
C1 Conversion Chemistries:

Industrial Applications and Outlook

Jonathan “Jo” Melville
CSP Strategy Meeting
March 3rd, 2022



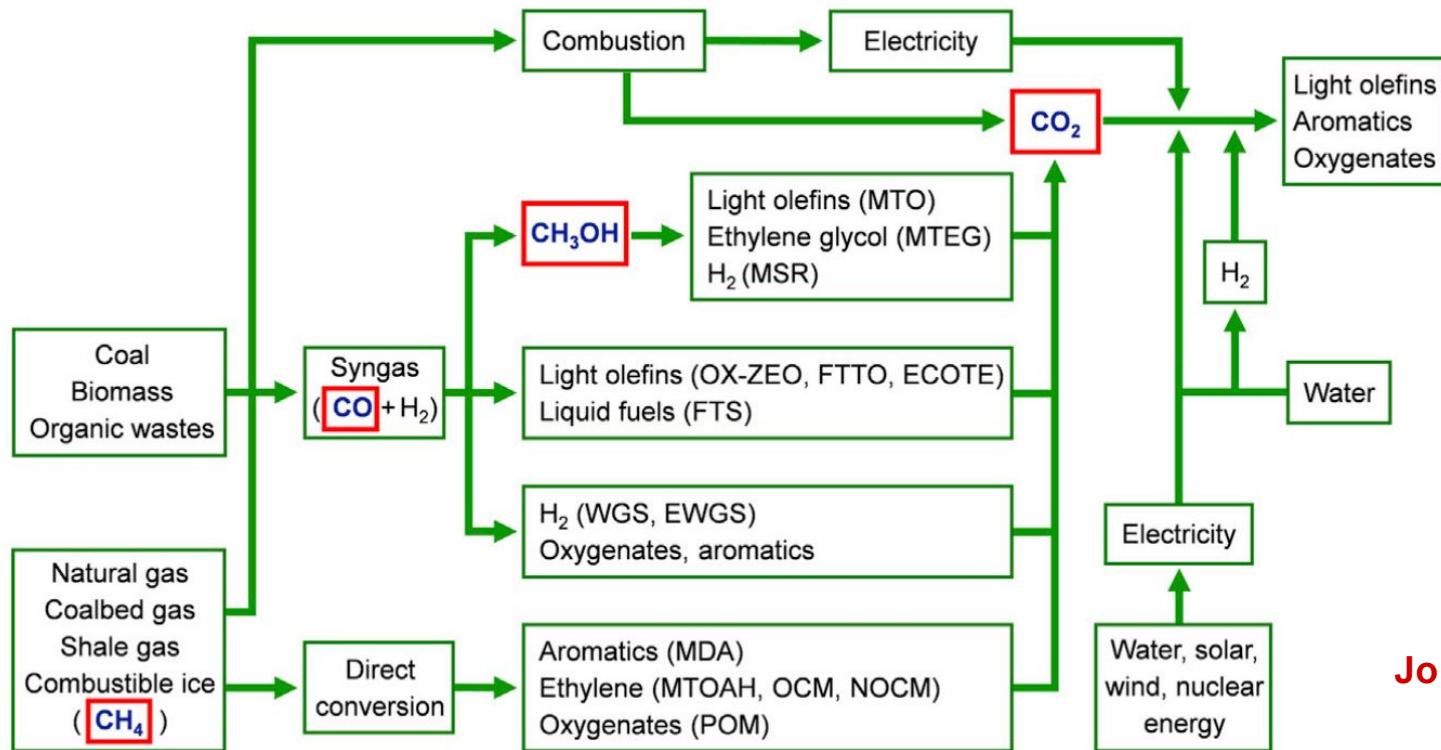
SOLAR ENERGY
TECHNOLOGIES OFFICE
U.S. Department Of Energy



U.S. DEPARTMENT OF
ENERGY

Energy Efficiency &
Renewable Energy

C1 Reaction Space: Very Big



Jo (very small):



The Usual Suspects

- More oxygen \rightarrow more oxidized!

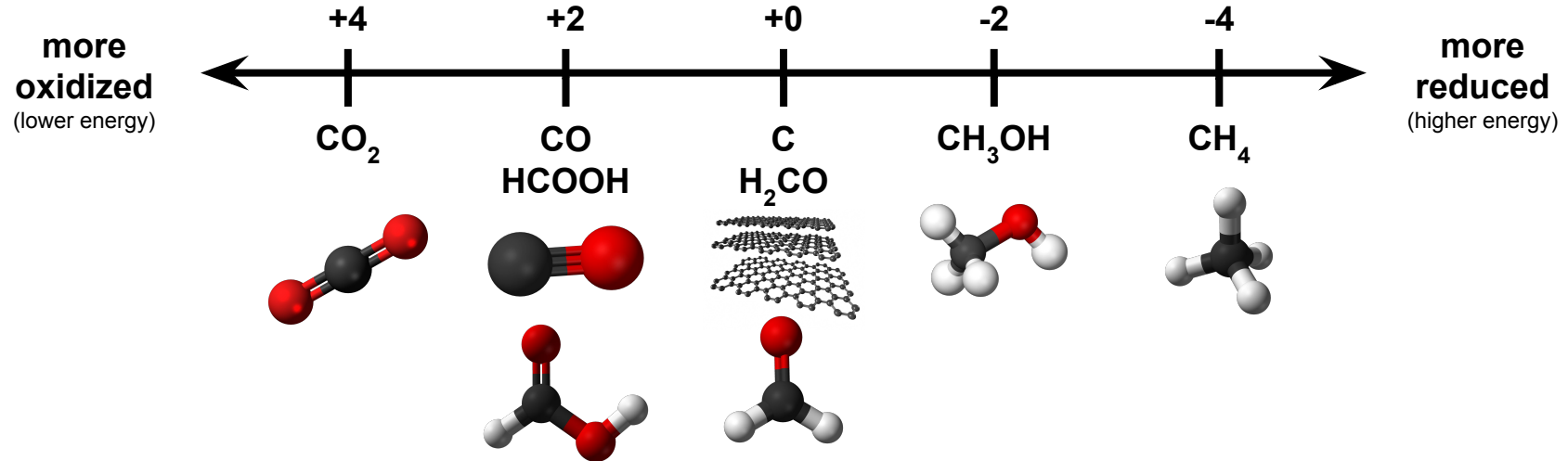


Table of Contents (CH₄ Feedstock)

- Steam Methane Reforming (SMR)
 - Partial CH₄ Oxidation
 - Methane Pyrolysis
 - On solid catalysts
 - In liquid metals
 - Oxidative CH₄ Coupling (OCM)
 - Nonoxidative CH₄ Coupling (NOCM)
 - Methane to Olefins/Aromatics/Hydrogen (MTOAH)
-

Table of Contents (MeOH Feedstock)

- Methanol Steam Reforming (MSR)
- Methanol to Olefins Upgrading (MTO)
- Methanol to Ethylene Glycol (MTEG)



Table of Contents (CO Feedstock)

- Fischer-Tropsch (F-T)
 - Methanation
 - Boudouard Reaction
 - Electrochemical CO to Ethylene (ECOTE)
 - Oxide-Zeolite Syngas Upconversion (OX-ZEO)
 - Electrochemical Water-Gas Shift (RT-EWGS)
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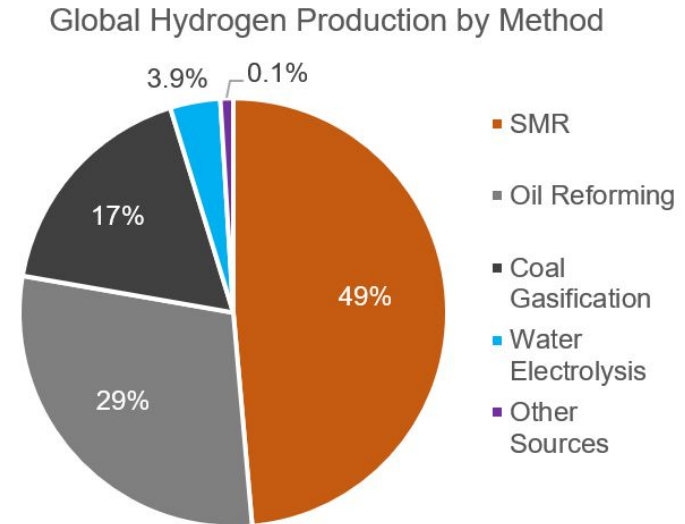
Table of Contents (CO₂ Feedstock)

- Thermochemical CO₂ Splitting on Solid Oxides
 - [Reverse] Water Gas Shift (RWGS)
 - Electrochemical CO₂ reduction (eCDR)
 - to CO, HCOOH
 - to C₂H₄, EtOH, etc.
 - on gas-diffusion electrodes (low-T)
 - on solid-oxide electrodes (high-T)
-

Methane

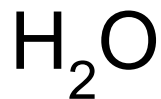
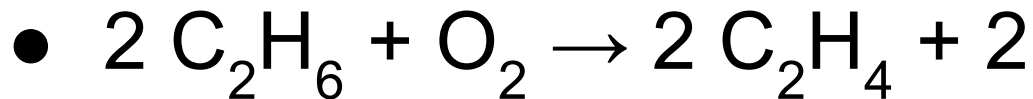
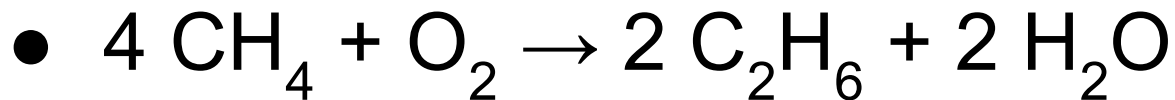
Steam Methane Reforming (SMR)

- $\text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3 \text{H}_2$
 - $\Delta H = 206 \text{ kJ/mol}$
 - T: 650~900 °C; P: 20~30 bar
 - Catalysts: e.g. Ni/MgO
- Autothermal reforming:
 - Uses purified O_2 instead of air for oxidant feedstock
 - Allows control of H_2 :CO ratio



(Dincer & Acar, 2015)

Oxidative CH₄ Coupling (OCM)

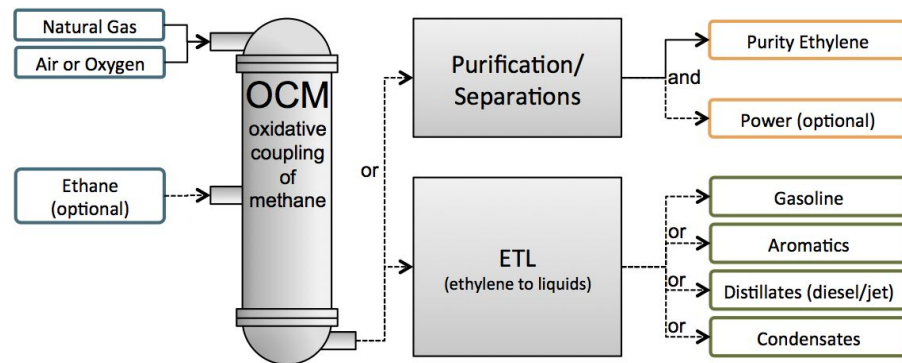


- T ~750 °C
- Catalyst: Li/MgO
- 50-80% C₂ selectivity
- 20-40% CH₄ conversion

- Radicaloid mechanism

 **siluria**
TECHNOLOGIES

(raised \$100m, bought out in 2019)



Nonoxidative CH₄ Coupling (NOCM)

- $n \text{CH}_4 \rightarrow \text{C}_n \text{H}_{2n+2} + \text{H}_2$ ($n = 2-6$)
 - $T = 250-1100 \text{ }^\circ\text{C}$
 - Catalyst: Pt/SiO₂, Mo/zeolite
 - 40-95% C₂₊ selectivity
 - 1-45% CH₄ conversion
- Low CH₄ conversion, coking are problems

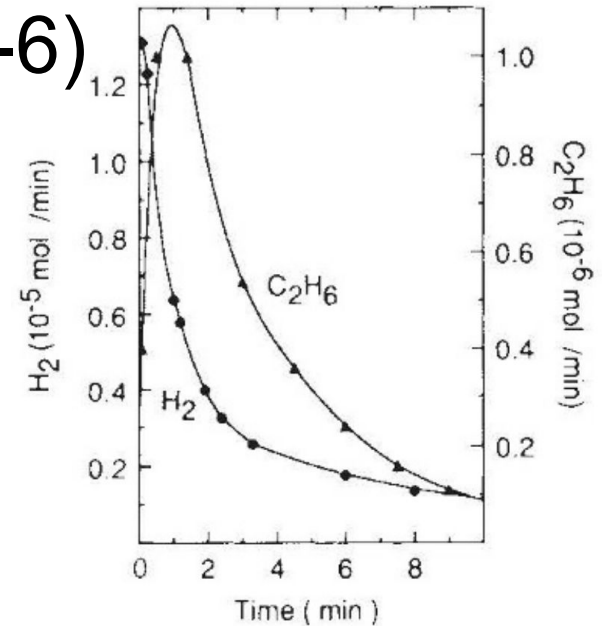
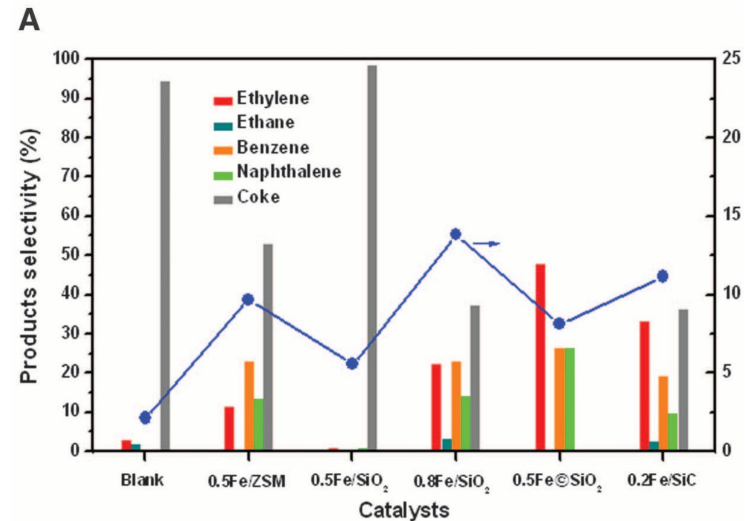


FIG. 1 Molar flow rates of H₂ and C₂H₆ at the exit of the reactor during the exposure of the Pt to CH₄ at 250 °C. Sample mass: 100 mg of EURO PT-1 (see text). Flow rate of CH₄: 400 ml min⁻¹ under ordinary pressure.

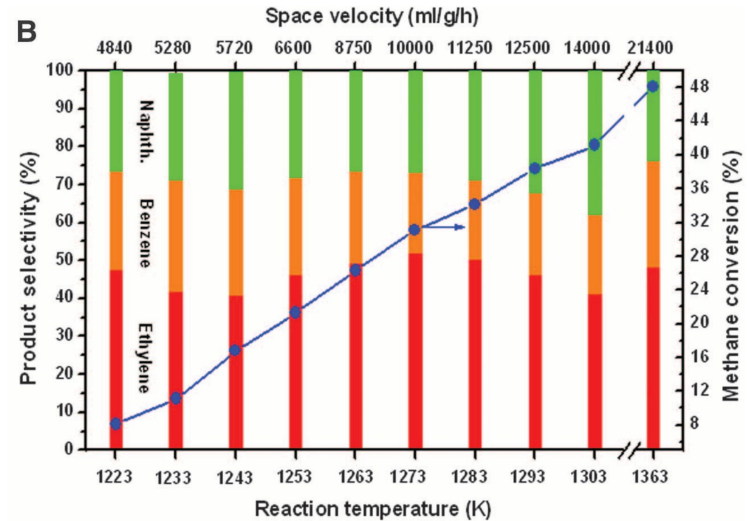
Methane to Olefins/Aromatics/Hydrogen (MTOAH)

- $\text{CH}_4 \rightarrow \text{C}_2\text{H}_4$, aromatics, H_2
 - $T \sim 1100^\circ\text{C}$
 - Catalyst: $\text{Fe}_1\text{@SiO}_2$
 - 48.1% CH_4 conversion
 - 48.4% C_2H_4 selectivity
- No coking!
- Radicaloid surface mechanism



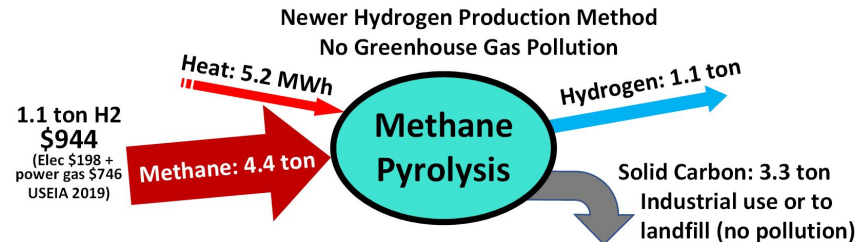
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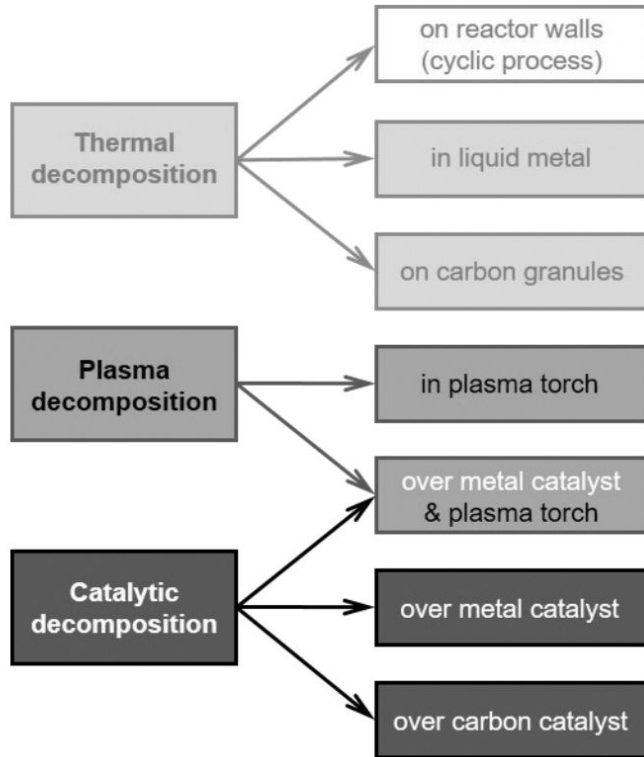


Methane Pyrolysis

- $\text{CH}_4 \rightarrow \text{C} + 2 \text{H}_2$
 - $\Delta H = 75 \text{ kJ/mol (298 K)} \rightarrow 93 \text{ kJ/mol (1600 K)}$
 - Compare $\Delta H = 126 \text{ kJ/mol}$ for SMR (incl. $\Delta_{\text{vap}} H$)
 - $\Delta G = 0 \text{ kJ/mol @ } \sim 550 \text{ }^\circ\text{C}$
 - T generally 600~2000 $^\circ\text{C}$ -- as low as 400~500 C w/ right catalysts (Ni)
 - P = 1 bar



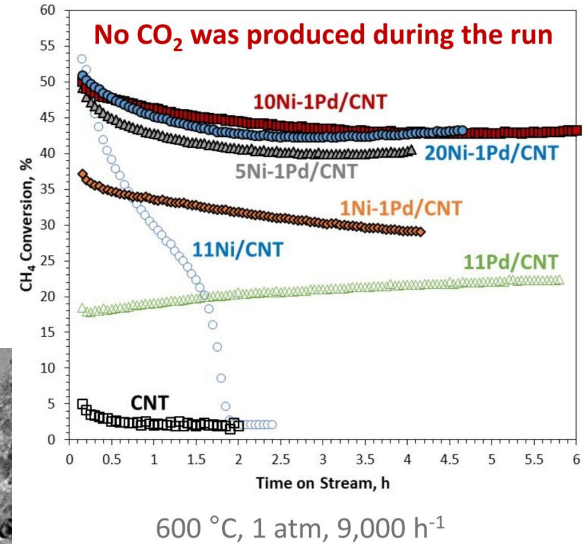
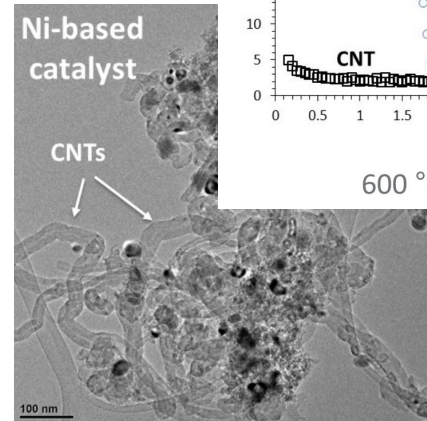
Methane Pyrolysis



- 1 ton $\text{CH}_4 \rightarrow$
250 kg H_2 + 750 kg C
- 50 GJ + $\Delta_R H \rightarrow$
30 GJ + 24.6 GJ
- >40% the energy is sequestered as C!

Methane Pyrolysis

- Catalysts for methane pyrolysis:
 - TMs (**Ni**, Pd, Pt, Fe, Co) on Al_2O_3 , MgO, SiO_2 , TiO_2
 - Nanotubes (?!)
 - Regeneration is difficult (esp. w/o burning off C)



Accomplishments and Progress

Process Models for Methane Pyrolysis Indicate >80% Reduction in GHG Possible

	Raw Material		Utility	Byproduct	Performance	
	Natural gas (kg/kg H ₂)	HNO ₃ (kg/kg H ₂)	Electricity (kWh/kg H ₂)	Carbon (kg/kg H ₂)	CO ₂ Emission (kg/kg H ₂)	Efficiency (%, LHV) ^(d)
SMR ^(a, b)	3.42		0.28-2.10		9.6-11.5	70-80
SMR+CCS ^(c)	3.68		0.60		2.98	71.4
C1 Pyrolysis	4.65	0.18	3.13	3.05	1.67	53.5

(a) PEP Yearbook, Hydrogen production by steam reforming of natural gas, 1E-586, 2014.

(b) PEP Yearbook, Hydrogen small scale by steam reforming, 1E-573, 2014.

(c) NREL, case study: central natural gas, future central hydrogen production from natural gas with CO₂ sequestration version 3, 2018.

(d) Carbon product is excluded.

- ▶ Process models developed comparing this pyrolysis process and baseline SMR and SMR + CCS cases.
- ▶ Raw material cost and stoichiometry disfavor ANY methane pyrolysis technology over steam reforming:
 - Pyrolysis: $\text{CH}_4 \rightarrow \text{C} + 2\text{H}_2$
 - Steam Reforming: $\text{CH}_4 + 2\text{H}_2\text{O} \rightarrow \text{CO}_2 + 4\text{H}_2$

Emission reductions and sale of carbon co-product are benefits for pyrolysis. Methane pyrolysis technologies being developed MUST produce a value-add carbon co-product to compete with SMR on a purely cost basis (although regulations could provide additional incentive).

Methane Pyrolysis

- Pyrolysis mostly makes carbon black
 - Primary application: “reinforcing filler” for tire rubber -- up to 50 wt% carbon black (~70%)
 - Also generic rubber additive (~20%), pigments
 - Market size: ~18 Mt/yr, value: ~\$18.7bn
 - Corresponds to ~6 Mt H₂ (out of 60~80 Mt/y globally)
- Might make nanotubes/filaments on the right catalysts?
(at low T though → low conversion)
 - C black: ~\$1/kg; graphitic C: ~\$10/kg; C fibres: ~\$50/kg
- TL;DR don't count on carbon commercializability



Challenges in Methane Pyrolysis

- Solid C product causes coking/clogging
 - Liquid metal pyrolysis attempts to solve this
- Side products: hydrocarbons, PAHs
- Effects of other NG components is unclear
 - But may actually have positive catalytic effects???
 - radicals, man

Liquid-Metal Methane Pyrolysis

- Liquid Ga/Sn/Pb/Bi (200-700 C)
 - Low-melting, minimal catalytic activity
 - Could be a carrier for active metal catalysts
- Liquid Ni/Pd/Pt/Co/Fe (700-1200 C)
 - Active pyrolysis catalysts, but higher-melting
- 95% CH₄ conversion for Ni_{0.27}Bi_{0.73} @ 1065 C
 - “As far as it is known to date, there is arguably no practical procedure to continuously collect and separate the floating carbon, even if it does not appear as a particular obstacle given the existing

Solar Thermal Methane Pyrolysis?

Reference	Year	Heating Mode	Catalyst	Carbon Co-Feed	T (°C)	τ_r (s)	X _{CH₄} (%)
Kogan and Kogan [107]	2003	Indirect irradiation	No catalyst	None	1047	NA	27.3
Dahl et al. [95]	2004	Indirect irradiation	No catalyst	CB	1860	0.01	90
Abanades and Flamant [14]	2007	Direct irradiation	No catalyst	None	1385	0.1	97
Abanades and Flamant [112]	2008	Direct irradiation	No catalyst	None	1400	0.25	99
Abanades et al. [98]	2008	Indirect irradiation	No catalyst	None	1580	0.018	99
Rodat et al. [103]	2009	Indirect irradiation	No catalyst	None	1550	0.011	78
					1700	0.032	100
					1800	0.011	93
					1800	0.011	100
					1500	0.032	98
Rodat et al. [104]	2009	Indirect irradiation	No catalyst	None	1470	0.012	62
Maag et al. [108]	2009	Direct irradiation	No catalyst	CB	1043	<2	98.8
					1520	0.061	99
Rodat et al. [102]	2010	Indirect heating	No catalyst	None	1700	0.011	93
Rodat et al. [96]	2011	Indirect irradiation	No catalyst	None	1800	0.011	100
					1450		100
					1200	NA	50
Yehekel and Epstein [106]	2011	Direct irradiation	No catalyst	None	800		15–20
			Fe(CO) ₅				
			Fe(C ₅ H ₅) ₂				
Abanades et al. [113]	2014	Indirect irradiation	CB	None	1200	0.12	≈100
Paxman et al. [109]	2014	Indirect irradiation	No catalyst	None	1100	NA	69
Abanades et al. [110]	2015	Indirect irradiation	CB (co-feed considered as catalyst)	CB	1250	0.113	50
					1250	0.038	15

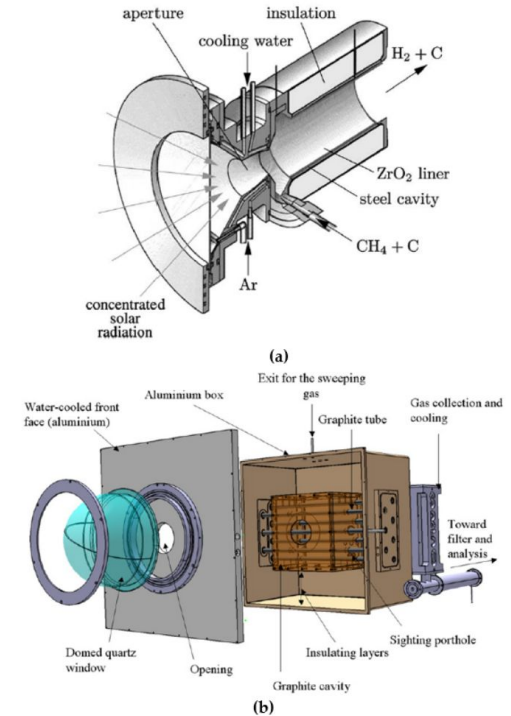
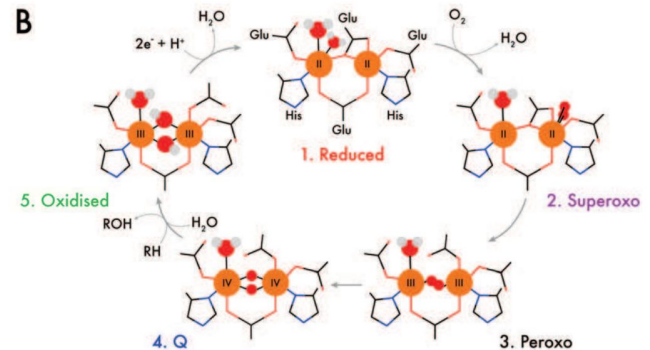
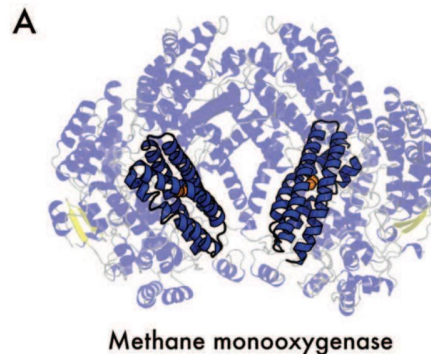


Figure 1. Directly- vs. indirectly-irradiated solar reactors used for methane pyrolysis: (a) 5 kW directly-irradiated reactor (Copied from Ref. [108] with Elsevier permission), (b) 50 kW indirectly-irradiated reactor (Copied from Ref. [102] with Elsevier permission).

Partial Methane Oxidation

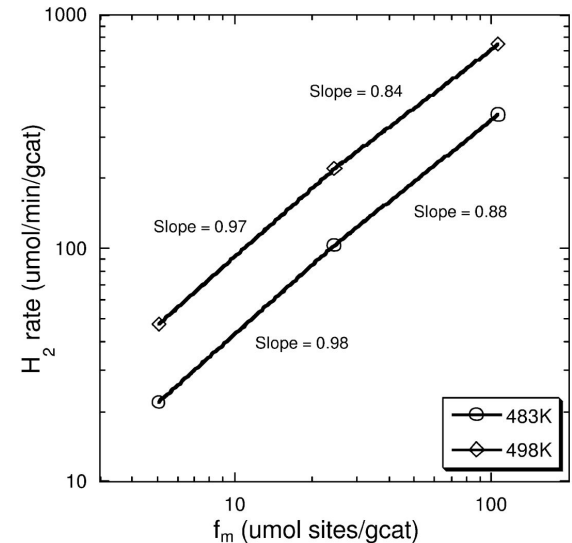
- $\text{CH}_4 + \text{O}_2 \rightarrow \text{CH}_3\text{OH} / \text{CH}_3\text{COOH}$
 - $T \sim 200\text{-}400\text{ }^\circ\text{C}$
 - Catalyst: zeolite (Cu-ZSM-5) or MMO
 - ~97% selectivity, ~17% conversion
- Overoxidation!



Methanol

Methanol Steam Reforming (MSR)

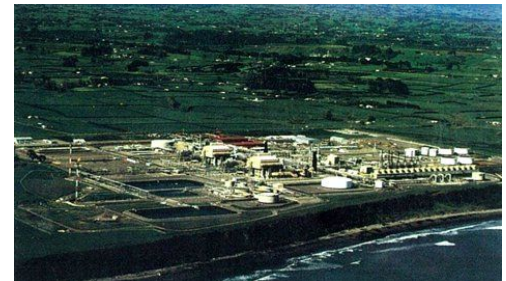
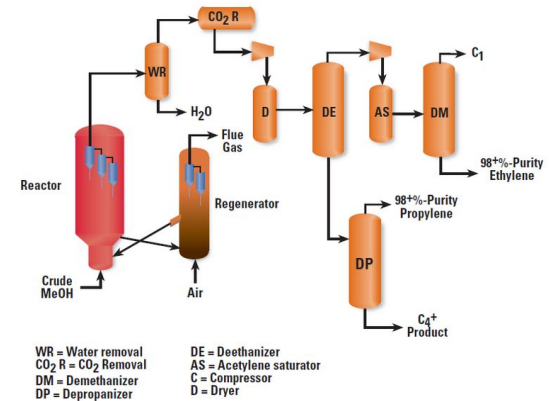
- $\text{CH}_3\text{OH} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + 3 \text{H}_2$
 - $T=150\text{-}250\text{ }^\circ\text{C}$
 - Catalyst: Cu/ZnO or CuAl_2O_4 spinel;
- Challenges: suppressing CO, non-noble catalysts, preventing sintering



Mobil Methanol-to-Olefins (MTO)

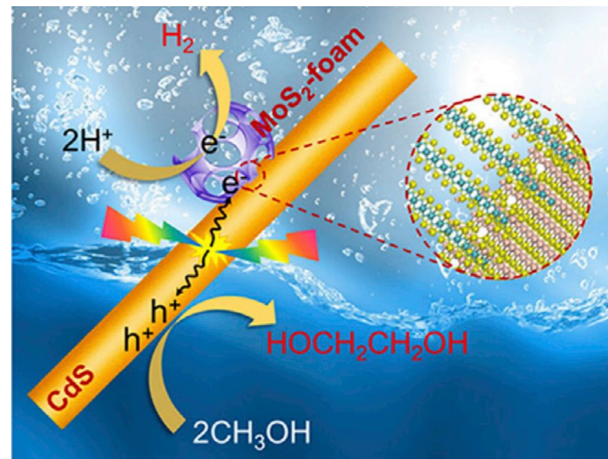
- $2 \text{CH}_3\text{OH} \rightarrow \text{CH}_3\text{OCH}_3 + \text{H}_2\text{O}$;
 $\text{CH}_3\text{OCH}_3 \rightarrow \text{C}_n\text{H}_{2n} + \text{H}_2\text{O}$
 - $T \sim 250 \text{ }^\circ\text{C}$, $P: 50\sim 100 \text{ bar}$
 - Catalyst: ZSM-5 / SAPO-34
 - Primarily $\text{C}_2\text{-C}_3$ products
 - Briefly commercialized (Motonui, NZ)
 - Used for coal liquefaction (Jincheng, China)

UOP/HYDRO MTO Process



Methanol to Ethylene Glycol (MTEG)

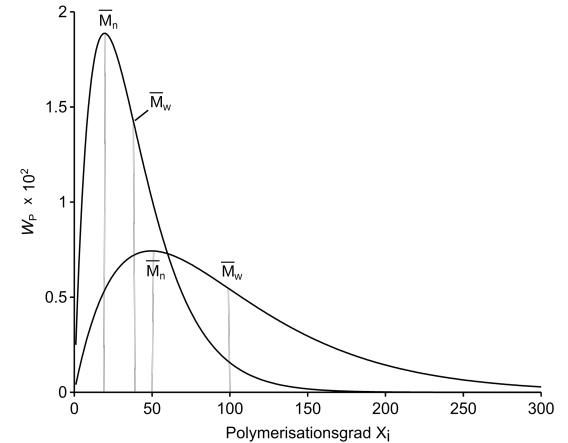
- $2 \text{CH}_3\text{OH} \rightarrow \text{HOCH}_2\text{CH}_2\text{OH} + \text{H}_2$
 - Photocatalytic! (Vis)
 - Room temperature, 1 atm
 - Catalysts: ZnS, CdS, MoS₂
 - 2~20% CH₃OH conversion
 - ~90% EG selectivity
 - Prone to overoxidation.
 - No known thermochemical route! (lol)



Carbon Monoxide

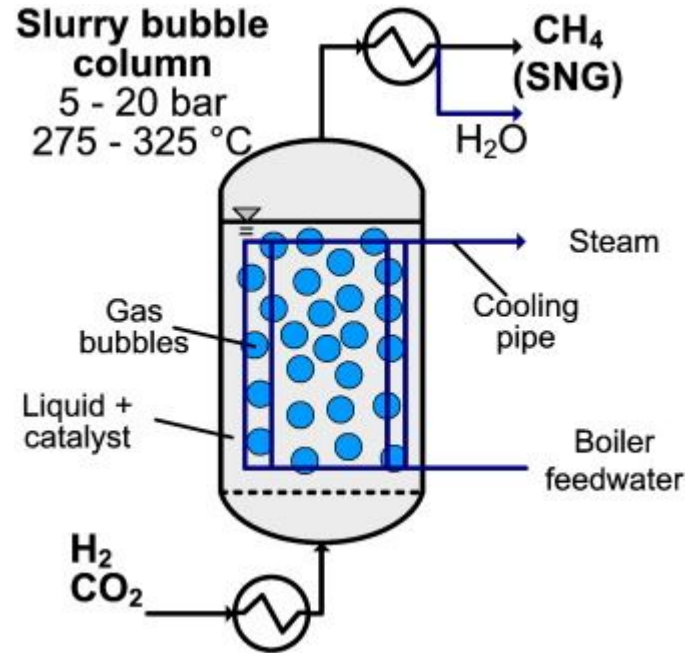
Fischer-Tropsch (F-T)

- $n \text{ CO} + \text{H}_2 \rightarrow \text{C}_n \text{H}_{2n} + \text{H}_2\text{O}$
 - Can make light olefins ($n=2-4$), paraffins ($n=10-20$)
 - T: 200-300 °C (LTFT), 300-350 °C (HTFT); P: 1~20 bar
 - Catalysts: Co/Fe/Ru/Mo/Ni on zeolites, zirconia
- Challenge: C_{2-4} selectivity >58%



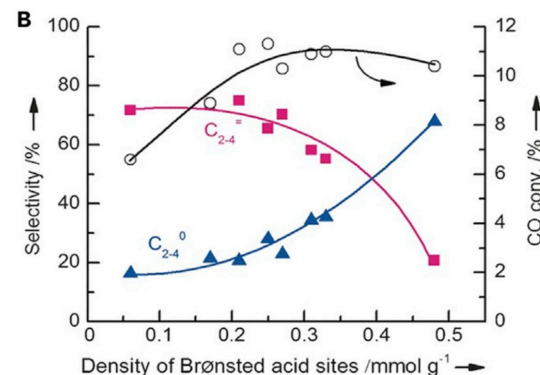
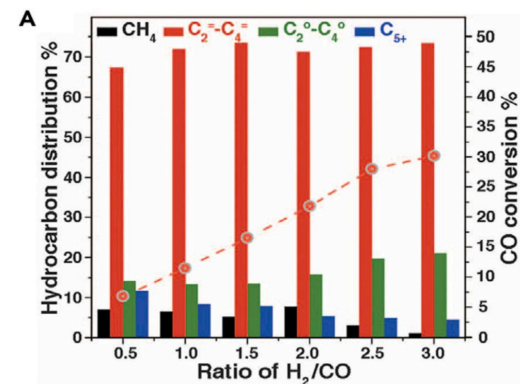
Fischer-Tropsch Methanation

- $\text{CO} + 3\text{H}_2 \rightarrow \text{CH}_4 + \text{H}_2\text{O}$
 - T: 250–375 °C
 - $\Delta H = -206 \text{ kJ/mol}$
 - Catalyst: Ni/Ru/Rh
- The opposite of SMR
- Useful for clearing CO poisons (e.g. H-B)



Oxide-Zeolite Syngas Upconversion (OX-ZEO)

- Novel syngas upgrading catalysts capable of breaking 58% C_{2-4} = AFS barrier
 - T: 400 °C; P: 10-25 bar
 - Catalyst: $ZnCrO_x$ on mesoporous SAPO zeolites
 - Up to 94% C_{2-4} conversion

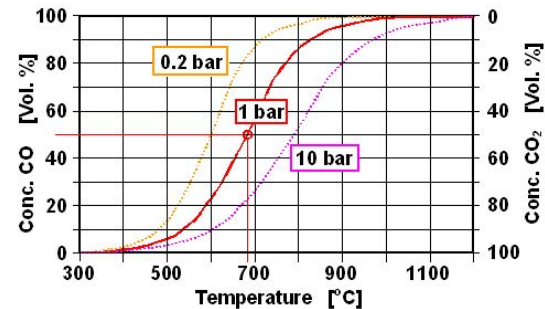
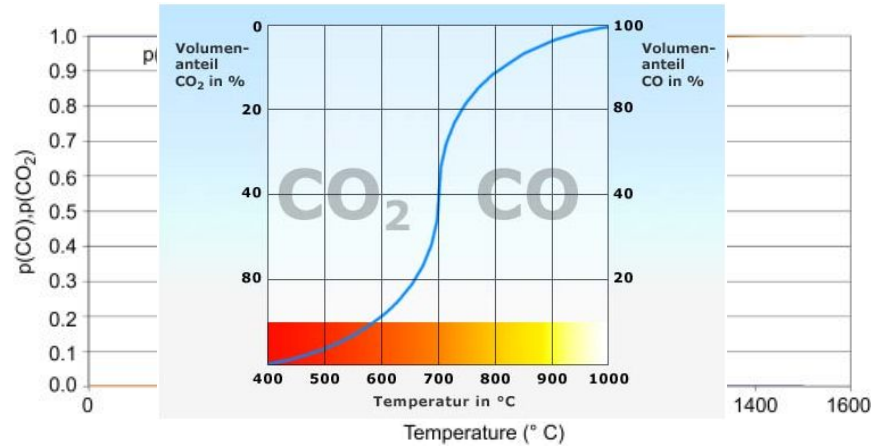


Science **2016**, 351 (6277), 1065–1068.

Angew. Chem. Int. Ed. **2019**, 58 (22), 7400–7404.

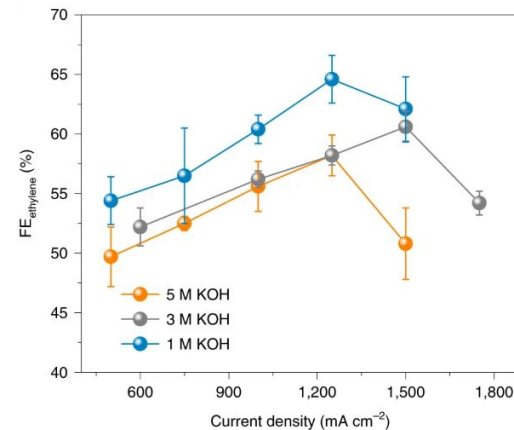
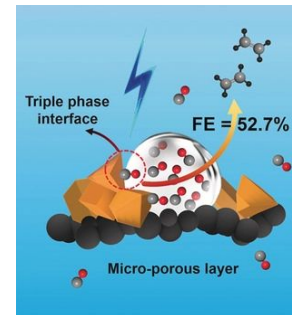
The Boudouard Reaction

- $2\text{CO} \rightleftharpoons \text{CO}_2 + \text{C}$
- $K=1$ at $700\text{ }^\circ\text{C}$ (1 bar)
 - Not really a C1 conversion chemistry but this is why so many high-T industrial reactions output CO instead of CO_2



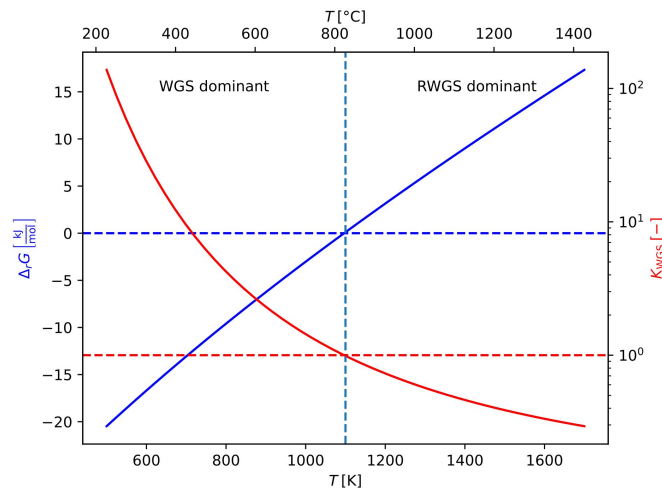
Electrocatalytic CO Reduction to Ethylene (ECOTE)

- CO reduction to ethylene is one of few eCDR reactions with “decent” selectivity
 - r.t., aqueous electrolyte
 - FE%s: 40%~90%
 - j s: 400-1200 mA/cm²
- Better C₂ selectivity than F-T



[Reverse] Water-Gas Shift ([R]WGS)

- $\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2$
 - $\Delta H = -41.2 \text{ kJ/mol}$
 - $\Delta S = -42 \text{ J/mol K}$
 - P: 10~60 bar
- “HT/LT” catalysts:
 - 200~250 °C: CuO on ZnO/Al₂O₃
 - 300~450 °C: Fe₂O₃/Cr₂O₃/MgO



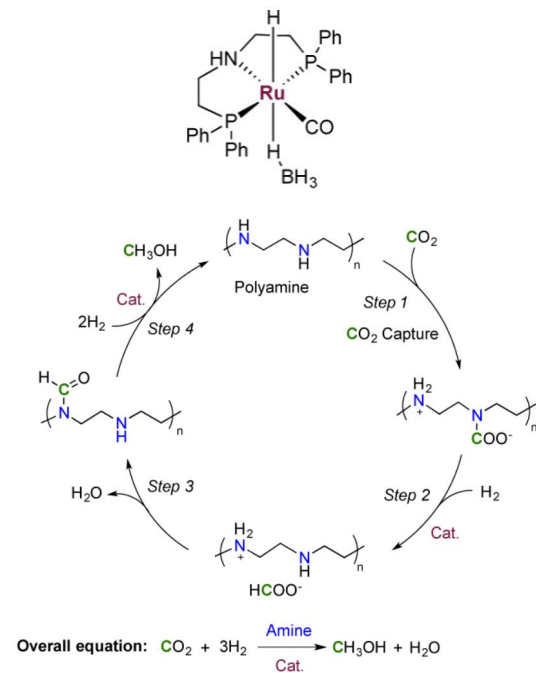
Low-T Electrochemical Water-Gas Shift (RT-EWGS)

- Anode: $\text{CO} + 4 \text{OH}^- \rightarrow \text{CO}_3^{2-} + 2 \text{H}_2\text{O} + 2 \text{e}^-$
- Cathode: $2 \text{H}_2\text{O} + 2 \text{e}^- \rightarrow \text{H}_2 + 2 \text{OH}^-$
- Net reaction: $\text{CO} + 2 \text{OH}^- \rightarrow \text{H}_2 + \text{CO}_3^{2-}$
 - T: 25~150 °C; P: 1 bar
 - Catalyst: Au/ α -MoC on SiO_2 /zeolite; T < 150 C
 - ~100% FE, >99.99% H_2 ; 70 mA/cm² @ 0.6 V

Carbon Dioxide

Homogeneous CO₂ Hydrogenation

- $\text{CO}_2 + 3 \text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$
 - T: 115-165 °C
 - Homogeneous Ru catalyst
 - 79% selectivity for CH₃OH
 - Polyamine CO₂ chemisorbent:
 - CO₂ capture at 400 ppm
- Good luck scaling this up



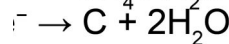
Heterogeneous CO₂ Hydrogenation

- $\text{CO}_2 + 3 \text{H}_2 \rightarrow \text{CH}_3\text{OH} + \text{H}_2\text{O}$
 - T: 220~400 °C; P: 5~50 bar
 - Juice P to >350 bar for >95% selectivity and conversion
 - Selectivity: 30~70%
 - Conversion: <30%
 - Catalysts: Cu-ZnO/Al₂O₃; Cu@MOFs; Pd/In₂O₃; ZnO/ZrO₂; Au-CeO_x/TiO₂

Low-Temperature Gas-Diffusion Electrolysis

Faradaic Efficiencies of Products in CO₂ Reduction at Various Metal Electrodes. Electrolyte: 0.1 M KHCO₃, T = 18.5 ± 0.5°C. Reprinted from Ref. 23, Copyright (1994) with Permission from Elsevier

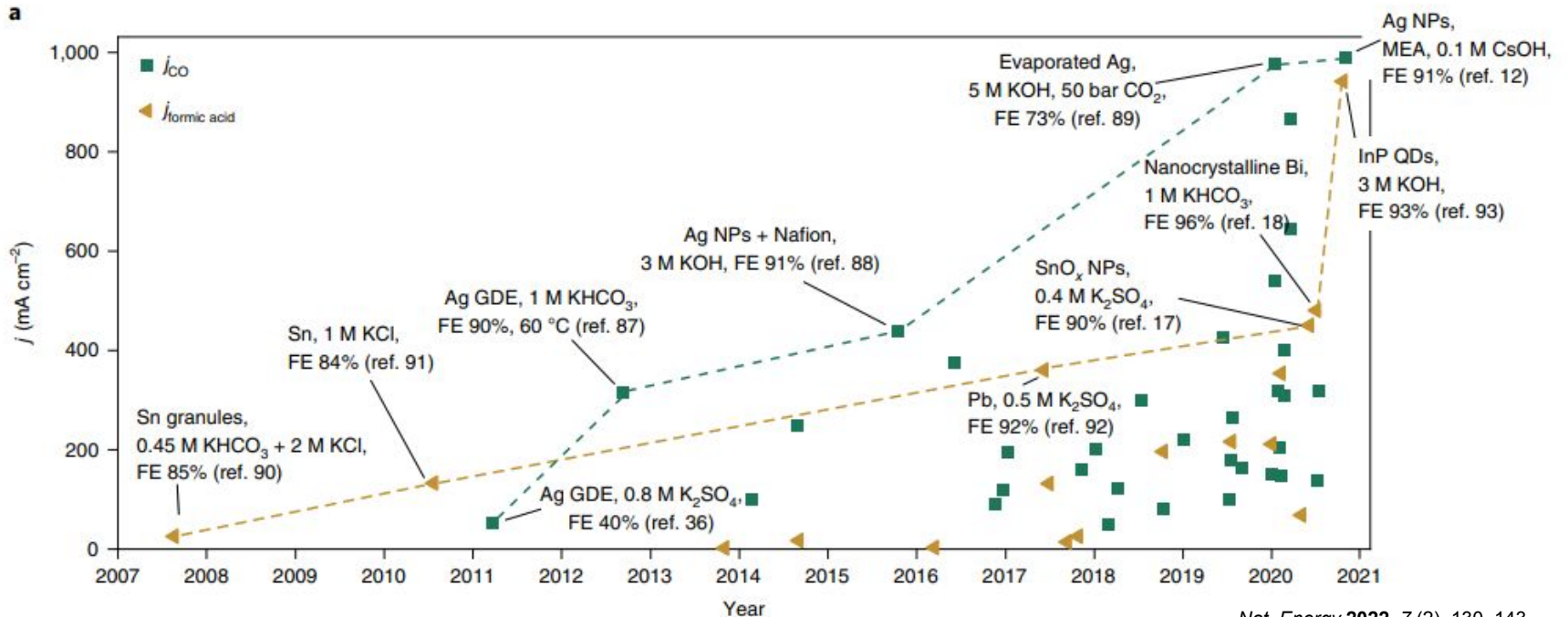
Electrode	Potential vs. SHE V	Current density mA cm ⁻²	Faradaic efficiency, %							
			CH ₄	C ₂ H ₄	EtOH ^a	PrOH ^b	CO	HCOO ⁻	H ₂	Total
Pb	-1.63	5.0	0.0	0.0	0.0	0.0	0.0	97.4	5.0	102.4
Hg	-1.51	0.5	0.0	0.0	0.0	0.0	0.0	99.5	0.0	99.5
Tl	-1.60	5.0	0.0	0.0	0.0	0.0	0.0	95.1	6.2	101.3
In	-1.55	5.0	0.0	0.0	0.0	0.0	2.1	94.9	3.3	100.3
Sn	-1.48	5.0	0.0	0.0	0.0	0.0	7.1	88.4	4.6	100.1
Cd	-1.63	5.0	1.3	0.0	0.0	0.0	13.9	78.4	9.4	103.0
Bi ^c	-1.56	1.2	-	-	-	-	-	77	-	-
Au	-1.14	5.0	0.0	0.0	0.0	0.0	87.1	0.7	10.2	98.0
Ag	-1.37	5.0	0.0	0.0	0.0	0.0	81.5	0.8	12.4	94.6
Zn	-1.54	5.0	0.0	0.0	0.0	0.0	79.4	6.1	9.9	95.4
Pd	-1.20	5.0	2.9	0.0	0.0	0.0	28.3	2.8	26.2	60.2
Ga	-1.24	5.0	0.0	0.0	0.0	0.0	23.2	0.0	79.0	102.0
Cu	-1.44	5.0	33.3	25.5	5.7	3.0	1.3	9.4	20.5	103.5 ^d
Ni	-1.48	5.0	1.8	0.1	0.0	0.0	0.0	1.4	88.9	92.4 ^e
Fe	-0.91	5.0	0.0	0.0	0.0	0.0	0.0	0.0	94.8	94.8
Pt	-1.07	5.0	0.0	0.0	0.0	0.0	0.0	0.1	95.7	95.8
Ti	-1.60	5.0	0.0	0.0	0.0	0.0	tr.	0.0	99.7	99.7



^aethanol; ^bn-propanol; ^cthe data are taken from Hori et al.²³ except Bi which is read from an illustration in a paper by Kunugi et al.¹¹⁷; ^dthe total value contains C₃H₅OH(1.4%), CH₃CHO(1.1%), C₂H₃CHO(2.3%) in addition to the tabulated substances; ^ethe total value contains C₂H₆(0.2%)

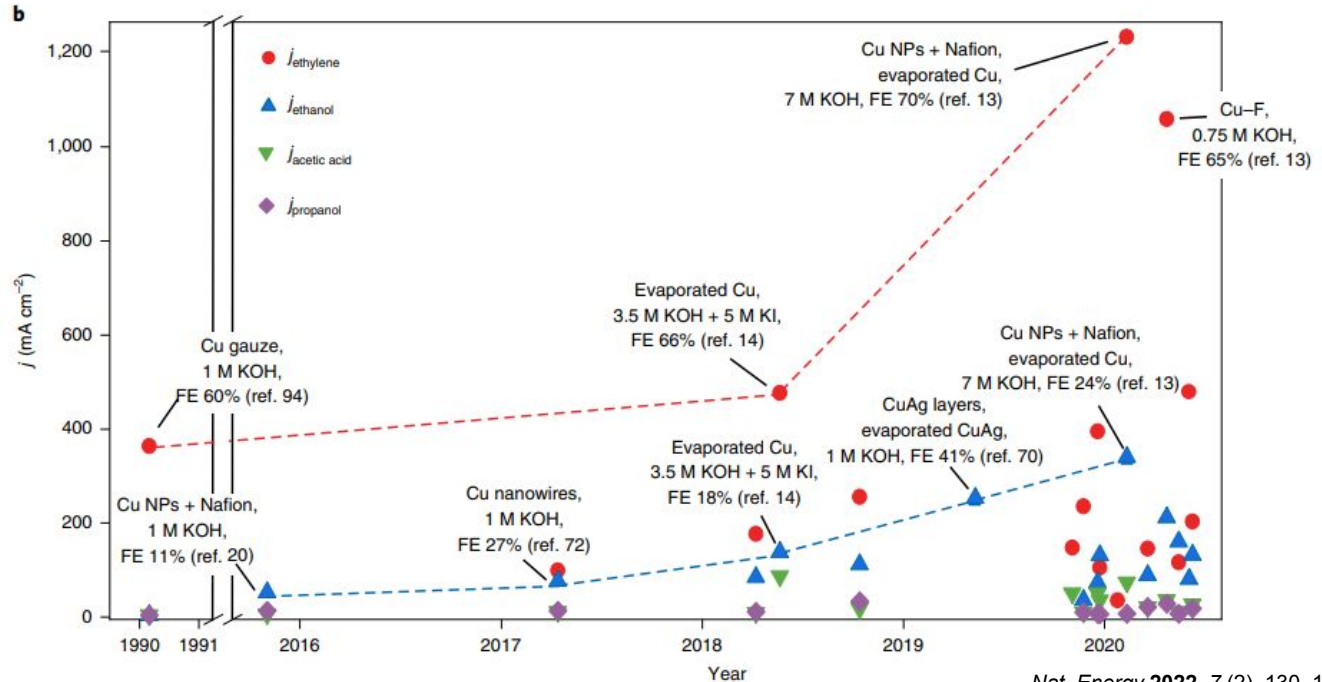
Low-Temperature Gas-Diffusion Electrolysis

CO and HCOOH:



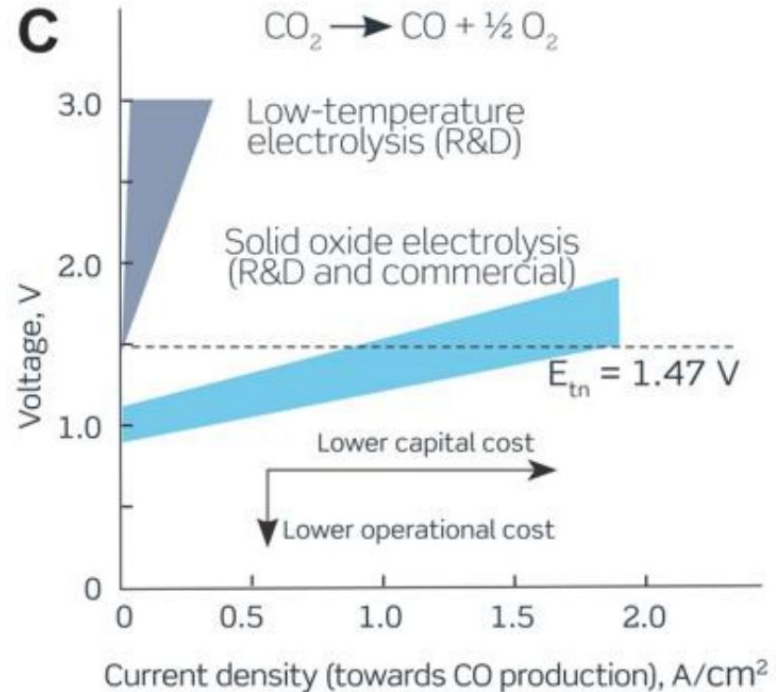
Low-Temperature Gas-Diffusion Electrolysis

C_n products (C_2H_4 , EtOH, PrOH, CH_3COOH):
from CO



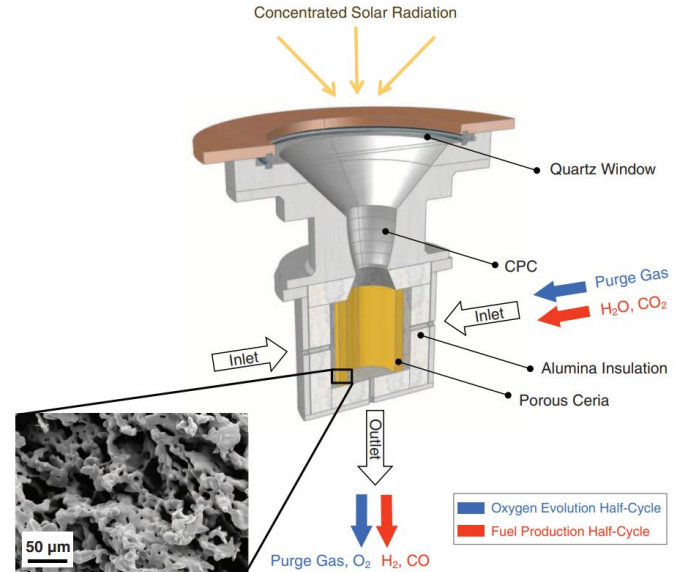
High-T Solid-Oxide Electrolysis

- $\text{CO}_2 \rightarrow \text{CO} + \frac{1}{2} \text{O}_2$
 - T: 500~1000 °C
 - j : 100~1500 mA/cm²
 - FE%: 80~98%
 - Catalysts: doped CeO_2 , ZrO_2 , La_2O_3

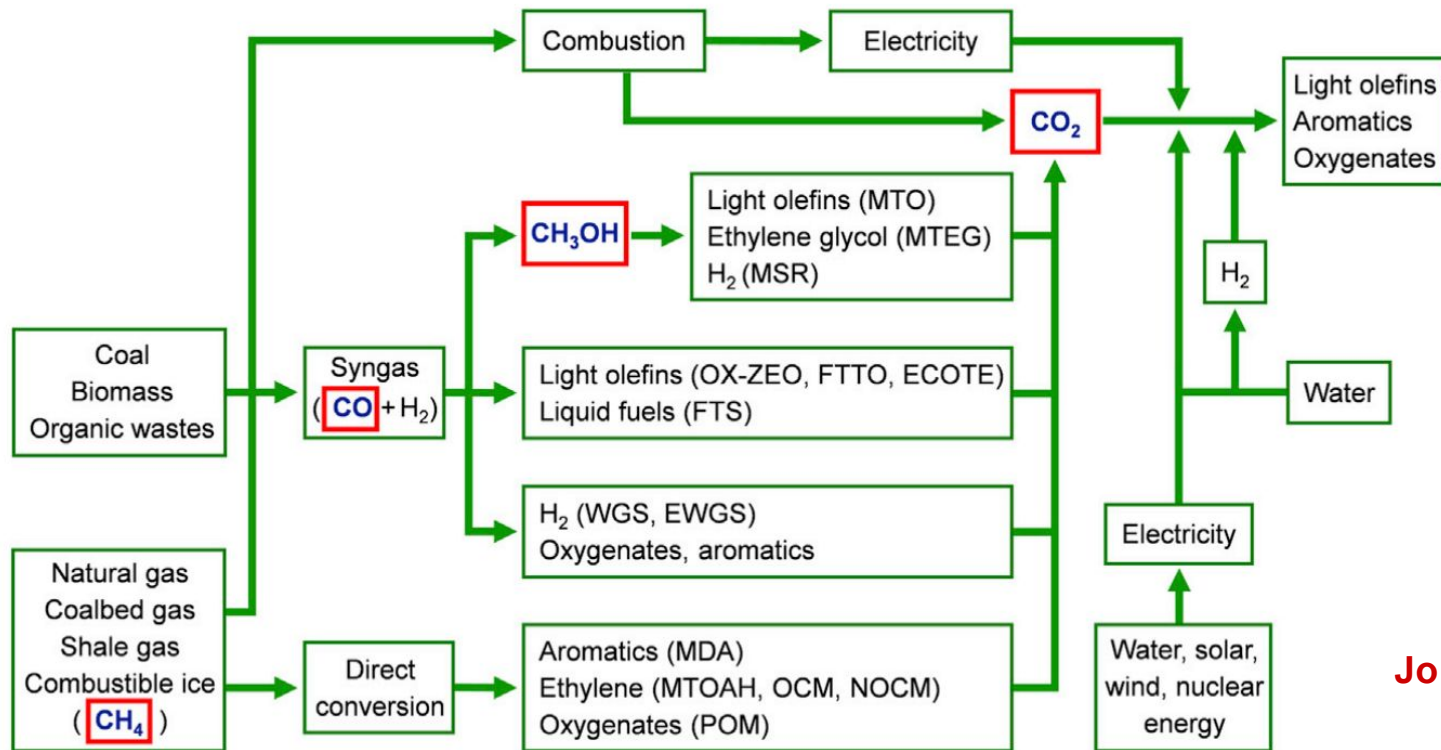


High-T Solid-Oxide Thermolysis

- $\text{CO}_2 \rightarrow \text{CO} + \frac{1}{2} \text{O}_2$
 - $T > 1500 \text{ }^\circ\text{C}$ (up to $2300 \text{ }^\circ\text{C}$)
 - Onset $T \sim 900 \text{ }^\circ\text{C}$
 - Catalyst: $\text{CeO}_{2-\delta}$
 - Energetic efficiencies: $\sim 1\%$
- Challenges:
 - Undesired downstream WGS
 - Radiative heat loss, material stability

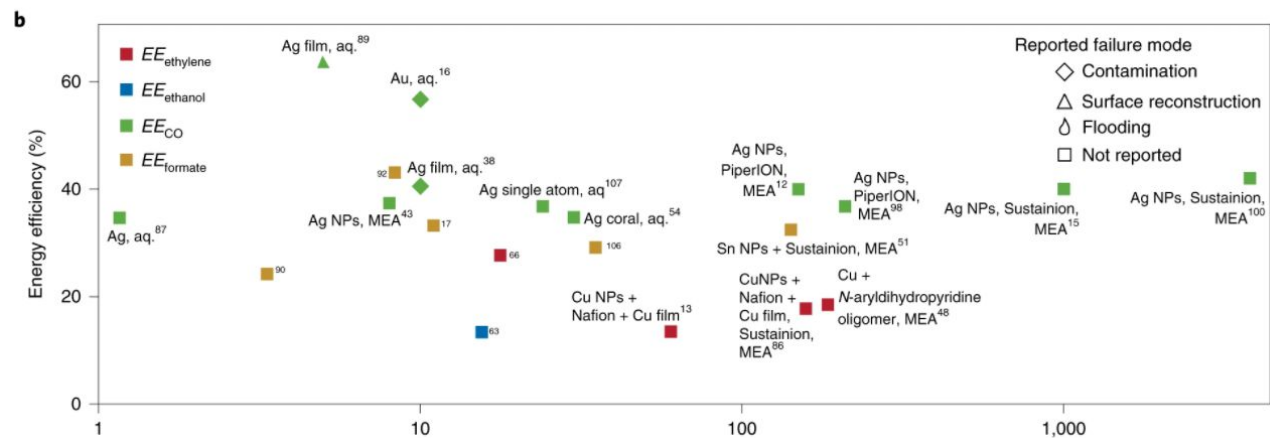
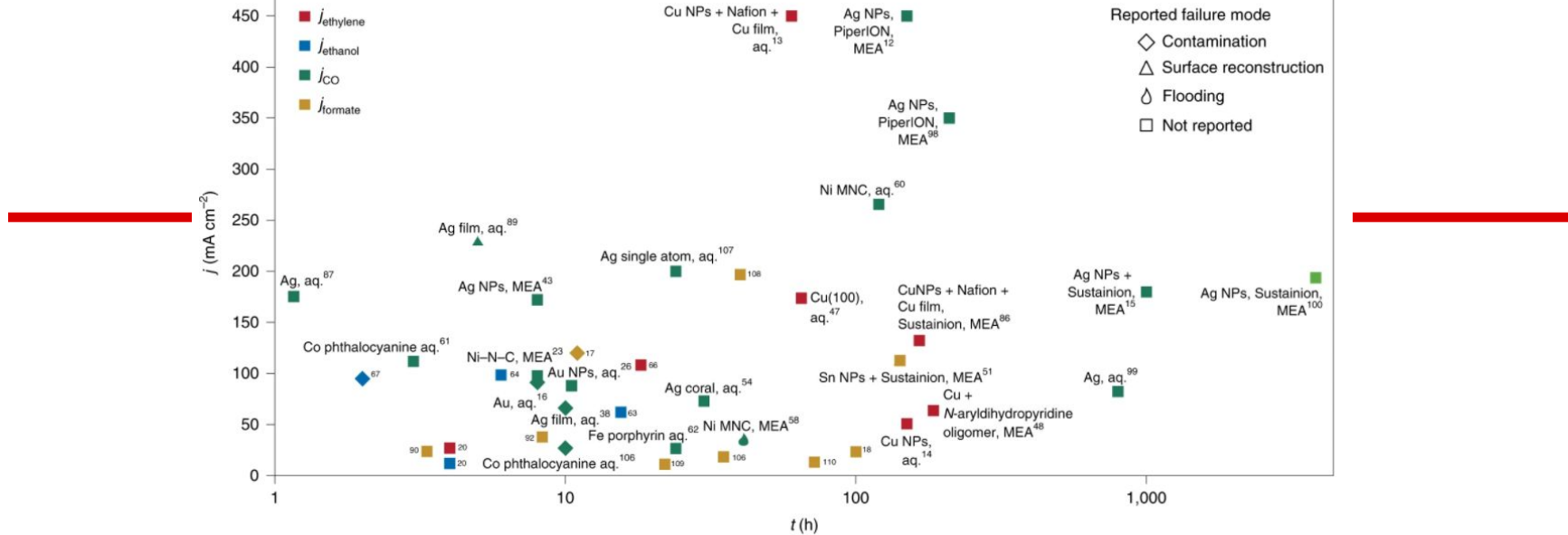


C1 Reaction Space: Very Big



Jo (very small):





CO

- Fischer-Tropsch

- $n \text{ CO} + \text{H}_2 \rightarrow \text{C}_n\text{H}_{2n} + \text{H}_2\text{O}$
- Can make light olefins ($n=2-4$), paraffins ($n=10-20$)
- Catalysts: Co/Fe/Ru/Mo/Ni on zeolites, zirconia
- $T \sim 200-350 \text{ C}$

- Water-gas Shift

- $\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2; \Delta H = -41 \text{ kJ/mol}$
- $T: 300-500 \text{ C}; \text{Fe}_2\text{O}_3\text{-Cr}_2\text{O}_3 \mid \text{Cu/ZnO/Al}_2\text{O}_3$
- Often paired with methanation in order to clear

CO Hydrogenation

- $\text{CO} + \text{H}_2 \rightarrow \text{CH}_3\text{OH}$
 - Cu/ZnO/Al₂O₃ catalyst
 - 30-70% selectivity, <30% conversion
 - T: 220-300 C, P: <50 bar
 - Highly P-dependent; at 360 bar, 98% selectivity, 95% conversion
-

CO₂-to-Liquid-Fuels

- CO₂ to light olefins
 - Typically RWGS to CO and F-T to olefins (n=2-4)
 - Can also be CH₃OH-mediated (ZnZrO_x/SAPO-34); 75-80% selectivity for C₂⁼-C₄⁼, 12-35% CO₂ conversion at 350-400 C
-

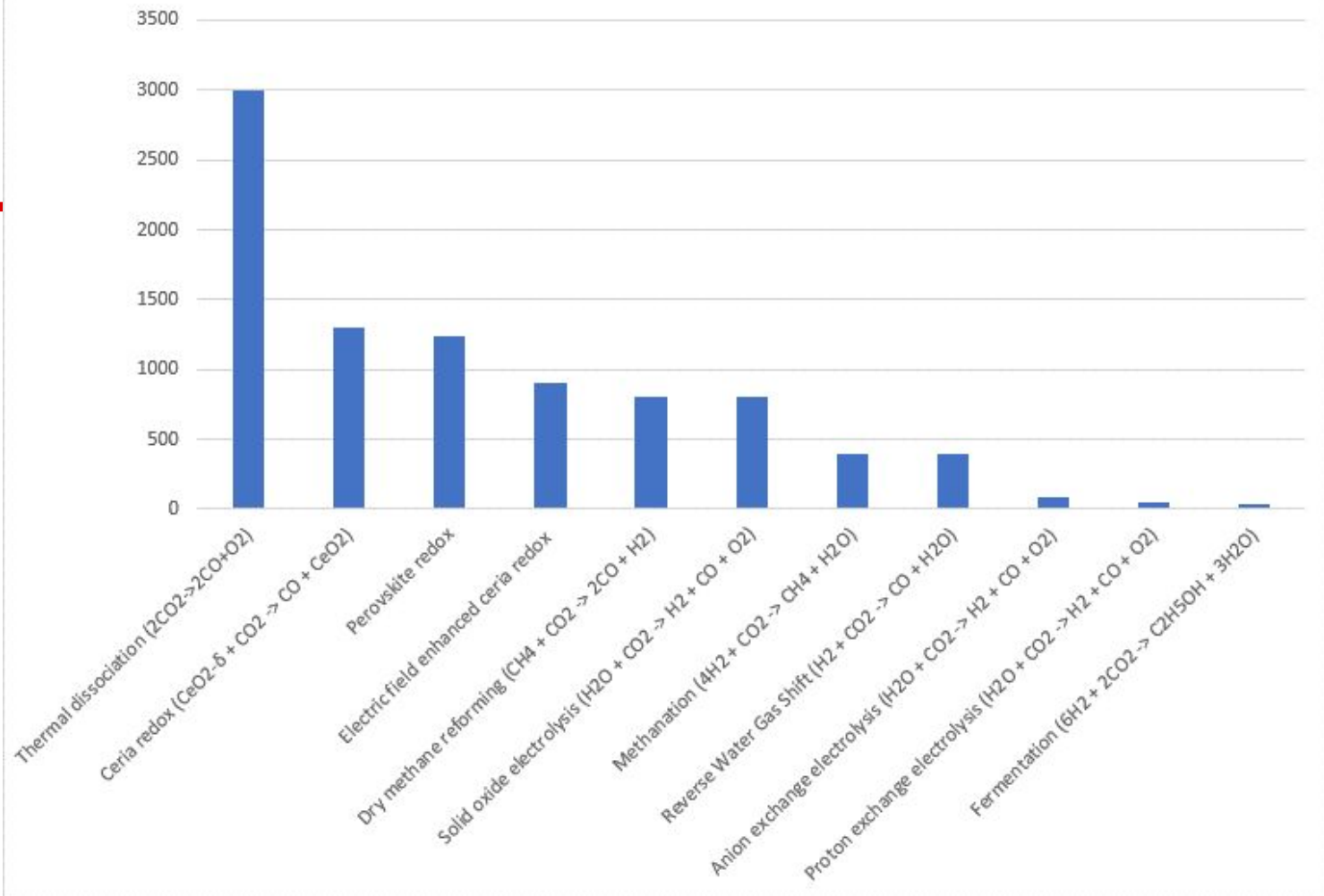
One-carbon (C1) chemistry has emerged as a beneficial solution to the problem of crude oil depletion and is a sustainable, environmentally friendly reaction step that contributes to human development. C1 chemistry is based on the chemical synthesis of a series of significant chemicals and fuels from compounds containing one-carbon atom, such as CO, CO₂, CH₄, HCOH, HCOOH and CH₃OH. This Research Topic focuses on electro-, photo-, thermo-, plasma-, bio-catalytic conversion of C1 molecules, such as production of dimethyl ether and liquid fuels from CO/CO₂; production of methanol, light olefins, and even aromatics from CH₄; and production of hydrogen from HCOOH/CH₃OH. However, due to the complex and variable conversion process, selective control, energy saving and emission reduction are still great challenges for C1 chemistry. Therefore, we hope that this Research Topic would contribute to the development of C1 chemistry.

Although great progress has been made in C1 molecular transformation, many challenges remain to be addressed. The aim of this Research Topic is to cover promising, recent, and novel research works on addressing the challenges in C1 molecules conversion. For example, the current thermochemical conversion of C1 molecules requires high temperature and high pressure. New efforts should focus on reducing the reaction pressure and temperature to optimize the reaction process, or using photocatalysis and electrocatalysis that are not limited by thermodynamic or kinetic control. In addition, the reaction mechanism of the catalyst catalyzing the conversion of C1 molecules is not yet clear, and the exploration of the reaction mechanism has a significant role in promoting the preparation of efficient catalysts, and thus the development of C1 chemistry.

The articles in the forms of Original Research, Review, Mini-review and Perspective are welcomed. Potential topics include but are not limited to the following:

- Advances in the C1 molecules conversion, especially on the CO₂ conversion.
- Conversion of C1 molecules via electro-, photo-, thermo-, plasma-, bio-, and other related chemical reactions.
- Numerous products from conversion of C1 molecules, e.g., production of hydrogen, methanol, light olefins, and even aromatics.

• The improvement of C1 molecular transformation in industrialization



Methanol Steam Reforming (MSR)

Challenge: finding non-noble catalysts

CuAlO_4 has high activity at low T, but limited by sintering, CO formation (pyrolysis + RWGS)

Upconversion Notes

- Bifunctional metal oxide/zeolite catalysts for C_{2+} conversion suffer from parasitic [R]WGS due to high reaction temperatures
 - Selectivity is problematic: (Anderson-Schulz-Flory (ASF) Distribution)
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