Modeling energy transitions under physical and resource constraints

20th October 2026

Iñigo Capellán-Pérez

Observatoire de la Politique Climatique

https://opc-luxembourg.lu/en/event/competitiveness-within-a-safe-operating-space/

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Core messages

1. **Economic growth and competitiveness** are driven by more and better-quality energy use, and rely on a healthy environment

2. Transition to **renewable**s is urgent and unavoidable:
   - Leaving out land, materials and energy return on investment lead to overestimate what renewables can deliver

3. **Growth scenarios** worsen these dynamics and limits

4. **Post/De-growth scenarios** help reducing impacts and attaining goals

5. Biophysical characteristics of renewables **do not determine what can be achieved; they condition it**

Nature and ecosystems: the foundation of human need satisfaction





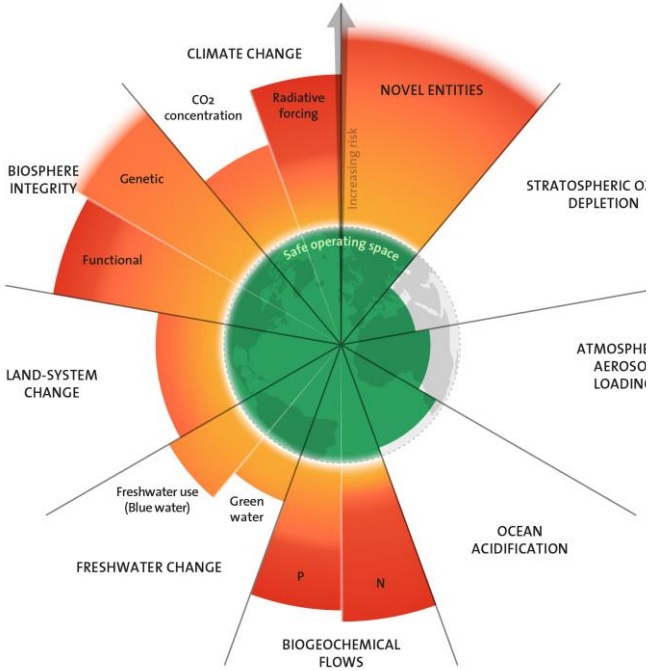


ECOLOGICAL BASIS

PROVISIONING SYSTEMS

HUMAN NEED SATISFACTION

The sustainability paradox: unmet global human needs despite severe environmental degradation







LS Life satisfaction
LE Healthy life expectancy
NU Nutrition
SA Sanitation
IN Income
EN Access to energy
ED Education
SS Social support
DQ Democratic quality
EQ Equality
EM Employment

ECOLOGICAL BASIS

PROVISIONING SYSTEMS

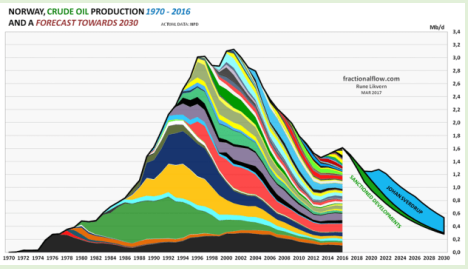
HUMAN NEED SATISFACTION

Ecological basis: environmental functions



- Sources
- Sinks
- Life support

Social metabolism & limits



- Fossil fuels
- Metals
- Non-metallic minerals

Non-renewable materials

Functions & structures

HUMANITY SOCIAL METABOLISM

Rich

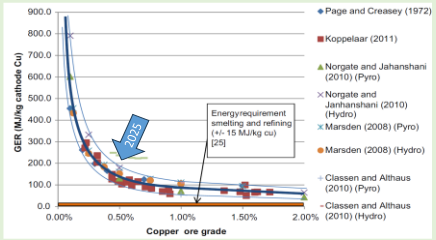
Poor

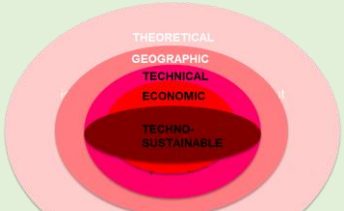
- Social im
- Δdefens
  expendi

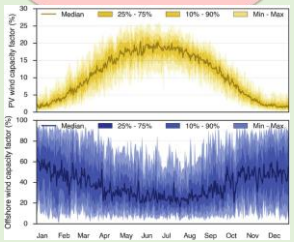
Renewable resources

- Renewable flows
- Renewable stocks

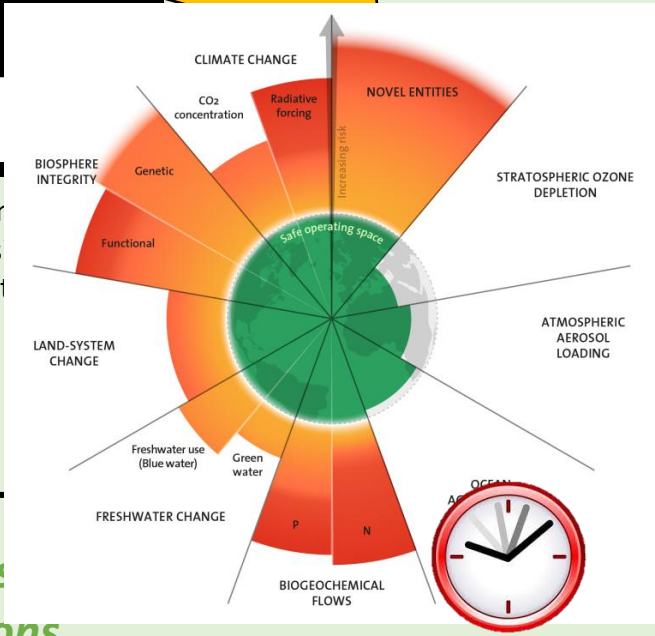
regenerate…







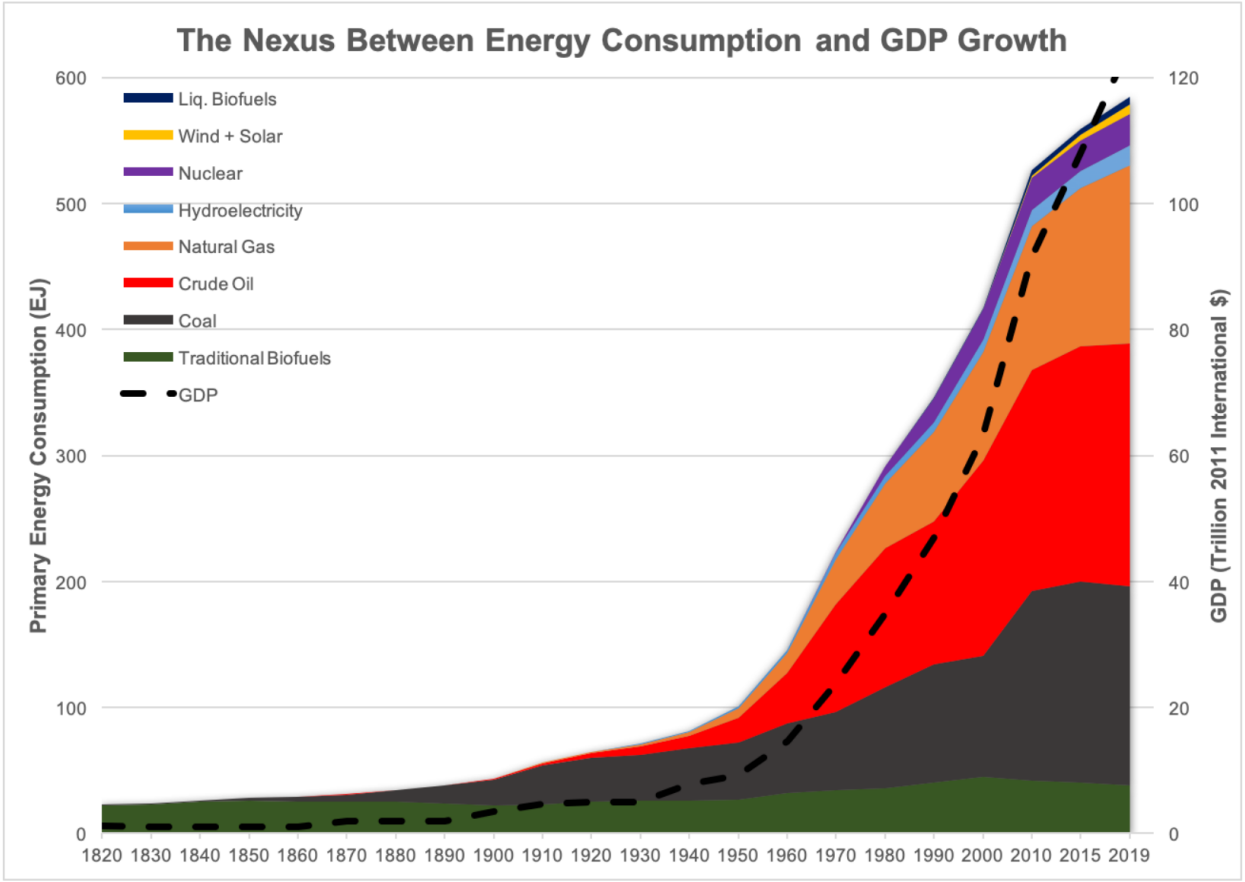




Biosphere processes

ecosystem functions

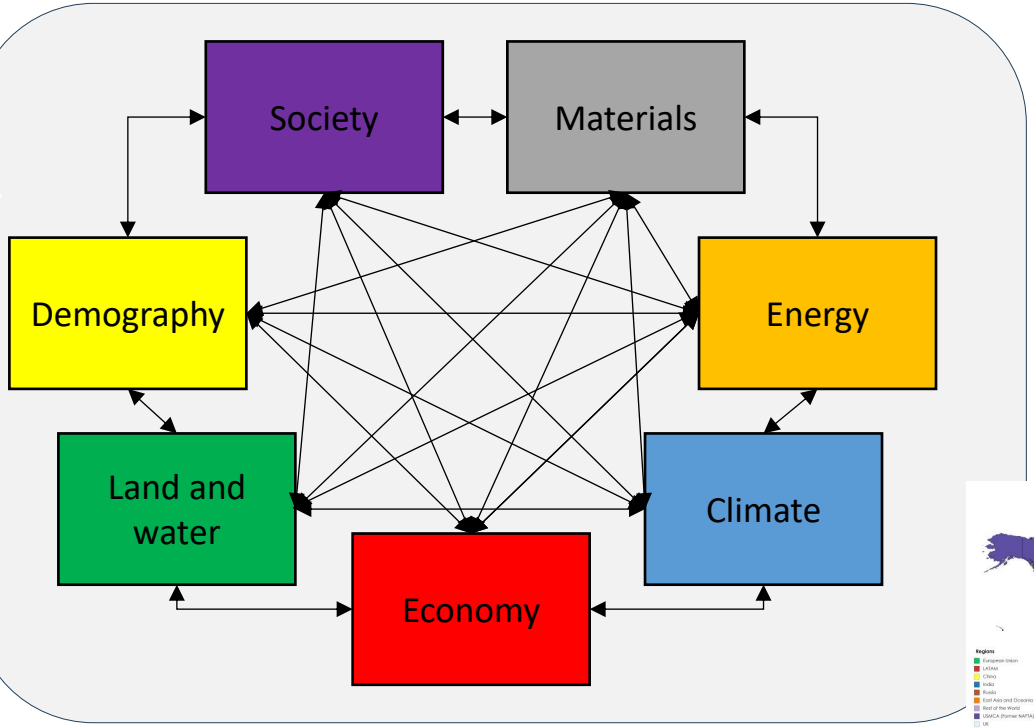
Economic growth is driven by more and higher quality energy use



Modelling & scenario framework

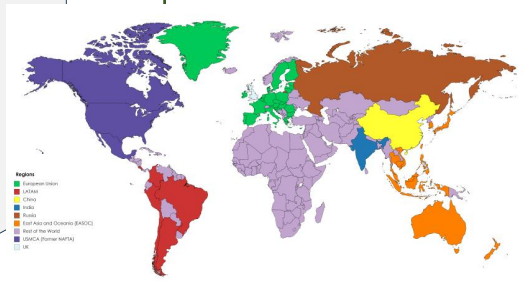
Methods: global multiregional Integrated Assessment Modelling

Socio-technical scenarios



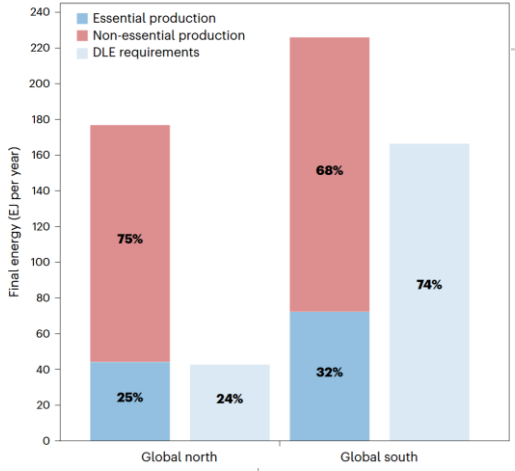
Results

Policy recommendations

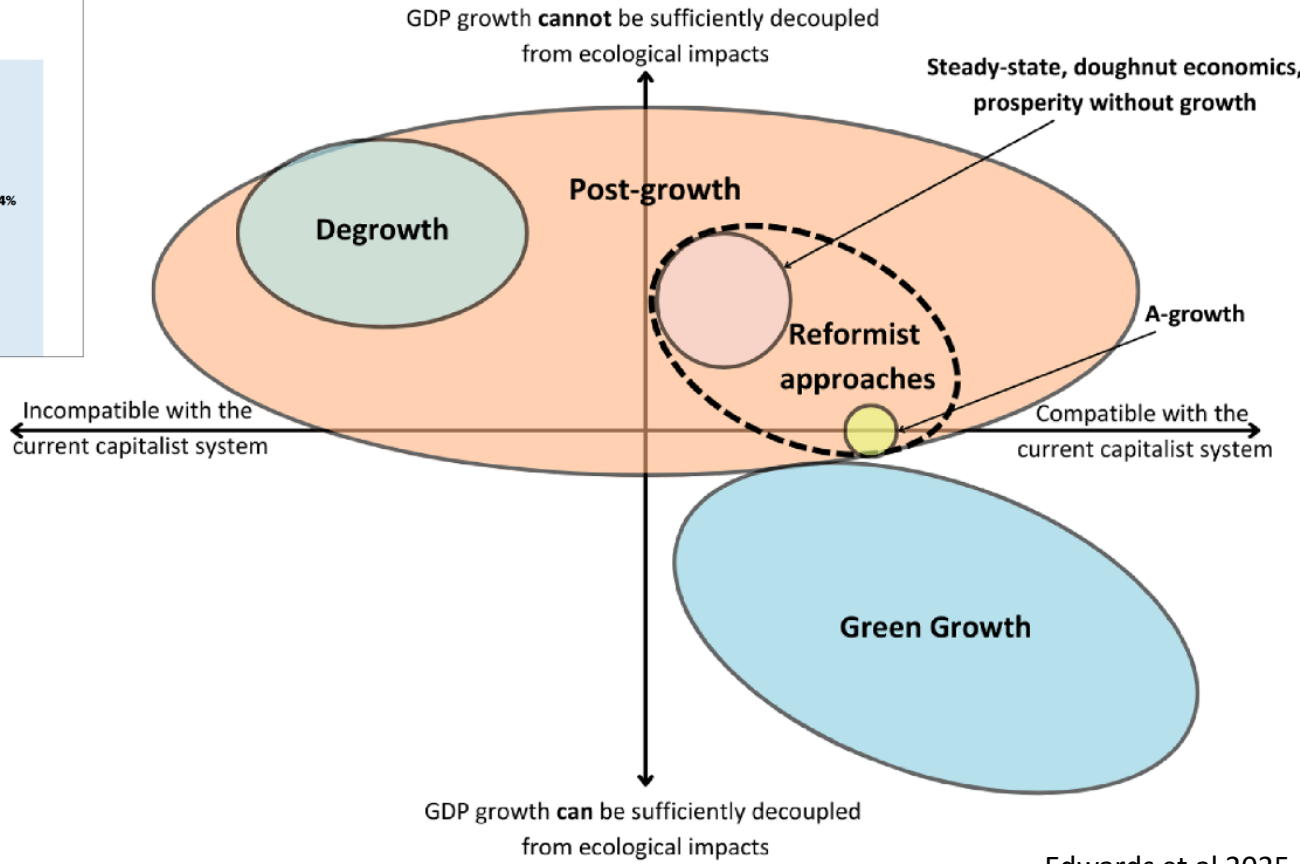


WILIAM regions

Transition narratives

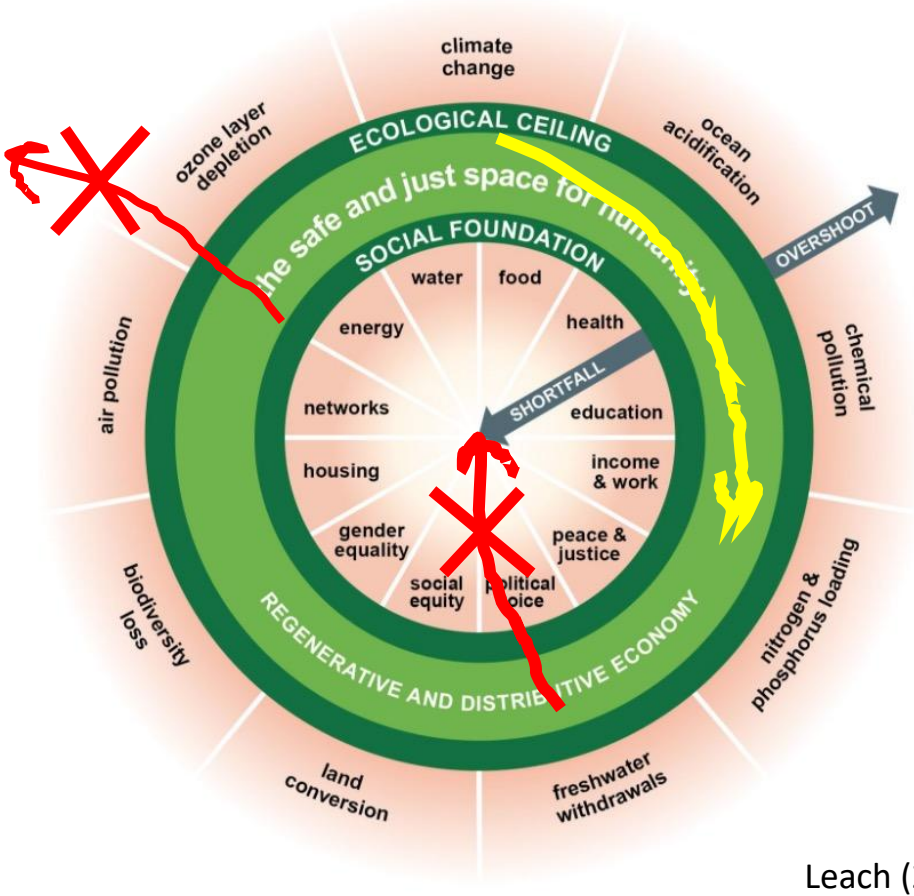


Slameršak et al 2026



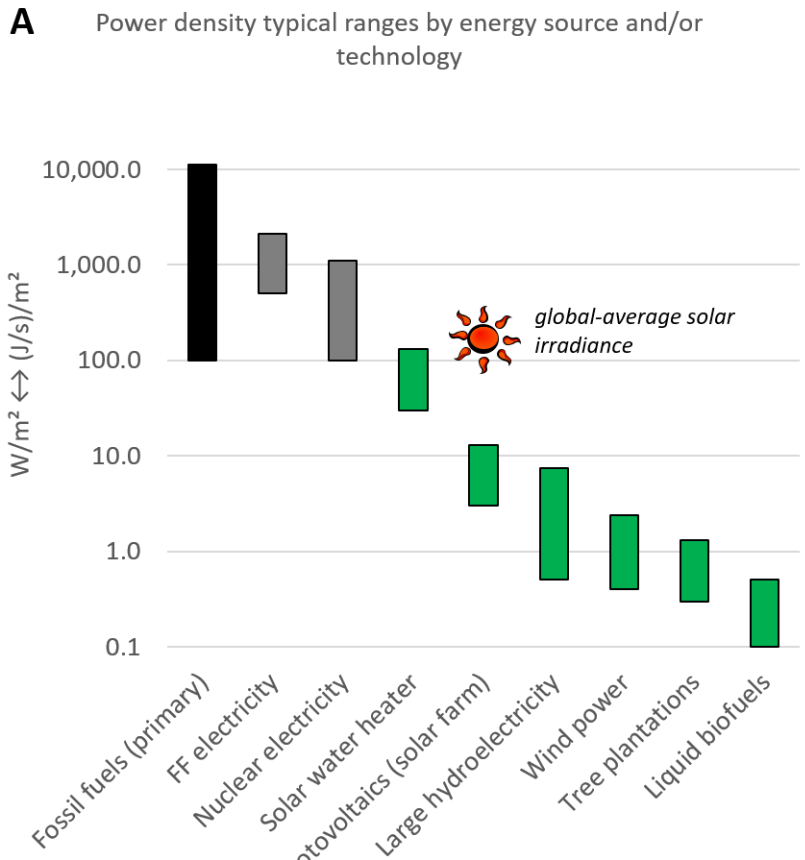
Edwards et al 2025

In the search of sustainability pathways



Leach (2013)

Power density of energy resources



- Fossils: concentrated energy
- Renewables: dispersed energy → + land!

Capellán-Pérez & de Castro (2022)

Hydropower



Xingú river; Amazonas

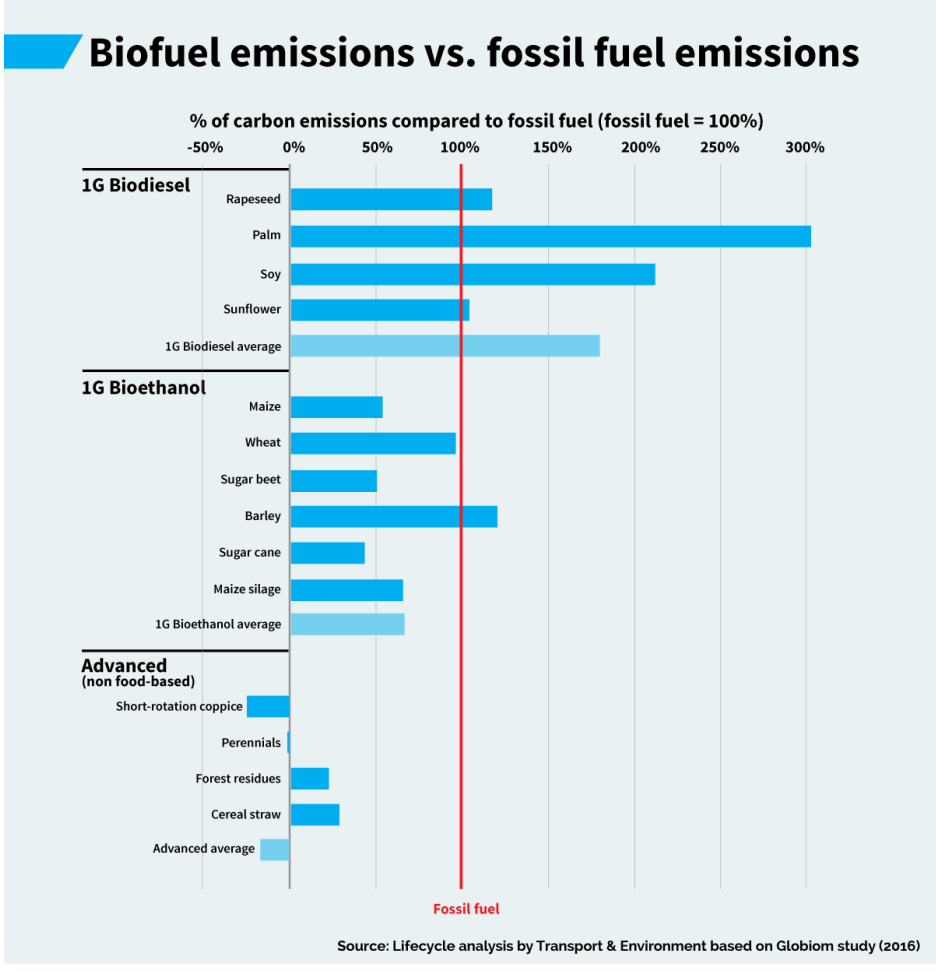
https://earthobservatory.nasa.gov/images/91083/reshaping-the-xingu-river

Biofuels



Indonesia, Palm oil

Indirect Land Use Changes (ILUC)



Land for solar

www.nature.com/scientificreports

scientific reports

Check for updates

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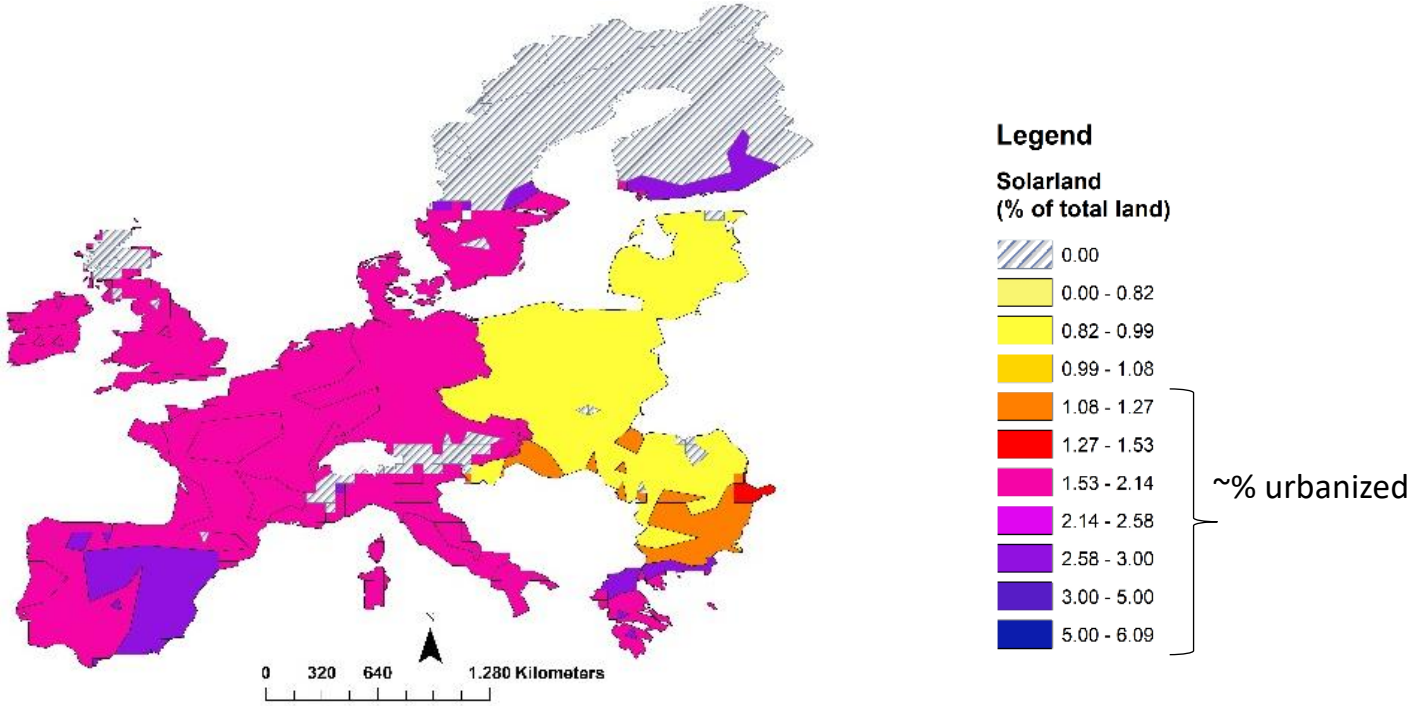
The potential land requirements and related land use change emissions of solar energy

Dirk-Jan van de Ven[1✉], Iñigo Capellan-Peréz[2], Iñaki Arto[1], Ignacio Cazcarro[1,3], Carlos de Castro[2], Pralit Patel[4] & Mikel Gonzalez-Eguino[1,5]

Although the transition to renewable energies will intensify the global competition for land, the potential impacts driven by solar energy remain unexplored. In this work, the potential solar land requirements and related land use change emissions are computed for the EU, India, Japan and South Korea. A novel method is developed within an integrated assessment model which links socioeconomic, energy, land and climate systems. At 25–80% penetration in the electricity mix of those regions by 2050, we find that solar energy may occupy 0.5–5% of total land. The resulting land cover changes, including indirect effects, will likely cause a net release of carbon ranging from 0 to 50 gCO_2/kWh, depending on the region, scale of expansion, solar technology efficiency and land management practices in solar parks. Hence, a coordinated planning and regulation of new solar energy infrastructures should be enforced to avoid a significant increase in their life cycle emissions through terrestrial carbon losses.

Land for solar

Simulation: land for solar assuming 50% penetration in the electricity mix in 2050 (after accounting for rooftop PV):



Renewable energy sprawl is already causing considerable social conflict

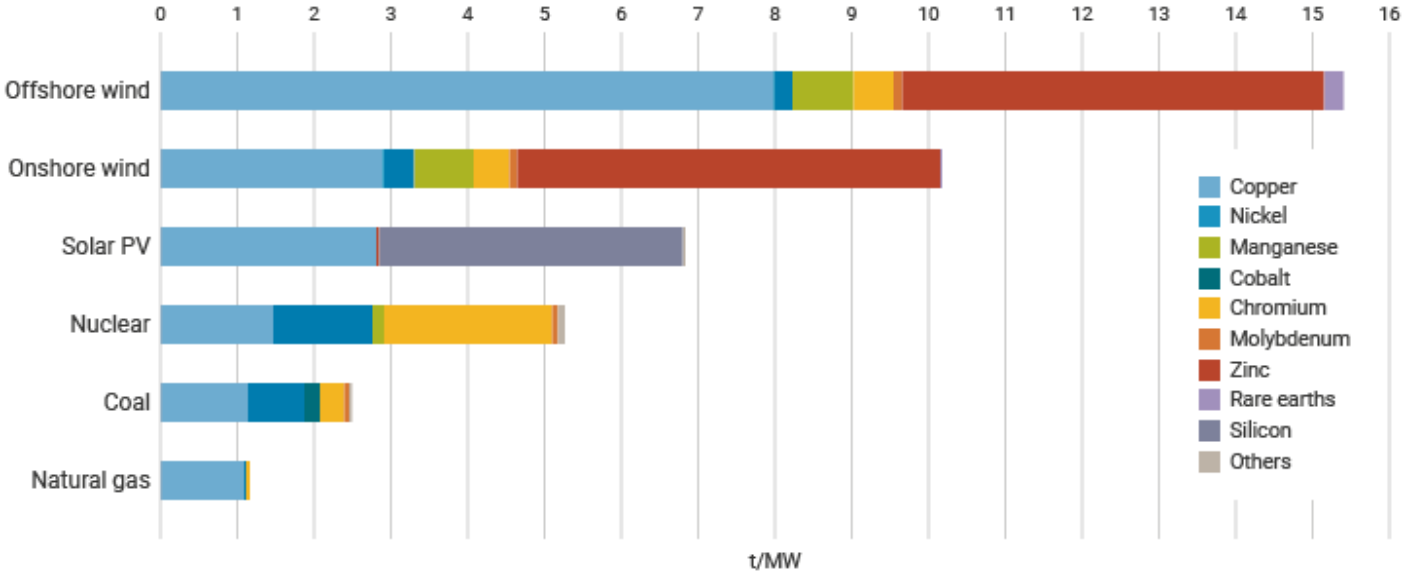


Spain

This is not biophysical determinism, but a consequence of the biophysical characteristics of renewables combined with deficient or non-existent planning.

Materials for renewables

Due to lower power density and lower capacity factors:



Critical minerals required for different generating technologies (source: IEA)

+ auxiliar infrastructure for variability management! (grids, storage, etc.)

GHG & materials of sustainable mobility

Energy Strategy Reviews 32 (2020) 100543

Contents lists available at ScienceDirect

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The limits of transport decarbonization under the current growth paradigm

Ignacio de Blas [a,b,*], Margarita Mediavilla [a,b], Iñigo Capellán-Pérez [a], Carmen Duce [a]

[a] Group of Energy, Economy and System Dynamics of the University of Valladolid (GEEDS), Valladolid, Spain
[b] Department of Systems Engineering and Automatic Control, Escuela de Ingenierías Industriales, Paseo del Cauce s/n, University of Valladolid, 47011, Valladolid, Spain

Energy & Environmental Science

ROYAL SOCIETY OF CHEMISTRY

ANALYSIS

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Cite this: DOI: 10.1039/d2ee00802e

Material and energy requirements of transport electrification†

Daniel Pulido-Sánchez, [a] Iñigo Capellán-Pérez, [*ab] Carlos de Castro [ac] and Fernando Frechoso [ad]

Global transport decarbonization pathways

OBJECTIVE: substantial global GHG reductions (-80%) in transport wihout speculative technologies and within the current level of mineral availability

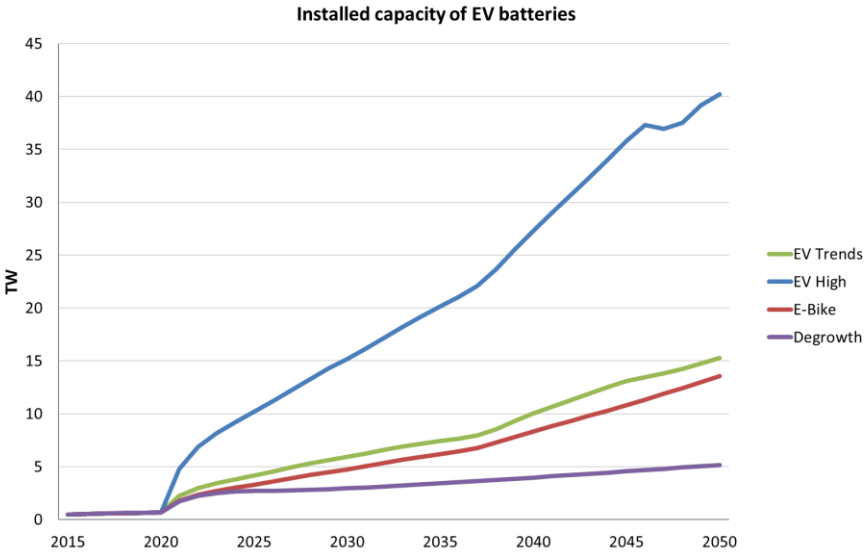
Name	Description
Expected EV trends	BAU: projection of current trends
Green Growth: EV high	Very high electrification in inland transportation
Green Growth: e-bike	**'EV high'** + shift to light electric vehicles + non-motorized modes
Degrowth	**'e-bike'** + reduction of overall transport demand, especially for air transport.

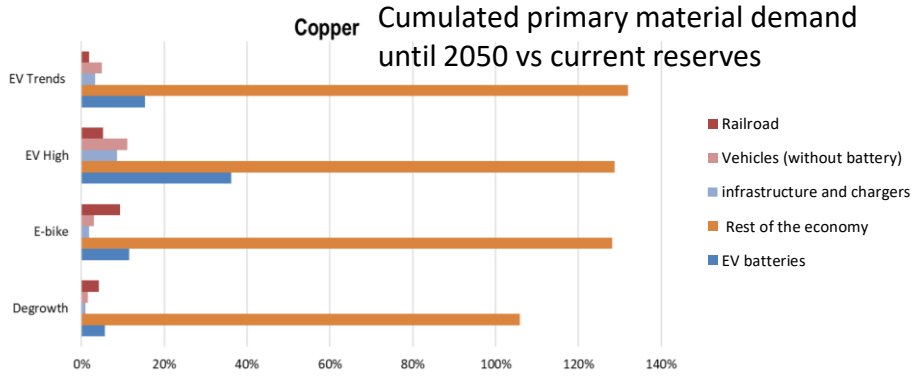
No improvement in recycling rates of minerals

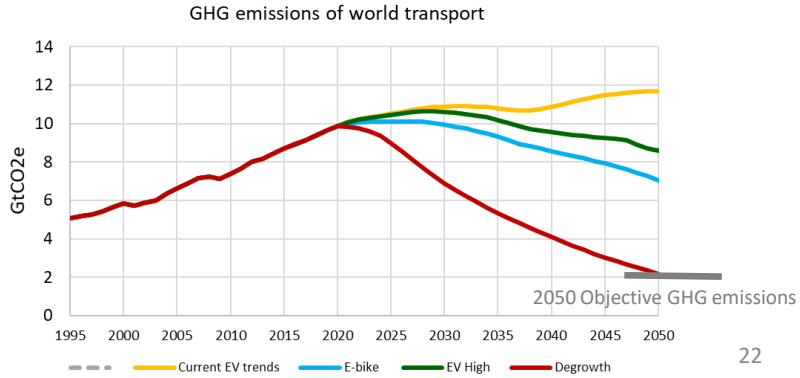
Improvement in (end of life, EOL) recycling rates of minerals

Results

- Lower demand & change of provisioning system → - environmental pressures
- Growth hinders the scale of recycling
- Issues with Li, Mn, Ni, Cu, Co, graphite
- Degrowth puts less pressure, but still surpasses reserves by 2050







22

Energy Return on Energy Investment (EROI)

Energy Return on Energy Invested:

$$EROI = \frac{Gross\ energy\ returned}{energy\ invested}$$

- If societal EROI < 1:1 -> collapse
- To be functional: societal EROI >> 1:1

Results - ¿metabolic implications?

Energy Strategy Reviews 26 (2019) 100399

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Dynamic Energy Return on Energy Investment (EROI) and material requirements in scenarios of global transition to renewable energies

Iñigo Capellán-Pérez[a,b,*], Carlos de Castro[a,c], Luis Javier Miguel González[a,b]

[a] Research Group on Energy, Economy and System Dynamics, Escuela de Ingenierías Industriales, Paseo del Cauce s/n, University of Valladolid, 47011 Valladolid, Spain
[b] Deparment of Systems Engineering and Automatic Control, Escuela de Ingenierías Industriales, Paseo del Cauce s/n, University of Valladolid, 47011 Valladolid, Spain
[c] Deparment of Applied Physics, Escuela de Arquitectura, Av Salamanca, 18, University of Valladolid, 47014, Valladolid, Spain

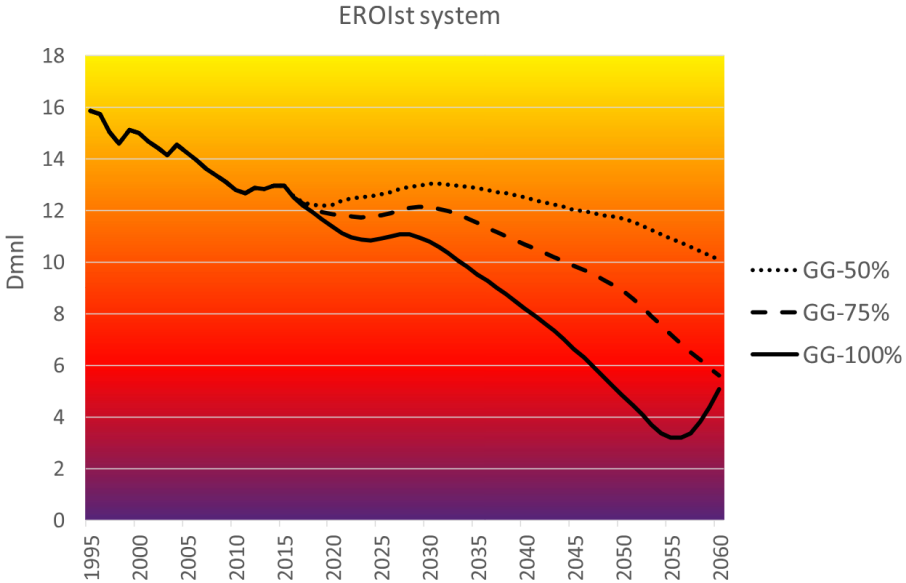
ARTICLE INFO

Keywords:
Energy return on energy investment
Transition to renewable energies
Energy trap
Green growth
Integrated assessment modelling

ABSTRACT

A novel methodology is developed to dynamically assess the energy and material investments required over time to achieve the transition from fossil fuels to renewable energy sources in the electricity sector. The obtained results indicate that a fast transition achieving a 100% renewable electric system globally by 2060 consistent with the *Green Growth* narrative could decrease the EROI of the energy system from current ~12:1 to ~3:1 by the mid-century, stabilizing thereafter at ~5:1. These EROI levels are well below the thresholds identified in the literature required to sustain industrial complex societies. Moreover, this transition could drive a substantial re-materialization of the economy, exacerbating risk availability in the future for some minerals. Hence, the results obtained put into question the consistence and viability of the *Green Growth* narrative.

3 global Green Growth scenarios of transition to RES



- Addressing also hard-to-abate sector worsens the net energy assessment
- High sensitivity to overall demand and renewable variability management

Conclusions

1. **Economic growth and competitiveness** are driven by more and better-quality energy use, and rely on a healthy environment
2. Transition to **renewable**s is urgent and unavoidable:
   - Leaving out land, materials and energy return on investment lead to overestimate what renewables can deliver
   - "Time" trade-offs: speed of transition vs net energy returns vs democratic decisions vs time for putting in place the new system.
3. **Growth scenarios** worsen these dynamics and limits:
   - Higher scale of natural resources requirements
   - Rebound effects
4. **Post/De-growth scenarios** help reducing impacts and attaining goals:
   - Lower energy demand is a core part of the pathway
   - How the transition is designed socially matters as much as its technology.
5. Biophysical characteristics of renewables **do not determine what can be achieved; they condition it.** Transition to renewables represent an **opportunity of transformation**!

Thank you!

Iñigo Capellán Pérez

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www.geeds.eu

References

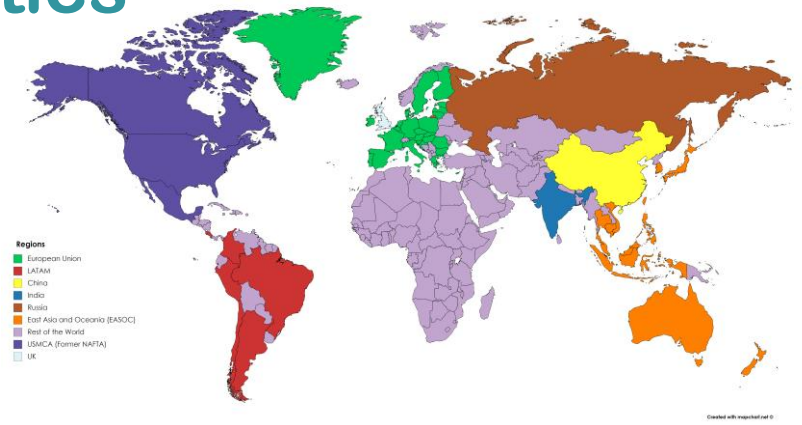
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- WILIAM 1.4. *WILIAM 1.4 Model Wiki*. 2025. https://github.com/LOCOMOTION-h2020/WILIAM_model_VENSIM/wiki.

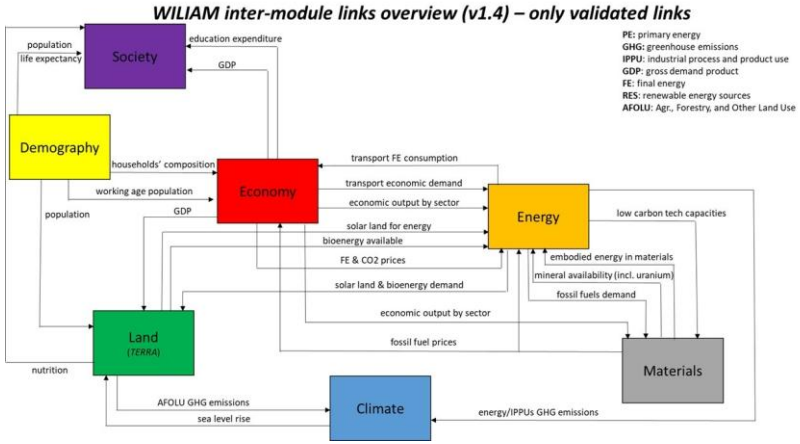
Supporting slides

WILIAM – General characteristics

- Time resolution: 1 year
- Time horizon: 2050-2100
- Baseline/historic period: 2005-2015/2020
- Global multiregional (8 global regions + EU27 / 27 EU MS)
- Methods:
  - Combination of complex systems (System Dynamics) with Input-Output análisis, LCAs, econometric analysis, etc.
  - Consistency between monetary and physical dimensions
- Policy-simulation
- Very large size (>7000 symbols; millions of equations, ~700Mb)
- Modular structure
  - Coordinated and distrubuted programming (github)
  - Validation
- Open source GitHub https://github.com/LOCOMOTION-h2020/WILIAM_model_VENSIM
- Accesible documentation (wiki)
- BETA (very advanced) versión
- Collaborative development financed through EU projects, PhDs, permanent/self-financed researchers, etc.



WILIAM regions. For some modules, the EU27 is further disaggregated by member state.



Results - ¿metabolic implications?

Expansion of policies to hard-to-abate sectors with H2 and H2-fuels:

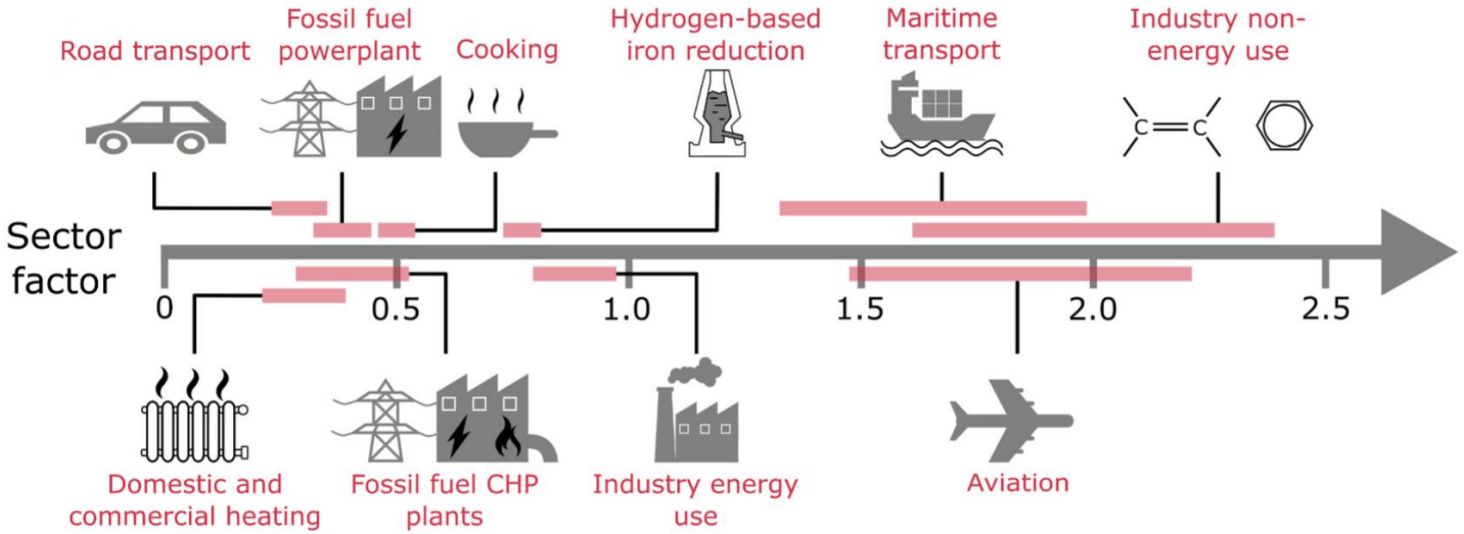
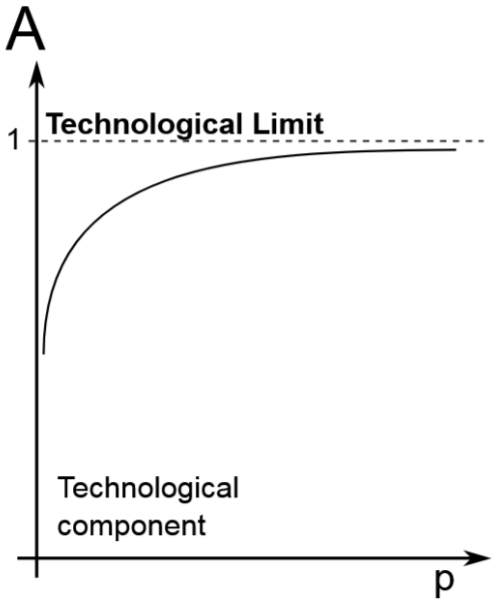


Fig. 3. | Summary of the sector factors calculated. Sectors on the left have lower sector factors, meaning less electricity is required to substitute a unit of fossil fuel in this sector, while sectors on the right have higher sector factors. The shaded bars represent the likely range (3 standard deviations) of the values given current estimates, and the maturity of the technology used. Marine transport, aviation and industry non-energy use (i.e., energy carriers that are used as raw materials in production processes, for example chemical feedstock for plastics, lubricants, or asphalt) are based on the least mature technologies and hence have the largest uncertainties and ranges. All values and sources used are available in Supplementary note 2.

Legendre et al (2026)

Innovation vs thermodynamics

Quality of resource (t)



Dale, Michael, Susan Krumdieck, and Pat Bodger. "A Dynamic Function for Energy Return on Investment." *Sustainability* 3, no. 10 (2011): 1972–85. https://doi.org/10.3390/su3101972.

Limits to techn improvements (1)

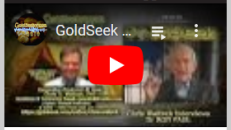


Limits to recycling

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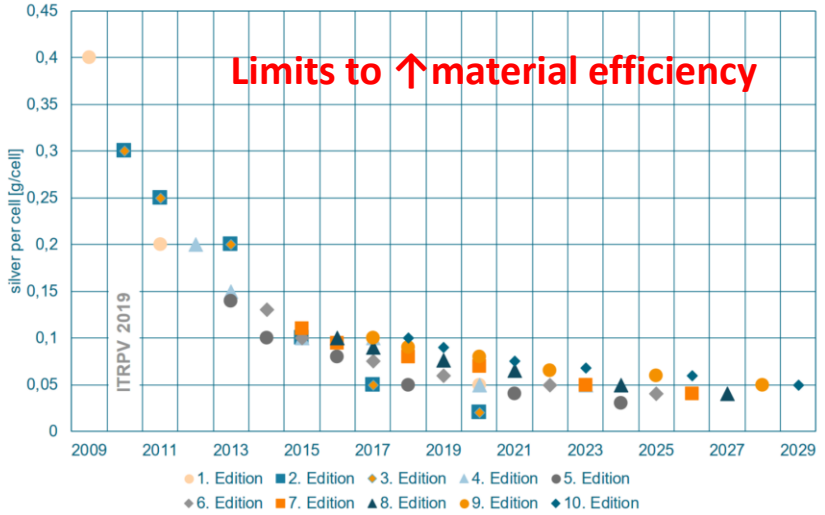
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4. Lifespan of 20 years

Shifting material criticalities

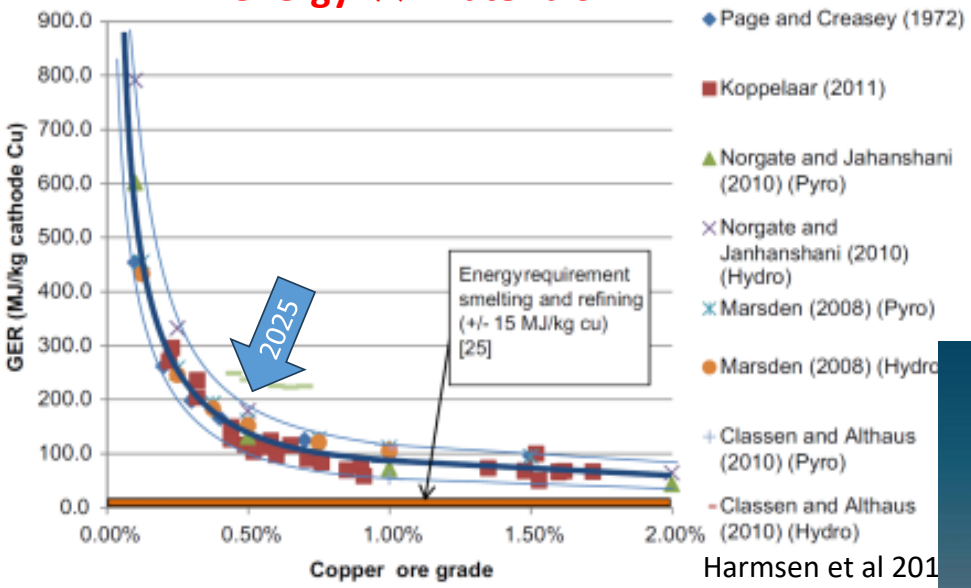
Review ITRPV predictions

Silver amount per cell



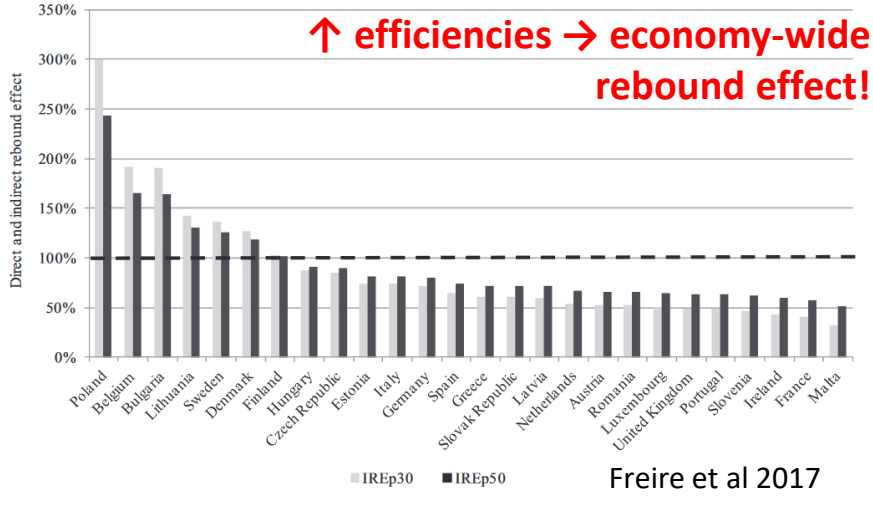
Limits to techn improvements (2)

energy ↔ materials

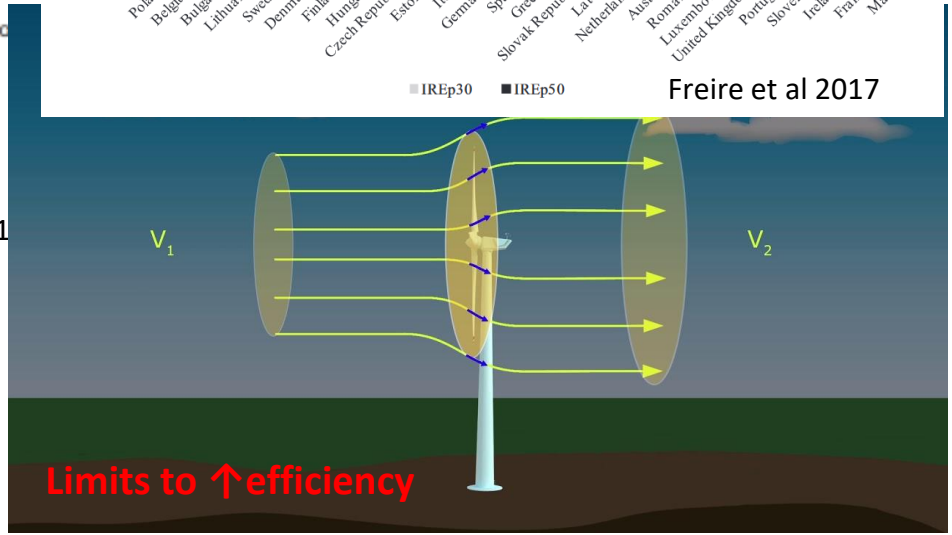


Harmsen et al 201

↑ efficiencies → economy-wide rebound effect!



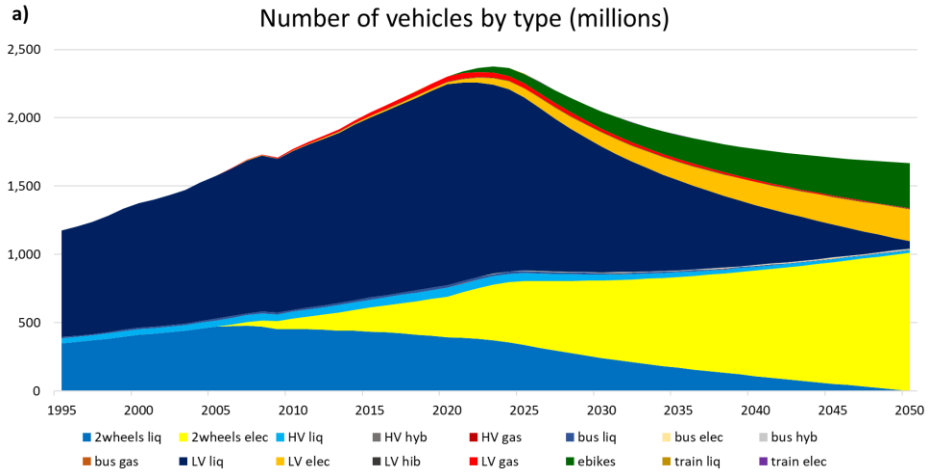
Freire et al 2017

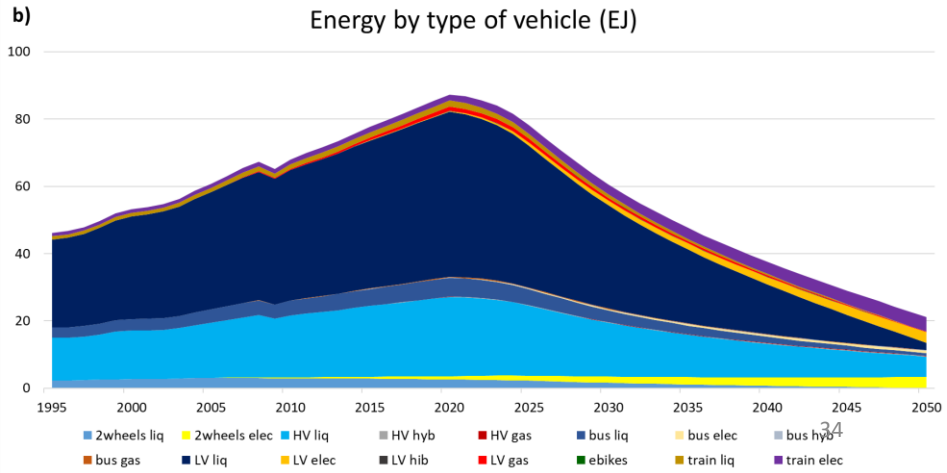


Results for the Degrowth scenario

Degrowth scenario is the one reaching the targets of:

- -80% GHG by 2050
- Avoiding energy shortages
- Minimizing mineral scarcities





de Blas, I., Mediavilla, M., Capellán-Pérez, I., Duce, C., 2020. The limits of transport decarbonization under the current growth paradigm. Energy Strategy Reviews 32, 100543. https://doi.org/10.1016/j.esr.2020.100543