THE ENVIRONMENTAL COSTS OF 1 KWH

A COMPARISON OF ELECTRICITY GENERATION OPTIONS

Thomas Gibon

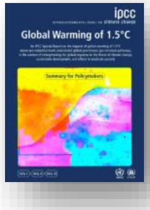
Luxembourg Institute of Science and Technology (LIST)

on behalf of United Nations Economic Commission for Europe (UNECE)

November 23rd 2022, Electrification Academy 16

LIFE CYCLE ASSESSMENT

WHY ENVIRONMENTAL IMPACT ASSESSMENT?



Figures from IPCC 1.5°C report
https://report.ipcc.ch/sr15/pdf/sr15_spm_final.pdf

Motivation and implications

Human activities’ pressure on the environment is skyrocketing.

On the one hand we need to support decision-making with complete, accurate and detailed information about the **environmental impacts** of **products**, **technologies**, **organizations** and **lifestyles…**

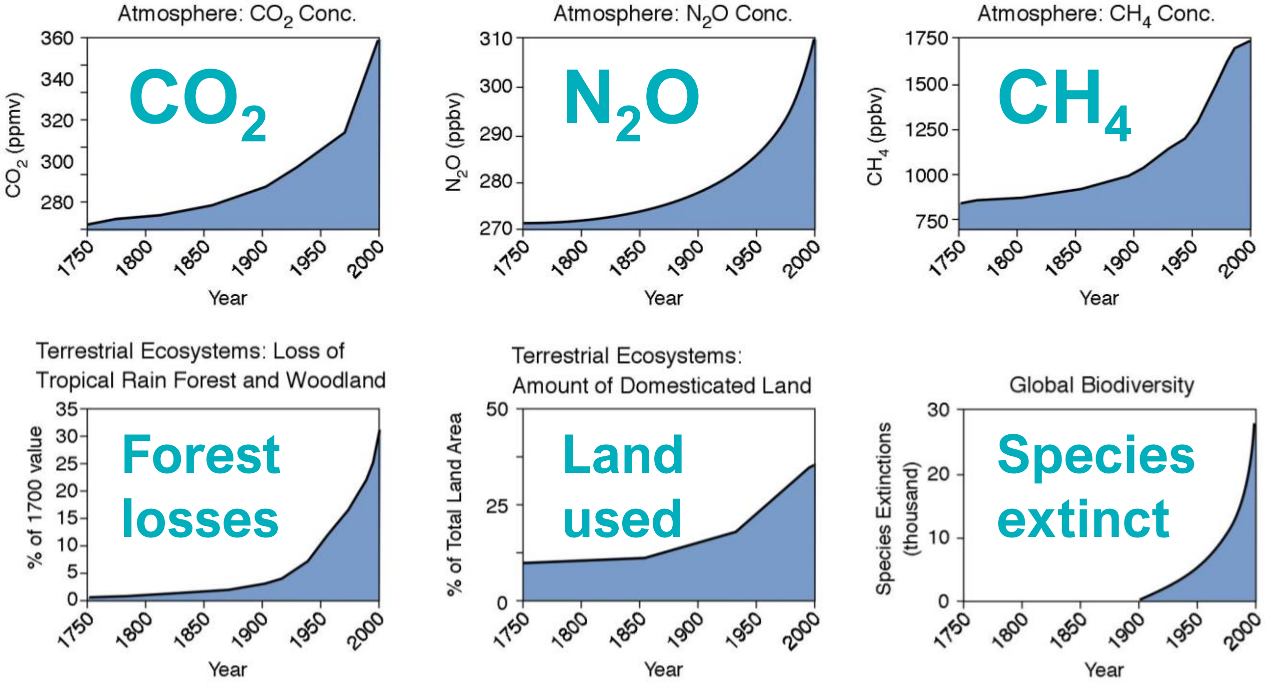
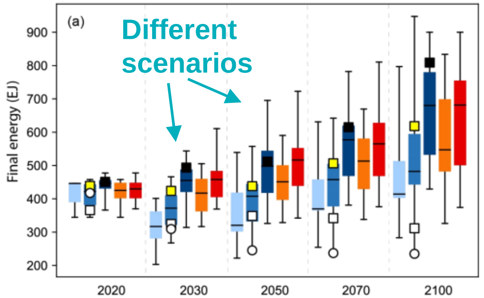


Figure: Steffen et al. 2004

On the other hand, we need to ensure a **safe**, **affordable**, and **fulfilling** future to humanity, by delivering a minimum level of energy that allows decent living conditions



Global energy demand keeps increasing

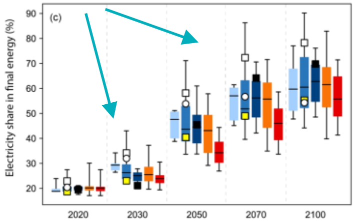
Land use?

Materials?

Water stress?

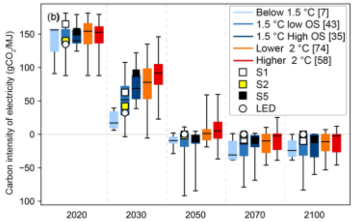
At what environmental costs?

Ambitious scenarios require early effort



>60% of the economy needs electrification (services, industry, transport) from 20% today

Carbon content of electricity



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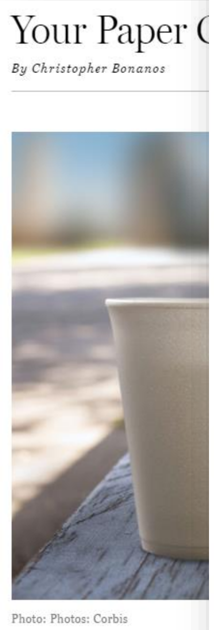
Simultaneously, electricity will need to be produced from low-carbon sources

HOW DO WE ASSESS OUR OPTIONS?


Your Paper C

By Christopher Bonanos

Photo: Photos: Corbis


GREGORY BARBER SCIENCE AUG 8, 2022 7:00 AM

How Clean Is 'Clean' Hydrogen?

Batteries and renewable energy alone can't decarbonize industries, and recent propo
economy" could bridge those gaps.

PHOTOGRAPH: PATRICK T. FALLON/BLOOMBERG/GETTY IMAGES

http://nymag.com/int
destroying-the-world.html

https://www.wired.com/story/how-clean-is-clean-hydrogen/


are

https://www.bbc.com/news/science-environment-46459714


SCIENCE ENVIRONMENT

Are cotton totes better for the Earth than plasti bags? It depends on what you care about

Of course the answer is never easy

By Alessandra Potenza | @ale_potenza | May 12, 2018, 9:00am EDT

https://www.theverge.com/2018/5/12/17337602/plastic-tote-bags-climate-change-litter-life-cycle-assessments-environment


Solar cells

How clean is solar power?

A new paper may have the answer


n alternative to fossil

land resources at the cost
e and doesn't guarantee

uels


Nuclear power is the greenest option, say top scientists

Environmentalists urged to ditch their historical antagonism and embrace a broad energy mix

Steve Connor | @SteveAConnor | Sunday 4 January 2015 01:00 |

206 comments

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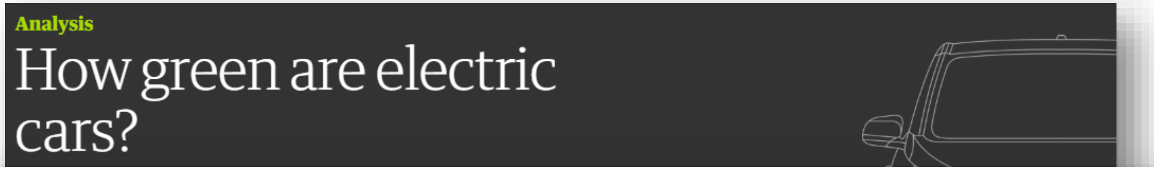
https://www.independent.co.uk/news/science/nuclear-power-is-the-greenest-option-say-top-scientists-9955997.html


Analysis

How green are electric cars?


Sustainability | *Ecotrope*

The greener beer: In bottles or cans?

by **Cassandra Profita** Follow Ecotrope July 8, 2011 9:43 a.m. I Updated: Feb. 25, 2013 12:39 p.m.

https://www.opb.org/news/blog/ecotrope/the-greener-beer-bottles-v-cans/

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LIST

THE NECESSITY OF A LIFE CYCLE APPROACH

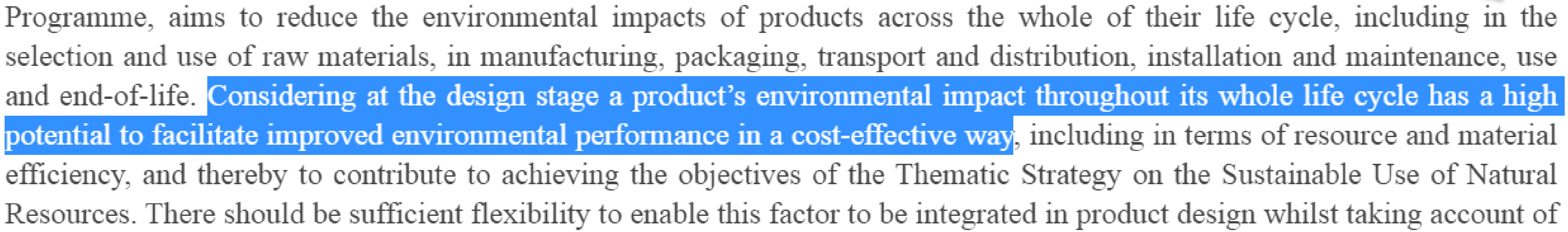
Some regulations/directives recommend or demand use of “life cycle assessment”. For example:

→ California low-carbon fuel standard (https://ww2.arb.ca.gov/news/carb-amends-low-carbon-fuel-standard-wider-impact)

→ EU directive on energy-related products (2009/125/EC) (https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:32009L0125)

→ EU waste framework directive (2008/98/EC)

→ EU proposal for a framework to facilitate sustainable investment (COM/2018/353 final – https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52018PC0353 – still under development)



Programme, aims to reduce the environmental impacts of products across the whole of their life cycle, including in the selection and use of raw materials, in manufacturing, packaging, transport and distribution, installation and maintenance, use and end-of-life. Considering at the design stage a product’s environmental impact throughout its whole life cycle has a high potential to facilitate improved environmental performance in a cost-effective way, including in terms of resource and material efficiency, and thereby to contribute to achieving the objectives of the Thematic Strategy on the Sustainable Use of Natural Resources. There should be sufficient flexibility to enable this factor to be integrated in product design whilst taking account of

LIFE CYCLE ASSESSMENT (LCA)

Definition

A method and tool for attributing environmental impacts to products and services

Considering impacts over the life cycle

Production, use, end-of-life

Considering impacts upstream in supply chains

Resource extraction, transport, etc.

→ *Holistic*

Example: low-carbon technologies do not emit CO_2 directly, but require the potentially carbon-intensive production of infrastructure

And typically:

Considering hundreds of **emitted substances** and **extracted resources**

Considering a range of impact types

Human health, ecosystem health, natural resource use

→ *Multicriteria*

Example: low-carbon technologies emit less CO2 on a lifecycle basis, but have higher material or land requirements than conventional alternatives

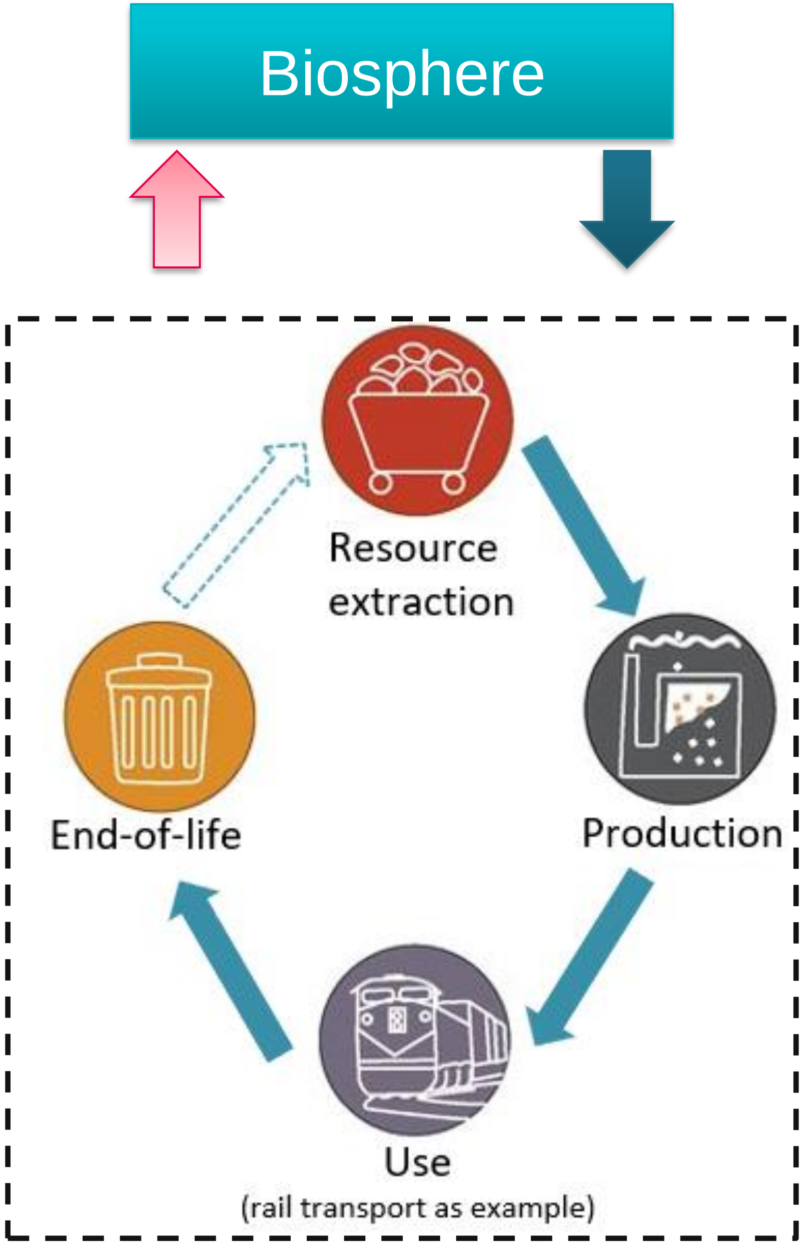


Figure: Adapted from Hellweg & Mila i Canals (2014)

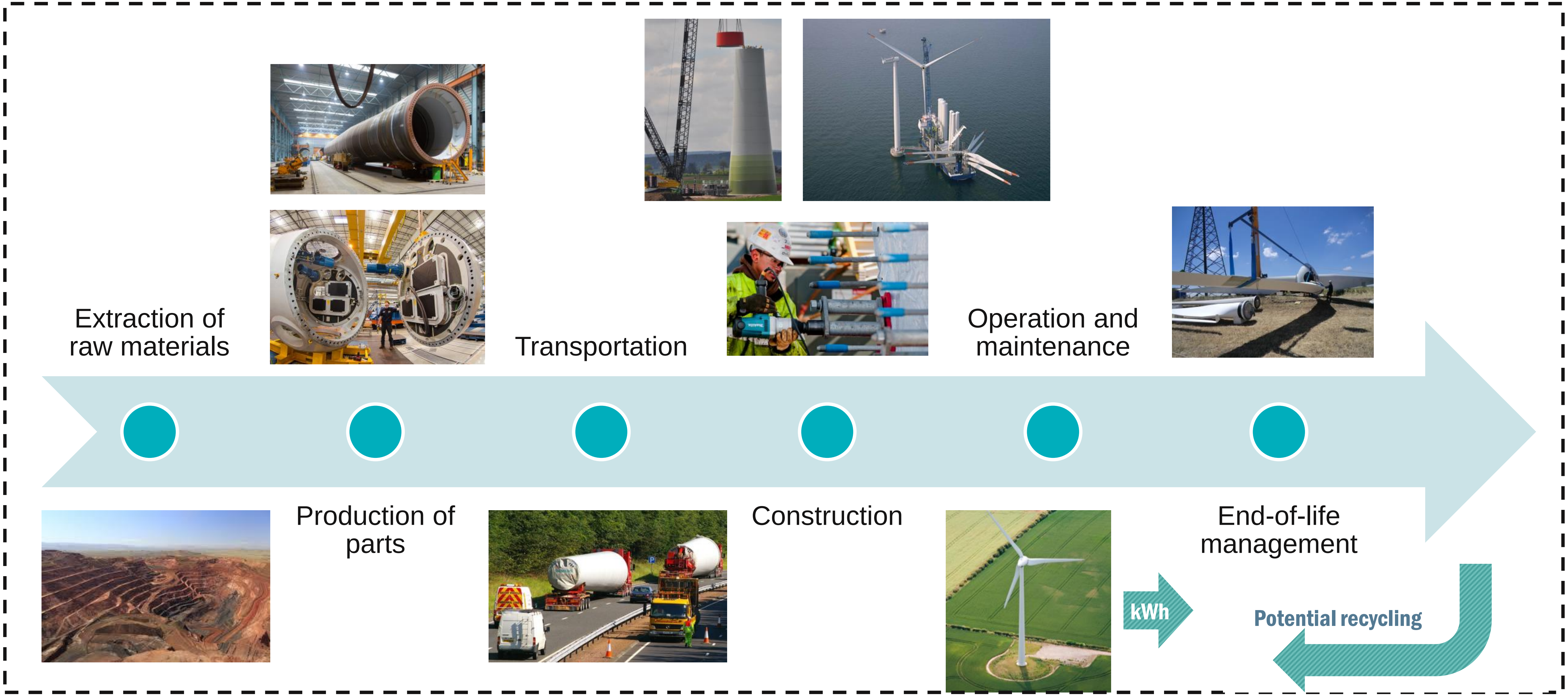
LIFE CYCLE ASSESSMENT

Example: wind power

Biosphere

Total ~10 g CO_2 eq./kWh …

~70 mg Ni/kWh …



Extraction of raw materials

Production of parts

Transportation

Construction

Operation and maintenance

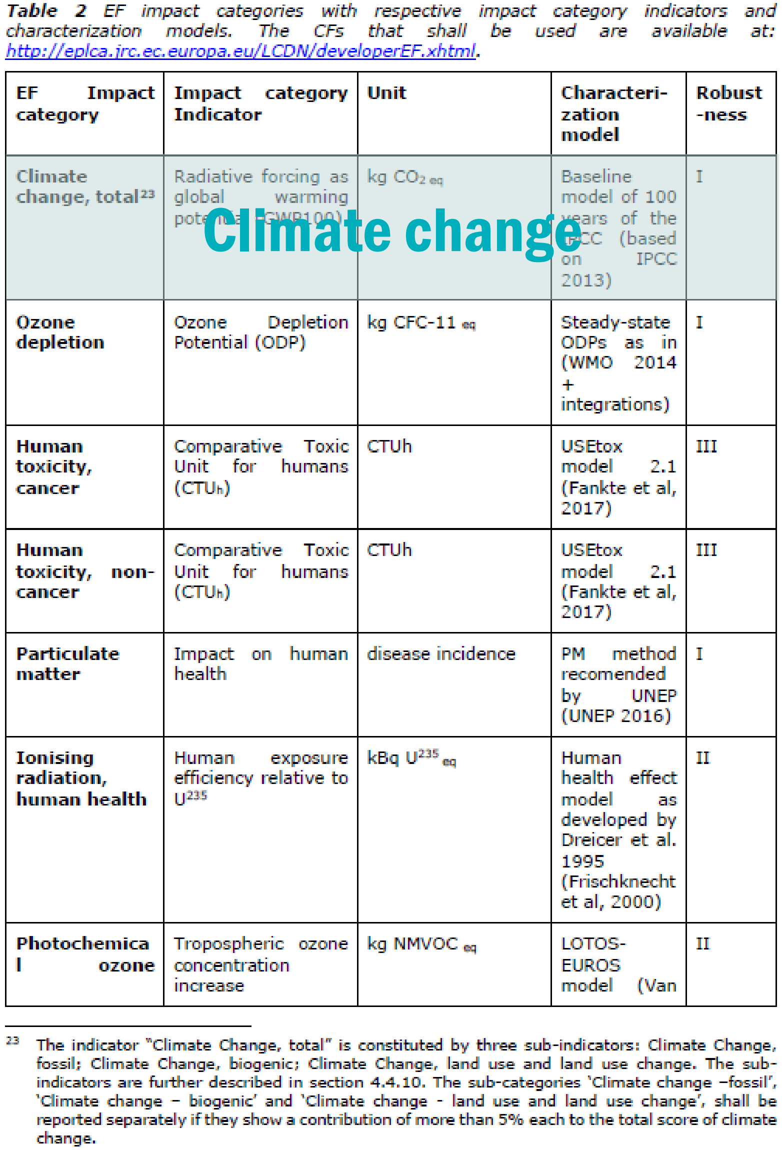
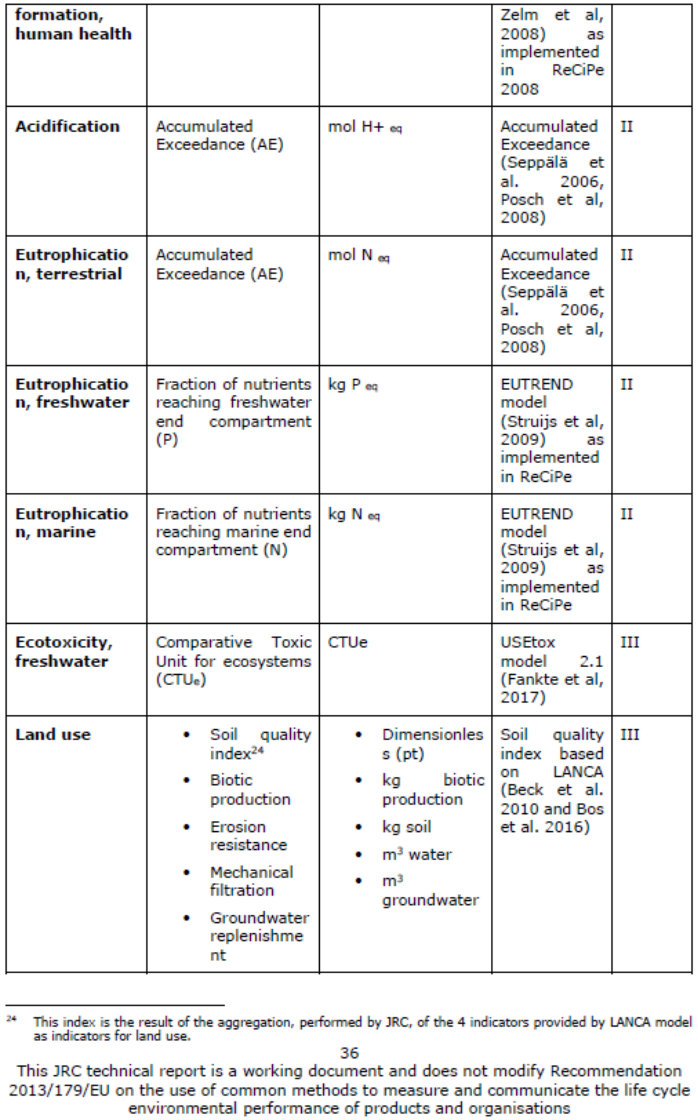
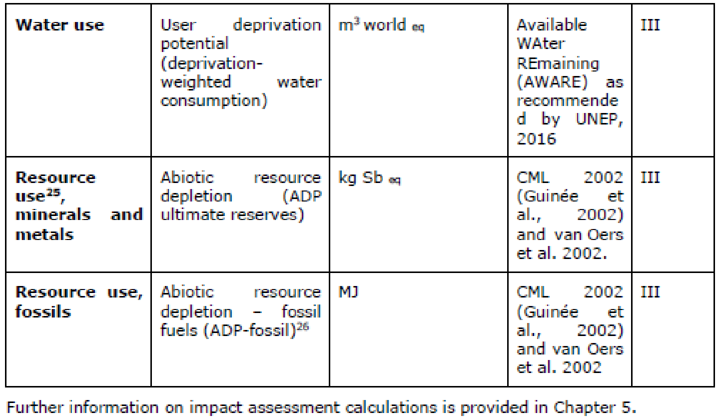
End-of-life management

kWh

Potential recycling

WHAT CAN WE ASSESS IN ENVIRONMENTAL LCA?

Climate change

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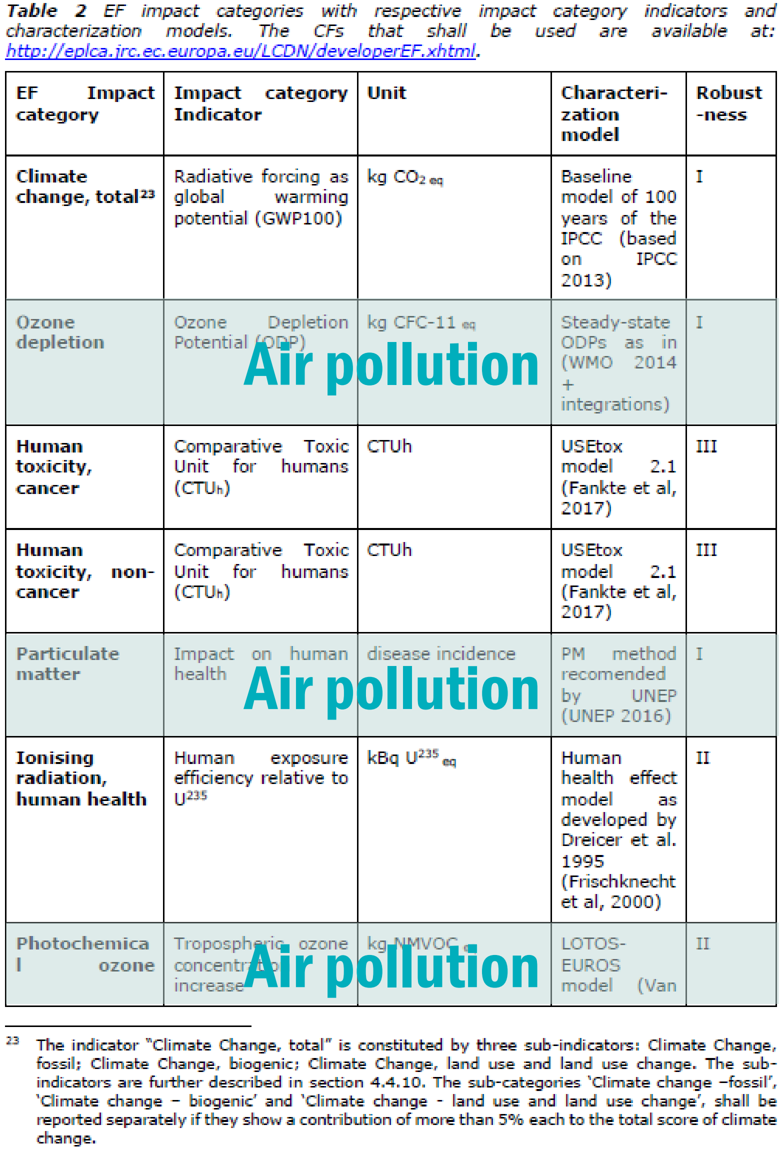

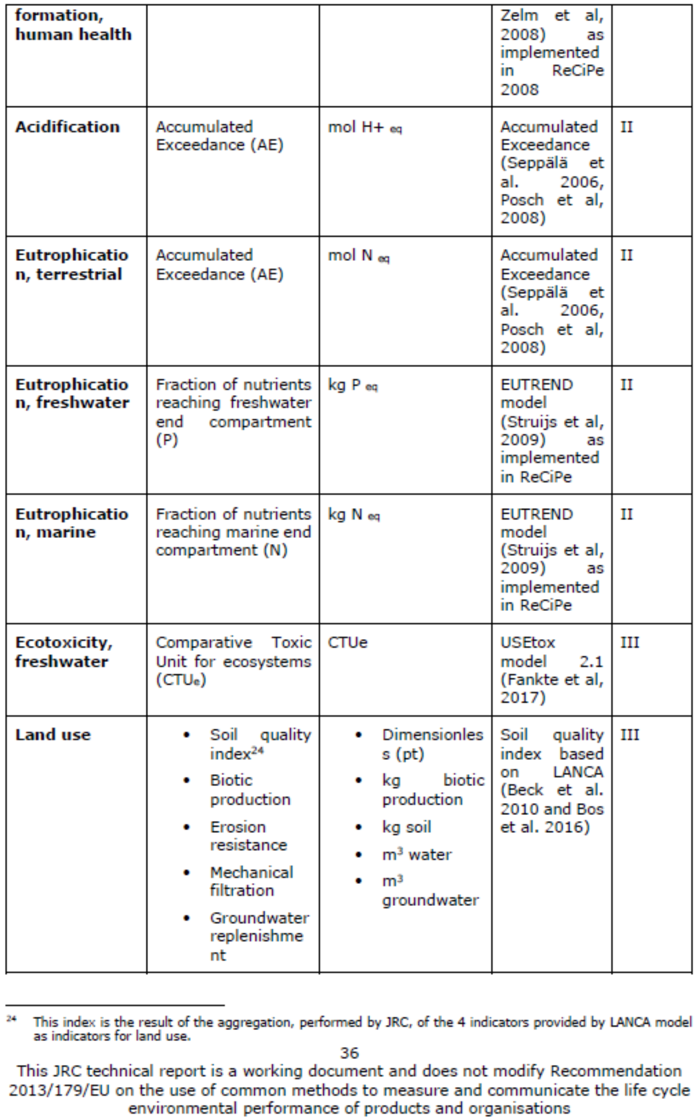

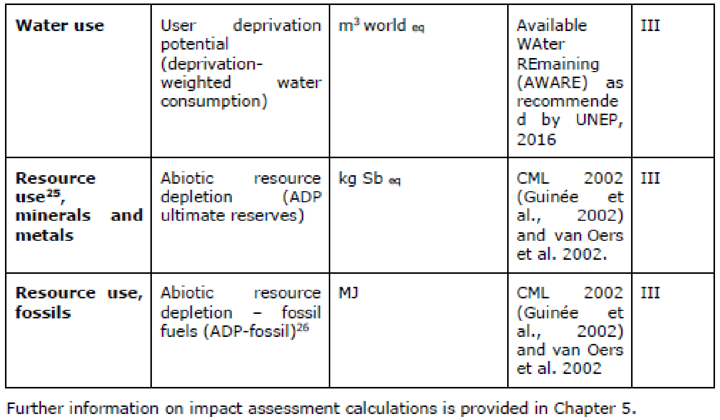

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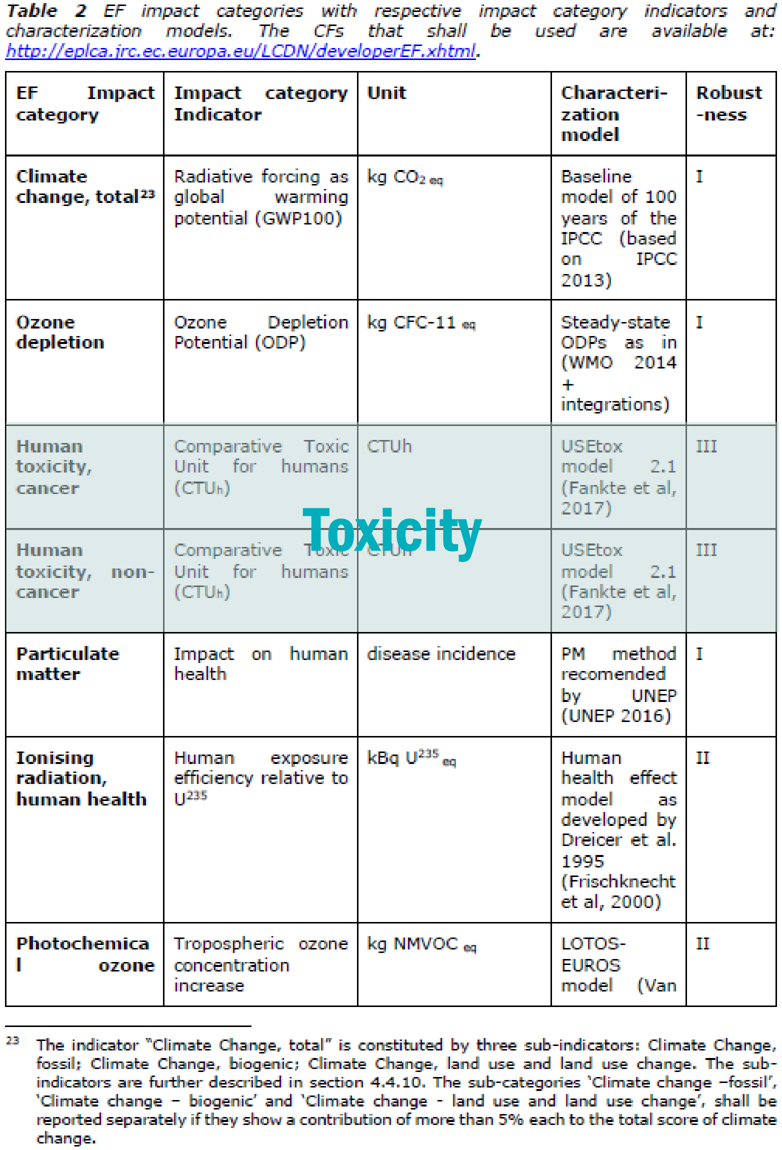

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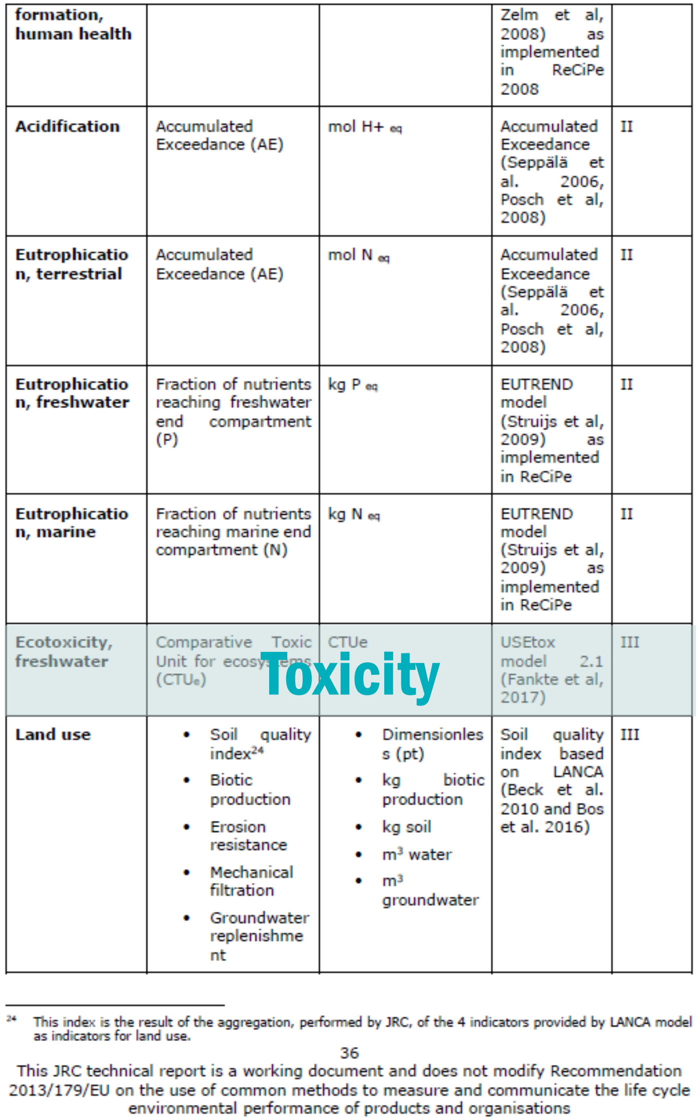

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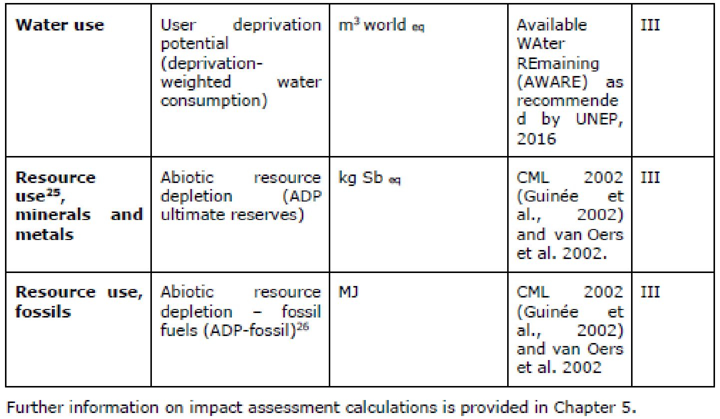

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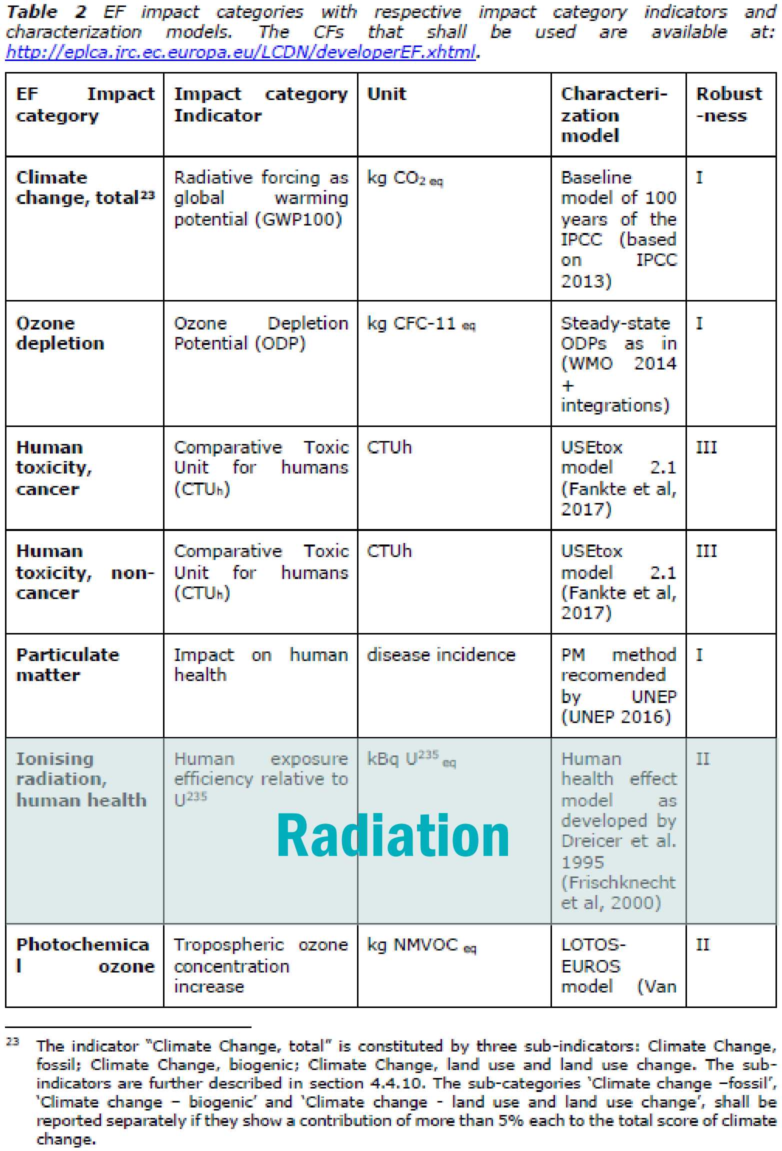

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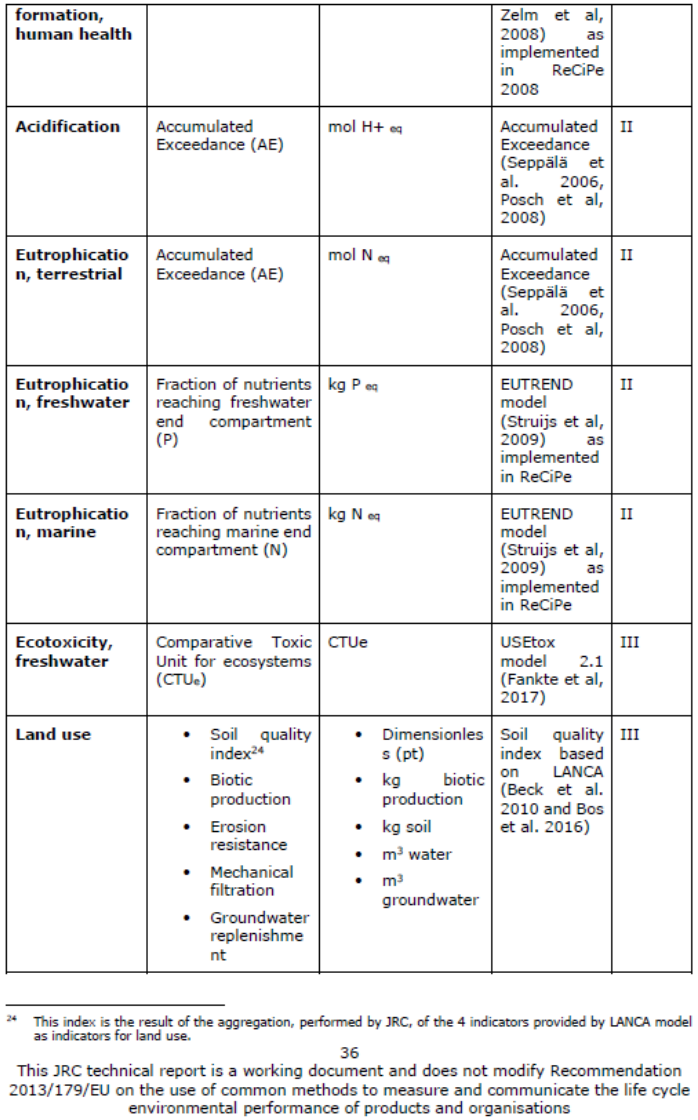

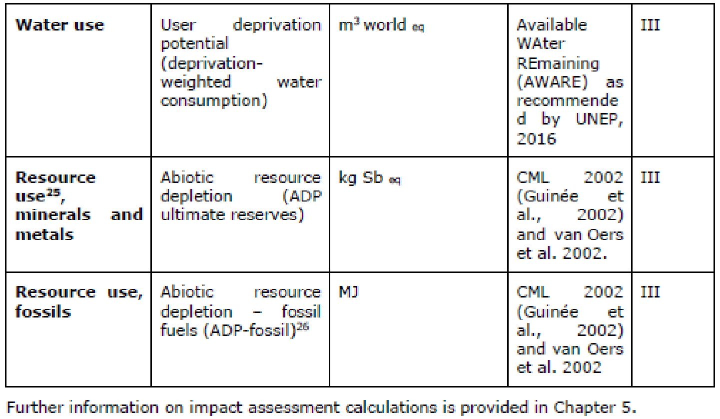

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Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)[26]	MJ	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002	III

Radiation

Further information on impact assessment calculations is provided in Chapter 5.

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JRC TECHNICAL REPORTS

Suggestions for updating the Product Environmental Footprint (PEF) method

Zampori L, Pant R

2019

LIST OF ASSESSED ENVIRONMENTAL IMPACTS

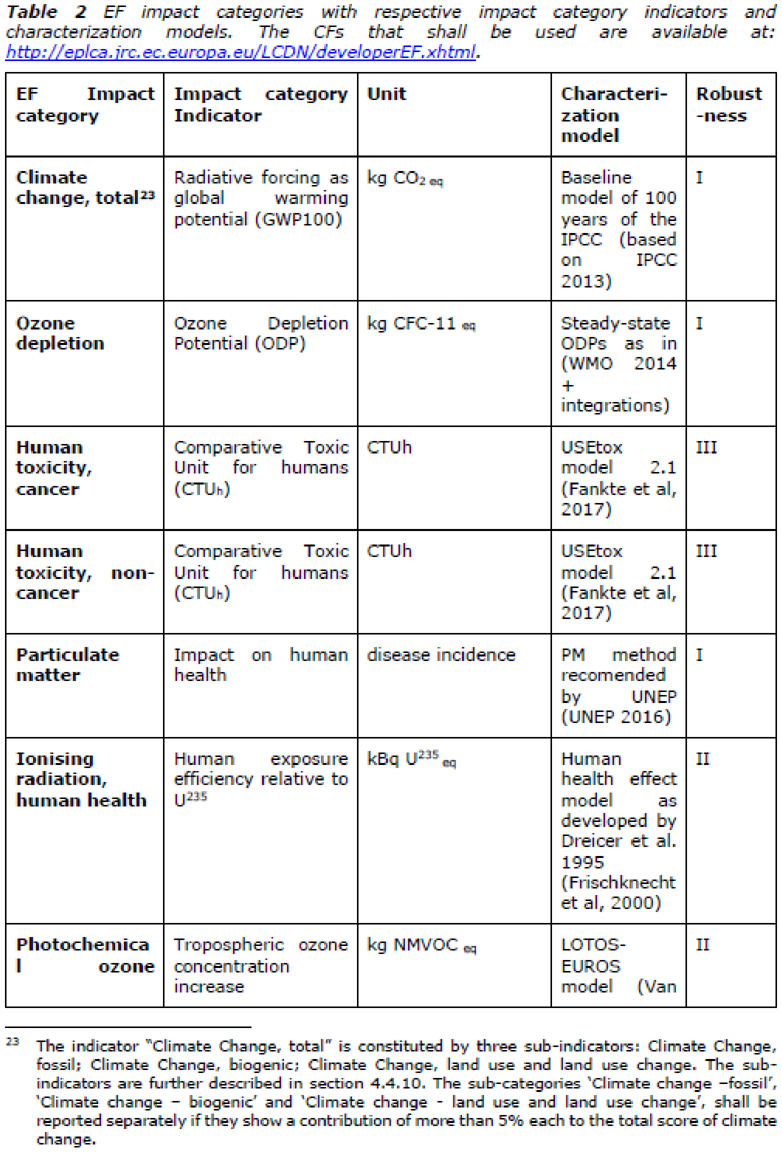
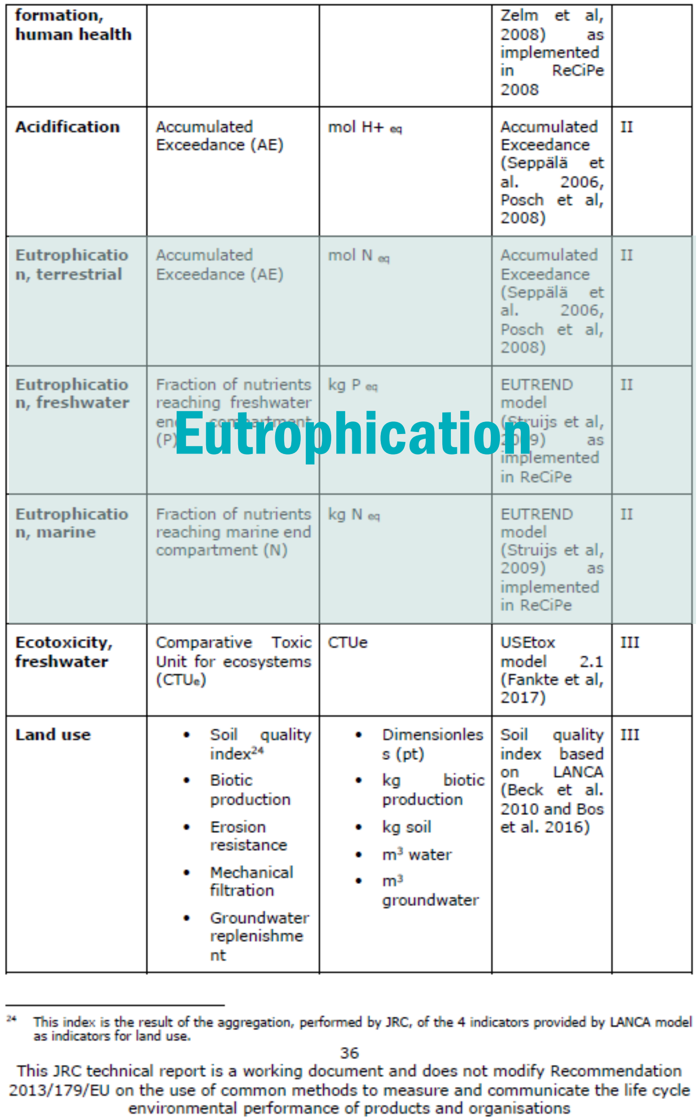
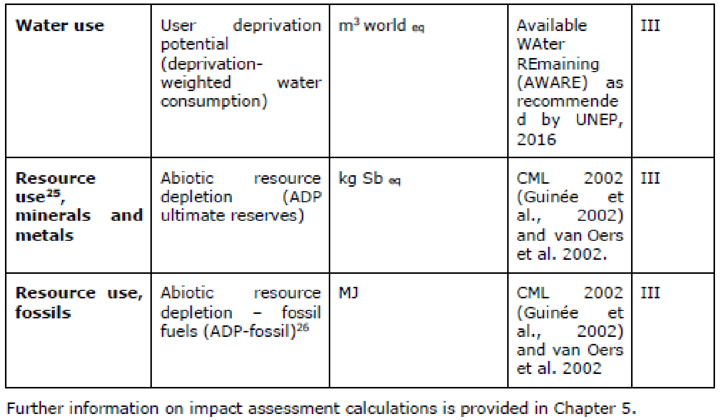

***Table 2** EF impact categories with respective impact category indicators and characterization models. The CFs that shall be used are available at: http://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml.*

EF Impact category	**Impact category Indicator**	**Unit**	**Characteri-zation model**	**Robust-ness**
Climate change, total[23]	Radiative forcing as global warming potential (GWP100)	kg CO_2 eq	Baseline model of 100 years of the IPCC (based on IPCC 2013)	I
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 eq	Steady-state ODPs as in (WMO 2014 + integrations)	I
Human toxicity, cancer	Comparative Toxic Unit for humans (CTU$_h$)	CTUh	USEtox model 2.1 (Fankte et al, 2017)	III
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTU$_h$)	CTUh	USEtox model 2.1 (Fankte et al, 2017)	III
Particulate matter	Impact on human health	disease incidence	PM method recomended by UNEP (UNEP 2016)	I
Ionising radiation, human health	Human exposure efficiency relative to U^{235}	kBq U^{235} eq	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000)	II
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg NMVOC eq	LOTOS-EUROS model (Van Zelm et al, 2008) as implemented in ReCiPe 2008	II
Acidification	Accumulated Exceedance (AE)	mol H+ eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	II
Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N eq	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	II
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe	II
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N eq	EUTREND model (Struijs et al, 2009) as implemented in ReCiPe	II
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTU$_e$)	CTUe	USEtox model 2.1 (Fankte et al, 2017)	III
Land use	• Soil quality index[24] • Biotic production • Erosion resistance • Mechanical filtration • Groundwater replenishment	• Dimensionless (pt) • kg biotic production • kg soil • m^3 water • m^3 groundwater	Soil quality index based on LANCA (Beck et al. 2010 and Bos et al. 2016)	III
Water use	User deprivation potential (deprivation-weighted water consumption)	m^3 world eq	Available WAter REmaining (AWARE) as recommended by UNEP, 2016	III
Resource use[25]**, minerals and metals**	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002.	III
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Eutrophication

Further information on impact assessment calculations is provided in Chapter 5.

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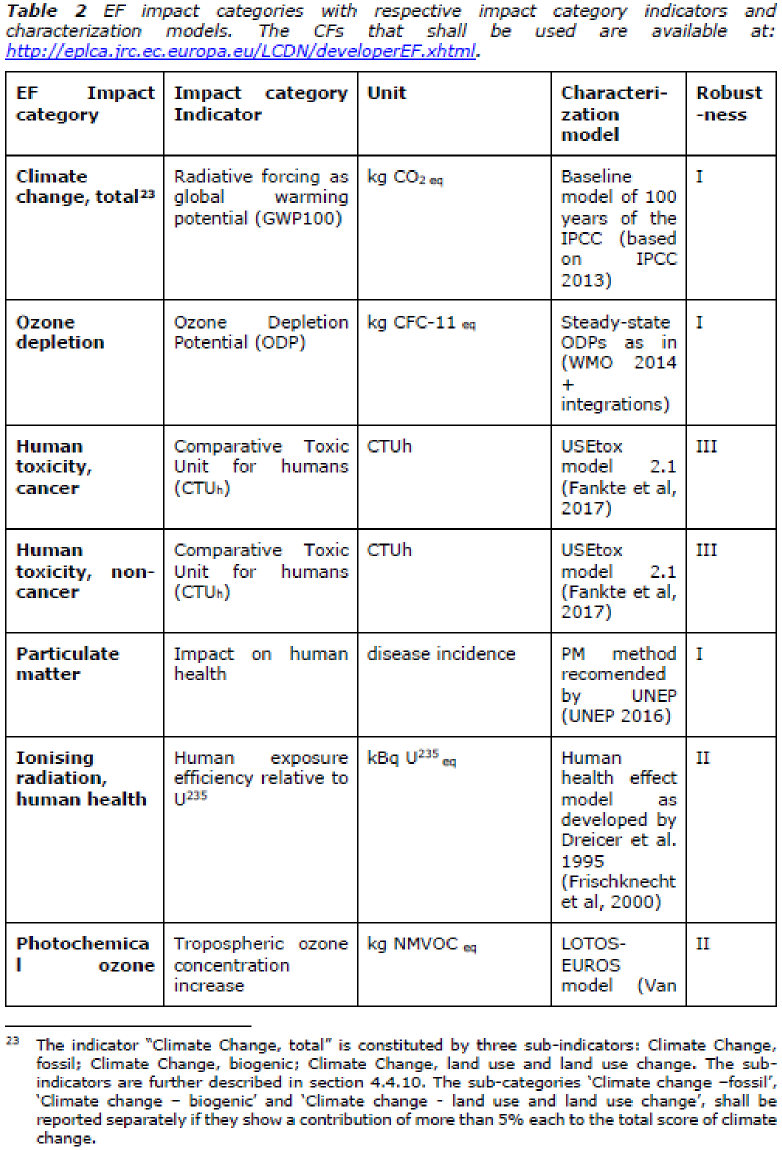
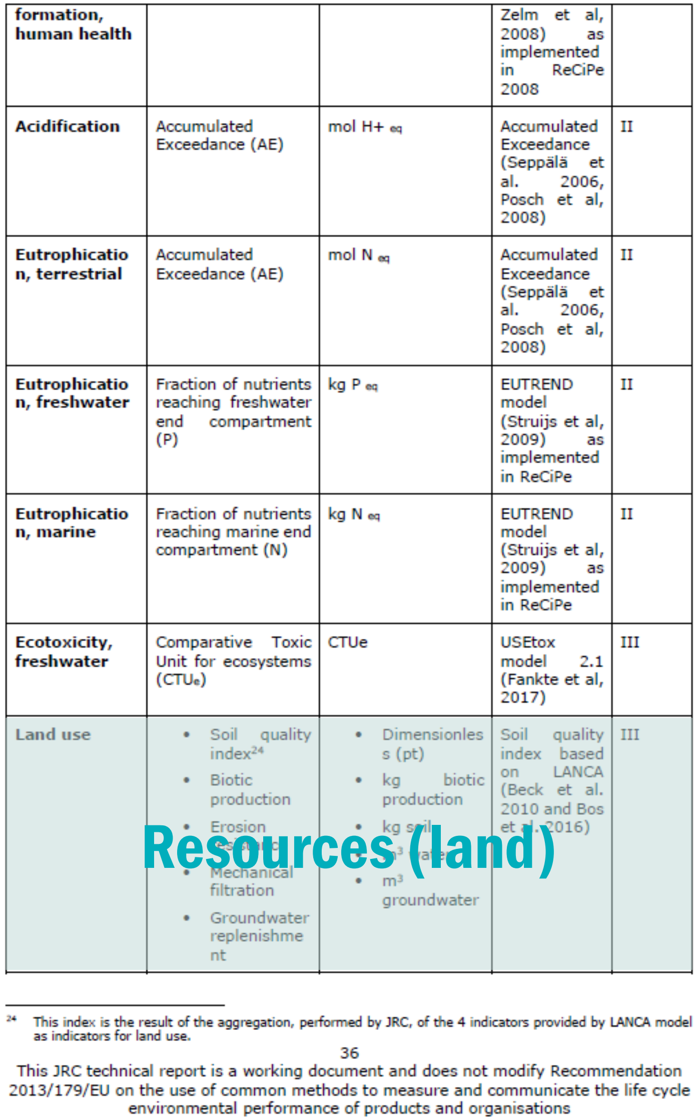
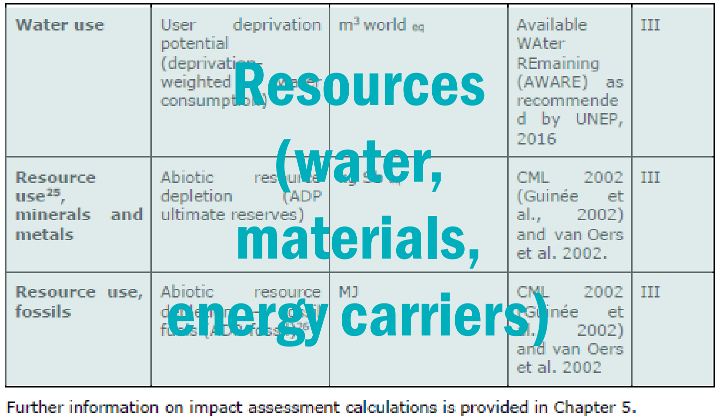
LIST OF ASSESSED ENVIRONMENTAL IMPACTS







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Resources (land)

Resources (water, materials, energy carriers)

Further information on impact assessment calculations is provided in Chapter 5.

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This JRC technical report is a working document and does not modify Recommendation 2013/179/EU on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations

JRC TECHNICAL REPORTS

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2019

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UNECE CARBON NEUTRALITY TOOLKIT

UNECE Toolkit for policy makers to make informed decisions and attain carbon neutrality

ENERGY

UNECE

TECHNOLOGY BRIEF

CARBON CAPTURE, USE AND STORAGE (CCUS)

UNECE

TECHNOLOGY BRIEF| DECARBONISING ENERGY INTENSIVE INDUSTRIES IN UNECE REGION

UNECE

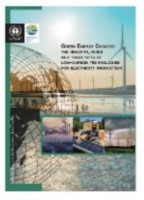
TECHNOLOGY BRIEF

HYDROGEN

UNECE

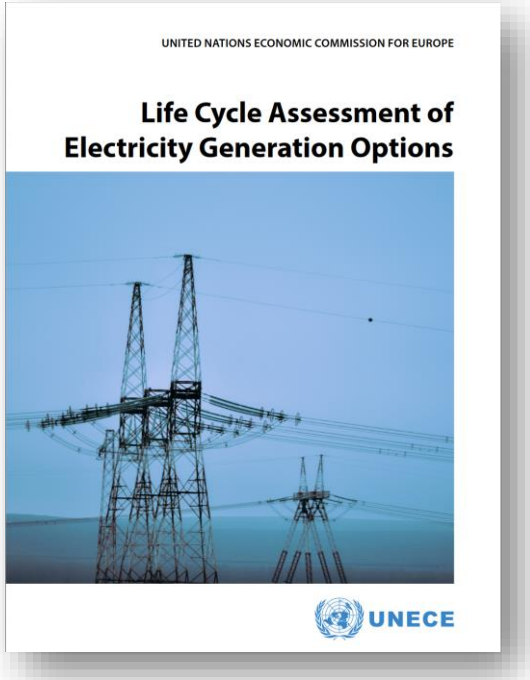
TECHNOLOGY BRIEF

NUCLEAR POWER



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

UPDATE



UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE

Life Cycle Assessment of Electricity Generation Options

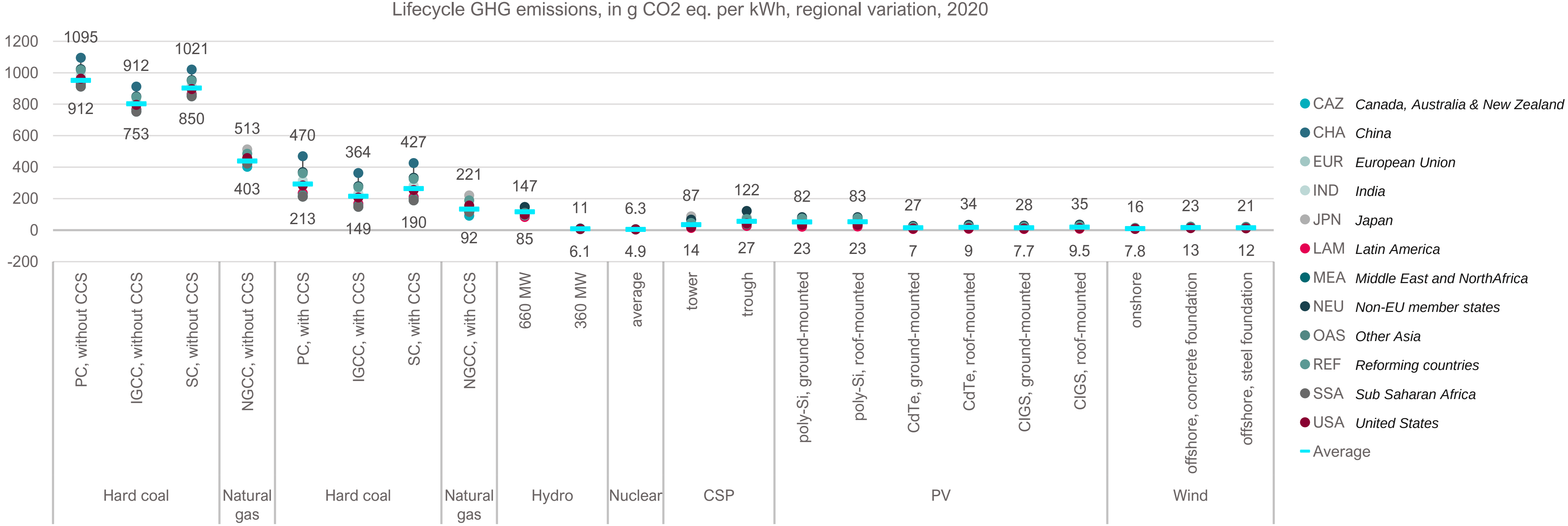
UNECE

https://unece.org/sed/documents/2021/10/reports/life-cycle-assessment-electricity-generation-options

TECHNOLOGY COMPARISON

CLIMATE

Life cycle greenhouse gas emissions for each region, g CO_2 eq./kWh


Lifecycle GHG emissions, in g CO2 eq. per kWh, regional variation, 2020

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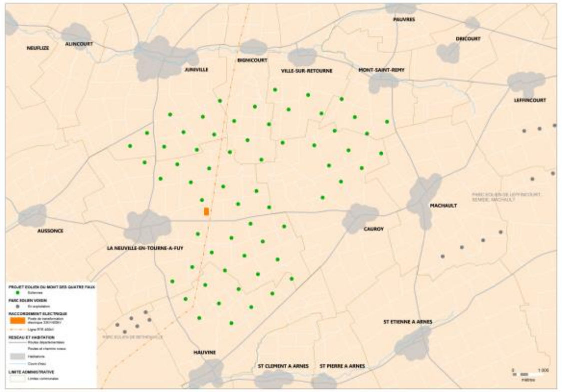
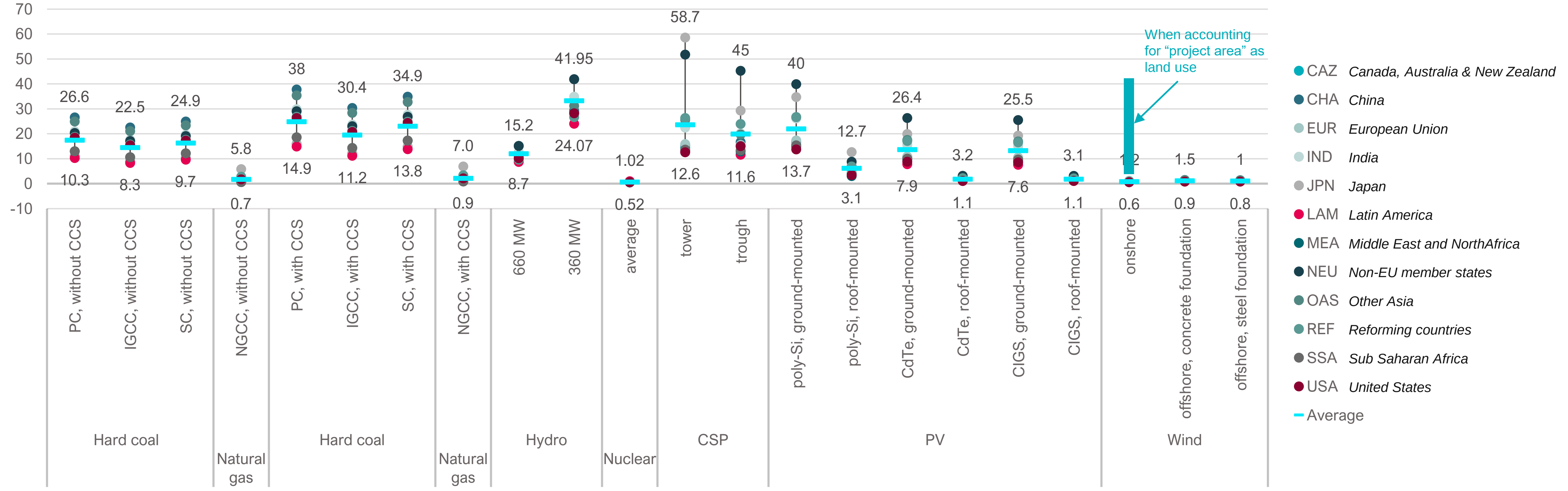
LAND USE

Life cycle land occupation, in m2-annum/MWh



Total land occupation (agricultural and urban), in m^2a per TWh, regional variation, 2020



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LAND USE

Direct vs. project area

Land use is highly dependent on

…performance of the equipment (when measured by unit of energy), i.e. normal irradiation, wind regimes

…the potential combination with other uses (e.g. roof-mounted vs. ground-mounted PV)

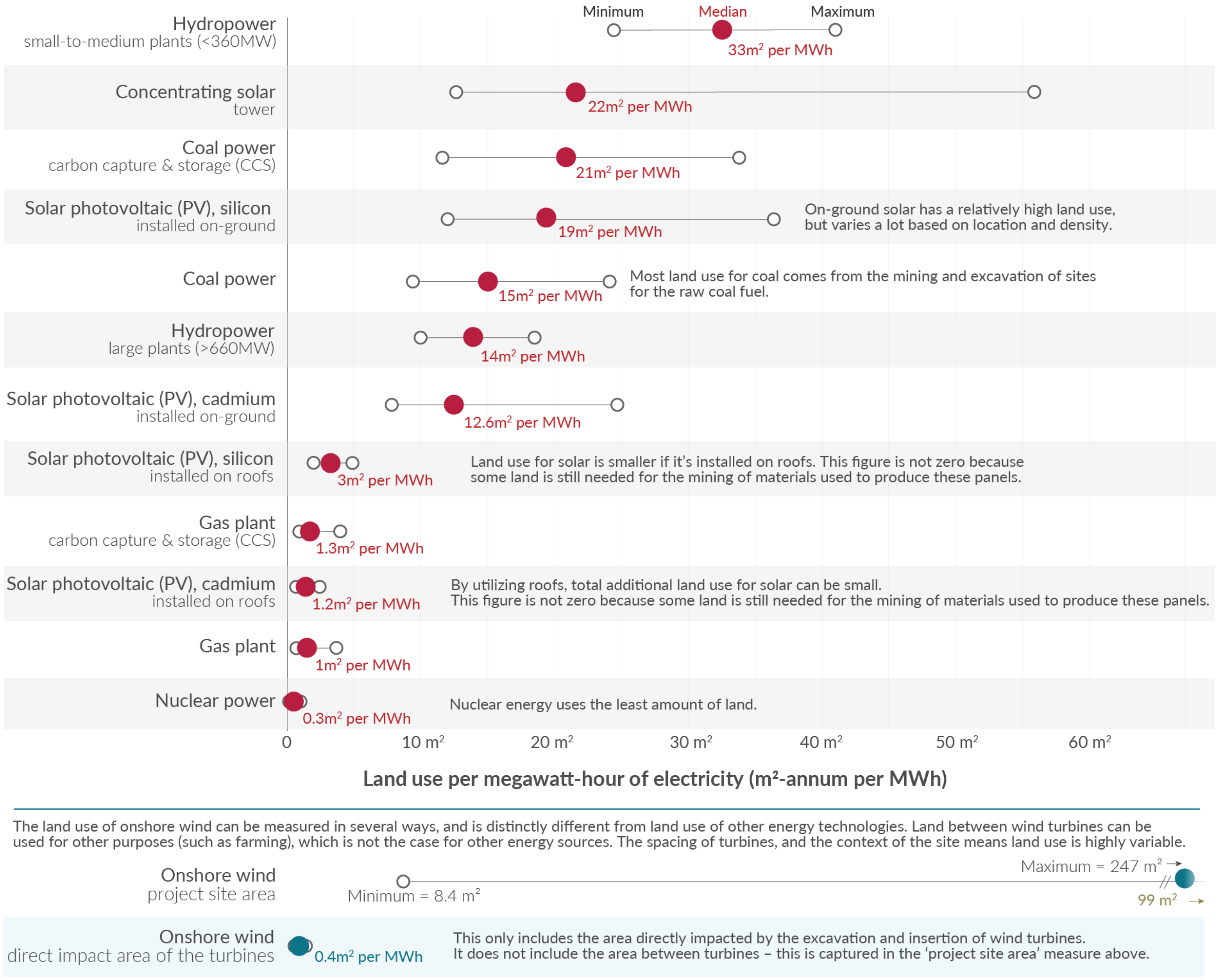
…what is considered as land use: direct or project area

← see NREL (2009)

https://ourworldindata.org/land-use-per-energy-source

Land use of energy sources per unit of electricity

Land use is based on life-cycle assessment; this means it does not only account for the land of the energy plant itself but also land used for the mining of materials used for its construction, fuel inputs, decommissioning, and the handling of waste.



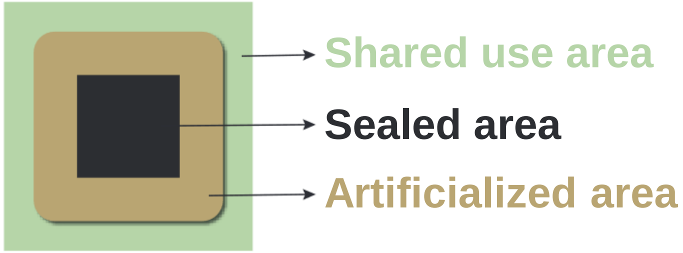
Note: Capacity factors are taken into account for each technology which adjusts for intermittency. Land use of energy storage is not included since the quantity of storage depends on the composition of the electricity mix.

Source: UNECE (2021). Lifecycle Assessment of Electricity Generation Options. *United Nations Economic Commission for Europe* for all data except wind. Wind land use calculated by the author.

See OurWorldinData.org/land-use-per-energy-source for more research on this topic.

LAND USE

Direct vs. project area


Shared use area
Sealed area
Artificialized area

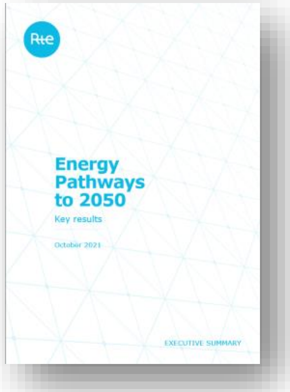
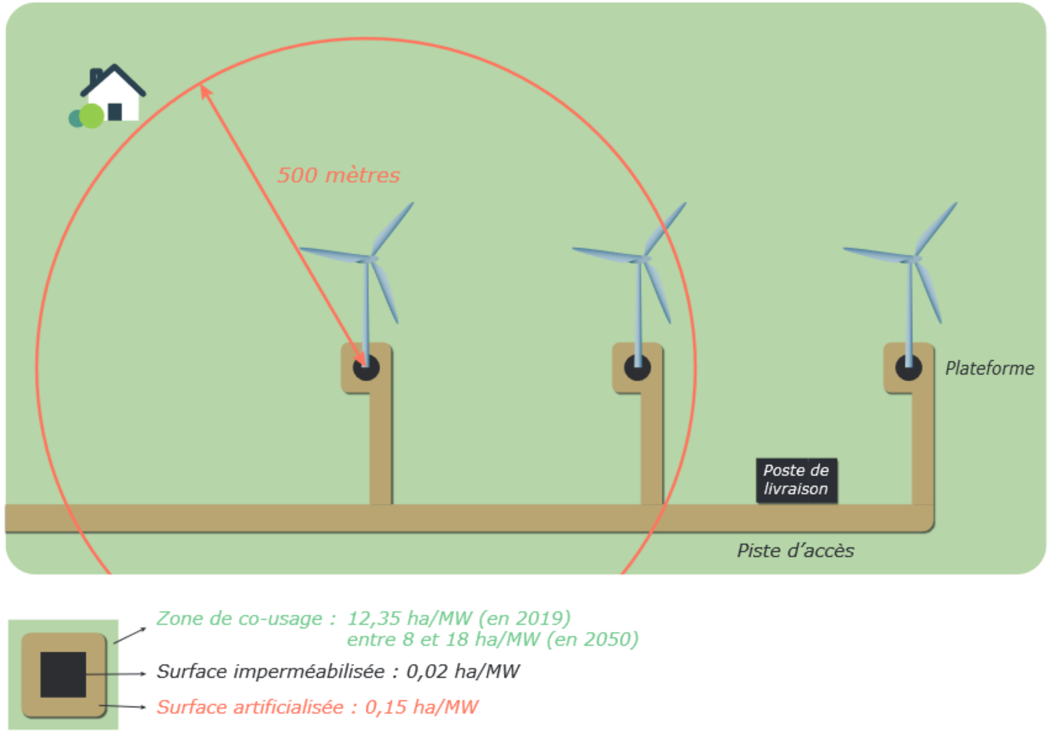
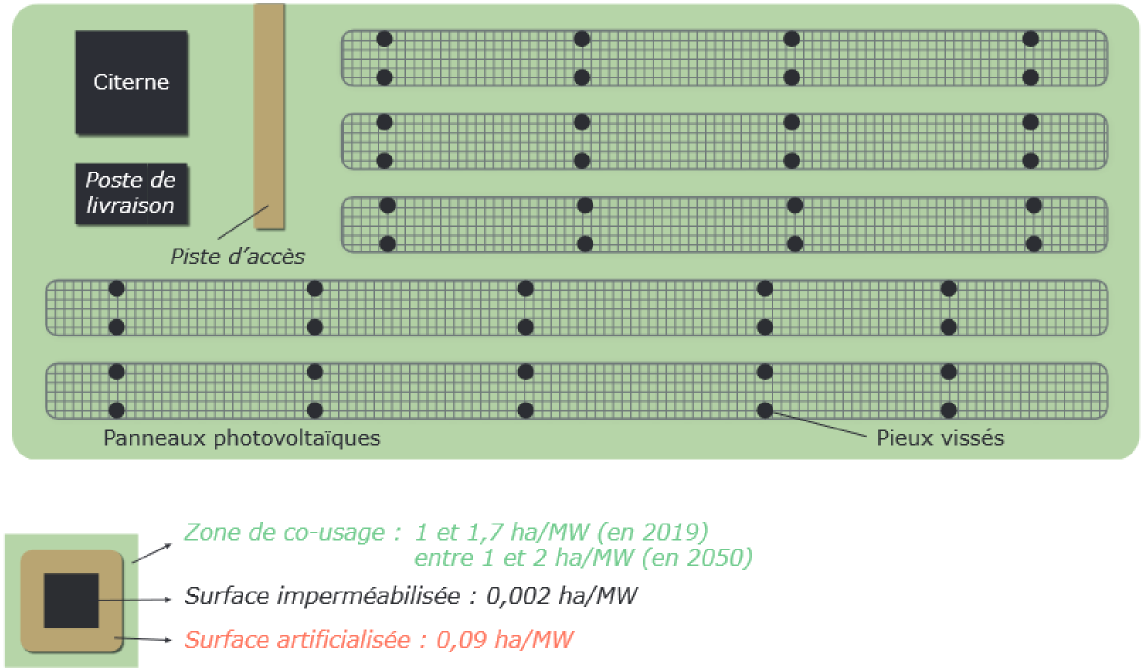

Energy Pathways to 2050
Key results

Figure 12.50 Wind farm – area occupied by type



Zone de co-usage : 12,35 ha/MW (en 2019)
entre 8 et 18 ha/MW (en 2050)
Surface imperméabilisée : 0,02 ha/MW
Surface artificialisée : 0,15 ha/MW

Figure 12.52 PV farm – area occupied by type



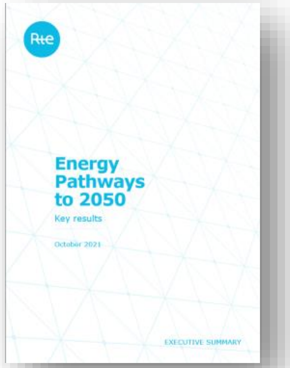
Zone de co-usage : 1 et 1,7 ha/MW (en 2019)
entre 1 et 2 ha/MW (en 2050)
Surface imperméabilisée : 0,002 ha/MW
Surface artificialisée : 0,09 ha/MW

https://assets.rte-france.com/prod/public/2022-01/Energy%20pathways%202050_Key%20results.pdf

LAND USE

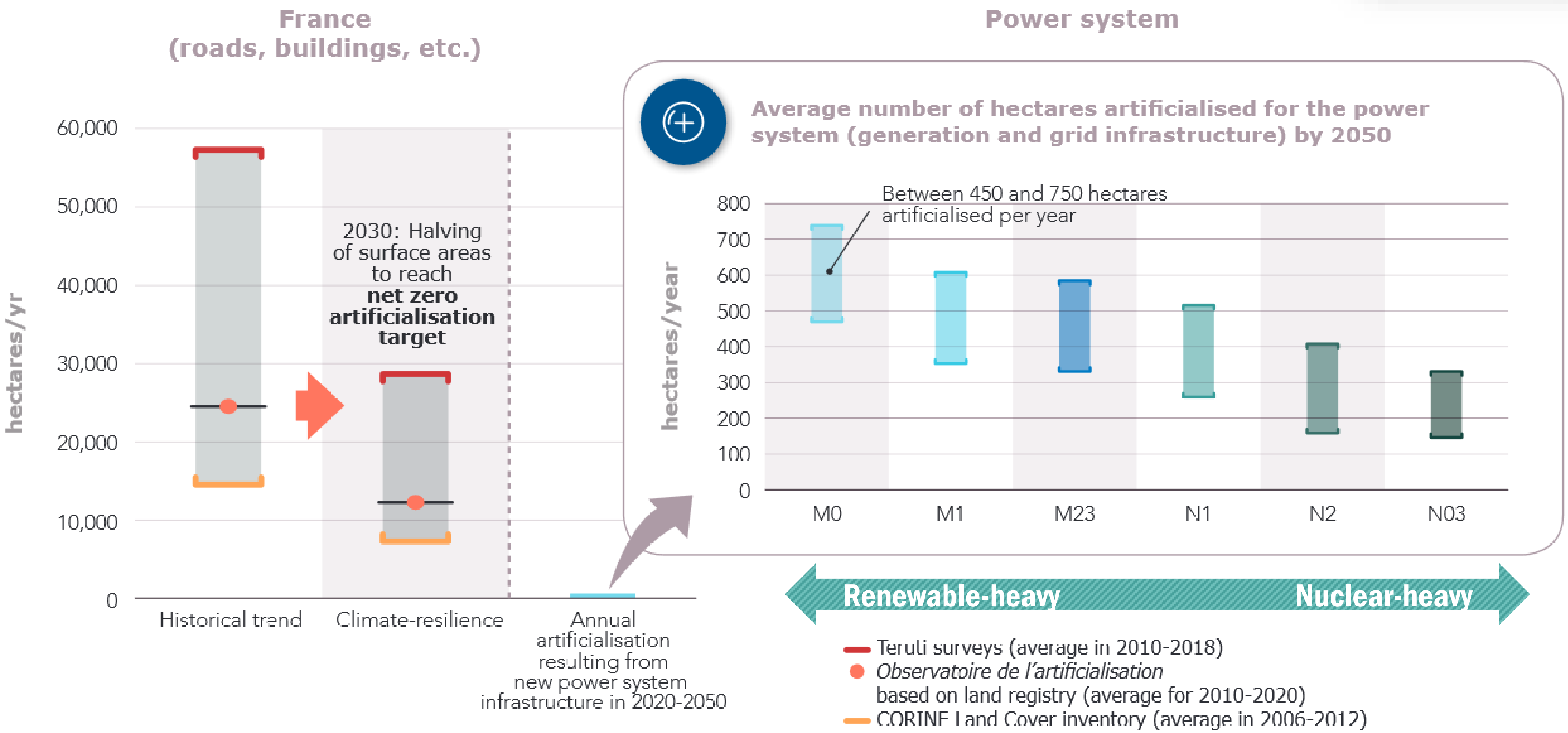
Direct vs. project area

Excerpt from a report by the French electricity TSO comparing land occupied by new power infrastructure with land sealed by other infrastructure (roads, buildings…)



Artificialisation **remains minor** when compared to existing and future infrastructure such as **roads** and **buildings**

Key finding 13 Projected trend in artificialisation through 2050 in the scenarios across all of France (historical trend and target for 2030)

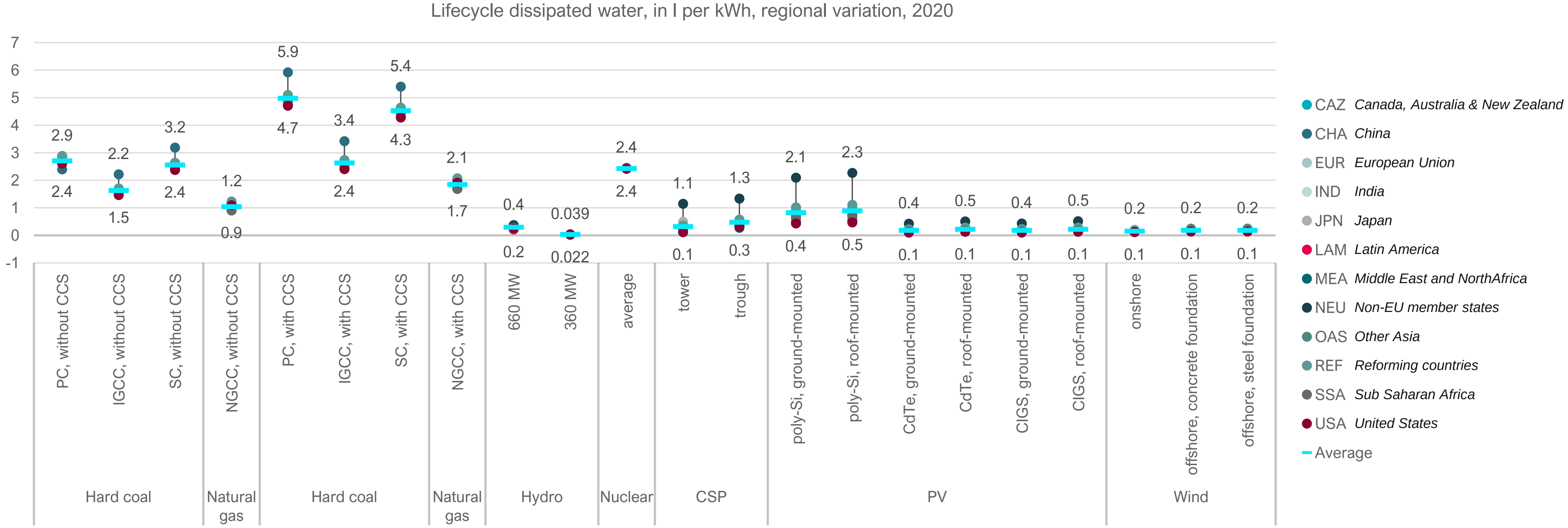


Source: CEREMA, 2021, "The determinants of the use of space".
Note: Artificialisation volumes vary depending on the valuation method used (land registry, sample surveys).
In accordance with the agreement set forth the climate and resilience act, the surface area under solar panels is counted as artificialised surface area here.

https://assets.rte-france.com/prod/public/2022-01/Energy%20pathways%202050_Key%20results.pdf

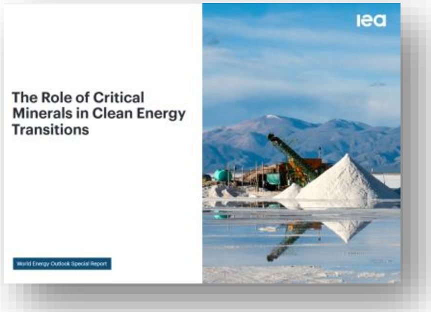
DISSIPATED WATER

Lifecycle water requirements, in m^3/MWh (l/kWh)


Lifecycle dissipated water, in l per kWh, regional variation, 2020

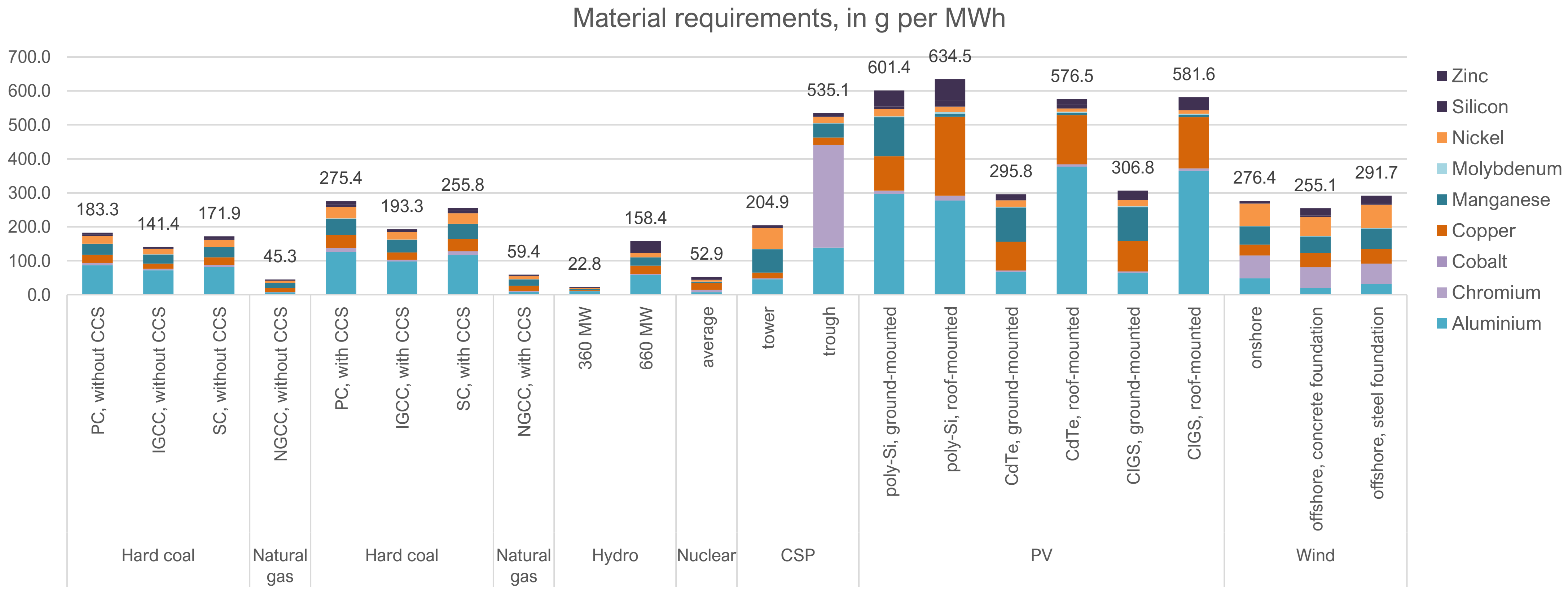
MATERIAL REQUIREMENTS

⚠ Material footprint ≠ Amount of material in bill of materials



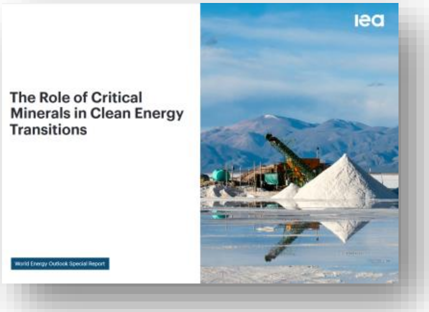
The Role of Critical Minerals in Clean Energy Transitions

Life cycle material footprint (for a select list), in g per MWh



Material requirements, in g per MWh

MATERIAL REQUIREMENTS

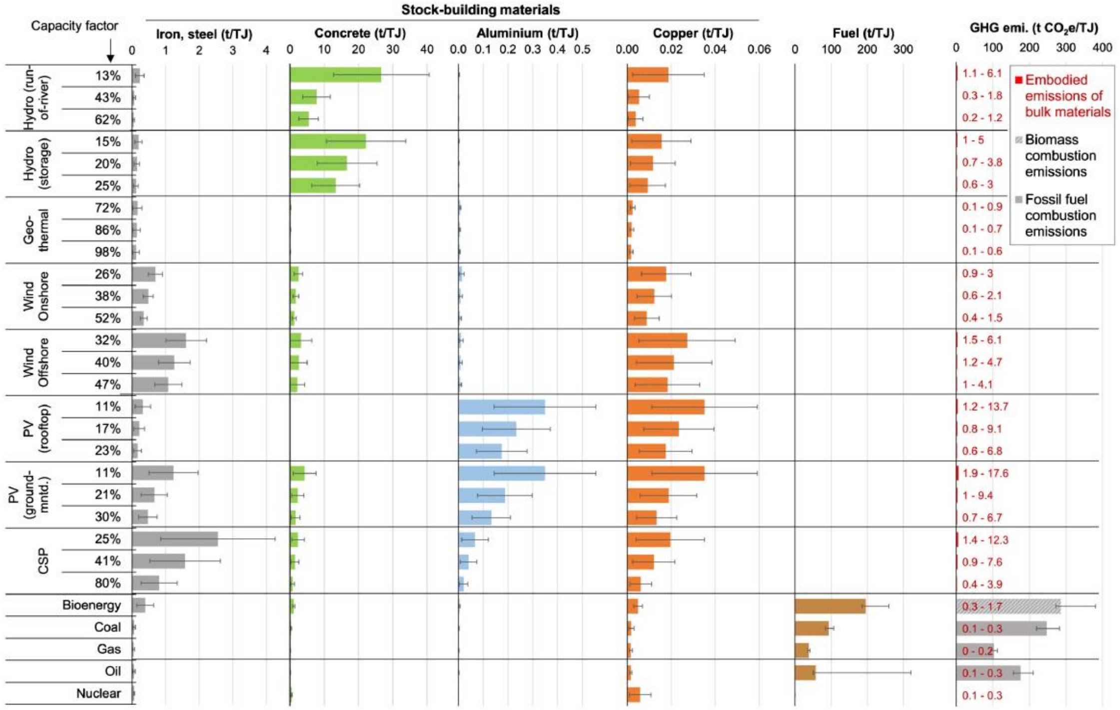


The Role of Critical Minerals in Clean Energy Transitions

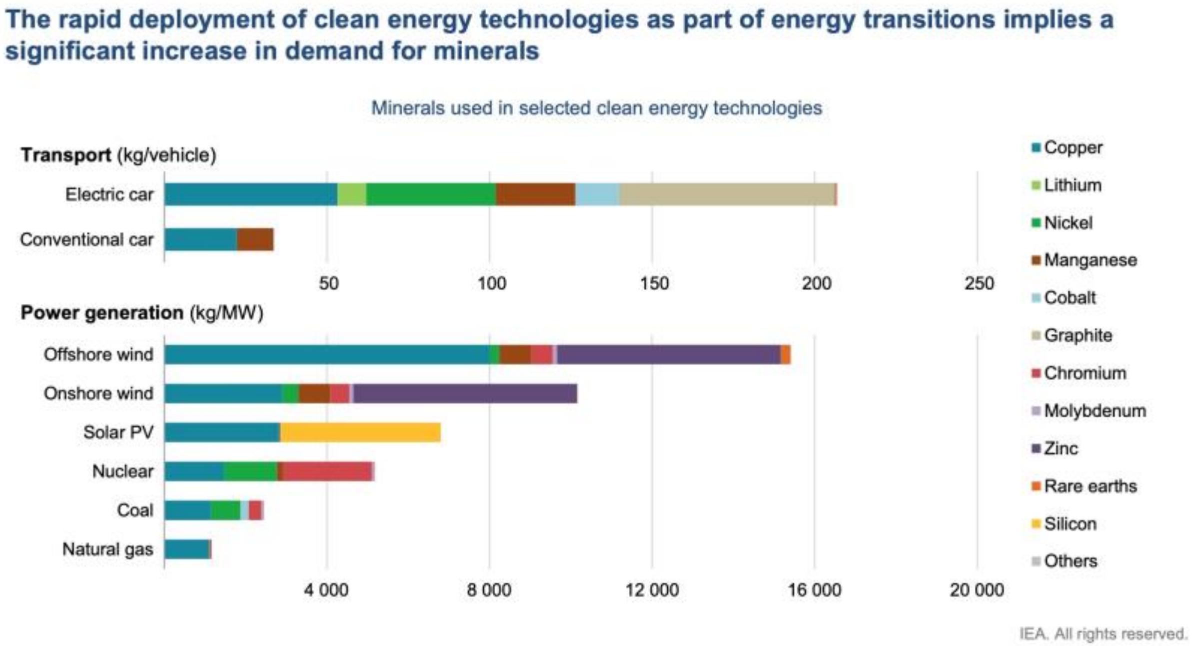
World Energy Outlook Special Report

Many estimates, little agreement on criticality

Bulk materials



“Critical” minerals, IEA



The rapid deployment of clean energy technologies as part of energy transitions implies a significant increase in demand for minerals

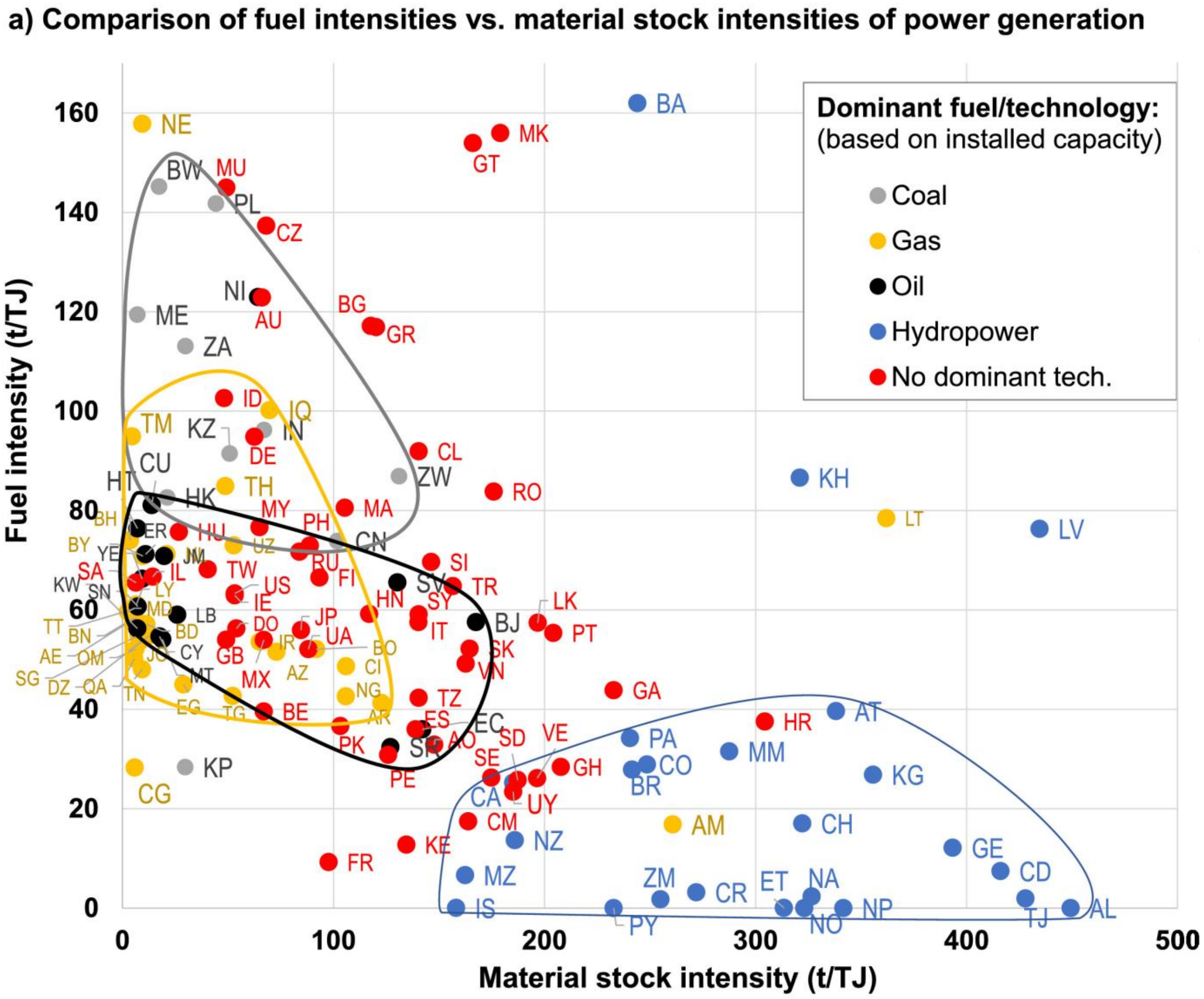
Minerals used in selected clean energy technologies

IEA. All rights reserved.

Kalt, G., Thunshirn, P., Wiedenhofer, D., Krausmann, F., Haas, W., & Haberl, H. (2021). Material stocks in global electricity infrastructures–An empirical analysis of the power sector's stock-flow-service nexus. *Resources, Conservation and Recycling*, *173*, 105723.

MATERIAL REQUIREMENTS

Is decarbonization shifting pressure from fossil fuels to materials?



In terms of volume, bulk materials (steel, concrete, aluminium, copper) are dominant

The shift from carbon-intensive to material-intensive is mostly due to hydropower, because of the amounts of concrete in dams

But this is not representative of the actual “stress” or “criticality” of using materials

Kalt, G., Thunshirn, P., Wiedenhofer, D., Krausmann, F., Haas, W., & Haberl, H. (2021). Material stocks in global electricity infrastructures–An empirical analysis of the power sector's stock-flow-service nexus. *Resources, Conservation and Recycling*, *173*, 105723.

MATERIAL REQUIREMENTS

Material-specific ESG indicators?

nature COMMUNICATIONS

ARTICLE

https://doi.org/10.1038/s41467-020-18661-9 OPEN

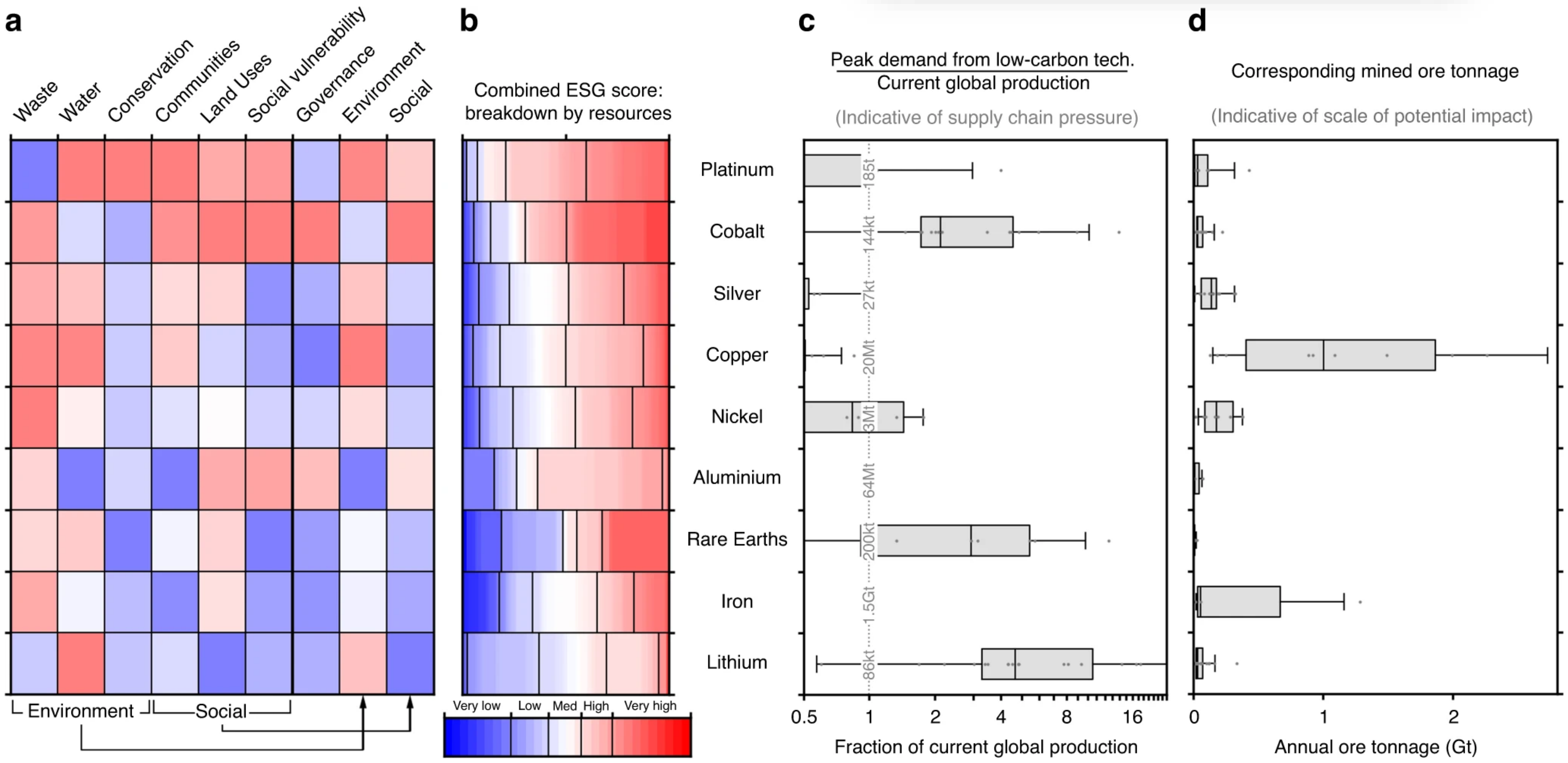
Check for updates

The social and environmental complexities of extracting energy transition metals

Éléonore Lèbre [1✉], Martin Stringer [2✉], Kamila Svobodova [1], John R. Owen [1], Deanna Kemp [1], Claire Côte [3], Andrea Arratia-Solar [1] & Rick K. Valenta [2]

A more refined way to assess the criticality of a material would be to evaluate the various **environmental**, **social**, or **governance** dimensions associated with extraction

…and compare future demand with current production to assess the "extraction gap" for each material



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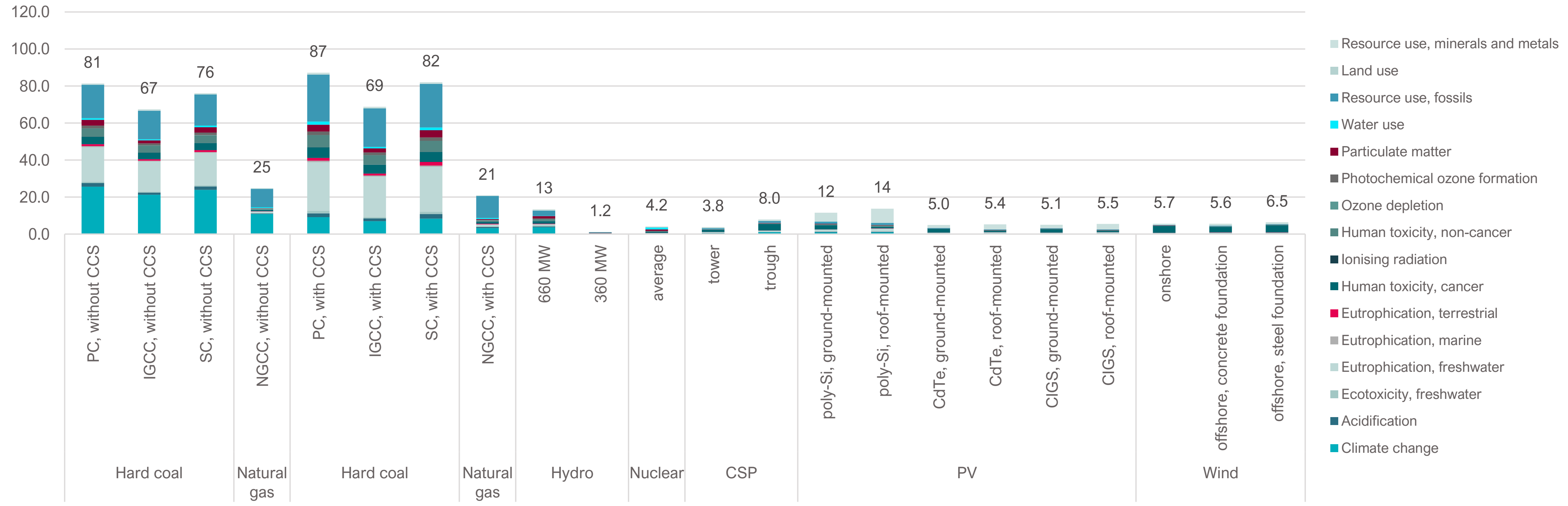
NORMALISED AND WEIGHTED RESULTS

Impact categories can be normalised and aggregated (handle with care!)

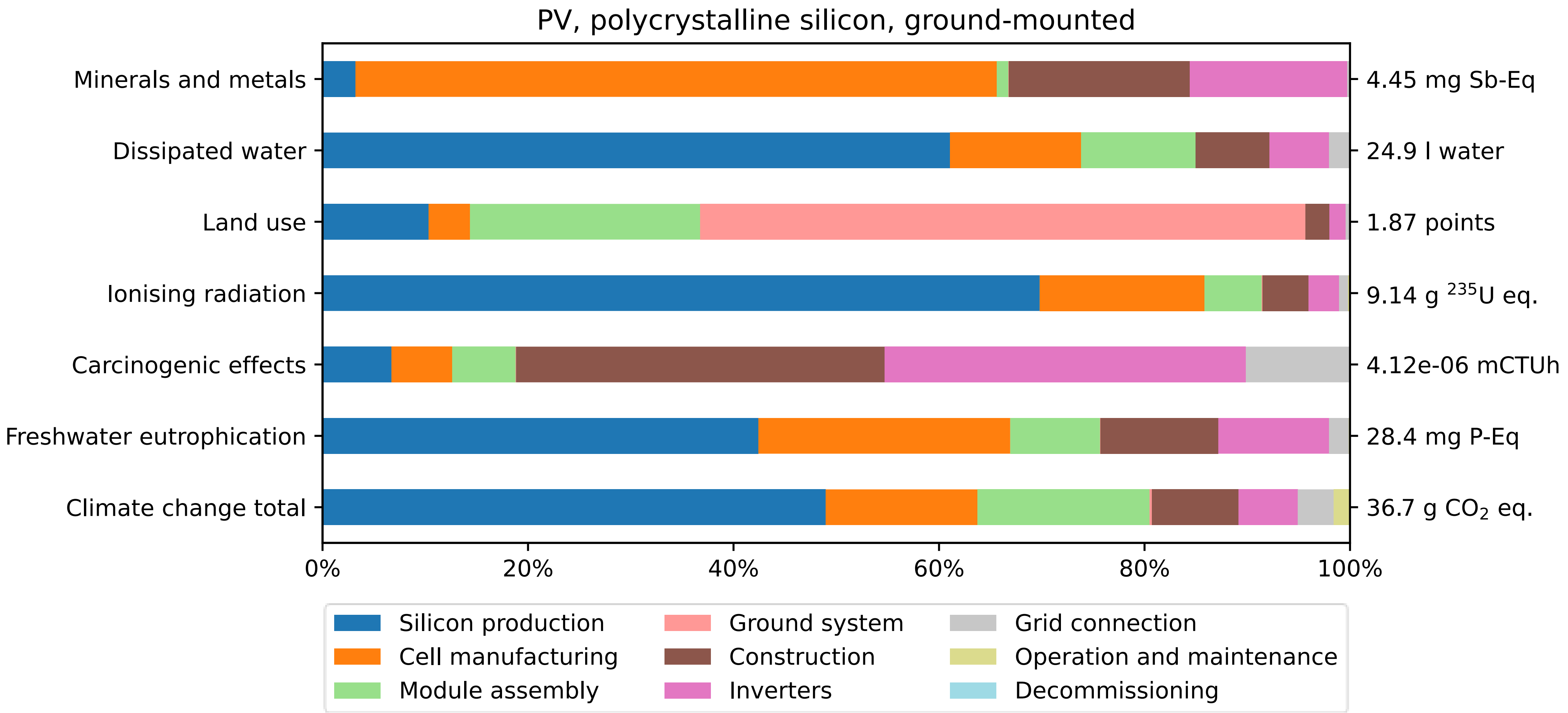
Normalised lifecycle impacts, weighted, of the production of 1 TWh, per technology, Europe, 2020



BUT WHERE DO IMPACTS COME FROM?

PHOTOVOLTAICS

Lifecycle impacts per kWh (PV, silicon, ground-mounted)



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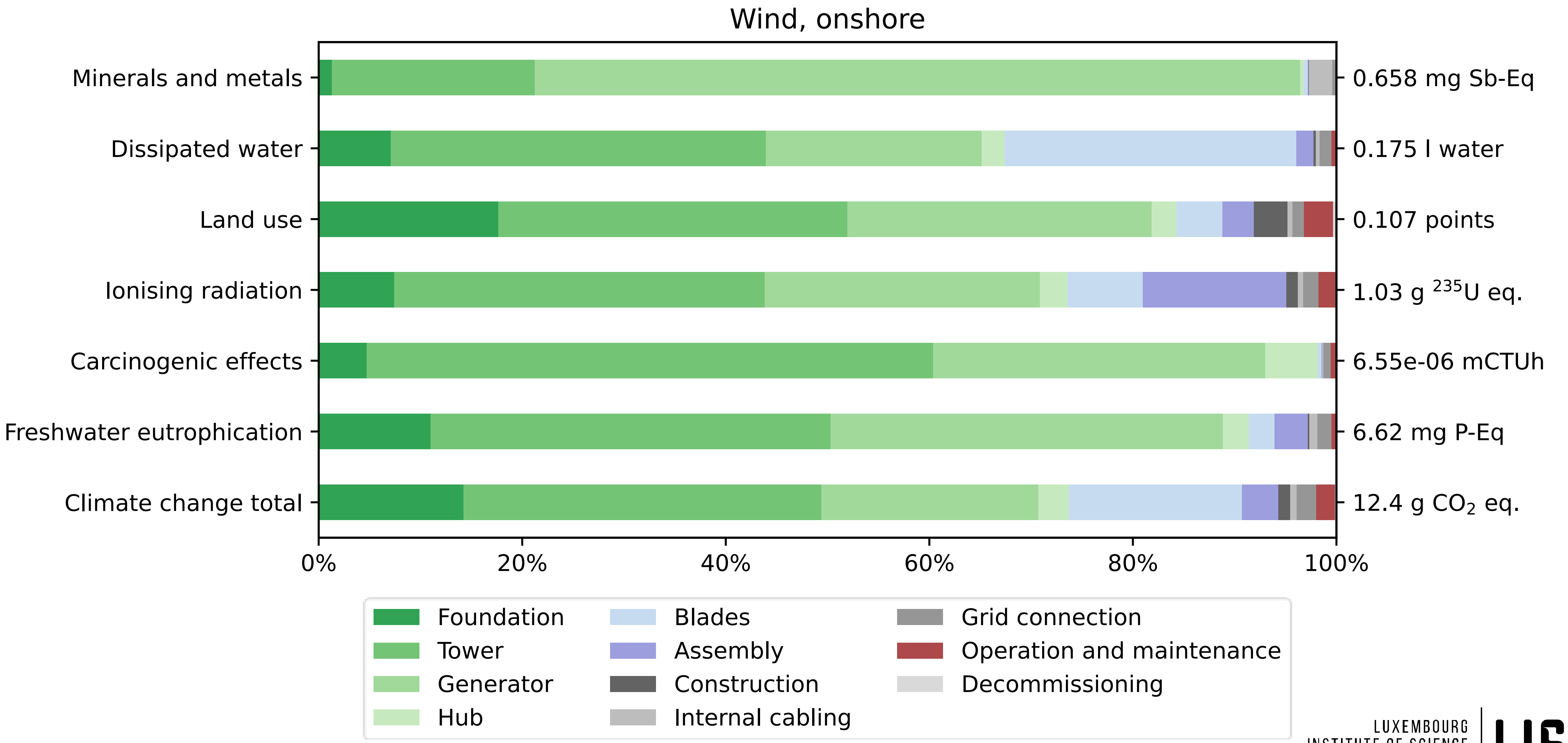
WIND POWER

Lifecycle impacts per kWh (onshore, 2.5 MW, 20-year)



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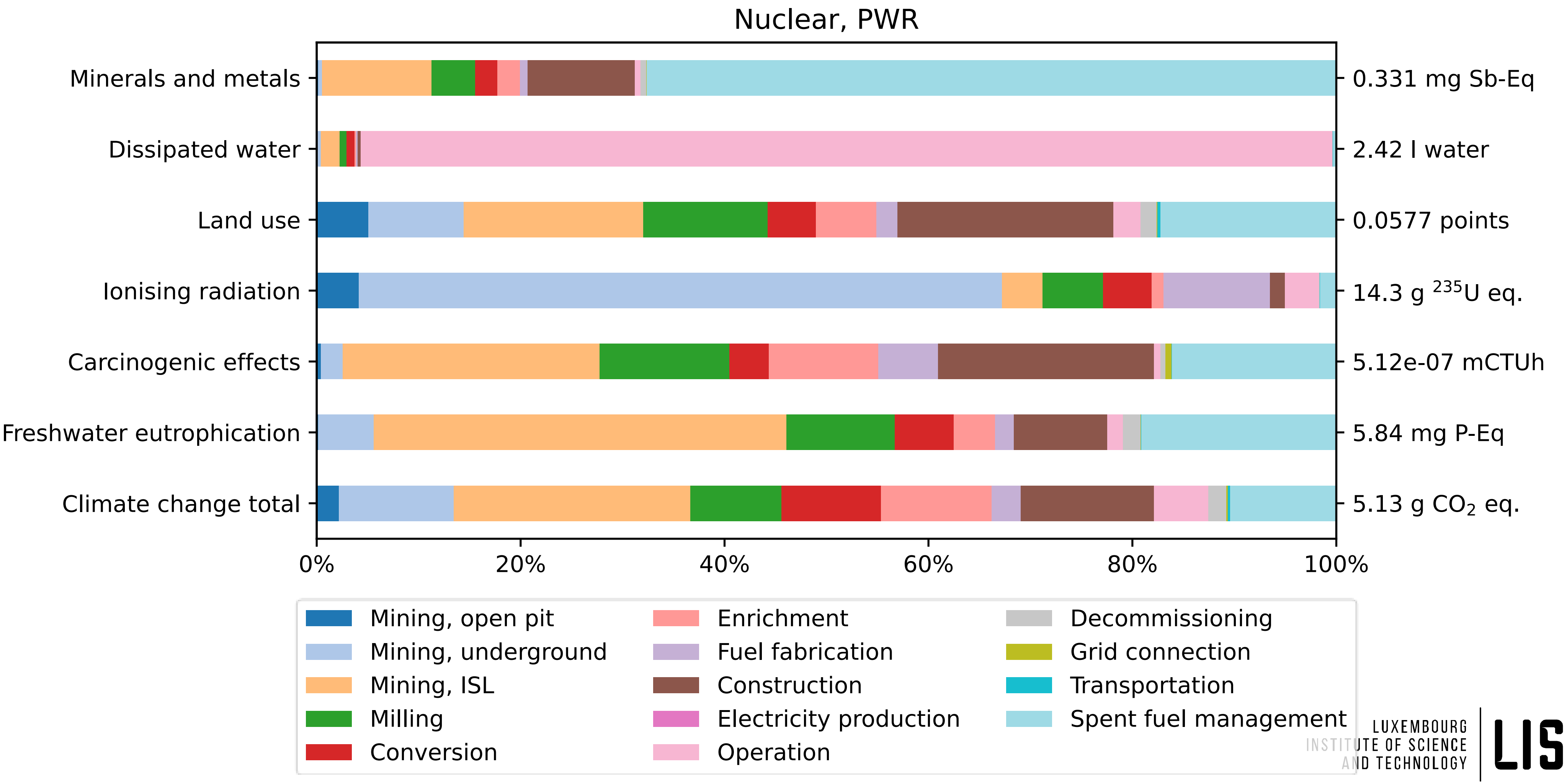
NUCLEAR POWER

Lifecycle impacts per kWh (1000 MW PWR, 60 year lifetime)



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TAKE-AWAY MESSAGES

All electricity sources have an impact, the question is “how much?”

GHG emissions are very low for all renewables (**wind: 8-20, PV 20-80**) and nuclear power (**5-7 g CO_2 eq./kWh**)

For renewables, most emissions are embodied in infrastructure – the cleaner the economy, the cleaner the power, etc.

Nuclear power has an environmental profile that shows low impact on all indicators – due to the very high energy density of uranium

Land occupation can be a concern, depending on what is accounted for (plant- vs. park-level, sealed vs. occupied, etc.) – utility PV: 20, NGCC or nuclear: 1 m^2a/MWh

Material requirements (bulk) might be of concern, as demand (for e.g. copper) will increase significantly with high-renewable scenarios

Specialty materials (precious metals, REEs) may become subject to supply risks with wind and solar (and batteries), but substitutability and underestimated reserves may be alleviating this stress

SOME WORDS ON SCENARIO COMPARISON

Assessing global pathways

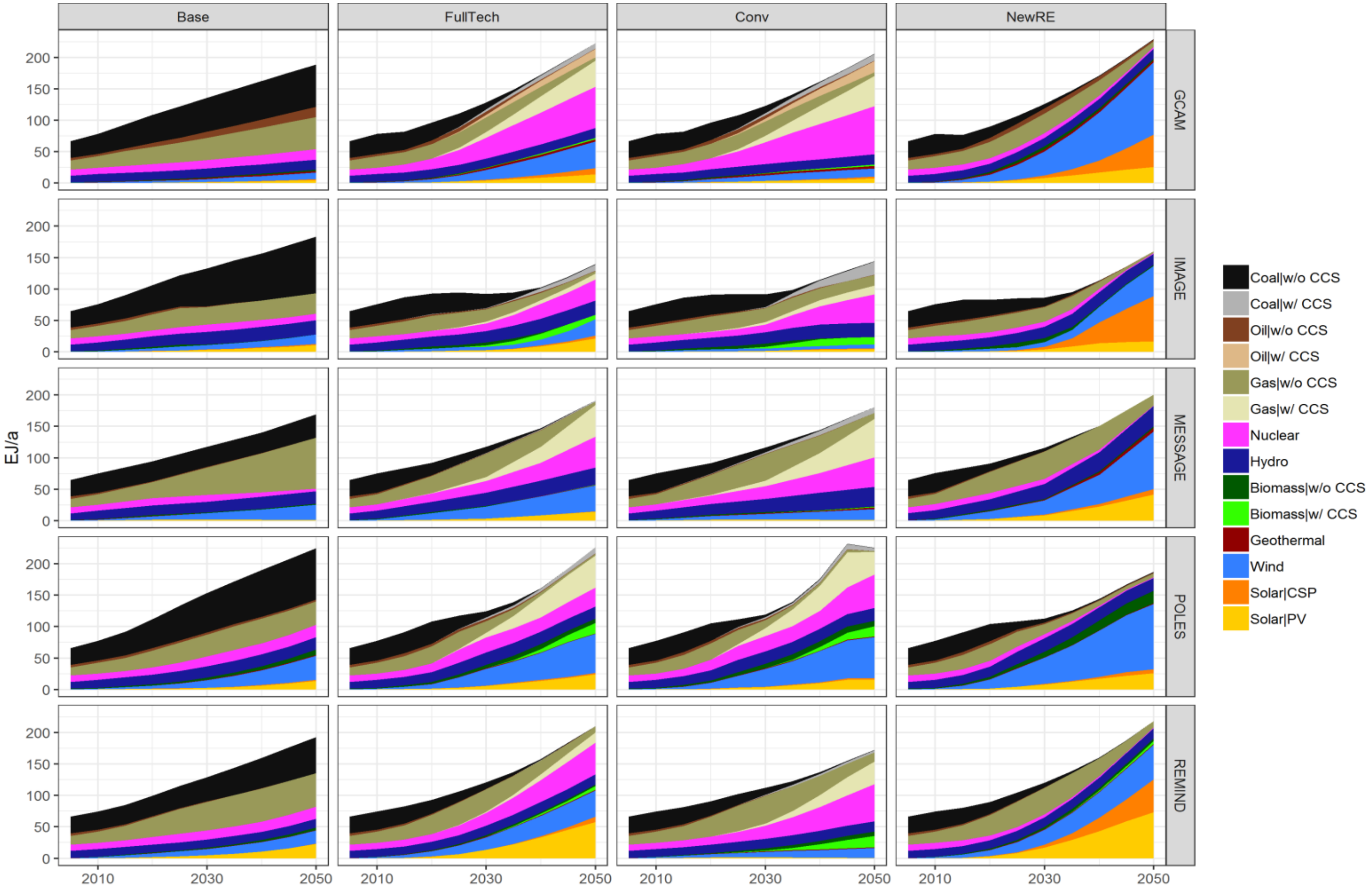
Upscaling environmental impacts with various decarbonization pathways can reveal potential issues

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.

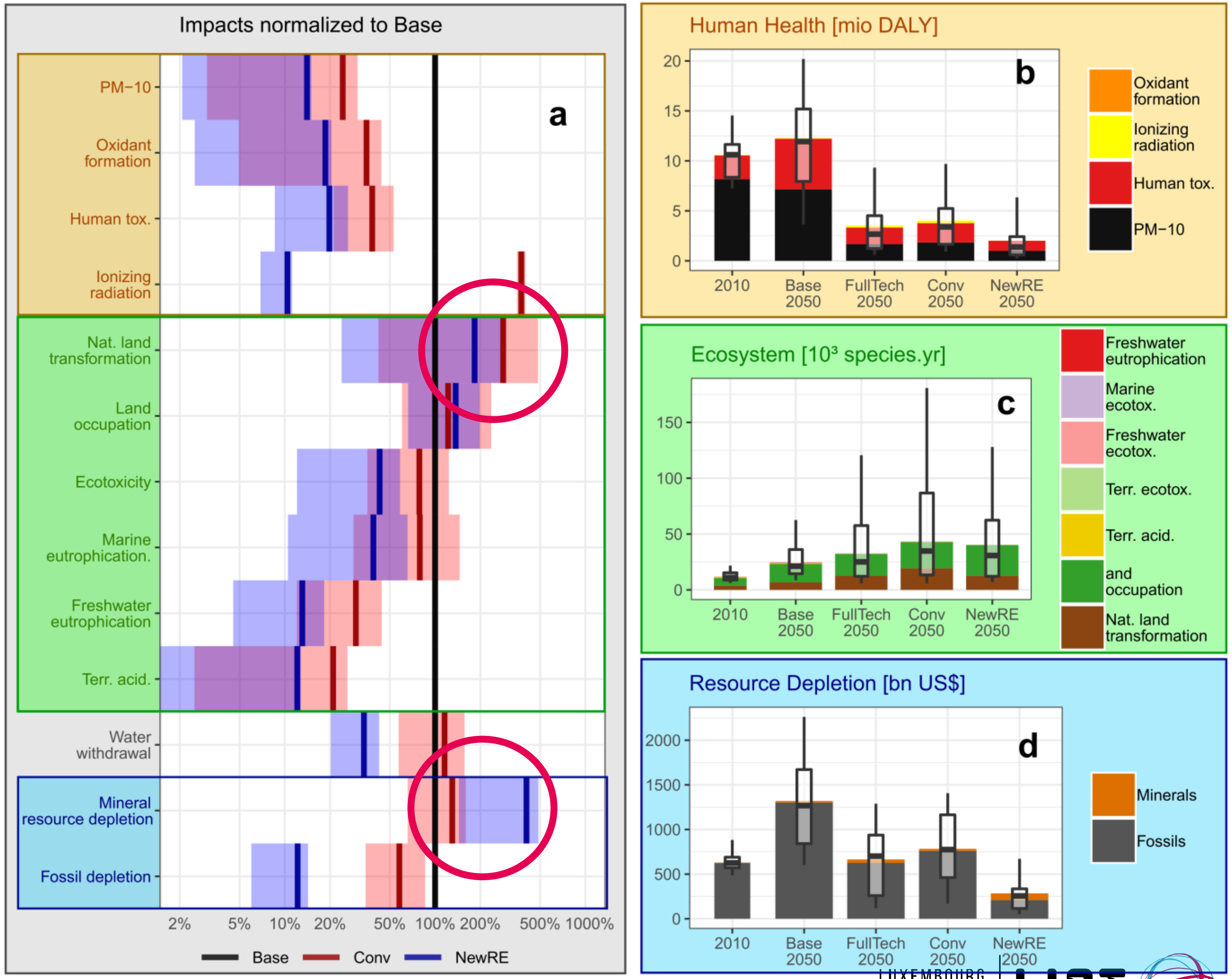
SOME WORDS ON SCENARIO COMPARISON

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



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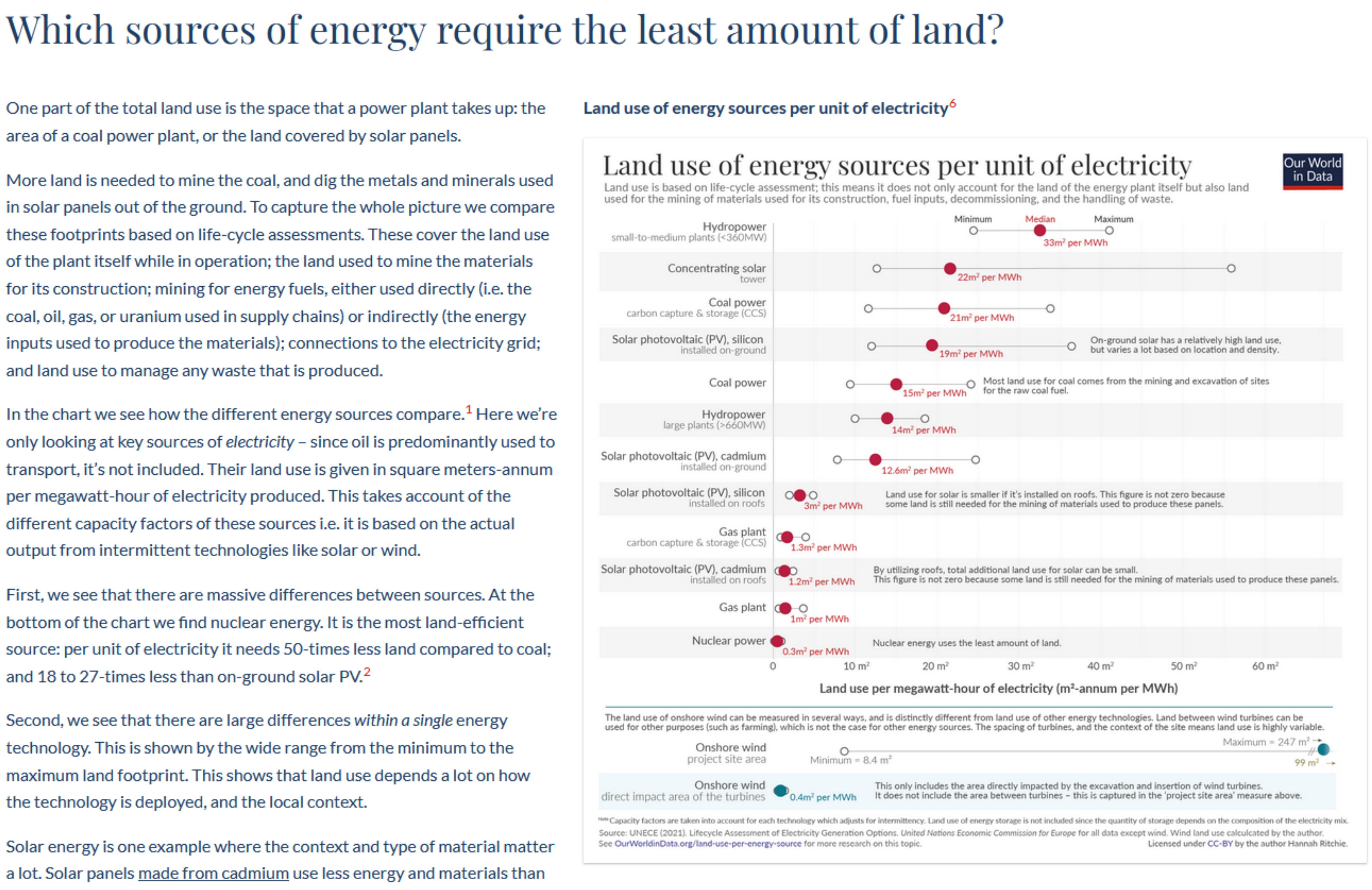
Luderer, G., Pehl, M., Arvesen, A., Gibon, T., Bodirsky, B. L., de Boer, H. S., ... & Hertwich E. G. (2019). Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies. *Nature communications*, *10*(1), 1-13.

UNECE REPORT USED IN OTHER INITIATIVES

Our World in Data

https://ourworldindata.org/land-use-per-energy-source

Great visualisation of land use differences among technologies



Which sources of energy require the least amount of land?

One part of the total land use is the space that a power plant takes up: the area of a coal power plant, or the land covered by solar panels.

More land is needed to mine the coal, and dig the metals and minerals used in solar panels out of the ground. To capture the whole picture we compare these footprints based on life-cycle assessments. These cover the land use of the plant itself while in operation; the land used to mine the materials for its construction; mining for energy fuels, either used directly (i.e. the coal, oil, gas, or uranium used in supply chains) or indirectly (the energy inputs used to produce the materials); connections to the electricity grid; and land use to manage any waste that is produced.

In the chart we see how the different energy sources compare.[1] Here we're only looking at key sources of *electricity* – since oil is predominantly used to transport, it's not included. Their land use is given in square meters-annum per megawatt-hour of electricity produced. This takes account of the different capacity factors of these sources i.e. it is based on the actual output from intermittent technologies like solar or wind.

First, we see that there are massive differences between sources. At the bottom of the chart we find nuclear energy. It is the most land-efficient source: per unit of electricity it needs 50-times less land compared to coal; and 18 to 27-times less than on-ground solar PV.[2]

Second, we see that there are large differences *within a single* energy technology. This is shown by the wide range from the minimum to the maximum land footprint. This shows that land use depends a lot on how the technology is deployed, and the local context.

Solar energy is one example where the context and type of material matter a lot. Solar panels made from cadmium use less energy and materials than

Land use of energy sources per unit of electricity[6]

Land use of energy sources per unit of electricity

Land use is based on life-cycle assessment; this means it does not only account for the land of the energy plant itself but also land used for the mining of materials used for its construction, fuel inputs, decommissioning, and the handling of waste.

On-ground solar has a relatively high land use, but varies a lot based on location and density.

Most land use for coal comes from the mining and excavation of sites for the raw coal fuel.

Land use for solar is smaller if it's installed on roofs. This figure is not zero because some land is still needed for the mining of materials used to produce these panels.

By utilizing roofs, total additional land use for solar can be small. This figure is not zero because some land is still needed for the mining of materials used to produce these panels.

Nuclear energy uses the least amount of land.

The land use of onshore wind can be measured in several ways, and is distinctly different from land use of other energy technologies. Land between wind turbines can be used for other purposes (such as farming), which is not the case for other energy sources. The spacing of turbines, and the context of the site means land use is highly variable.

This only includes the area directly impacted by the excavation and insertion of wind turbines. It does not include the area between turbines – this is captured in the 'project site area' measure above.

Note Capacity factors are taken into account for each technology which adjusts for intermittency. Land use of energy storage is not included since the quantity of storage depends on the composition of the electricity mix.

Source: UNECE (2021). Lifecycle Assessment of Electricity Generation Options. *United Nations Economic Commission for Europe* for all data except wind. Wind land use calculated by the author.

See OurWorldinData.org/land-use-per-energy-source for more research on this topic.

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UNECE REPORT USED IN OTHER INITIATIVES

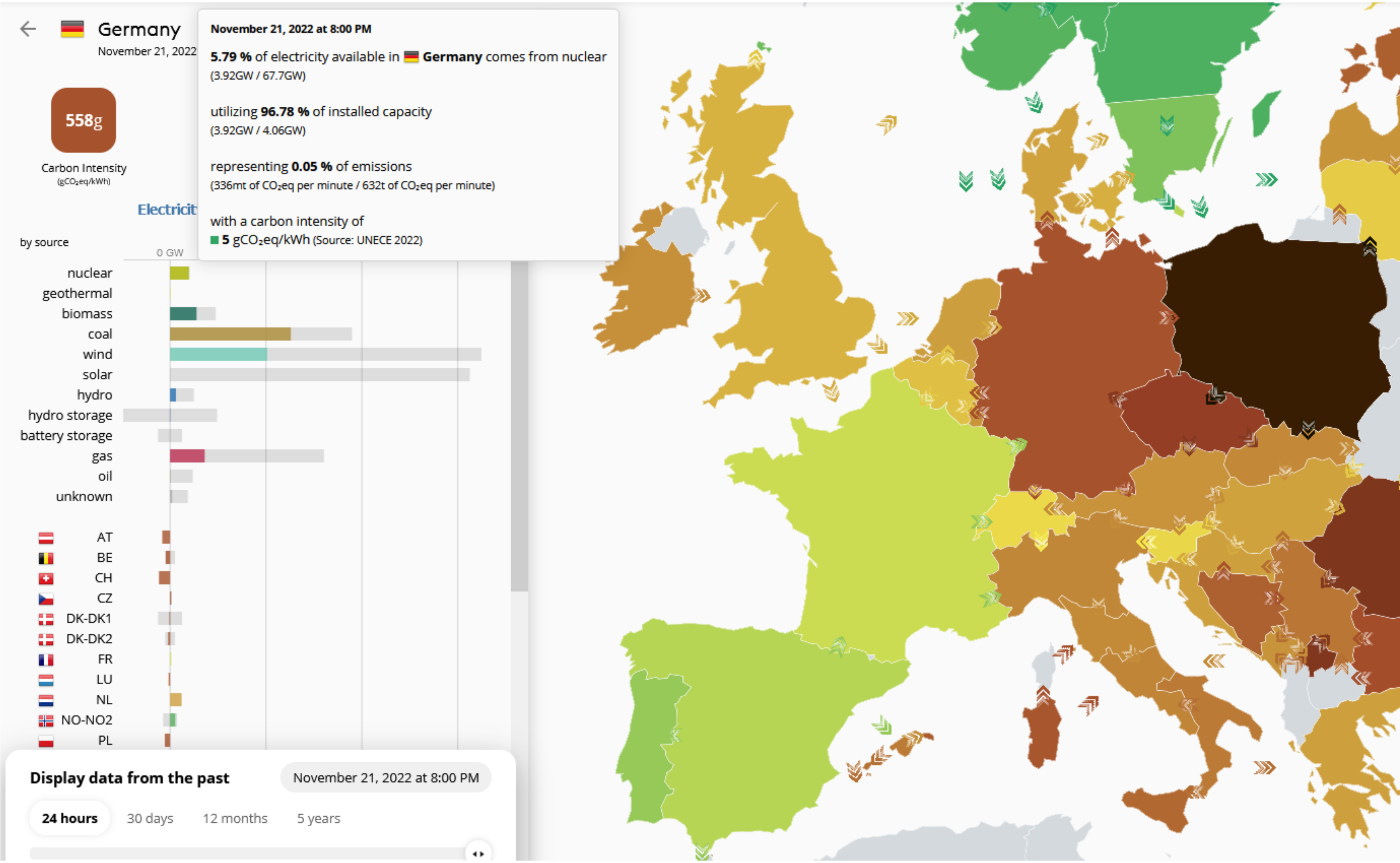
ElectricityMaps

https://app.electricitymaps.com

Real-time monitoring of electricity production and consumption

Reporting volumes and greenhouse gas emissions

On an hourly basis



November 21, 2022 at 8:00 PM

5.79 % of electricity available in **Germany** comes from nuclear
(3.92GW / 67.7GW)

utilizing **96.78 %** of installed capacity
(3.92GW / 4.06GW)

representing **0.05 %** of emissions
(336mt of CO_2eq per minute / 632t of CO_2eq per minute)

with a carbon intensity of
🟩 **5** gCO_2eq/kWh (Source: UNECE 2022)

THANK YOU

thomas.gibon@list.lu

UNECE LCA report: https://unece.org/sites/default/files/2021-10/LCA-2.pdf

Scenario assessment: https://www.nature.com/articles/s41467-019-13067-8

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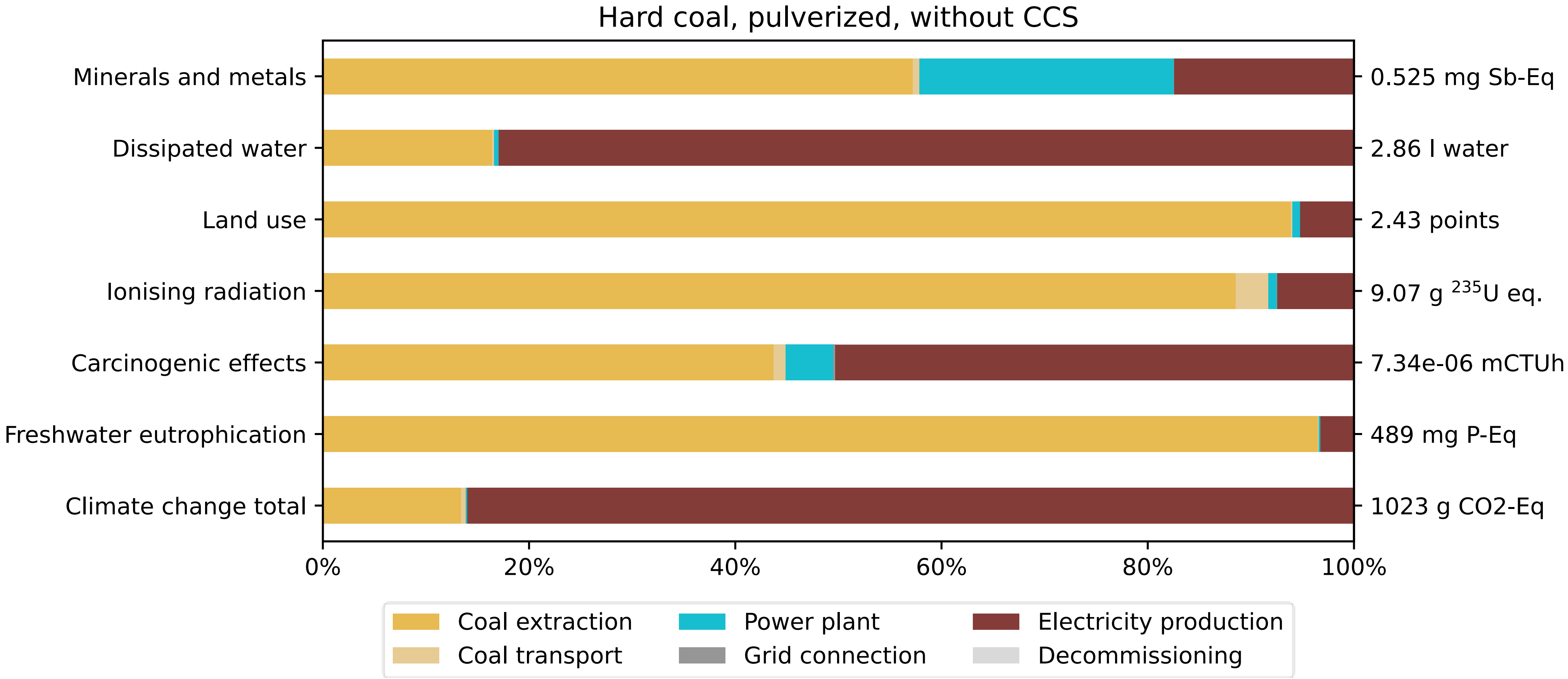
EXTRA SLIDES

COAL POWER

Lifecycle impacts per kWh (PC 550 MW, 30-year lifetime)



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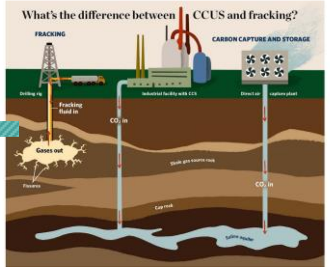
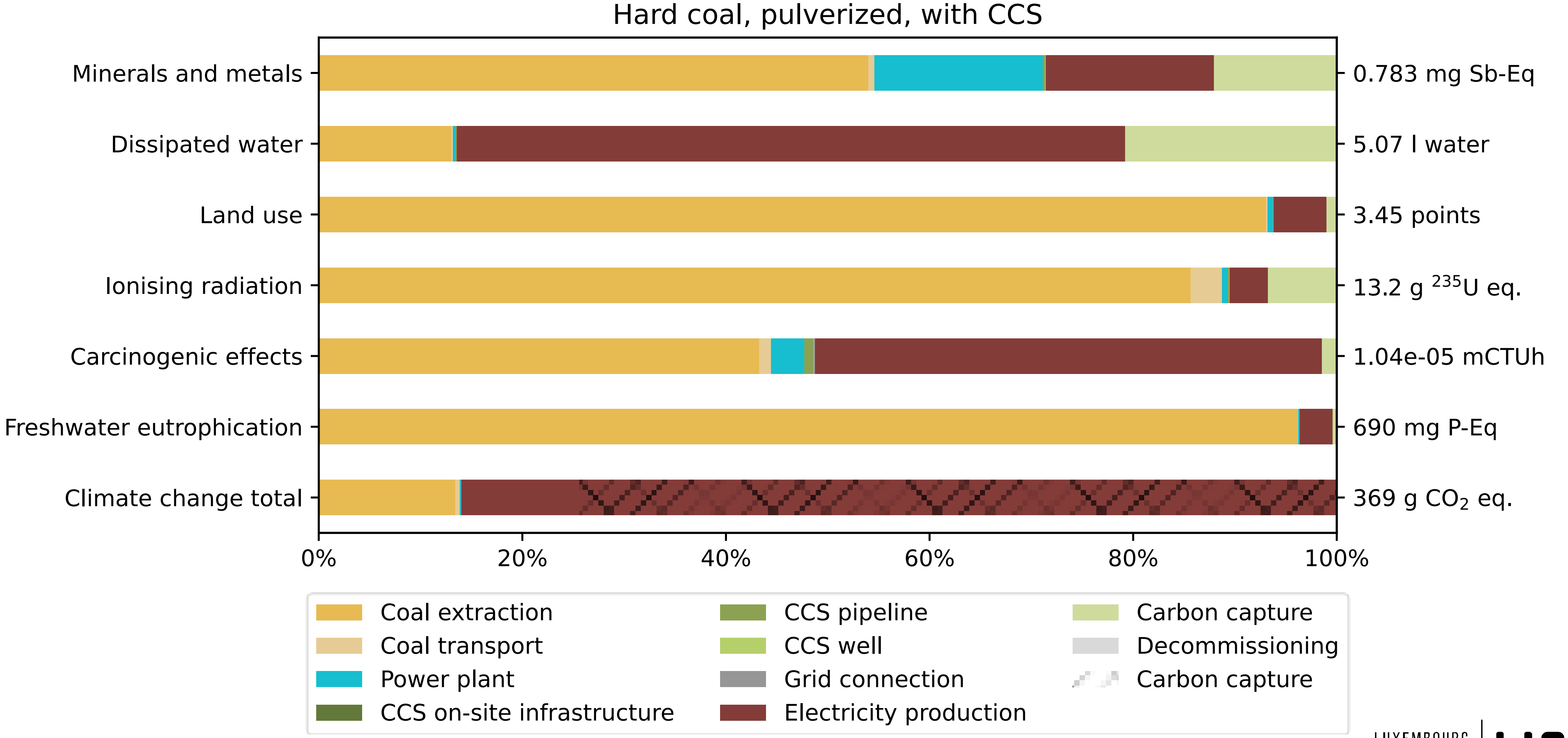
COAL POWER WITH CCS

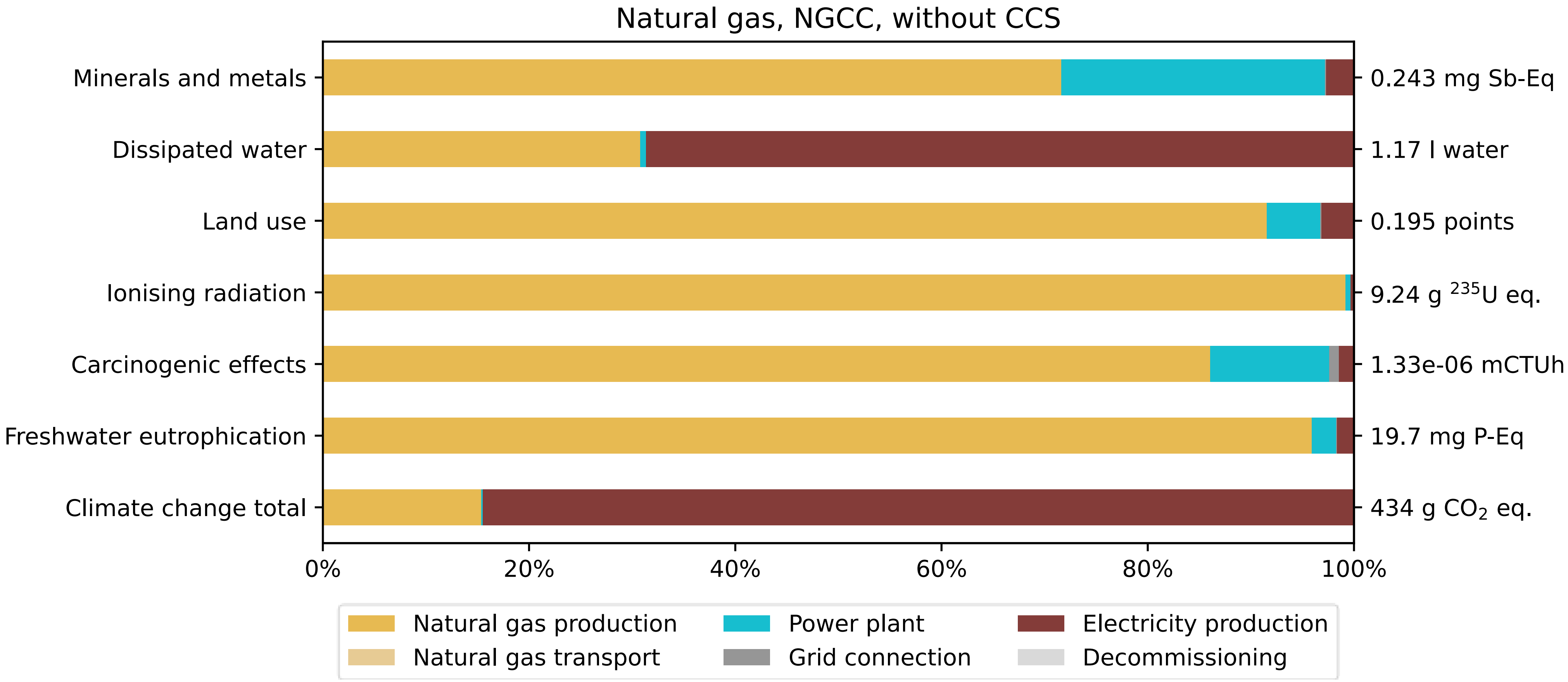


Lifecycle impacts per kWh (PC 550 MW, 30-year lifetime)

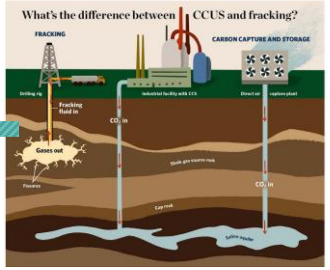


NATURAL GAS

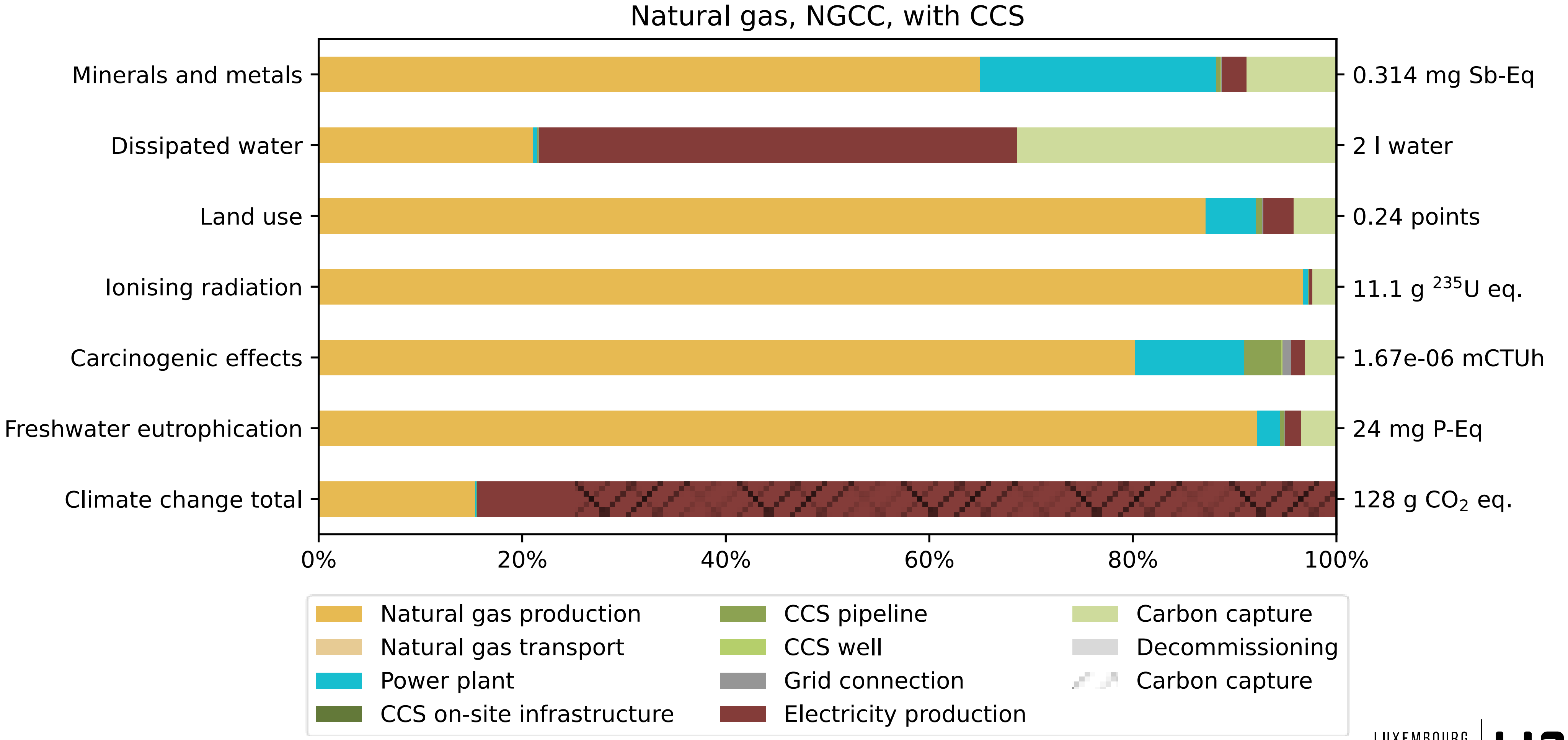
Lifecycle impacts per kWh (NGCC 555 MW, 30-year lifetime)



NATURAL GAS WITH CCS

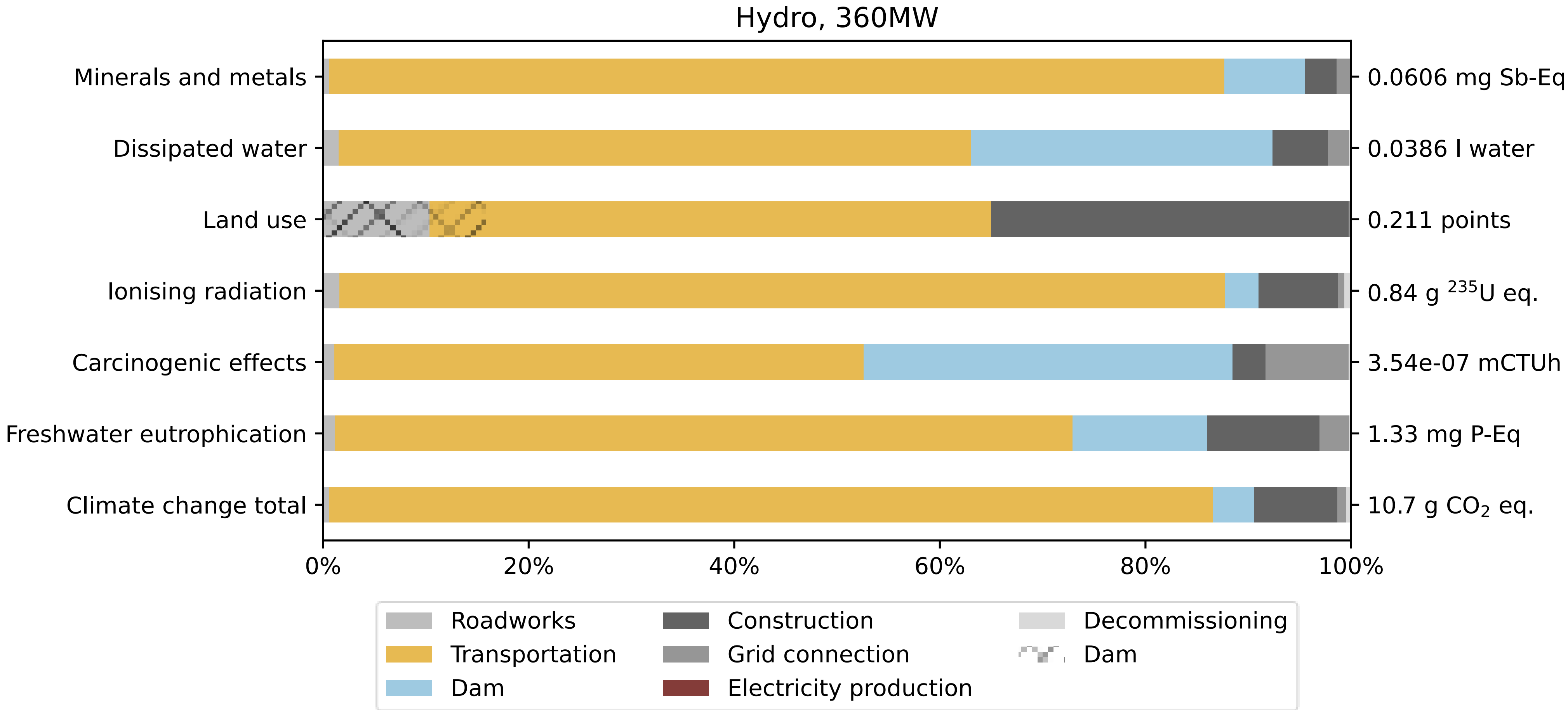


Lifecycle impacts per kWh (NGCC 555 MW, 30-year lifetime)



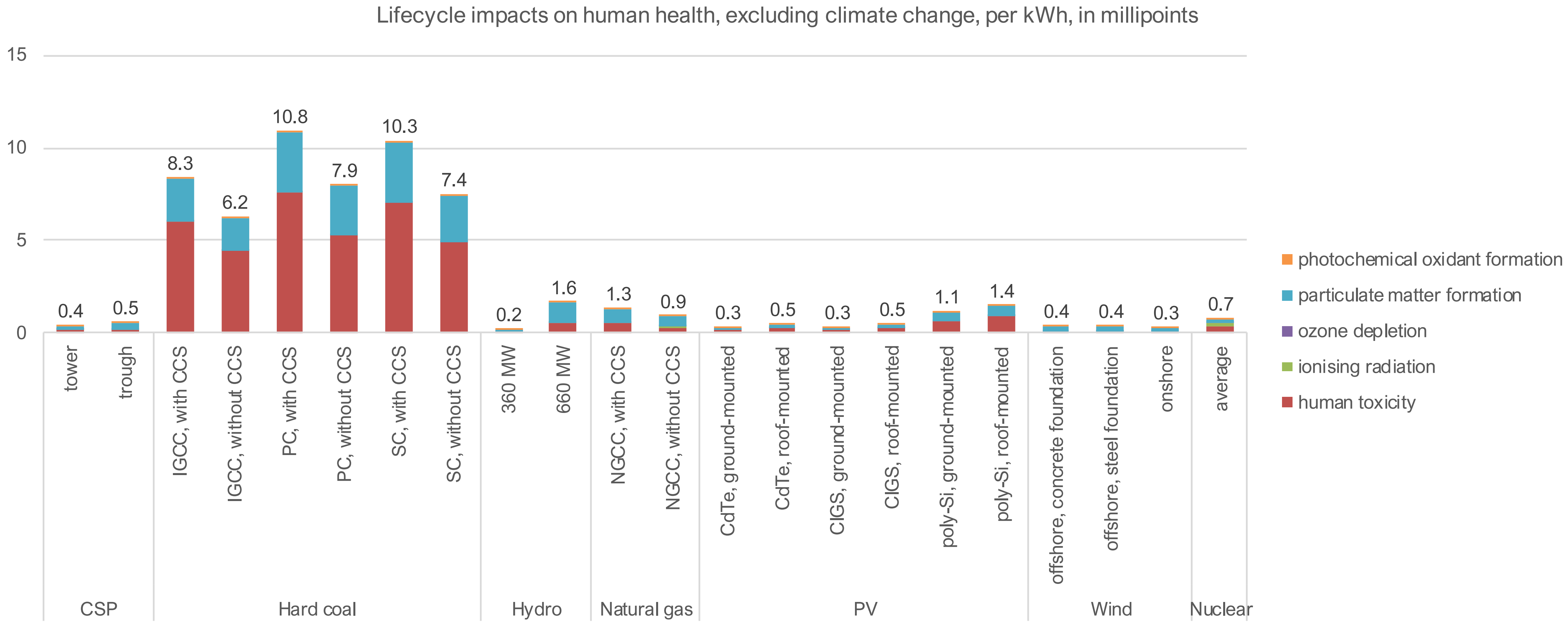
HYDROPOWER

Lifecycle impacts per kWh (360 MW, 80-year lifetime)



AGGREGATED SCORES

Endpoint indicators: human health



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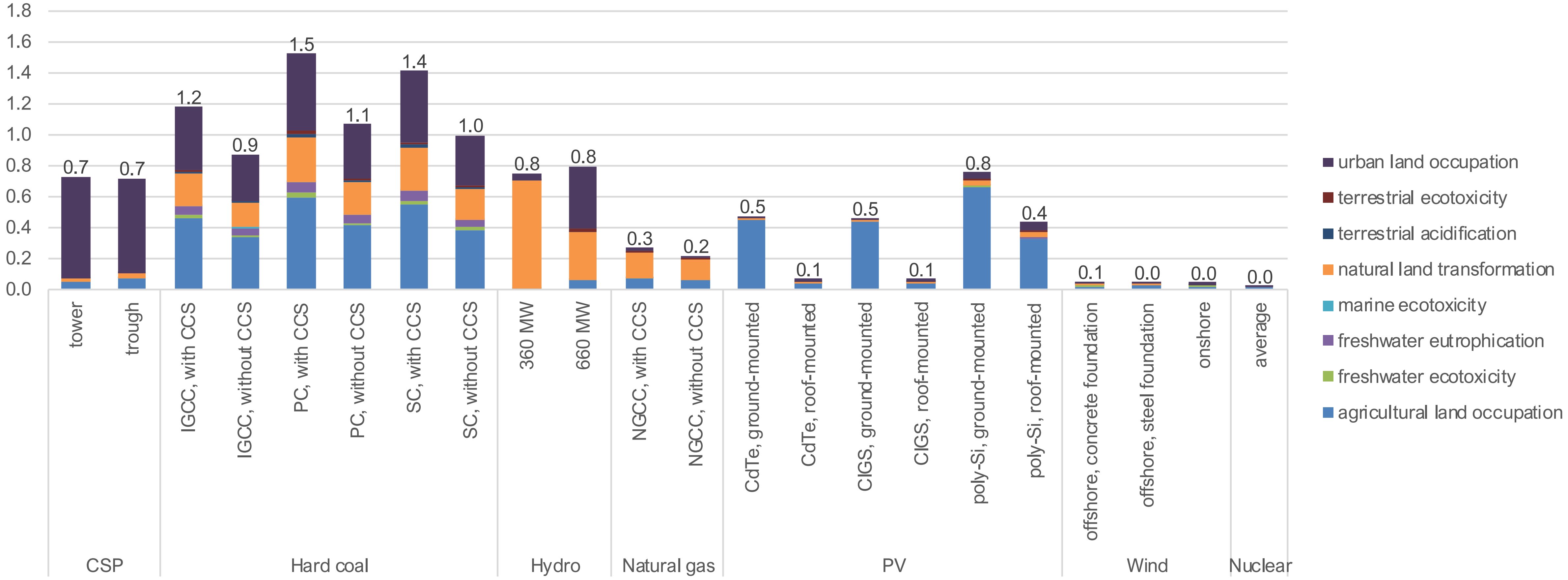
AGGREGATED SCORES

Endpoint indicators: ecosystems

Lifecycle impacts on ecosystems, excluding climate change, per kWh, in micropoints



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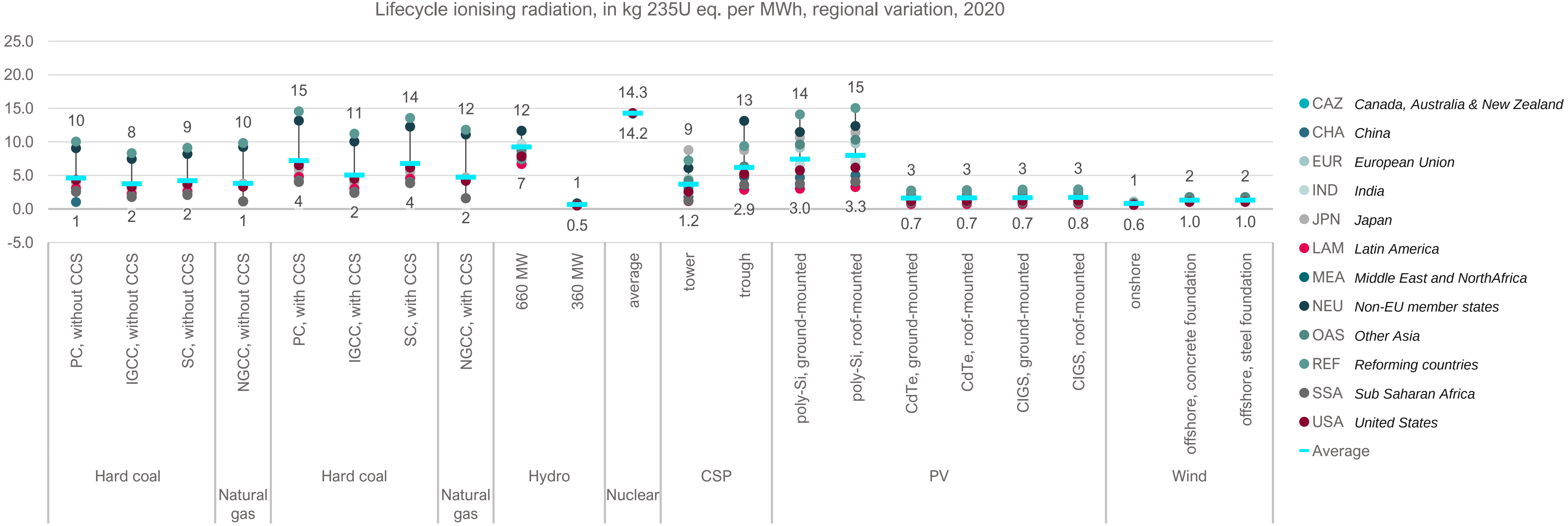
IONISING RADIATION

Life cycle emissions for each region, kg ^{235}U eq./MWh



Lifecycle ionising radiation, in kg 235U eq. per MWh, regional variation, 2020

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IONISING RADIATION

From UNSCEAR

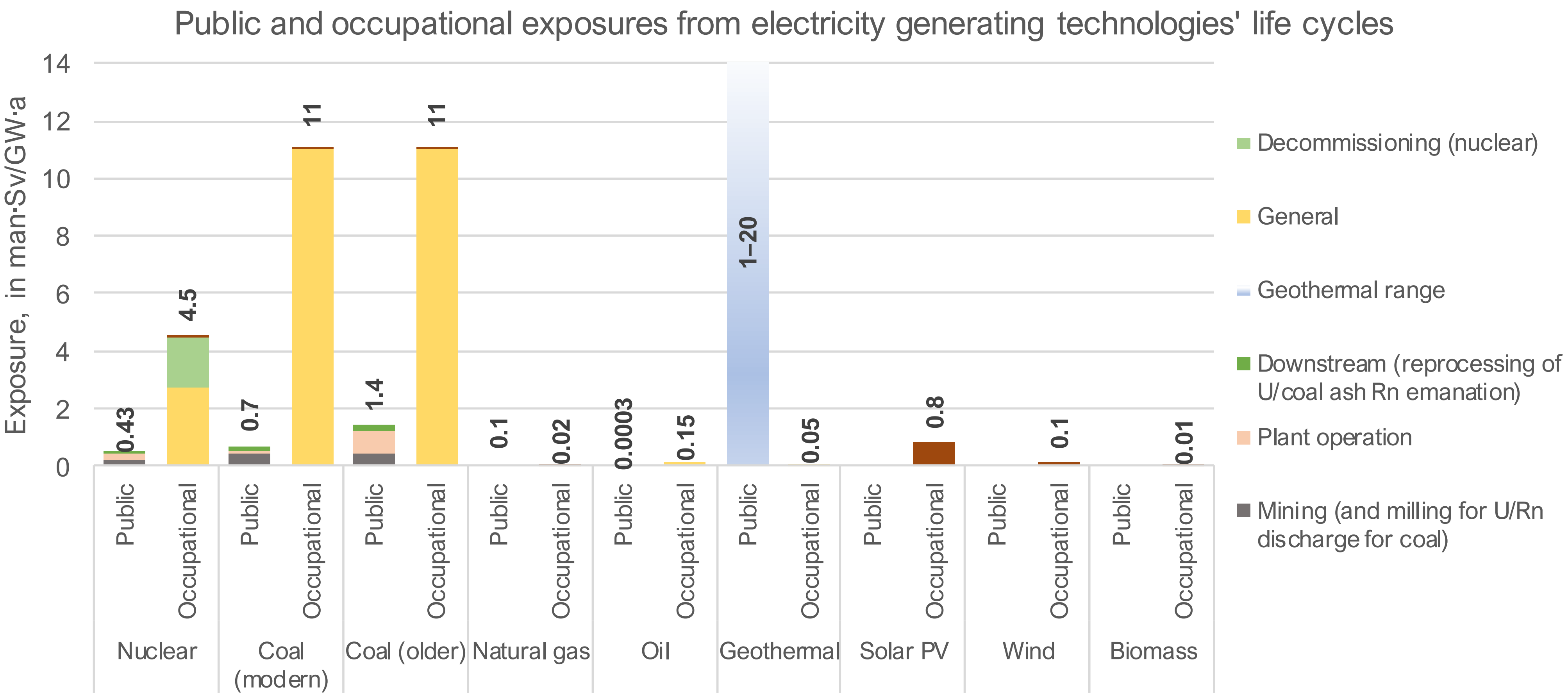
Public and occupational exposures from electricity generating technologies' life cycles

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Table 14 LCIA results for region EUR (Europe EU 28), in 2020, all ILCD 2.0 indicators, three significant figures . Climate change (total) in bold.

PER KWH		CLIMATE CHANGE BIOGENIC	CLIMATE CHANGE FOSSIL	CLIMATE CHANGE LAND USE AND LAND USE CHANGE	CLIMATE CHANGE TOTAL	FRESHWATER AND TERRESTRIAL ACIDIFICATION	FRESHWATER ECOTOXICITY	FRESHWATER EUTROPHICATION	MARINE EUTROPHICATION	TERRESTRIAL EUTROPHICATION	CARCINOGENIC EFFECTS	IONISING RADIATION	NON-CARCINOGENIC EFFECTS	OZONE LAYER DEPLETION	PHOTOCHEMICAL OZONE CREATION	RESPIRATORY EFFECTS, INORGANICS	DISSIPATED WATER	FOSSILS	LAND USE	MINERALS AND METALS
		[kg CO_2-Eq]	[kg CO_2-Eq]	[kg CO_2-Eq]	[kg CO_2-Eq]	[mol H+-Eq]	[CTU]	[kg P-Eq]	[kg N-Eq]	[mol N-Eq]	[CTUh]	[kg U235-Eq]	[CTUh]	[kg CFC-11.]	[kg NMVOC-.]	[disease I.]	[m^3 water-.]	[megajoule]	[points]	[kg Sb-Eq]
Hard coal	PC, without CCS	6.87E-05	1.02E+00	1.67E-04	**1.02E+00**	1.73E-03	4.72E-01	4.89E-04	5.14E-04	4.97E-03	7.34E-09	8.74E-03	1.14E-07	1.04E-08	1.25E-03	2.51E-08	1.23E-01	1.41E+01	2.43E+00	5.25E-07
Hard coal	IGCC, without CCS	5.38E-05	8.49E-01	1.40E-04	**8.49E-01**	1.05E-03	3.46E-01	4.24E-04	4.18E-04	4.00E-03	6.43E-09	7.47E-03	9.57E-08	8.74E-09	9.78E-04	1.36E-08	7.23E-02	1.21E+01	2.06E+00	5.89E-07
Hard coal	SC, without CCS	6.45E-05	9.53E-01	1.56E-04	**9.53E-01**	1.63E-03	4.33E-01	4.58E-04	4.82E-04	4.69E-03	6.90E-09	8.19E-03	1.06E-07	9.76E-09	1.16E-03	2.36E-08	1.12E-01	1.32E+01	2.28E+00	5.00E-07
Natural gas	NGCC, without CCS	7.78E-05	4.34E-01	8.21E-05	**4.34E-01**	3.26E-04	1.16E-01	1.97E-05	4.96E-05	7.49E-04	1.33E-09	9.24E-03	7.49E-09	6.66E-08	2.25E-04	1.33E-09	5.02E-02	7.86E+00	1.95E-01	2.43E-07
Hard coal	PC, with CCS	1.06E-04	3.68E-01	2.47E-04	**3.69E-01**	1.80E-03	8.26E-01	6.90E-04	7.29E-04	6.82E-03	1.04E-08	1.32E-02	1.66E-07	1.57E-08	1.68E-03	2.93E-08	2.18E-01	2.00E+01	3.45E+00	7.83E-07
Hard coal	IGCC, with CCS	7.23E-05	2.79E-01	1.89E-04	**2.79E-01**	1.35E-03	4.94E-01	5.71E-04	5.36E-04	5.10E-03	8.62E-09	1.01E-02	1.30E-07	1.18E-08	1.25E-03	1.72E-08	1.16E-01	1.63E+01	2.77E+00	6.85E-07
Hard coal	SC, with CCS	9.90E-05	3.33E-01	2.34E-04	**3.33E-01**	2.25E-03	7.51E-01	6.37E-04	6.92E-04	8.93E-03	9.66E-09	1.23E-02	1.53E-07	1.49E-08	1.55E-03	3.13E-08	1.98E-01	1.84E+01	3.18E+00	7.43E-07
Natural gas	NGCC, with CCS	9.39E-05	1.28E-01	9.93E-05	**1.28E-01**	6.07E-04	2.34E-01	2.40E-05	7.42E-05	1.87E-03	1.67E-09	1.11E-02	1.30E-08	7.81E-08	2.70E-04	3.14E-09	8.59E-02	9.26E+00	2.40E-01	3.14E-07
Hydro	660 MW	5.32E-05	1.47E-01	1.09E-04	**1.47E-01**	4.15E-04	3.97E-01	1.26E-05	9.54E-05	1.04E-03	2.56E-09	1.16E-02	2.17E-08	3.40E-08	3.85E-04	9.45E-09	1.58E-02	2.24E+00	2.45E+00	6.06E-07
Hydro	360 MW	1.80E-05	1.07E-02	9.21E-06	**1.07E-02**	4.45E-05	2.73E-02	1.33E-06	1.23E-05	1.43E-04	3.54E-10	8.40E-04	1.39E-09	2.37E-09	4.30E-05	8.07E-10	1.66E-03	1.63E-01	2.11E-01	6.06E-08
Nuclear	average	2.56E-05	5.24E-03	2.26E-05	**5.29E-03**	4.28E-05	2.70E-02	6.45E-06	8.20E-05	9.70E-05	5.51E-10	1.43E-02	5.50E-09	4.62E-10	2.65E-05	2.21E-09	1.31E-01	1.64E+01	6.25E-02	3.33E-07
CSP	tower	3.02E-05	2.16E-02	3.36E-05	**2.17E-02**	9.24E-05	3.65E-02	1.11E-05	2.21E-05	2.46E-04	2.09E-09	4.46E-03	2.61E-09	2.69E-09	7.54E-05	8.82E-10	7.60E-03	3.91E-01	3.62E+00	3.36E-07
CSP	trough	4.57E-05	4.19E-02	5.60E-05	**4.20E-02**	1.51E-04	1.10E-01	1.38E-05	2.88E-05	3.61E-04	6.25E-09	6.12E-03	4.61E-09	5.61E-09	1.05E-04	1.86E-09	1.47E-02	6.88E-01	3.54E+00	6.45E-07
PV	poly-SI, ground-mounted	3.43E-04	3.62E-02	1.51E-04	**3.67E-02**	3.01E-04	7.91E-02	2.84E-05	4.62E-05	4.48E-04	4.12E-09	9.14E-03	7.83E-09	6.97E-09	1.30E-04	2.21E-09	2.49E-02	6.43E-01	1.87E+00	4.45E-06
PV	poly-SI, roof-mounted	3.34E-04	3.67E-02	1.69E-04	**3.72E-02**	3.34E-04	6.99E-02	3.93E-05	5.12E-05	5.10E-04	1.63E-09	9.76E-03	1.38E-08	7.18E-09	1.43E-04	2.31E-09	2.72E-02	6.64E-01	4.43E-01	7.21E-06
PV	CdTe, ground-mounted	8.86E-05	1.18E-02	2.54E-05	**1.19E-02**	6.27E-05	5.59E-02	8.75E-06	1.27E-05	1.39E-04	3.44E-09	1.86E-03	3.67E-09	1.03E-09	4.16E-05	6.40E-10	5.63E-03	1.83E-01	1.39E+00	1.53E-06
PV	CdTe, roof-mounted	5.59E-05	1.45E-02	4.38E-05	**1.46E-02**	8.82E-05	3.96E-02	1.42E-05	1.54E-05	1.73E-04	1.14E-09	1.89E-03	7.46E-09	9.49E-10	4.86E-05	7.68E-10	7.05E-03	2.20E-01	1.48E-01	2.64E-06
PV	CIGS, ground-mounted	8.58E-05	1.13E-02	2.52E-05	**1.14E-02**	6.11E-05	5.58E-02	8.76E-06	1.25E-05	1.36E-04	3.39E-09	1.75E-03	3.77E-09	9.91E-10	4.08E-05	6.20E-10	5.64E-03	1.75E-01	1.35E+00	1.66E-06
PV	CIGS, roof-mounted	5.47E-05	1.40E-02	4.33E-05	**1.41E-02**	8.64E-05	4.02E-02	1.42E-05	1.52E-05	1.71E-04	1.14E-09	1.79E-03	7.59E-09	9.10E-10	4.79E-05	7.48E-10	7.08E-03	2.12E-01	1.47E-01	2.81E-06
Wind	onshore	1.87E-05	1.24E-02	1.99E-05	**1.24E-02**	5.28E-05	7.48E-02	6.67E-06	1.39E-05	1.26E-04	6.56E-09	1.03E-03	2.98E-09	6.71E-10	4.63E-05	7.06E-10	7.52E-03	1.75E-01	1.08E-01	6.75E-07
Wind	offshore, concrete foundation	1.74E-05	1.42E-02	2.58E-05	**1.42E-02**	1.00E-04	6.62E-02	6.98E-06	2.84E-05	2.93E-04	5.52E-09	1.19E-03	3.17E-09	1.24E-09	8.99E-05	6.57E-10	6.74E-03	1.97E-01	1.11E-01	9.77E-07
Wind	offshore, steel foundation	1.87E-05	1.33E-02	2.46E-05	**1.33E-02**	9.45E-05	7.94E-02	6.84E-06	2.69E-05	2.76E-04	7.00E-09	1.19E-03	3.41E-09	1.18E-09	8.44E-05	6.19E-10	6.67E-03	1.90E-01	9.94E-02	9.93E-07