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Energy requirements for recovery of (metallic) nanoparticulate material from waste

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Introduction

- Increased use of nanoparticulate (NP) material will (or already does) give increased amounts of these in end-of-life products
- Energy requirements for producing NP material are significant or high and the same will hold for NP recovery from wastes
- Exergy analysis, normalizing all energy to "the capacity to work" without quality decriptions (like temperature of heat) is a useful and proper tool for energy use (efficiency) assessment
- Here, three products containing metallic NPs are addressed:
  - Silver (Ag) in textile (cotton) giving anti-bacterial properties
  - Zinc (Zn) in plastics (PP) as flame retardant
  - Copper (Cu) in water to give a nano-fluid coolant
- Goal: recovery as metal (preferably NP), avoiding oxidation!

Exergy of (diluted) Ag, Cu, Zn NPs

- Energy needed to separate a material at (molar) fraction x from a mixture can be calculated as exergy of "unmixing" using

$$\textbf{Exergy of unmixing}\ (\mathrm{J/kg}) = T^{o} \cdot R \cdot \frac{x \cdot \ln(x) + (1-x) \cdot \ln(1-x)}{x} \cdot M$$

with gas constant R, surroundings temperature T° (K) and molar mass M for the material to be separated.

Here, activity coefficients are = 1 for material in different (solid) phases.

- This can be used to calculate the thermodynamic minimum energy requirements for producing (or recovering) a pure (here: metallic) species from ore, a waste stream, or sea water.
- **This work** addresses three metals and nanoparticles of these.

Three metals and products with NP

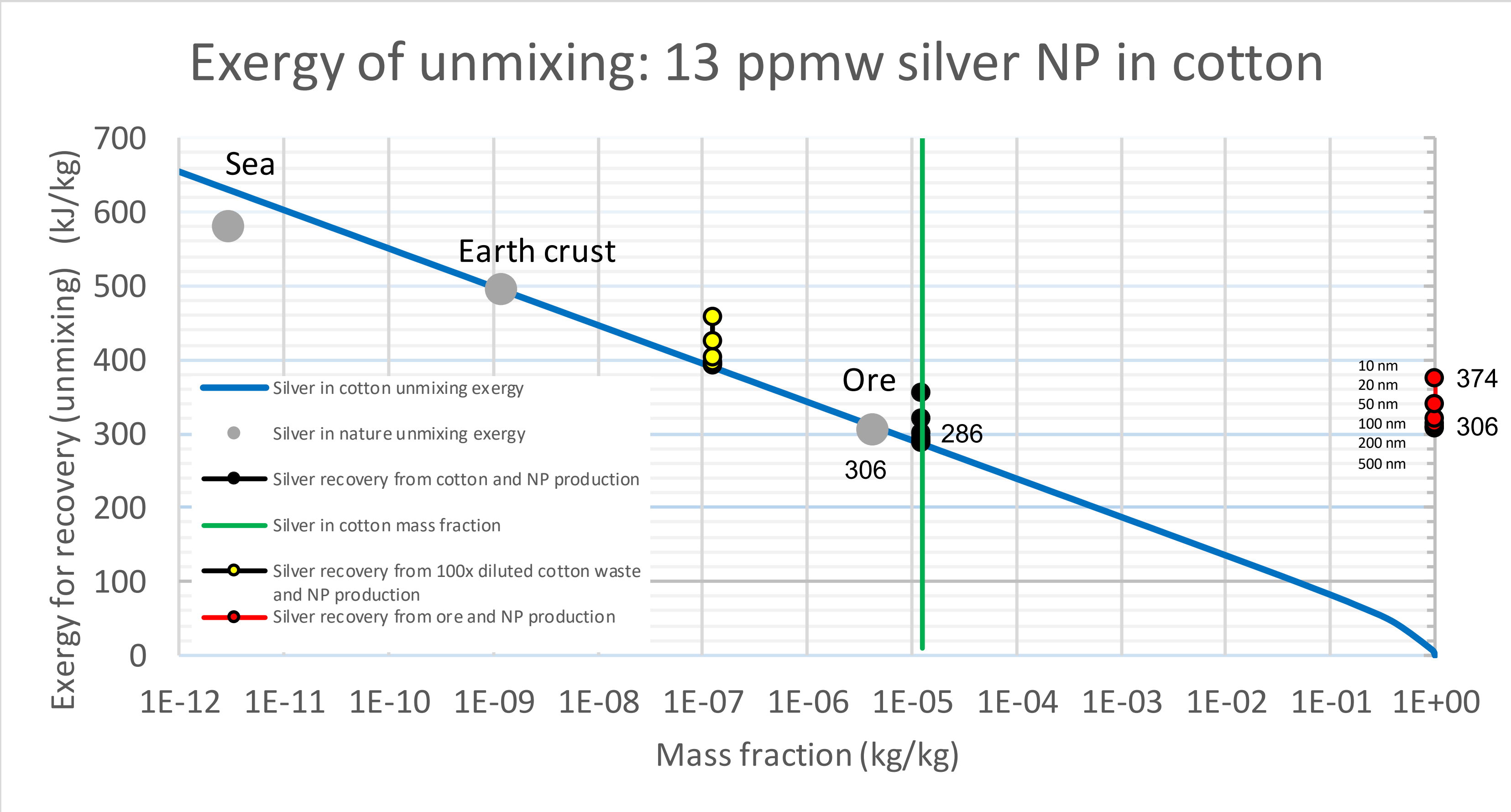
	Concentration in ocean water kg/kg	Concentration in earth upper crust kg/kg	Concentration in typical ore kg/kg	Concentration as NP in product kg/kg	Description of product containing NP
Silver, Ag	3×10^{-12}	1.2×10^{-9}	0.0043×10^{-3}	0.013×10^{-3}	**Antibacterial textile**
Copper, Cu	120×10^{-12}	4.1×10^{-9}	5.8×10^{-3}	0.27	**Nanofluid coolant**
Zinc, Zn	390×10^{-12}	0.47×10^{-9}	41×10^{-3}	5×10^{-3}	**Flame redardant for polymer**

BUONAPART•E Better Upscaling and Optimization of Nanoparticle and Nanostructure Production by Means of Electrical Discharges

EU FP7 2012-2016

Sources: *Zevenhoven and Beyene (2014) doi:10.5541/ijot.5000070194 (open source)*
Slotte et al. (2015) doi: 10.1007/s40095-015-0171-3 (open source)
Slotte and Zevenhoven (2017) doi: 10.1016/j.jclepro.2017.01.083
Slotte and Zevenhoven (2017) doi: 10.3390/en10101605 (open source)
Valero Capillla and Valero Delgado (2015) ISBN 978-9814273930

Exergy of "unmixing": Ag NP, cotton



Molar mass Ag, cotton, sea water, earth crust, "ore" = 107.9, 162.1, 18, 155.2, 131.5 kg/kmol

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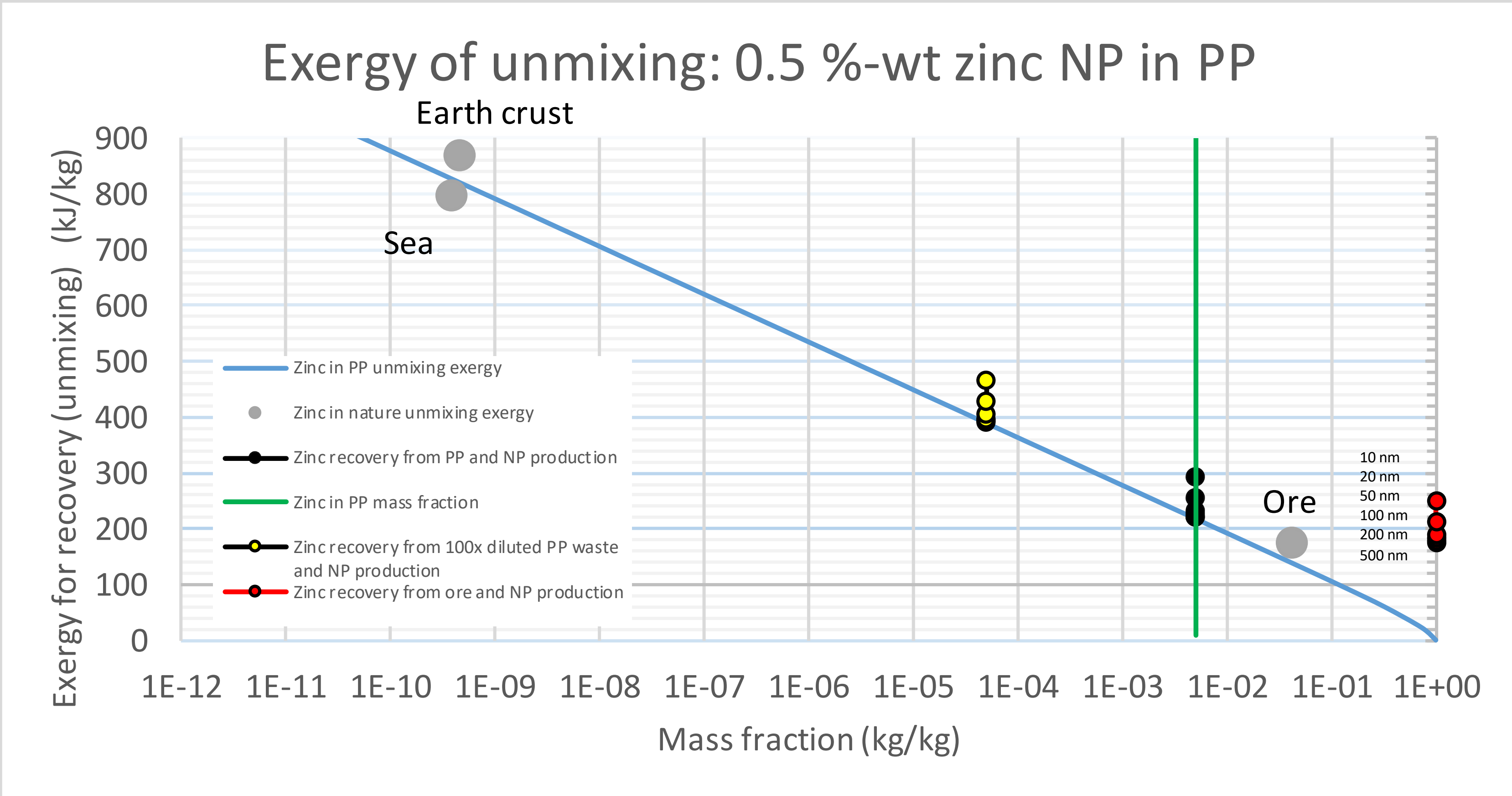
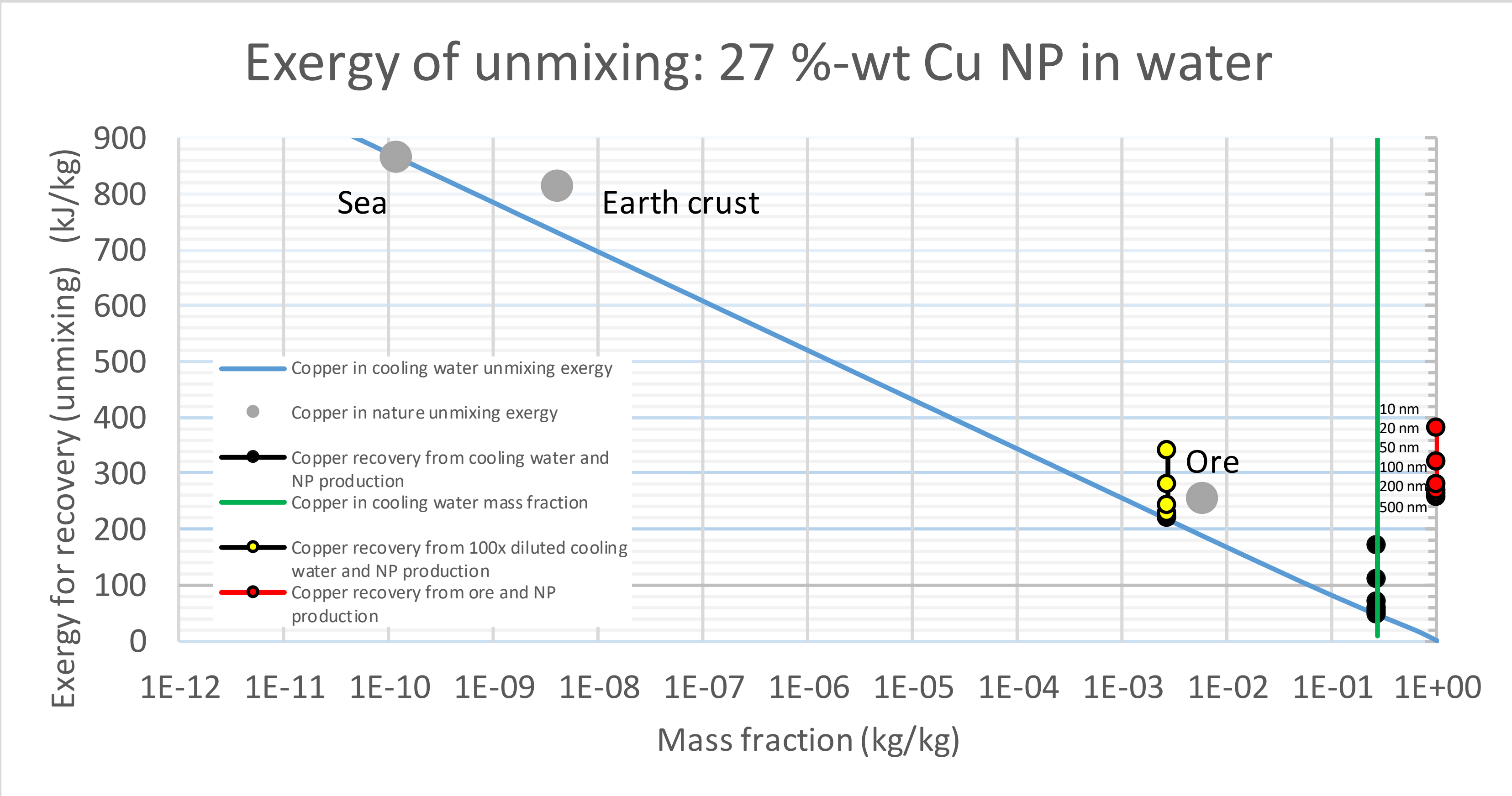
Exergy of “unmixing”: Zn NP, PP



Molar mass Zn, PP, sea water, earth crust, ”ore” = 65.4, 42.1, 18, 155.2, 110.3 kg/kmol

Exergy of "unmixing": Cu NP, water



Molar mass Cu, water, sea water, earth crust, "ore" = 63.7, 18, 18, 155.2, 109.4 kg/kmol

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Conclusions

- Exergy analysis allows for quantifying minimum "unmixing" energy requirement for species such as (metal) nanoparticles (NP) in wastes / end-of-life products containing these
- Dilution to levels similar to concentrations in ore can make metal production from ore + NP production more attractive
- For silver NP in cotton, concentrations are similar to ores: NP recovery is motivated by energy needed for NP production from pure silver. Cotton + NP waste dilution should be avoided!
- For zinc NP in PP plastic, production of metal NP from ore can be motivated by relatively low zinc (and NP) production energy
- For copper NP in cooling water, recovery as NP is motivated until high levels of dilution
- This theoretical assessment gives guidelines for future technology