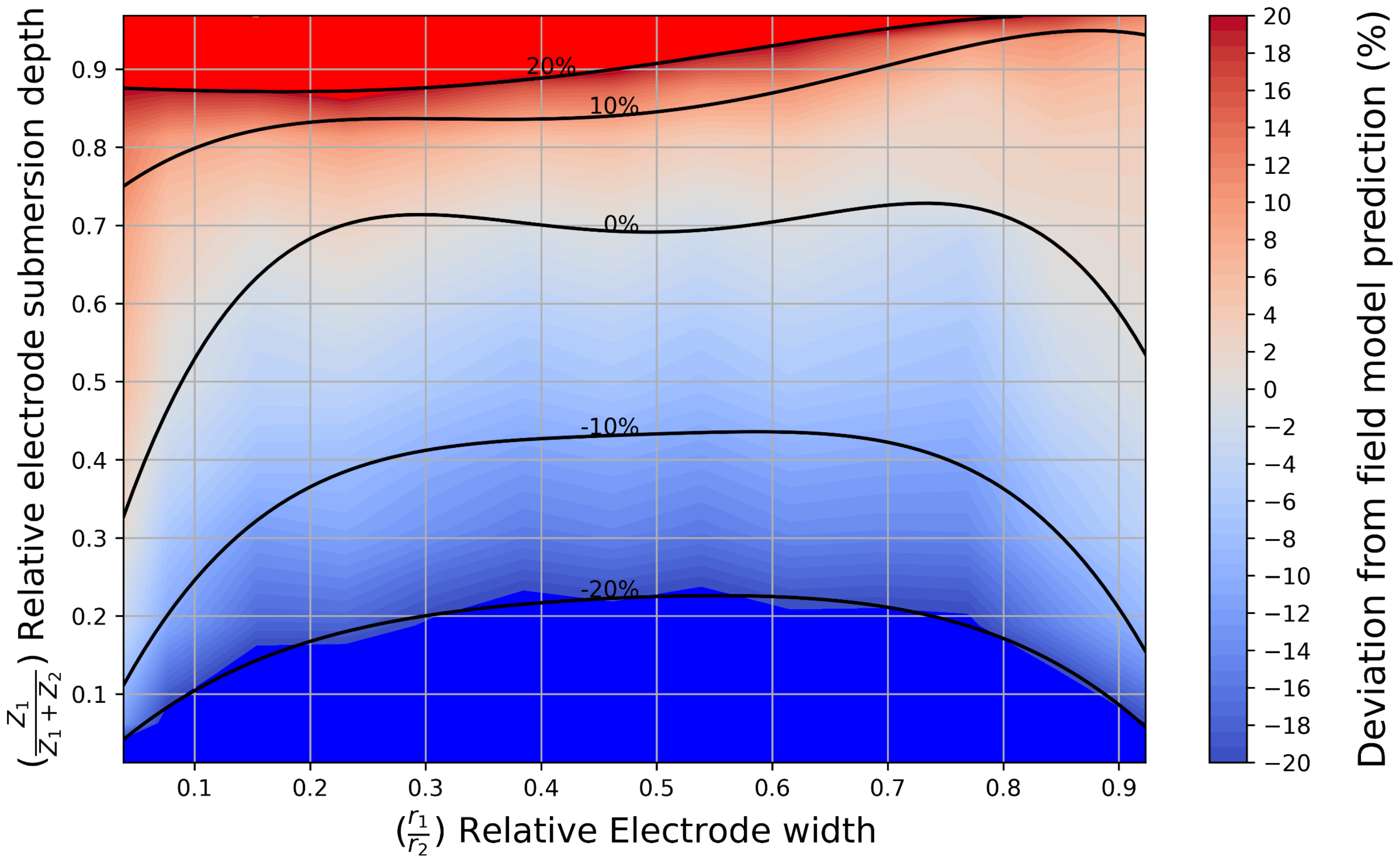
COS decomposition





- COS decomposition to CO and sulphur
- temperatures up to 800-1200 °C
- in situ heat generation by joule heating

LFM vs CPM results



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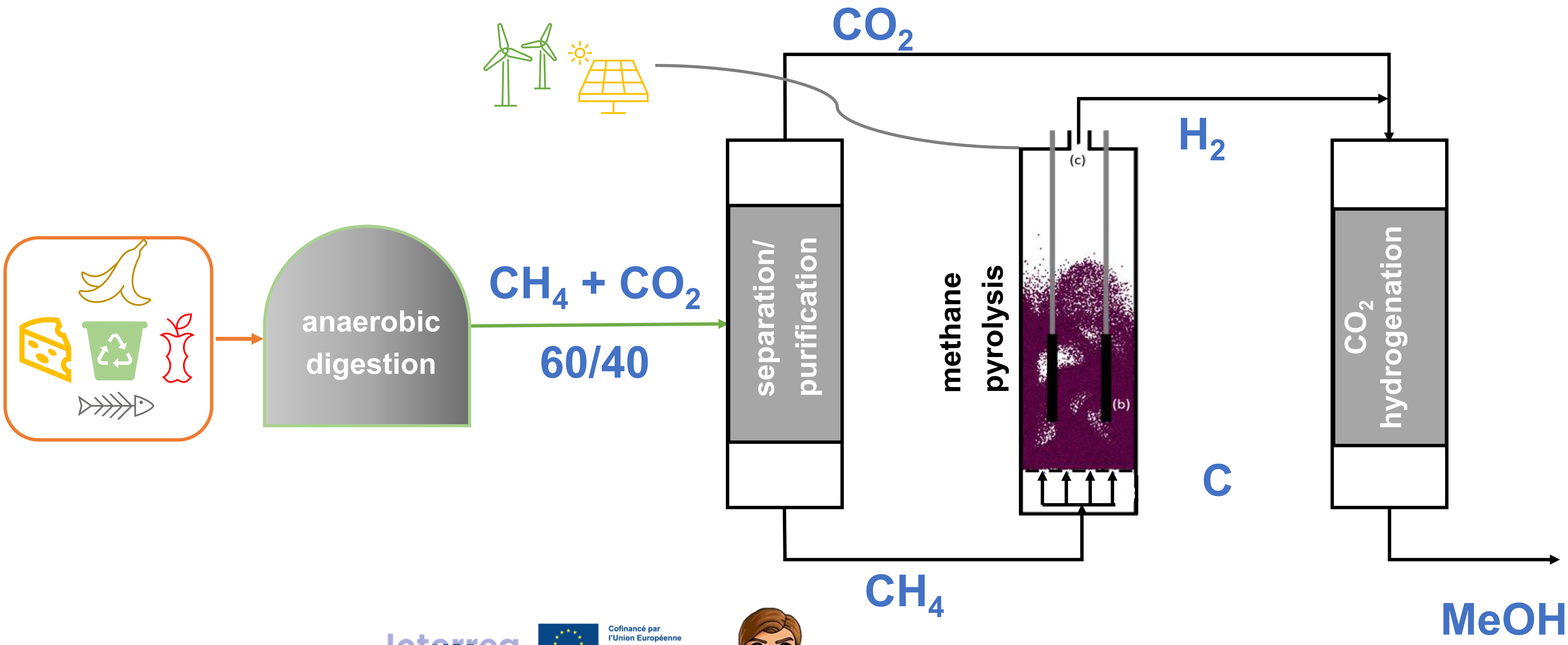
OBIWAN: process lay-out



OBIWAN start: October 2024

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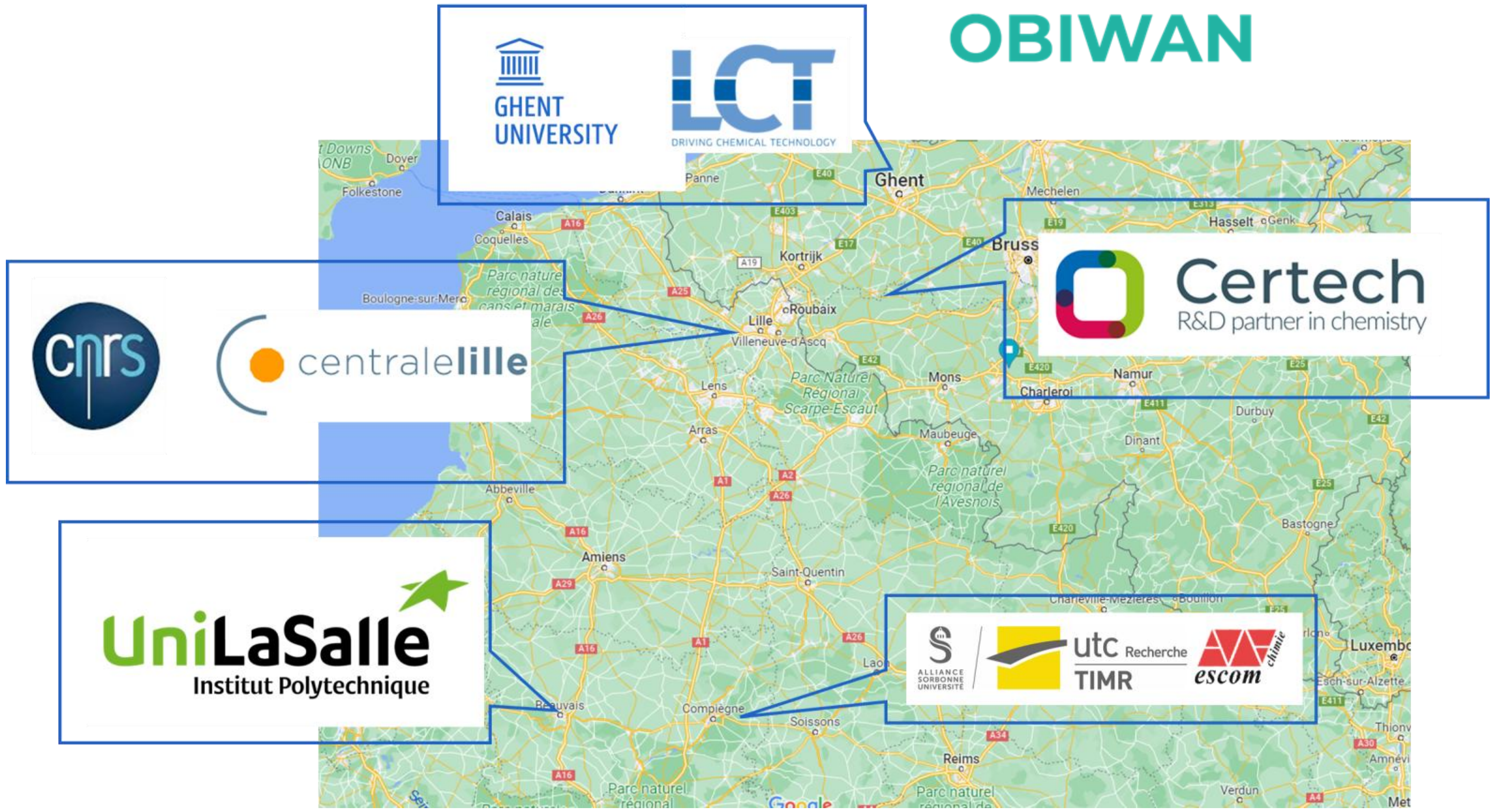
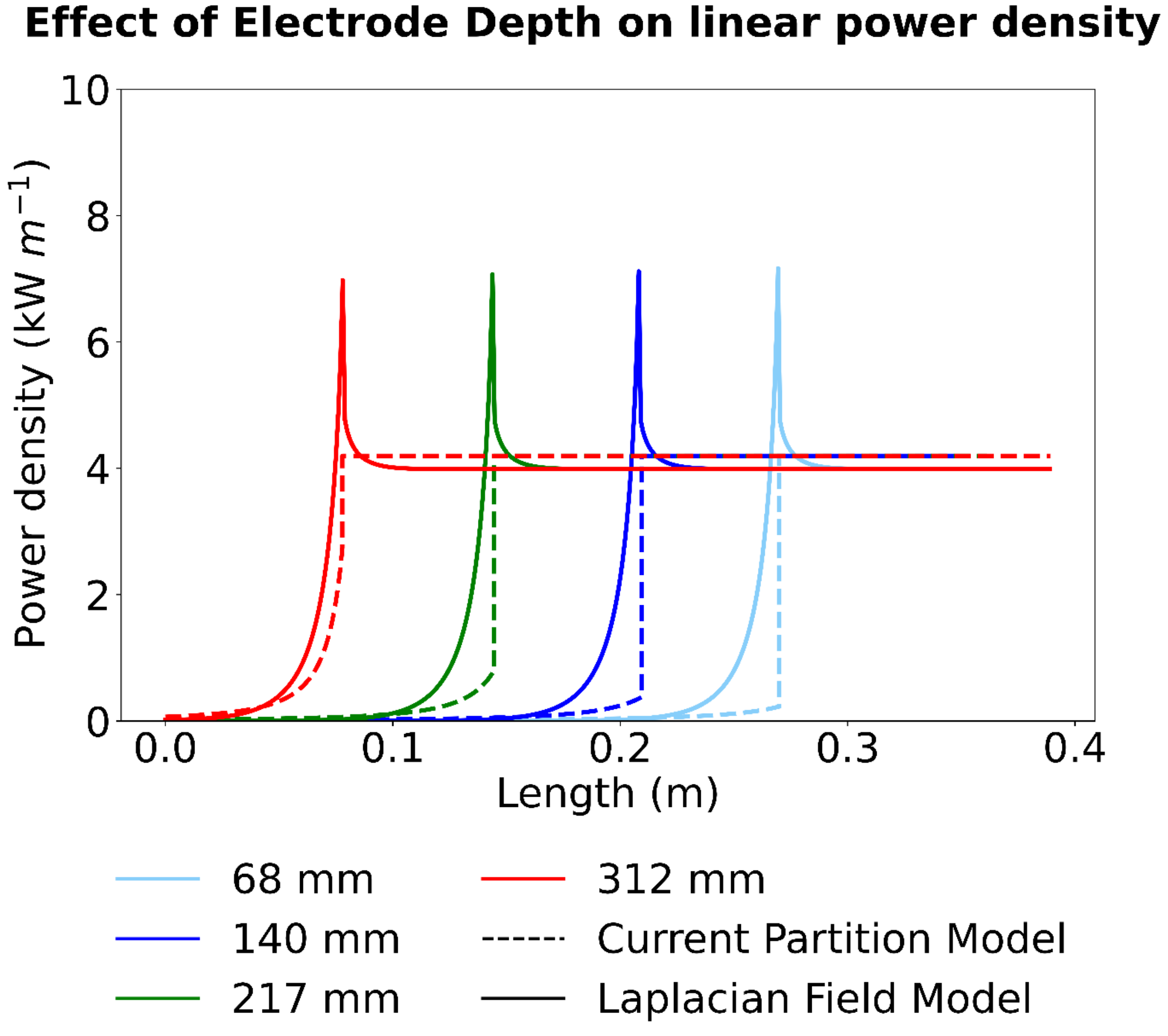
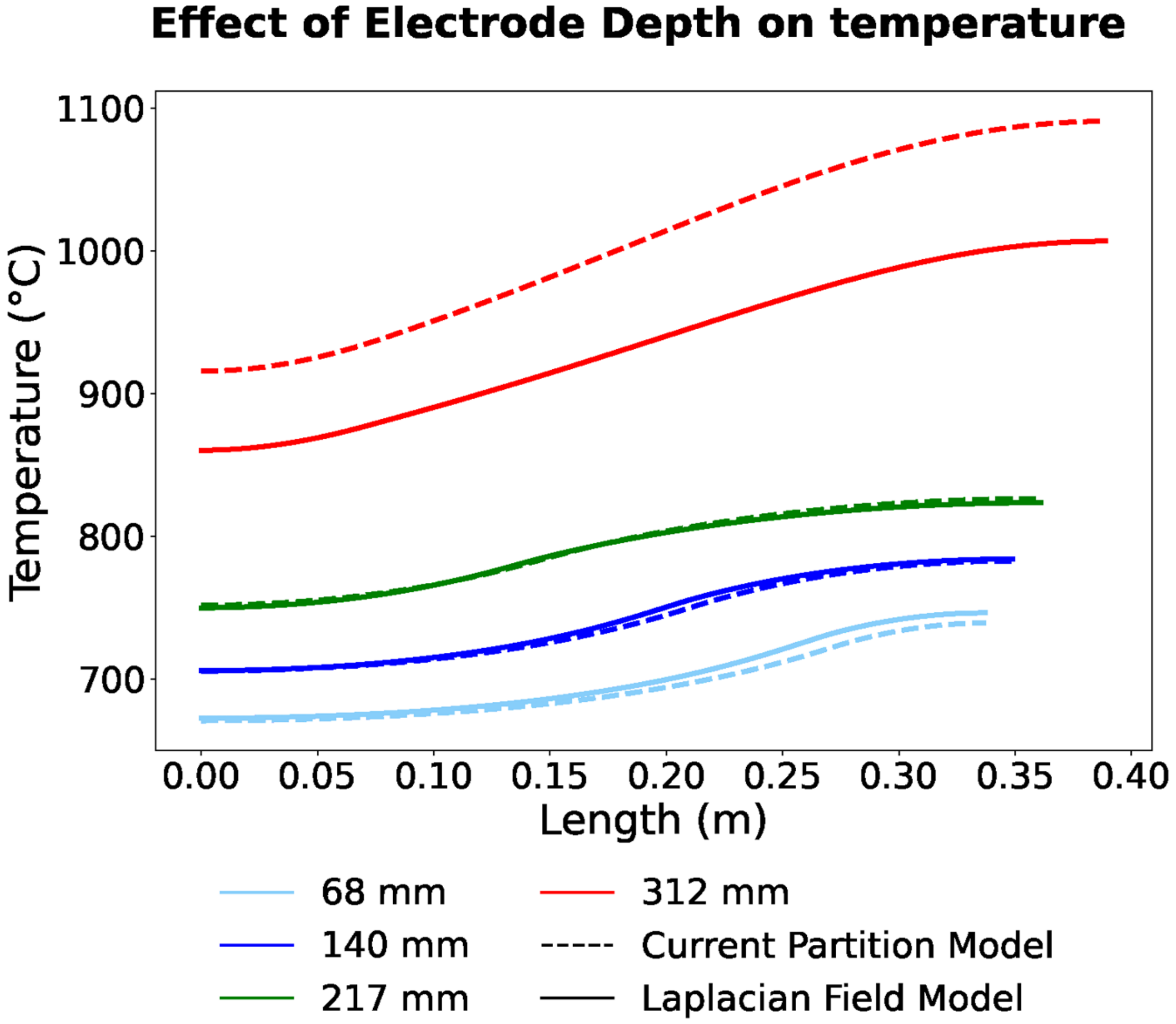
OBIWAN: context

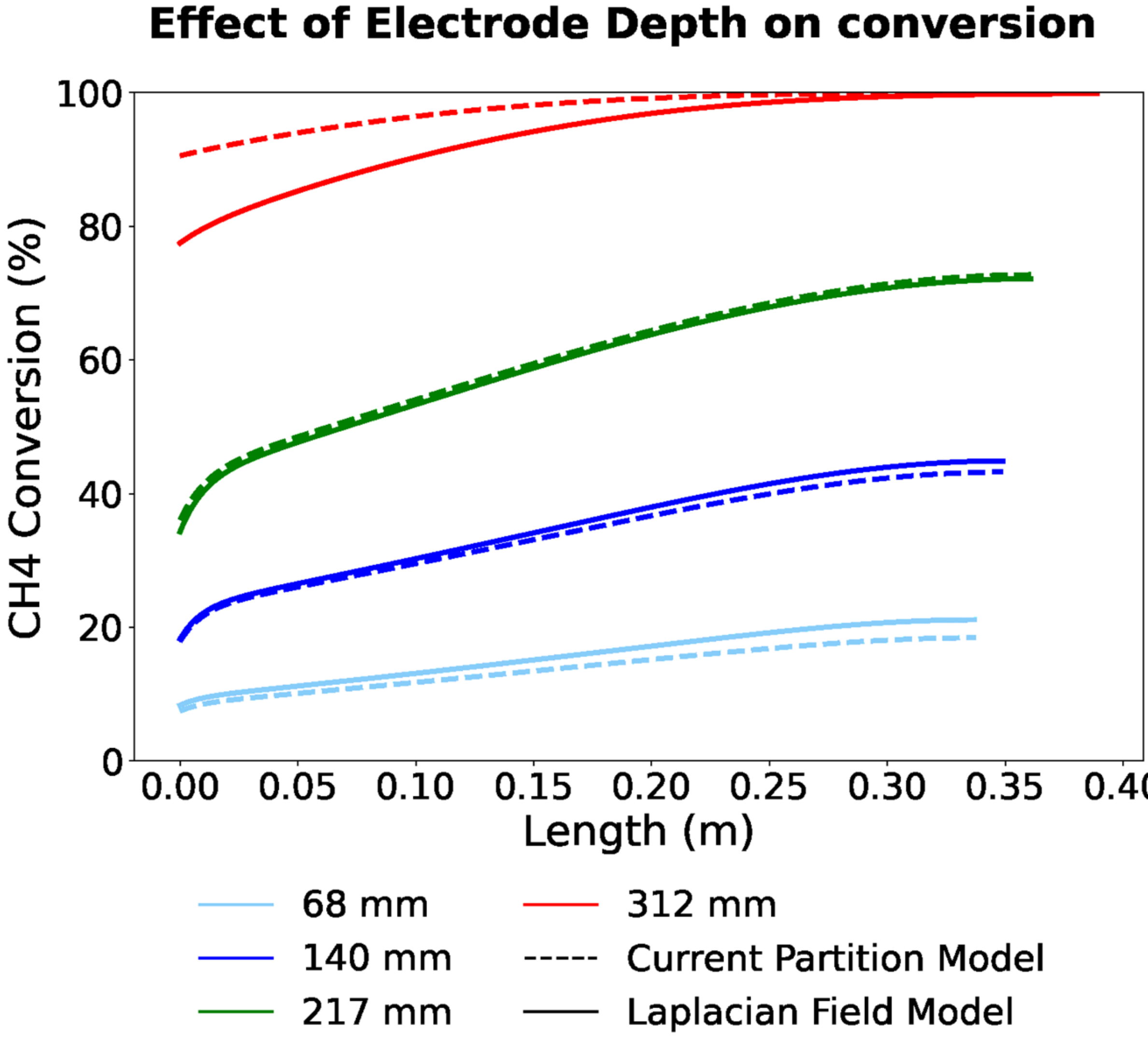
- biogas (CH_4 + CO_2) valorization
  - calorific
  - to chemicals/(sustainable aviation fuels)



CH_4 pyrolysis in ETFBR


Effect of Electrode Depth on linear power density


Effect of Electrode Depth on temperature


Effect of Electrode Depth on conversion

CH_4 = 0.72 kg hr^{-1} , T_{in} = 600°C, P = 1atm, ST = 1 kg h m^{-3}, $\sigma = 50\ \Omega\,.\,cm,\ \Delta V = 20V$

conclusions, opportunities and perspectives

- “electricity is in the catalyst”
  - reactor electrification more than connecting an electric heater to the grid
  - reasoning from the inside: ElectroThermal Fluidized Bed (ETFB) reactor

- opportunities (for endothermic reactions):
  - acid gas conversion (decomposition of COS)
  - bio-gas upcycling (CH_4 pyrolysis)
  - …

- challenges
  - (renewable) electricity availability
  - impact on chemistry
  - …

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acknowledgments

e-CODUCT

The e-CODUCT project is funded under Horizon Europe Grant Agreement n°101058100

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acknowledgements (2)

Group leader

Prof. Joris Thybaut

(former) post docs

Ana Bjelic

Jeroen Lauwaert

Jeroen Poissonnier

Alexandra Bouriakova

Zahra Mohammadbagheri

Sebastien Siradze

Pieter Janssens

(former) PhD students

Alejandro Romero Limones

Anoop Chakkingal

Bert Biesemans

Beruk Alemu Bekele

Bram Van Wettere

César Pernalete

Kevin De Ras

Klaus Jacobs

Laura Pirro

Loïc Eloi

Lucas Ivan Garbarino

Maria Herrero Manzano

Marie-Elisabeth Lissens

Noor Aljammal

Raman Ghassemi

Reza Monjezi

Tom Vandevyvere

Willem De Meyer

Wout Callewaert

Arne De Landsheere

Iliyas Melnikov

Katrien De Gusseme

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LABORATORY FOR CHEMICAL TECHNOLOGY

Technologiepark 125, 9052 Ghent, Belgium

E info.lct@ugent.be
T 003293311757

https://www.lct.ugent.be

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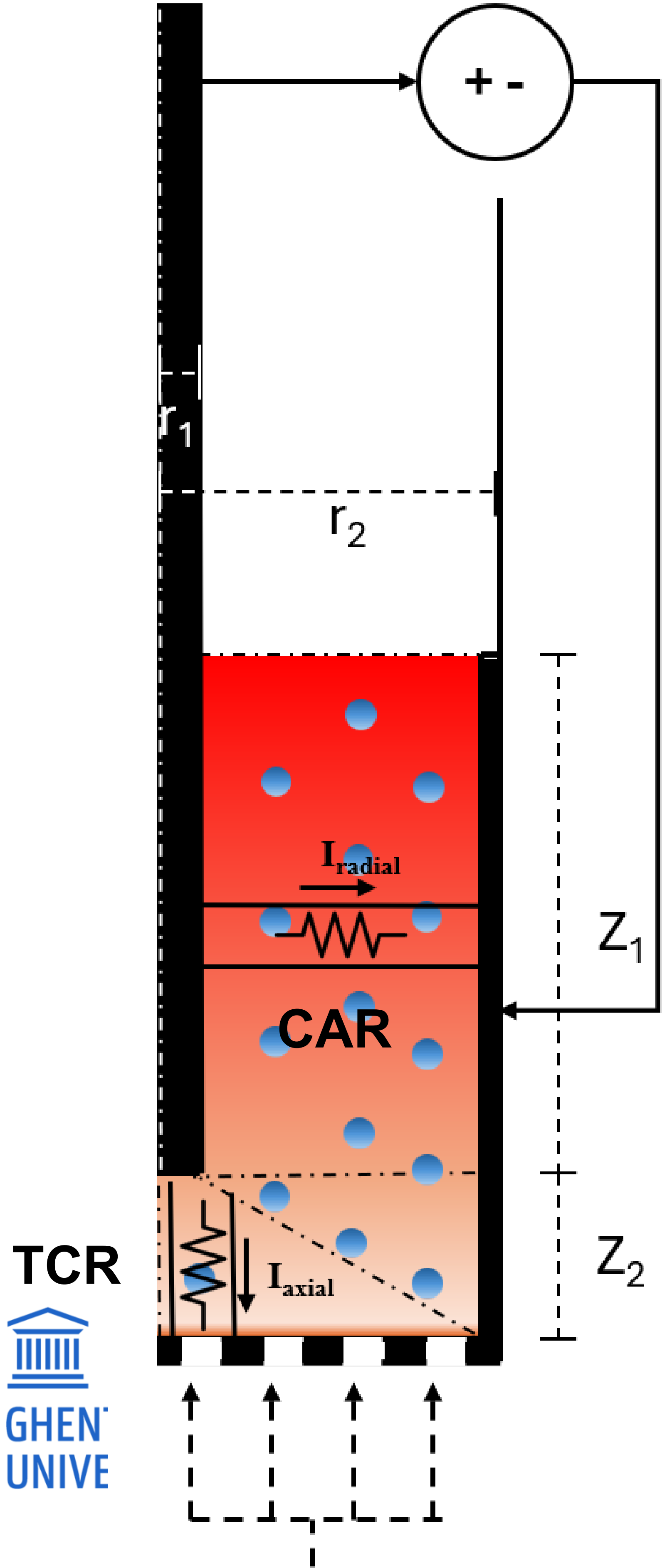
CAR and TCR resistor formulation



- Identification of the characteristic length (L) and the cross-sectional area to the flow of the current (A_c) for both resistors

$$R = \frac{s_{bed} L}{A_c} \rightarrow L_{CAR} = r, A_{c,CAR} = 2\pi r z$$

$$\rightarrow L_{TCR} = z, A_{c,TCR} = \pi r^2$$

- Coaxial resistor
- Truncated cone resistor

$$dR_{CAR} = \frac{s_{bed}}{2\pi dz_1} Ln\left(\frac{r_2}{r_1}\right)$$

$$dR_{TCR} = \frac{s_{bed} dz_2}{\pi r^2}$$

resistances in parallel

resistances in series

⇩ ⇩

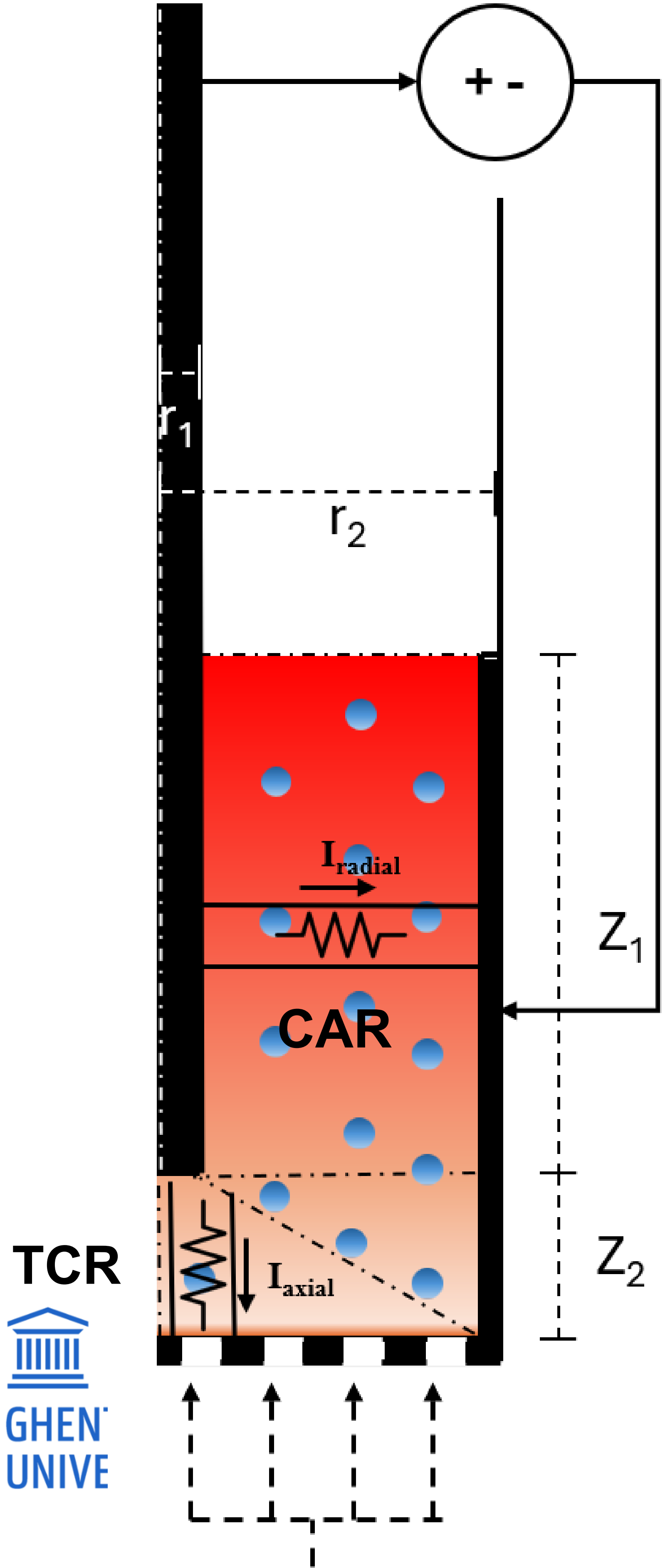
Replace resistances expressions in the Joule heating equation

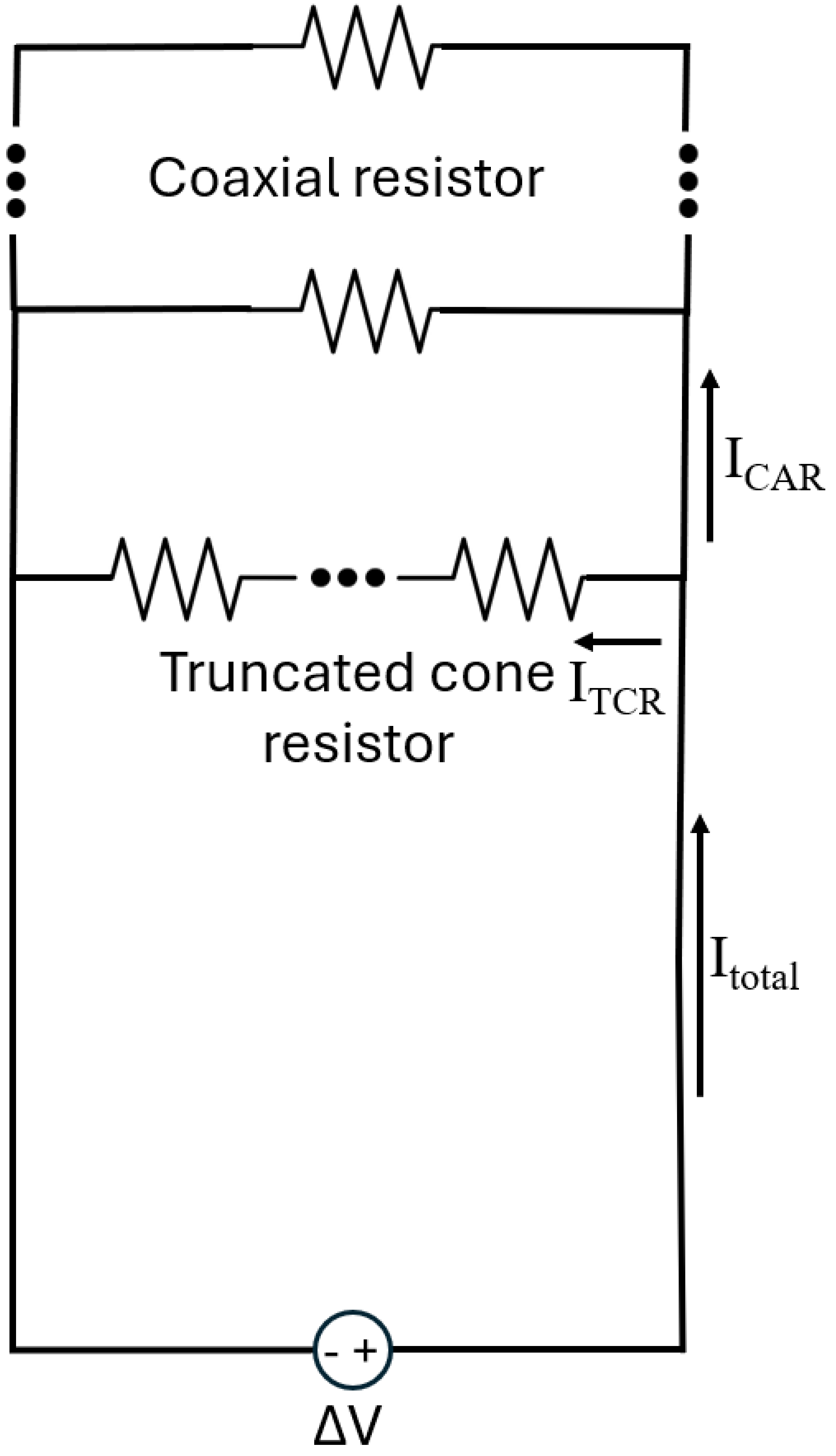
⇩ ⇩

$$\boldsymbol{dQ_{JH,CAR} = \frac{V^2 2\pi dz_1}{s_{bed} ln\left(\frac{r_2}{r_1}\right)}}$$

$$\boldsymbol{dQ_{JH,TCR} = \frac{I_{TCR}^2 s_{bed} dz_2}{\pi r^2}}$$

Dual zone electrothermal model



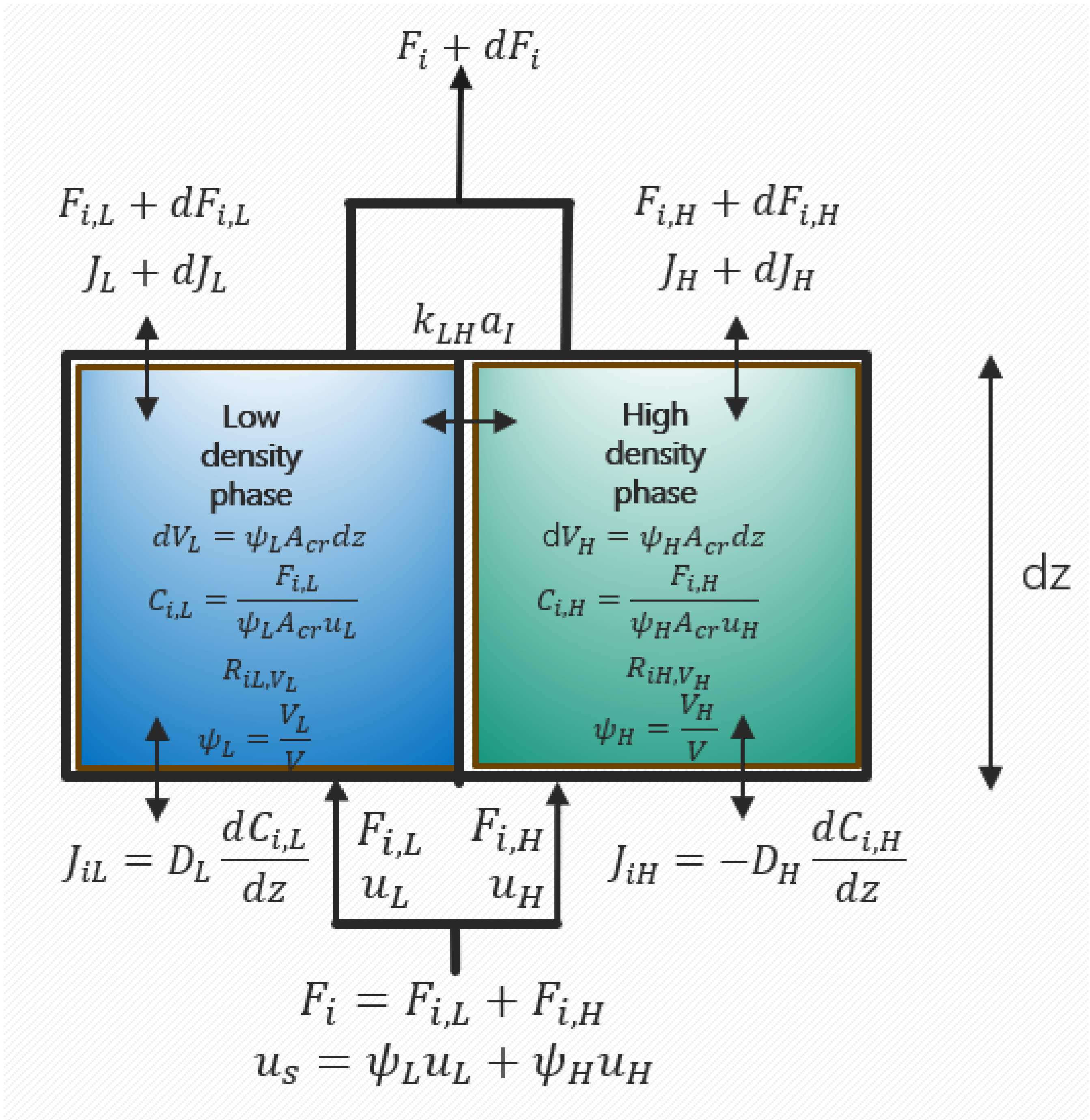


- Assuming contact resistances with the electrodes are negligible
- CARs and TCRs are represented as two resistors in parallel

$$R_{total} = \left(\frac{1}{R_{CAR}} + \frac{1}{R_{TCR}}\right)^{-1}$$

$$Q_{JH,total} = \frac{V^2}{R_{total}} = I_{total}^2 R_{total} = V I_{total}$$

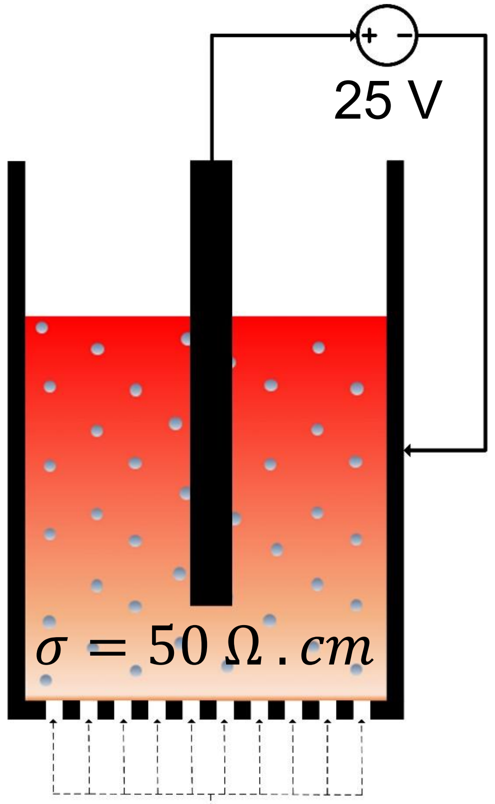
ETFBR Mass balance



Assumptions

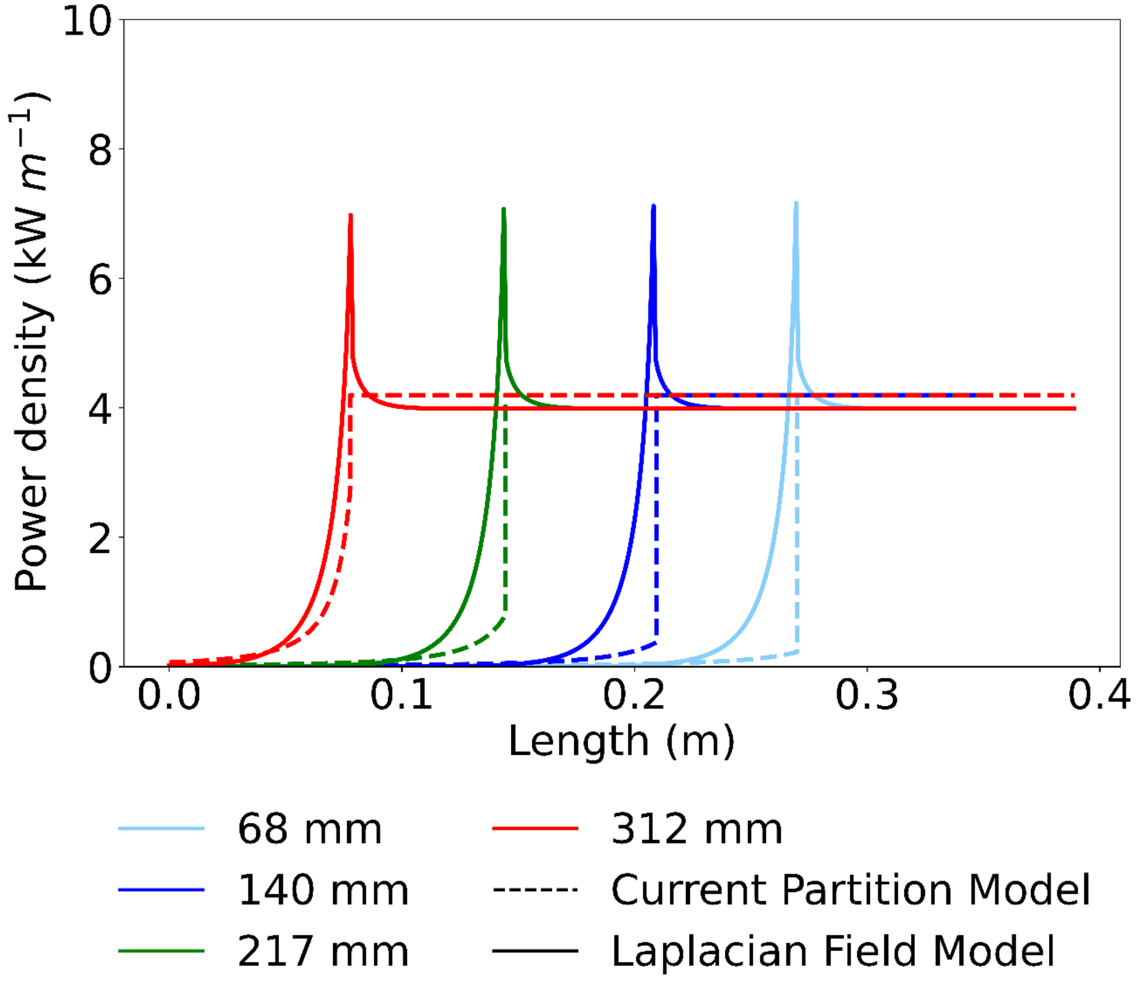
- Bed is divided into two phases
  - High density phase
  - Low density phase
- No radial profiles
- Constant properties
  - At average bed temperature and average composition
- High density phase at minimum fluidization condition
- Steady state operation
- Bubbling fluidization regime

ETFBR for CH_4 pyrolysis

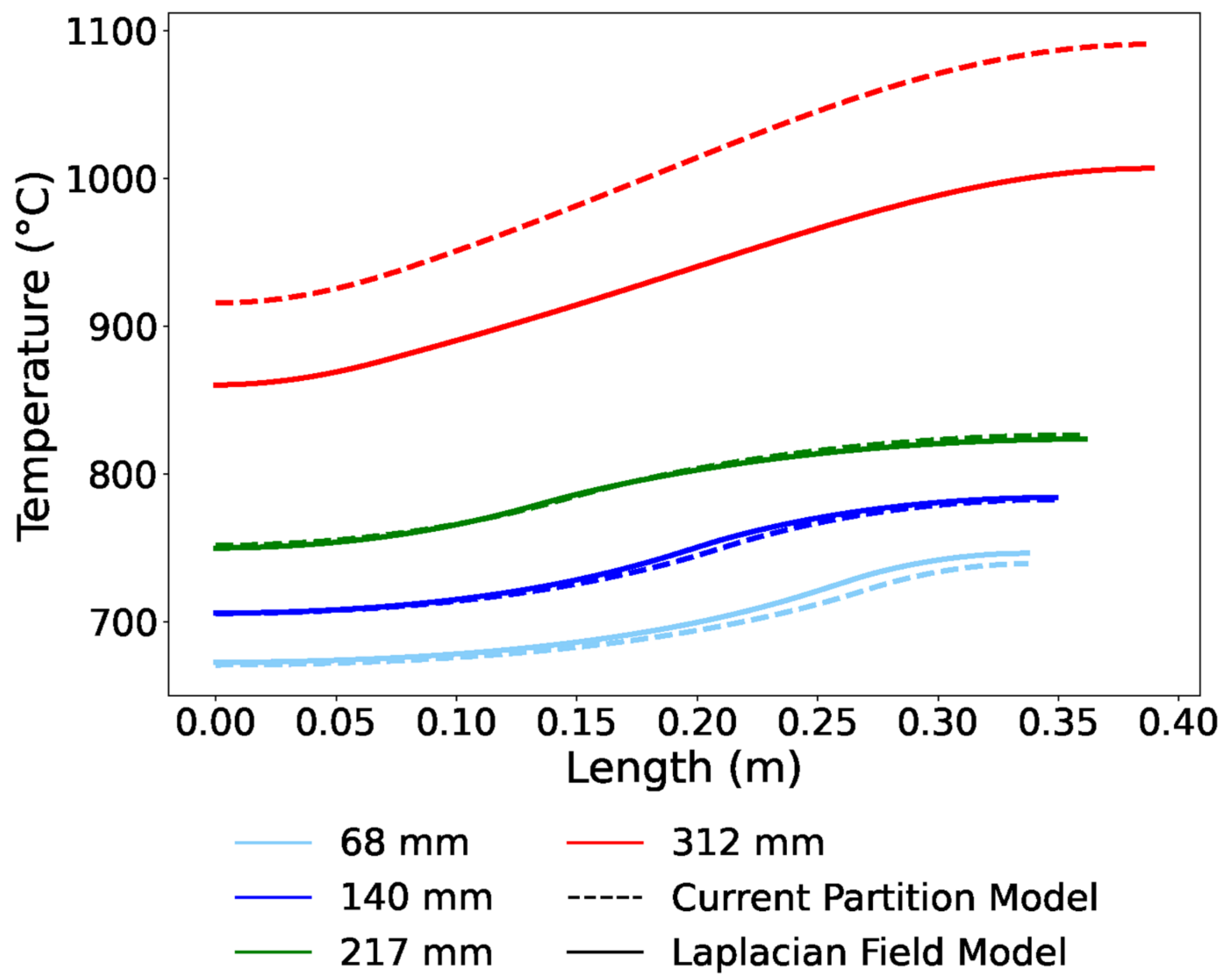


CH_4: 0.72 kg hr^{-1}
T_{in} : 600°C
P : 1atm
ST : 1 kg h m^{-3}

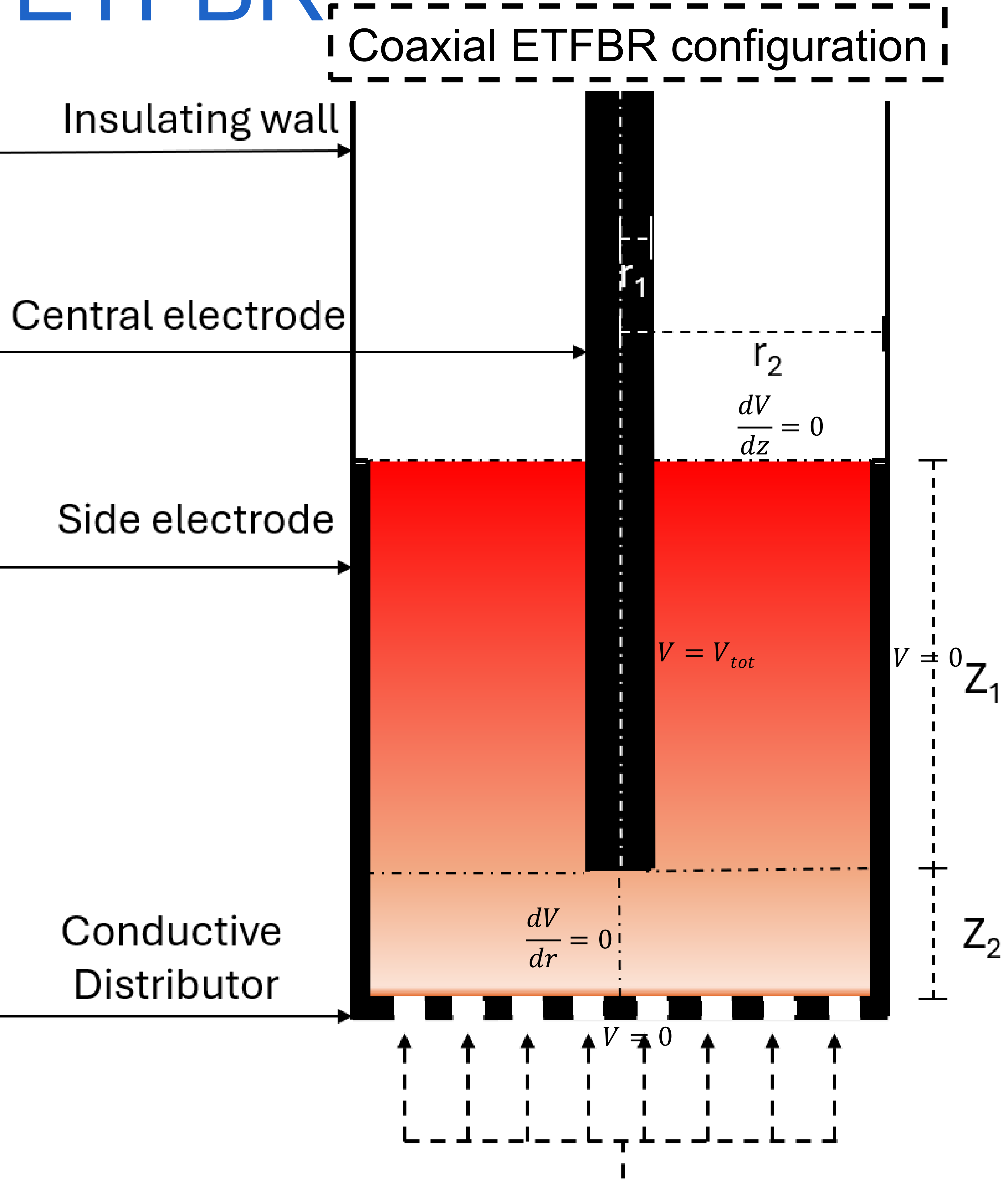
Effect of Electrode Depth on linear power density



Effect of Electrode Depth on temperature



Field characteristics of the electrical properties in an ETFBR



- Electric potential field determination
  - Uniform resistivity of the bed
  - Voltage is uniform along the electrode surfaces
    - 2D Laplace equation over cylindrical coordinates

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

- Current density

$$J_r = -\frac{1}{S_{bed}}\frac{dV}{dr}, \qquad J_z = -\frac{1}{S_{bed}}\frac{dV}{dz}$$

- Current

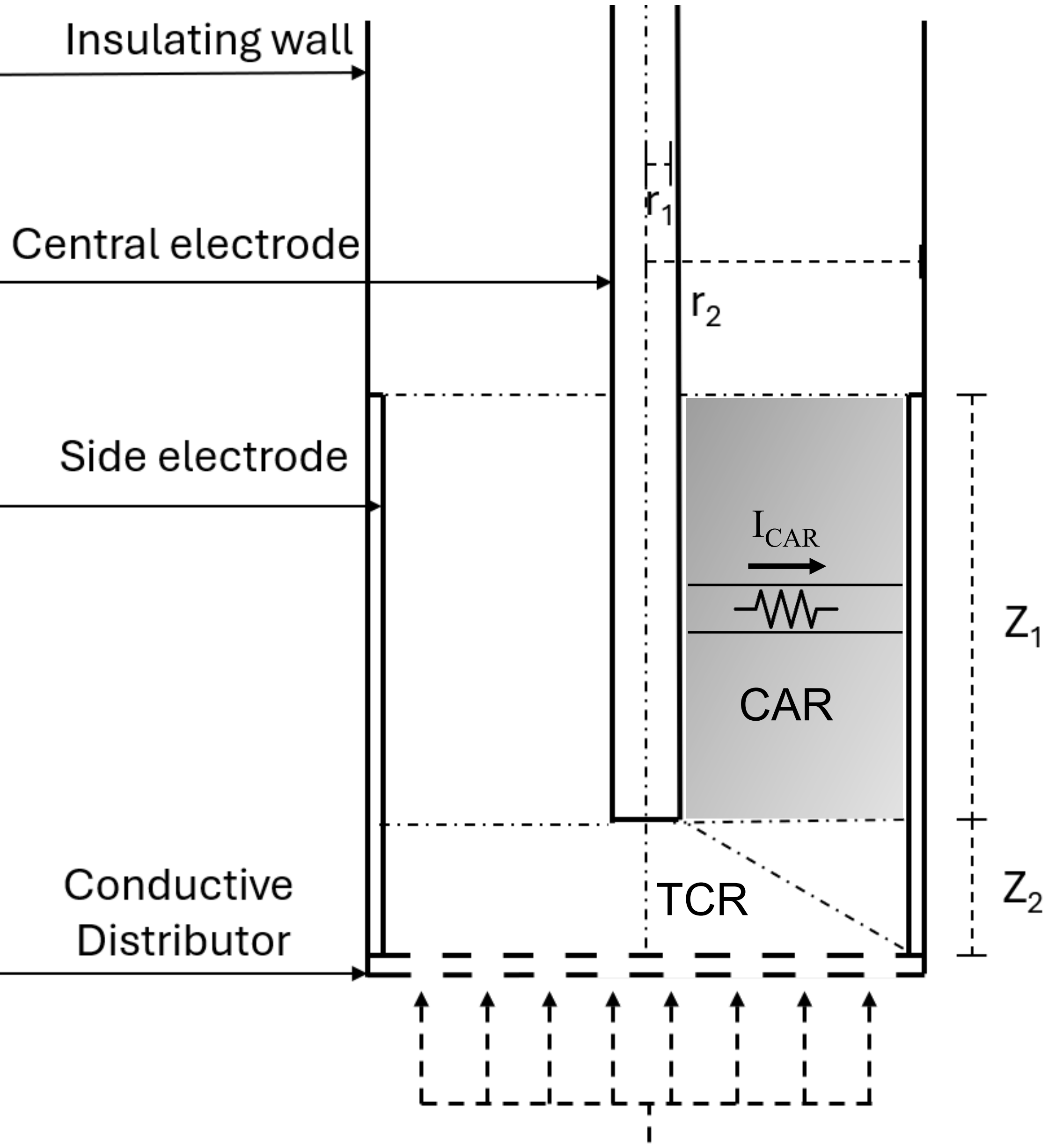
$$I_r = \int_0^{2\pi}\int_0^{H} J_r r dz d\Theta, \qquad I_z = \int_0^{2\pi}\int_0^{R} J_z r dr d\Theta$$

- Joule heating

$$P_r = \int_0^{2\pi}\int_0^{H}\int_0^{R} -\frac{1}{S_{bed}}\left(\frac{dV}{dr}\right)^2 r dr dz d\Theta$$

$$P_z = \int_0^{2\pi}\int_0^{H}\int_0^{R} -\frac{1}{S_{bed}}\left(\frac{dV}{dz}\right)^2 r dr dz d\Theta$$

Derivation of the Coaxial Resistor Expression



- Identification of the characteristic length (L) and the cross-sectional area to the flow of the current ($A_{c,I}$)

$$R = \frac{s_{bed} L}{A_c} \rightarrow L = r, A_{c,I} = 2\pi r Z_1$$

- Derivation of the Coaxial resistor expression

$$R_{CAR} = \frac{s_{bed}}{2\pi Z_1} Ln\left(\frac{r_2}{r_1}\right) = \left(\sum_1^N \frac{1}{\frac{s_{bed}}{2\pi dz_1} Ln\left(\frac{r_2}{r_1}\right)}\right)^{-1} \overrightarrow{over\ dz_1}\ dR_{CAR} = \frac{s_{bed}}{2\pi dz_1} Ln\left(\frac{r_2}{r_1}\right)$$

If V is constant along the axial direction → Differential resistances in the coaxial resistor can be treated as resistances in parallel

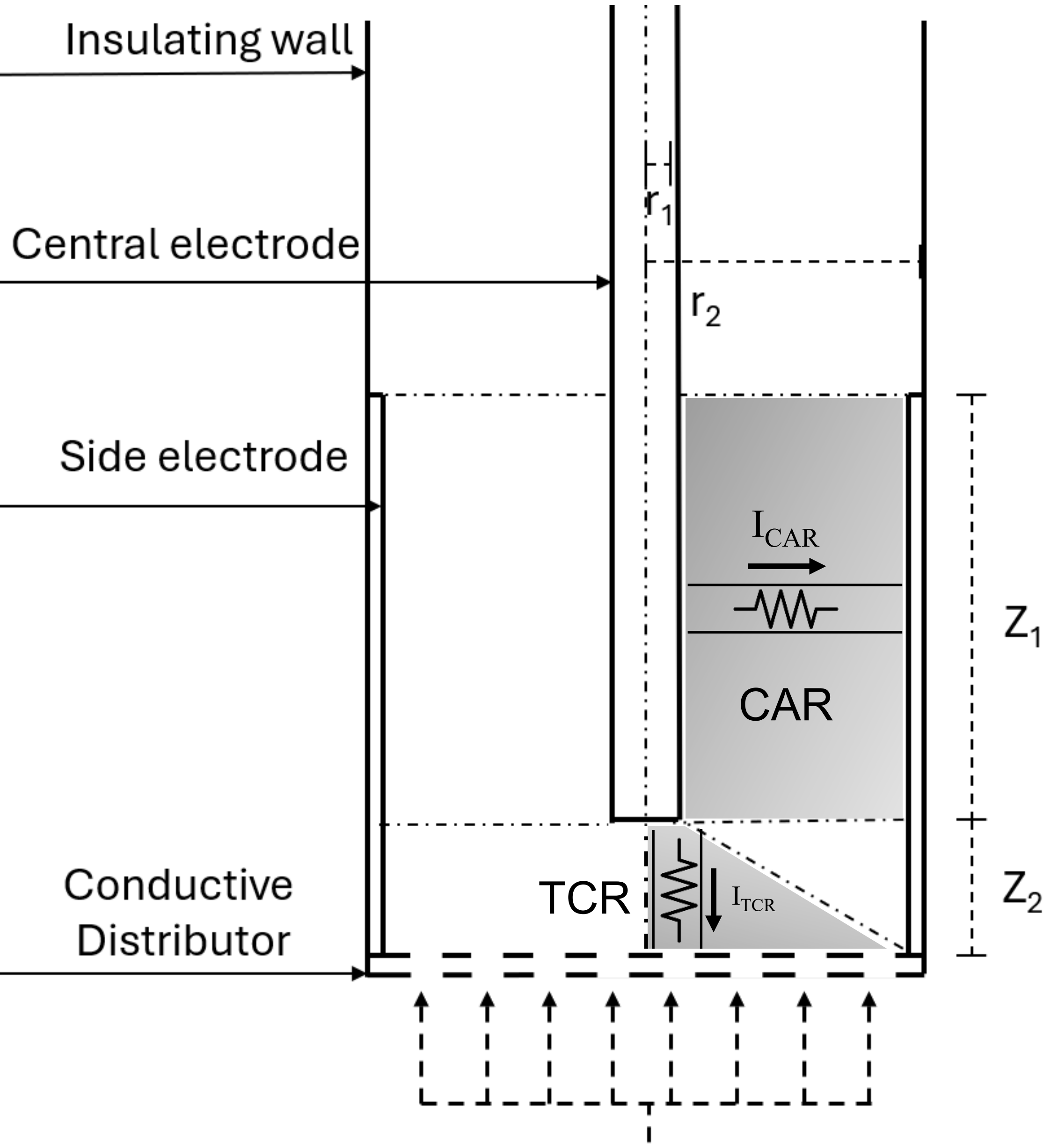
⇩

- Replace the coaxial resistance in the Joule heating equation

$$Q_{JH,CAR} = \frac{V^2}{R_{CAR}} = \frac{V^2 2\pi Z_1}{s_{bed}\, Ln\left(\frac{r_2}{r_1}\right)}$$

$$\boldsymbol{dQ_{JH,CAR} = \frac{V^2 2\pi dz_1}{s_{bed} ln\left(\frac{r_2}{r_1}\right)}}$$

Derivation of the Truncated Cone Resistor Expression



- Identification of the characteristic length (L) and the cross-sectional area to the flow of the current ($A_{c,I}$)

$$R = \frac{s_{bed} L}{A_c} \to L = z \; A_{c,I} = \pi r^2$$

- Derivation of the Coaxial resistor expression

$$R_{TCR} = \frac{s_{bed} z_2}{\pi r_1 r_2} = \sum \frac{s_{bed} dz_2}{\pi r_1 r_2} \overrightarrow{over\ dz_2} \, dR_{TCR} = \frac{s_{bed} dz_2}{\pi r_1 r_2}$$

If I is constant along the axial direction → Differential resistances in the truncated cone resistor can be treated as resistances in series

⇩

- Replace the truncated cone resistance in the Joule heating equation

$$Q_{JH,TCR} = I_{TCR}^2 R_{TCR} = \frac{I_{TCR}^2 s_{bed} Z_2}{\pi r^2}$$

$$\boldsymbol{dQ_{JH,TCR} = \frac{I_{TCR}^2 s_{bed} dz_2}{\pi r^2}}$$