The mineral resources - energy nexus in the context of energy transition

*Dynamic modeling* of

1) Mineral resources demand and energy cost, emitted CO2 for three energy scenarios 2060

2) Future price of commodities and capacities of production

3) Level of sustainability until 2200
The reduction of GHG emissions is a big challenge of the XXI\textsuperscript{st} century

The COP21 Paris agreements: 30\% reduction of global emissions and achievement of "carbon neutrality" worldwide by 2050+. This implies:

- To replace in 40 years the existing fossil fuels based system of energy generation, storage, transport, distribution and use
- To shift from \textit{stocks} of concentrated fossil energies to \textit{intermittent flows} of diluted renewable energies
Renewable energies are diluted => large infrastructures are required

6 Mw, > 150 m, 1500 t steel
3t permanent magnet, 1t REE
(Nd, Dy, Sm, Gd, or Pr)

700 wind turbines to produce the same annual energy (Wh) as a 1300 MW nuclear power plant
Material intensity of electricity-generation facilities (t/MW)

Concrete

Renewables

Steel

Renewables

Aluminum

Renewables

Copper

Renewables

Concrete

Steel

Aluminum

Copper

Material intensity includes concrete, steel, aluminum, and copper.
The transition towards low-carbon energy requires large amounts of mineral resources

- How much primary metal? (scenario and technology dependent)
- Are they available?
- What are the environmental impacts of their production?

Dynamic modeling
Raw Materials and energy requirements: a stock and flow problem...

\[ \text{primary production} \Rightarrow \text{stock in infrastructure} \]

Collecting rate

Recycling rate

Life Time

Lost metal

Recycled metal

40 years

Cumulative Losses
Generated electricity

RTS (iea2017)
53000 TWh/yr in 2060

B2DS (iea2017)
53000 TWh/yr in 2060

WWF (2012)
30000 TWh/yr in 2060

TWh/yr

2000 2020 2040 2060

Generated electricity in 2060:

- RTS (iea2017): 53000 TWh/yr
- B2DS (iea2017): 53000 TWh/yr
- WWF (2012): 30000 TWh/yr

TWh/yr

2000 2020 2040 2060

RTS (iea2017):
- Oil
- Coal
- Nuclear
- Gas

B2DS (iea2017):
- Oil
- Coal
- Nuclear
- Gas

WWF (2012):
- Oil
- Coal
- Nuclear
- Gas

TWh/yr

2000 2012 2024 2036 2048 2060

RTS (iea2017):
- CSP
- PV
- Bio-waste
- Wind
- Hydro

B2DS (iea2017):
- CSP
- PV
- Bio-waste
- Wind
- Hydro

WWF (2012):
- CSP
- PV
- Bio-waste
- Wind
- Hydro
Cumulative needs in Fe, Al & Cu (Mt)

- **RTS (iea2017)**
  - Infrastructure
  - Fe (2015)
- **B2DS (iea2017)**
  - Infrastructure
- **WWF (2012)**
  - Infrastructure

- **Primary production**
  - x1
  - x2
  - x3
  - x4
  - x5
  - x6
Cumulative needs in Fe, Al & Cu (Mt)

**RTS (iea2017)**
- 53000 TWh/yr in 2060

**WWF (2012)**
- 30000 TWh/yr in 2060

Doubling the needs for half the amount of generated electricity

Primary production

+3%/yr

x6
x2
x5

Cumulative needs in Fe, Al & Cu (Mt)
Oil
Coal
Gas
Biowaste
Nuclear

Primary Energy (600 EJ)

Power station

Consummed energy (390 EJ)

73 EJ

-50%

-12%

40%

Industry

Transport

Others Incl.building

Raw Materials

Iron and steel
Chemical and petrochemical
Non-ferrous metals
Non-metallic minerals
Transport equipment
Machinery
Mining and quarrying
Food and tobacco
Paper pulp and print
Wood and wood products
Construction
Textile and leather
Non-specified (industry)

Residential

Commerce and public services
Agriculture/forestry
Fishing
Non-specified (other)
Primary Energy (600 EJ)

- Oil
- Coal
- Gas
- Biowaste
- RE (4%)
- Nuclear

Consummed energy (390 EJ)

- Power station

Refinery

Raw Materials

Industry

Transport

Others Incl.building

- Residential
- Commerce and public services
- Agriculture/forestry
- Fishing
- Non-specified (other)

Total final consumption (400 049 PJ)

- Stock changes

-12%

40%

-50%

73 EJ

110 EJ

-50%
Cumulative need in copper for LDV (2017)

**RTS (iea2017)**

**WWF (2012)**

*Similar needs of base metals for less vehicles*

**Primary production**

- **EV + Hybrid**
- **Thermic**

- **10 yr**
- **12 yr**
- **1.2 yr**

- **5000**
- **1000**
- **200**

- **2500**
- **500**
- **100**

- **10 yr**
- **10 yr**
- **0.8 yr**

- **0.8 yr**
Total needs in copper

200 to 300 Mt Cu are needed for electricity generation and transport, = 10 to 15 years of 2015 global production

75-120 Mt production

3 Mt storage

>150 Mt Cu Use

10-20 Mt Transport & distribution

200 to 300 Mt Cu are needed for electricity generation and transport, = 10 to 15 years of 2015 global production
Since 1906, six billion tons of rocks have been removed from this pit to extract **18 million tons copper** – equivalent to one year of global primary Cu production.

Kennecott Copper Mine (Utah) $3.2 \times 1.2 \times 1.2 \text{ km}^3$.

200 to 300 Mt Cu
400 Mt Al
4000 Mt Fe
For the power sector
Transport LDV – high tech metals

Conventional vehicle: 20-30 kg Cu /car, EV: 60-80 kg Cu /car

Battery 50 kwh (EV)
=> Li: 6 - 20 kg (100 kWhTesla), Ni: 30 kg, Co: 10 kg, Mn: 10 kg, graphite: 50 kg

Battery PHEV (NiMH)
REE: 10 kg – Prius

Competition with other sectors of uses (ICT)
Stock of high tech metals for the batteries of LDV

**RTS (iea2017)**

- **Nbre of vehicles**
  - EV + Hybrid
  - Thermic
- More high-tech metals for less vehicles

**WWF (2012)**

- **Nbre of vehicles**
  - EV + Hybrid
  - Thermic

**Ni Reserves 2018**

- +10%/yr

- Mn, Li, Co

Stock of high tech metals for the batteries of LDV
Exclusive: Tesla expects global shortage of electric vehicle battery minerals -sources

WASHINGTON (Reuters) - Tesla Inc expects global shortages of nickel, copper and other electric-vehicle battery minerals down the road due to underinvestment in the mining sector, the company's global supply manager for battery metals told an industry conference on Thursday, according to two sources.
The availability of metals

Concentration in the crust
Average ore grade
Location

Reserves

Availability

Price

Global Demand

Energy

Other uses

+ Technology
The demand/capita levels off above 15000 $ GDP/capita

ABARES Australian Commodities; World Metal Statistics, various years; BREE Resources and Energy Statistics 2011; United Nations World Population Prospects: The 2010 Revision and The Conference Board Total Economy Database, January 2012
The future global demand in copper

**GDP (10^{13} \text{ $})**

**Population (10^9)**

**Copper**

**Known reserves**

**Cumulative production**

- **Ultimate resources USGS**
- **no recycling**

**Yearly production**
- **20 Mt/yr in 2020**
- **70 Mt/yr in 2100**

**Cumulative production**
- **20 Mt/yr in 2020**
- **70 Mt/yr in 2100**
With recycling

x 45 in 2050
x 150 in 2100
x 275 in 2200

and so forth...

Kennecott Copper Mine (Utah) 3.2 x 1.2 x 1.2 km$^3$
The availability of metals

- Concentration in the crust
- Average ore grade
- Location

Reserves

- + Technology

Availability

Price

Demand
Ore grade (%)

Reserves (Mt)

Amount of Cu (Mt)

Cu distribution in the crust

grade(%) = 8.1 \times 10^{-10} e^{-0.0125t}

740 Mt in 2017

550 Mt in 2016

25 Mt in 1900

Source: Xylogy

World Consulting March 2018
Embodied energy and price

\[ \text{Price} = a \cdot \left( \frac{1}{C_{\text{metal}}} \right)^u \]

\[ \text{Energy} = b \cdot \left( \frac{1}{C_{\text{metal}}} \right)^v \]

Deflated Price

- **Price (US$/lb)**
  - 0.01
  - 0.1
  - 1
  - 10
  - 100
  - 1000
  - 10000
  - 100000
  - 1000000

- **Dilution (kg ore/kg metal)**
  - 0.1
  - 1
  - 10
  - 100
  - 1000
  - 10000
  - 100000
  - 1000000

- **Embodied energy (MJ/kg)**
  - 1
  - 10
  - 100
  - 1000
  - 10000
  - 100000
  - 1000000

- **Ore grade**

- **Price ($/t)**
  - 65 MJ/kg
  - 2700$/t

- **Time**
  - 1900
  - 1950
  - 2000
  - 2050
  - 2100
The availability of metals

Concentration in the crust
Average ore grade
Location

Reserves

Availability

Demand

Price

Profits

Investment

Production infrastructure

Production

+ Technology
Doubling the recycling rate is necessary to meet the expected demand in 2100.
The embodied energy and CO₂ emissions of recycling are much lower than those of primary production.

![Graph showing embodied energy and CO₂ emissions](image-url)
Total energy & energy for raw materials

Share of industrial energy used for the RM production

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“EprodRM/Industry”: Current
Total energy & GHG emissions

GHG emissions (t CO2eq)
Copper CRRR = 40%

CRRR = 70%

Demand (GDP & Population)

Transport

Power

Building

B2DS

Production

WWF

Production
The only path to sustainability is sobriety => lower increase of GDP (or population) with time
Sobriety...

Tesla S

230-250 km/h
2100-2500 kg
18 kWh/100 km
@ 90 km/h
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<thead>
<tr>
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<tbody>
<tr>
<td>RM demand for energy</td>
<td>Increase</td>
<td>&gt;&gt; BAU + High Tech</td>
<td>Increase + High tech</td>
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<tr>
<td>RM global demand</td>
<td>Increase</td>
<td>&gt; BAU</td>
<td>&lt; BAU</td>
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<tr>
<td>GDP</td>
<td>Increase</td>
<td>Increase</td>
<td>&lt; BAU</td>
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<tr>
<td>Temperature increase</td>
<td>+4 to 6°C</td>
<td>+1.5 to 2.5°C</td>
<td>+1.5 to 2°C</td>
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<td></td>
<td>Crash before 2100</td>
<td>Crash before 2200</td>
<td>Sustainable until 2200</td>
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Thank you for your attention!
Cumulative need in copper for LDV (2017)

Number of vehicles

EV + Hybrid

Thermic

Copper

Primary

Recycling losses
LT = 15 years

Infrastructure LDV

EV