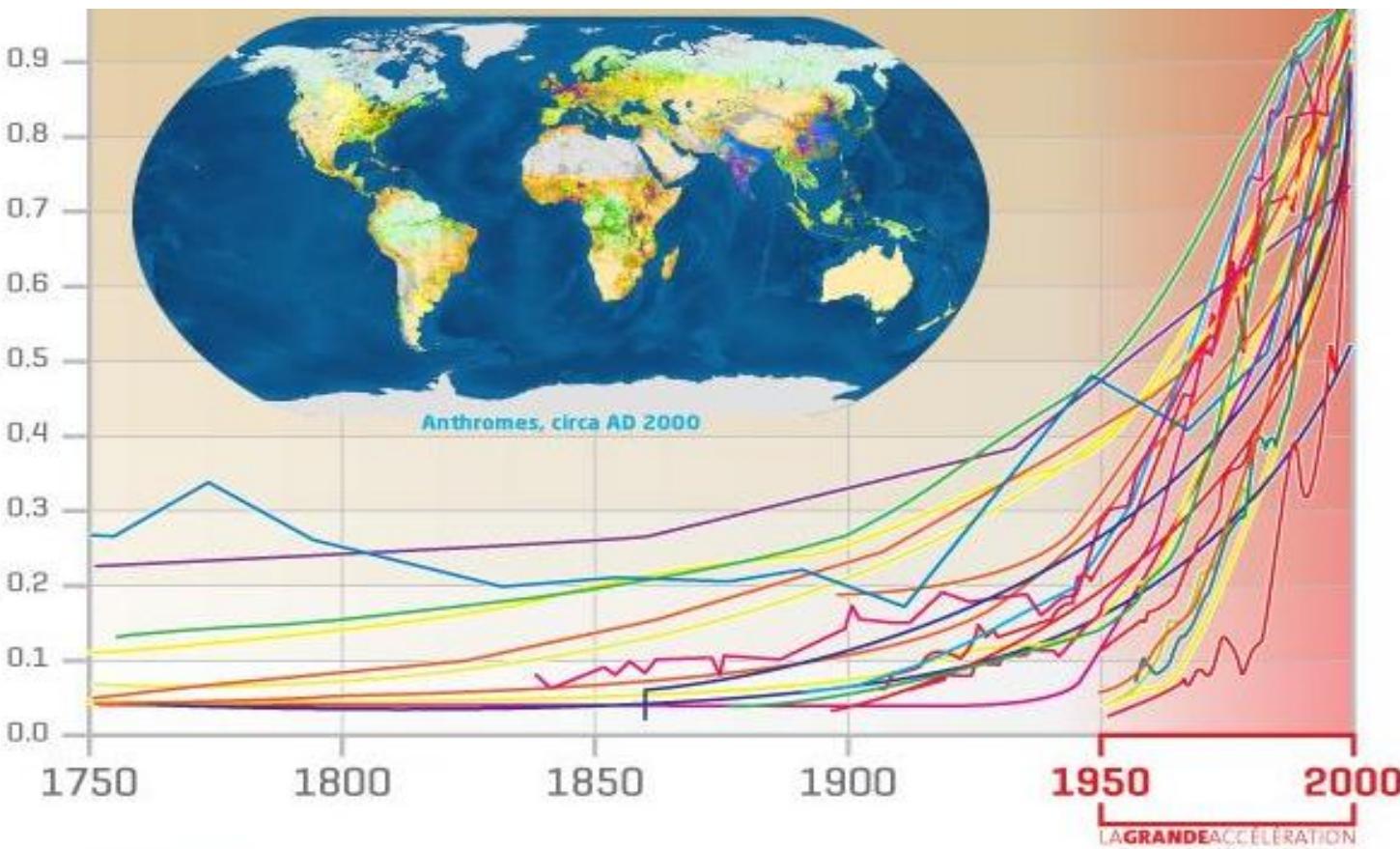


# The mineral resources - energy nexus in the context of energy transition to renewables

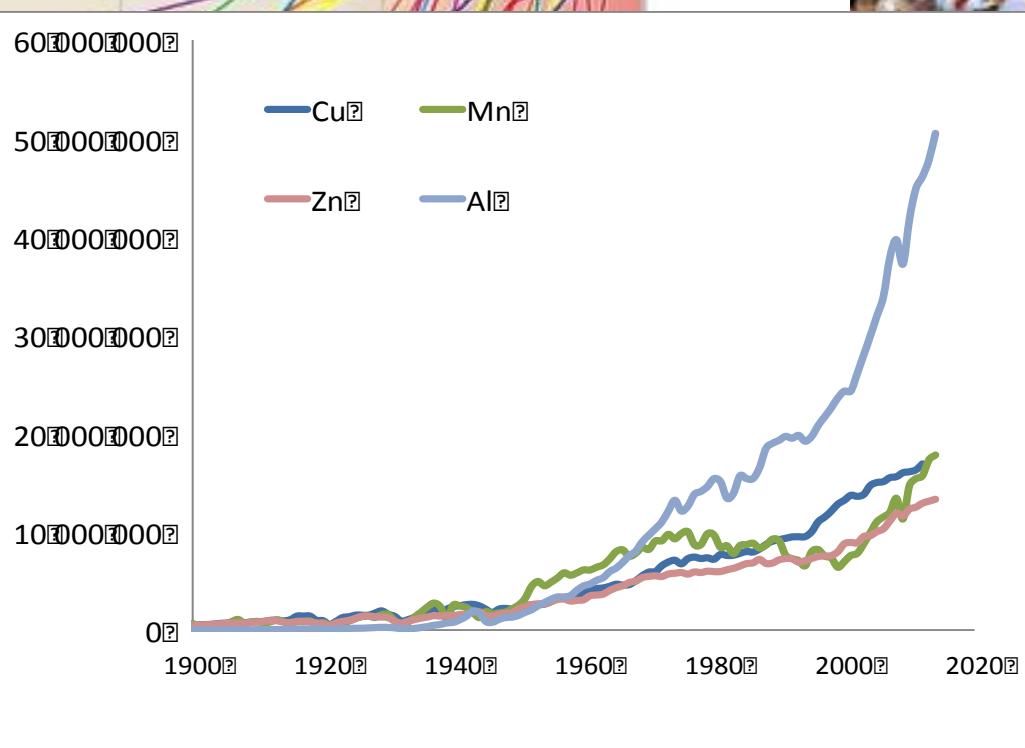
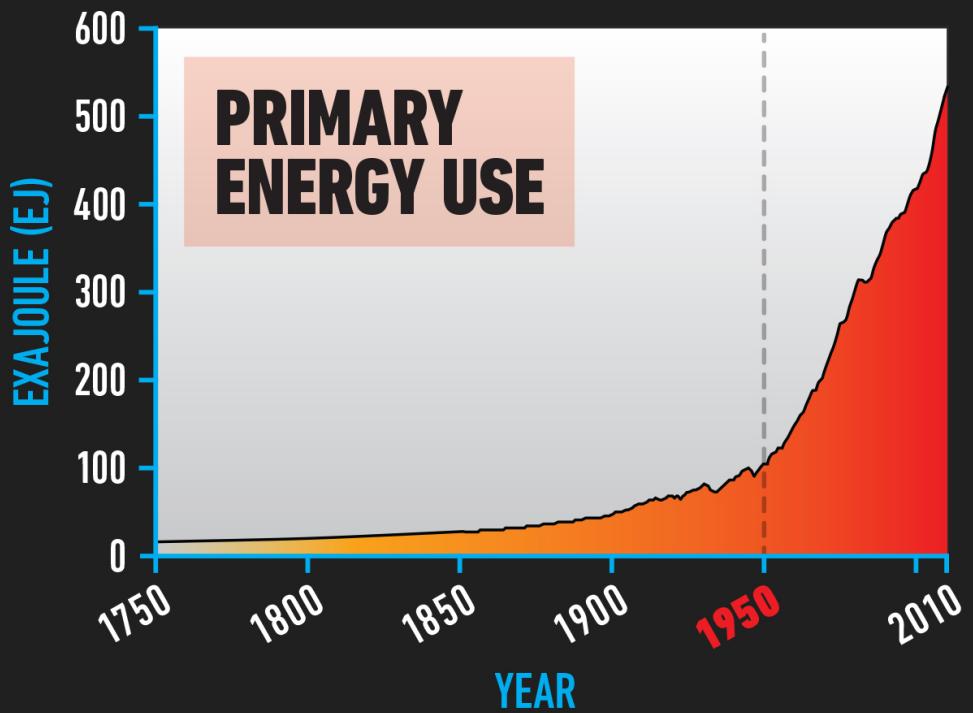
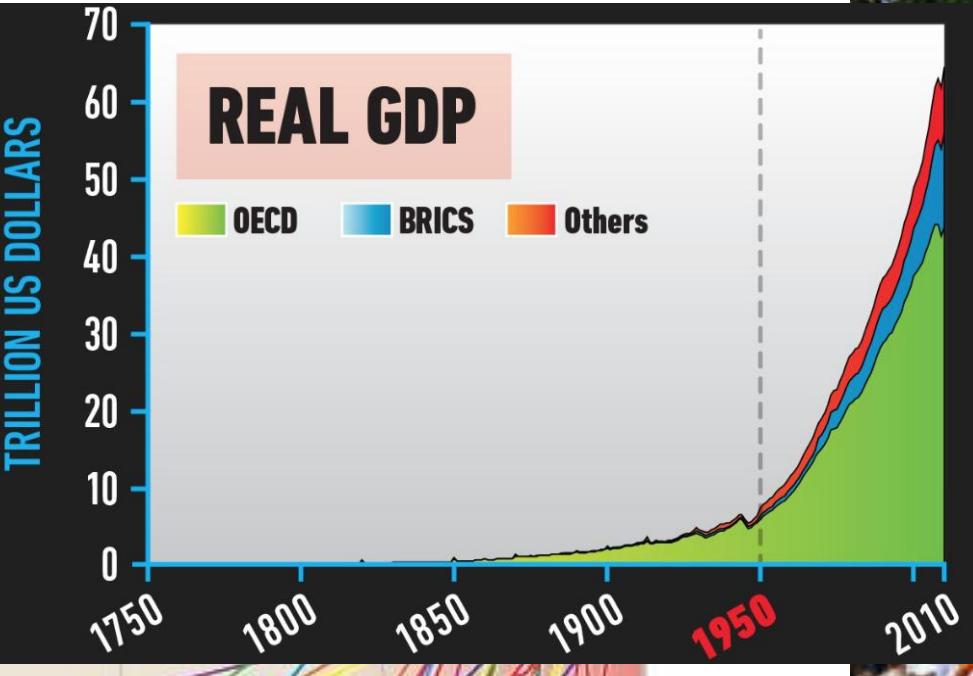
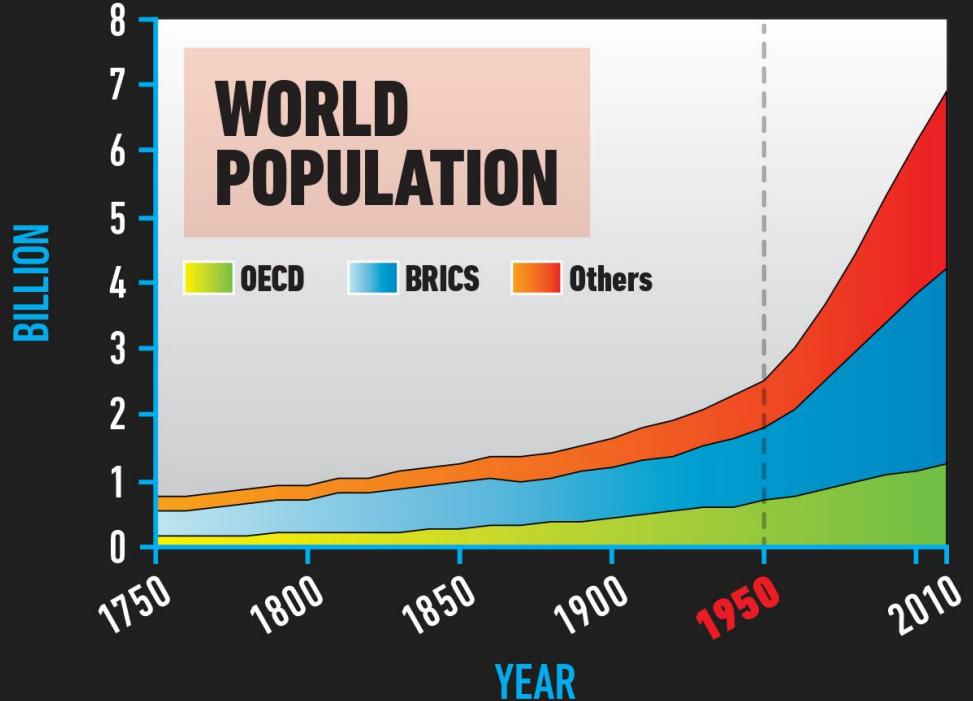
- Mineral resources are needed to built the new infrastructure of energy
- Energy is needed to produce the raw materials

Adapted from Steffen et al. (2015) [The trajectory of the Anthropocene: The Great Acceleration \(Anthropocene Review\)](#)



**LES INDICATEURS:**

1. Population mondiale
2. Total du PIB réel
3. Investissements directs à l'étranger
4. Concentration du CO<sub>2</sub> atmosphérique
5. Concentration du N<sub>2</sub>O atmosphérique
6. Concentration du CH<sub>4</sub> atmosphérique
7. Appauvrissement de l'ozone atmosphérique
8. Températures surfaciques de l'hémisphère Nord
9. Grandes inondations
10. Construction des barrages de rivières
11. Utilisation de l'eau
12. Consommation de fertilisants
13. Population urbaine
14. Consommation de papier
15. Nombre de restaurant McDonald
16. Nombre des pêcheries exploitées
17. Structures des zones côtières
18. Biogéochimie des zones côtières
19. Véhicules motorisés
20. Nombre de téléphones
21. Tourisme International
22. Disparition des forêts tropicales et prairies
23. Terres domestiquées
24. Nombre d'espèces éteintes



# Structural raw materials – cement, steel, Al, Cu

$$(1.06)^{12\text{ans}} = 2$$

Steel consumption (+ 6%/year 2000-2014)

Steel Consumption by Nation  
(million of tonnes)



China - 623.9



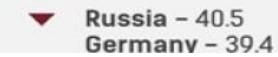
USA - 89.1



India - 67.8  
Japan - 64.1



South Korea - 56.4



Russia - 40.5  
Germany - 39.4

▼ Turkey - 26.9  
Italy - 26.7  
Brazil - 25  
Iran - 19.2

▼ Mexico - 18

Canada - 14.2

France - 13.6

Spain - 13.1

Poland - 11

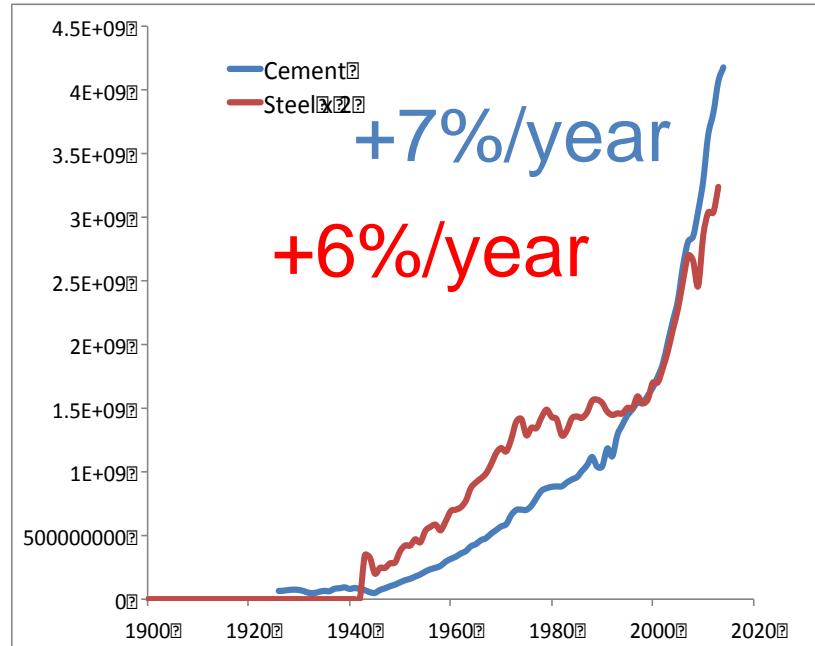
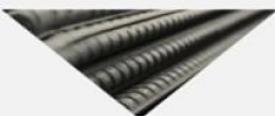
UK - 9.1

Egypt - 7.3

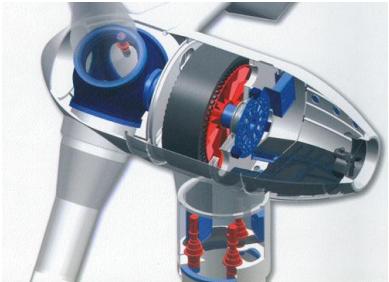
Australia/NZ - 7

Ukraine - 6.5

▼ South Africa - 5.3  
Argentina - 5.3  
Belgium - 4.6  
Sweden - 3.9  
Austria - 3.9  
Netherlands - 3.7  
Romania - 3.3  
Venezuela - 2.6



## « High-tech » metals



B, Nd, Dy



Ga, In, Se



[1980s]

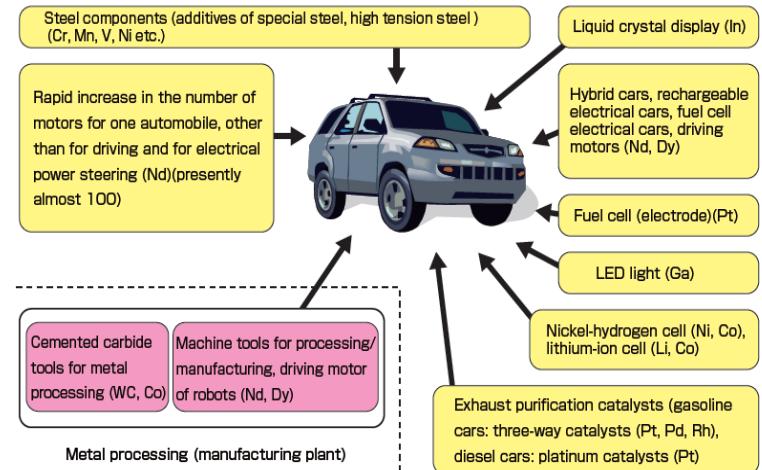
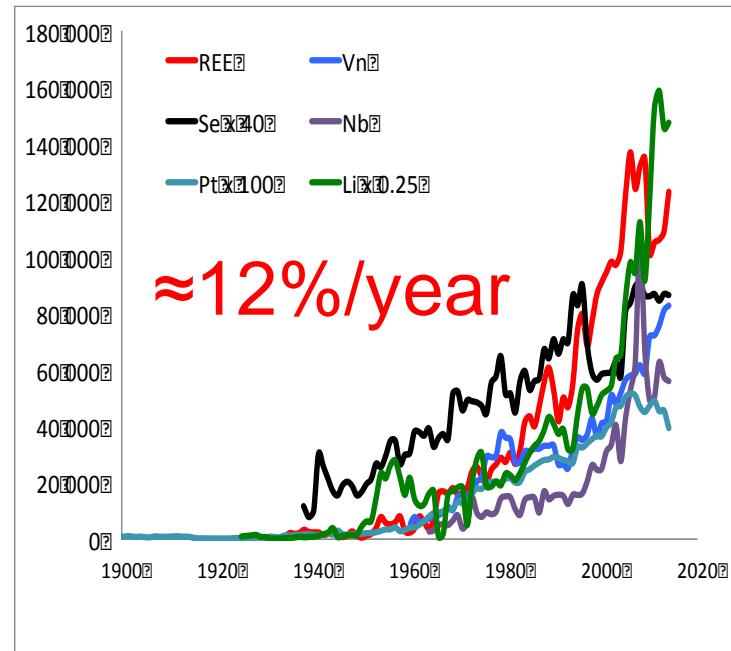
1  
10  
40

+4 elements

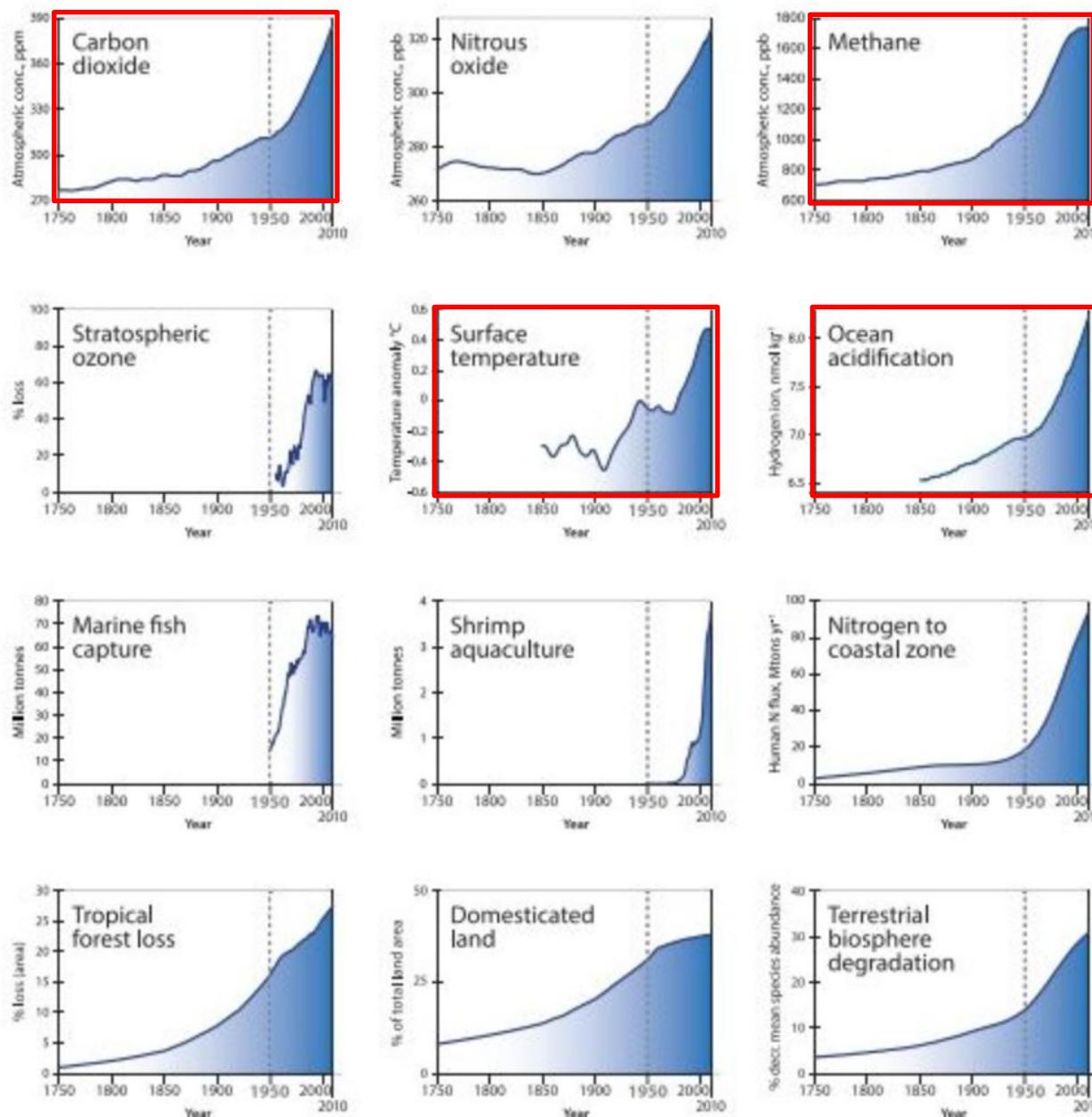
[1990s]  [2000s]

12 elements

Co, Ga,  
In, Nb,  
Ta, W,  
PGE, REE,  
Cu, Ni, Pb, Bi  
, Li, Ag, Au



## Earth system trends



Steffen  
et al. (2015)

# The production of raw materials is energy intensive

21 % of the global energy consumed by the industry is used for the production of steel + cement (*international energy outlook 2013*)

1 tCO <sub>2</sub> is generated for 1t of produced cement	(4500 Mt/year)
2 tCO <sub>2</sub> are generated for 1 t of produced steel (primary)	(3000 Mt/year)
5 tCO <sub>2</sub> is generated for 1t of produced copper (primary)	(90 Mt/year)
70 t CO <sub>2</sub> are generated for 1 t of produced Nd	(<0.05 Mt/year)

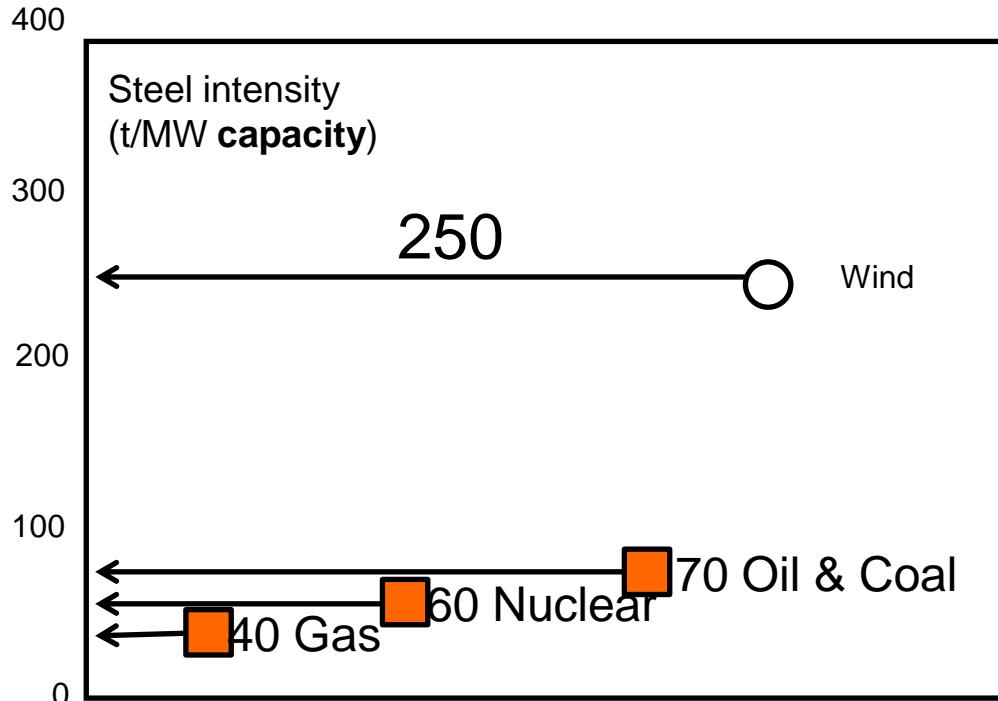
# The reduction of CO<sub>2</sub> emissions is a big challenge of the XXI<sup>st</sup> century:

The COP21 Paris agreements : strong reduction of emissions and "carbon neutrality" worldwide by 2050

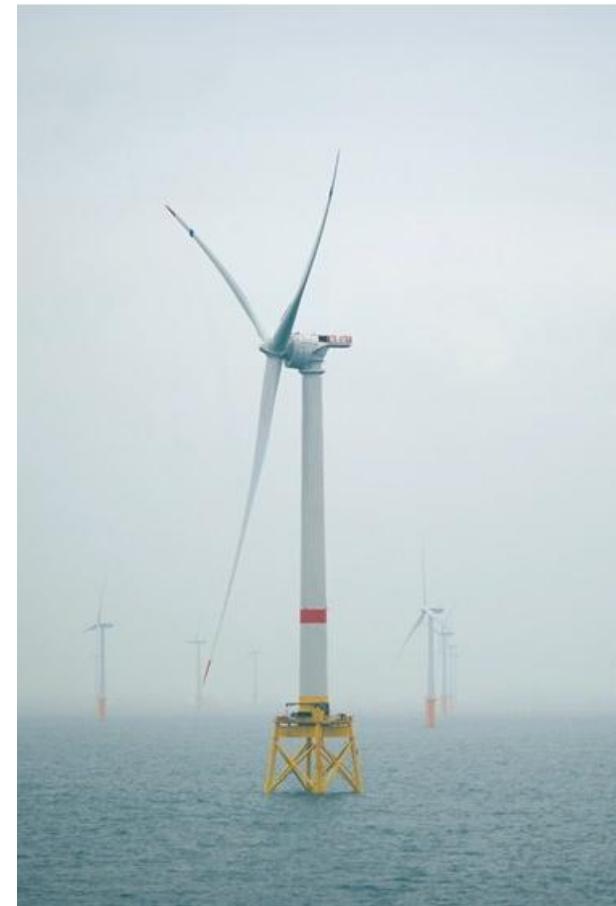
This implies replacing in 40 years the existing fossil fuels based system of energy generation, storage, transport, distribution and use

Renewable energies are diluted => large infrastructures are required

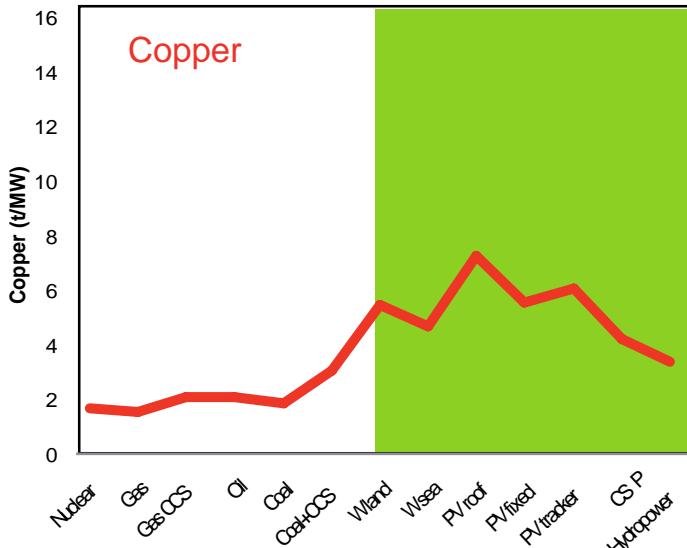
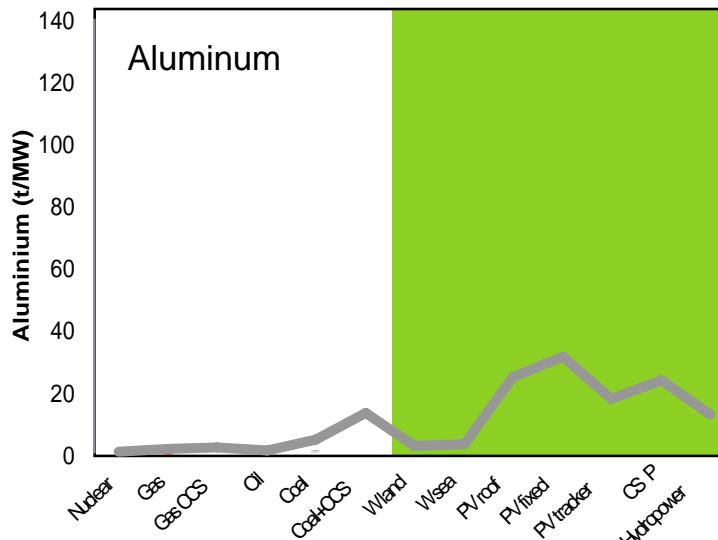
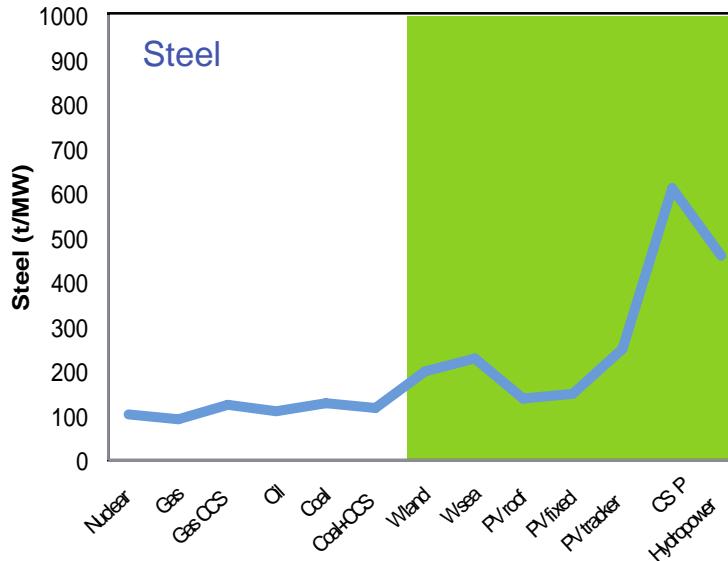
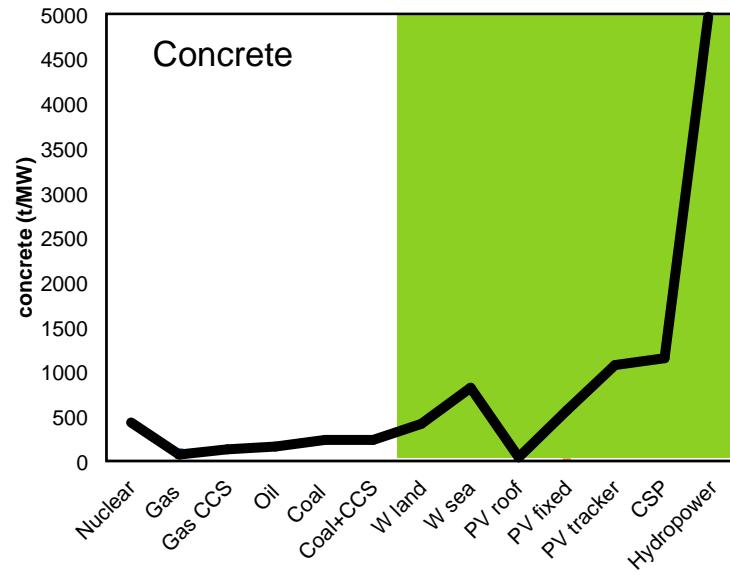
6 Mw, > 150 m, 1500 t steel  
Permanent magnet  $\approx$  1 t REE  
(Nd, Dy, Sm, Gd, or Pr)



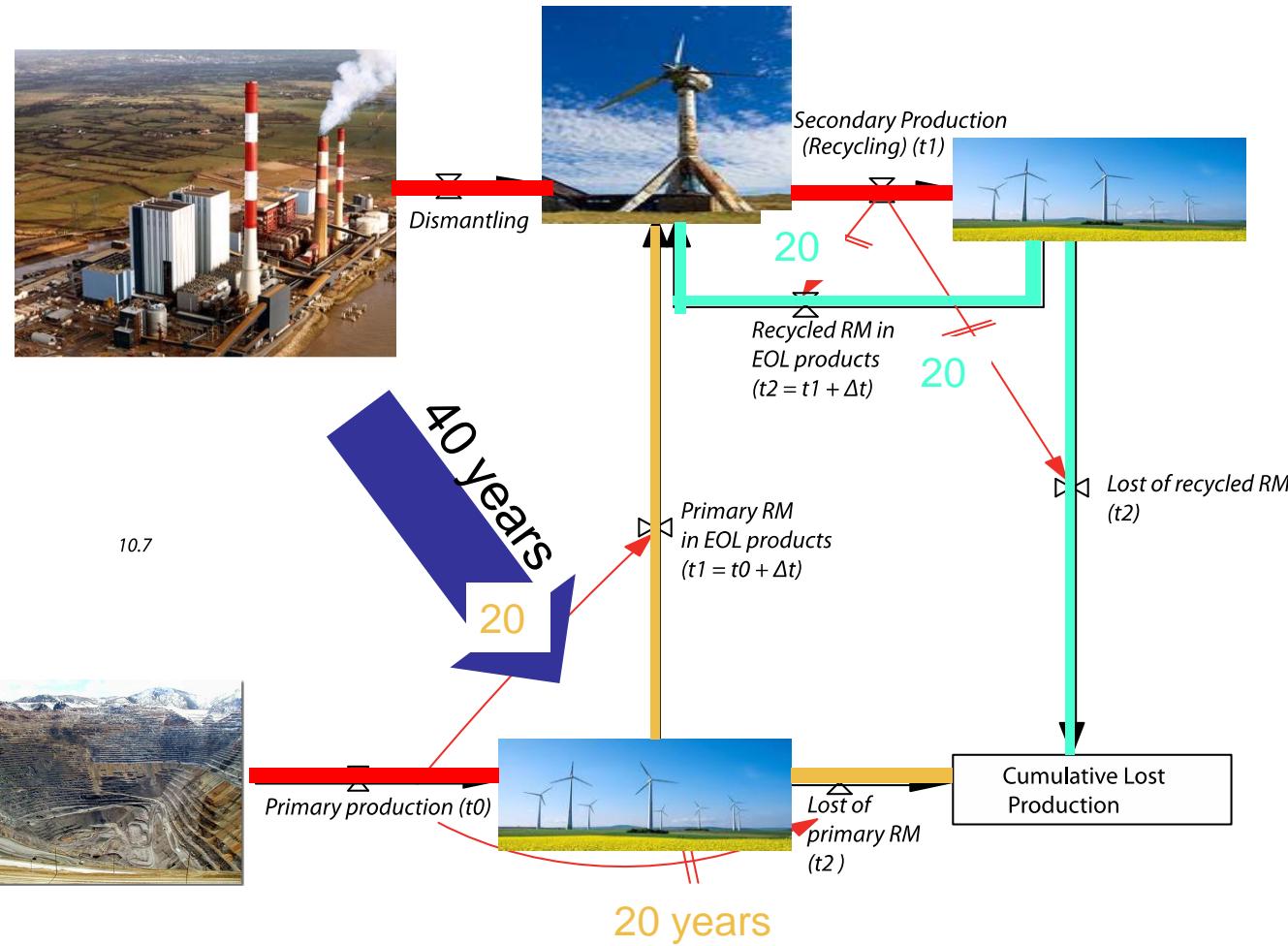
700 wind turbines to produce the same annual energy (Wh) as a 1300 MW nuclear power plant



# Material intensity of energy-generation facilities (t/Mw)



# Raw Materials and energy requirements: problem...

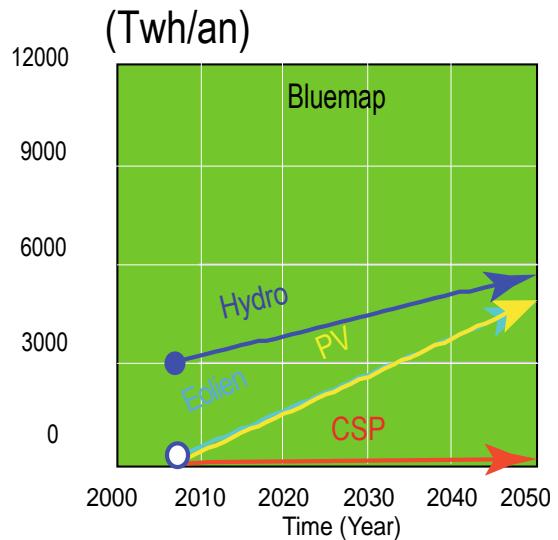


- Primary and secondary production flows,
- Stocks of RM in the infrastructure and lost,
- Amount of E used to produce the RM and CO<sub>2</sub> emissions.

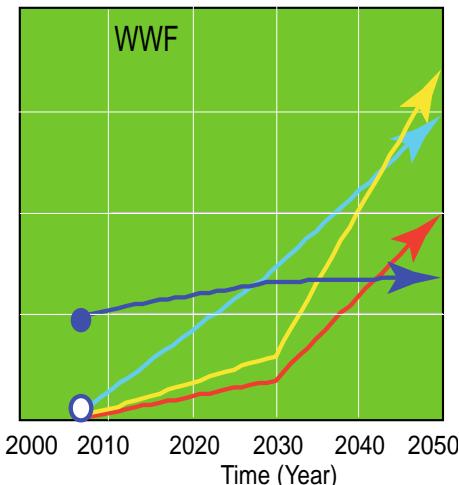
3 Different scenarios,  
4 RM

# Three contrasted scenarios of energy

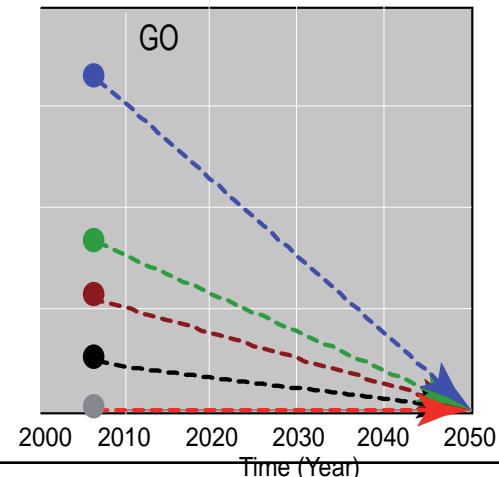
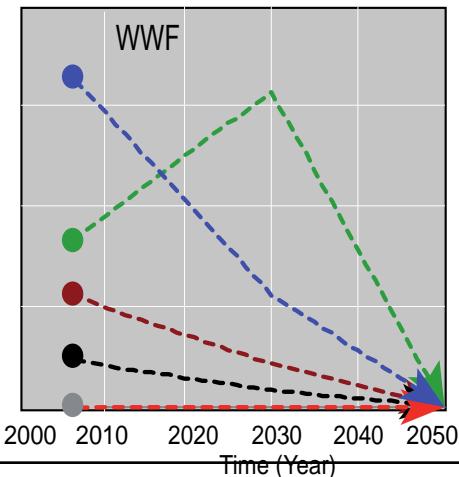
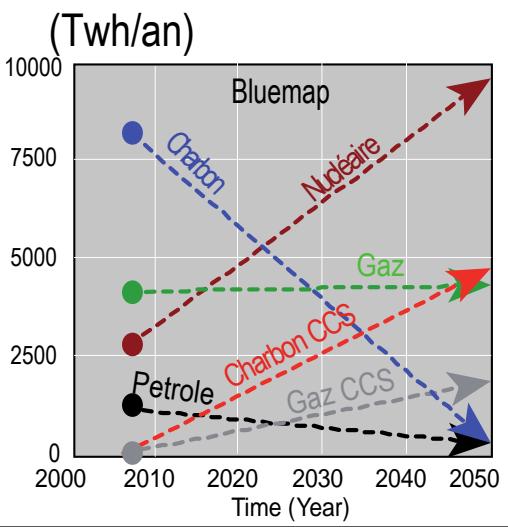
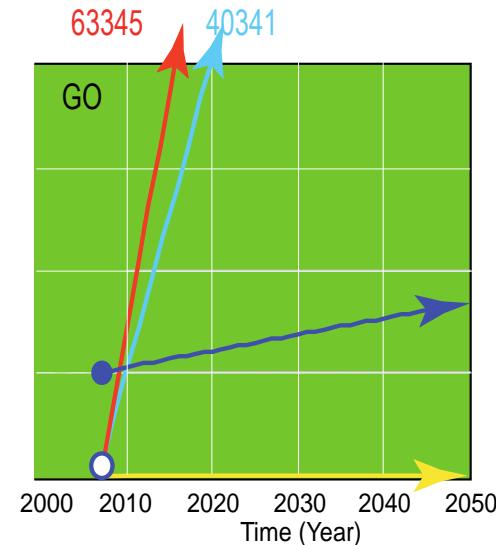
Blue Map IEA (2010)  
36 PWeh, 42% renewables



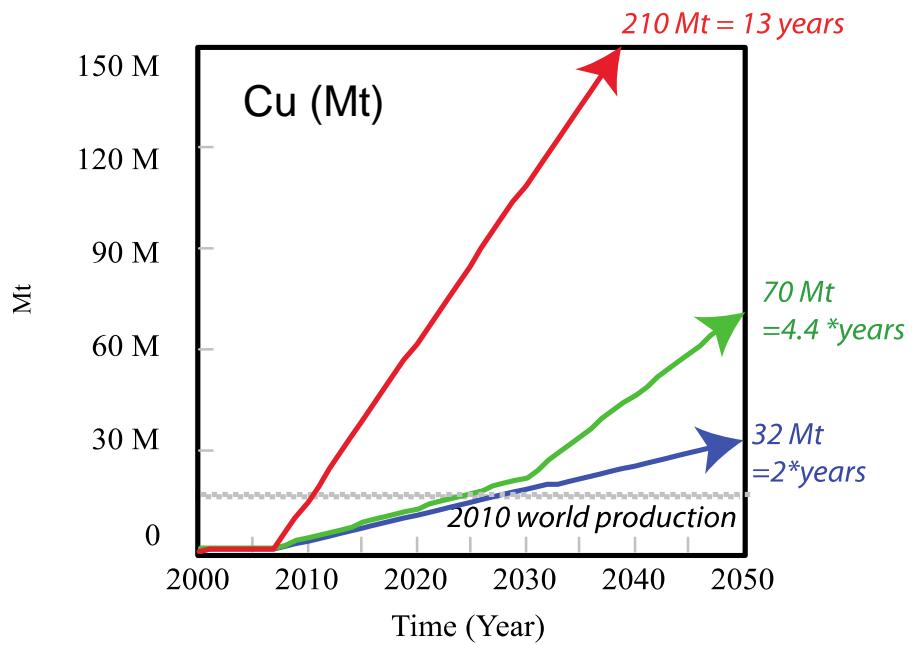
Ecofys-WWF (2012)  
29 PWeh, 100% renewable



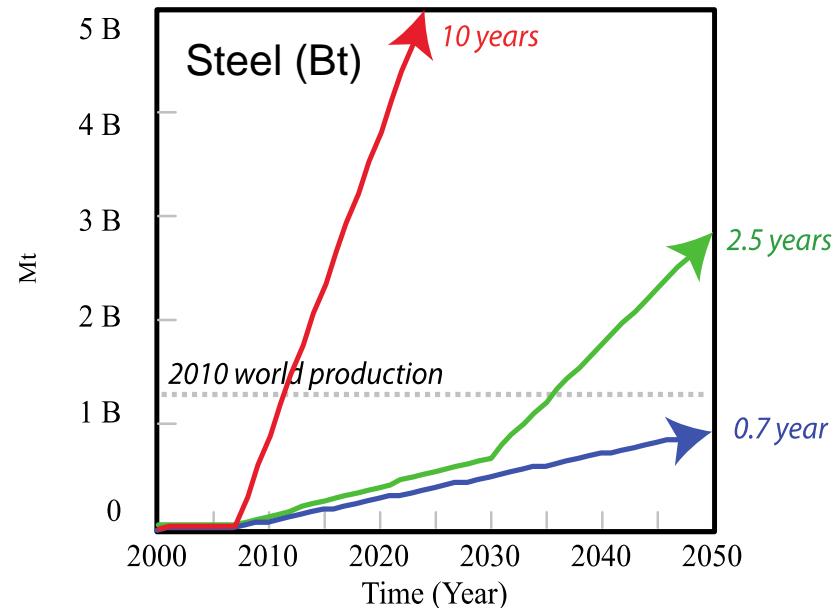
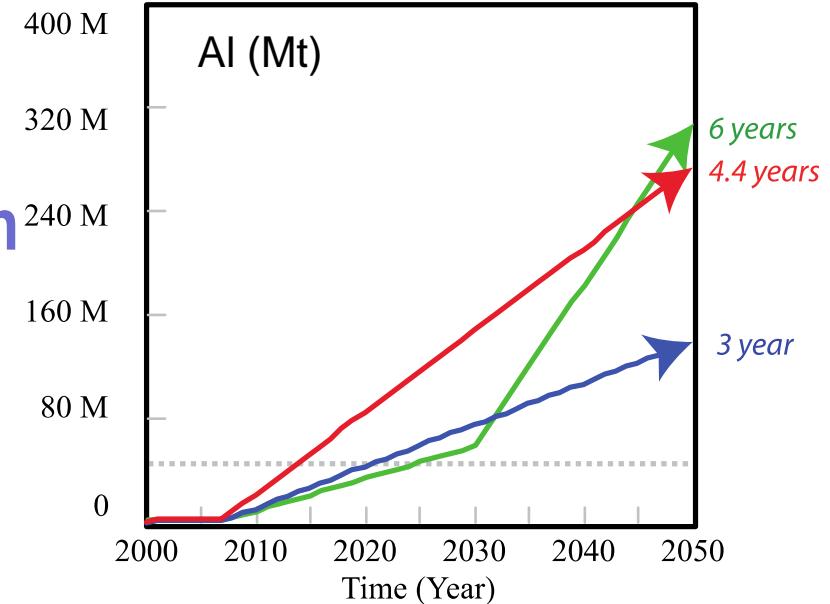
Garcia-Olivares (2013)  
109 PWeh, 100% renewable  
only electricity

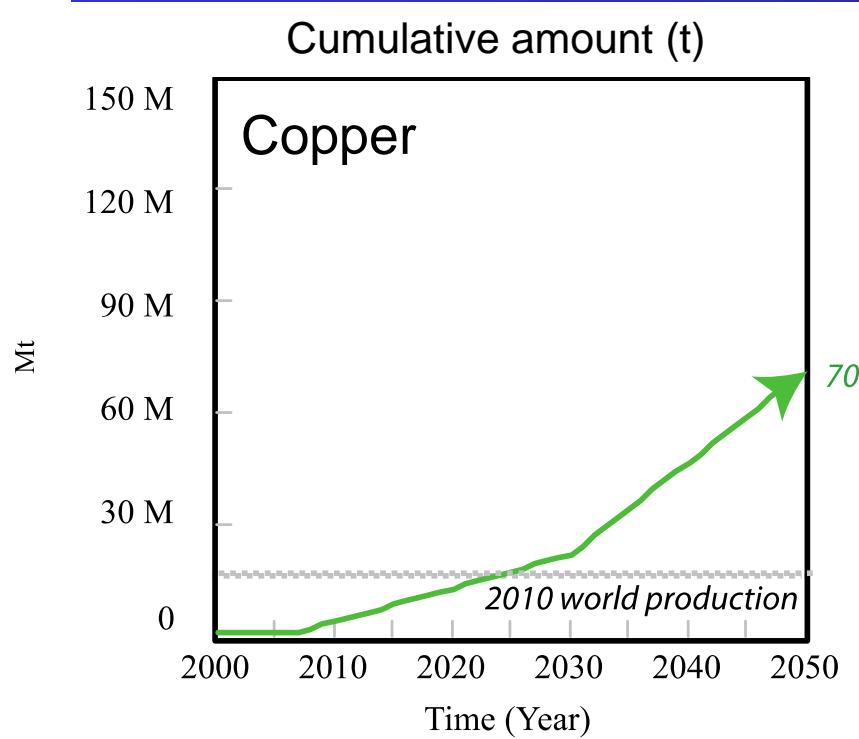


# Results of calculation: Cumulated amounts of metals in the infrastructure of electricity production



In 2050, the **cumulative** amount of steel, Al, Cu sequestered in hydropower, wind and solar facilities could be up to 10 times the global 2010 production

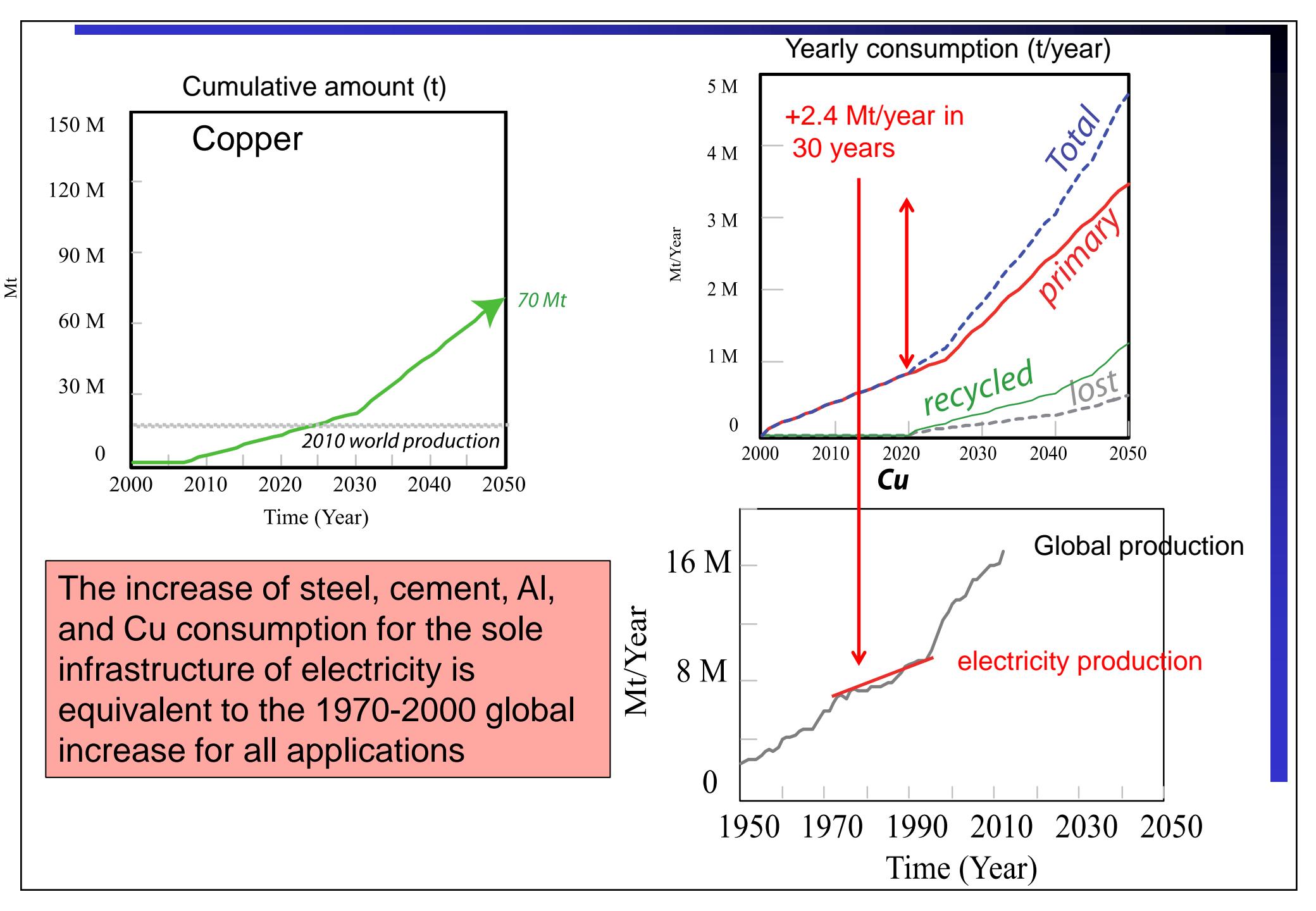




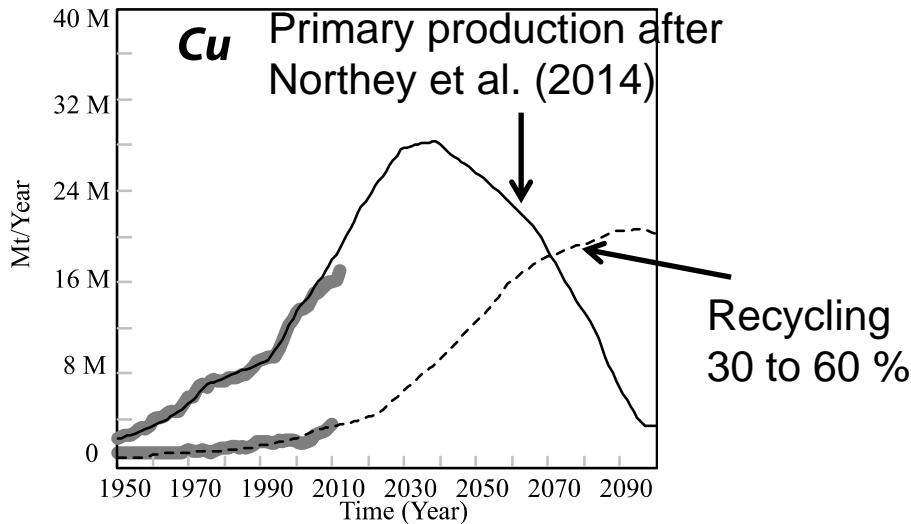
**The largest human excavation on Earth:**  
Kennecott Copper Mine (Utah)  $3.2 \times 1.2 \times 1.2 \text{ km}^3$ .



Since 1906, six billion tons have been removed from this pit to extract **18 millions tons copper** – equivalent to one year of global Cu production

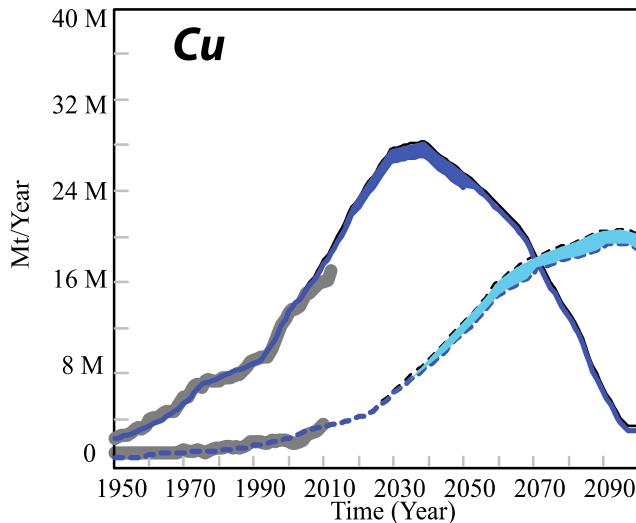


# Comparison with the global production of mineral resources

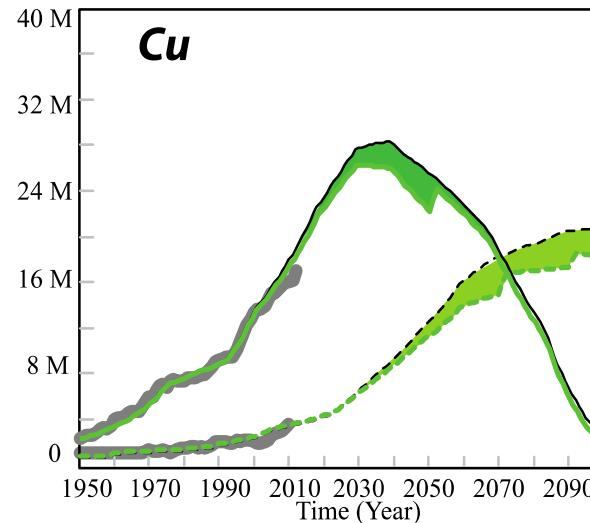


Even with high recycling, the peak demand for renewable energy occurs at the global peak of primary production

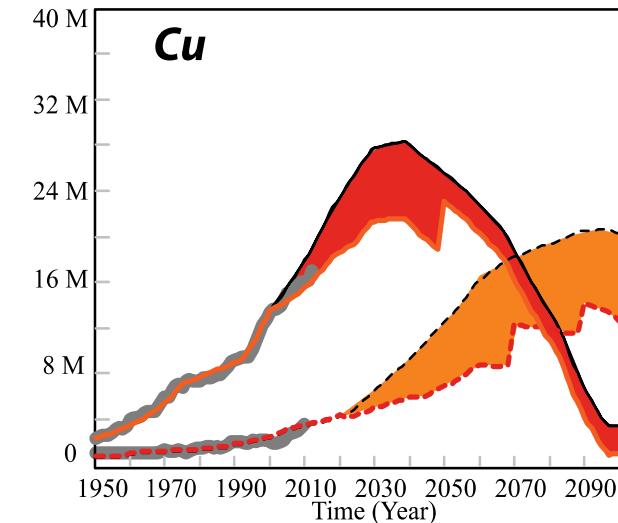
36500 TWeh BM (2010)

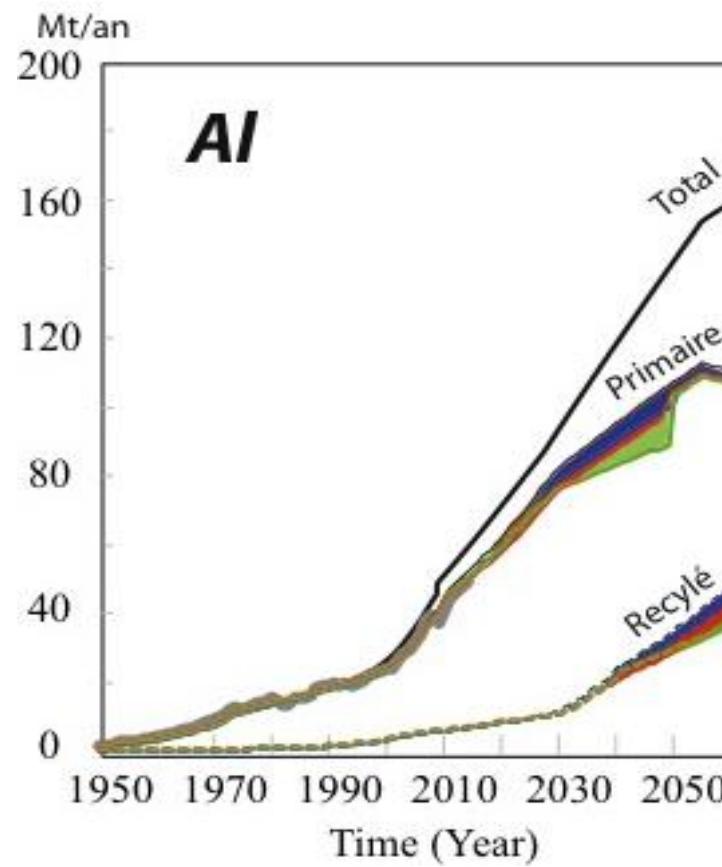
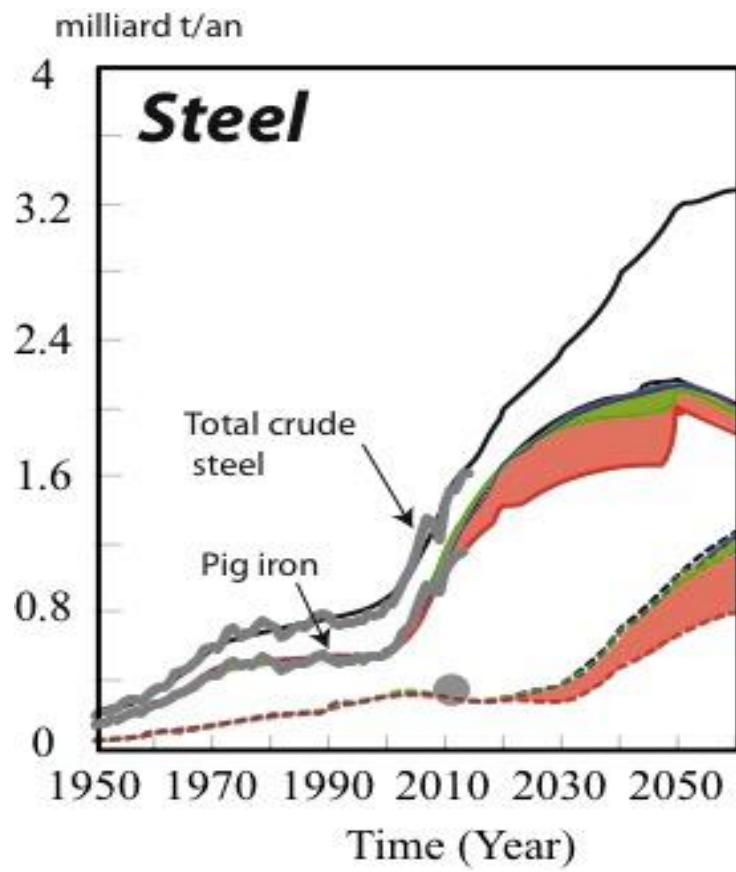


29300 TWeh Ecofys-WWF (2012)



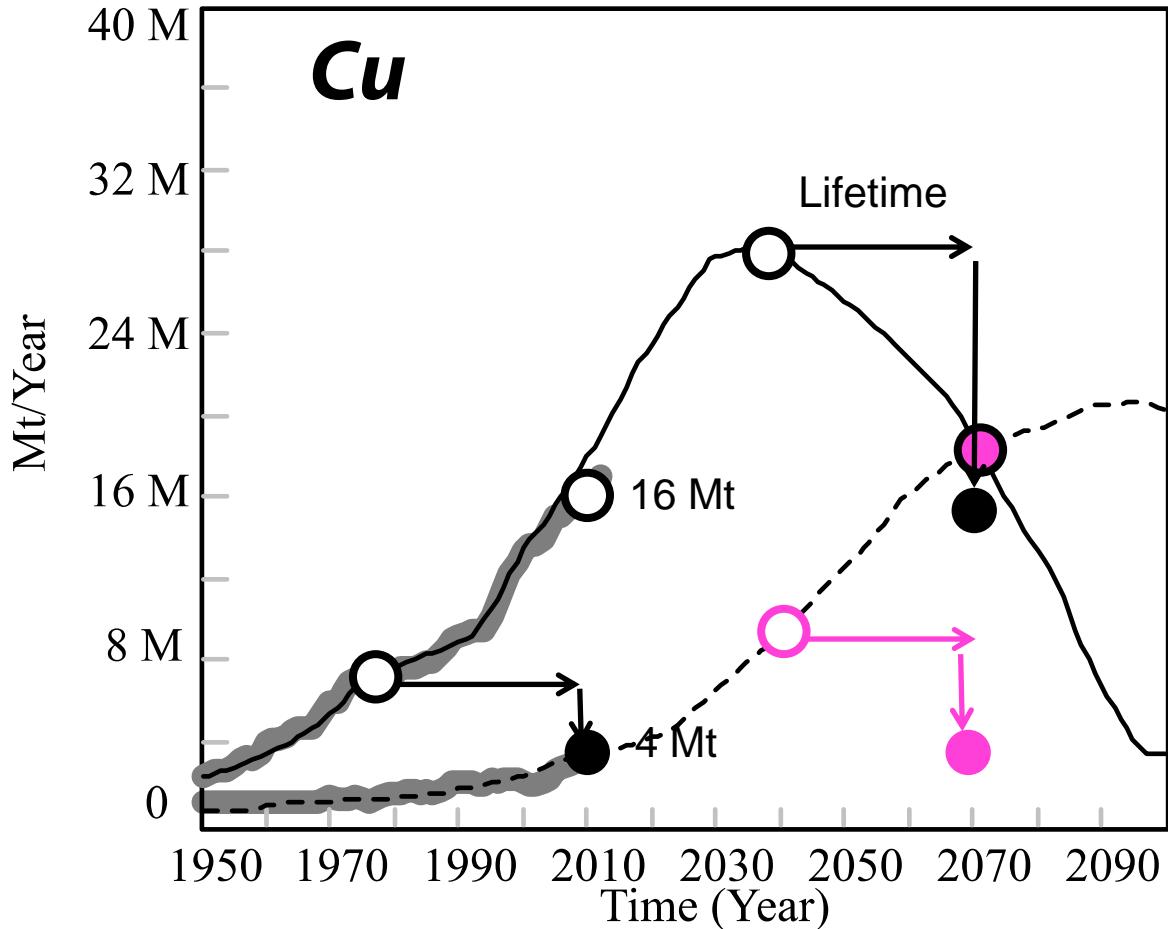
108800 TWeh Garcia-Olivares (2013)





- The peak demand for renewables is close to the global peak of primary production
- The recycling capacity needs to be multiplied by 3 in 35 years.  
*Is it possible ?*

# The limits of recycling: 1) the “reserves” (EOL)



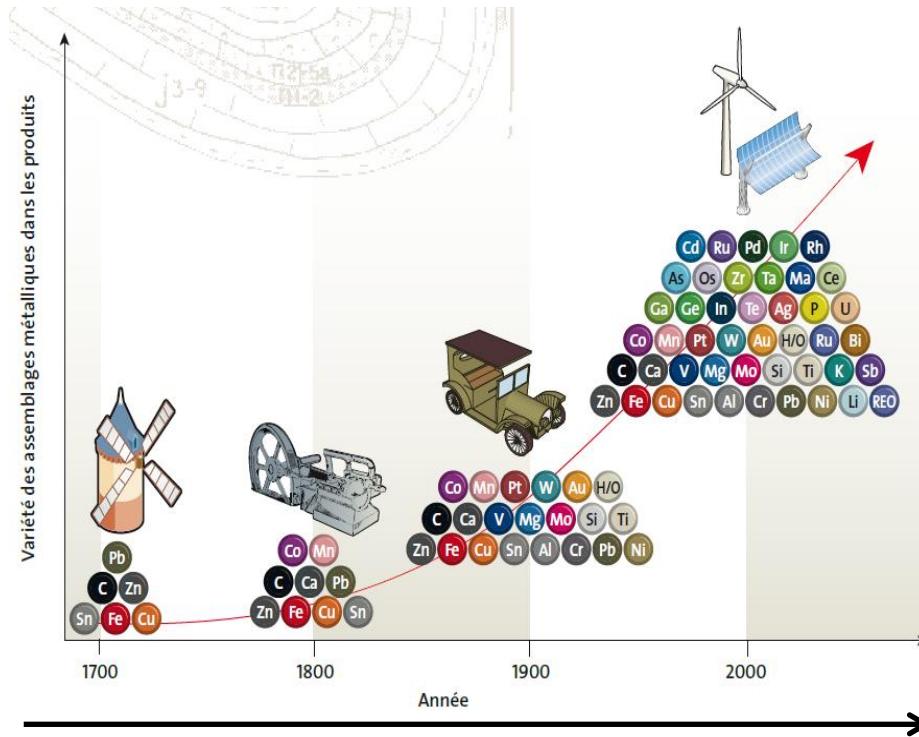
The contribution of recycling  
is low in periods of growth

# The limits of recycling : 2) the cost

E of recycling = E of separation = - mixing entropy

Cost (€)

$$= RT \cdot \sum_1^n X_i \cdot \ln X_i$$



The potential of recycling is decreasing (constant technology)

# The limits of recycling : 2) the cost

**recycling**  
today®

News and Information for R

News ▾ Industry Tools ▾ Media ▾ Magazine ▾ Events ▾ Subscribe ▾

EXPERT SOLUTIONS FOR  
YOUR RECYCLING NEEDS



Learn More ►

## Solvay Opens Rare Earth Metals Recycling Plants in France

European chemical company invests \$19.5 million in two facilities.

October 3, 2012

Recycling Today Staff



Subscribe

Solvay Group, a chemical group headquartered in Brussels, has officially opened two rare earth metals recycling plants in France. The two plants are designed to allow the company to diversify its supply of rare earth metals and preserve resources.

Solvay says it has developed a process to recover rare earth metals from end-of-life products, such as light bulbs, batteries and magnets.

Research into and development of the process began in 2007 and took two years, followed by two years of industrialization studies and site selection, according to the company. The investment was officially approved in 2011.

Solvay says it focused initially on low-energy light bulbs because the recovery channels already existed. The light bulbs have an ample amount of six different rare earths—lanthanum, cerium, terbium, yttrium, europium and gadolinium—which Solvay is in position to recycle while preserving 100 percent of their

Hua adds, "The launch of these units illustrates our tangible contribution as a chemical manufacturer to sustainable development."

2016: the recycling facilities are closed

-> the cost of REE production is too high at the present price

2016: The Chinese primary iron (coal) is competitive/ recycled European steel (electricity)

# Additional needs

100 to **300** Mt Cu are needed, = 6 to 18 x 2010 global production

**70 Mt Cu**  
production



**1 Mt Cu**

storage



**30 Mt Cu**

Use

Transport &  
distribution

**3 Mt Cu**



# Additional needs

H																				He
Li	Be																			
Na	Mg																			
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr			
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe			
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn			
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Uub	Uut	Uuq	Uup	Uuh					Uuo

Lanthanides	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Hm	Er	Tm	Yb	Lu
(Rare Earth)														
Actinides	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr



Stockage de l'énergie  
Connectique  
Economies d'énergie  
Catalyse (automobile, piles à combustible)



Production et transport de l'électricité  
Industrie électrique nucléaire  
Photovoltaïque  
Aimants permanents (véhicules électriques, éoliennes, TGV...)

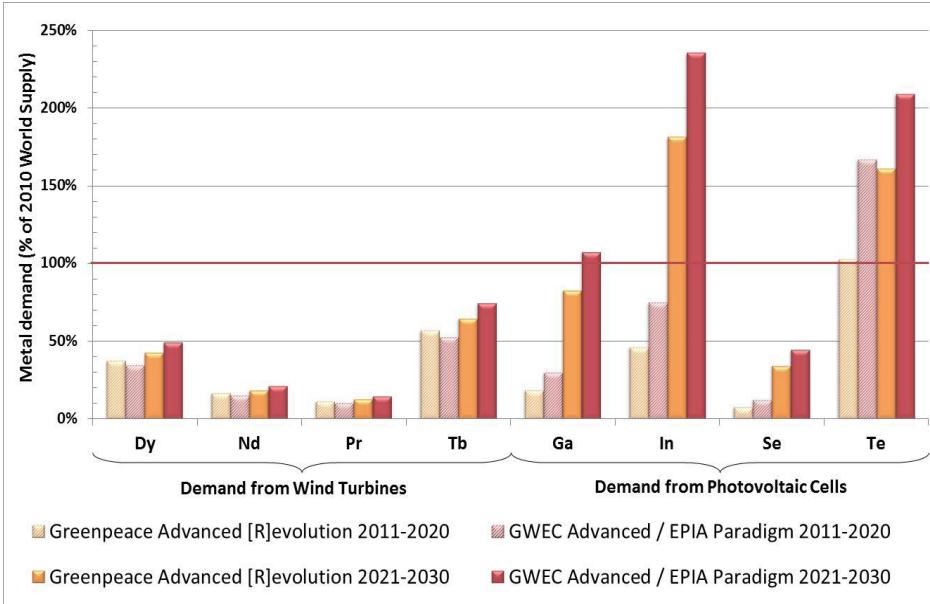


Eclairage  
Supraconducteurs

Compilation: P. Christmann, BRGM

Les symboles chimiques des éléments semi-conducteurs sont indiqués en lettres rouges

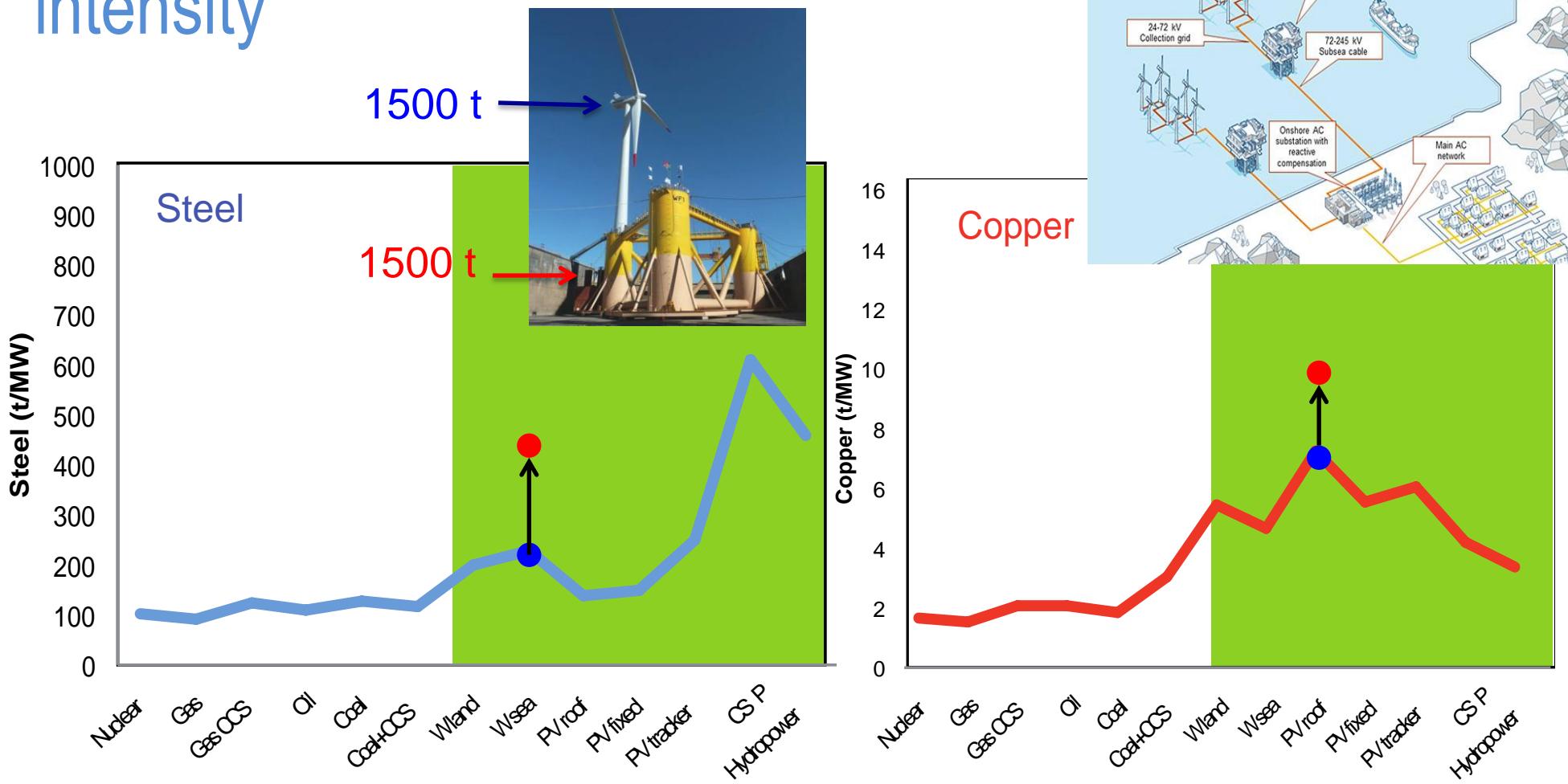
# The case of High Tech metals is more worrying on the short term



Until 2030, the yearly global demand in Ga, In, Se, Te, Dy, Nd, Pr and Tb for PV cells and wind turbines will be boosted to 10 to 230% of the 2010 world supply (Öhrlund, 2011)

- Their production requires much less energy than structural raw materials
  - Economy of use and substitution is possible, efficiency can be improved:
    - *High-efficiency permanent magnet with no REE (Hitachi, 2012).*
    - *Reluctance motors using electro instead of permanent magnets are an option for electrical vehicles.*
    - *Two-fold increase of the Net Energy Ratio of PV in 10 years (Koppelaar et al., 2016)*
- ⇒ Innovation is likely to improve the situation. **This is not the case for steel, Al, Cu, concrete**

# Additional needs: the technical innovation can increase the RM intensity



# Should we worry ?

The most exigent scenario (Garcia-Olivares et al., 2013) requires by 2050:

300 Mt Cu: 18 years of present production, 50% of known reserves

8 Mt Li: 100 years of production, 50% of known reserves

66 Mt Ni: 40 years, 95% of known reserves

31 Mt Pt: 19 years, 44% of known reserves

...and a considerable amount of energy to produce these raw materials

# The energy cost of RM production

Scenarios WWF and Garcia-Olivares: 300 Mt Al

Energy requirement

Primary Al production: 210 GJ/t  
*(Drezet, 2014*

<http://ecoinfo.cnrs.fr/article329.html>)



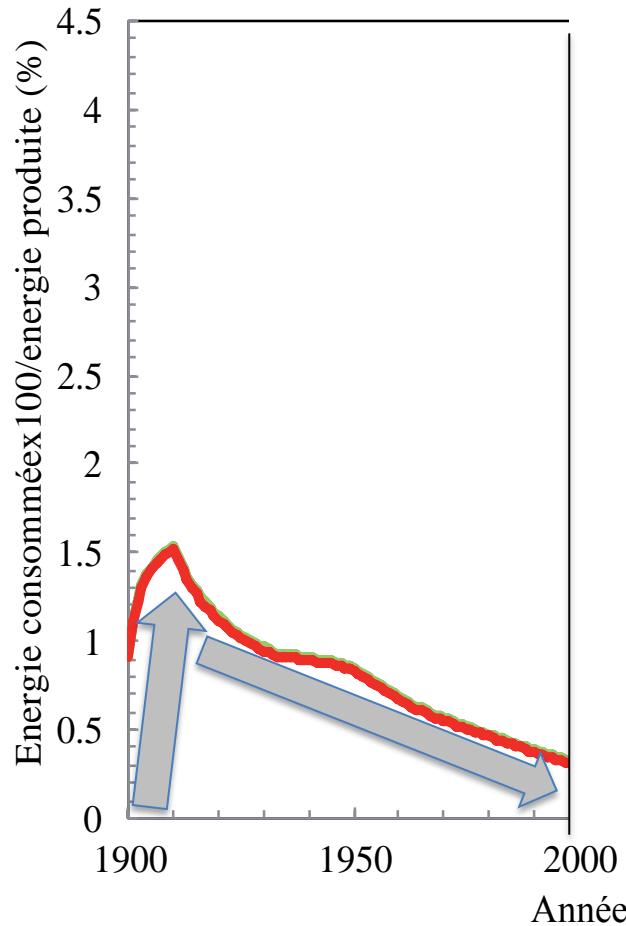
$10 \cdot 10^9$  Barrels of Oil Equivalent

5 months of crude oil global production

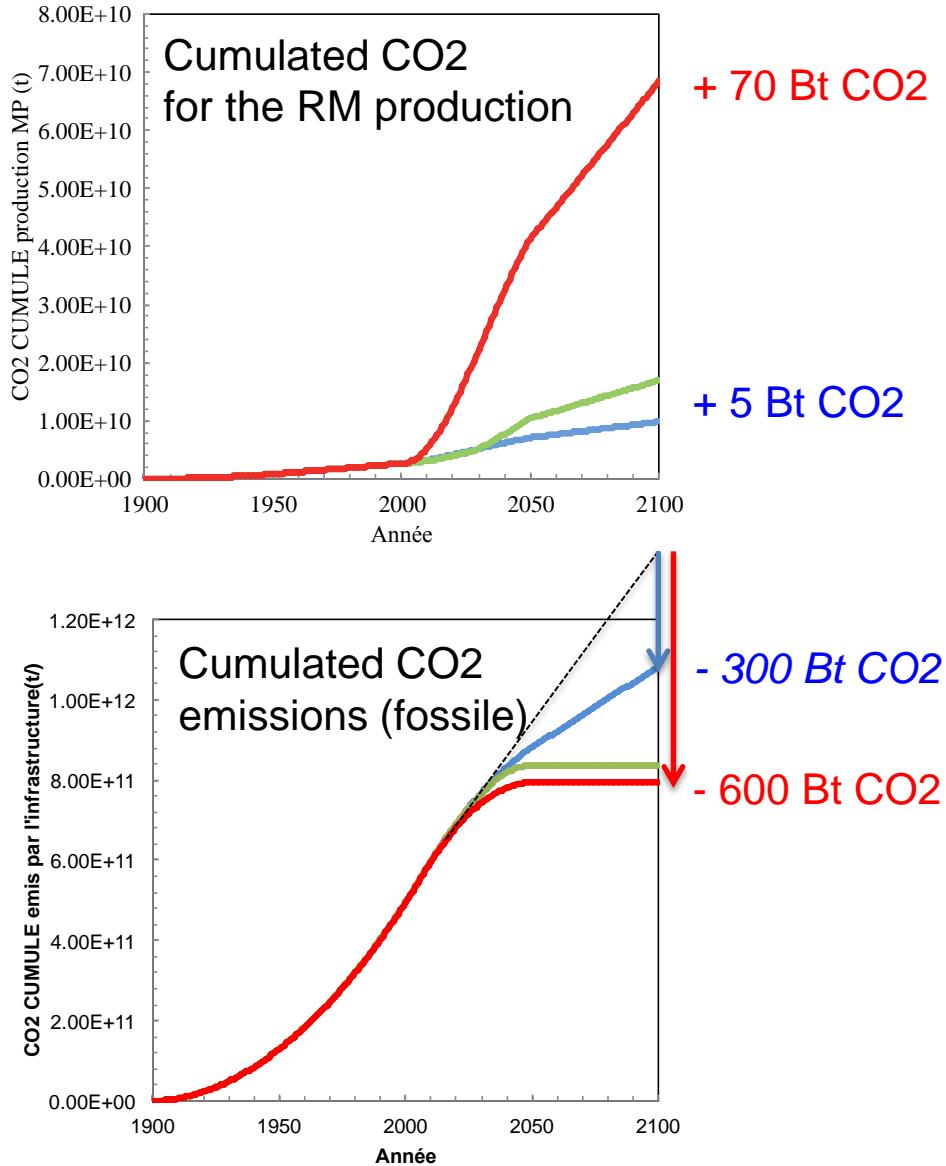
With concrete and steel: energy equivalent to 1.5 year of crude oil production in order to make the raw materials used in the infrastructure of electricity generation

# Energy to produce the RM for the infrastructure

## Energy generated by the infrastructure



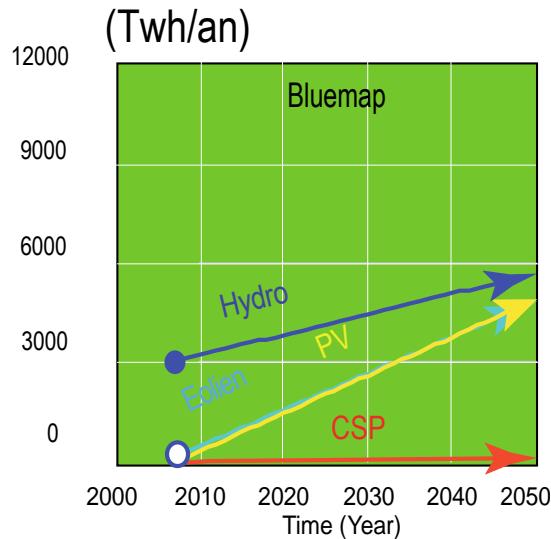
# The CO<sub>2</sub> budget



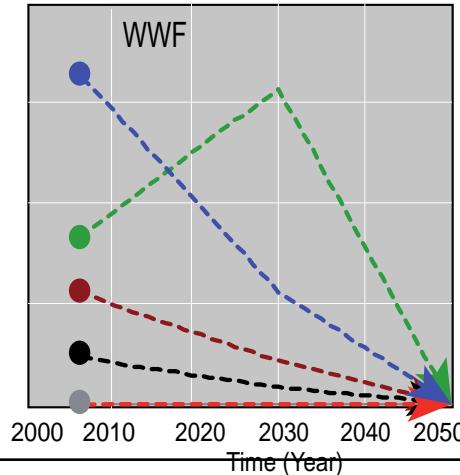
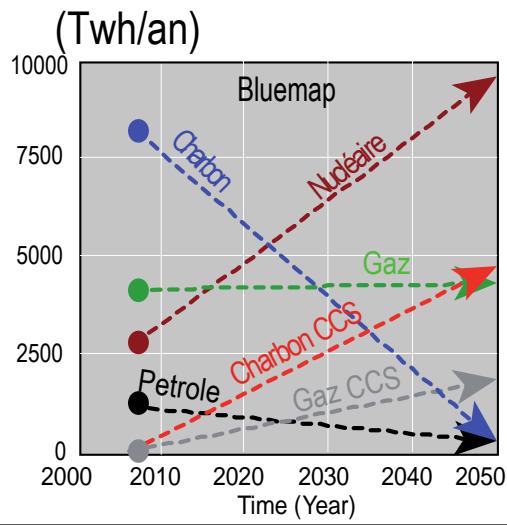
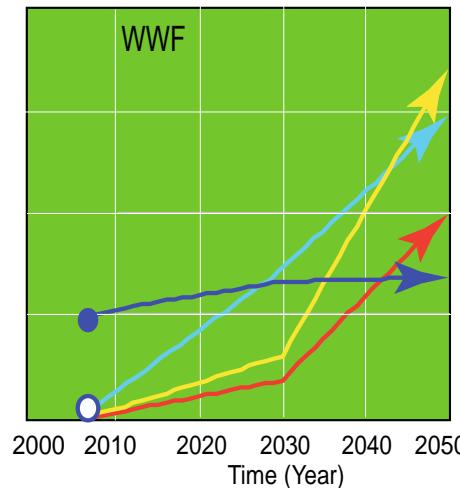
Even though the shift to renewables needs RM and energy, the cumulative amount of emitted CO<sub>2</sub> is strongly reduced... after 2050

# What is the best scenario ?

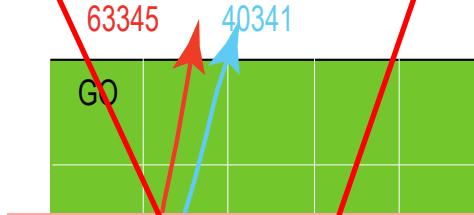
Blue Map IEA (2010)  
36 PWeh, 42% renewables



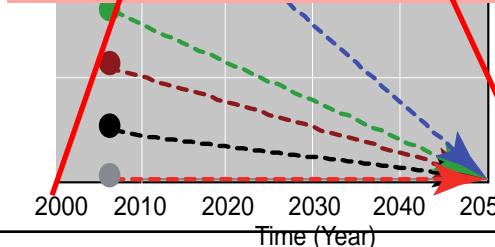
Ecofys-WWF (2012)  
29 PWeh, 100% renewable



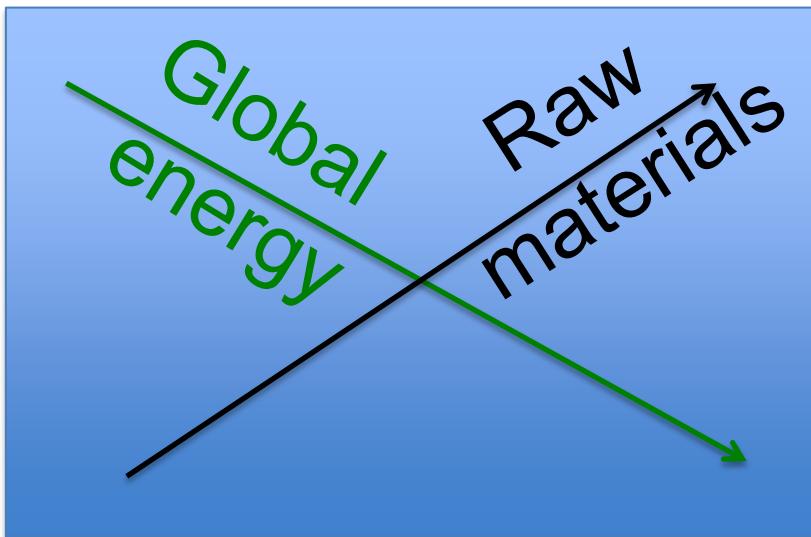
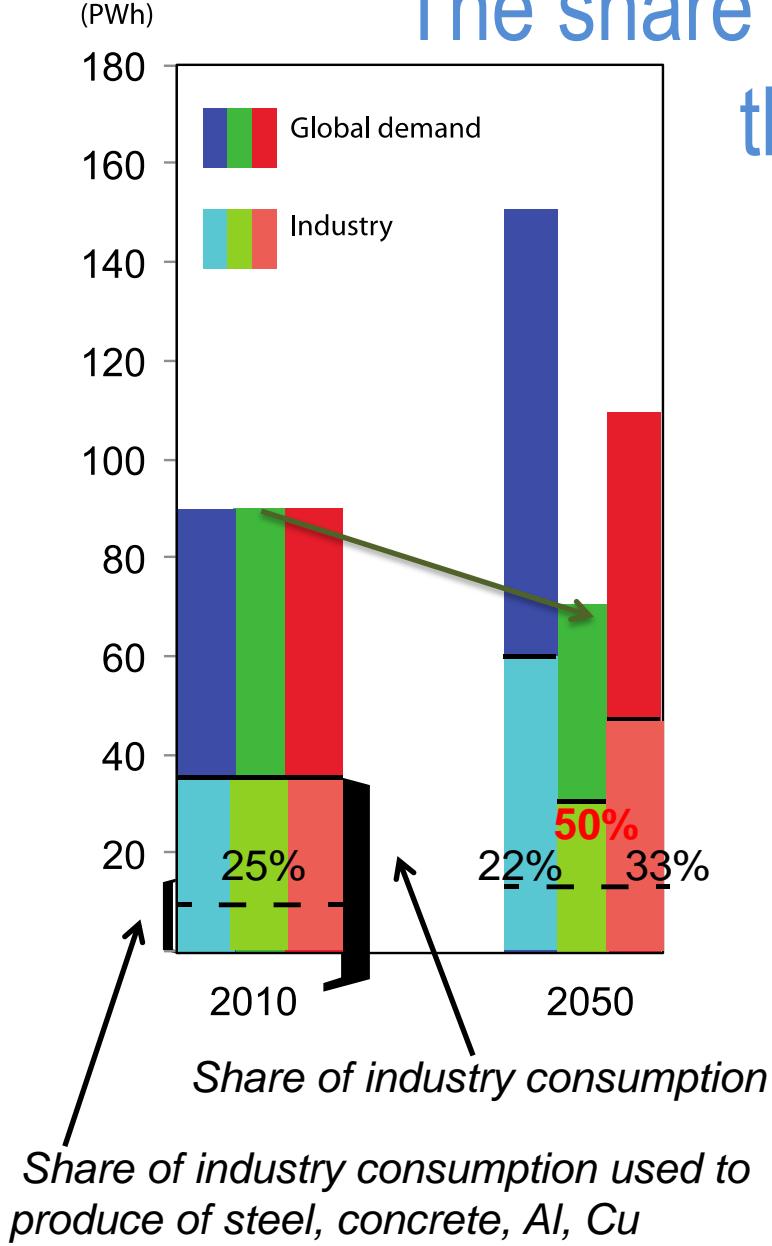
Garcia-Olivares (2013)  
109 PWeh, 100% renewable  
only electricity



Maximises the reduction of CO<sub>2</sub> but it requires too much raw materials



# The share of global energy used to produce the RM (all applications)



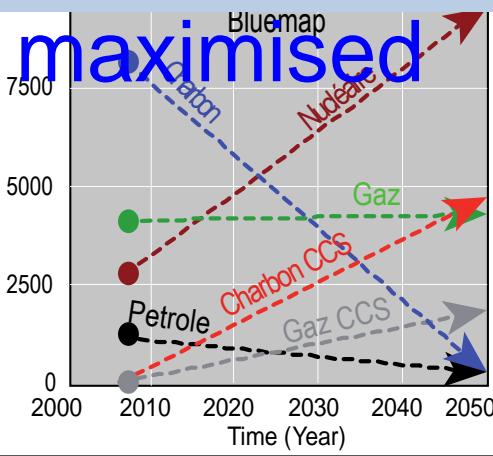
A huge and uncertain increase  
of efficiency is required for the  
WWF scenario

# What is the best scenario ?

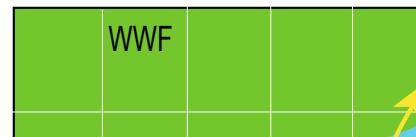
## Blue Map IEA (2010) 36 PW<sub>eh</sub>, 42% renewables



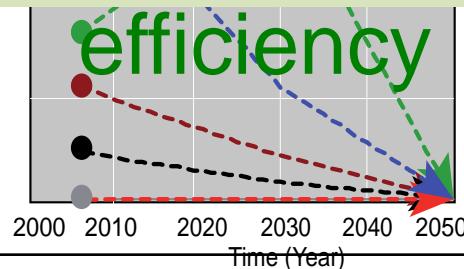
Realistic, but  
the reduction  
of CO<sub>2</sub>  
emission is not



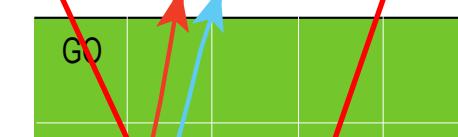
Ecofys-WWF (2012)  
29 PW<sub>eh</sub>, 100% renewable



Maximises the reduction of CO<sub>2</sub>? but it requires a strong improvement of energy

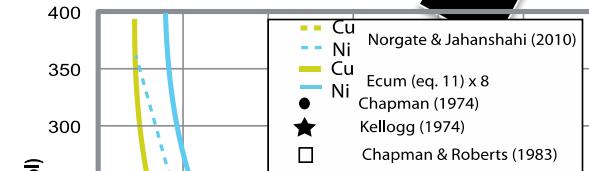


Garcia-Olivares (2013)  
109 PWeh, 100% renewable  
only electricity



~~Maximises the reduction of CO<sub>2</sub> but it requires too much raw materials~~

# How can we incorporate the economic dimension in the models ?



Discussing the future of raw materials requires dynamic and non-empirical models integrating the geological AND economic aspects AND the potential of technological improvements AND able to reproduce the historic trends

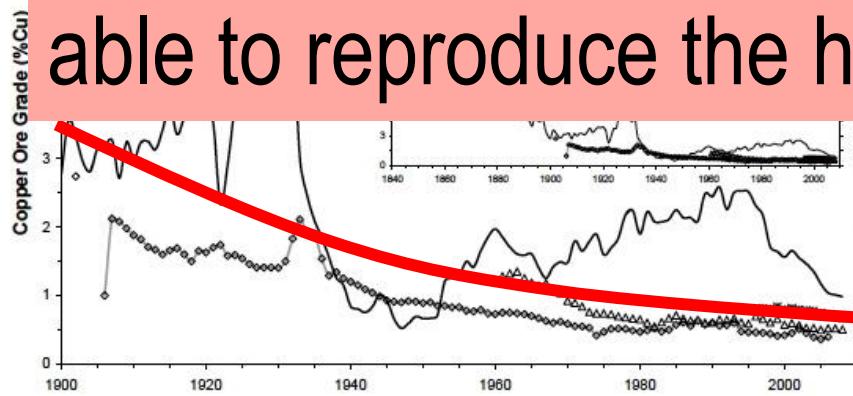
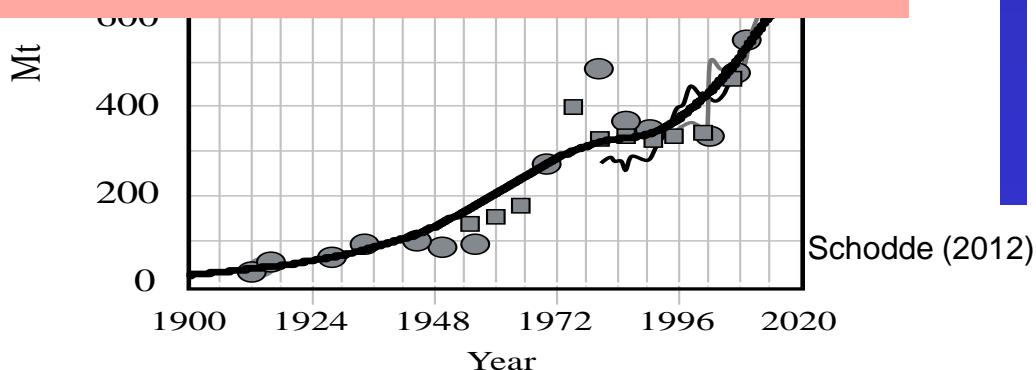


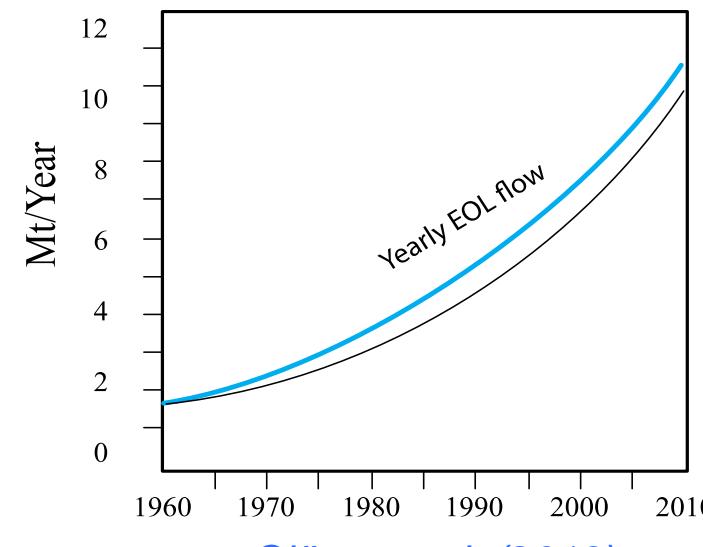
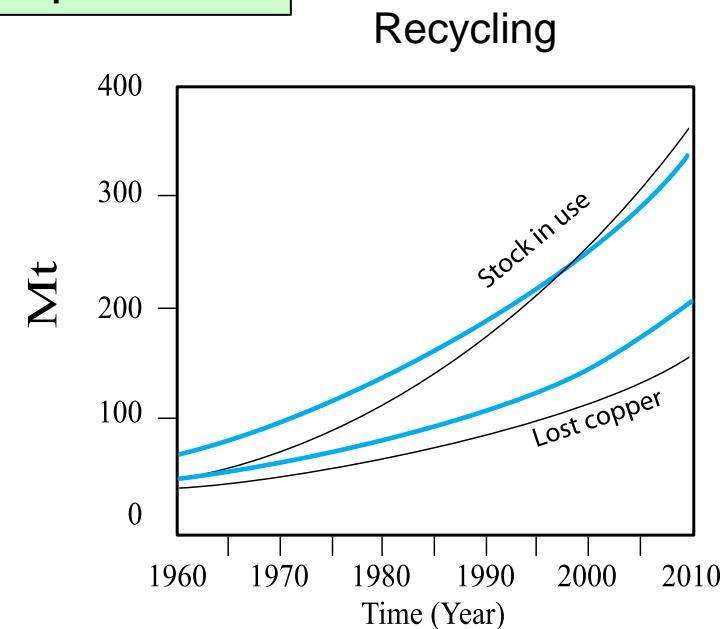
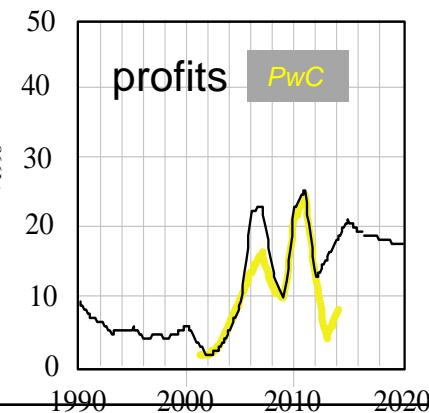
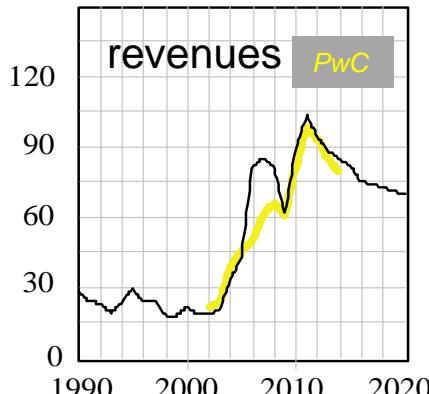
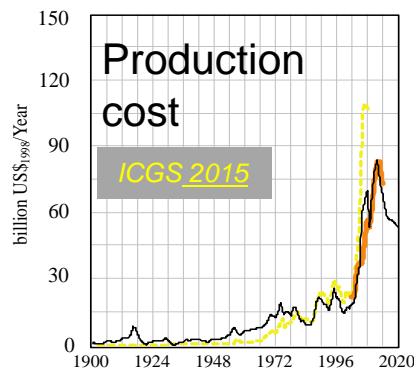
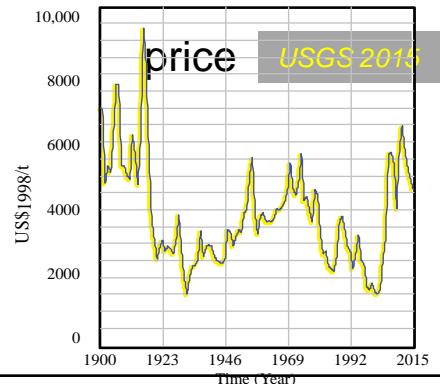
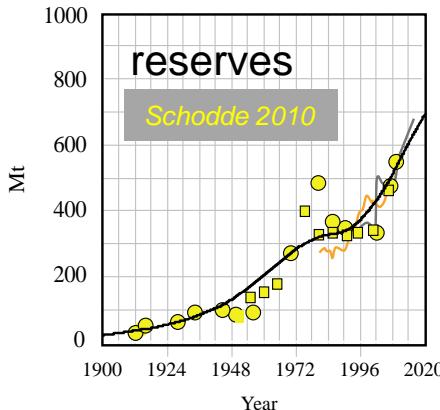
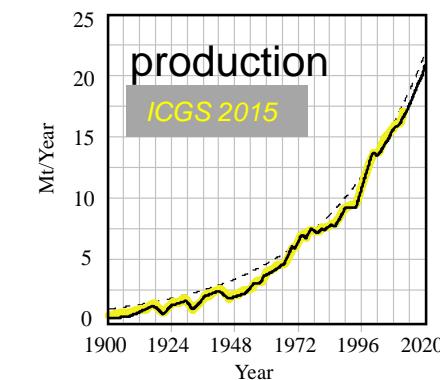
Figure 2 – Copper ore grades over time by country and approximate world average



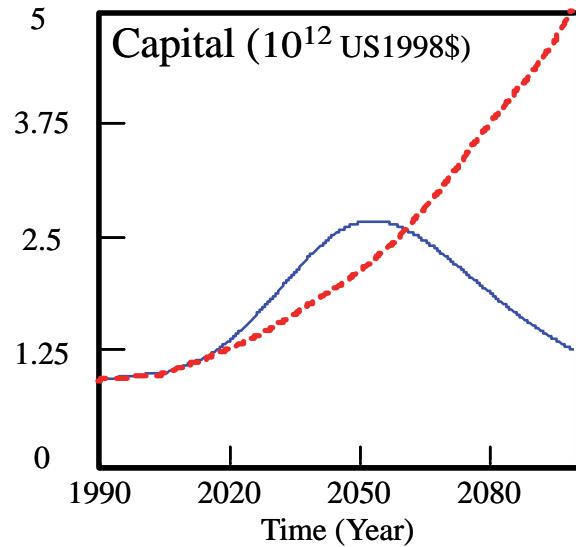
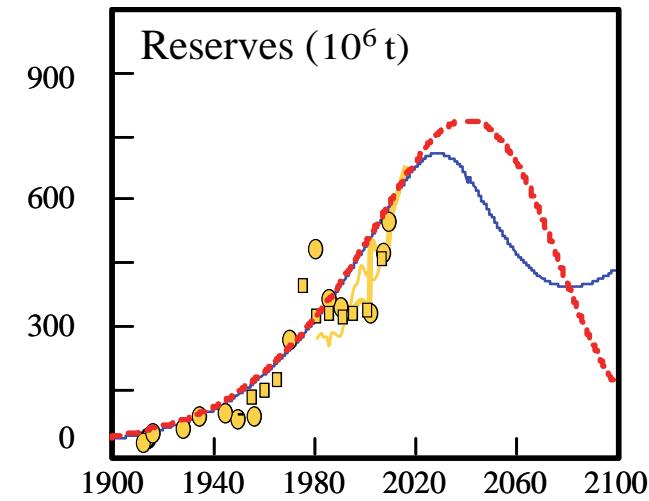
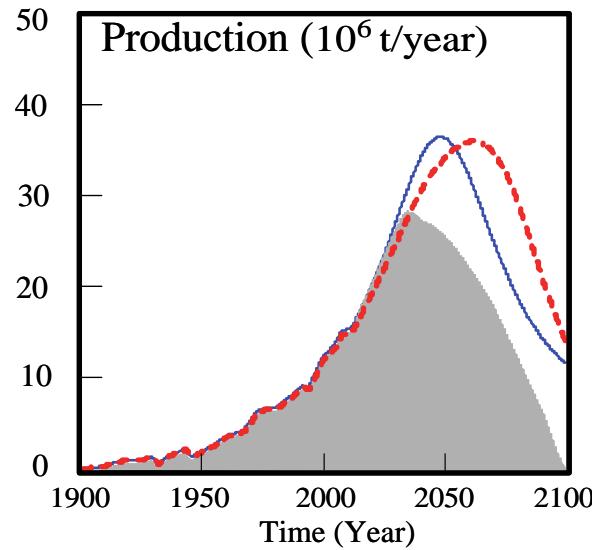
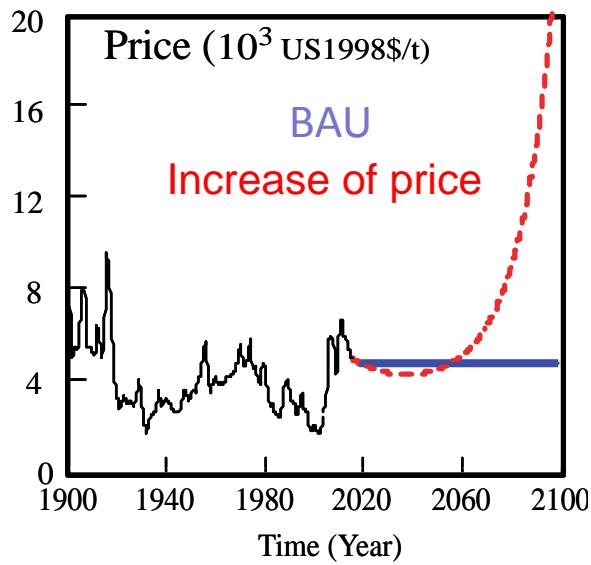
Schodde (2012)

Year

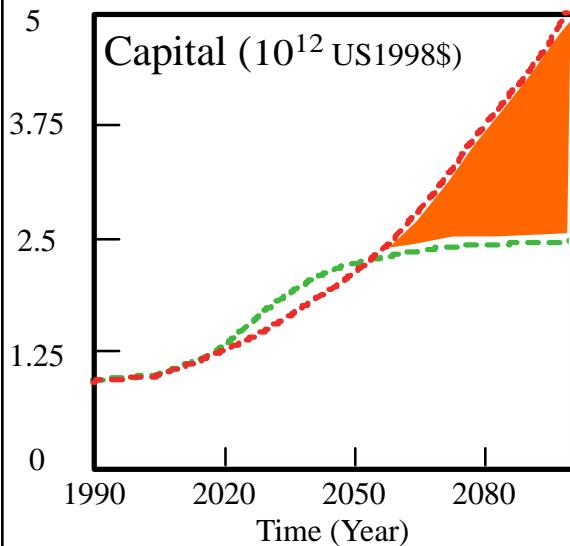
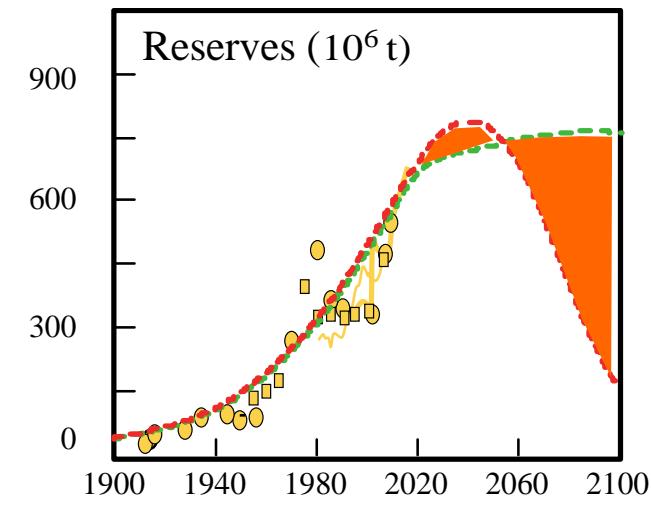
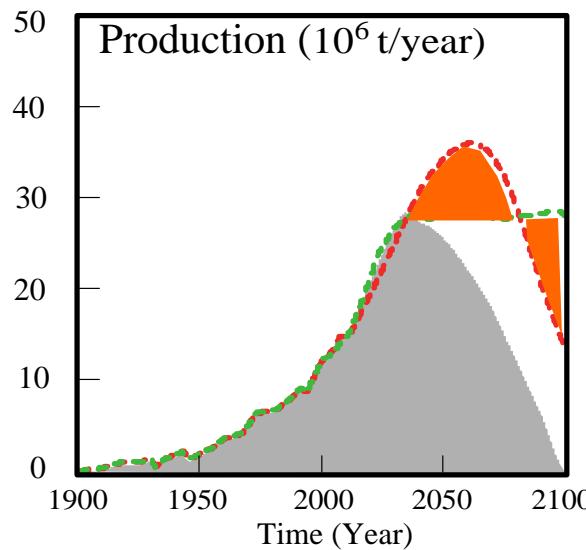
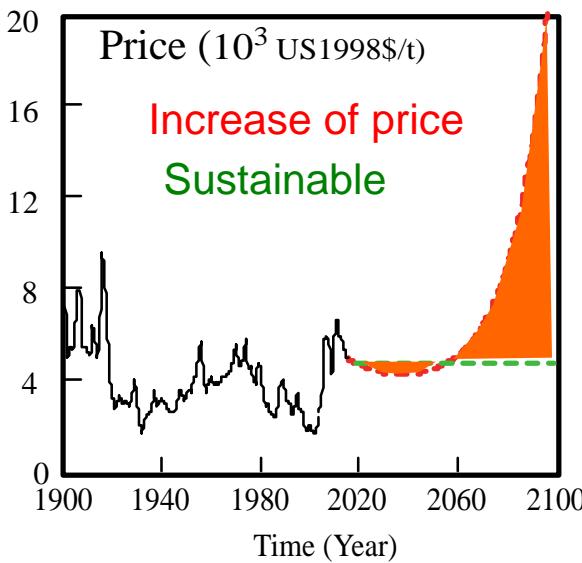
# Constraints: Global historical trends of Copper production



*Glöser et al. (2013)*



Bankruptcy  
of  
the mining  
sector



**1) There is no single future**

2) The economic constraints are as important as the geological ones

3) Recycling is fostered if the price is increasing

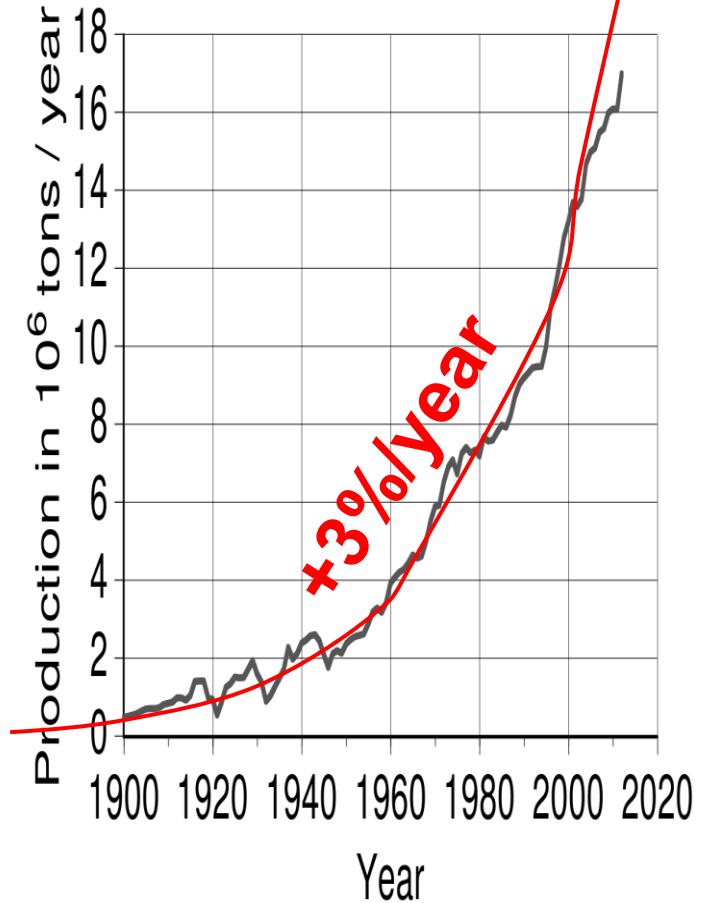
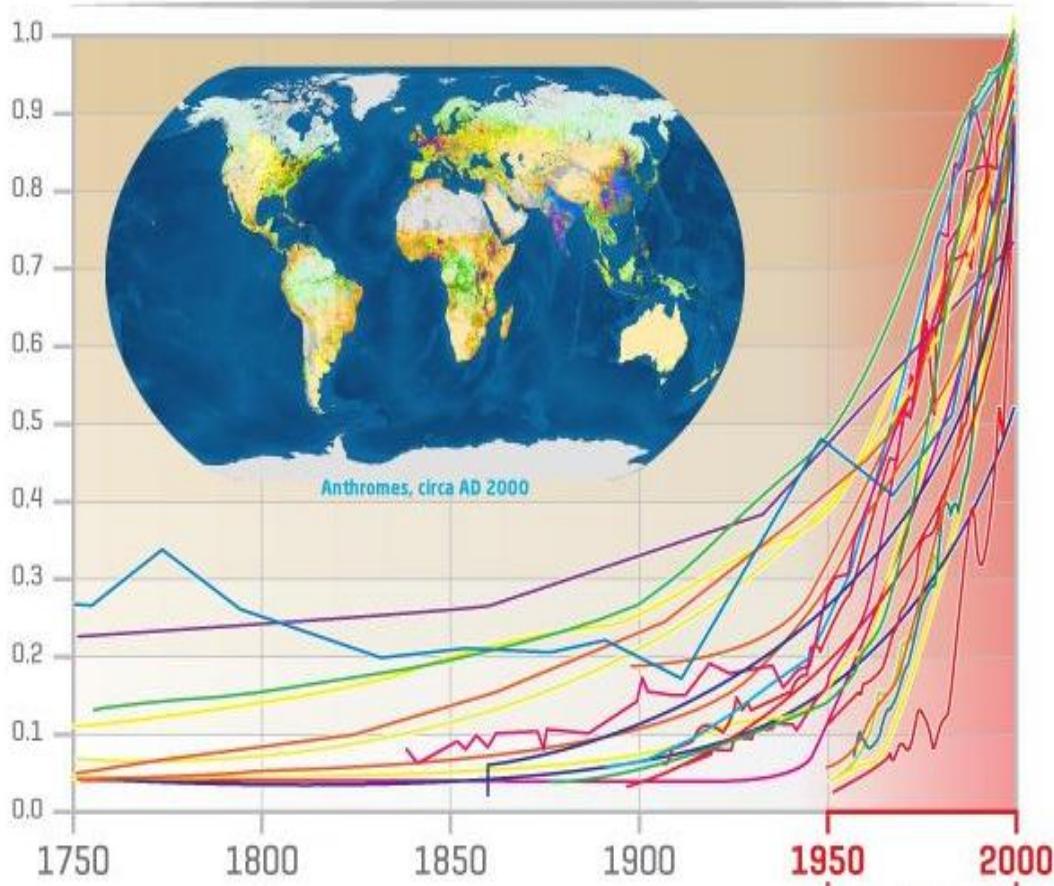
The environmental impacts and social aspects must be integrated to the model

# Conclusions

Achieving the transition toward low-carbon energy is a crucial challenge of the 21st century but **it will be costly** (energy, GHG emission, resources).

- This cost must be evaluated in regards to the availability of raw materials, energy and water and environmental impacts associated to their production. What is the best scenario ?
- What has been possible in the past (e.g. doubling the production of metals every 20 years) will not be possible forever. It is not only a matter of reserves, but also a matter of environmental and economic implications.

# A long lasting exponential growth is physically impossible



+3%/year: All the copper in the 30 km thick Earth's crust is extracted in 600 years (30m thick copper plate)

All the copper of the Universe is extracted in 6000 years

# Conclusions

Achieving the transition toward low-carbon energy is a crucial challenge of the 21st century but it will be costly (energy, GHG emission, resources).

- This cost must be evaluated in regards to the availability of raw materials, energy and water and environmental impacts associated to their production. What is the best scenario ?
- What has been possible in the past (e.g. doubling the production of metals every 20 years) will not be possible forever. It is not only a matter of reserves, but also a matter of social, environmental and economic implications.
- We should anticipate and be prepared for massive recycling

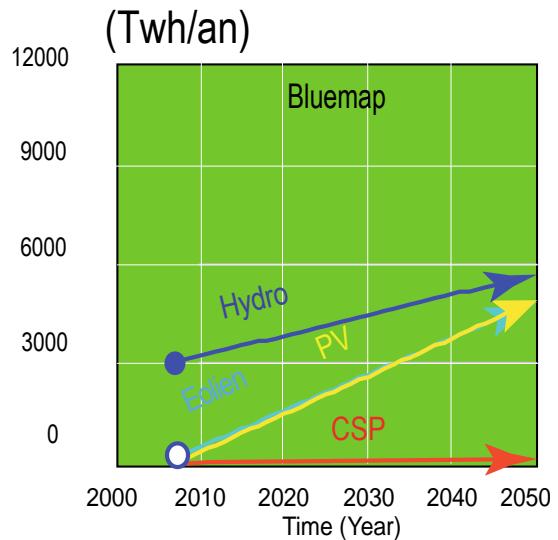
Address these issues as well as their couplings in a comprehensive and global framework (earth & environmental sciences, social sciences, economics, politics)

- Modelling to avoid blind driving. *Models able to link resources production-reserves-recycling-demand-price-cost of production and able to reproduce historic data...*

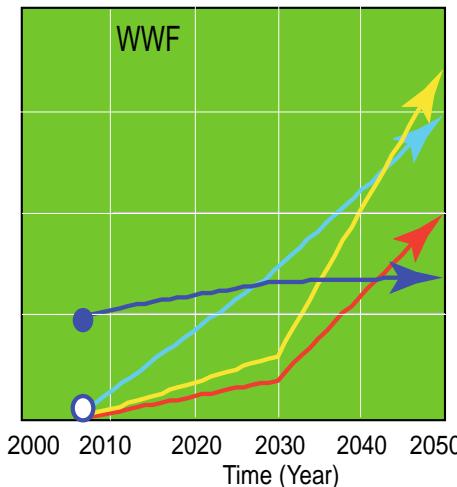
Thank you for your attention !

# Contrasted energy scenarios are proposed...

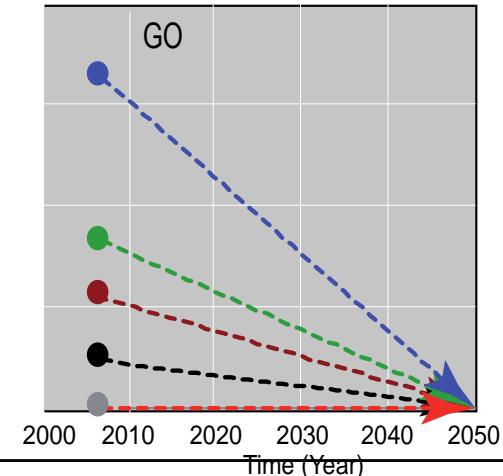
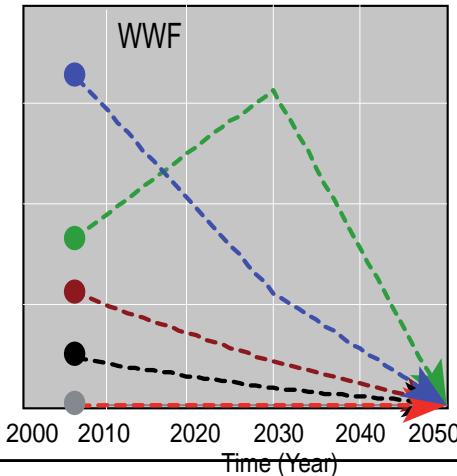
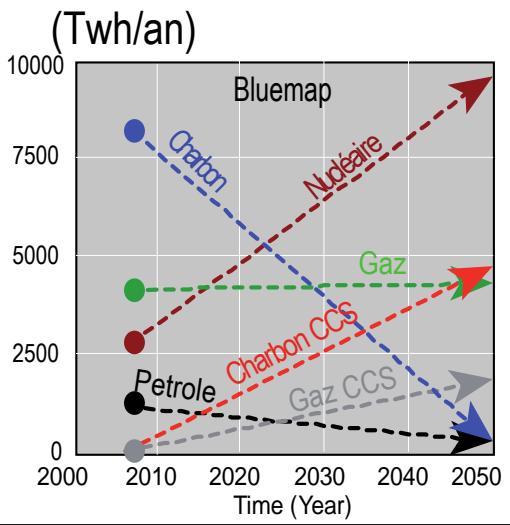
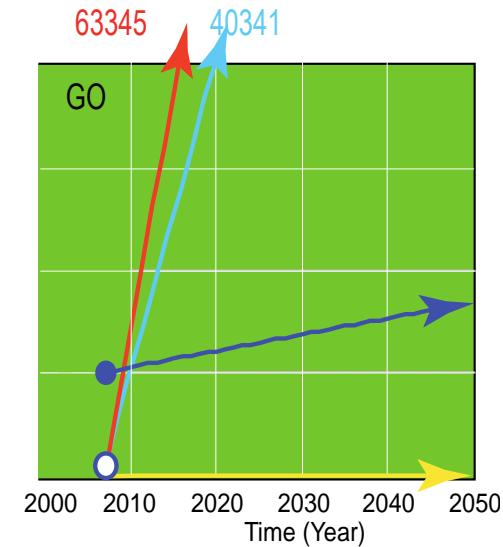
Blue Map IEA (2010)  
36 PWeh, 42% renewables



Ecofys-WWF (2012)  
29 PWeh, 100% renewable



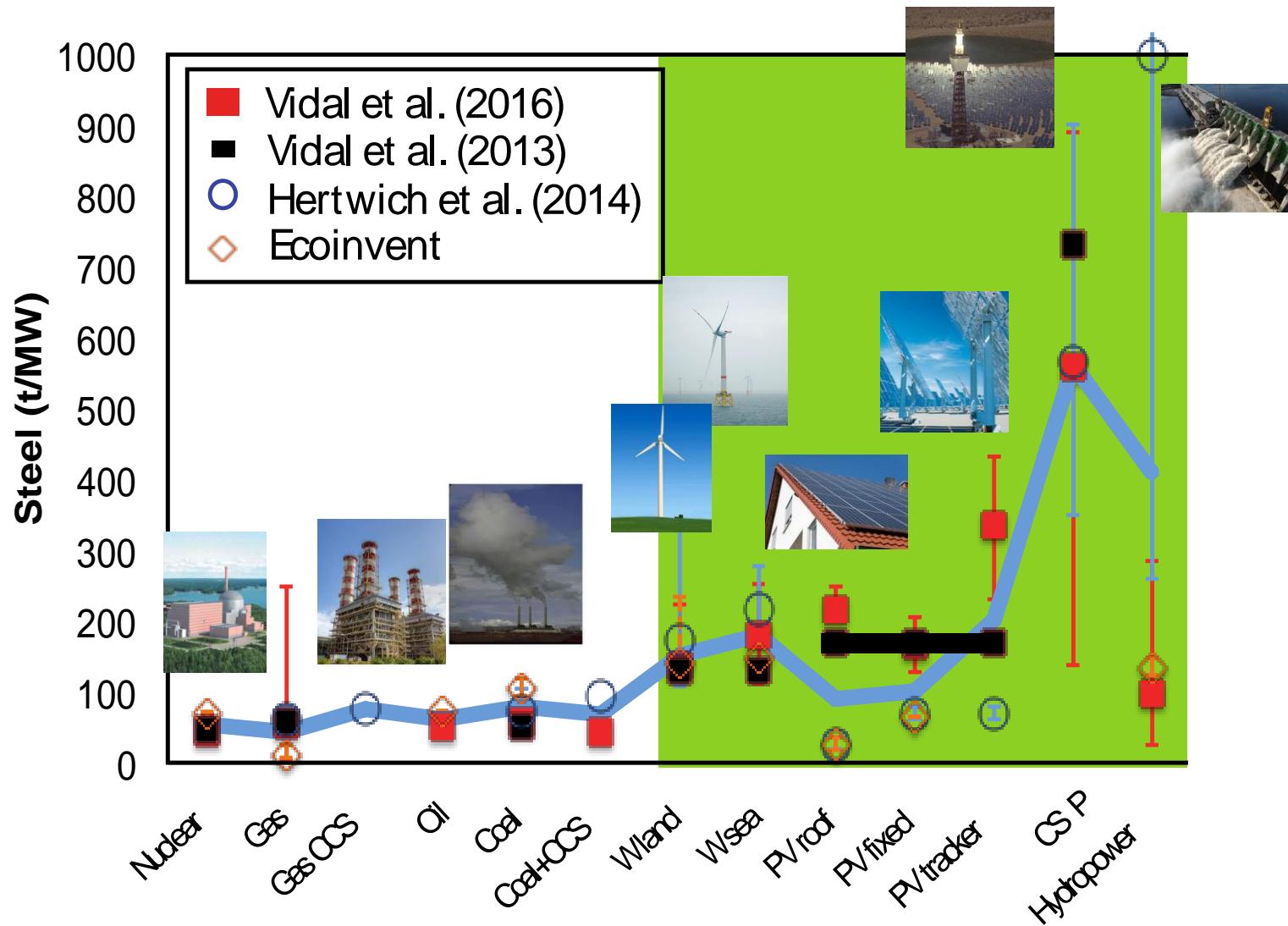
Garcia-Olivares (2013)  
109 PWeh, 100% renewable  
only electricity



# Les ressources minérales pour la transition énergétique

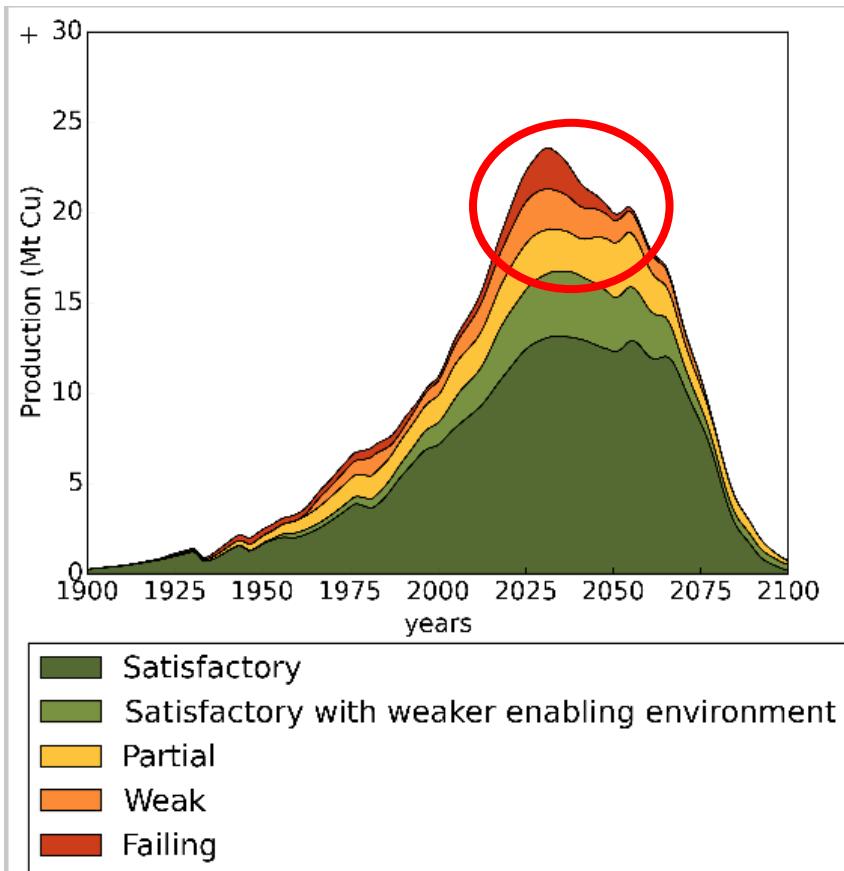
The existing scenarios focus on the reduction of CO<sub>2</sub> emissions and economic conditions. They neglect the raw materials and energy costs, which put additional constraints on the transition towards low-carbon energy.

# Material intensity of energy-generation facilities



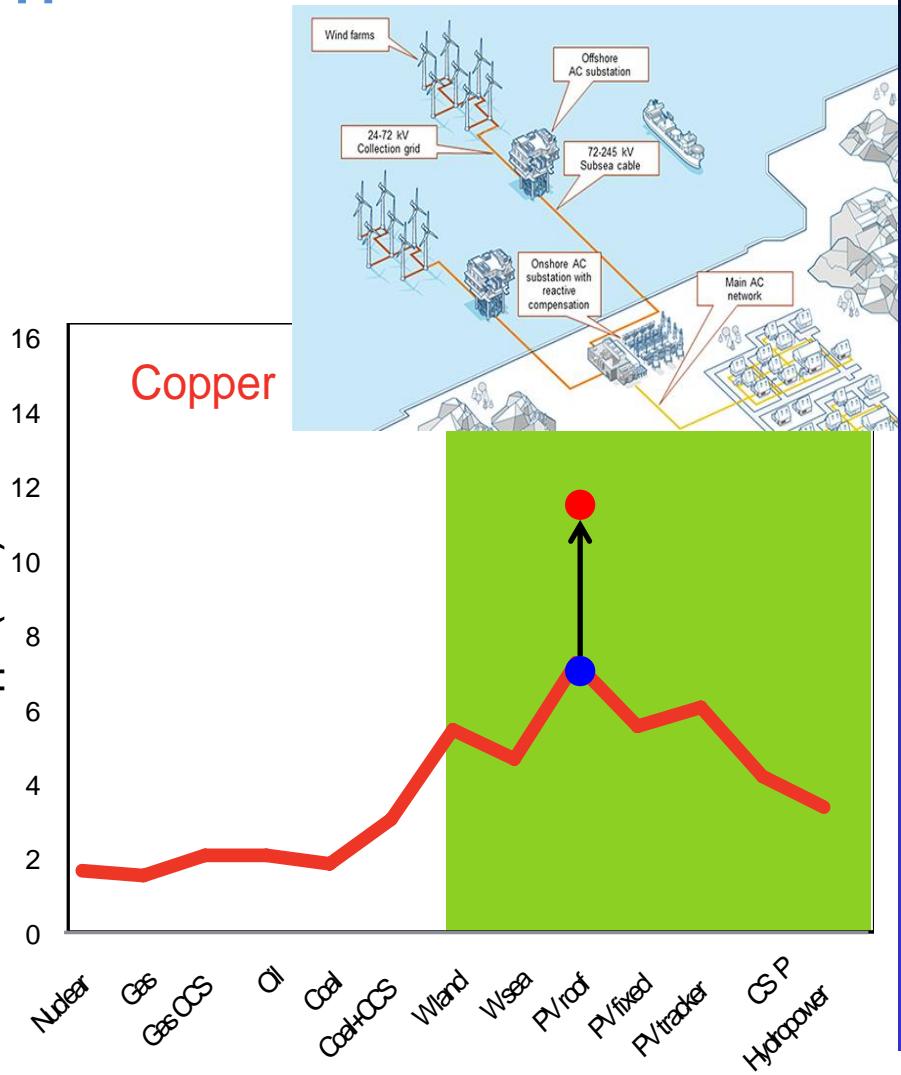
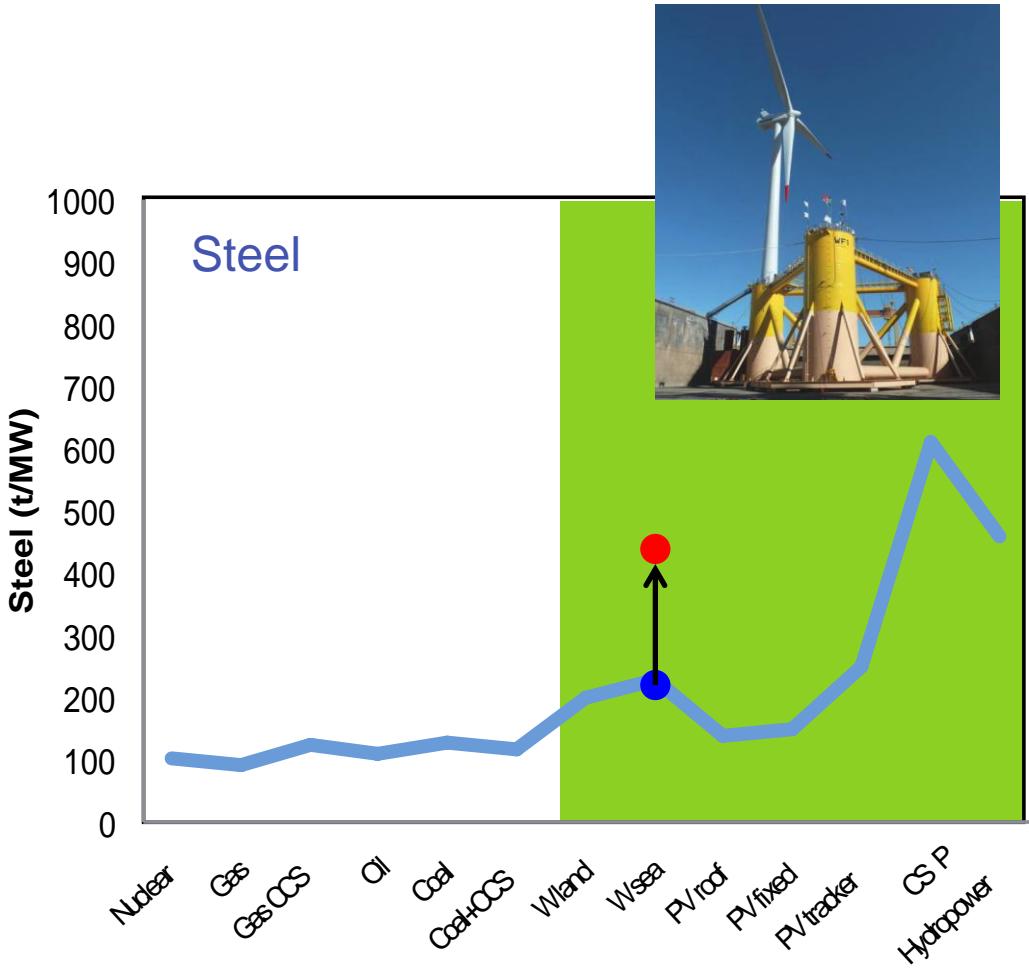
# The energy-RM-economy-geopolitical nexus

Reserves ranked according to the 2014 « Natural Resource Governance Index » :  
« Institutional and Legal Setting; Reporting Practices; Safeguards and Quality Controls, and Enabling Environment »

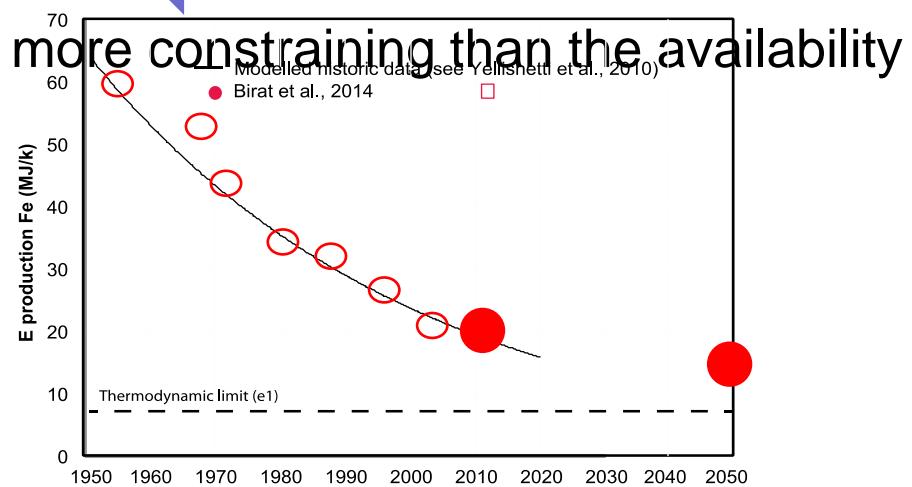
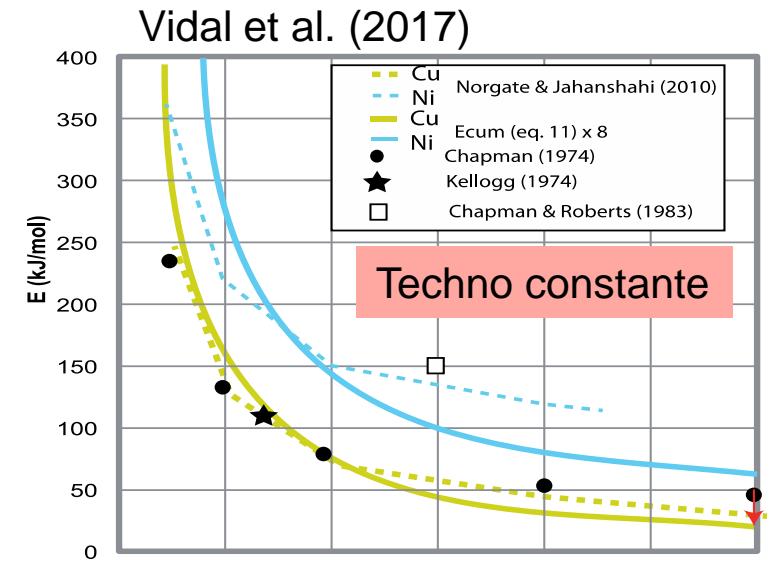
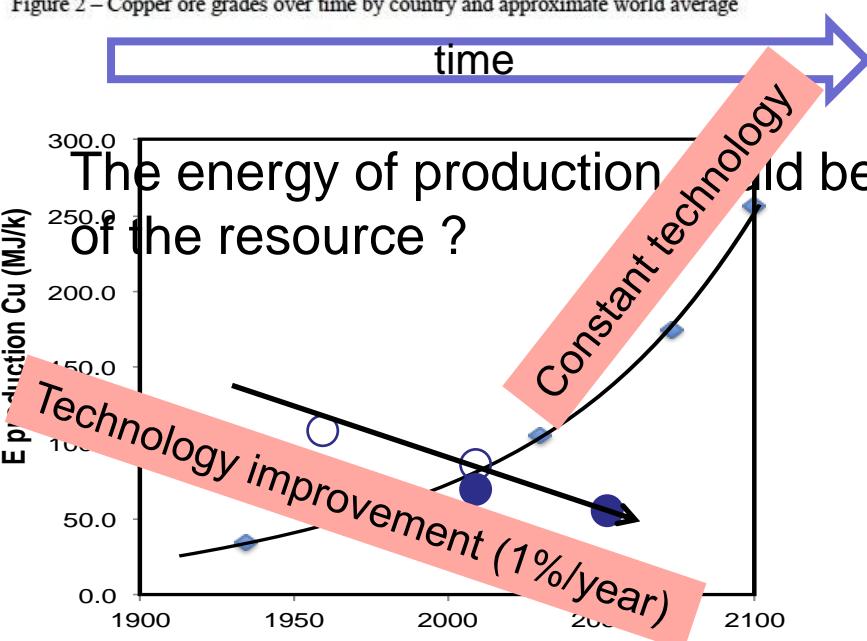
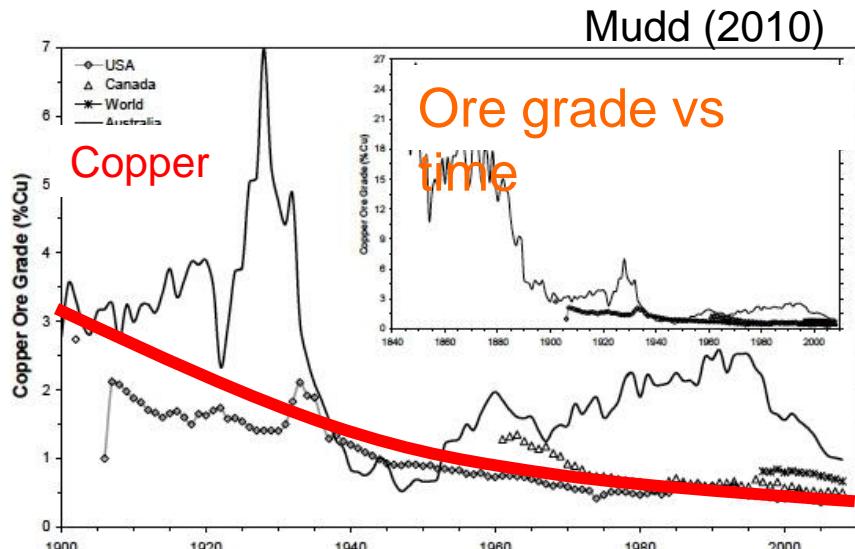


A third of known Cu resources are in countries with less than satisfactory governance... This adds a further risk, if production from these countries is to be needed to meet global demand

# The situation could be worse...

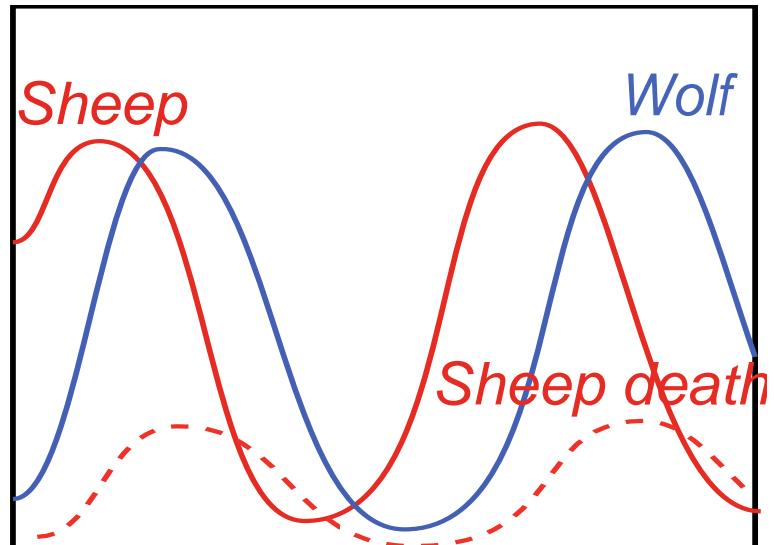


# The energy required to produce RM is dynamic



# A possible approach: The prey-predator model

(Lotka; Volterra, 1926)



$$\frac{dSheep}{dt} = Sheep \cdot (n_s - m_s)$$

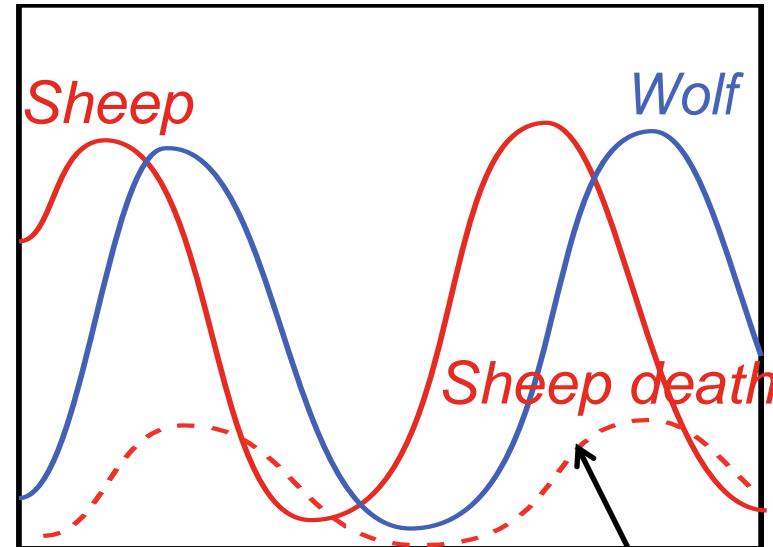
$$\frac{dWolf}{dt} = Wolf \cdot (n_w - m_w)$$



$$\frac{dSheep}{dt} = Sheep \cdot (n_s - \beta \cdot Wolf)$$

$$\frac{dWolf}{dt} = Wolf \cdot (\delta \cdot Sheep - m_w)$$

# A possible approach: The prey-predator model



**Sheep:** Reserve

**Wolf:** Wealth  
(capital, knowledge, etc)

Regeneration of Reserve

$$\frac{d\text{Sheep}}{dt} = \text{Sheep}.(n_s - \beta \cdot \text{Wolf})$$

Metal production

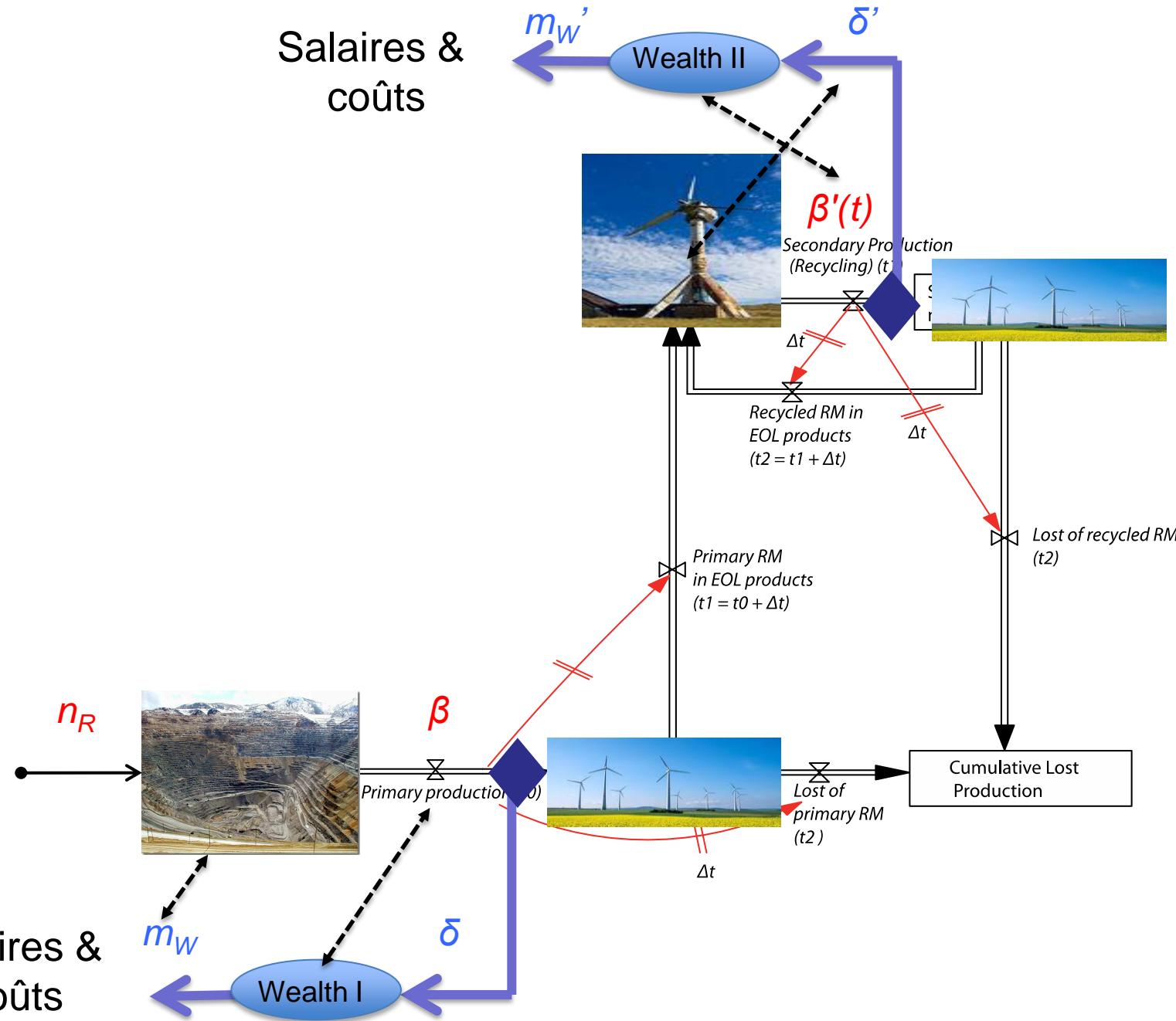
$$\frac{d\text{Wolf}}{dt} = \text{Wolf}.(\delta \cdot \text{Sheep} - m_w)$$

Increase of Capital

Capital erosion

$$\text{Price} = \delta/\beta$$

Salaires &  
coûts



## Constraints: Global historical trends of Copper production

