UNEP

International Resource Panel

SUMMARY FOR POLICY MAKERS

GREEN ENERGY CHOICES:

The Benefits, Risks and Trade-Offs of Low-Carbon Technologies for Electricity Production

Lead authors:
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Online-seminar: "*Identifying aspects and relevance of the climate-resource-nexus*"
Interactions between international measures for Climate Action and Resource Efficiency (ICARE)
29 September 2020

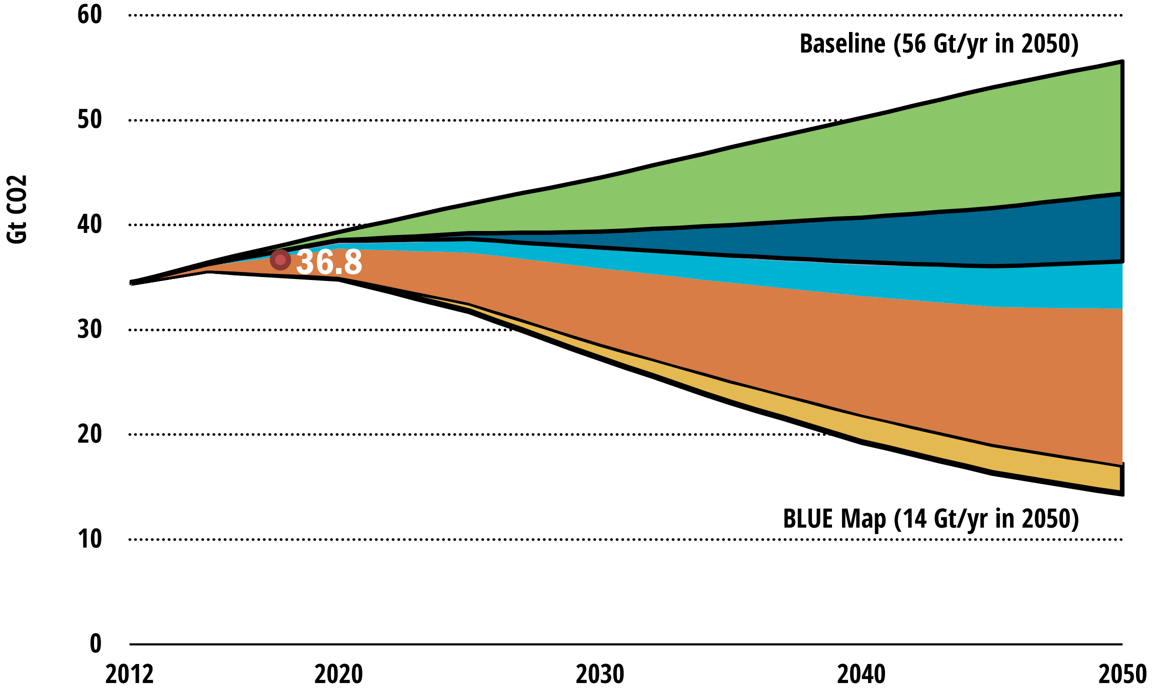
This research work was carried out at
NTNU
Norwegian University of Science and Technology

www.unep.org/resourcepanel

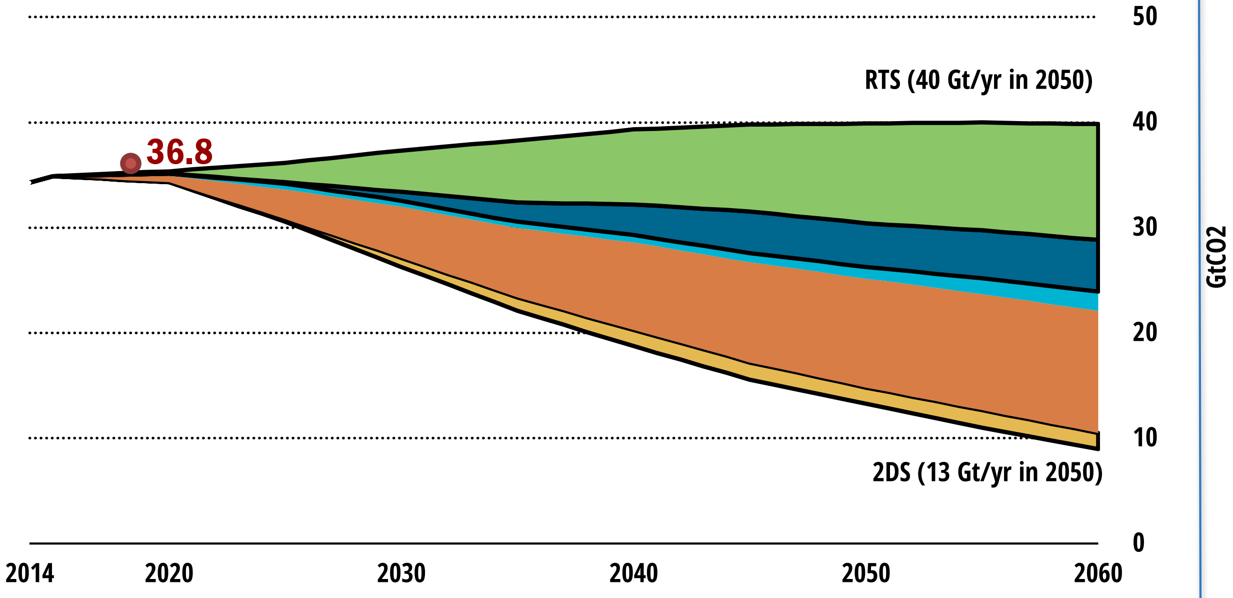
Context

Mitigation of greenhouse gas emissions globally

Baseline (4DS) to BLUE Map (2DS) [IEA 2016]



Reference Technology Scenario* (4DS) to 2DS [IEA 2017]



- Renewables 30% (35%)
- Power generation efficiency and fuel switching 1%
- End-use fuel and electricity efficiency 38% (40%)
- CCS 13% (14%)
- End-use fuel switching 10% (5%)
- Nuclear 8% (6%)

RTS takes into account existing energy- and climate-related commitments by countries, including Nationally Determined Contributions pledged under the Paris Agreement.

International Energy Agency (2016) Energy Technology Perspectives 2016 – Towards Sustainable Urban Energy Systems

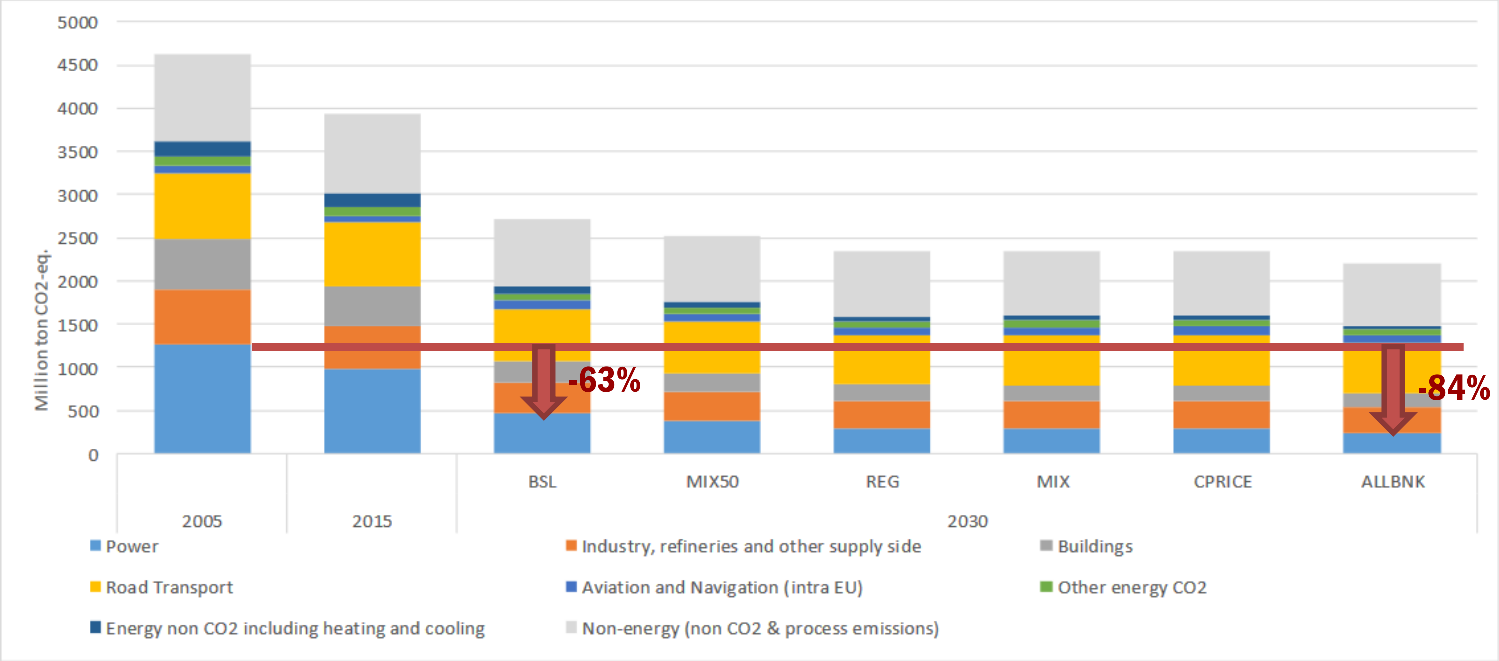
International Energy Agency (2017) Energy Technology. Perspectives 2017 – Catalysing Energy Technology Transformations

Context

At the European level

Power is the key sector to decarbonize in Europe to reach the 2030 55% target

Figure 4: Sectoral GHG reductions, focus on energy system emissions



Source: PRIMES model, GAINS model

"Stepping up Europe's 2030 climate ambition", published 17.09.2020 https://ec.europa.eu/clima/sites/clima/files/eu-climate-action/docs/impact_en.pdf

Greenhouse gas emissions of electricity technologies (1/2)

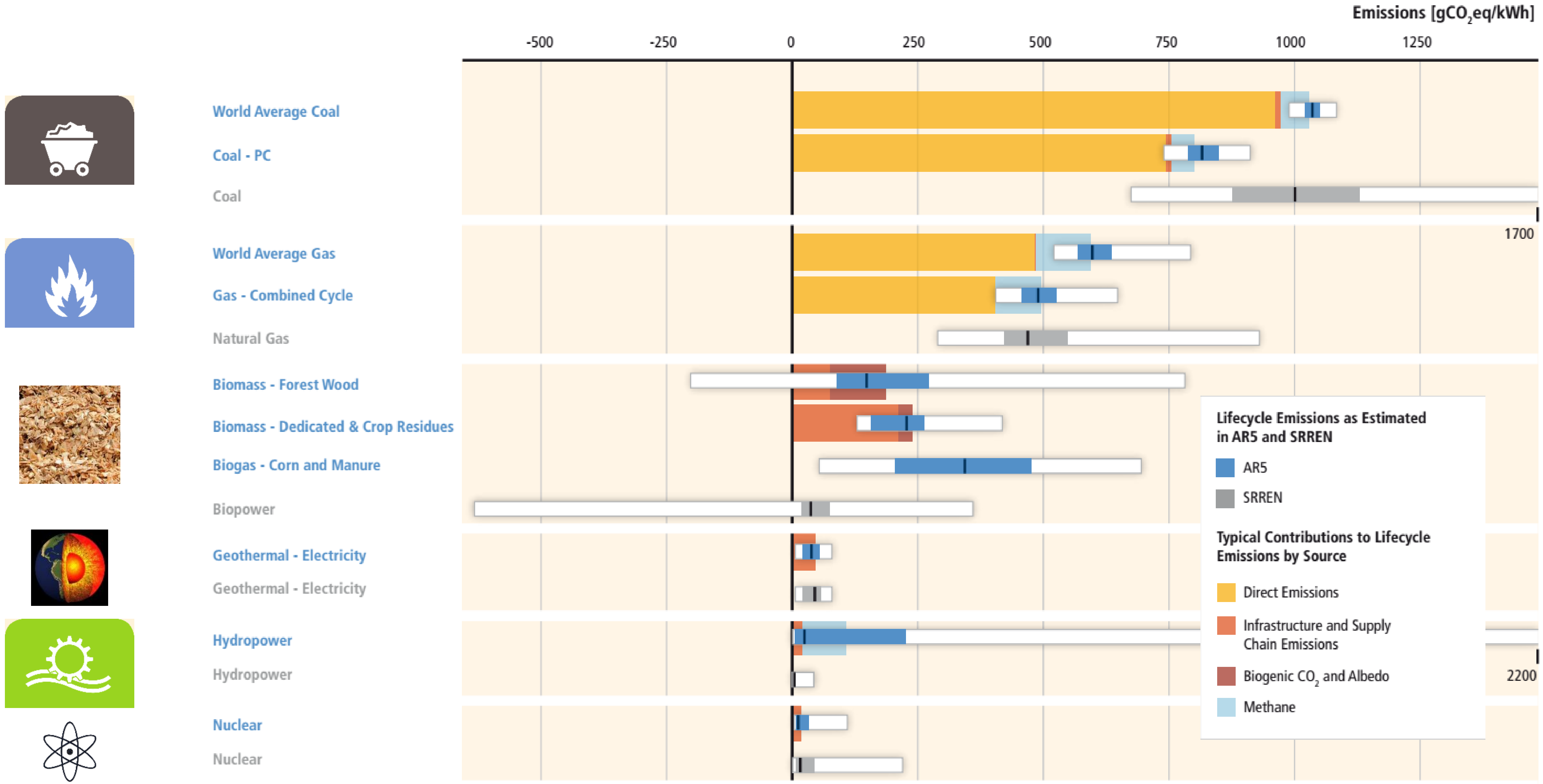


Fig. 7.6, IPCC WGIII AR5

Greenhouse gas emissions of electricity technologies (2/2)

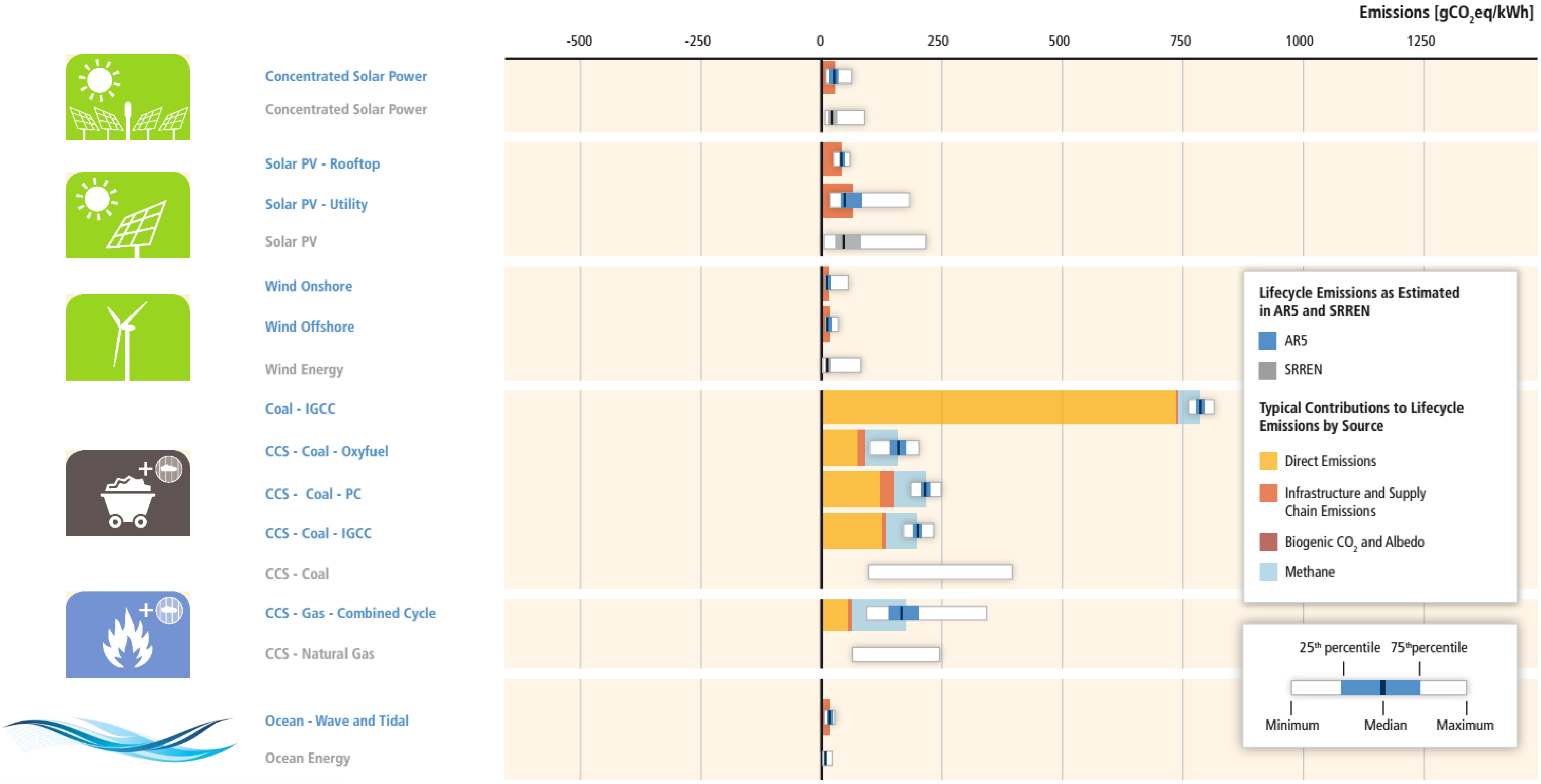


Fig. 7.6, IPCC WGIII AR5

Context

The question of co-benefits

- Climate change mitigation strategies have consequences **over the whole environmental (and more) spectrum**

- In policy design it is key, through a comprehensive "due diligence" exercise, to identify
  - …the **trade-offs**, impacts that will increase by adopting the strategies
  - …the **co-benefits**, impacts that will decrease together with greenhouse gas emissions, and other kinds of benefits

Watts, N., Adger, W. N., Agnolucci, P., Blackstock, J., Byass, P., Cai, W., ... & Cox, P. M. (2015). Health and climate change: policy responses to protect public health. The Lancet.

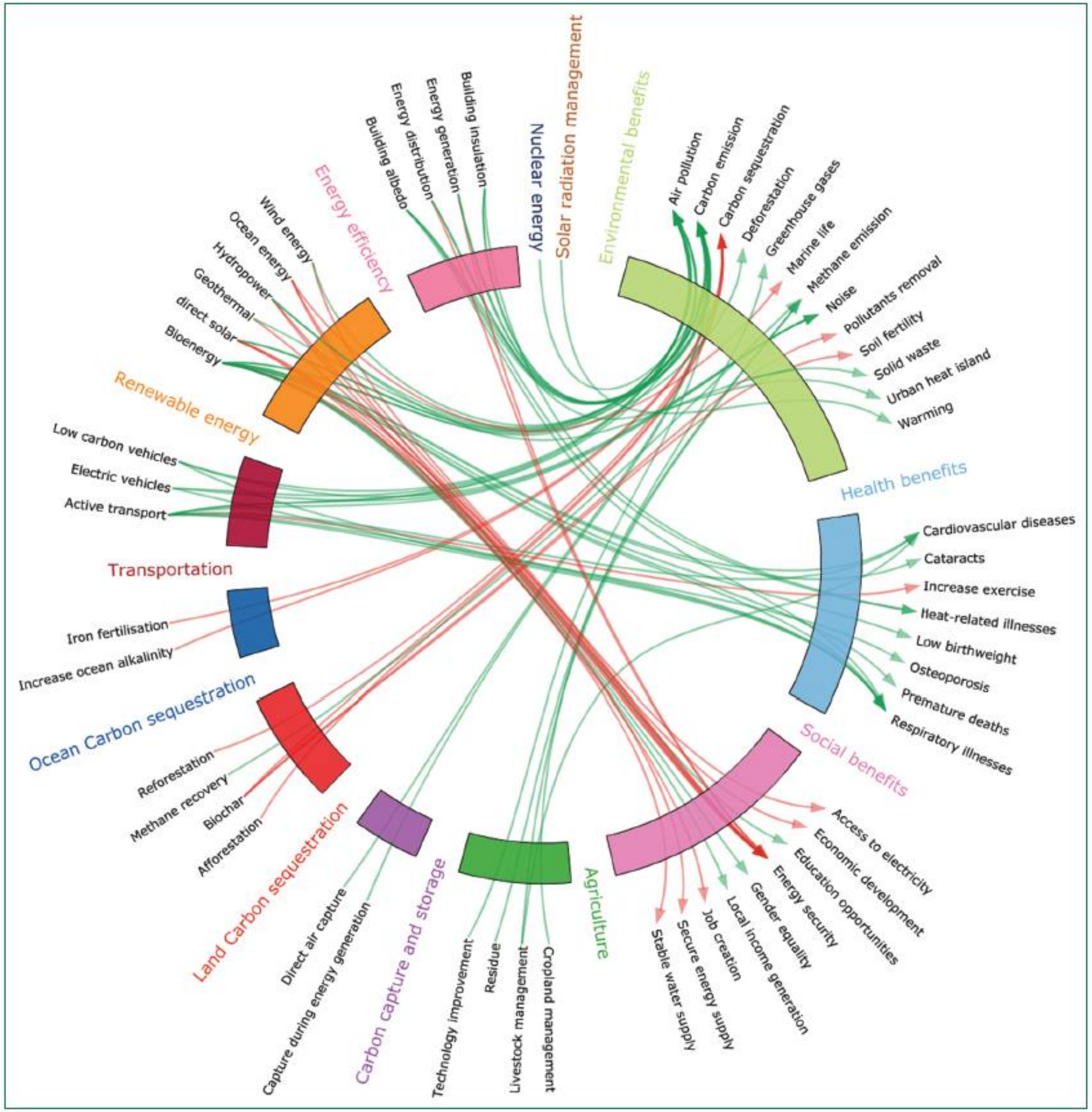


Figure 11: Frequently cited co-benefits of major mitigation techniques
Red arrows between a mitigation technology and an effect indicate that the technology will increase the effect; green arrows indicate an opposite trend.

Assessment approach, and method

Life cycle assessment

Nine **electricity technologies**

- Coal and…
- …gas with and without CO_2 capture and storage (CCS),
- Photovoltaic power,
- Concentrated solar power,
- Hydropower,
- Geothermal,
- Wind power,
- **+ Nuclear,**
- **+ Biopower.**

Impact categories

- **Damage on human health**
  particulate matter,
  human toxicity…
  Damage on ecosystems
  - ecotoxicity,
  - eutrophication,
  - acidification…
- **Resource use**
  - iron, copper, aluminium, cement,
  - energy, water and land

Life cycle perspective

- Extraction of raw materials,
- Fuel supply chain,
- Production of power plants,
- Transportation
- Operation,
- Maintenance,
- Decommissioning.

What are the environmental, health and resource use implications of a massive expansion of low-carbon electricity?

A 5MW offshore wind turbine requires 1200 tons of steel

350 000 such wind turbines would be required to provide **12%** electricity in 2050

Technology summary

Wind power

©Jeff Adkins

Key (##)

First symbol

(+) high agreement among studies (=) moderate agreement (-) low agreement

Second symbol

(+) robust evidence (many studies) (=) medium evidence (-) limited evidence

Climate change

- Very low GHG emissions **(++)**

Human Health

- Reduced exposure to particulate matter **(++)**
- Reduced human toxicity **(--)**

Ecosystems

- Collision fatalities of birds and bats **(+=)**
- Reduced ecotoxicity and eutrophication **(=-)**

Resources

- Increased consumption of bulk metals **(+=)**
- Low water use **(==)**
- Low direct land use **(==)**

Technology summary

Solar photovoltaics

©ElenaElisseeva/Shutterstock

Key (##)

First symbol

(+) high agreement among studies (=) moderate agreement (-) low agreement

Second symbol

(+) robust evidence (many studies) (=) medium evidence (-) limited evidence

Climate change

- Low carbon **(==)**

Human health

- Low particulate matter emissions **(+=)**
- Low human toxicity (**if proper recycling**, =-)

Ecosystem health

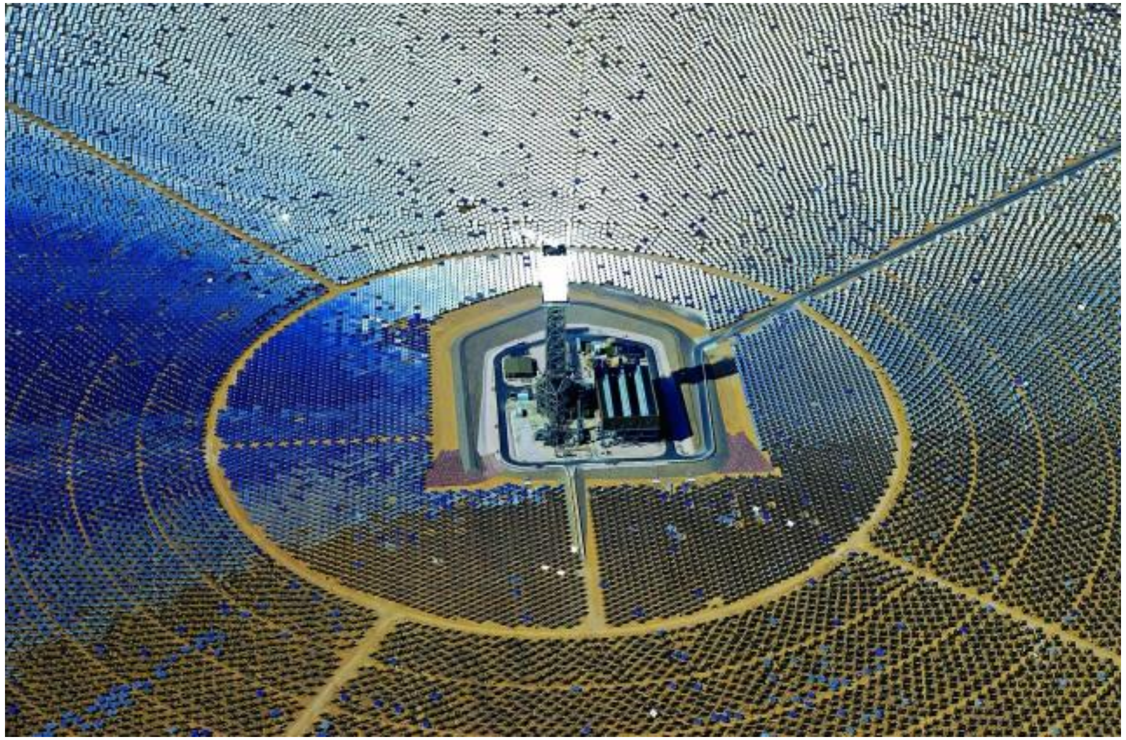
- Low eutrophication and ecotoxicity **(+-)**

Resources

- High metal use (balance of system, module, **+=**)
- High direct land use for ground-based systems **(++)**

Technology summary

Concentrating solar power



©Ethan Miller/Getty Images

Key (##)

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Second symbol

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Climate Change

- Low GHG emissions (==)

Human Health

- Low particular matter exposure (+=)
- Low human toxicity (=-)

Ecosystems

- Potential toxicity of heat transfer fluids (+=)
- Low ecotoxicity and eutrophication (+-)

Resources

- High water consumption, unless air cooled (++)
- High land use (++)
- High cement use (power tower, +-)

Technology summary

Hydropower

Key (##)

First symbol

(+) high agreement among studies (=) moderate agreement (-) low agreement

Second symbol

(+) robust evidence (many studies) (=) medium evidence (-) limited evidence

Climate change

- Low **fossil** carbon **(++)**
- High biogenic carbon from tropical dams **(==)**

Human health

- Low air pollution impacts **(=-)**
- Population displacement **(+-)**

Ecosystem health

- Riparian habitat change **(++)**

Resources

- Water use (evaporation, **+-**)
- High land use for reservoirs **(+=)**
- High cement use (**+-**)

Technology summary

Coal and natural gas power, with CO_2 capture and storage

©Reuters

Key (##)

First symbol

(+) high agreement among studies (=) moderate agreement (-) low agreement

Second symbol

(+) robust evidence (many studies) (=) medium evidence (-) limited evidence

Climate change

- Low GHG **(++)**
- Substantial fugitive methane emissions **(==)**
- Concern about CO_2 leakage **(-=)**

Human health

- Solvent related emissions **(==)**
- High particulate matter **(==)**
- High human toxicity **(=-)**

Ecosystem health

- High eutrophication (mining, ++)
- Ecotoxicity **(+=)**

Resources

- Increased fossil fuel consumption **(++)**
- Limited CO2 storage **(++)**

Comparative results

Climate

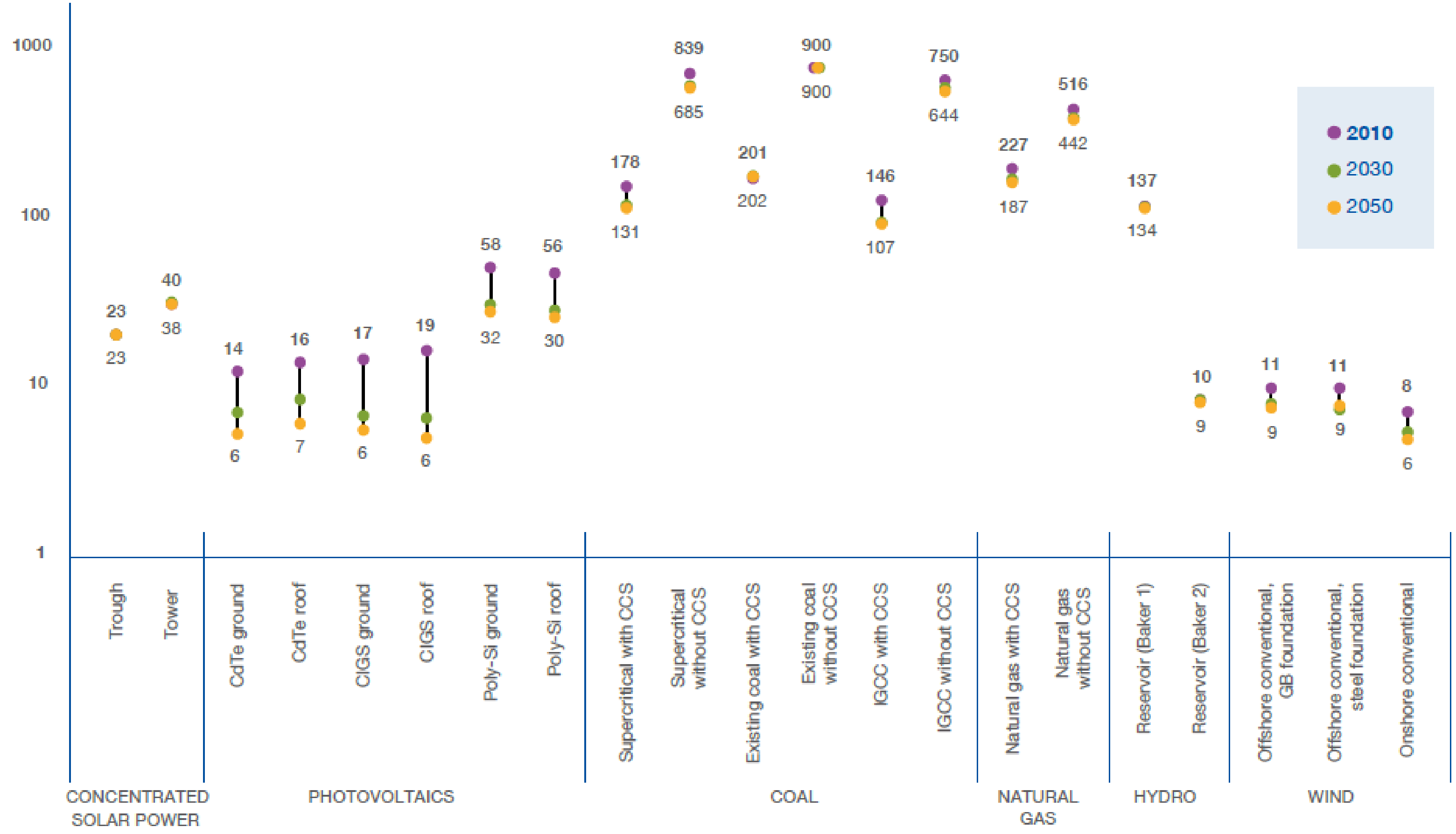
Logarithmic y-axis!

"2030" and "2050" include economy-wide changes (decarbonization, energy efficiency) following the IEA BLUE Map (2°C) scenario

Highlights

- CCS does not remove all lifecycle emissions
- Wide variability of hydropower (each reservoir is unique)
- Future emissions per kWh decrease because of technology improvements but also decarbonization of the economy

Figure 1: Life-cycle GHG emissions of different energy technologies, in gCO2e/kWh, reflecting application of the technology in Europe [12].
The numbers for future years reflect a reduction of emissions expected due to technical progress and the reduced emissions in the production of equipment following the implementation of a mitigation scenario.



Comparative results

Resources (materials and non-renewable primary energy)

Linear y-axis

Left: Bulk material demand

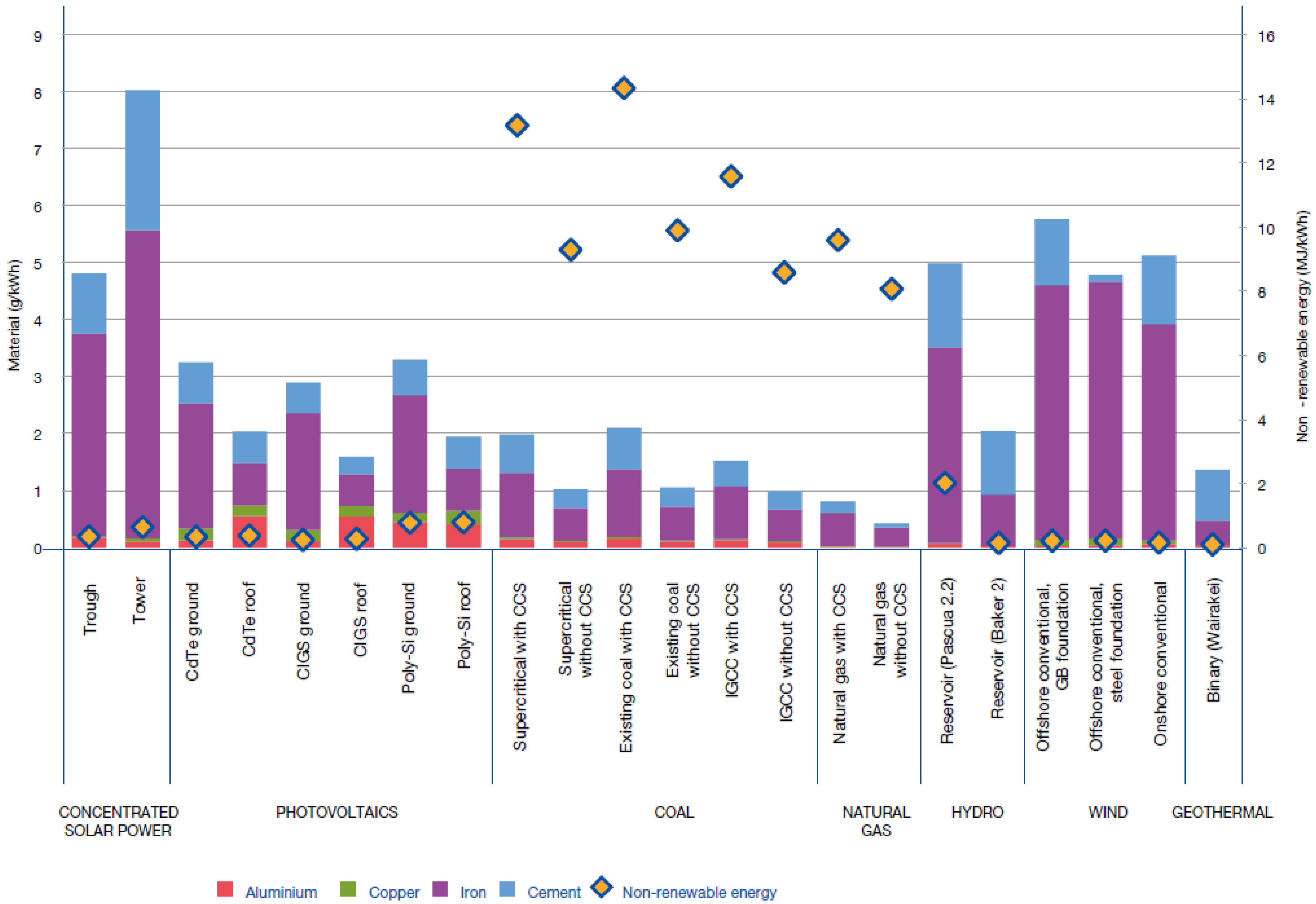
Right: CED (cumulative energy demand)

quantifies the amount of primary (non-renewable) energy extracted from nature per unit of output

~ non-ren. energy efficiency of the whole conversion system

Figure 5: Bulk material and non-renewable energy requirements per unit power produced.[28]

Fossil technologies have high cumulative non-renewable energy demand (CED) and low bulk material requirements.



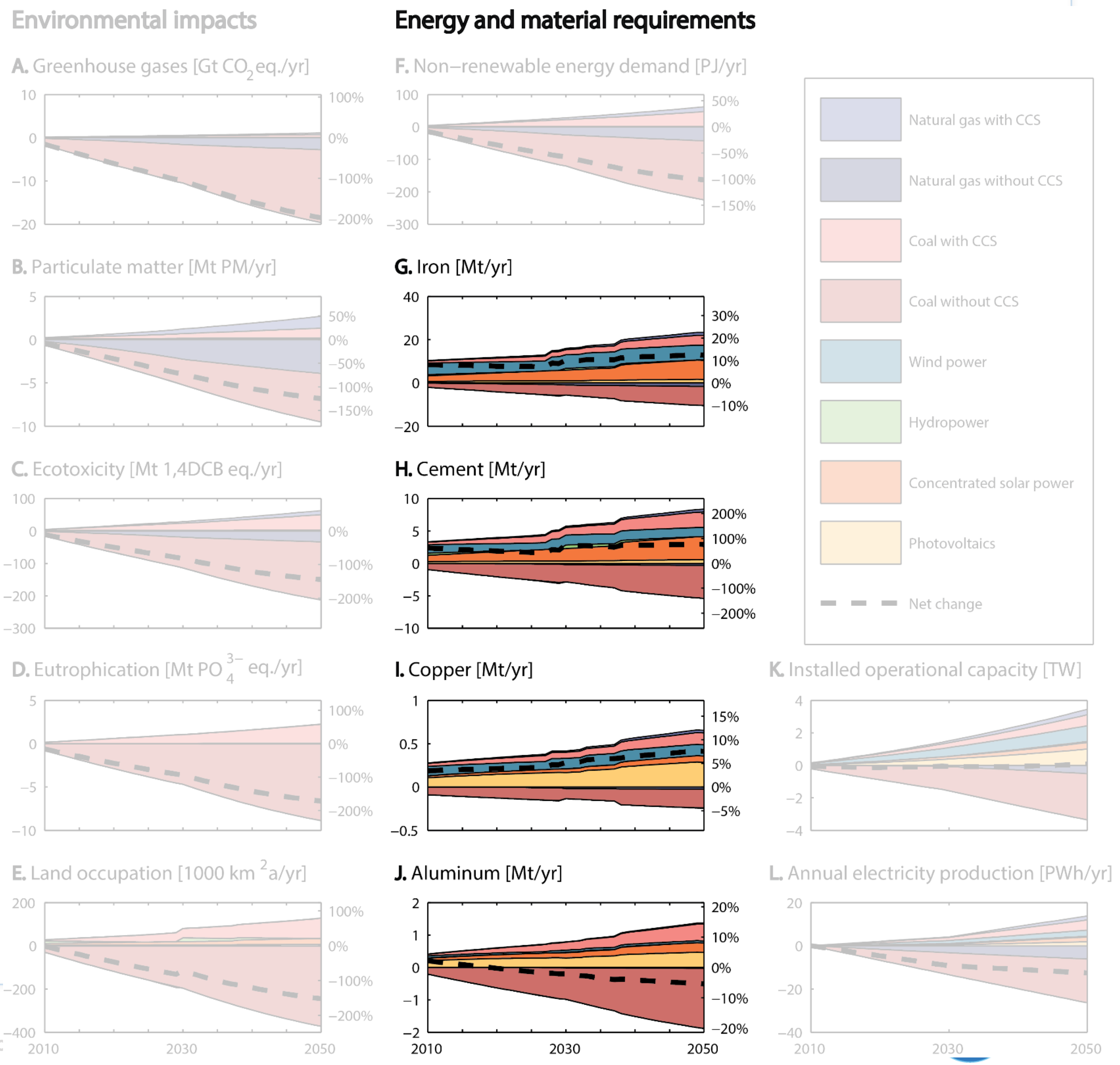
Scenario comparison

Assessing global pathways

Environmental and resource implications of electricity generation following the IEA BLUE Map scenario instead of the IEA Baseline scenario, addressing impacts from the indicated power sources

Left = absolute values

Right = % variation from 2007



Coal phaseout is a priority – multiple co-benefits

Material requirements are a clear trade-off

Hertwich EG, Gibon T, Bouman EA, et al (2015) Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. Proc Natl Acad Sci U S A 112:6277–82

More scenario comparison!

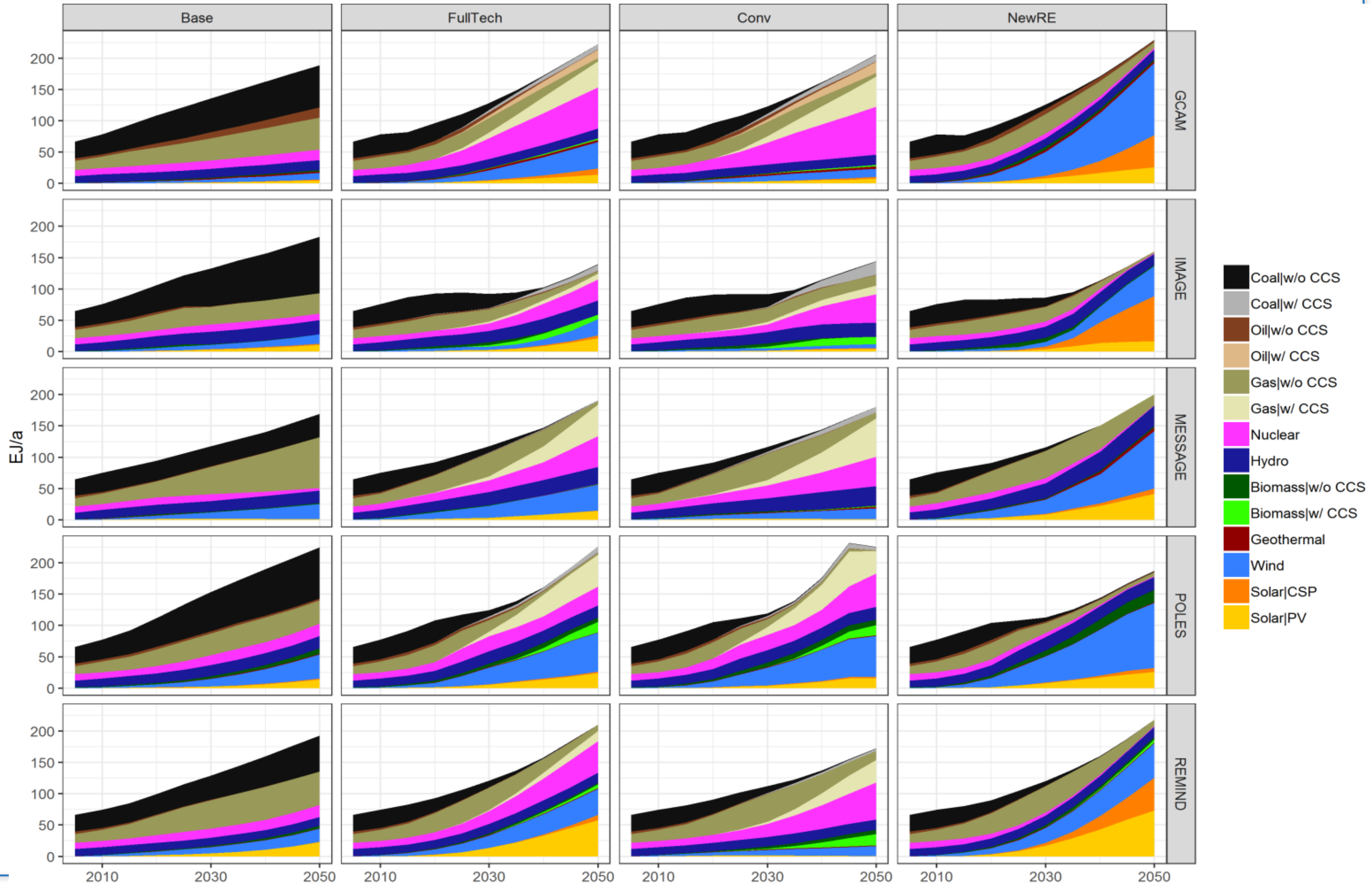
Assessing global pathways

Upscaling environmental impacts with various decarbonization pathways can reveal potential issues

4 scenarios × 5 integrated assessment models

(from 20 PWh to ~50 PWh in 2050)

No emissions constraint	Cumulative 2011-2050 power sector emissions limited to 240 $GtCO_2$.		
Full portfolio	Full portfolio	Wind and solar power limited to 10%	Nuclear phase-out, no CCS in the power sector



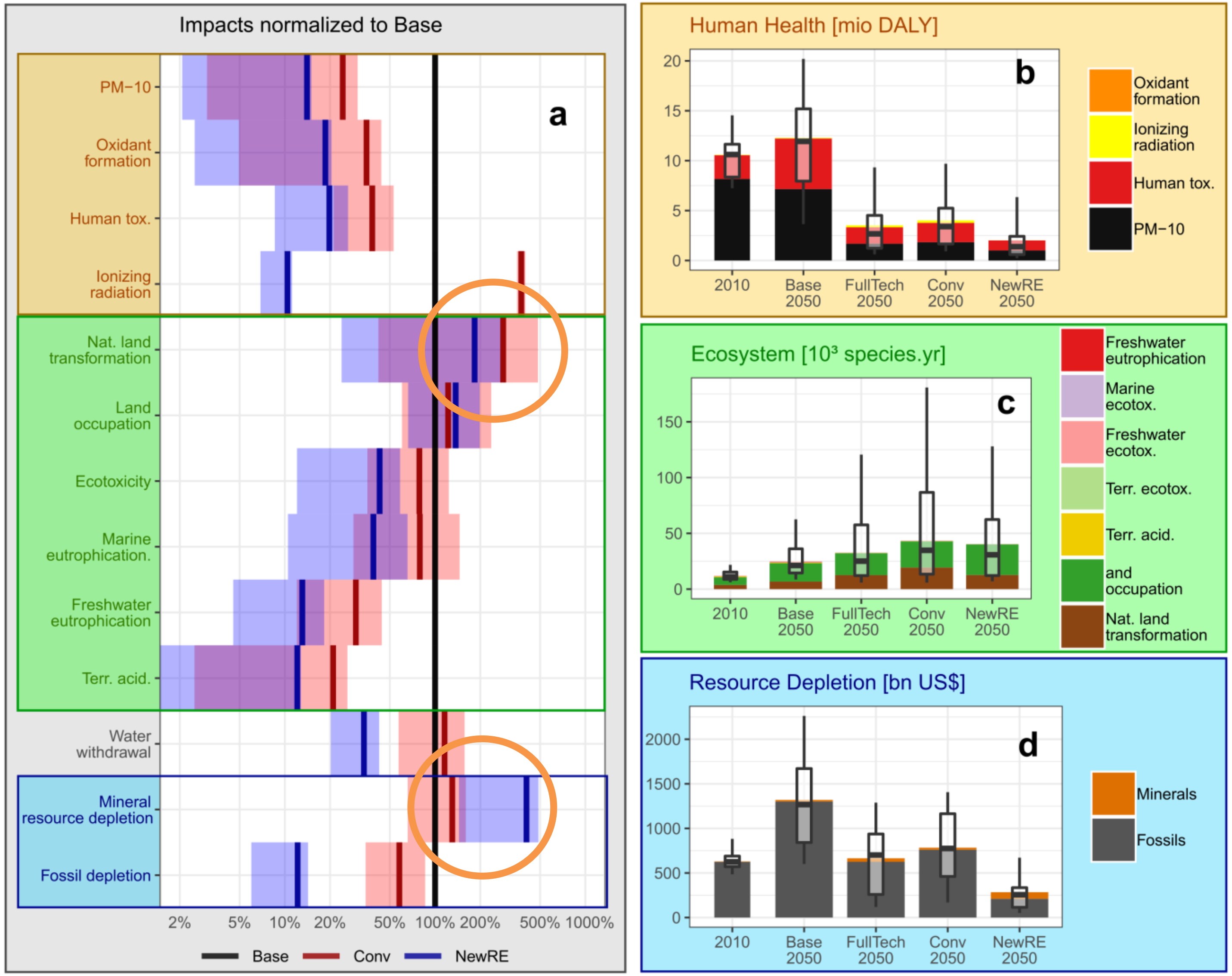
Luderer, G., Pehl, M., Arvesen, A., Gibon, T., Bodirsky, B. L., de Boer, H. S., ... & Hertwich E. G. (2019). Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nature communications*, *10*(1), 1-13.

More scenario comparison!

Assessing global pathways

Upscaling environmental impacts with various decarbonization pathways can reveal potential issues

- Land transformation and occupation, both in **“conventional”** and **“new renewable”** scenarios
- Mineral resource depletion, especially in **“new renewable”** scenario



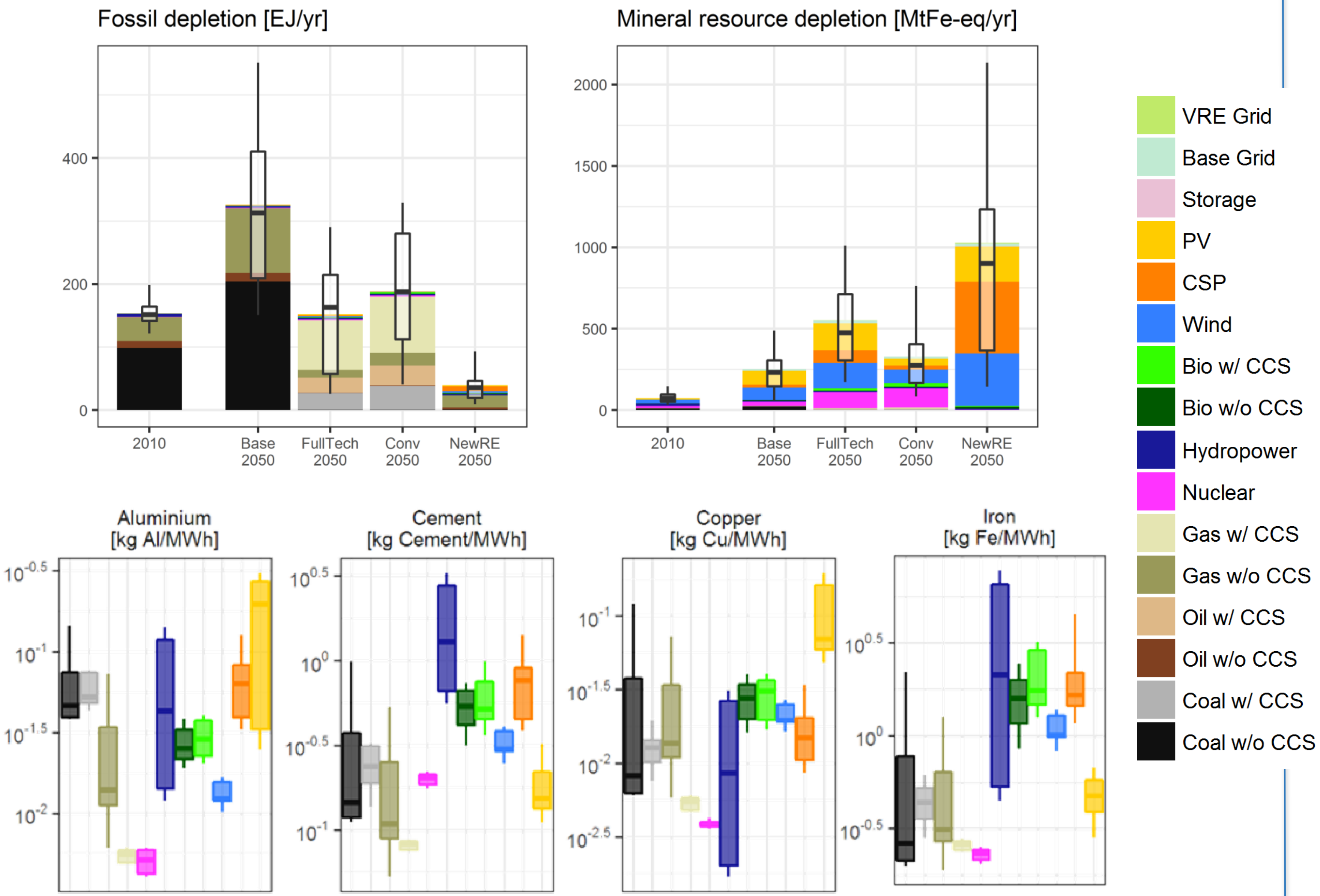
Luderer, G., Pehl, M., Arvesen, A., Gibon, T., Bodirsky, B. L., de Boer, H. S., ... & Hertwich E. G. (2019). Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nature communications*, *10*(1), 1-13.

Trade-offs

Fossil and material res.

Fossil extraction still necessary even in NewRE scenario

New renewables would quadruple mineral resource depletion in a 100% renewable scenario



Luderer, G., Pehl, M., Arvesen, A., Gibon, T., Bodirsky, B. L., de Boer, H. S., ... & Hertwich E. G. (2019). Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nature communications*, *10*(1), 1-13.

DISCUSSION

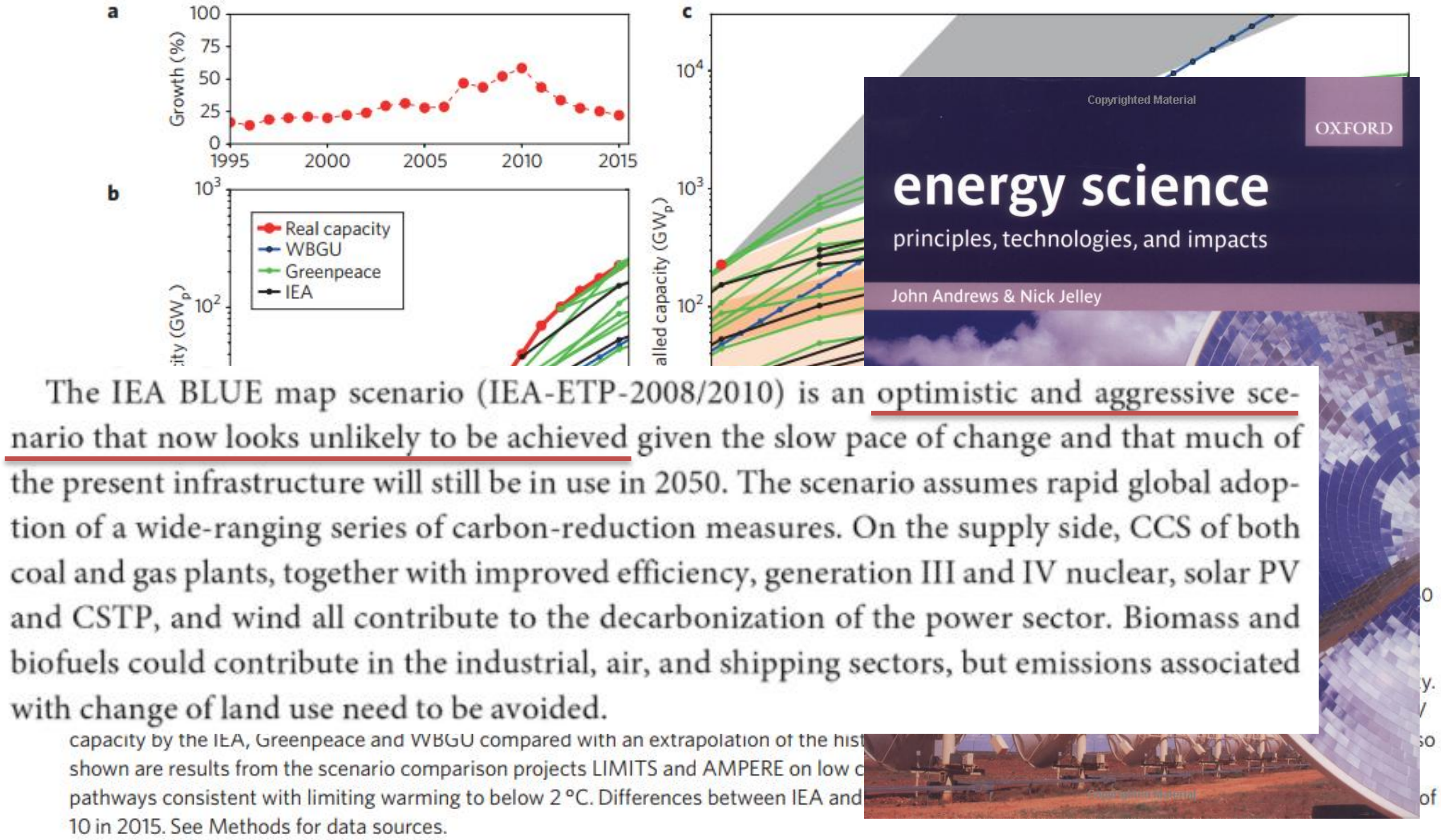
Discussion

Forecasting technology deployment

Scenarios ≠ forecasts

Overly optimistic by assuming aggressive mitigation policies…

…or pessimistic by underestimating capacity growth of various technologies (PV, wind…)



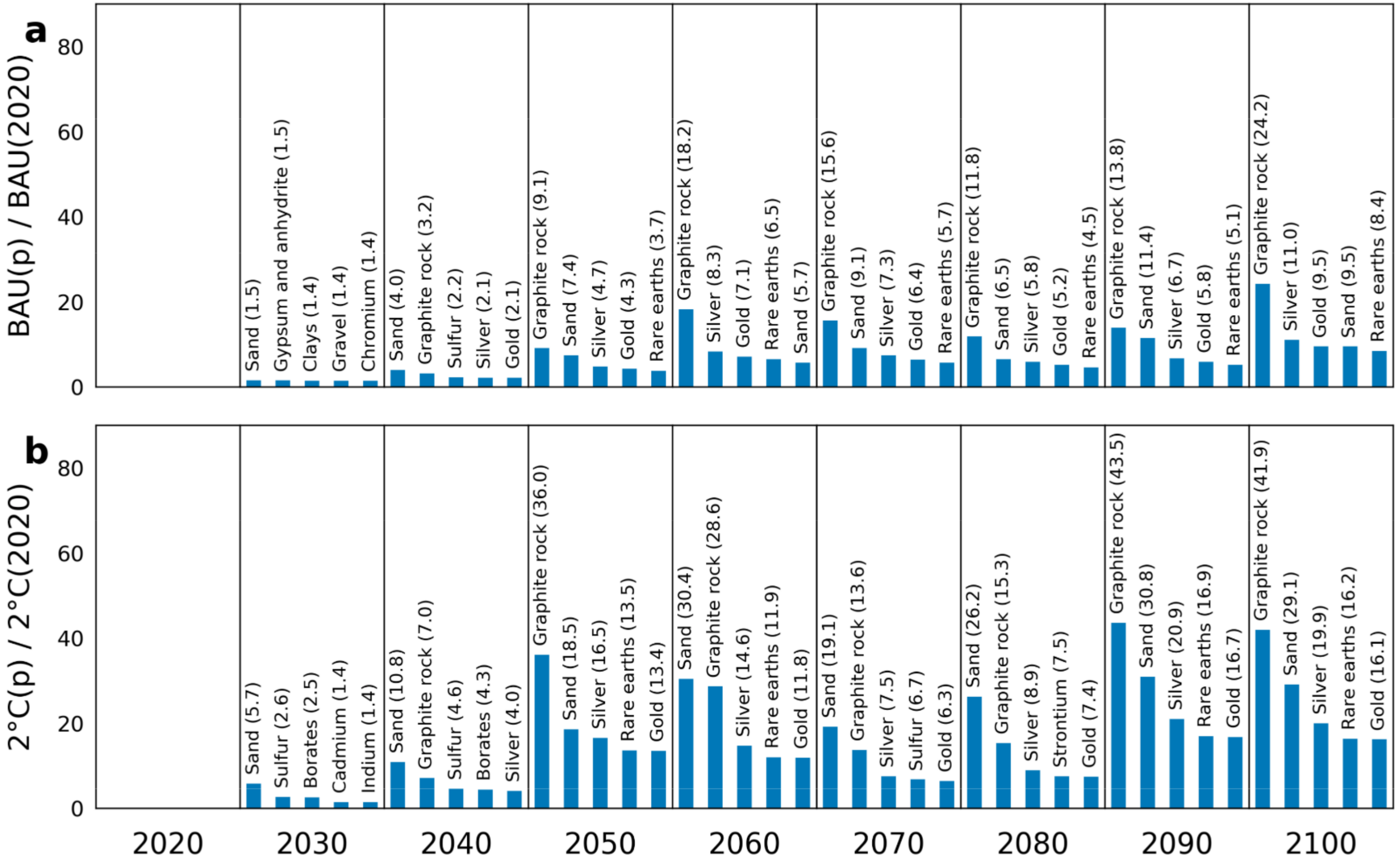
Creutzig, F., Agoston, P., Goldschmidt, J. C., Luderer, G., Nemet, G., & Pietzcker, R. C. (2017). The underestimated potential of solar energy to mitigate climate change. Nature Energy, 2(9)

Discussion

Forecasting material use

- Future assessments are based on today's technologies
- Limited material efficiency improvements
- Little or no material substitution accounted for

Increase in material requirements, TIAM-FR model, world



Boubault, A., & Maïzi, N. (2019). Devising mineral resource supply pathways to a low-carbon electricity generation by 2100. *Resources*, *8*(1), 33.

Discussion

Limitations – LCA method

- Generic technology data, only with regional adjustments
- Generic characterization factors (no time or regional differentiation)
- **No consensus on material criticality indicators,** especially for newer materials (neodymium, lithium, cobalt, thin-film PV elements...)
- Some elements even absent from life cycle databases

Critical Raw Materials list (2020)	in ecoinvent 2.2? (2010)	in ecoinvent 3.6? (2019)	characterized in EF3.0? (2020)*
Antimony	no	yes	yes
Baryte	yes	yes	no
Beryllium	no	yes	yes
Bismuth	no	yes	yes
Borax	yes	yes	no
Cobalt	yes	yes	yes
Coal	yes	yes	*as a fossil resource*
Fluorspar	yes	yes	no
Gallium	yes	yes	yes
Germanium	no	yes	yes
Hafnium	no	yes	no
Heavy Rare Earth Elements	*2/10*	*10/10*	*1/10*
Light Rare Earth Elements	*2/6*	*5/6*	*0/6*
Indium	yes	yes	yes
Magnesium	yes	yes	yes
Natural Graphite	yes	yes	no
Natural Rubber	no	no	no
Niobium	no	yes	yes
Platinum Group Metals	yes	yes	partly
Phosphate rock	no	no	no
Phosphorus	yes	yes	yes
Scandium	no	yes	no
Silicon	yes	yes	yes
Tantalum	yes	yes	yes
Tungsten	no	yes	yes
Vanadium	no	yes	yes
Bauxite	yes	yes	yes
Lithium	yes	yes	yes
Titanium	yes	yes	yes
Strontium	no	yes	yes

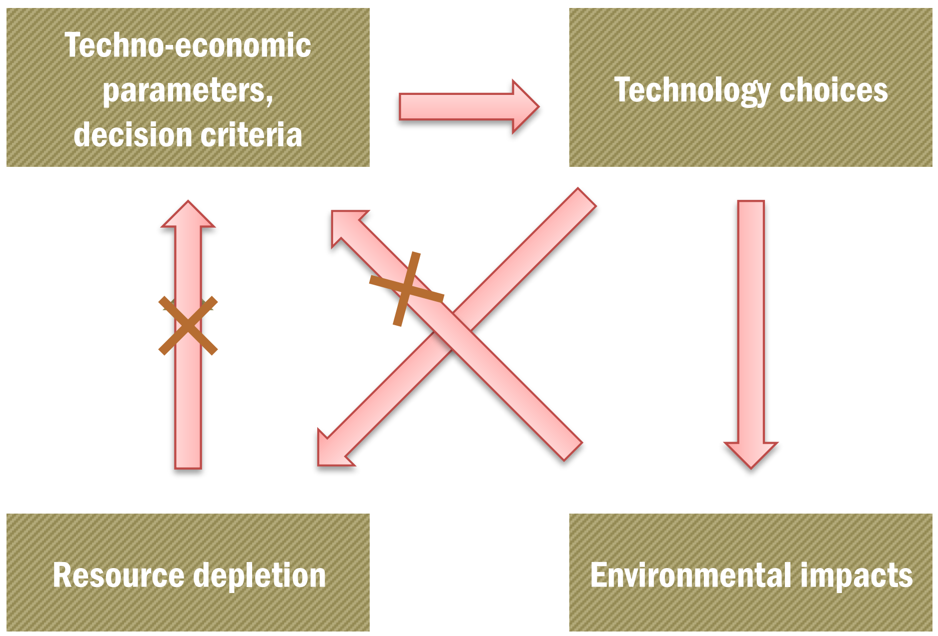
*Depletion model based on use-to-availability (ultimate reserves) ratio, substitutability only for fossils.

Discussion

Limitations – scenario modelling

Resource-economy feedback: **mineral resource availability does not influence technology choice in scenarios**

- Resource depletion
- Supply disruption
- Intersectoral competition
- Geopolitical tensions
- Lower-grade mining ore increasing environmental impacts
- Co-dependency of metals (Fe: rare earths, Al: Ga, Cu: Co, Rh, Mo, Te, Se...)



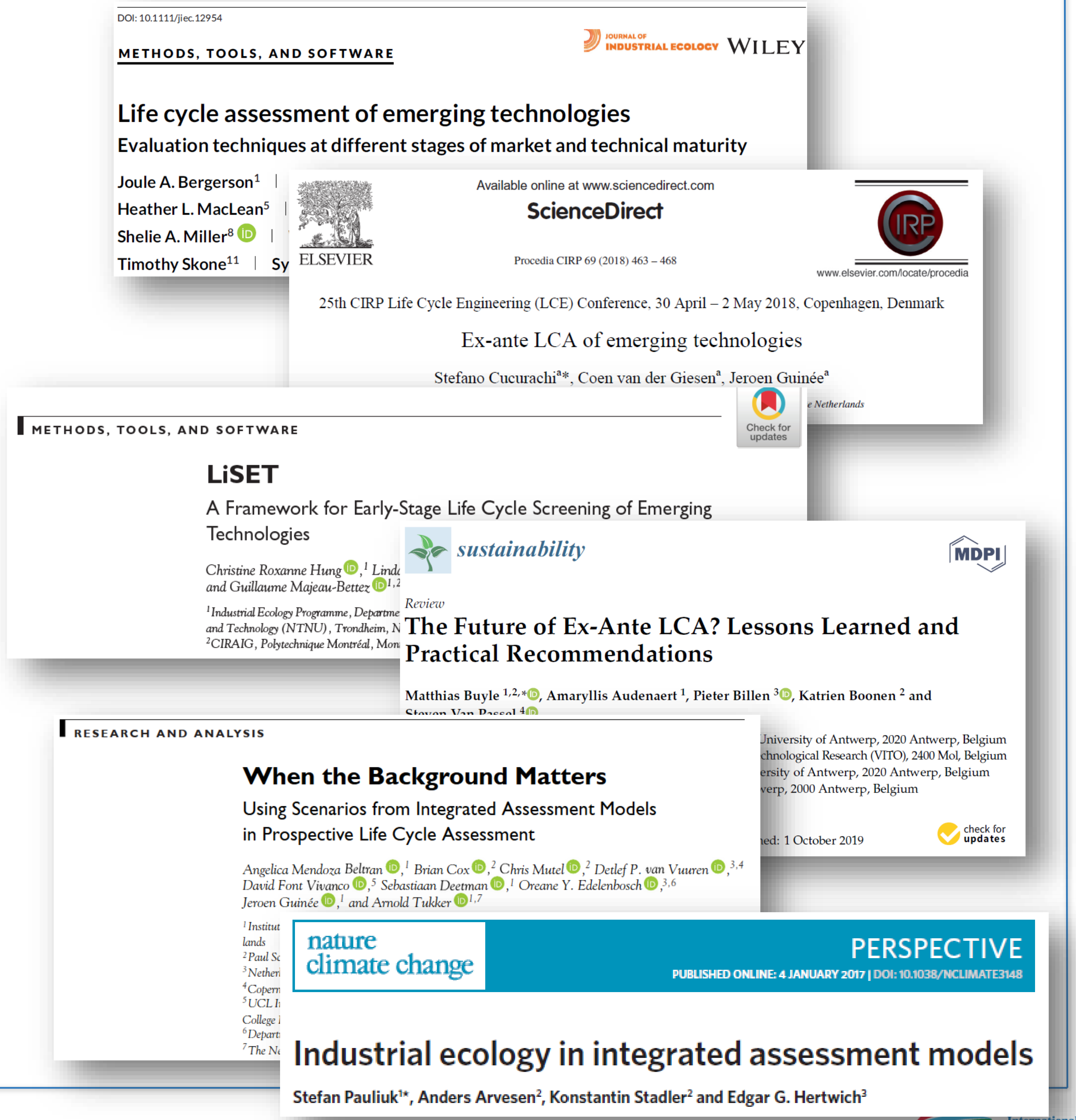
Boubault, A., & Maïzi, N. (2019). Devising mineral resource supply pathways to a low-carbon electricity generation by 2100. *Resources*, *8*(1), 33.

Outlook

Towards *ex-ante* LCA frameworks

LCA literature shows a rapid development in

- scenario integration (with IAMs);
- learning curves,
- substitutability,
- proxy technology transfer,
- scaling methods…


DOI: 10.1111/jiec.12954
METHODS, TOOLS, AND SOFTWARE
JOURNAL OF INDUSTRIAL ECOLOGY WILEY
Life cycle assessment of emerging technologies
Evaluation techniques at different stages of market and technical maturity
Joule A. Bergerson[1]
Heather L. MacLean[5]
Shelie A. Miller[8]
Timothy Skone[11]

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Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 69 (2018) 463 – 468
www.elsevier.com/locate/procedia
25th CIRP Life Cycle Engineering (LCE) Conference, 30 April – 2 May 2018, Copenhagen, Denmark
Ex-ante LCA of emerging technologies
Stefano Cucurachi[a]*, Coen van der Giesen[a], Jeroen Guinée[a]

METHODS, TOOLS, AND SOFTWARE
LiSET
A Framework for Early-Stage Life Cycle Screening of Emerging Technologies
Christine Roxanne Hung[1], and Guillaume Majeau-Bettez[1,2]

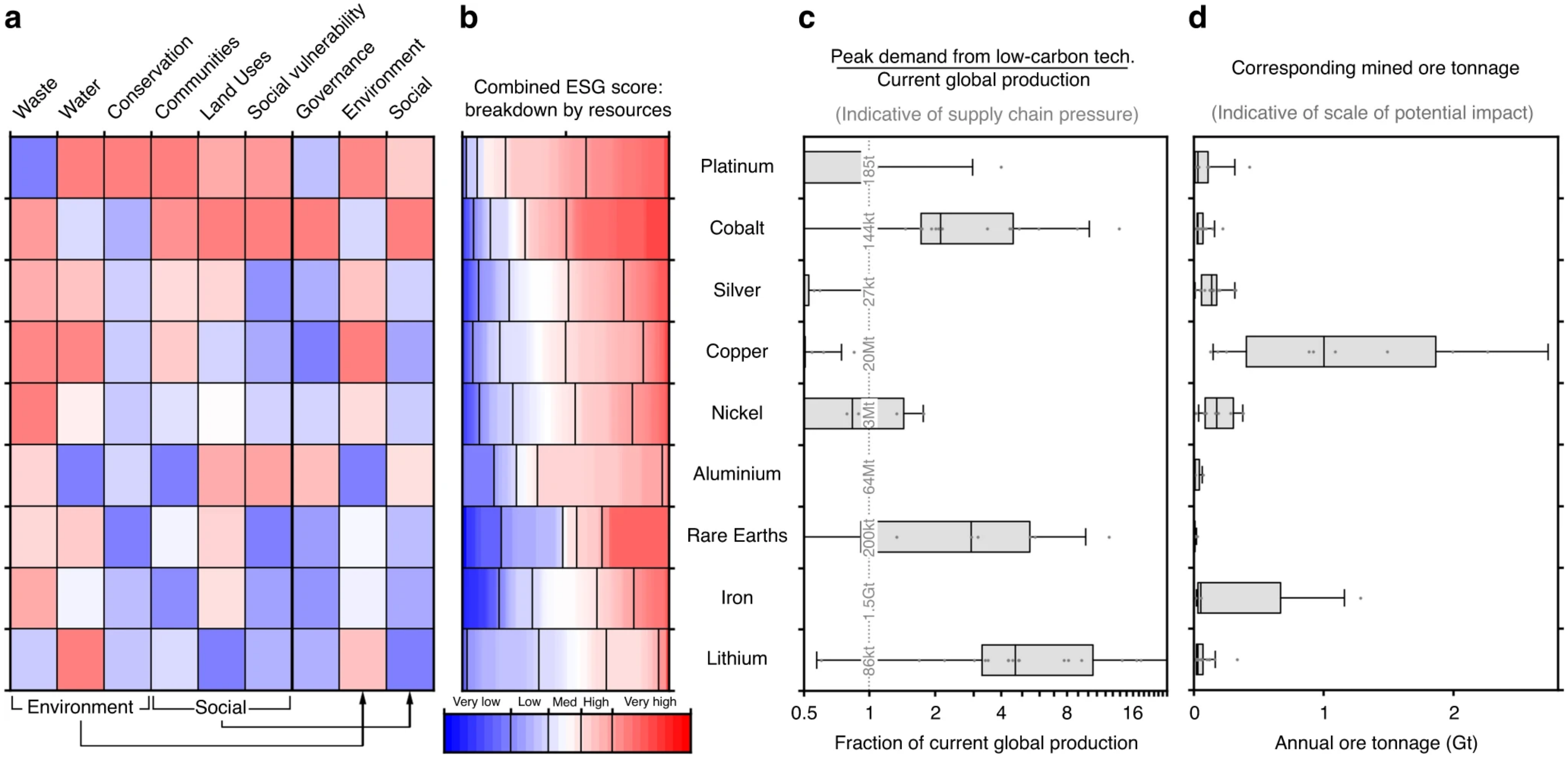
sustainability
MDPI
Review
The Future of Ex-Ante LCA? Lessons Learned and Practical Recommendations
Matthias Buyle[1,2,*], Amaryllis Audenaert[1], Pieter Billen[3], Katrien Boonen[2] and

RESEARCH AND ANALYSIS
When the Background Matters
Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment
Angelica Mendoza Beltran[1], Brian Cox[2], Chris Mutel[2], Detlef P. van Vuuren[3,4]
David Font Vivanco[5], Sebastiaan Deetman[1], Oreane Y. Edelenbosch[3,6]
Jeroen Guinée[1], and Arnold Tukker[1,7]

nature climate change
PERSPECTIVE
PUBLISHED ONLINE: 4 JANUARY 2017 | DOI: 10.1038/NCLIMATE3148
Industrial ecology in integrated assessment models
Stefan Pauliuk[1]*, Anders Arvesen[2], Konstantin Stadler[2] and Edgar G. Hertwich[3]

Outlook

Towards finer assessments of material criticality

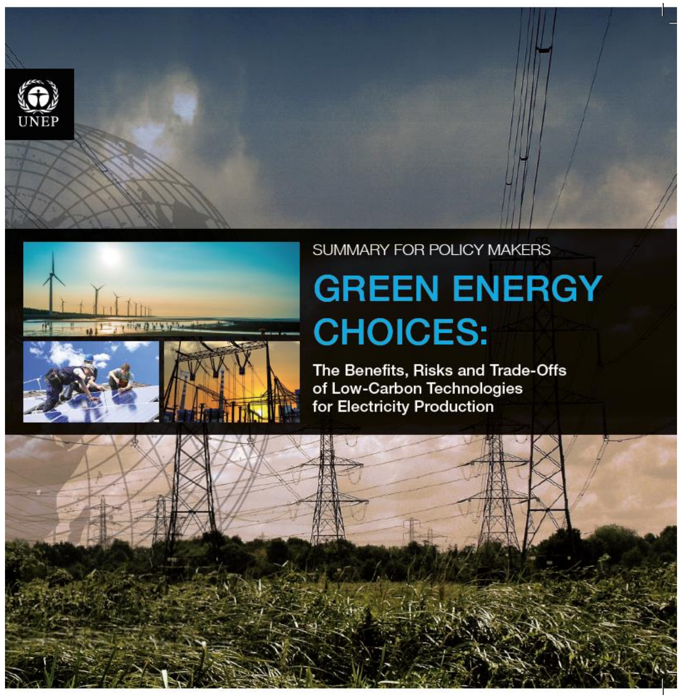


Lèbre, É., Stringer, M., Svobodova, K. *et al.* The social and environmental complexities of extracting energy transition metals. *Nature Communications* **11,** 4823 (2020). https://doi.org/10.1038/s41467-020-18661-9

Thank you! Questions?

This research work was carried out at

NTNU
Norwegian University of Science and Technology



Under the auspices of

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For more information please visit:
https://www.resourcepanel.org/reports/green-energy-choices-benefits-risks-and-trade-offs-low-carbon-technologies-electricity

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Extra slides

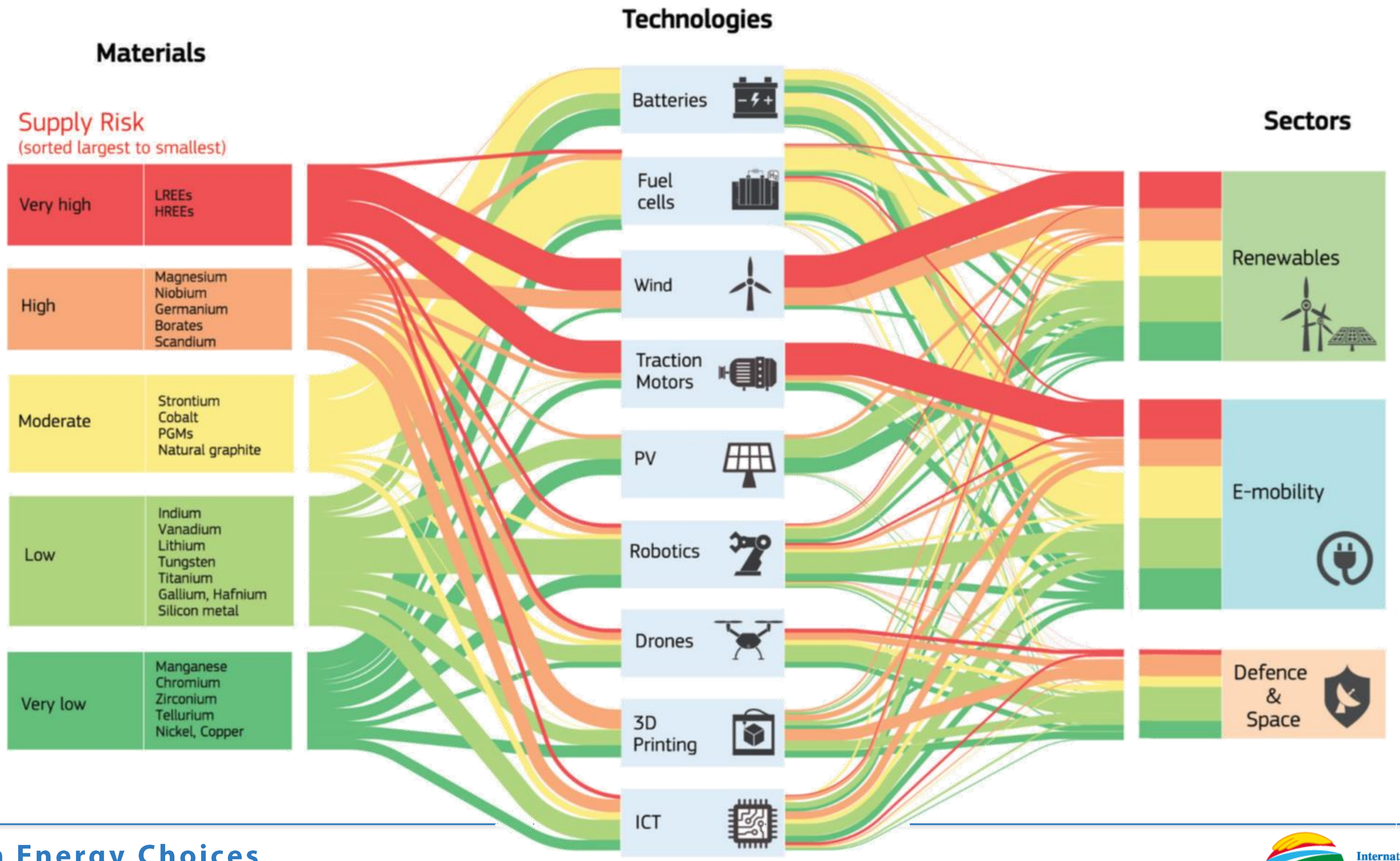
Outlook

Integrate more sectors

More complete picture of the situation

Consider interactions (vehicle-to-grid, IT in energy management…)

Semi-quantitative representation of flows of raw materials and their current supply risks to the nine selected technologies and three sectors
(European Commission 2020 https://ec.europa.eu/docsroom/documents/42882)



What are the environmental, health and resource use implications of a massive expansion of low-carbon electricity?

A typical photovoltaic power plant produces **0.3 kWh** per m^2 per day

©Lucas Braun

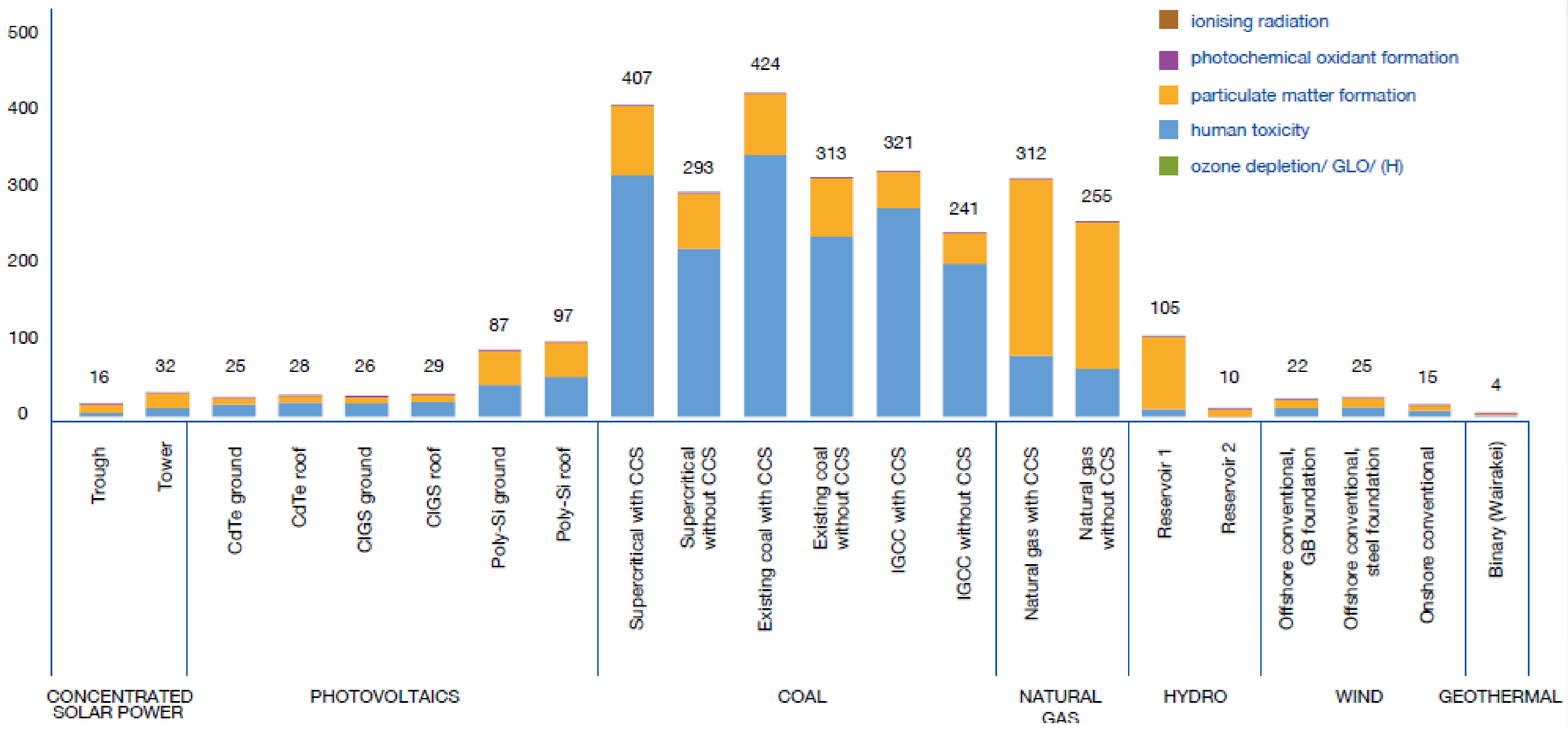
Comparative results

Human health

Linear y-axis

DALY (disability-adj. life year) *quantifies a year lived with a (weighted) disability ranging from a small handicap to premature death*

Figure 2: Human health impact in disability adjusted life years (DALY) per 1TWh of electricity generated, for Europe 2010 [20].



Comparative results

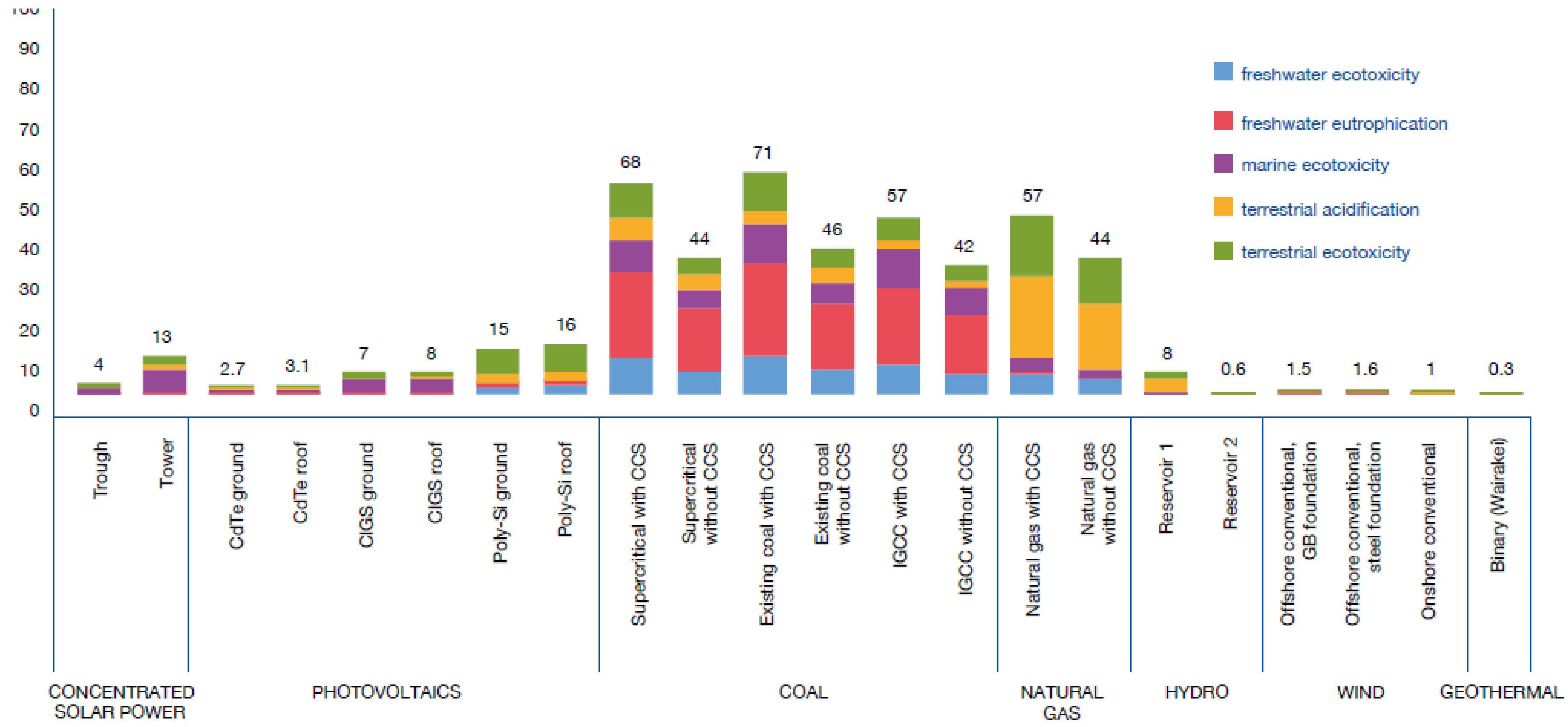
Ecosystems

Linear y-axis

species-year

quantifies the danger of species extinction over a year

Figure 3: Ecosystem impacts in species-year affected per 1000 TWh of electricity following different damage pathways, reflecting Europe 2010 [23].



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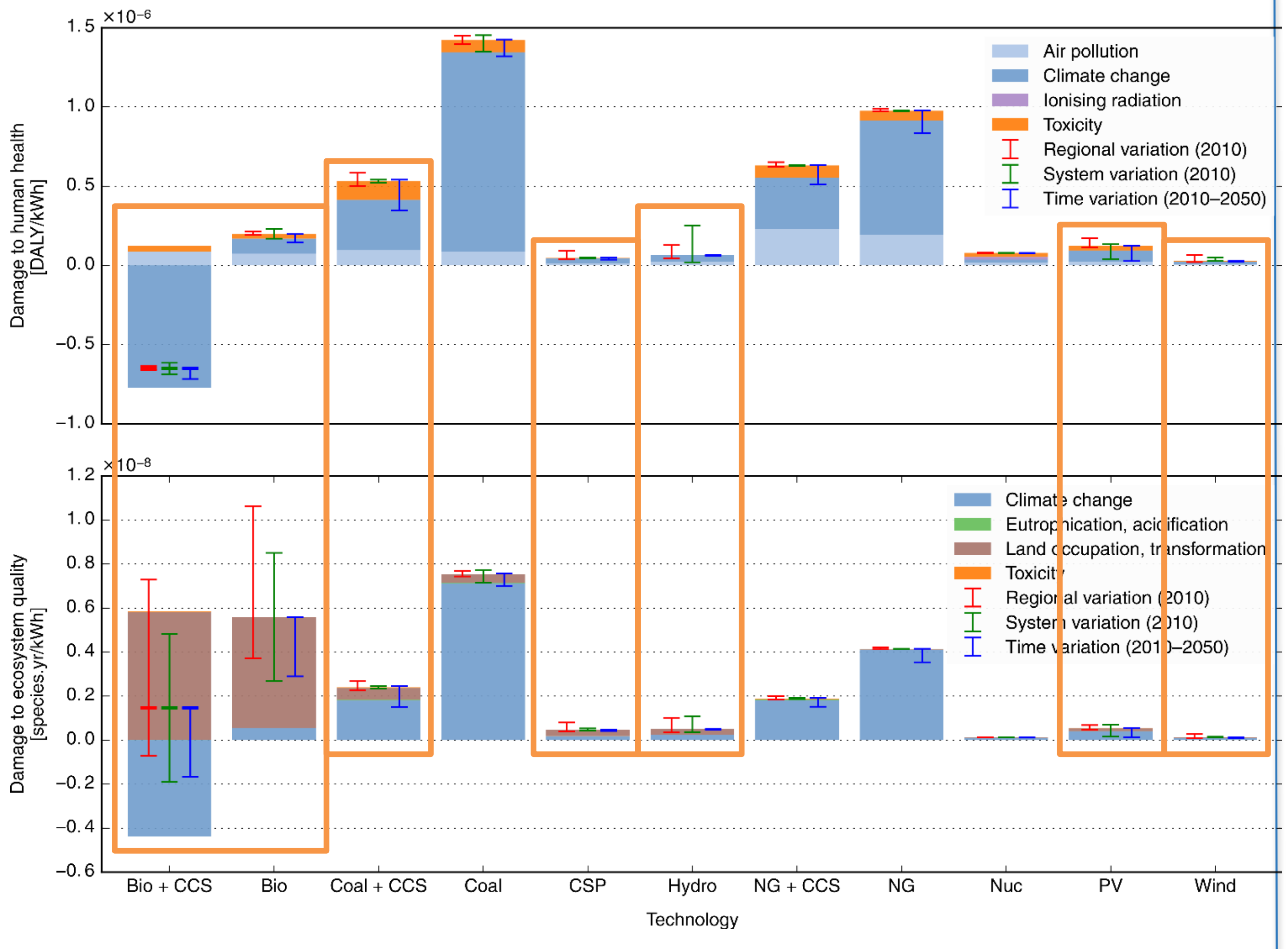
Completing the picture

+ biomass and nuclear, human health & ecosystem damage

- 11 technology groups, composed by 37 systems
- Variations captured:
  - Regional,
  - Technology/system,
  - Time
- Endpoint scores show high variation for
  - **Biomass**
    (regional: yield, system: energy crop vs. residues, time: increasing efficiency),
  - **Coal**
    (system, time: increasing efficiency),
  - **Hydro**
    (regional, system: high variation in direct emissions and transportation),
  - **Photovoltaic** (system: high variation poly-Si vs. thin-film, ground- vs. roof-mounted),
  - **Wind and CSP**
    (regional: climate conditions)



Unit results for the damage to human health (a) and ecosystem quality (b) of one kilowatt-hour of electricity at grid, weighted by global production. Bars represent variability, not uncertainty.

Gibon T, Hertwich EG, Arvesen A, et al (2017) Health benefits, ecological threats of low-carbon electricity. Environ Res Lett 12: . doi: 10.1088/1748-9326/aa6047

What are the environmental, health and resource use implications of a massive expansion of low-carbon electricity?

3.2 million premature deaths from particulate matter emissions