LCA OF ELECTRICITY GENERATION TECHNOLOGIES

UNECE modelling activities – Carbon neutrality project

14.07.2021

UNECE

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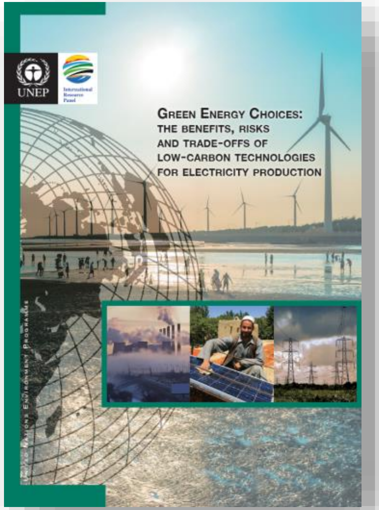
CONTEXT OF LIFE CYCLE ASSESSMENT TASK

Starting point: UNEP IRP report “Green Energy Choices”



Life cycle assessment (LCA) of electricity production technologies

Coal, natural gas, with and without CCS
Hydropower
Wind power
Concentrating solar power
Photovoltaic power
Geothermal power

Impact assessment over 2010-2050 period

Two IEA scenarios (Baseline, Blue Map) and 9 world regions

UN environment programme

International Resource Panel

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

REGIONS

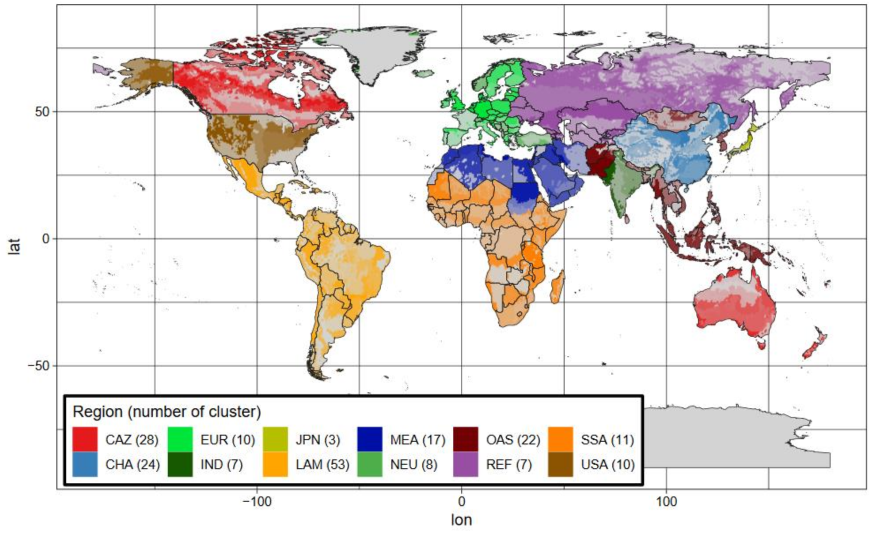
Why regionalizing?

Data representativeness

Electricity mixes can be systematically adapted to region, year, and a given scenario (with REMIND “Base SSP2” as baseline), as well as a few other processes (cement…)

Adapting load factors to regional climate conditions

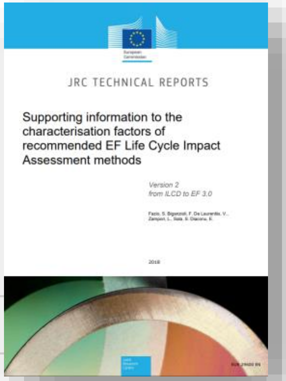
Solar irradiation
Wind regimes



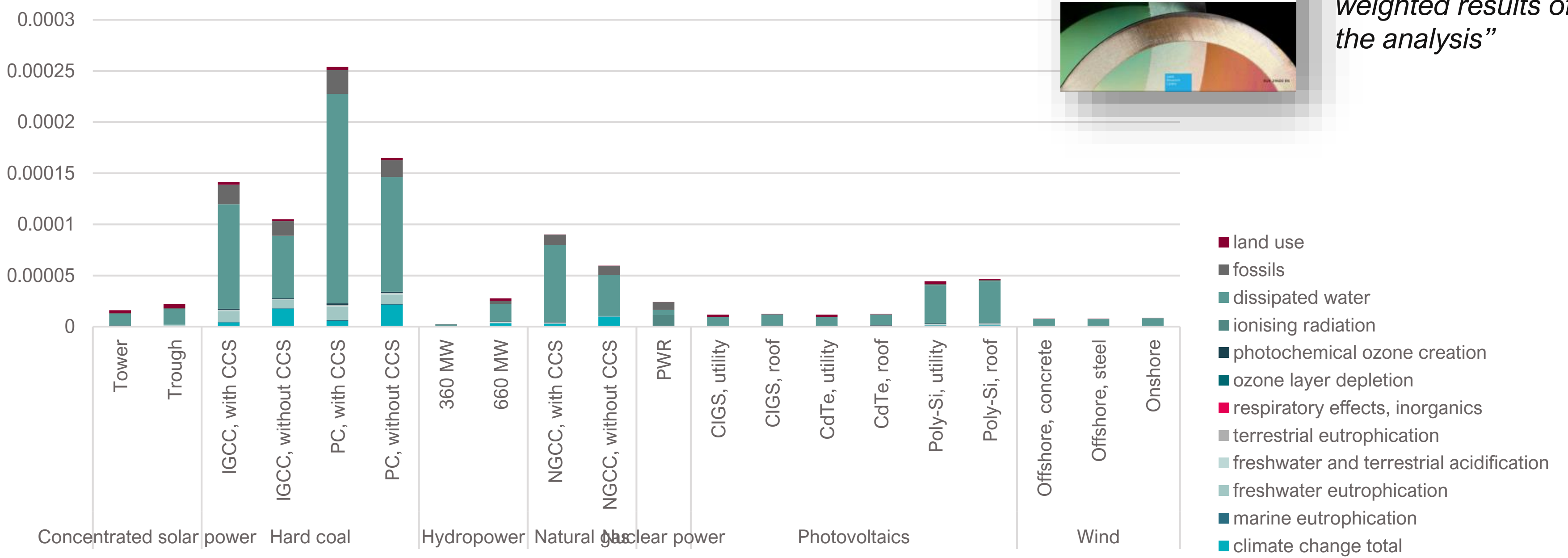
REMIND regions	Code
Canada, Australia & New Zealand	CAZ
China	CHA
European Union	EUR
India	IND
Japan	JPN
Latin America	LAM
Middle East and NorthAfrica	MEA
Non-EU member states	NEU
Other Asia	OAS
Reforming countries	REF
Sub Saharan Africa	SSA
United States	USA

CHOOSING INDICATORS

Results normalized & weighted, Europe EU region



"impact assessment categories should be selected depending on their contribution to the normalised and weighted results of the analysis"



CHOOSING INDICATORS

List of retained indicators, following EC recommendations

Category	Unit	Reference	Description
Climate change	kg CO_2 eq.	IPCC (2013)	Radiative forcing as Global Warming Potential (GWP100).
Freshwater eutrophication	kg P eq.	Struijs et al. (2009)	Expression of the degree to which the emitted nutrients reach the freshwater end compartment.
Ionising radiation (HH)	kBq ^{235}U eq	Frischknecht et al (2000)	Human exposure efficiency relative to U235.
Land use	points	LANCA model (Bos et al. 2016)	The LANCA model provides five indicators for assessing the impacts due to the use of soil: 1. erosion resistance, 2. mechanical filtration, 3. physicochemical filtration, 4. groundwater regeneration and 5. biotic production
Water resource depletion	m^3	Model for water consumption as in Swiss Ecoscarcity (Frischknecht et al, 2008)	Water use related to local scarcity of water
Mineral, fossil and renewable resource depletion	kg Sb eq.	Van Oers et al. (2002)	Scarcity of resource in relation to that of antimony. Scarcity is calculated as « reserve base ».

+ cumulative energy demand
+ endpoint score
as information

TECHNOLOGY SCOPES

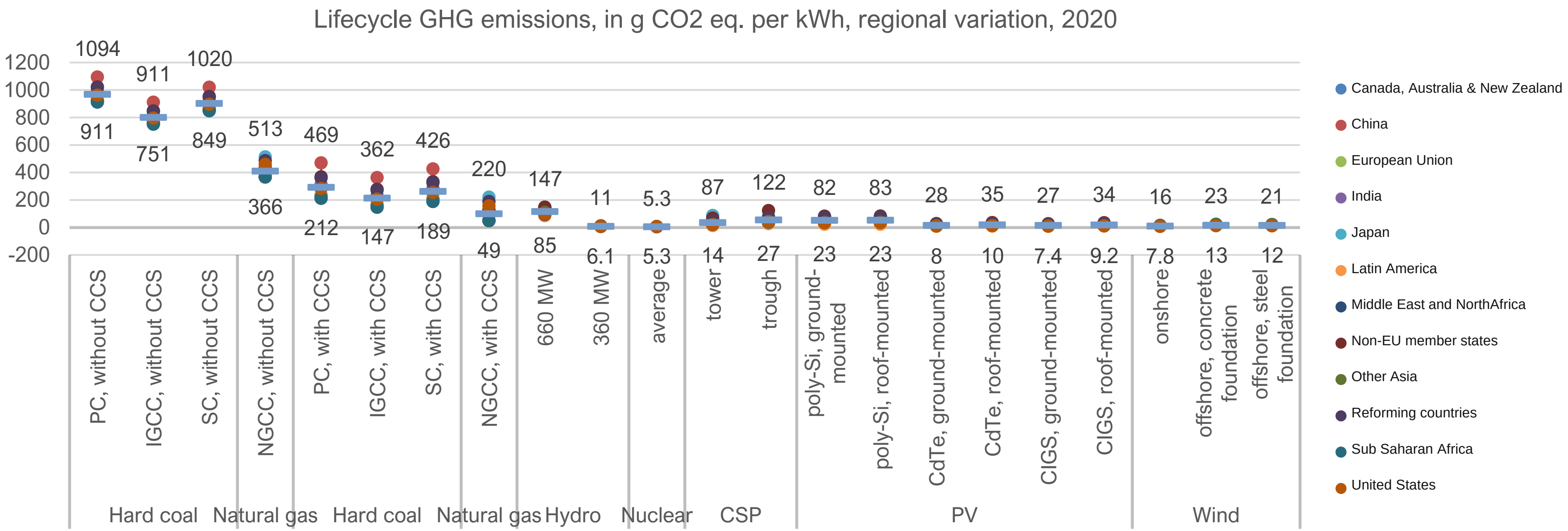
Technology		Included	Excluded
Coal power	without CCS	Energy carrier supply chain, from extraction to combustion, including methane leakage Infrastructure construction, operation, and dismantling (energy inputs and waste production) Connection to grid	Potential **recycling** from infrastructure deconstruction materials
	with CCS	Same as above, plus Capture equipment and chemicals, transportation of captured CO2 and storage infrastructure (well)	Same as above, plus Potential emissions **(leakage) from captured CO2 transportation or from the storage site**
Natural gas power	without CCS	Energy carrier supply chain, from extraction to combustion, including methane leakage Infrastructure construction, operation, and dismantling (energy inputs and waste production) Connection to grid	Potential **recycling** from infrastructure deconstruction materials
	with CCS	Same as above, plus Capture equipment and chemicals, transportation of captured CO2 and storage infrastructure (well)	Same as above, plus Potential emissions **(leakage) from captured CO2 transportation or from the storage site**
Hydropower		Construction, site preparation, transportation Connection to grid	Potential recycling of deconstruction materials **Site-specific biogenic emissions** of CO_2 and CH_4
Nuclear power		Fuel element supply chain (from extraction to fuel fabrication) Core processes (construction and decommissioning of power plant, as well as operation) Back-end processes: spent fuel management, storage, and final repository Connection to grid	Potential **recycling** of deconstruction materials **Reprocessing** of spent fuel (conservative assumption that all fuel is primary)
Concentrated solar power		Infrastructure, site preparation and occupation, operation and maintenance (including 6-hour storage) Decommissioning (energy inputs and waste production) Connection to grid	Potential recycling of deconstruction materials
Photovoltaics		Infrastructure, site preparation and occupation, operation and maintenance Decommissioning (energy inputs and waste production) Connection to grid	Potential recycling of dismantled equipment
Wind power		Infrastructure, site preparation and occupation, operation and maintenance Decommissioning (energy inputs and waste production) Connection to grid	Potential recycling of dismantled equipment

Results

CLIMATE CHANGE

Variations are due to region-specific electricity mixes, fossil fuel chain, and climate conditions

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



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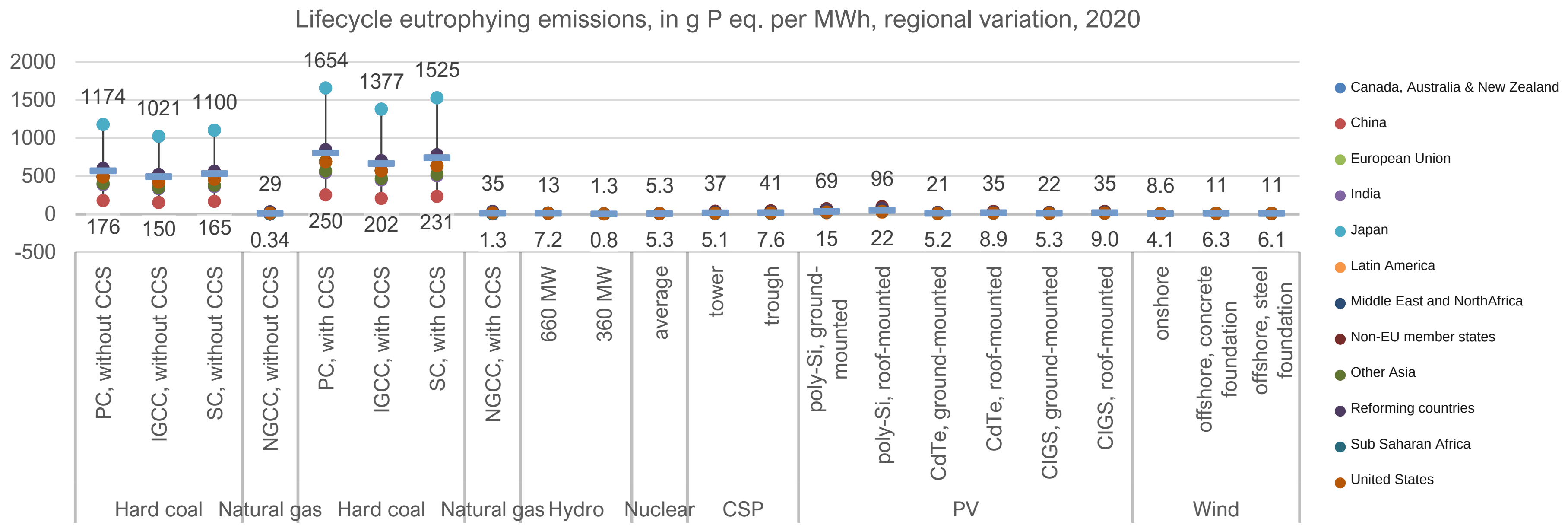
FRESHWATER EUTROPHICATION

Variations are due to region-specific electricity mixes, fossil fuel chain, and climate conditions

Life cycle emissions for each region, g phosphorus/MWh

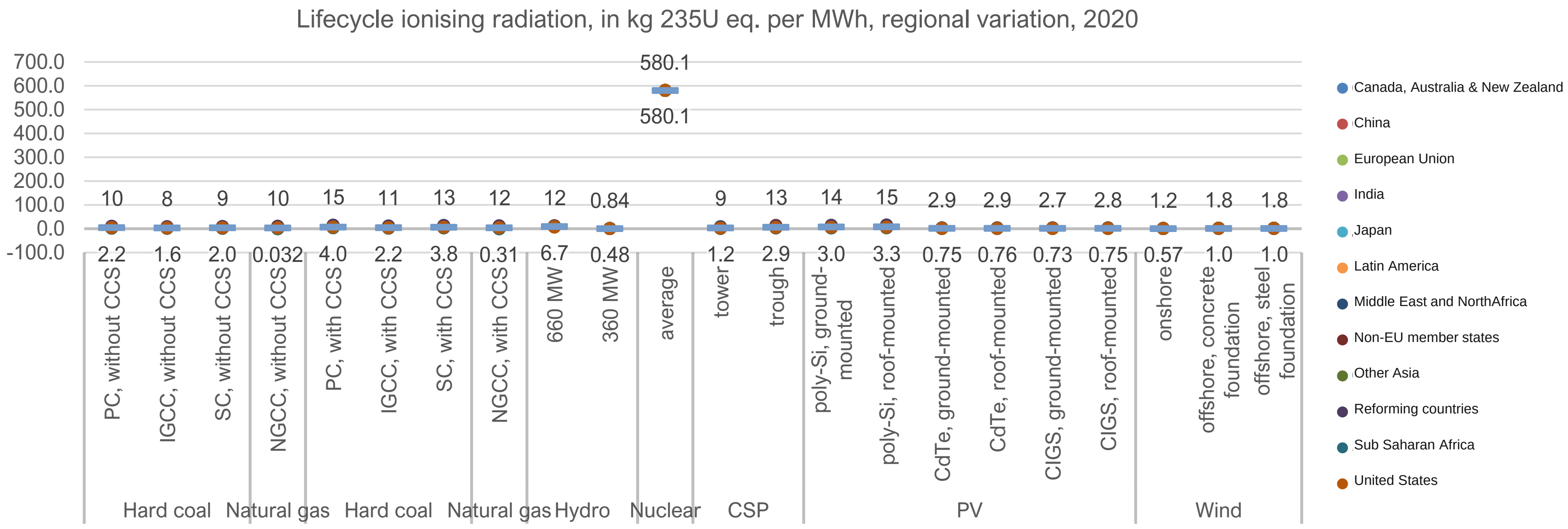


Mostly phosphate emissions from mining

IONISING RADIATION

Variations are due to region-specific electricity mixes, fossil fuel chain, and climate conditions

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



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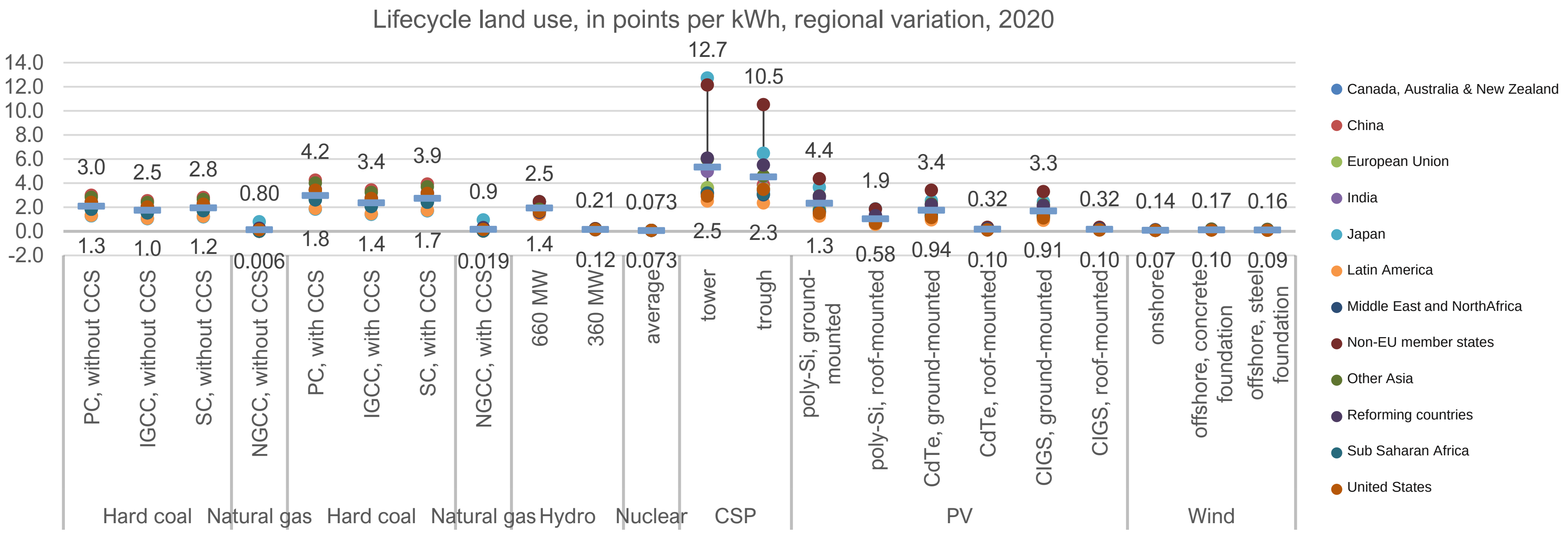
LAND USE

Lifecycle land occupation, in points*

*The LANCA model provides five indicators for assessing the impacts due to the use of soil:
1. **erosion resistance**,
2. **mechanical filtration**,
3. **physicochemical filtration**,
4. **groundwater regeneration** and
5. **biotic production**
– all aggregated as points.



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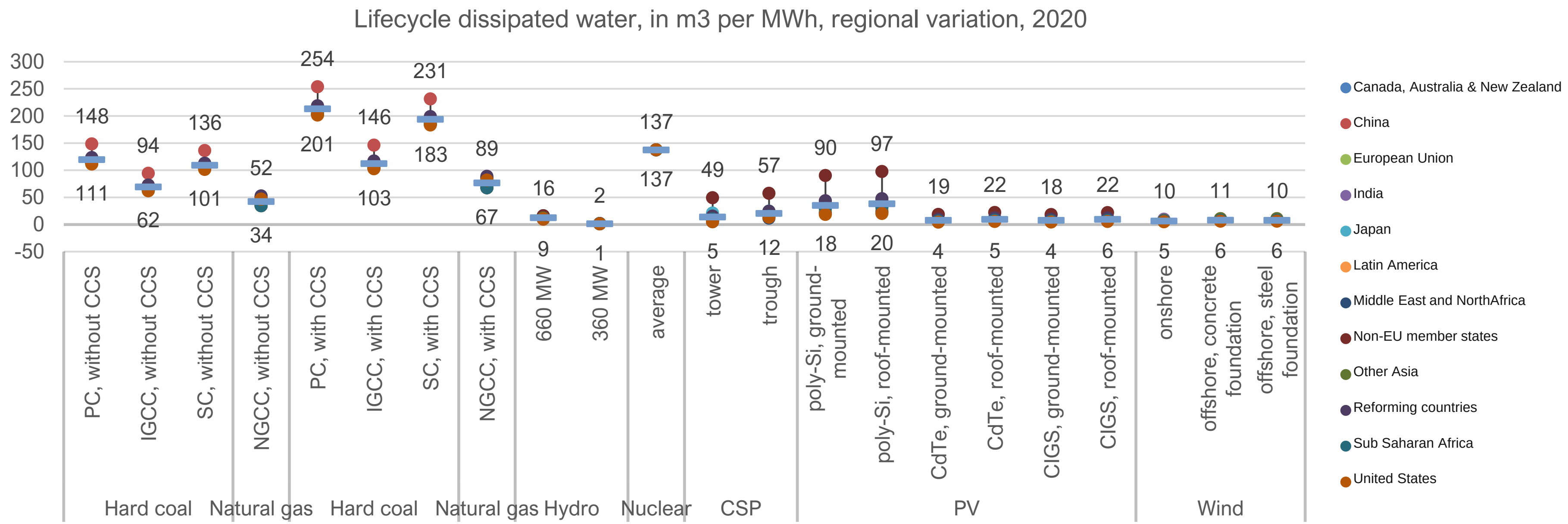
DISSIPATED WATER

Variations are due to region-specific electricity mixes, fossil fuel chain, and climate conditions

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



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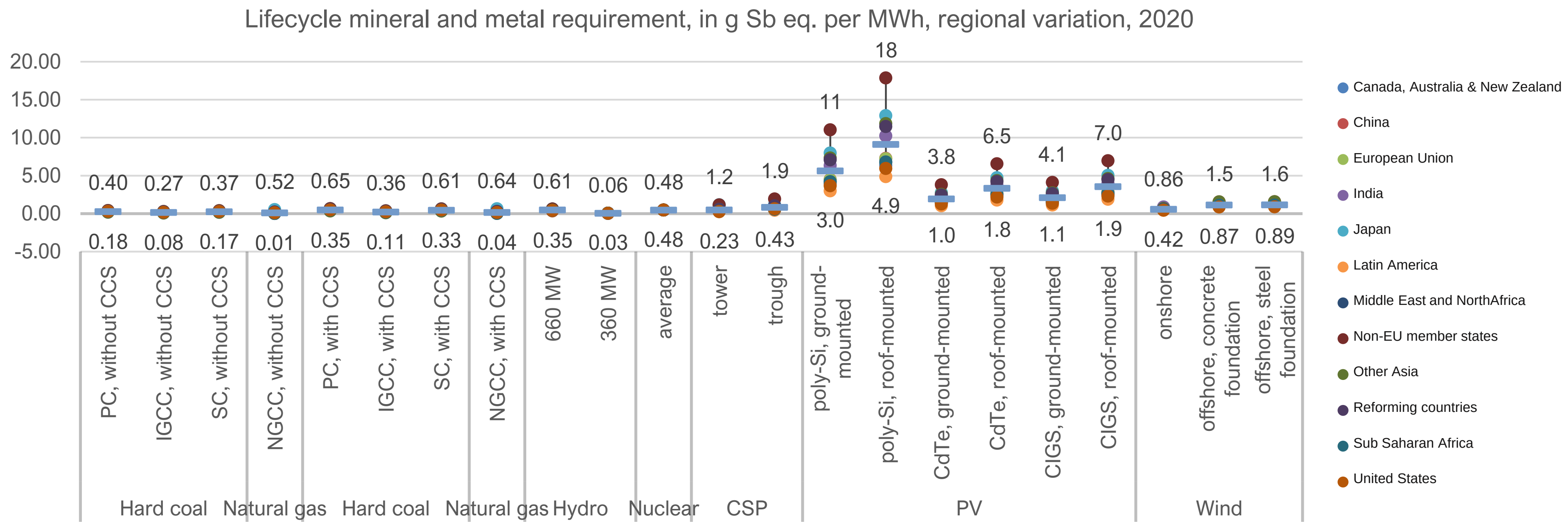
Variations are due to region-specific electricity mixes, fossil fuel chain, and climate conditions

RESOURCES, MATERIAL

Lifecycle resource requirements, scarcity-weighted, in g Sb eq./kWh



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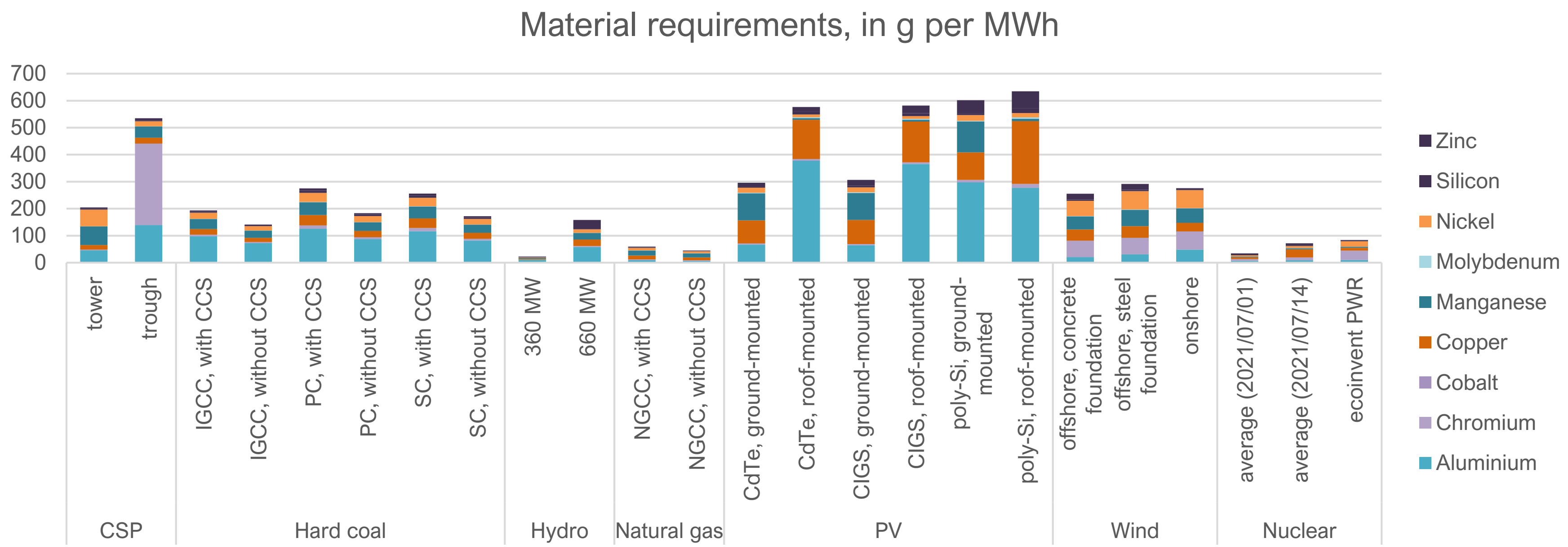
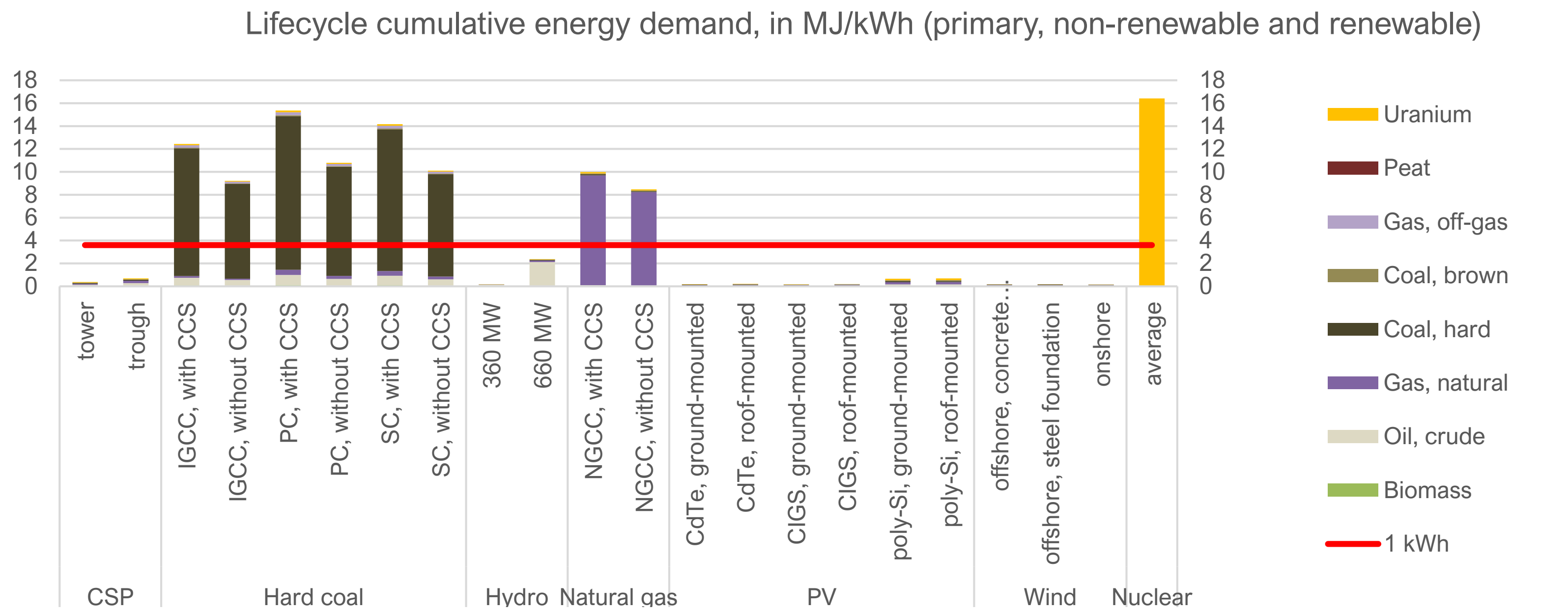
RESOURCES, MATERIAL

Lifecycle material requirements, extracted from ground, in g/MWh



RESOURCES, PRIMARY ENERGY

Primary energy demand over lifecycle, in MJ of energy carrier from ground



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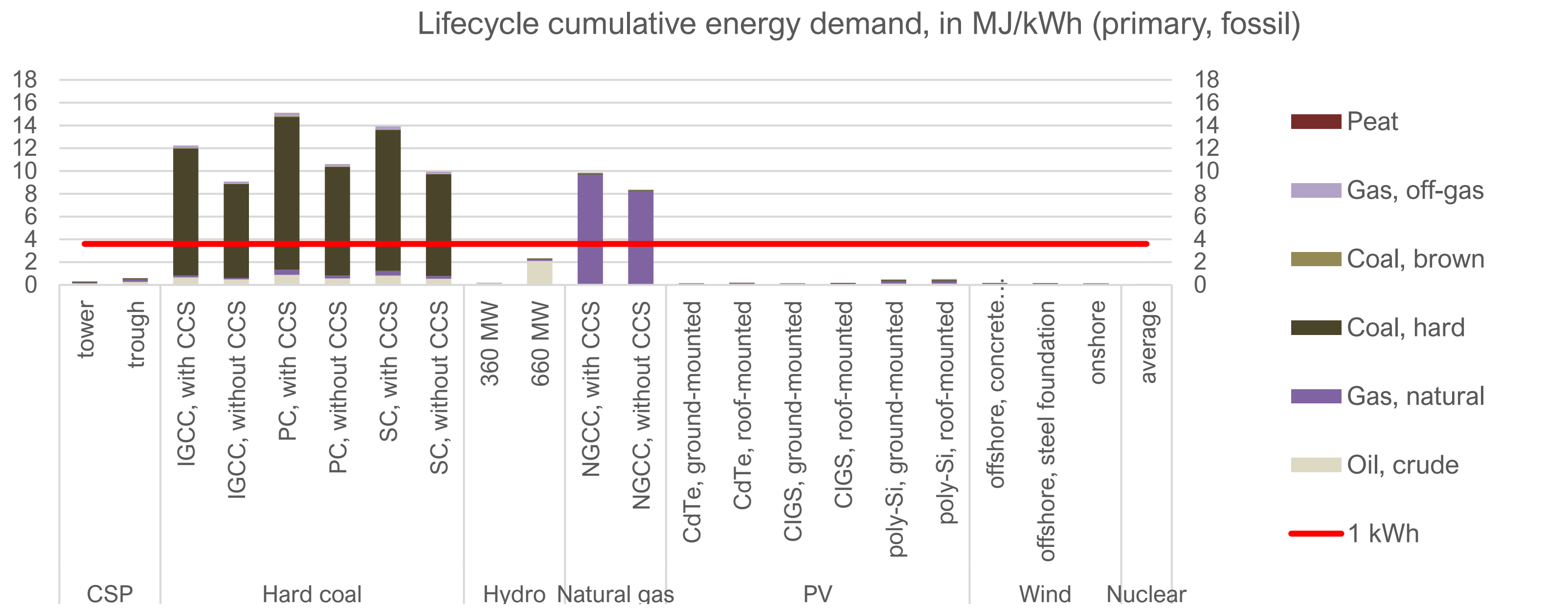
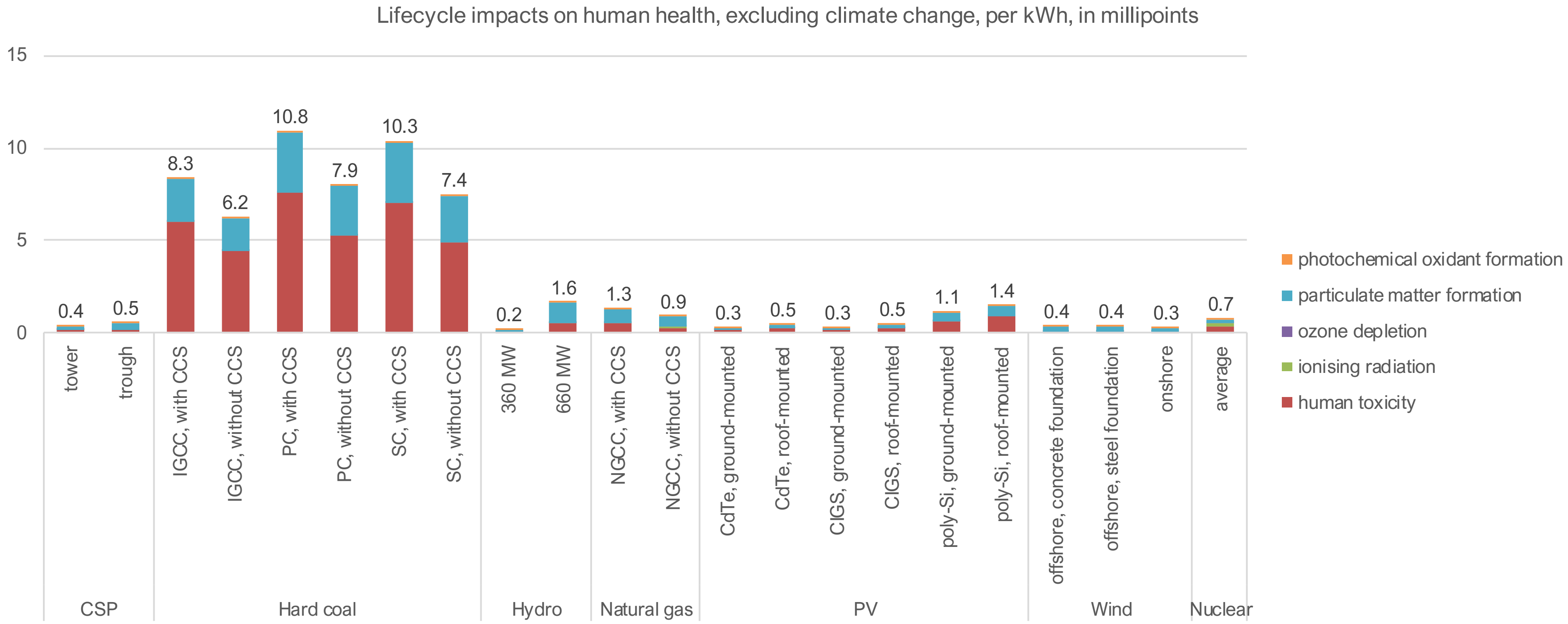
RESOURCES, PRIMARY ENERGY

Primary energy demand over lifecycle, in MJ of fossil energy from ground



AGGREGATED SCORES

Endpoint indicators: human health



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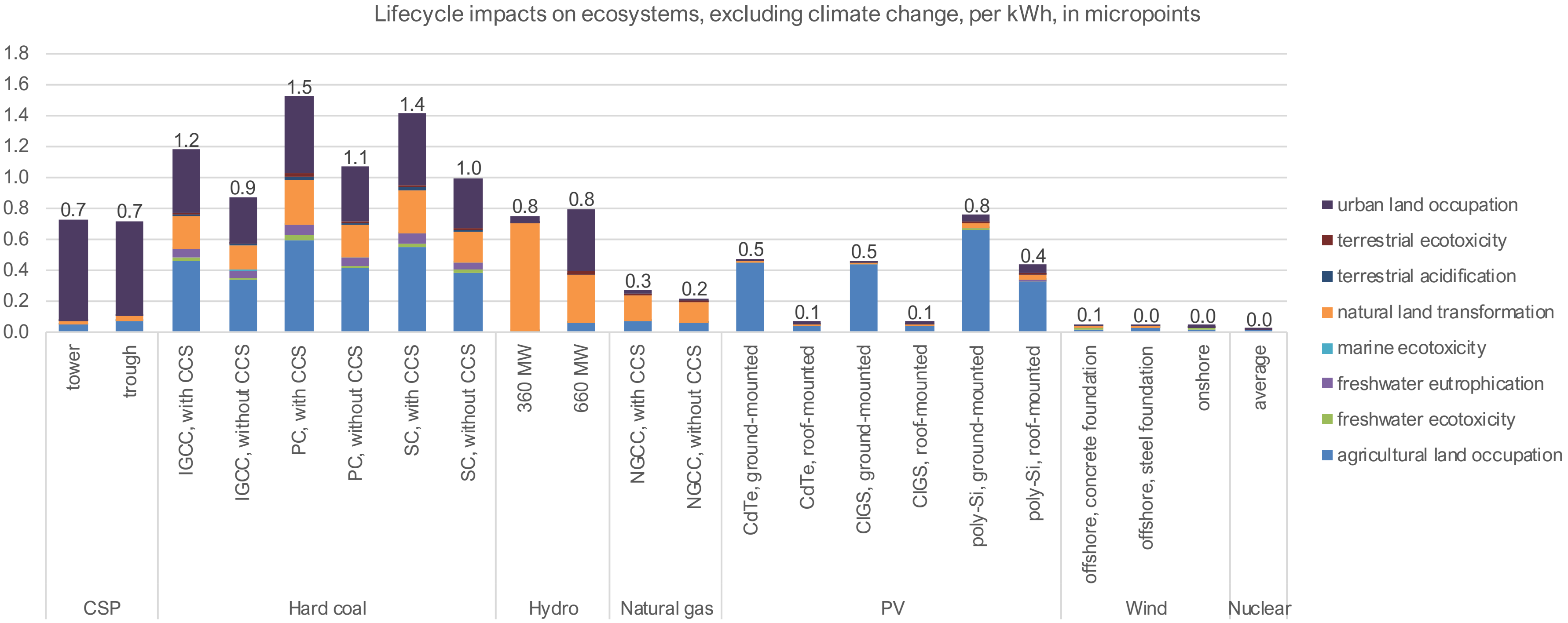
AGGREGATED SCORES

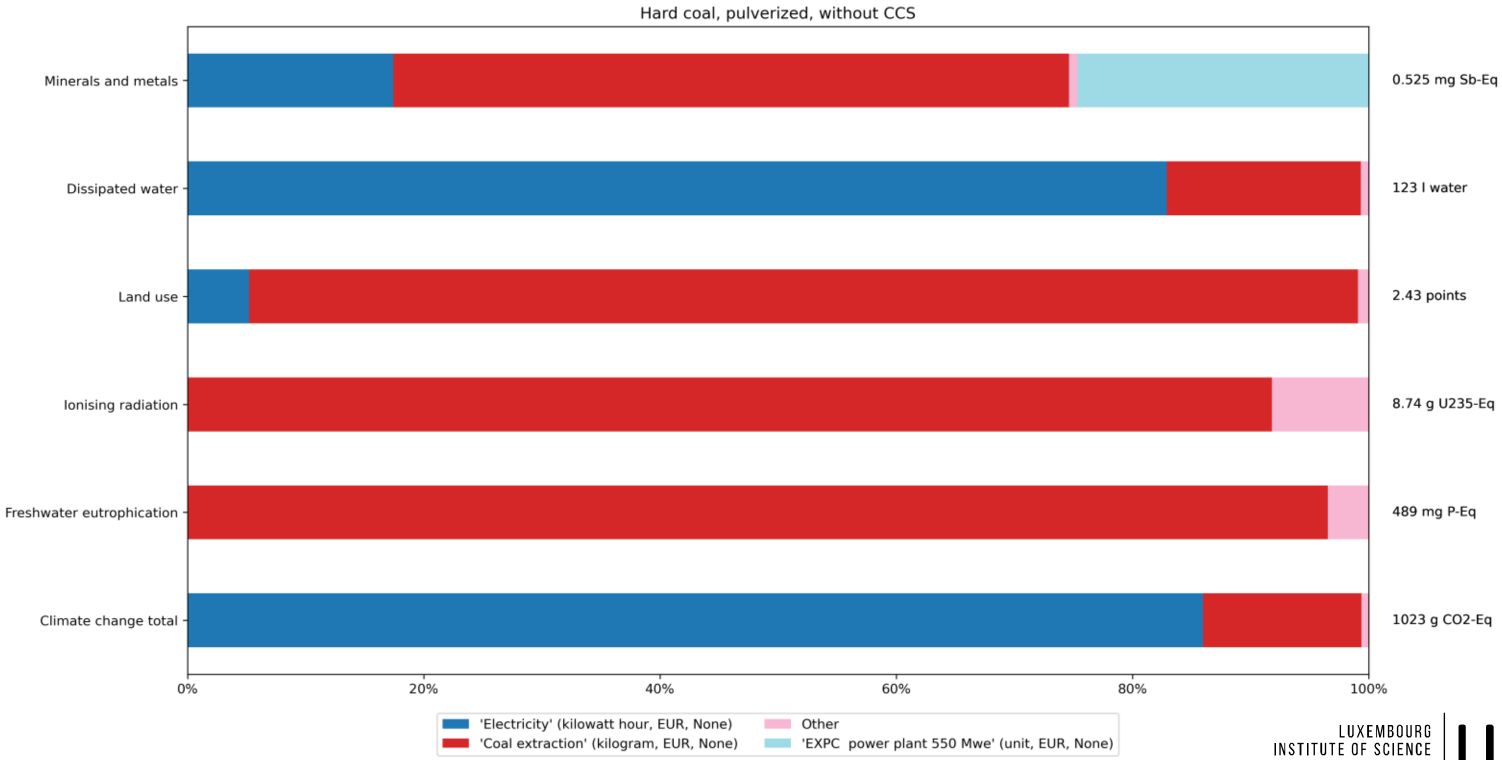
Endpoint indicators: human health



Results per technology

COAL POWER

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



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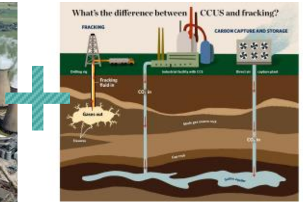
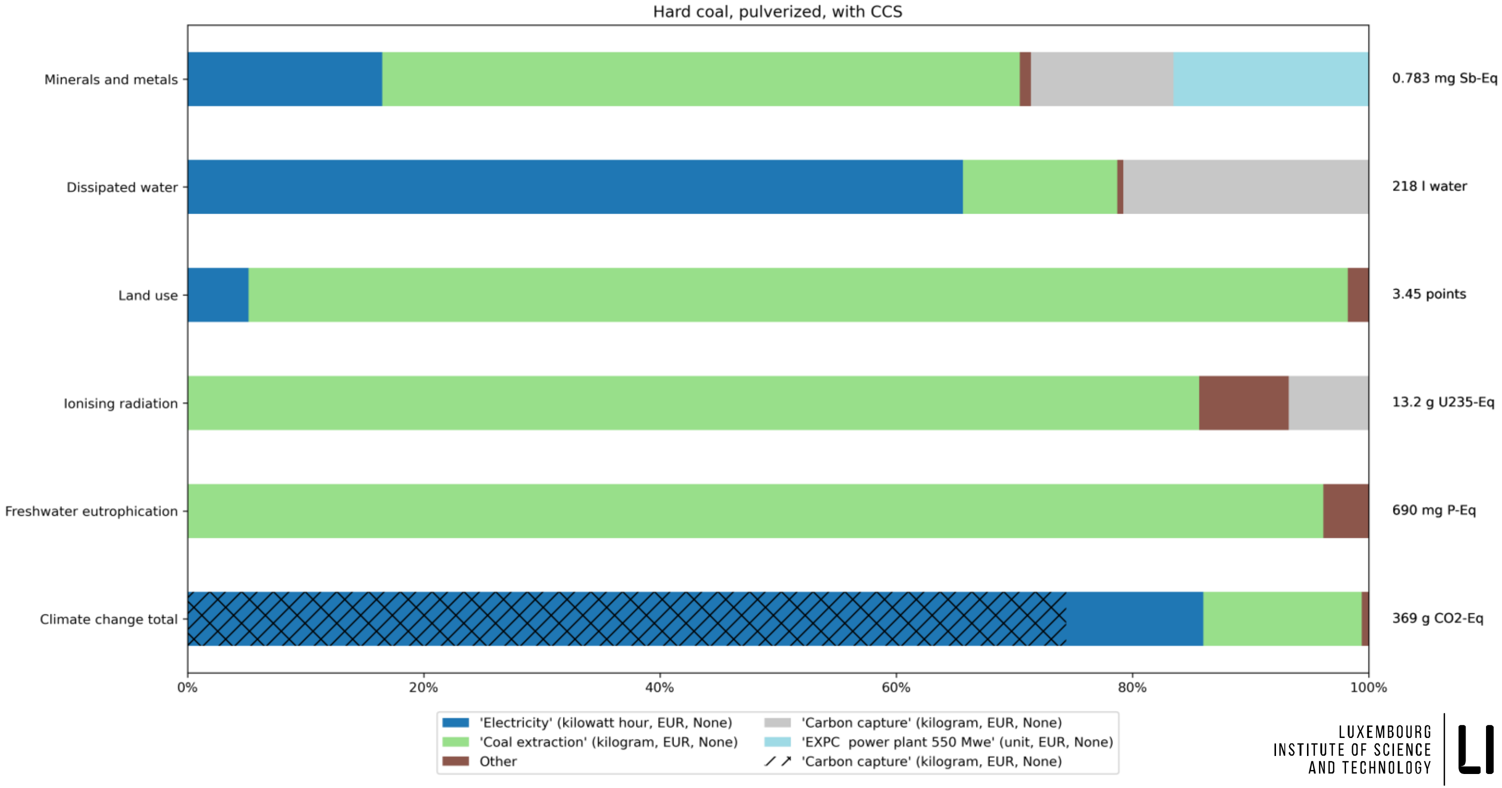
COAL POWER WITH CCS



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



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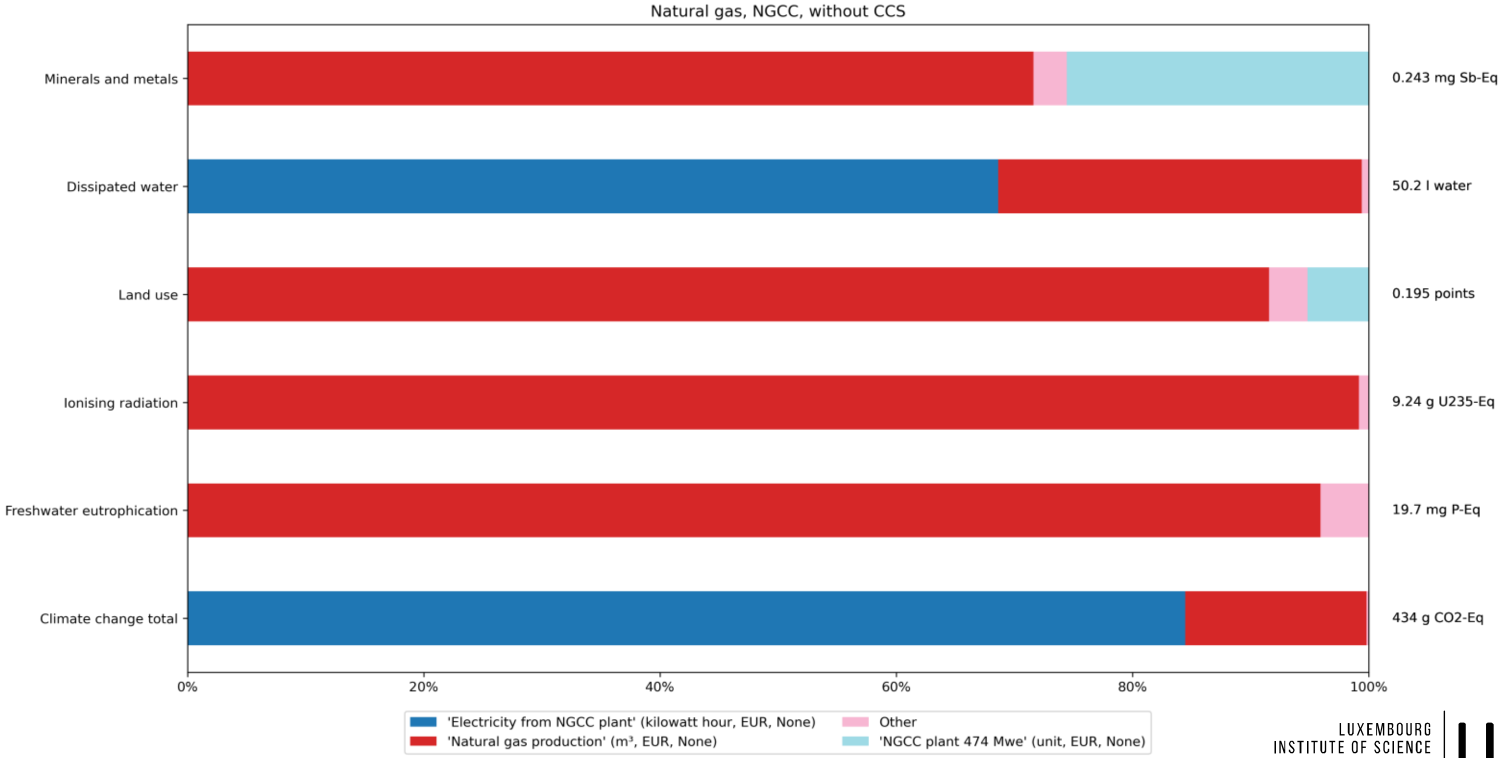
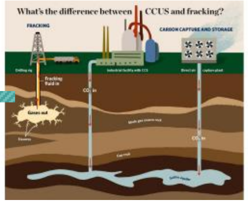
NATURAL GAS

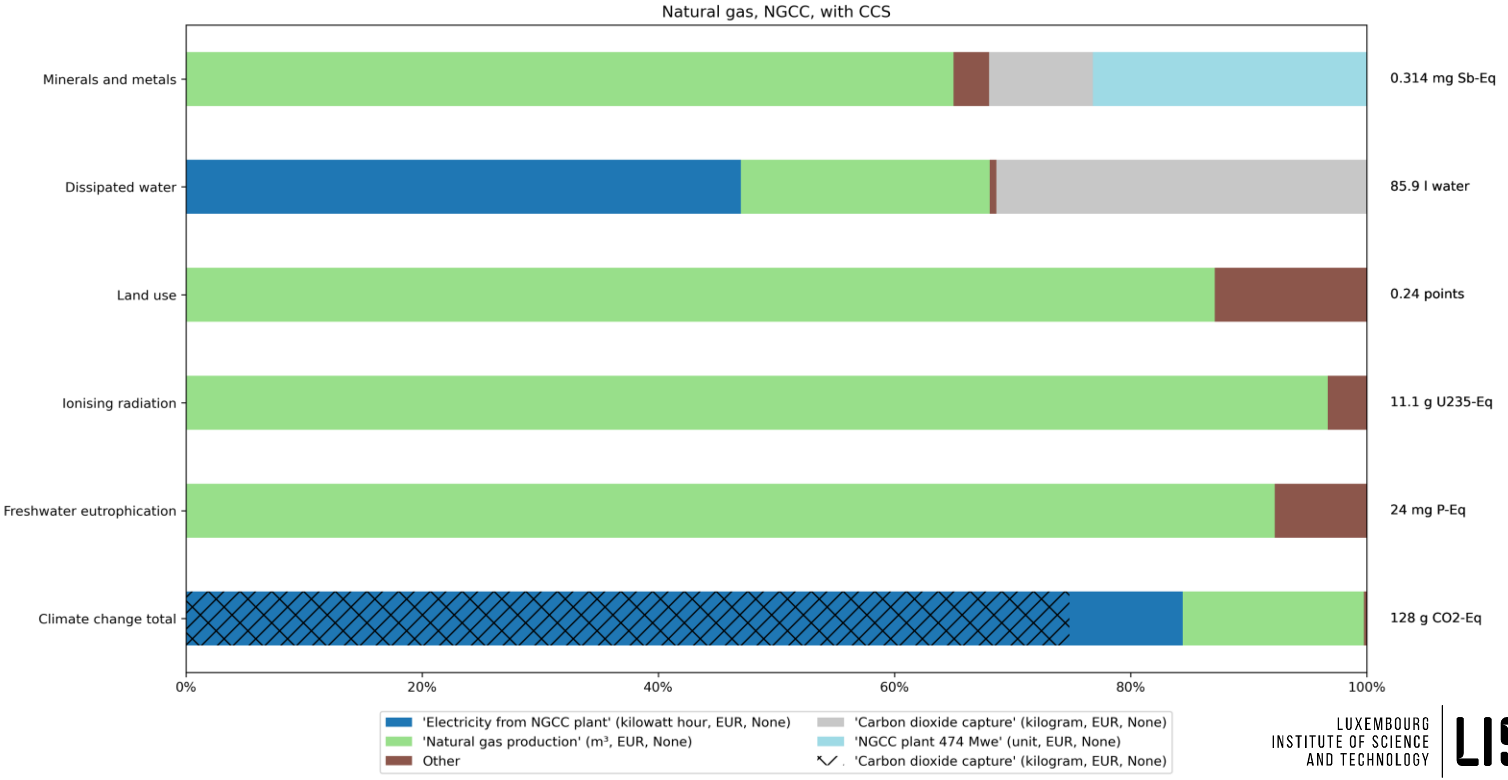
Lifecycle impacts per kWh (NGCC 555 MW, 30-year lifetime)



NATURAL GAS WITH CCS



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



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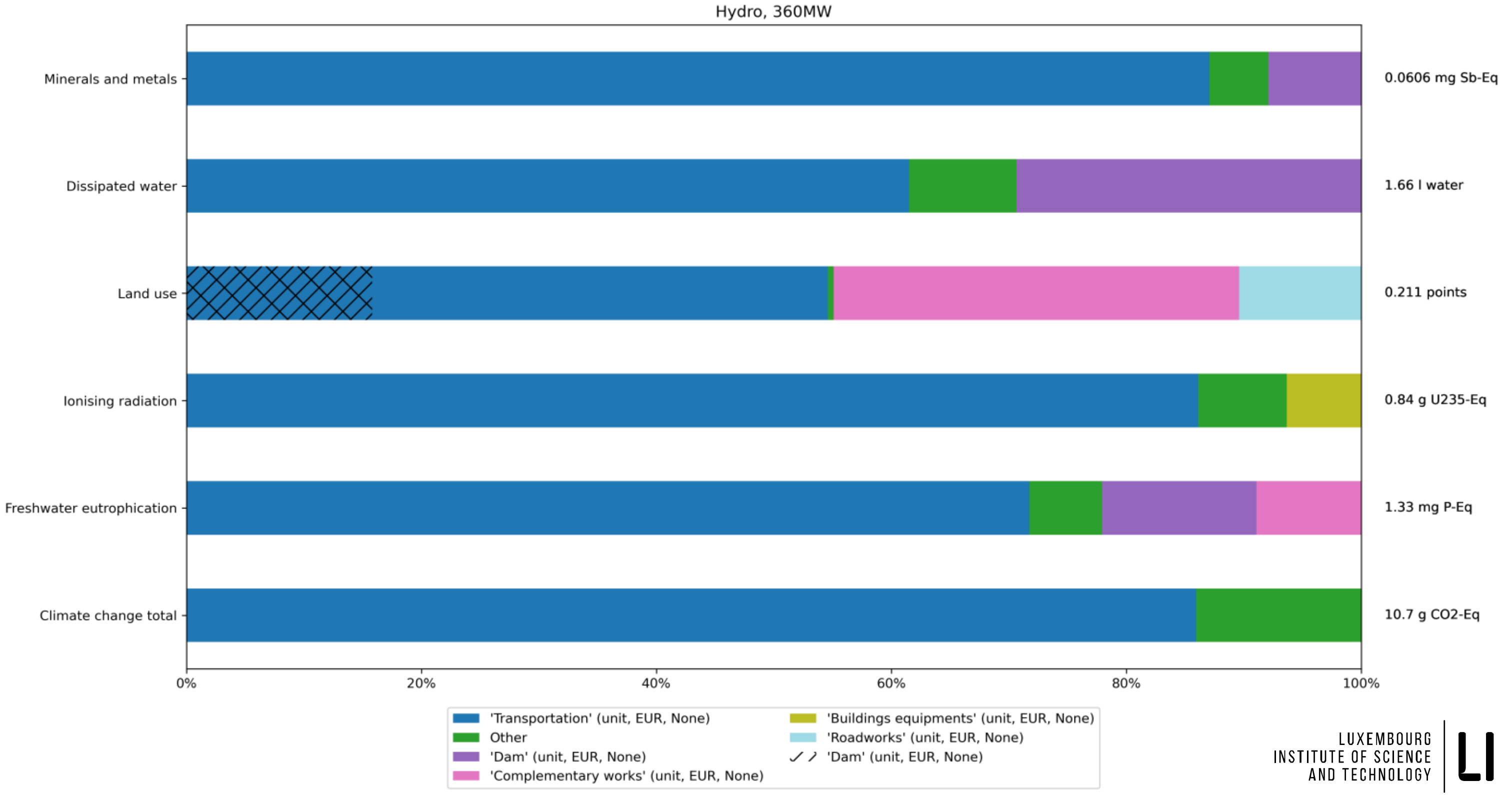
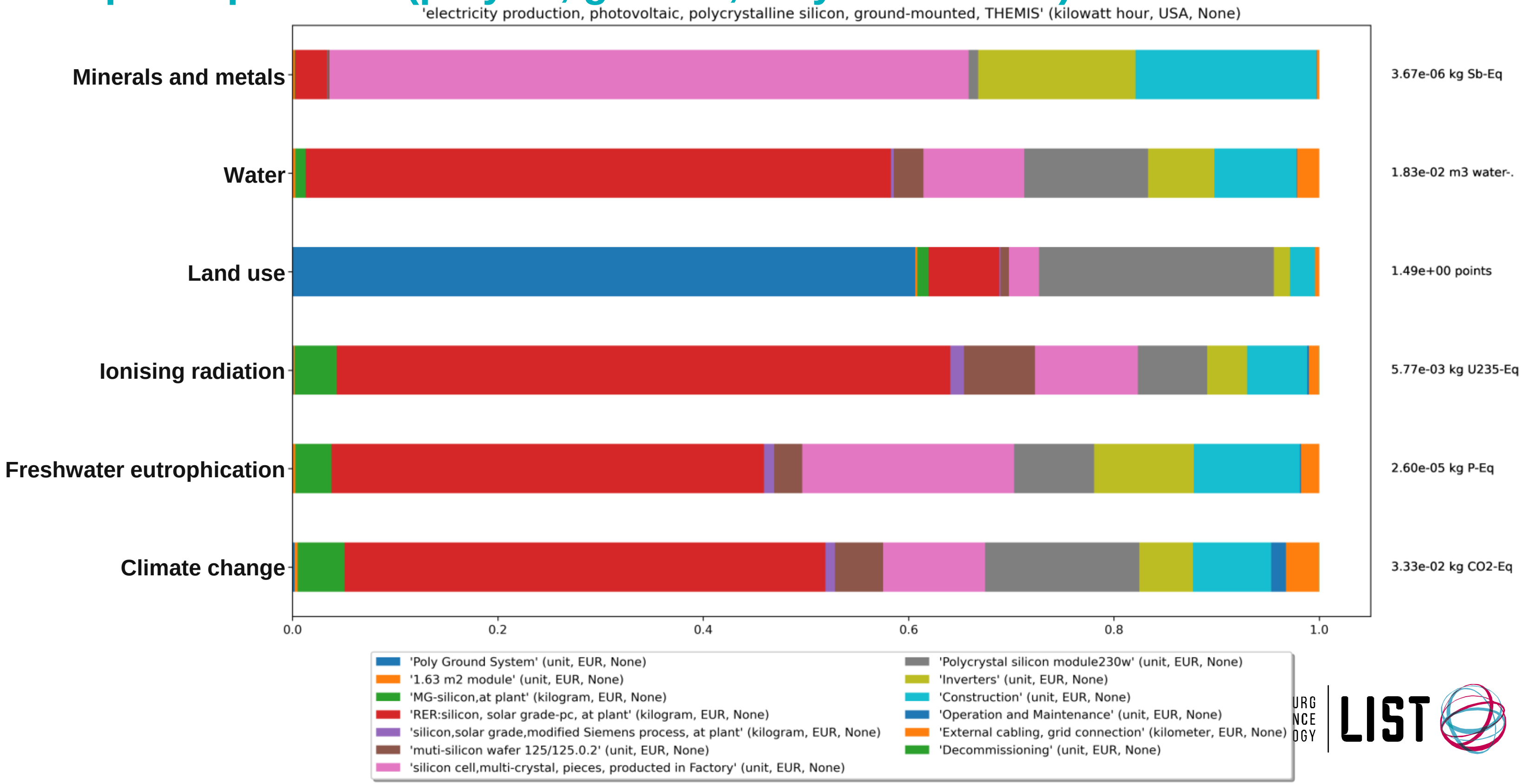
HYDROPOWER

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



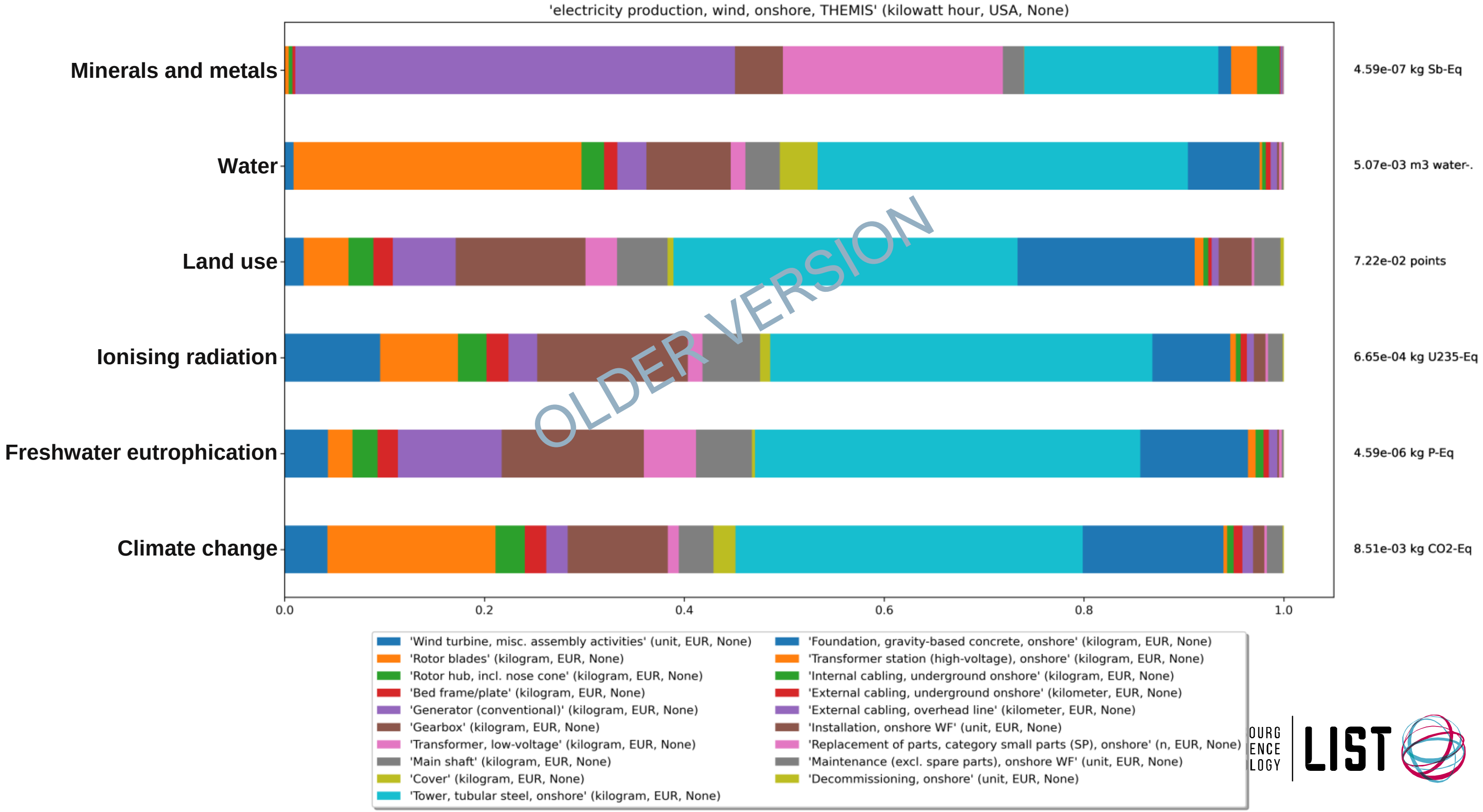
PHOTOVOLTAICS

Lifecycle impacts per kWh (poly-Si, ground, 25-year lifetime)



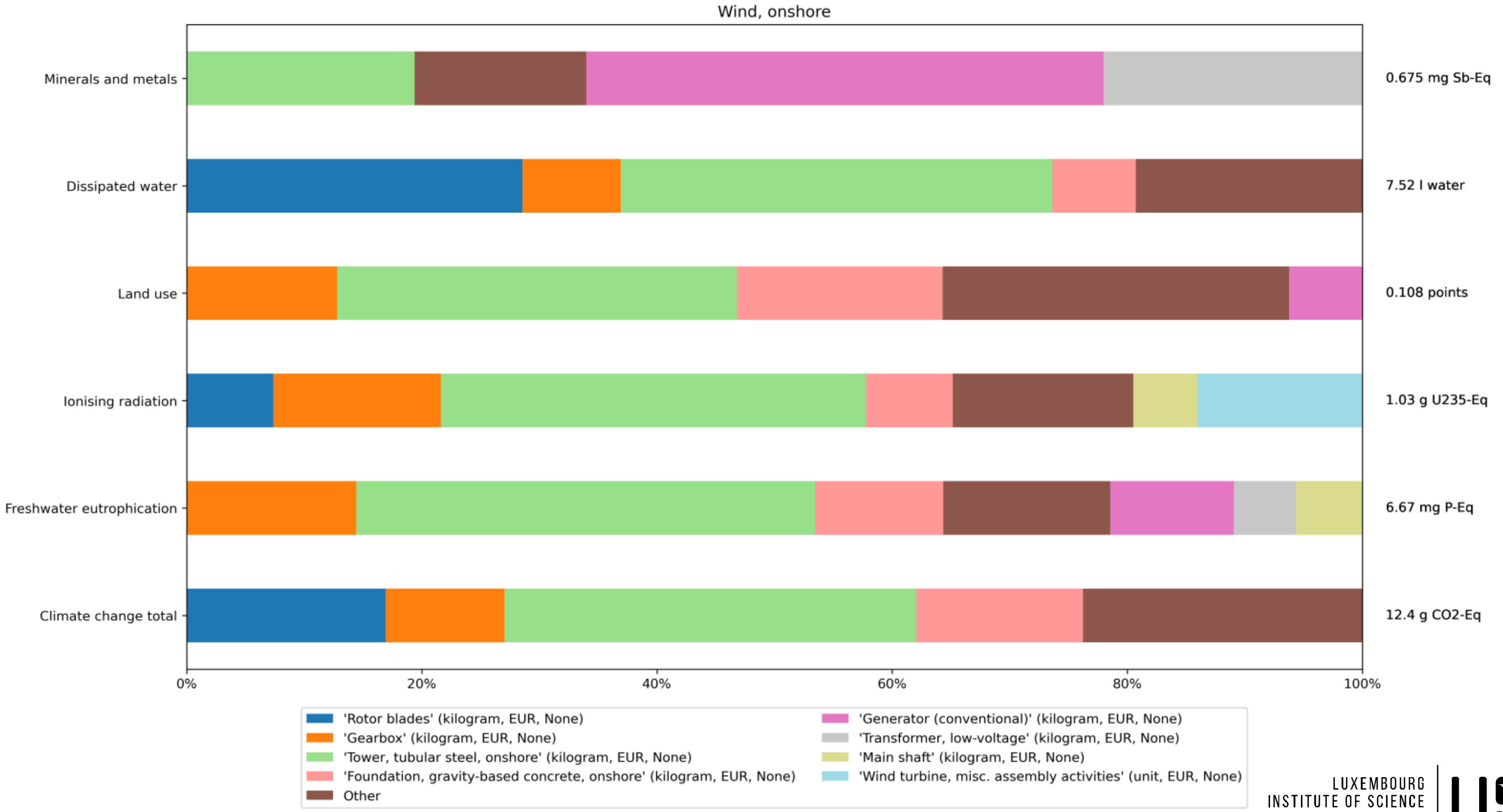
WIND POWER

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



WIND POWER

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



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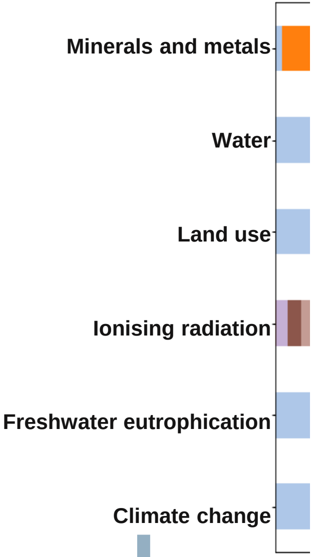
NUCLEAR POWER

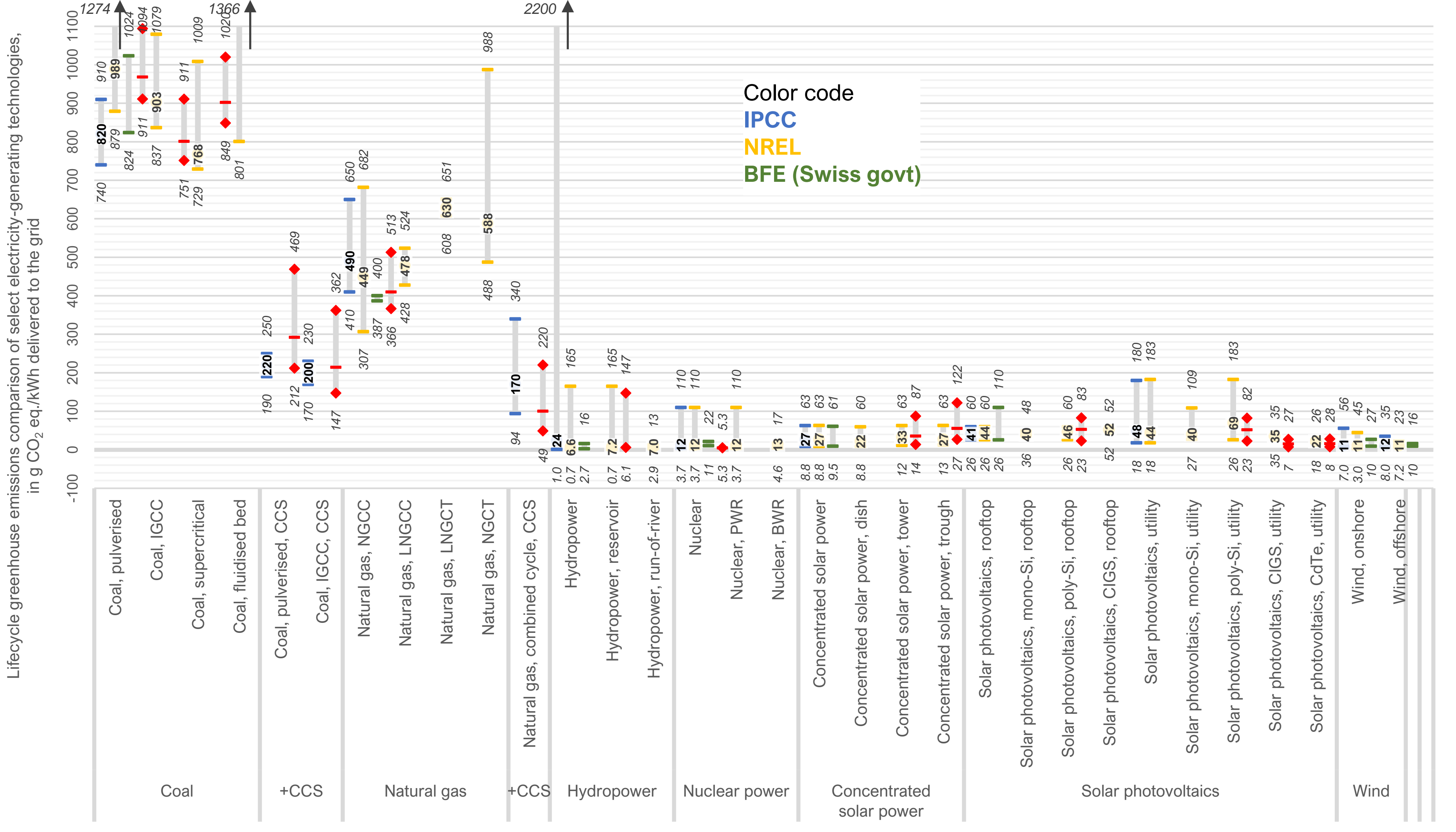
Lifecycle impacts



T. Hedman et al. / C. R. Physique 3 (2002) 903–913

Figure 3. Planned design of the Swedish spent fuel canister.

Main conclusions



Lifecycle greenhouse emissions comparison of select electricity-generating technologies, in g CO_2 eq./kWh delivered to the grid
Color code
IPCC
NREL
BFE (Swiss govt)
Coal, pulverised
Coal, IGCC
Coal, supercritical
Coal, fluidised bed
Coal, pulverised, CCS
Coal, IGCC, CCS
Natural gas, NGCC
Natural gas, LNGCC
Natural gas, LNGCT
Natural gas, NGCT
Natural gas, combined cycle, CCS
Hydropower
Hydropower, reservoir
Hydropower, run-of-river
Nuclear
Nuclear, PWR
Nuclear, BWR
Concentrated solar power
Concentrated solar power, dish
Concentrated solar power, tower
Concentrated solar power, trough
Solar photovoltaics, rooftop
Solar photovoltaics, mono-Si, rooftop
Solar photovoltaics, poly-Si, rooftop
Solar photovoltaics, CIGS, rooftop
Solar photovoltaics, utility
Solar photovoltaics, mono-Si, utility
Solar photovoltaics, poly-Si, utility
Solar photovoltaics, CIGS, utility
Solar photovoltaics, CdTe, utility
Wind, onshore
Wind, offshore
Coal
+CCS
Natural gas
+CCS
Hydropower
Nuclear power
Concentrated solar power
Solar photovoltaics
Wind

MAIN CONCLUSIONS

Fossil fuels

…emit **750-1100** g CO2 eq./kWh (hard coal), **370-510** g CO2 eq./kWh (natural gas)

…after abatement, can reach 150-470 g CO2 eq./kWh (coal), 50-220 g CO2 eq./kWh

…tend to show **higher emissions than previously published** (IPCC) because of **leakage** and **slower efficiency improvements** than expected, especially coal

…may cause high level of eutrophication (depending on mining), require significant amounts of water, and cause toxic and particulate matter emissions (coal)

…have low bulk material requirements, and virtually no specialty metals

Table A.III.2 | Emissions of selected electricity supply technologies (gCO_2eq/kWh)[i]

Options	Direct emissions	Infrastructure & supply chain emissions	Biogenic CO_2 emissions and albedo effect	Methane emissions	Lifecycle emissions (incl. albedo effect)
	Min/Median/Max	Typical values			Min/Median/Max
Currently Commercially Available Technologies					
Coal—PC	670/760/870	9.6	0	47	**740/820/910**
Gas—Combined Cycle	350/370/490	1.6	0	91	**410/490/650**
Biomass—cofiring	n. a. [ii]	–	–	–	**620/740/890**[iii]
Biomass—dedicated	n. a. [ii]	210	27	0	**130/230/420**[iv]
Geothermal	0	45	0	0	**6.0/38/79**
Hydropower	0	19	0	88	**1.0/24/2200**
Nuclear	0	18	0	0	**3.7/12/110**
Concentrated Solar Power	0	29	0	0	**8.8/27/63**
Solar PV—rooftop	0	42	0	0	**26/41/60**
Solar PV—utility	0	66	0	0	**18/48/180**
Wind onshore	0	15	0	0	**7.0/11/56**
Wind offshore	0	17	0	0	**8.0/12/35**
Pre-commercial Technologies					
CCS—Coal—Oxyfuel	14/76/110	17	0	67	**100/160/200**
CCS—Coal—PC	95/120/140	28	0	68	**190/220/250**
CCS—Coal—IGCC	100/120/150	9.9	0	62	**170/200/230**
CCS—Gas—Combined Cycle	30/57/98	8.9	0	110	**94/170/340**
Ocean	0	17	0	0	**5.6/17/28**

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MAIN CONCLUSIONS

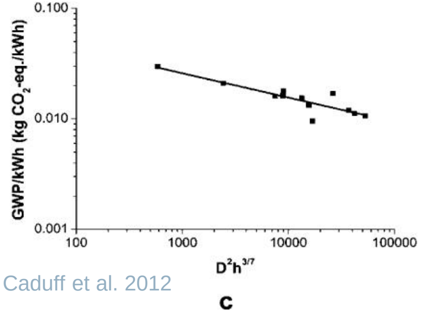
Wind power

…emits **7.8–23** g CO2 eq./kWh (slightly lower than IPCC)

…has high variability (load factors depend on climate), learning curves and increased size suggests lower future emissions

…lower impact overall (eutrophication, land use…)

…requires **significant amounts of bulk materials**, AND some specialty metals (even for gearbox designs)



Caduff et al. 2012

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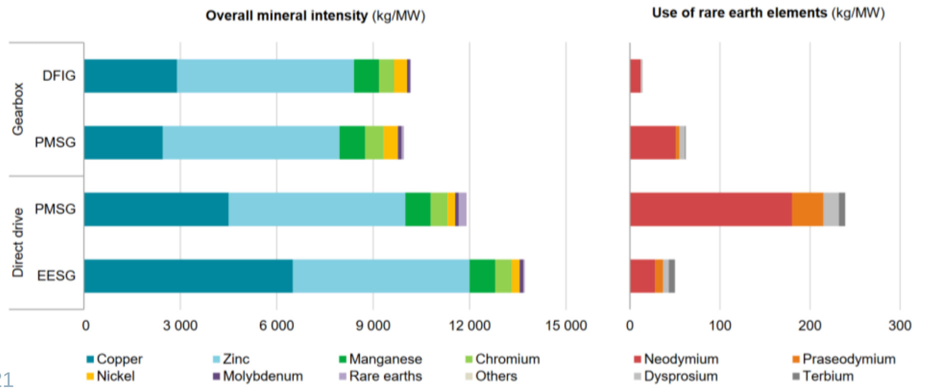

IEA 2021

MAIN CONCLUSIONS

Solar PV

…emits **25–85** g CO2 eq./kWh (poly-Si),
8–30 g CO2 eq./kWh (thin film)

…has high variability (load factors depend on climate), less subject to improvements unless technology changes (**unlike wind, device size matters much less for PV**)

…has high material requirements – critical depending on the choice of future technology (GaAs, perovskite, CdTe…)

Table A.III.2 | Emissions of selected electricity supply technologies (gCO_2eq/kWh)[i]

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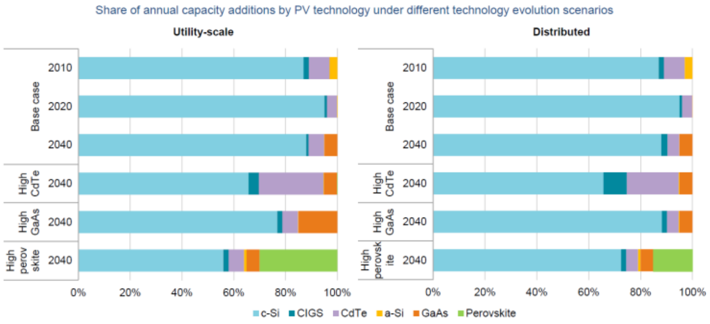
Solar PV: Crystalline silicon is expected to remain the dominant PV technology, but further progress on alternative technologies could see them taking significant market share by 2040



IEA 2021

Notes: c-Si = crystalline silicon; CIGS = copper indium gallium diselenide; CdTe = cadmium telluride; a-Si = amorphous silicon; GaAs = gallium arsenide.

MAIN CONCLUSIONS

Nuclear power

…emits around 5.2 g CO2 eq./kWh

…less than previously (= past 20 years) reported because

Changing mining mix (in-situ leaching increasingly used)

Enrichment is now centrifuge-only

Cleaner global electricity mix

Higher power plant lifetime assumed (60 years)

…has potential to decrease further, with a cleaner electricity mix and closed-loop fuel cycle (reprocessing of spent fuel)

…low overall environmental impact (land use, toxicity, air emissions…) – **moderate copper requirements** for spent fuel encapsulation

…**only tech with ionizing radiation** because only industry to measure radioactivity (robust data also available for coal but not included)

Table A.III.2 | Emissions of selected electricity supply technologies (gCO_2eq/kWh)[i]

Options	Direct emissions	Infrastructure & supply chain emissions	Biogenic CO_2 emissions and albedo effect	Methane emissions	Lifecycle emissions (incl. albedo effect)
	Min/Median/Max	Typical values			Min/Median/Max
Currently Commercially Available Technologies					
Coal—PC	670/760/870	9.6	0	47	740/820/910
Gas—Combined Cycle	350/370/490	1.6	0	91	410/490/650
Biomass—cofiring	n. a. [ii]	–	–	–	620/740/890[iii]
Biomass—dedicated	n. a. [ii]	210	27	0	130/230/420[iv]
Geothermal	0	45	0	0	6.0/38/79
Hydropower	0	19	0	88	1.0/24/2200
Nuclear	0	18	0	0	3.7/12/110
Concentrated Solar Power	0	29	0	0	8.8/27/63
Solar PV—rooftop	0	42	0	0	26/41/60
Solar PV—utility	0	66	0	0	18/48/180
Wind onshore	0	15	0	0	7.0/11/56
Wind offshore	0	17	0	0	8.0/12/35
Pre-commercial Technologies					
CCS—Coal—Oxyfuel	14/76/110	17	0	67	100/160/200
CCS—Coal—PC	95/120/140	28	0	68	190/220/250
CCS—Coal—IGCC	100/120/150	9.9	0	62	170/200/230
CCS—Gas—Combined Cycle	30/57/98	8.9	0	110	94/170/340
Ocean	0	17	0	0	5.6/17/28

21. The Committee conducted this study by investigating sources of exposure from electricity-generating technologies based on *(a)* nuclear power, *(b)* the combustion of coal, natural gas, oil and biofuels, and *(c)* geothermal, wind and solar power. Two electricity-generating technologies (nuclear power and combustion of coal) were investigated in detail, because a more robust database existed for these technologies. The Committee evaluated the main sources of radioactive discharges from the life cycle of these electricity-generating technologies. For nuclear power, these sources included uranium

UNSCEAR 2016

Centrifuges for U enrichment

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LIMITS OF LCA

Scope dictates interpretation

Boxes integrated to the report to cover areas not addressed by the LCA

- Boxes

MAIN CONCLUSIONS

Outlook and further thoughts

More data required to address “blind spots”

Robust methane leakage data

End-of-life treatment of renewable infrastructure

Nuclear power: model reprocessing, refine deep waste repository

Some technologies are maturing: include learning rates

Ionising radiation only accounted for nuclear

Linearity of LCA = no economies of scale

Some impacts not quantified: acceptance, costs, aesthetic, biodiversity threats (e.g. hydropower and riparian habitats), risks…