Metal Solar Fuels: The Future of Transportation

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Marianne Balat-Pichelin

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OUTLINE

I – Objective: Alternative fuels for sustainable development

II – Concept: Sustainable metal fuels through combustion/reduction cycles

III – Set-up: Solar vacuum-assisted carbothermal reduction of oxides

IV – Numerical simulation: gas circulation in Sol@rmet reactor

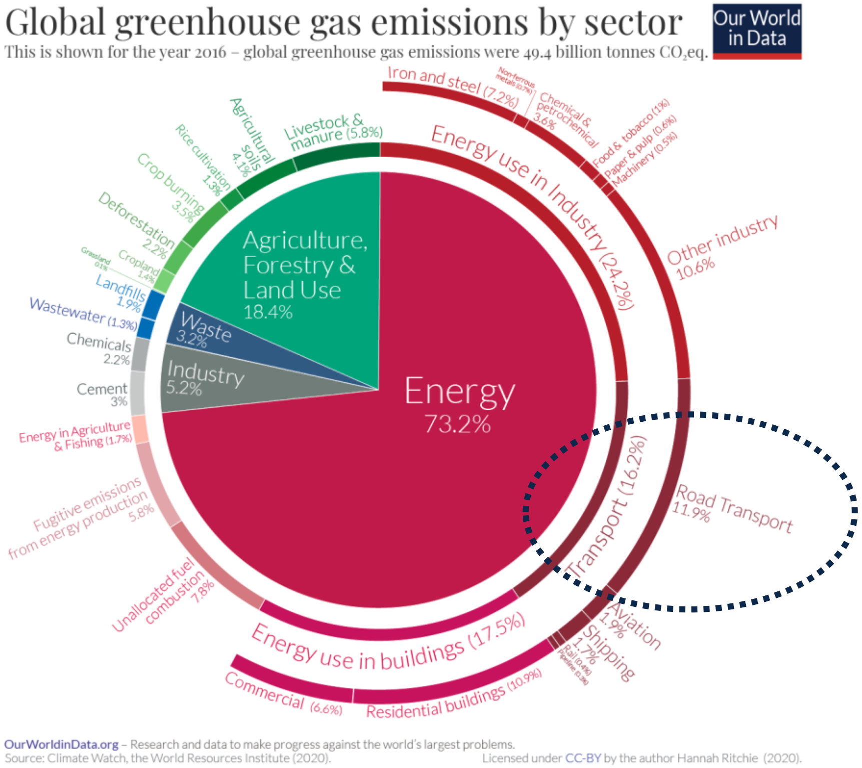
V – Magnesia reduction: Effect of gas circulation, mechanical milling, reductant properties, bentonite binder and catalysts

VI – Alumina reduction: Effect of the reactor pressure on the formation of Al-oxycarbides by-products

VII – Conclusions and perspectives

Alternative fuels for sustainable development

Why ??



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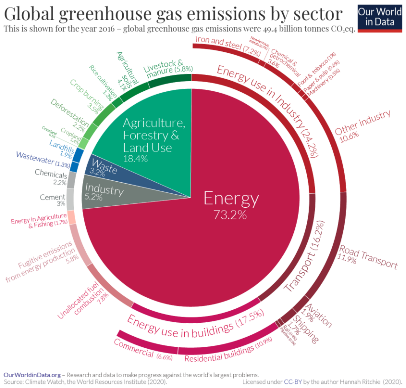
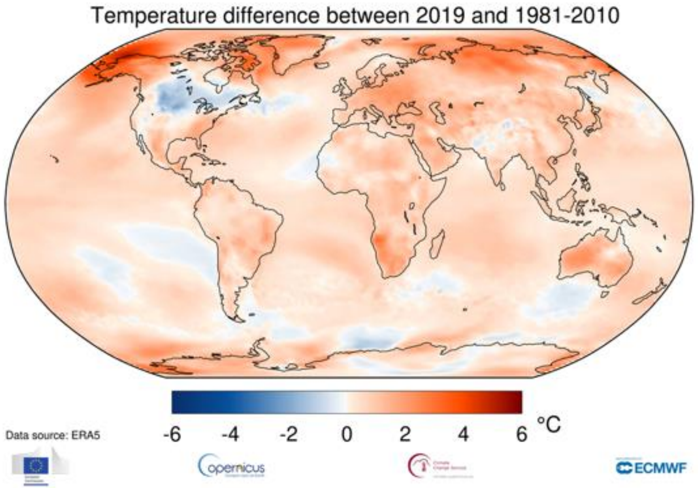
I Alternative fuels for sustainable development

Why ?? When ??



2019 was the second warmest year and the last five years were the warmest on record



Air temperature at a height of two metres for 2019, shown relative to its 1981–2010 average. Source: ERA5. Credit: Copernicus Climate Change Service (C3S)/ECMWF.

Copernicus Europe's eyes on Earth: https://climate.copernicus.eu/

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I Alternative fuels for sustainable development

Why ?? When ?? How??

EIT RawMaterials circular economy: https://eitrawmaterials.eu/

I Alternative fuels for sustainable development

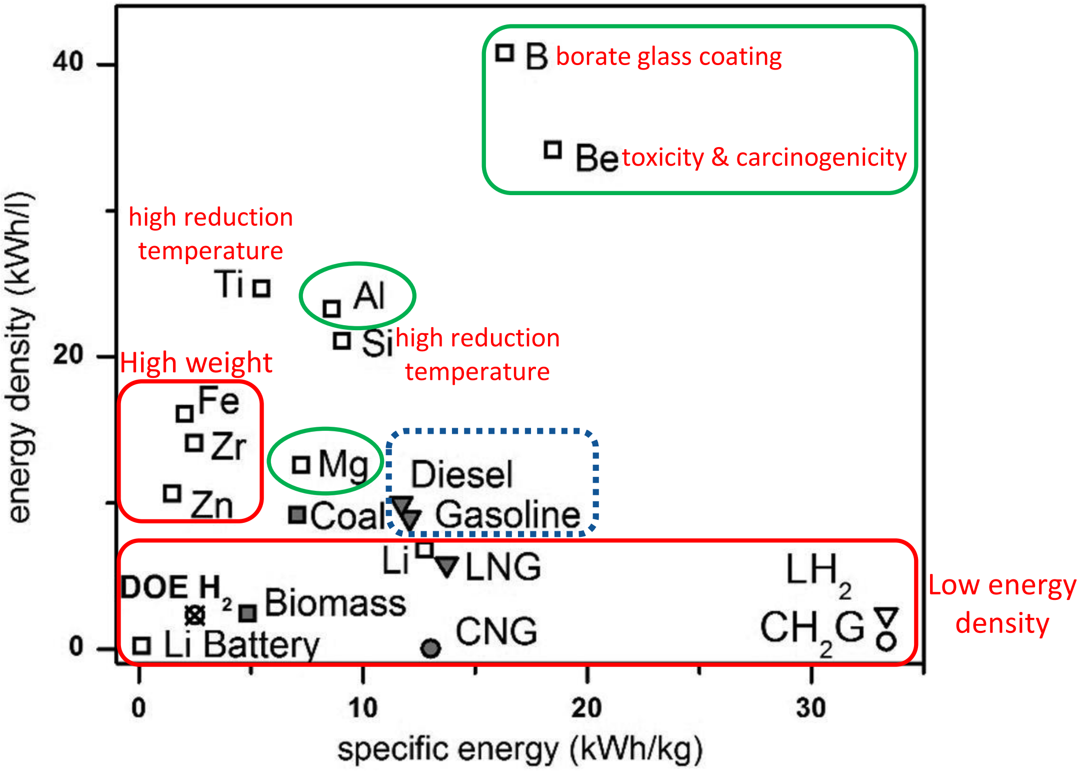
Why ?? When ?? How?? What??

EIT RawMaterials circular economy: https://eitrawmaterials.eu/

Photovoltaic PV panels (electricity)

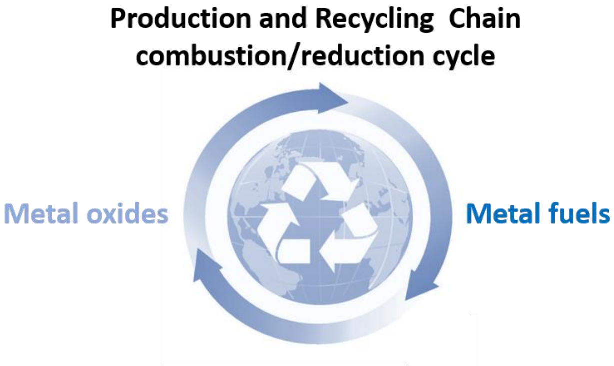
Concentrated solar power CSP (thermal)

Sustainable metal fuels through combustion/reduction cycles



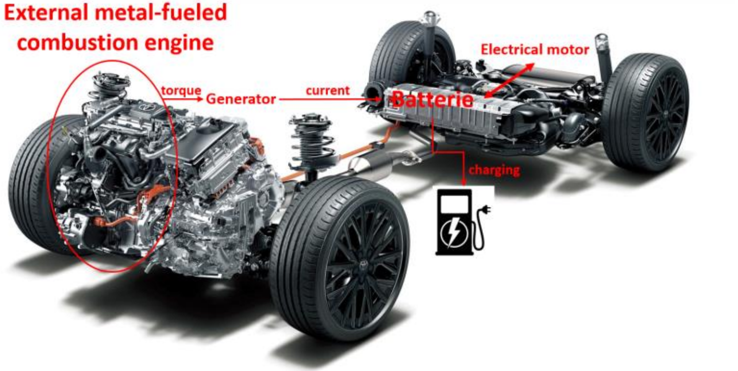
Bergthorson *et al.*, Appl. Energy 160 (2015) 368-382.

II Sustainable metal fuels through combustion/reduction cycles



II Sustainable metal fuels through combustion/reduction cycles

Production and Recycling Chain
combustion/reduction cycle



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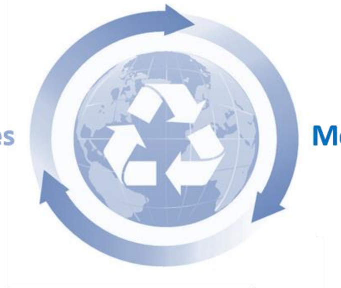
Sustainable metal fuels through combustion/reduction cycles

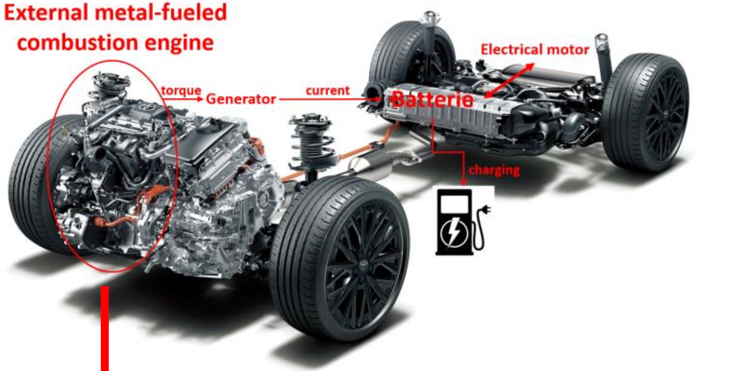
Production and Recycling Chain combustion/reduction cycle

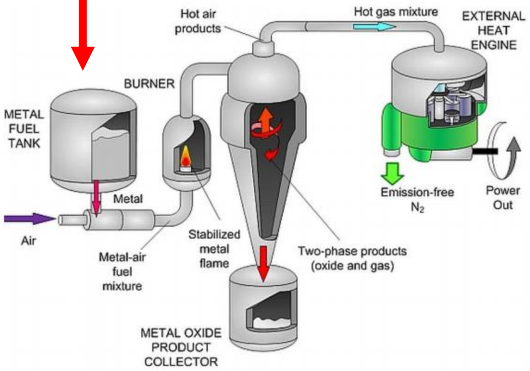
Metal oxides



Metal fuels

Combustion





Laboureur *et al.*, COFRET’18, Strasbourg, 2018, hal-01860128.

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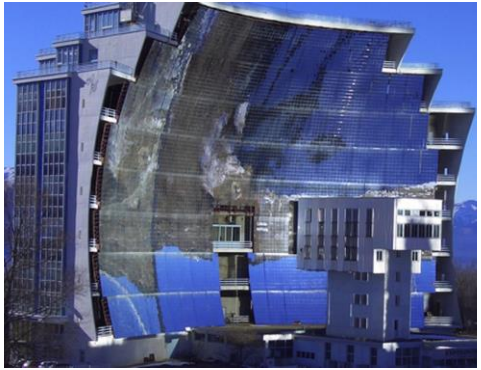
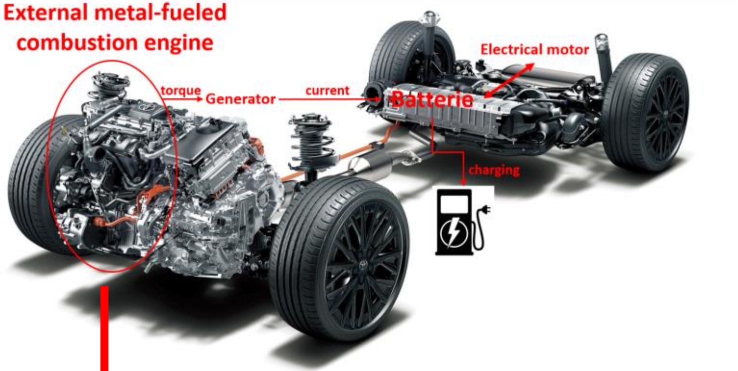
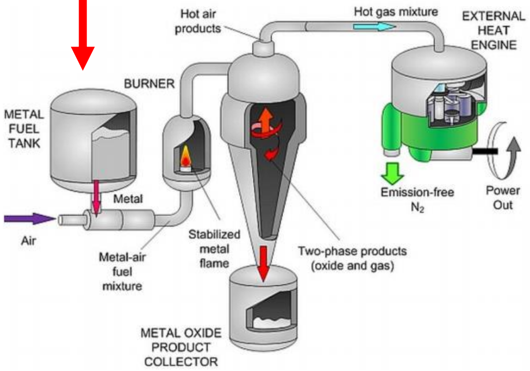


Solar Furnace (Odeillo)





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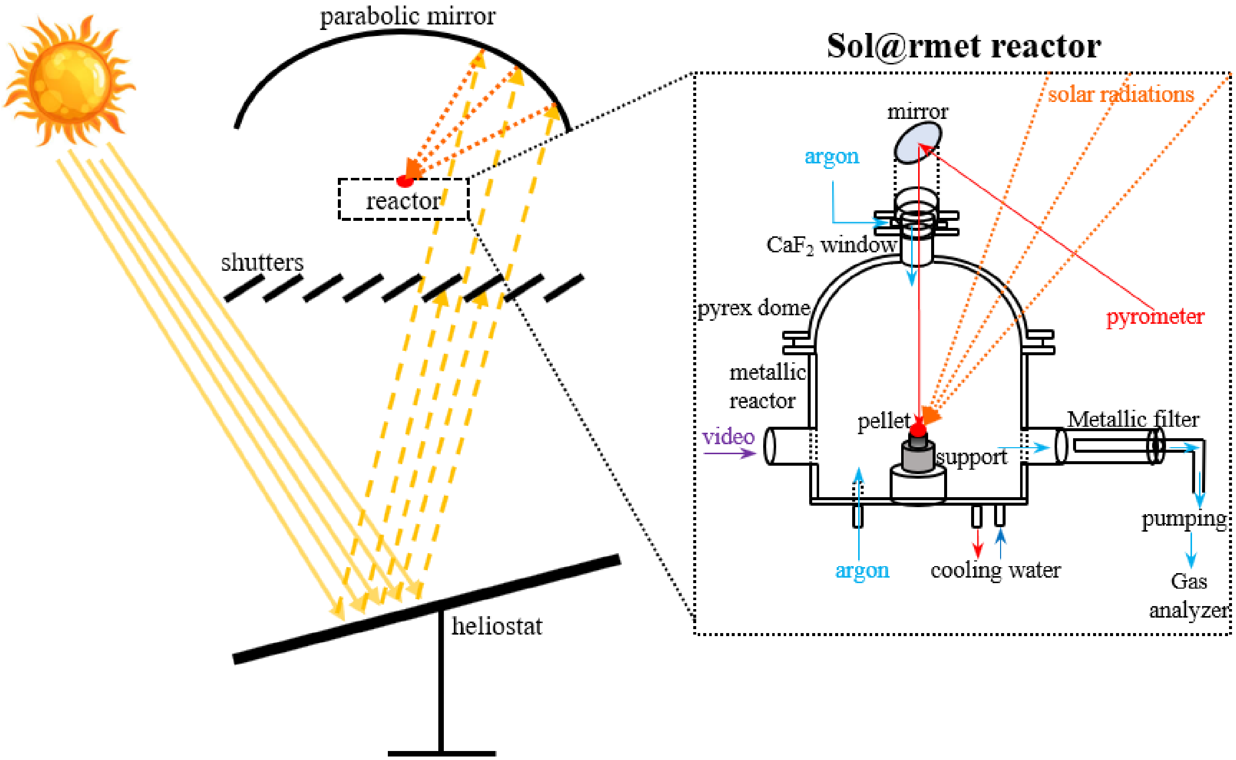
Solar vacuum-assisted carbothermal reduction of oxides



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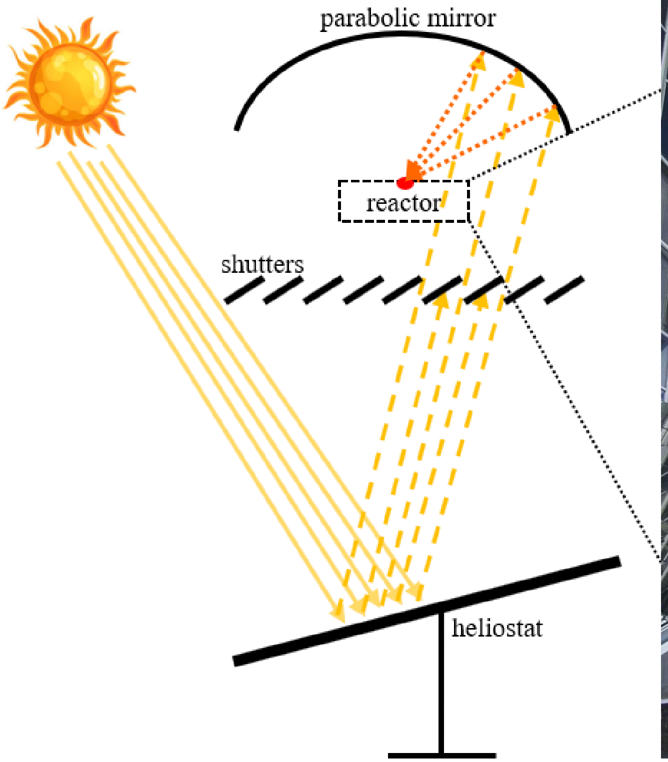

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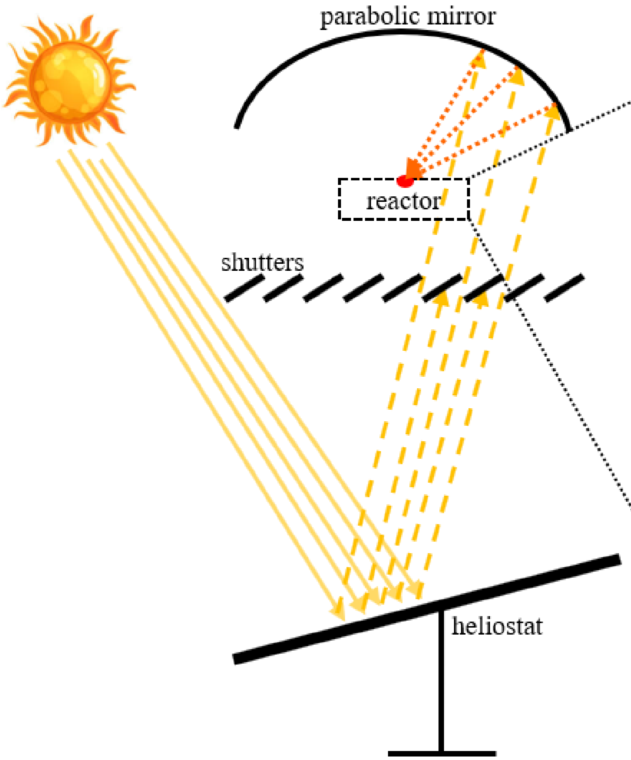

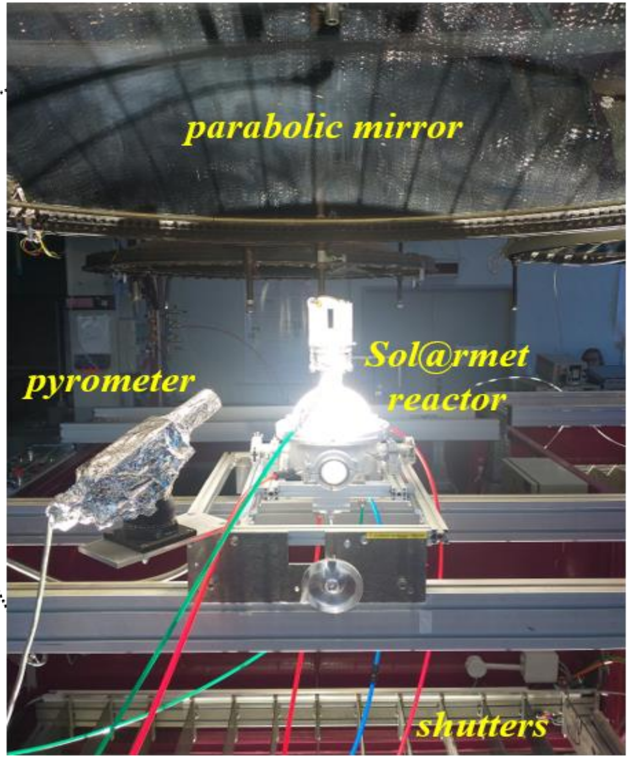

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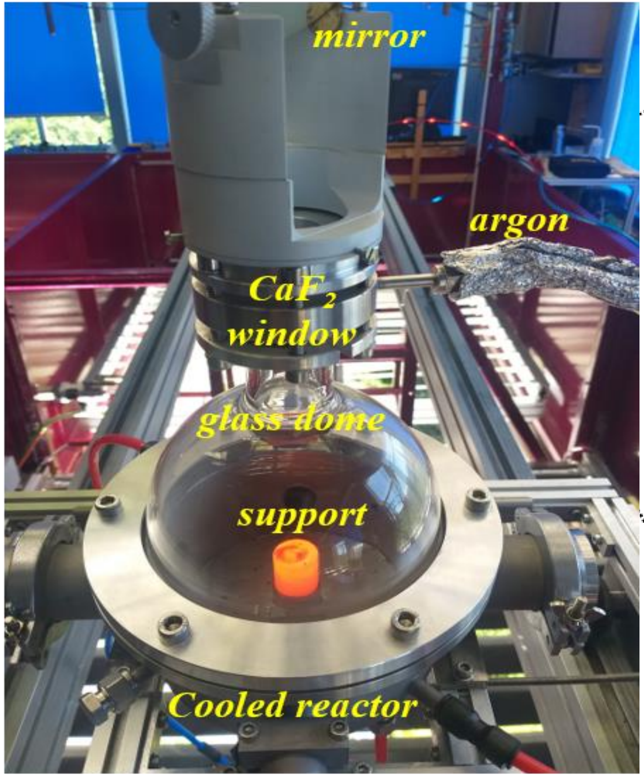
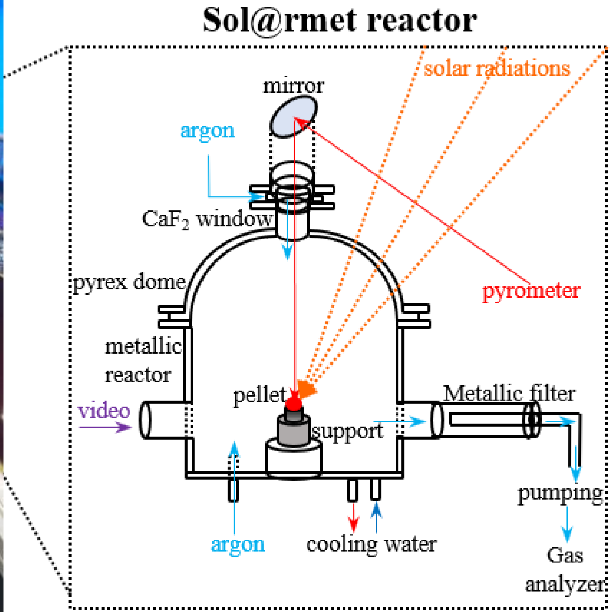
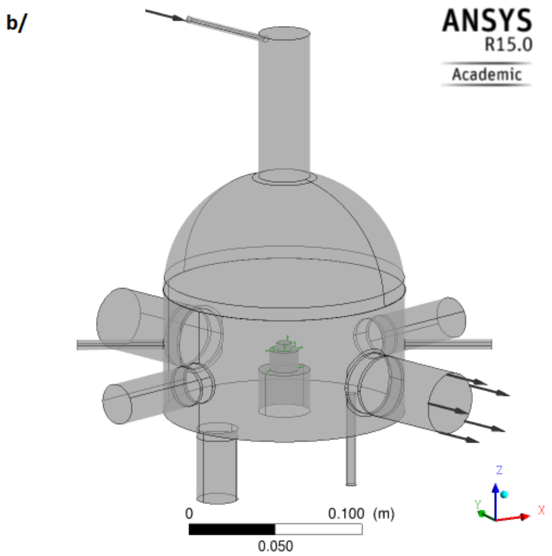
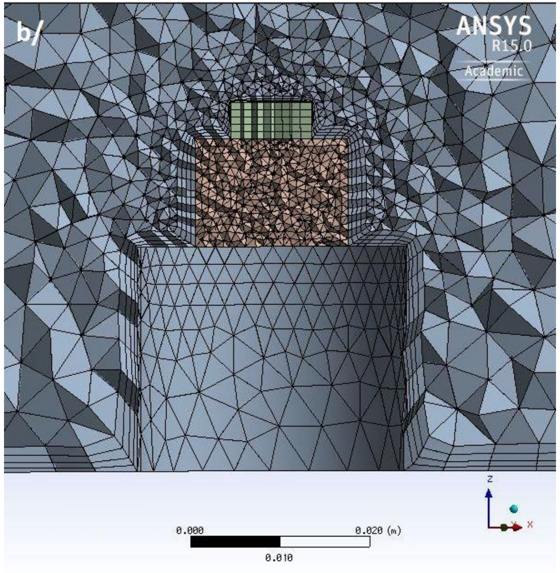




IV Numerical simulations of the gas circulation in Sol@rmet reactor



ANSYS-CFX software



Tetrahedral meshing

Berro *et al.*, J. Clean. Prod. 315 (2021) 128142.

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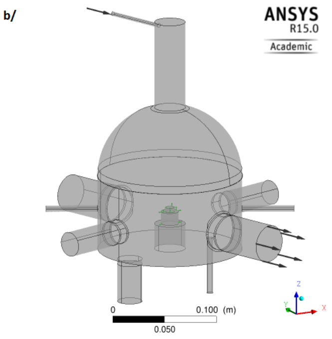

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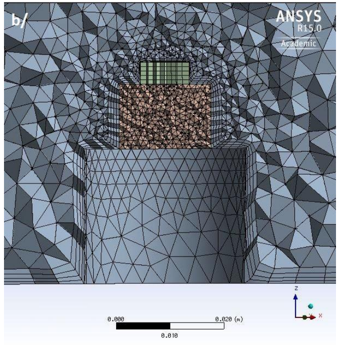

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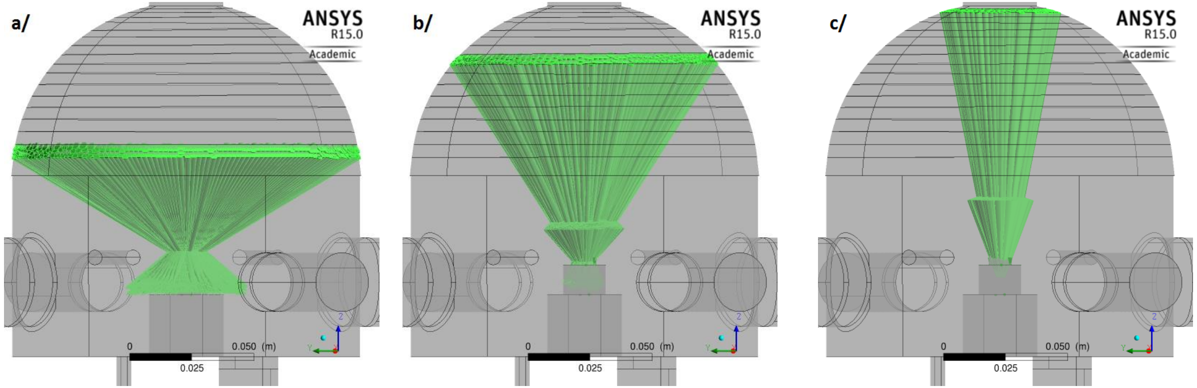

Monte-Carlo model to correlate the solar radiations on the pellet surface:

1.5 kW solar furnace, DNI of 1000 W·m^{-2}, total radiative flux of 15000 kW·m^{-2}

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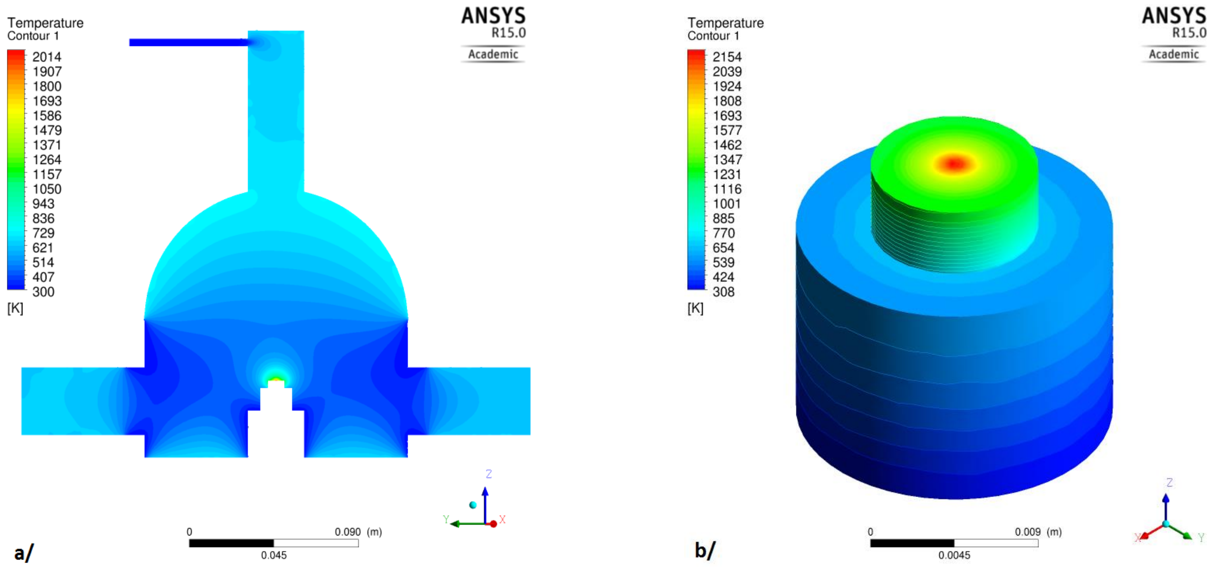

Temperature distribution on the Sol@rmet reactor and the surface of the C/oxide pellet

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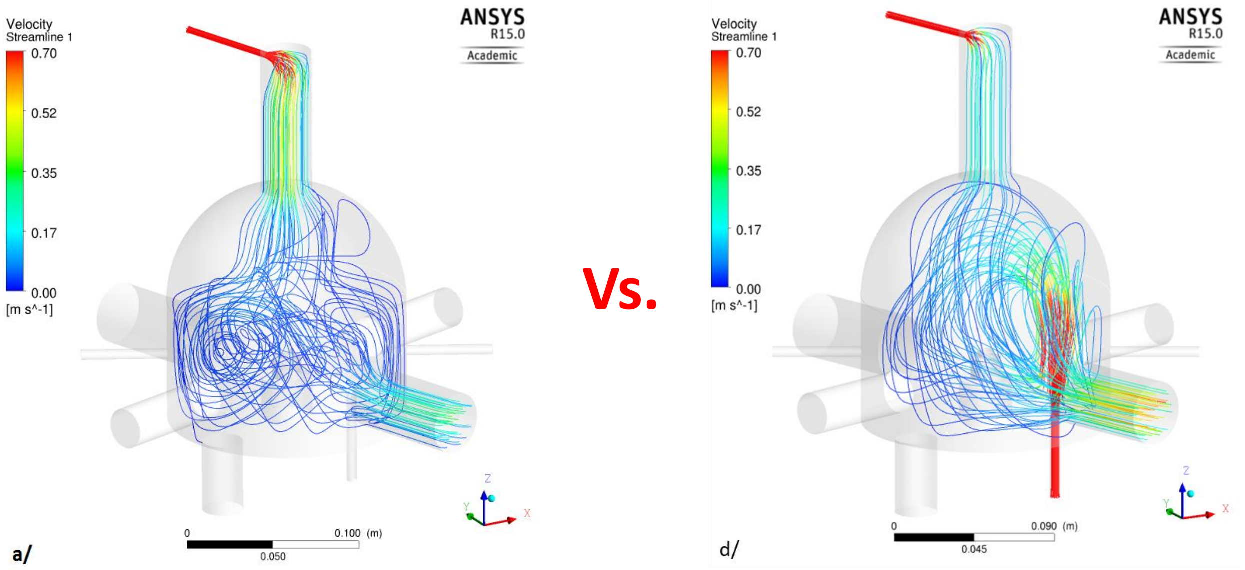

One argon entry vs. double argon entry:

- Swirl circulation
- Higher velocity in the exit tube (0.21 vs. 0.7 m·s^{-1})
- Better purging of products → Better reduction yield

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V Magnesia reduction: Effect of gas circulation, mechanical milling, reductant properties, bentonite binder and catalysts

Test	Carbon (pyrolysis conditions)	fixed C content (%)	$T_{max(reduction)}$ (K)	Mg yield (%)
A1	charcoal psyllium (rate = **2 K min^{-1}**, **1083 K** for 30 min)	85	2050	63.6
A2	charcoal psyllium (rate = 2 K min^{-1}, 783 K for 30 min)	78	1700	33.6
A3	charcoal psyllium (rate = 10 K min^{-1}, 1083 K for 30 min)	76	1560	26.0

Pyrolysis at high temperature (1083 K) and low rate (2 K min^{-1})

→ Higher fixed C content (> 80%)

→ Higher Mg yield and $T_{reduction}$

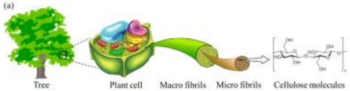

Psyllium


Okara


Chaga mushroom


Arrowroot starch


Cornstarch



Cellulose


Saccharose


Coconut sugar


Fucus vesiculosus

Biomass source: cellulose and starch-based are preferable over sugar-based charcoals

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VI

Magnesia reduction: Effect of gas circulation, mechanical milling, reductant properties, bentonite binder and catalysts

Progressive increase of temperature

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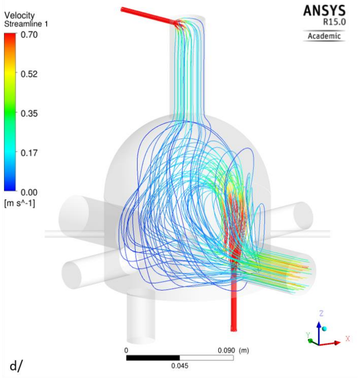

Solar experimental validation of the simulation results

Mg yield: 52 ↗ 68% using a double-argon entry

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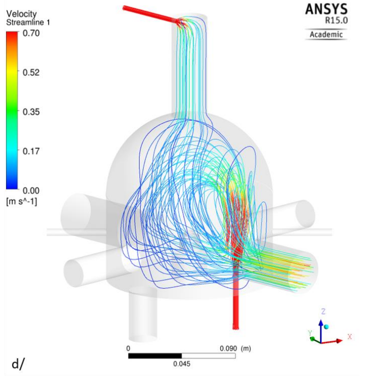

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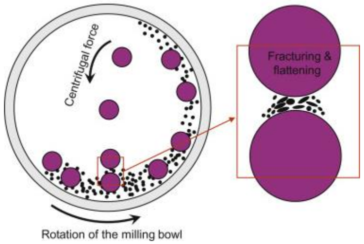

Mechanical milling C/MgO powders

- smaller particle size
- higher C/MgO contact
- Mg yield: 68 ↗ 85%

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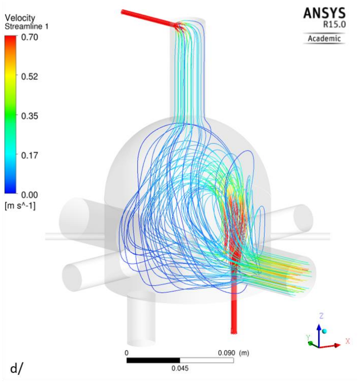

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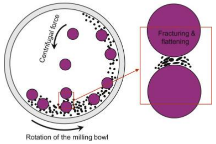

- Mg yield: 68 ↗ 85%

Catalysts (Fe, Ni, Fe-Ni) reduces the yield

- reaction accelerated at the beginning
- carbon consumed rapidly
- loss of the C/MgO contact and MgO sintering

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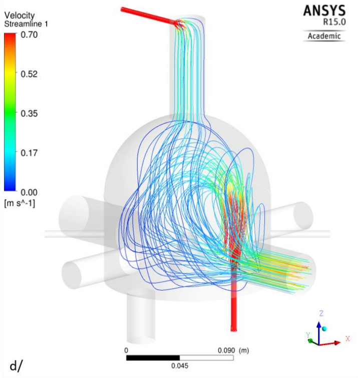

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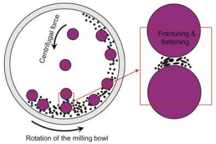

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Bentonite binder catalytic effect: Better C/MgO contact, prevents MgO sintering

→ Mg yield: 85 ↗ 96% (with 96% purity)

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Berro *et al.*, J. Clean. Prod. 315 (2021) 128142.
Berro *et al.*, Proceedings of MCM'21 (2021) mmme21.102.

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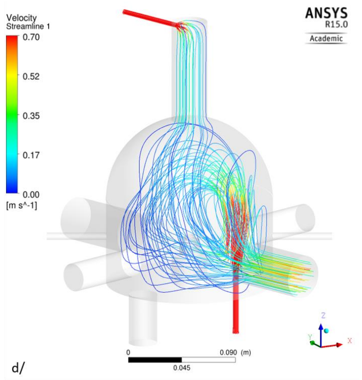

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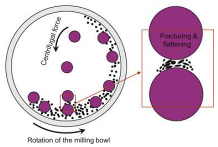
Mg yield: 52 $\nearrow$ 68% using a double-argon entry

Mechanical milling C/MgO powders



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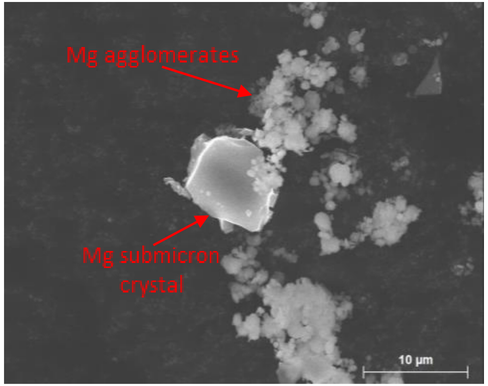

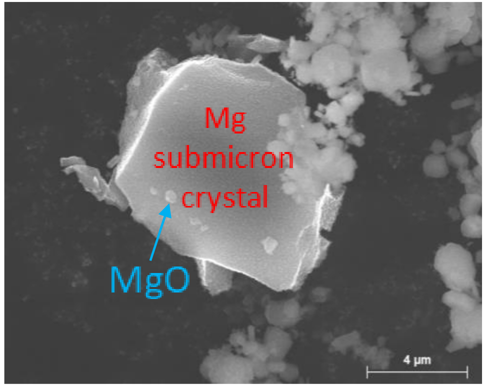

Granulometry: agglomerates of sub-micron Mg particles and crystals, D_{90} of 100 µm (40% are < 10 µm).

VI Alumina reduction: Effect of the reactor pressure on the formation of Al-oxycarbides by-products

Main problematic

Formation of Al-oxycarbides by-products

Mechanical milling C/Al_2O_3 powders

- Similar to MgO reduction
- Al yield improved by around 15%

Metal catalysts (Fe, Ni, Fe-Ni) and bentonite binder

- no or adverse effect
- formation of by-products

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Alumina reduction: Effect of the reactor pressure on the formation of Al-oxycarbides by-products

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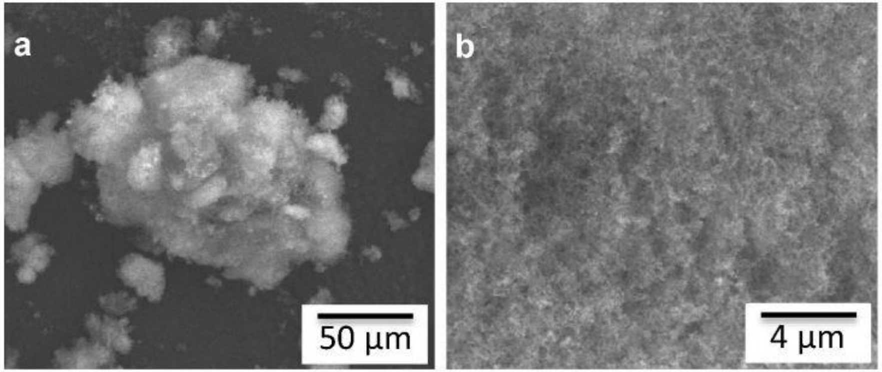
Effect of reactor pressure

- At 840 Pa: 74% yield (85% Al purity)
- P ↘ to 285 Pa: prevention of Al_2OC formation

→ **77% Al yield with 91% product purity**

(7% of Al_4C_3 and 2% of Al_2O_3 by-products)

- At 190 Pa: low gas circulation → easily oxidation of Al powders
  → low purity (54%) and yield (42%)



Granulometry: agglomerates of nano- and micro-sized Al particles, D_{90} of 3 µm (50% are < 50 nm).

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VII Conclusions and perspectives

Conclusions

- **Magnesia reduction:** 96% yield of highly pure (96% purity) Mg micron-sized crystals and particles
- **Alumina reduction:** 77% yield of pure Al (91% purity) nano- and micro-sized particles
- **Sustainability:** metal fuels recycling through solar vacuum-assisted carbothermal reduction of oxides
- **Metal fuels:** clean and sustainable substitutes for conventional fossil fuels

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- **Sustainability:** metal fuels recycling through solar vacuum-assisted carbothermal reduction of oxides
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Perspectives

- **Set-up:** semi-continuous process for higher production
- **Combustion experiments:** effectivity of combustion/reduction cycles
- **Economical study:** applicability of using solar metal fuels in vehicles

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