LCA of electricity generation technologies

UNECE modelling activities – Carbon neutrality project

02.06.2021

UNECE

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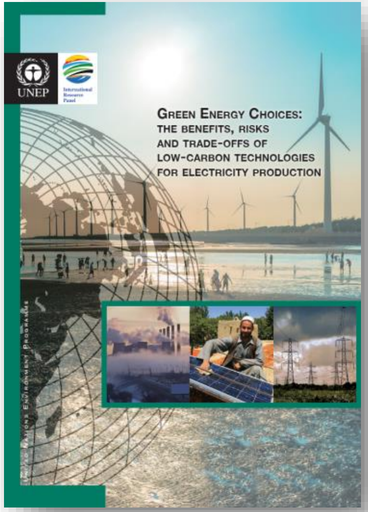
Context of life cycle assessment task



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

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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Life cycle assessment

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*

And typically:

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

Considering a range of impact types

Human health, ecosystem health, natural resource use

→ *Multicriteria*

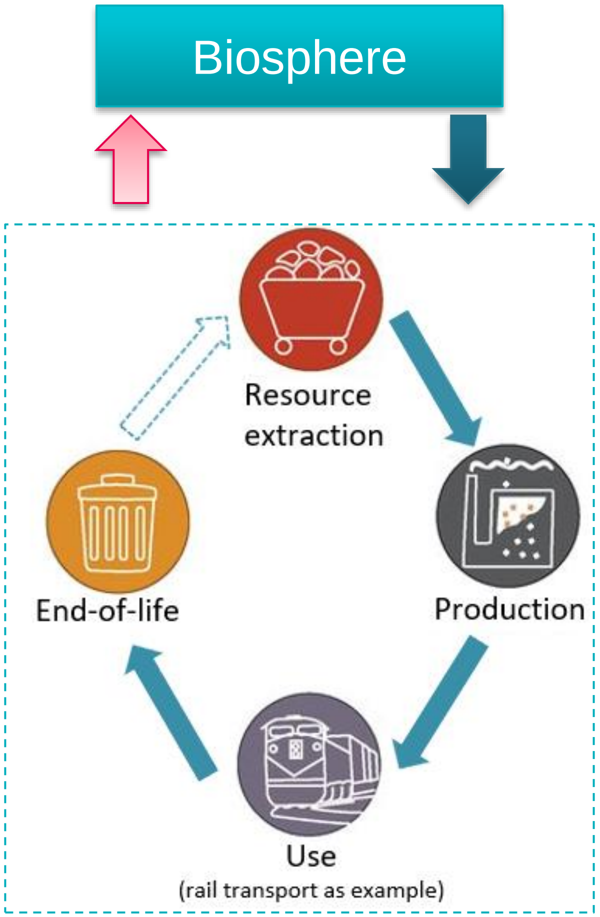

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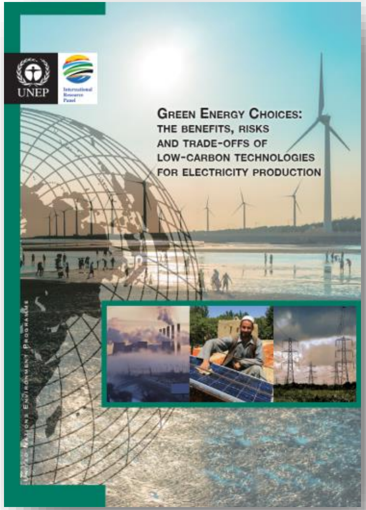
Figure: Adapted from Hellweg & Mila i Canals (2014)

Context of LCA task

Starting point: UNEP IRP report "Green Energy Choices"



Limitations

Absence of state-of-the-art nuclear power and biomass

==> need for expertise on these technologies

Optimistic efficiencies?

Limited consideration of methane leakage in fossil fuel extraction

No direct emissions in hydropower

No consistent end-of-life treatment consideration across technologies

Energy scenarios outdated: use REMIND? MESSAGE? …?

Update welcome!

Most data is 10 years

Add newer technologies (namely small modular reactors)

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

Technologies

Full list

Photovoltaics

Polycrystalline silicon, ground-/roof-mounted
CIGS, ground-/roof-mounted
CdTe, ground-/roof-mounted

CSP

Trough
Tower

Coal

Existing PC, with and without CCS
Integrated gasification CC, with and without CCS
Coal SCPC, with and without CCS

Gas

NGCC, with and without CCS

Hydropower

660 and 360 MW designs

Wind

Onshore
Offshore, concrete and steel foundation

Nuclear power

Boiling water reactor
Pressure water reactor

REgions

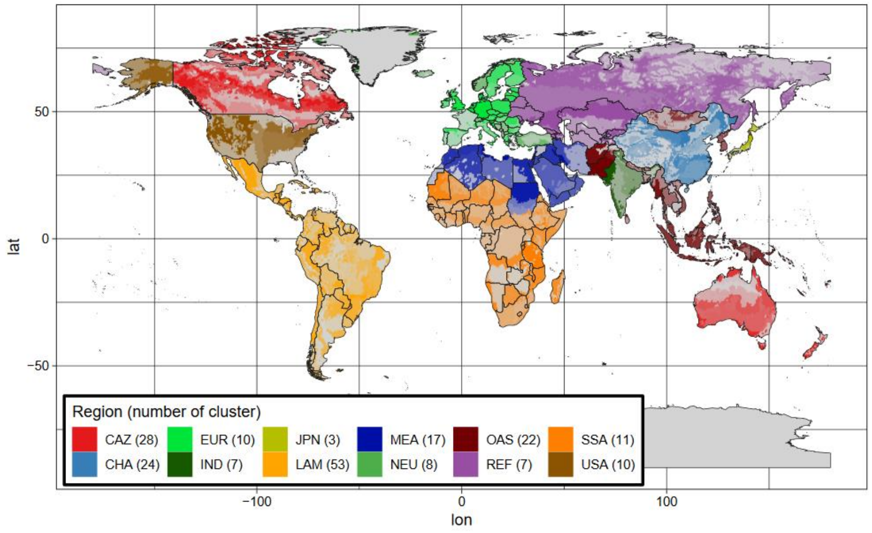
Why regionalizing?

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

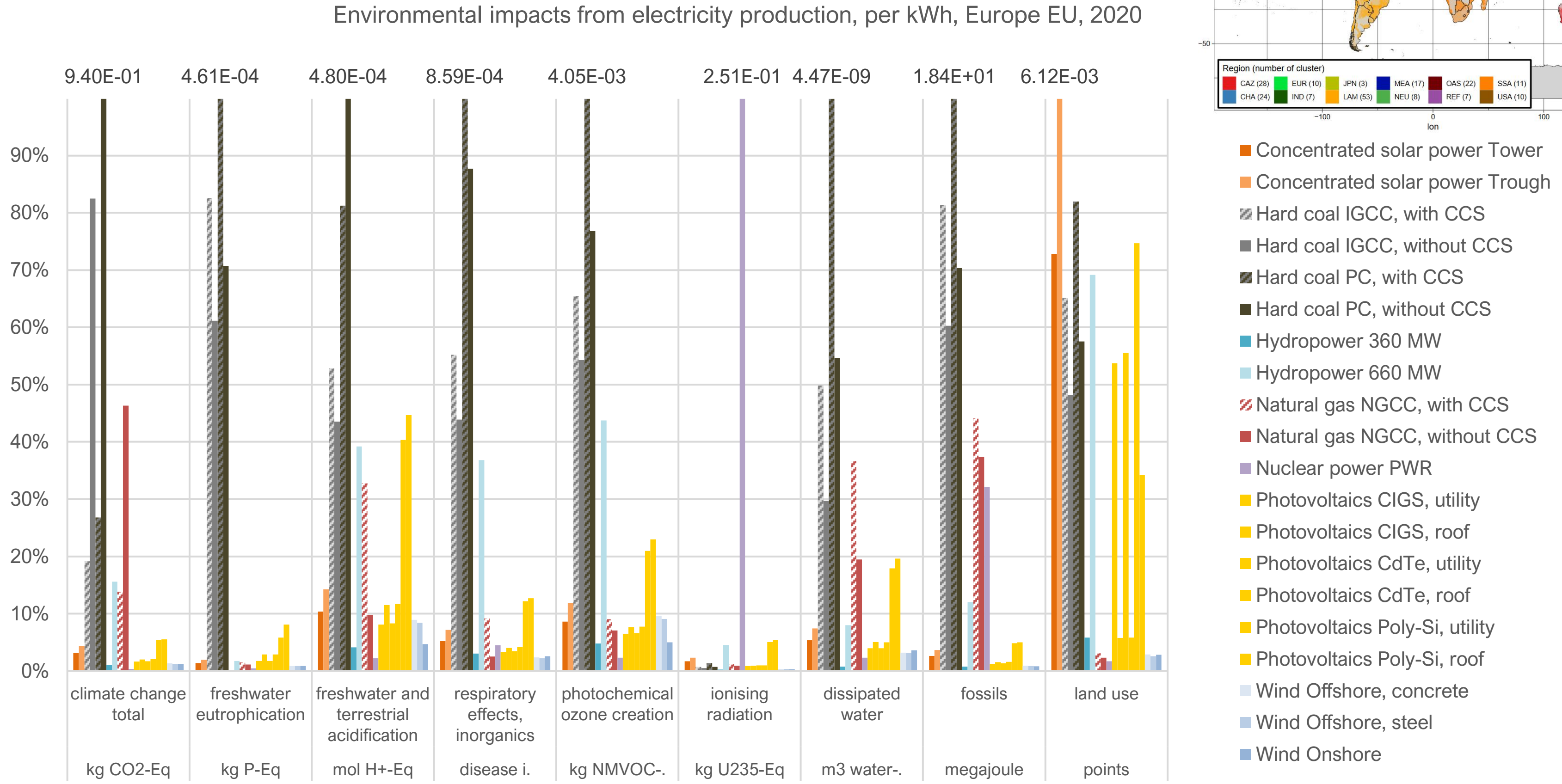


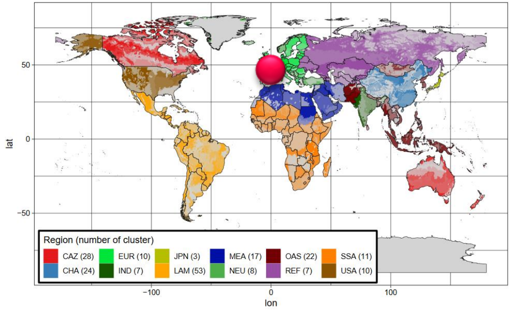
REMIND regions	Code
Canada, Australia & New Zealand	CAZ
China	CHA
European Union	EUR
India	IND
Japan	JPN
Latin America	LAM
Middle East and NorthAfrica	MEA
Non-EU member states	NEU
Other Asia	OAS
Reforming countries	REF
Sub Saharan Africa	SSA
United States	USA

Progress meeting June 2nd, 2021

Preliminary results

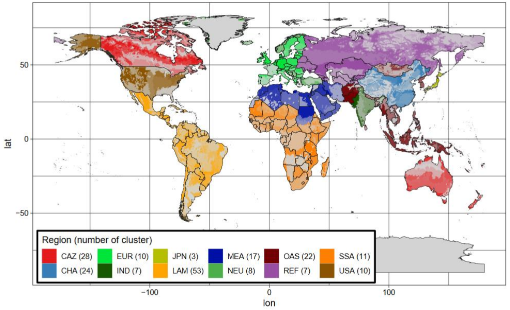
Results UNECE regions – EUR



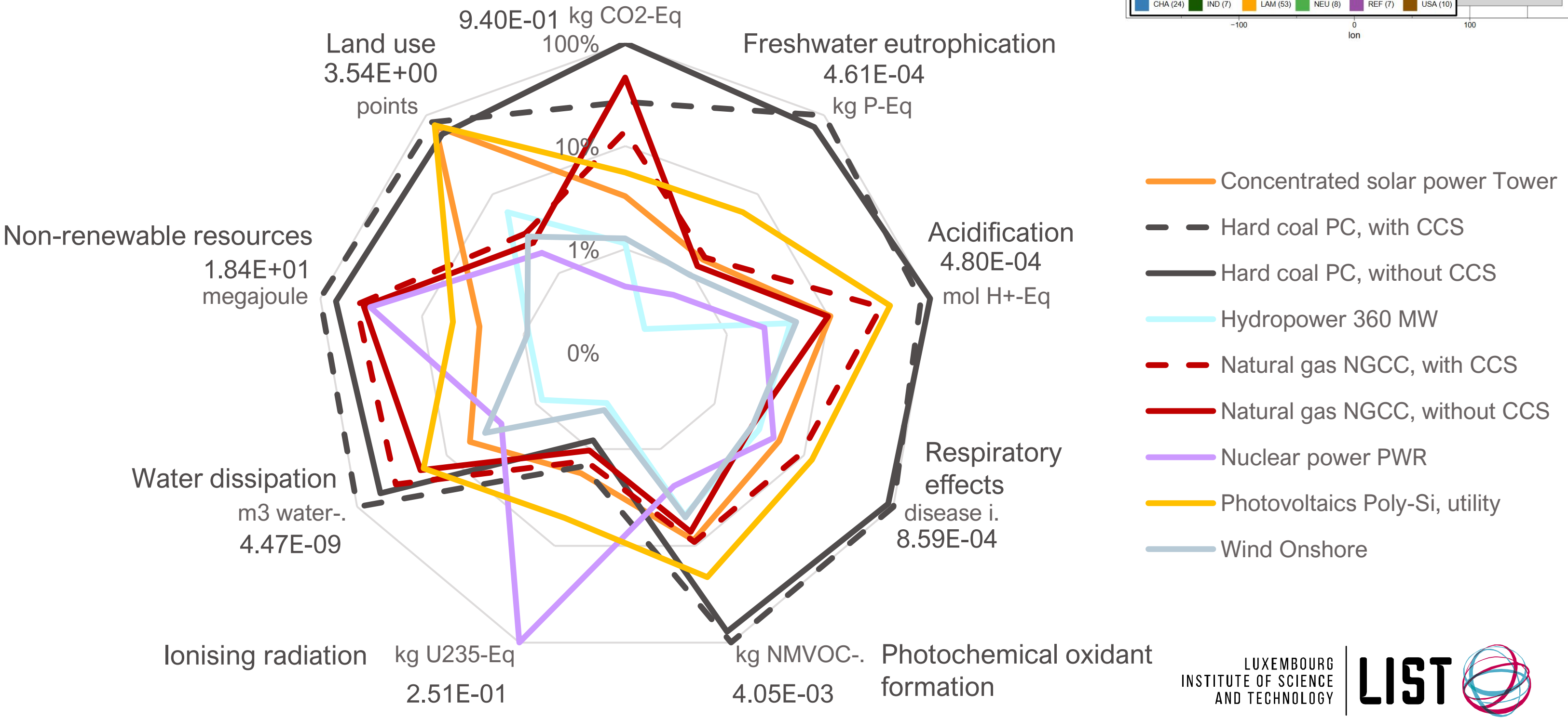


Results UNECE regions – EUR

Different visualisation



Environmental impacts from electricity production, Europe EU



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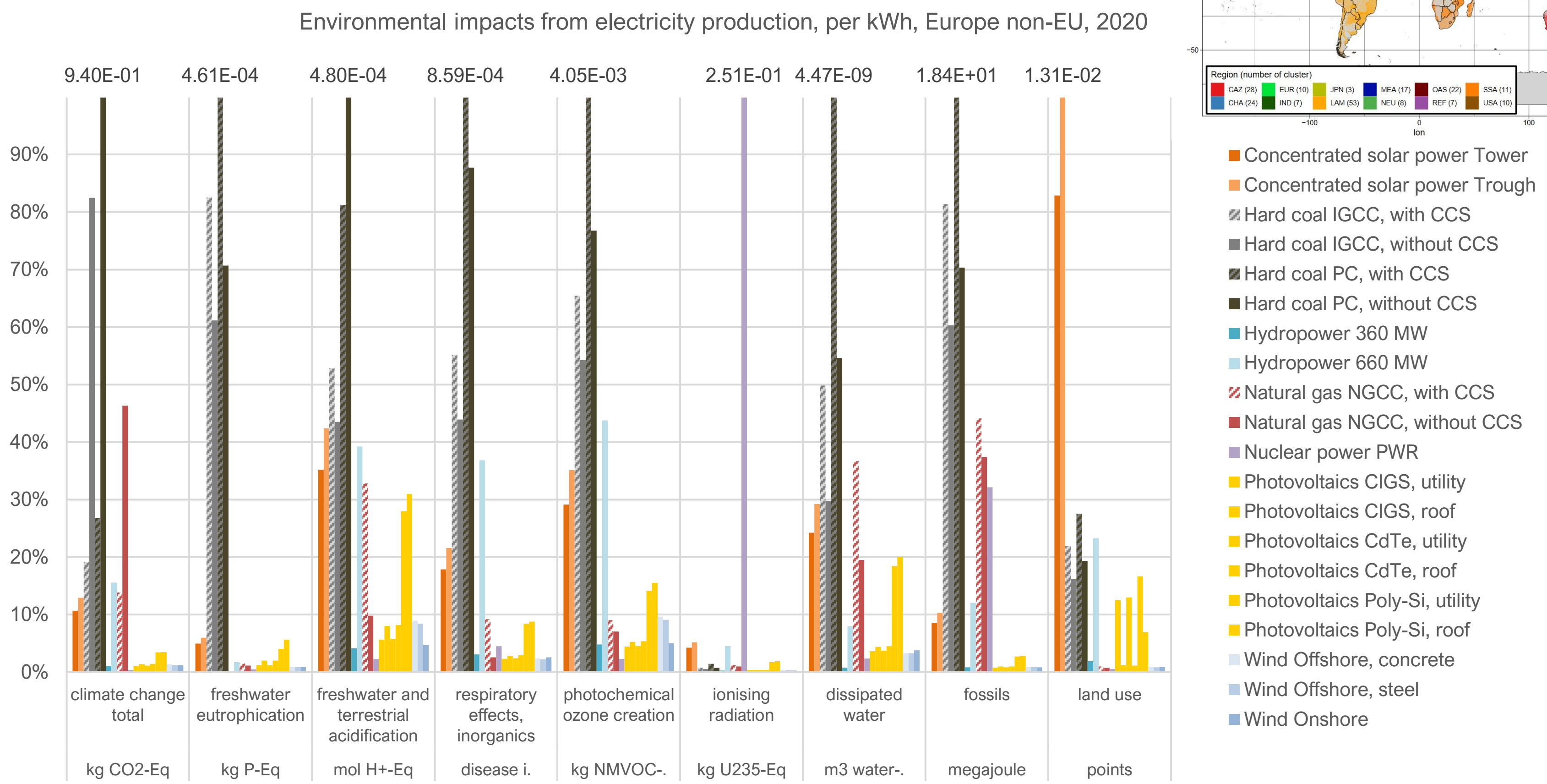
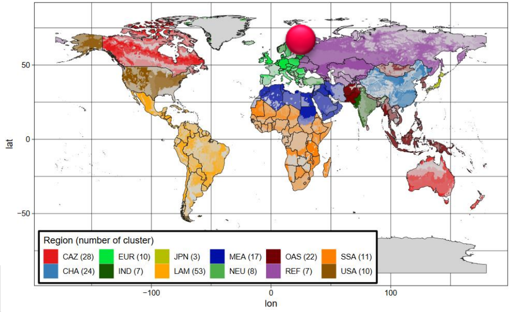
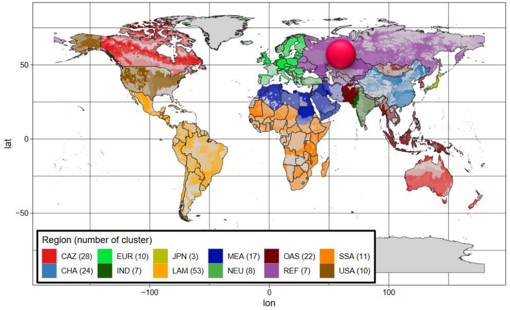
Results UNECE regions – NEU

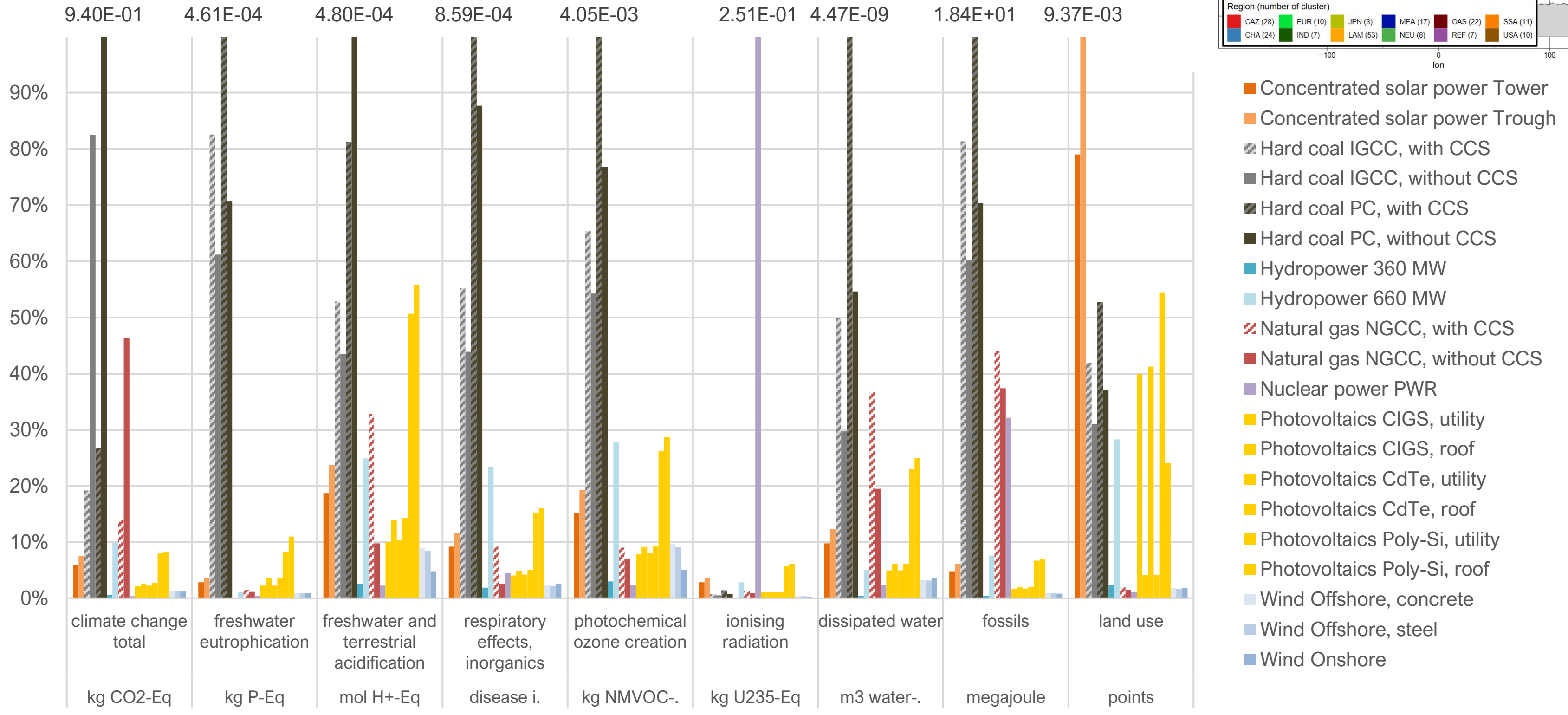




Results UNECE regions – REF



Environmental impacts from electricity production, per kWh, Reforming countries, 2020



CONCENTRATED SOLAR POWER

Region	Capacity factor Solar Tower	Capacity factor Parabolic Through	Reference location
CAZ	55.00%	38.93%	Australia (-32.594,137.856)
CHA	49.26%	33.89%	China (41.507, 108.588)
EUR	49.23%	36.95%	Spain (37.442,-6.25)
IND	36.23%	29.25%	India (27.601,72.224)
JPN	14.40%	20.60%	Japan(33.22,131.63)
LAM	70.95%	55.80%	Chile (27.601,72.224)
MEA	55.78%	42.76%	Morocco (30.218,-9.149)
NEU	14.40%	12.30%	Denmark(57.05,9.9)
OAS	29.27%	28.23%	Thailand (14.334,99.709)
REF	29.10%	23.70%	Russia(47.21,45.54)
SSA	55.19%	41.97%	South Africa (31.631,38.874)
USA	60.41%	37.49%	USA (35.017,-117.333)

Main parameters influencing the capacity factor:

Direct Normal Irradiation (DNI) and other meteorological parameters (e.g. latitude, wind, surface albedo)

Plant size

Technology (solar tower or parabolic through)

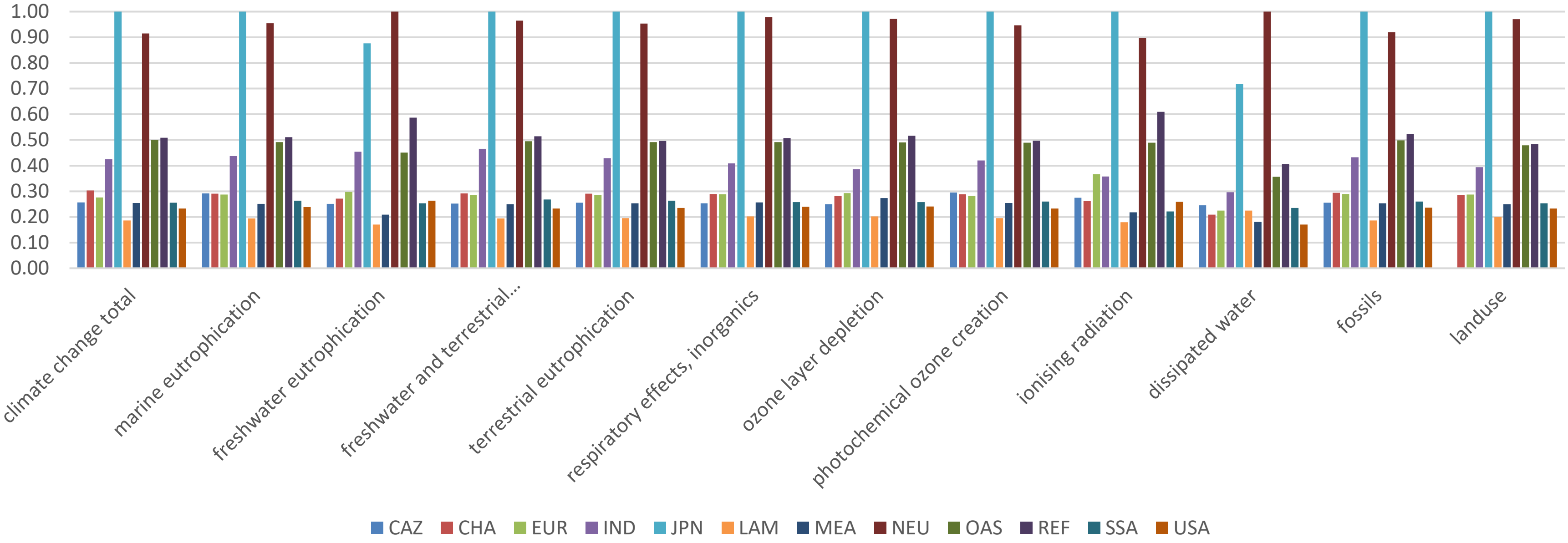
Storage

Year of construction

[1] Johan Lilliestam, Richard Thonig, Chuncheng Zang, & Alina Gilmanova (2021). CSP.guru (Version 2021-01-01) [Data set]. Zenodo. http://doi.org/10.5281/zenodo.4613099
[2] Chhatbar, K., & Meyer, R. (2011). The influence of meteorological parameters on the energy yield of solar thermal plants.
[3] National Renewable Energy Laboratory (NREL). (2021). *What Is the NSRDB?* National Solar Radiation Database. https://nsrdb.nrel.gov/.

Influence of location for each technology

CSP, tower



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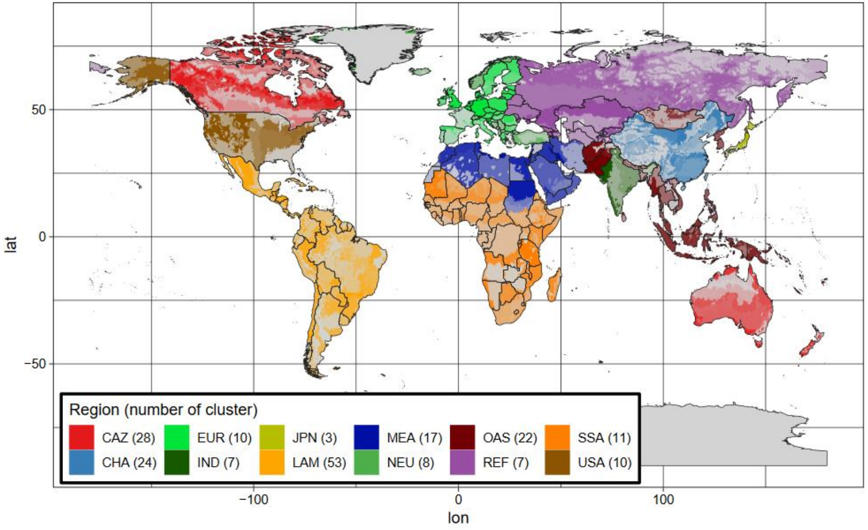
WIND

Region	Capacity factor On-shore	Capacity factor Off-shore
CAZ	29.16%	30.50%*
CHA	22.67%	22.68%
EUR	22.83%	36.18%
IND	17.80%	30.50%*
JPN	25.00%	30.00%
LAM	36.05%	30.50%*
MEA	29.56%	30.50%*
NEU	26.15%	31.43%
OAS	22.67%	22.68%**
REF	26.18%	30.50%*
SSA	29.16%	30.50%*
USA	33.35%	40.00%

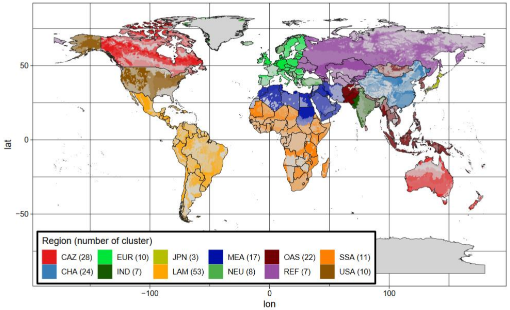


* Numbers not available. Average value is taken

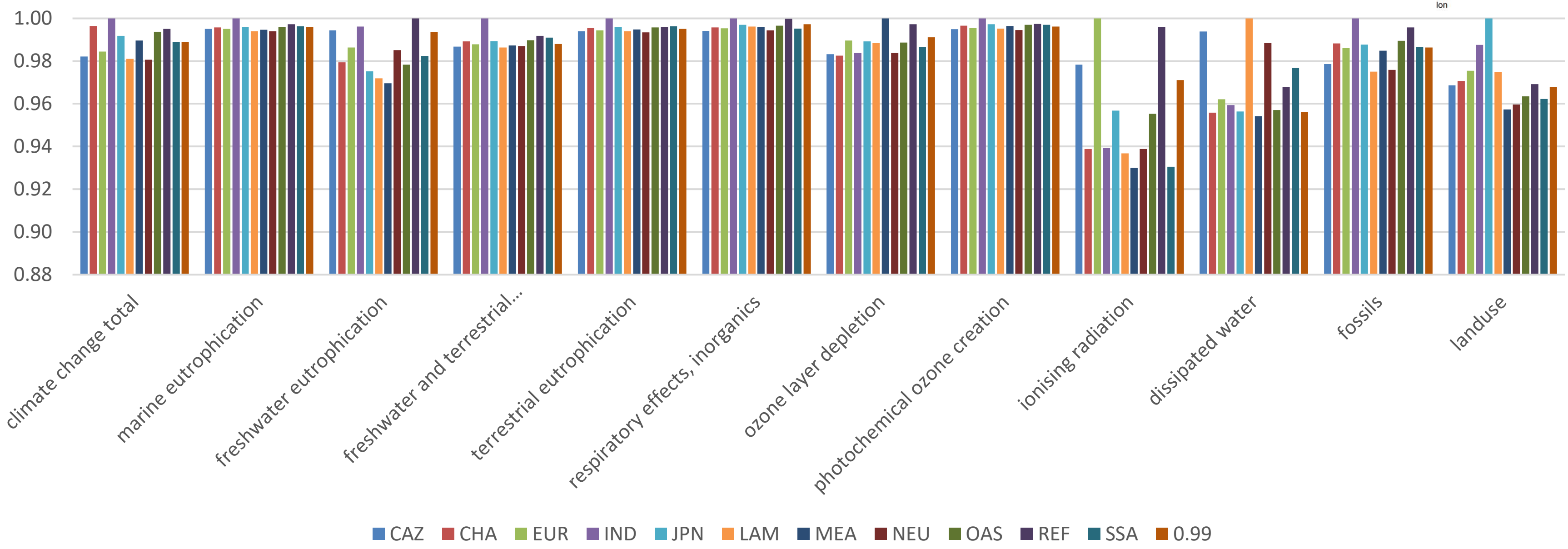
** Numbers not available. Value for China is taken

IRENA. (2021). *Query Tool*. IRENA International Renewable Energy Agency. https://www.irena.org/Statistics/Download-Data.

Influence of location for each technology



Wind, offshore, gravity-based foundation



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Influence of location for each technology

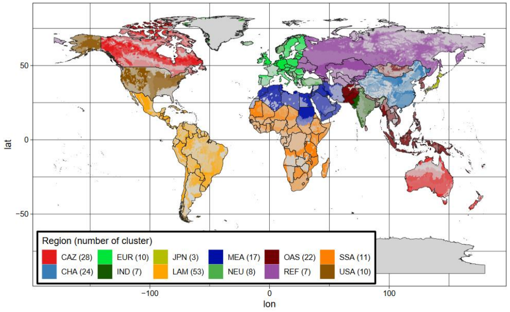
Hydro, 360MW

Table 5.3 Hydropower project capacity factors and capacity weighted averages for large hydropower projects by country/region, 2010-2019

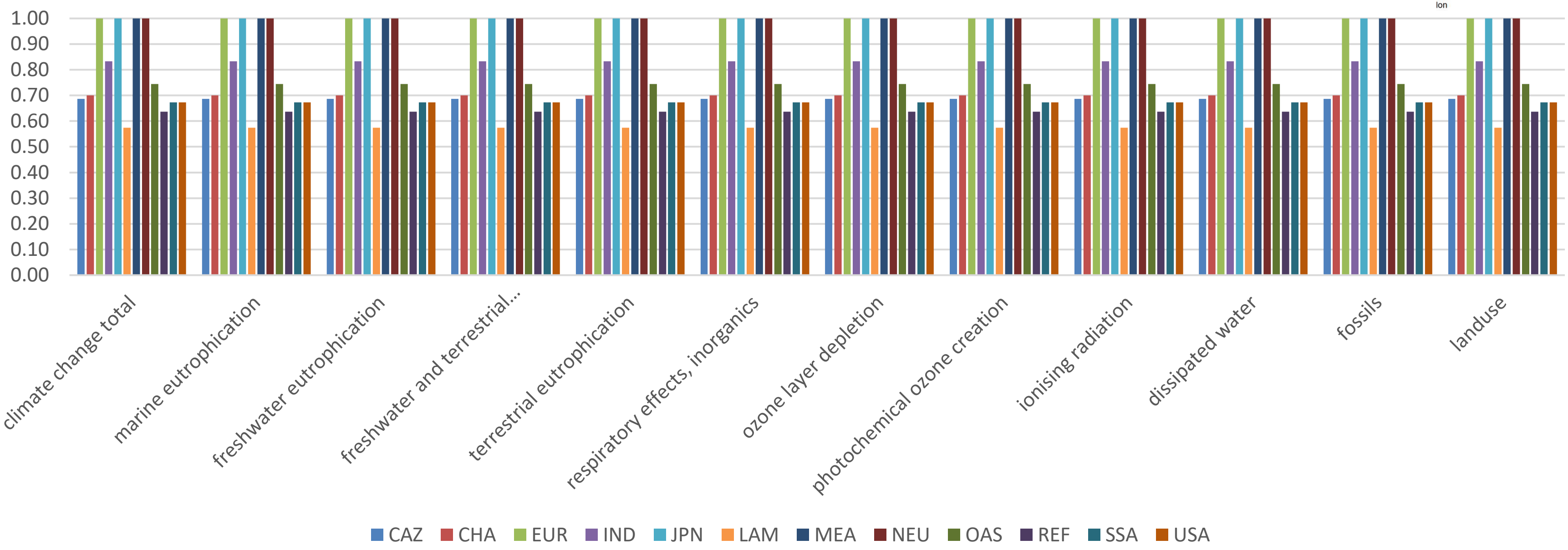
	2010-2014			2015-2019		
	5th percentile (%)	Weighted-average (%)	95th percentile (%)	5th percentile (%)	Weighted-average (%)	95th percentile (%)
Africa	28	**50**	72	35	**52**	82
Brazil	51	**65**	80	39	**47**	59
Central America	27	**48**	64	36	**53**	56
China	31	**45**	57	35	**50**	57
Eurasia	27	**31**	58	31	**55**	67
Europe	14	**33**	69	16	**35**	62
India	30	**47**	62	22	**42**	65
North America	18	**31**	80	34	**52**	75
Oceania	25	**29**	42	39	**45**	48
Other Asia	36	**48**	66	37	**47**	73
Other South America	45	**61**	83	49	**61**	85

Source: IRENA Renewable Cost Database.

Influence of location for each technology



Hydro, 360MW

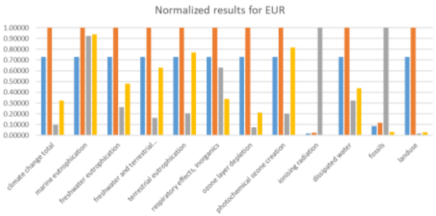


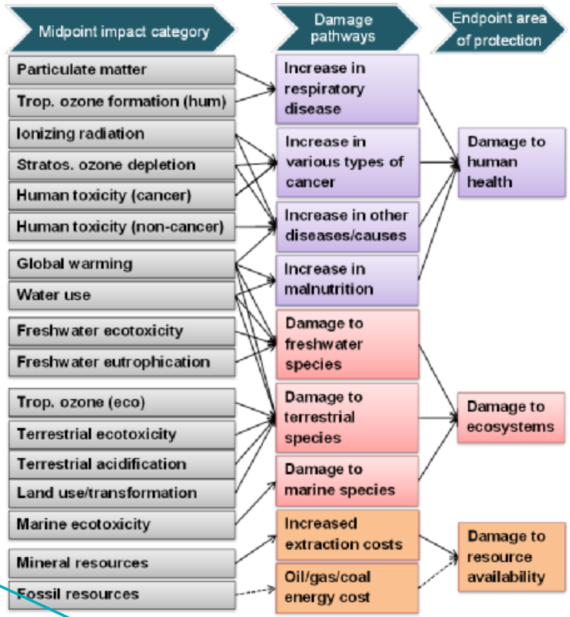
Results presentation/interpretation

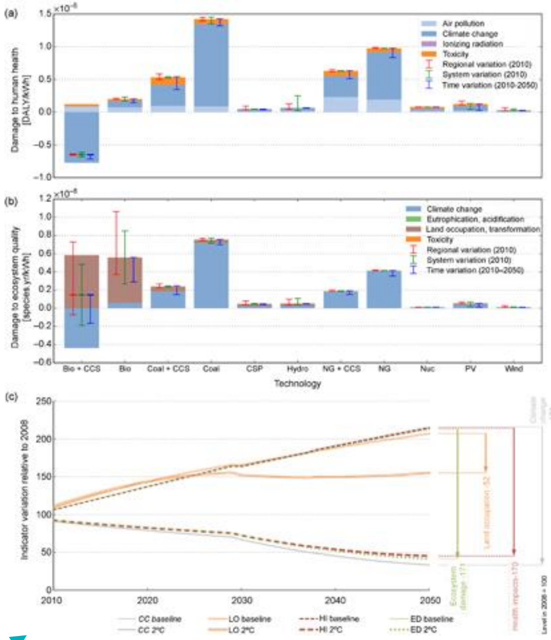
Options available for more policy-relevance

Results aggregation – Option 1

“Midpoint” vs. “endpoint” indicators







midpoint endpoint

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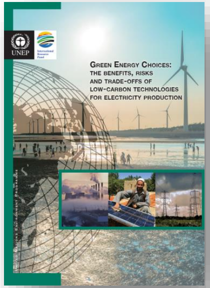
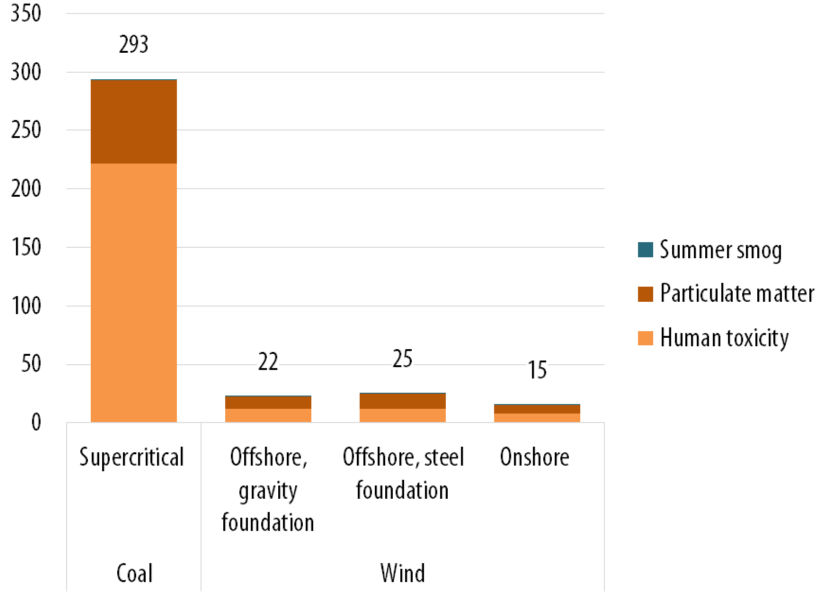
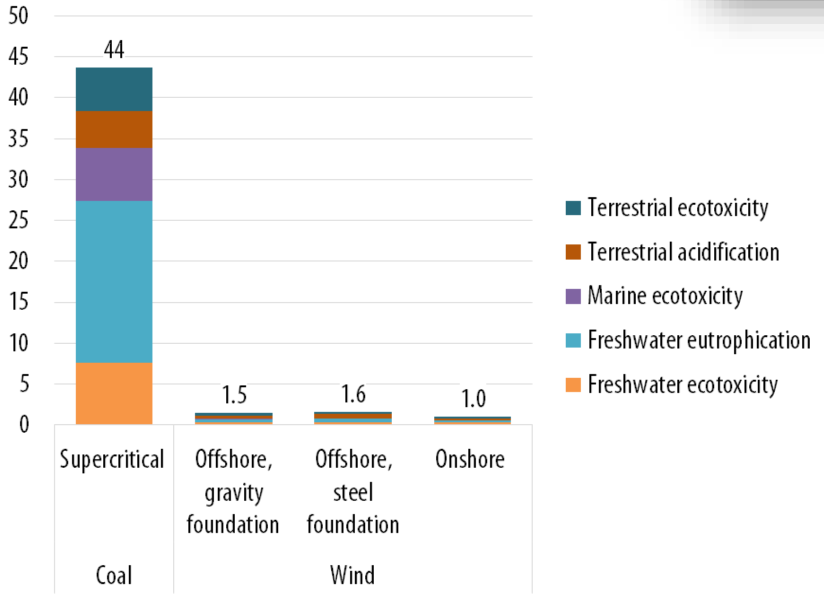
Results aggregation – Option 1 – Wind power



Human health impacts [DALY*/TWh]



Damage to ecosystems [species·yr/TWh]



**DALY = Disability-adjusted life year, a measure of overall disease burden, excl. effects of climate change*

Excluding effects of climate change and land use

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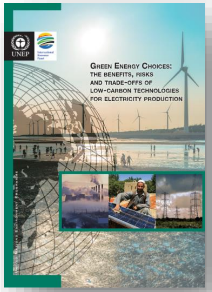
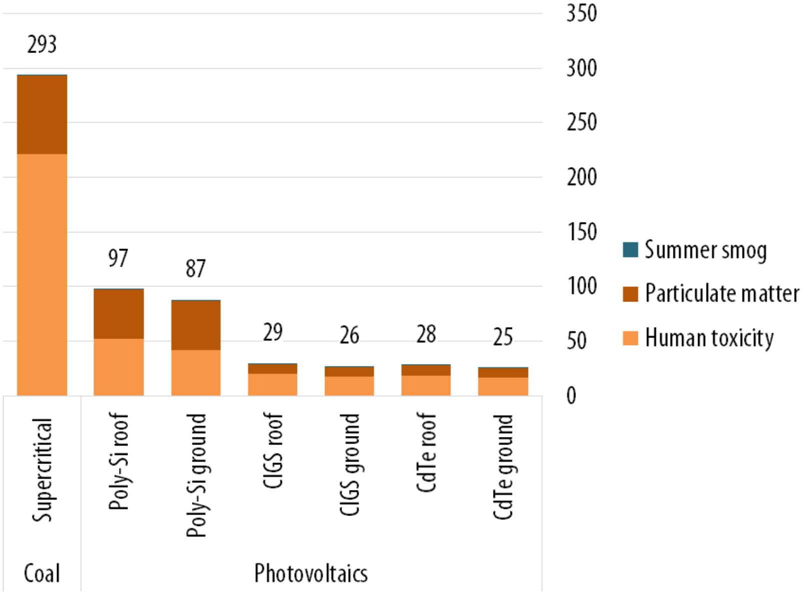
/!\ All results preliminary

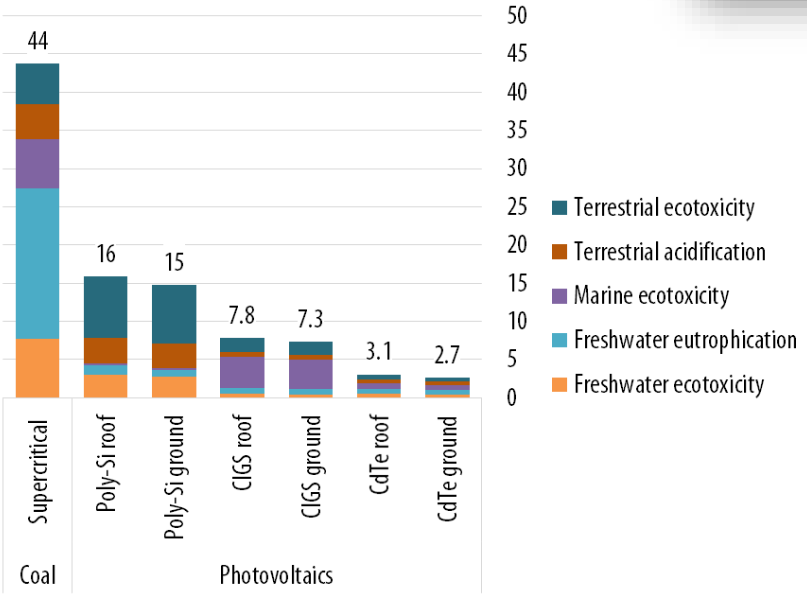
Results aggregation – Option 1 – Solar photovoltaics



Human health impacts [DALY*/TWh]



Damage to ecosystems [species·yr/TWh]



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Excluding effects of climate change and land use

/!\ All results preliminary

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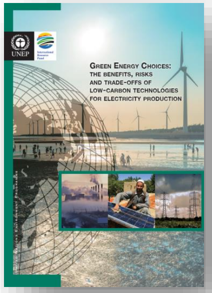
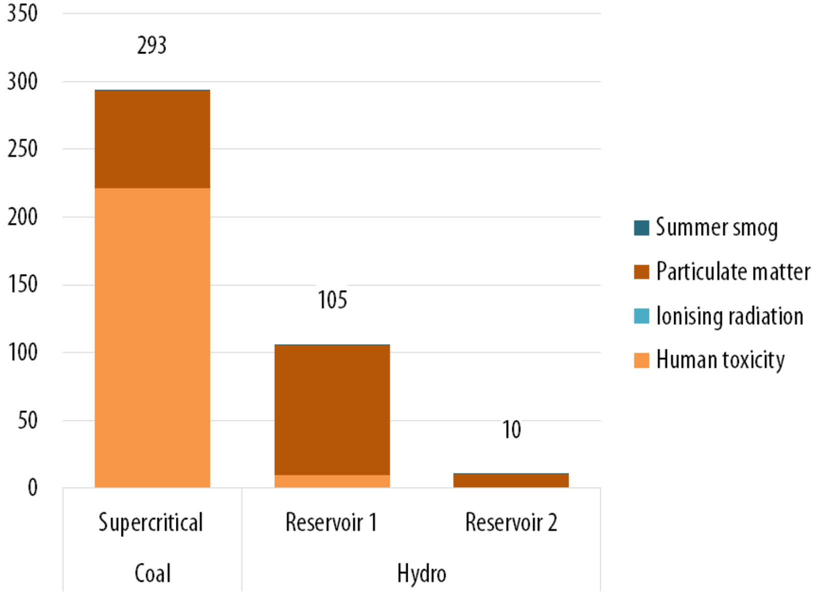
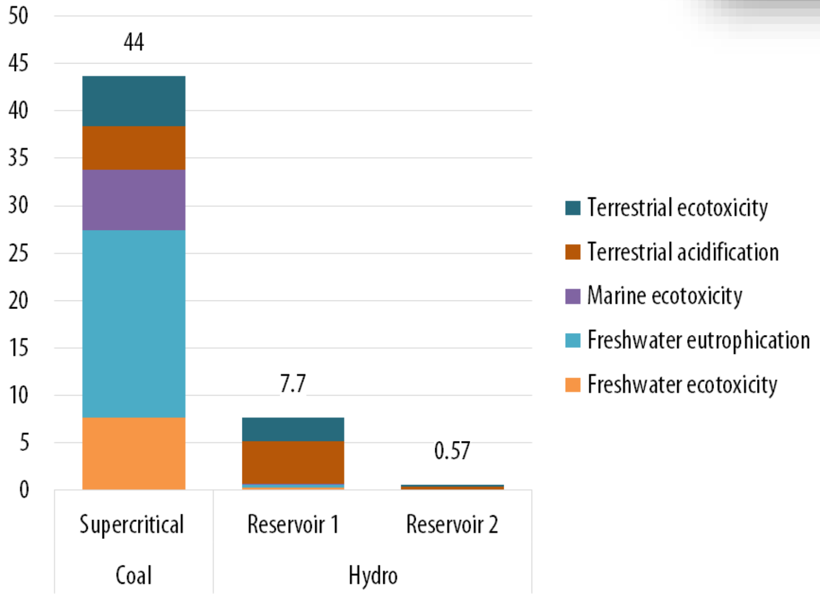
Results aggregation – Option 1 – Hydropower



Human health impacts [DALY*/TWh]



Damage to ecosystems [species·yr/TWh]



**DALY = Disability-adjusted life year, a measure of overall disease burden, excl. effects of climate change*

Excluding effects of climate change and land use

/!\ All results preliminary

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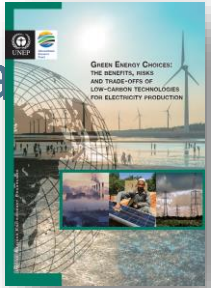
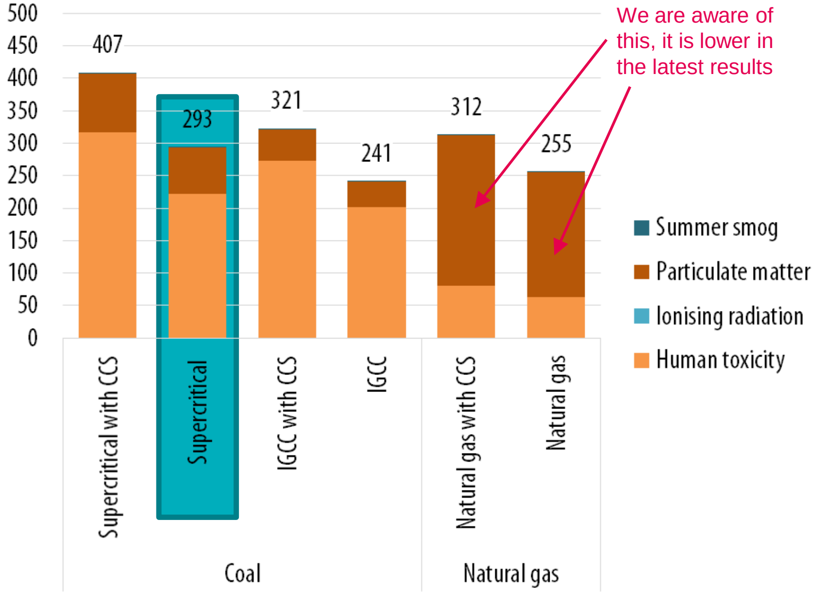
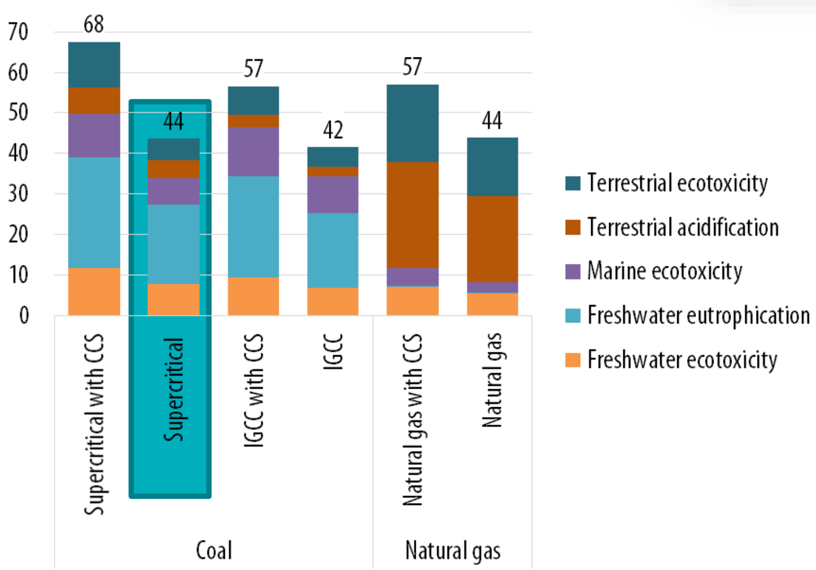
Results aggregation – Coal and NG, with CO_2 capture and storage



Human health impacts [DALY*/TWh]



Damage to ecosystems [species·yr/TWh]



**DALY = Disability-adjusted life year, a measure of overall disease burden, excl. effects of climate change*

Excluding effects of climate change and land use

/!\ All results preliminary

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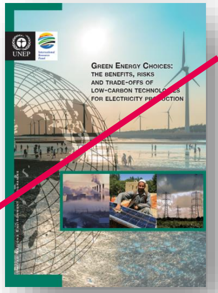
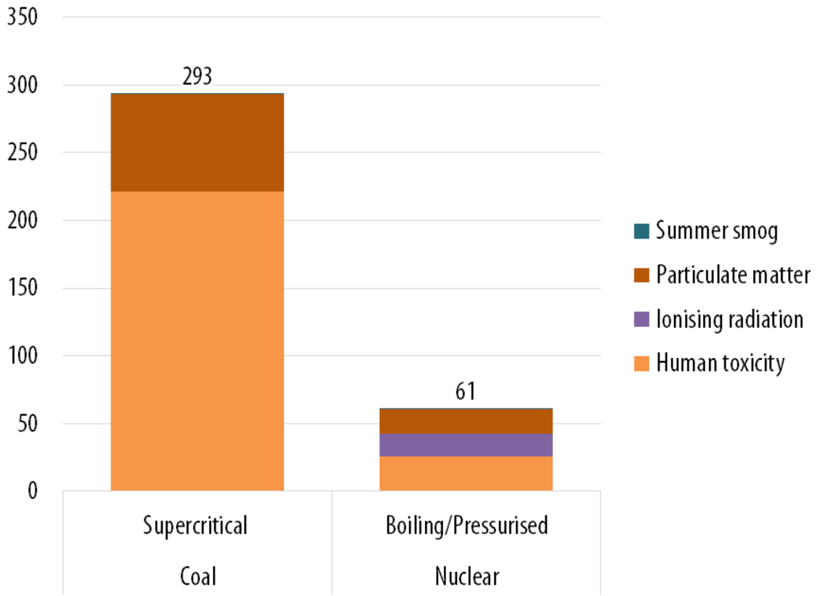
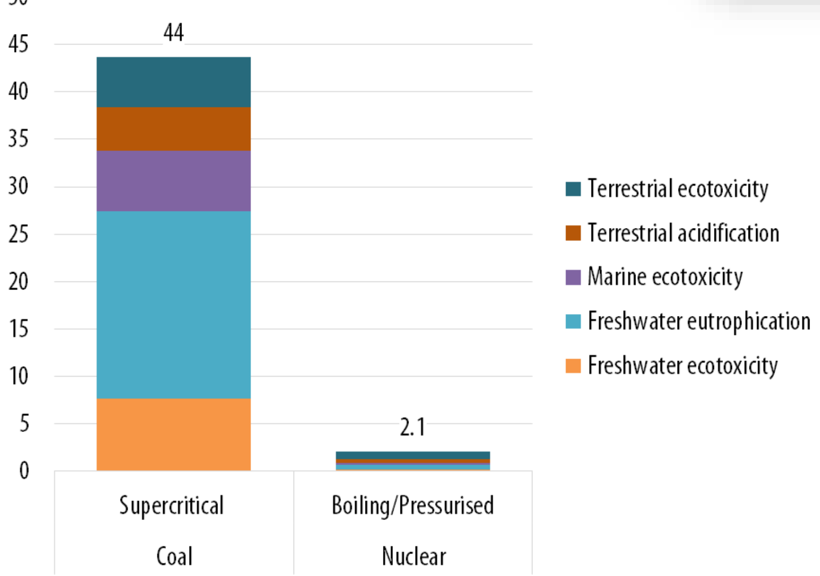
Results aggregation – Option 1 – Nuclear power



Human health impacts [DALY*/TWh]



Damage to ecosystems [species·yr/TWh]



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/!\ All results preliminary

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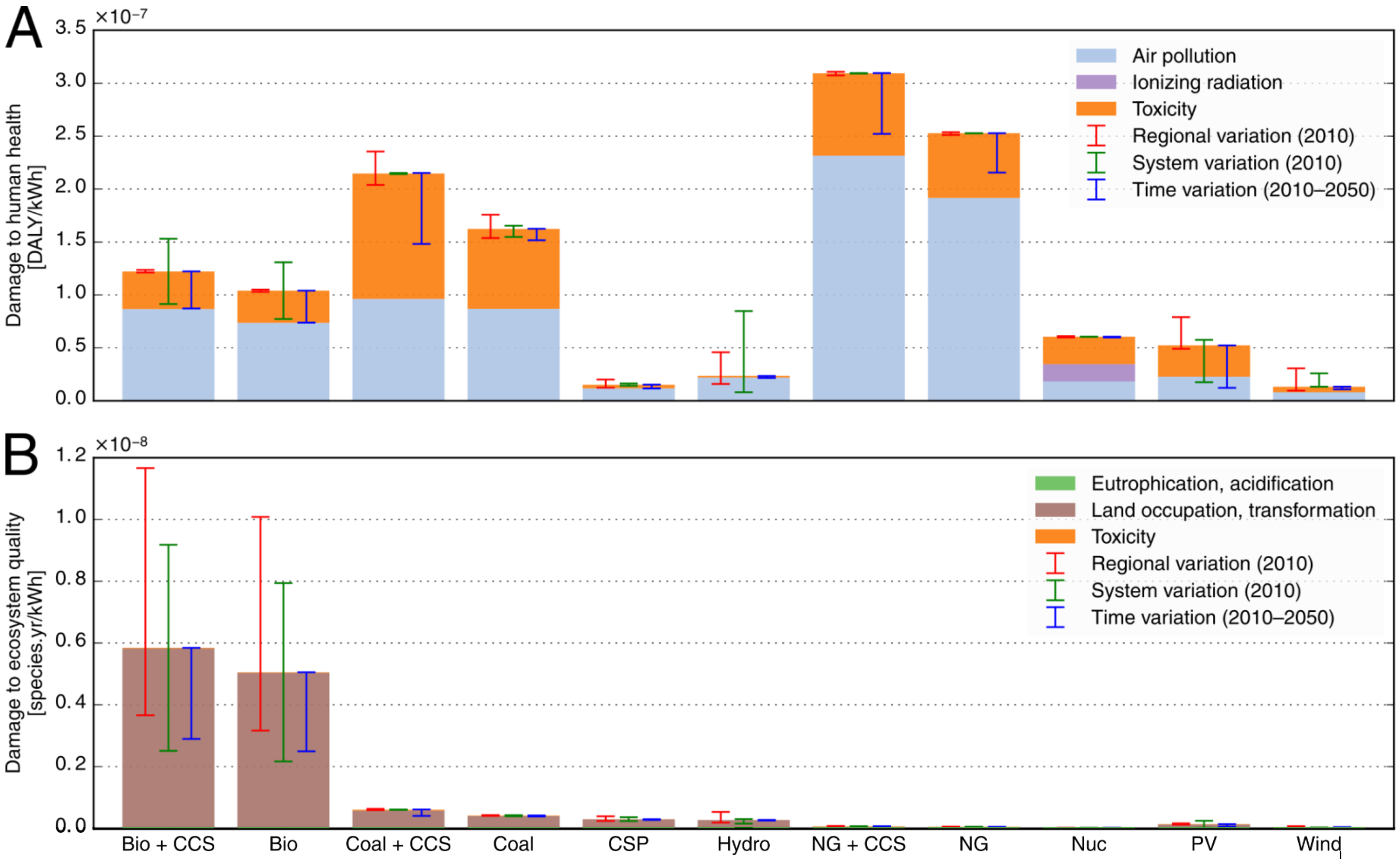

Gibon, T., Hertwich, E. G., Arvesen, A., Singh, B., & Verones, F. (2017). Health benefits, ecological threats of low-carbon electricity. *Environmental Research Letters*, *12*(3), 034023.

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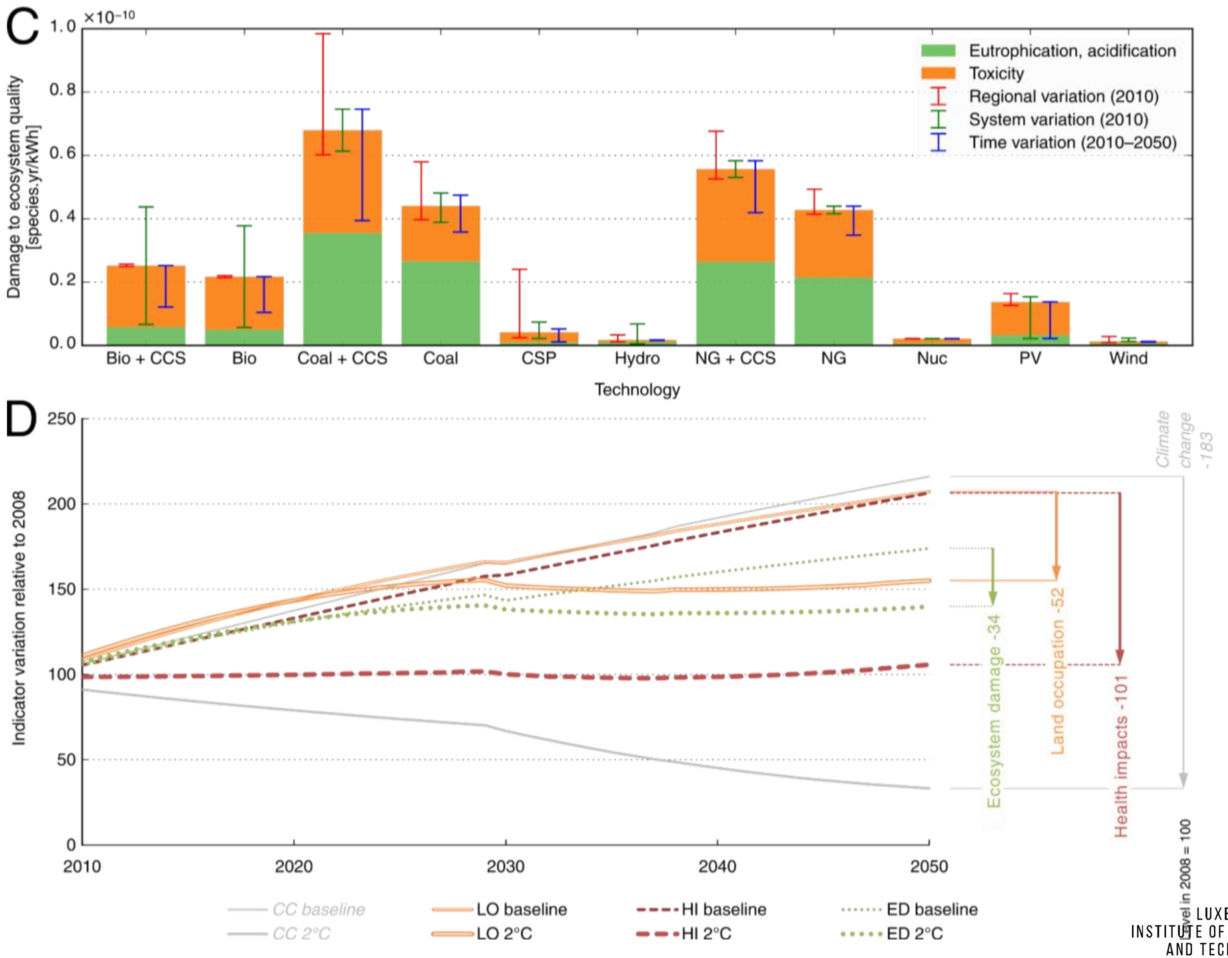

Gibon, T., Hertwich, E. G., Arvesen, A., Singh, B., & Verones, F. (2017). Health benefits, ecological threats of low-carbon electricity. *Environmental Research Letters*, *12*(3), 034023.

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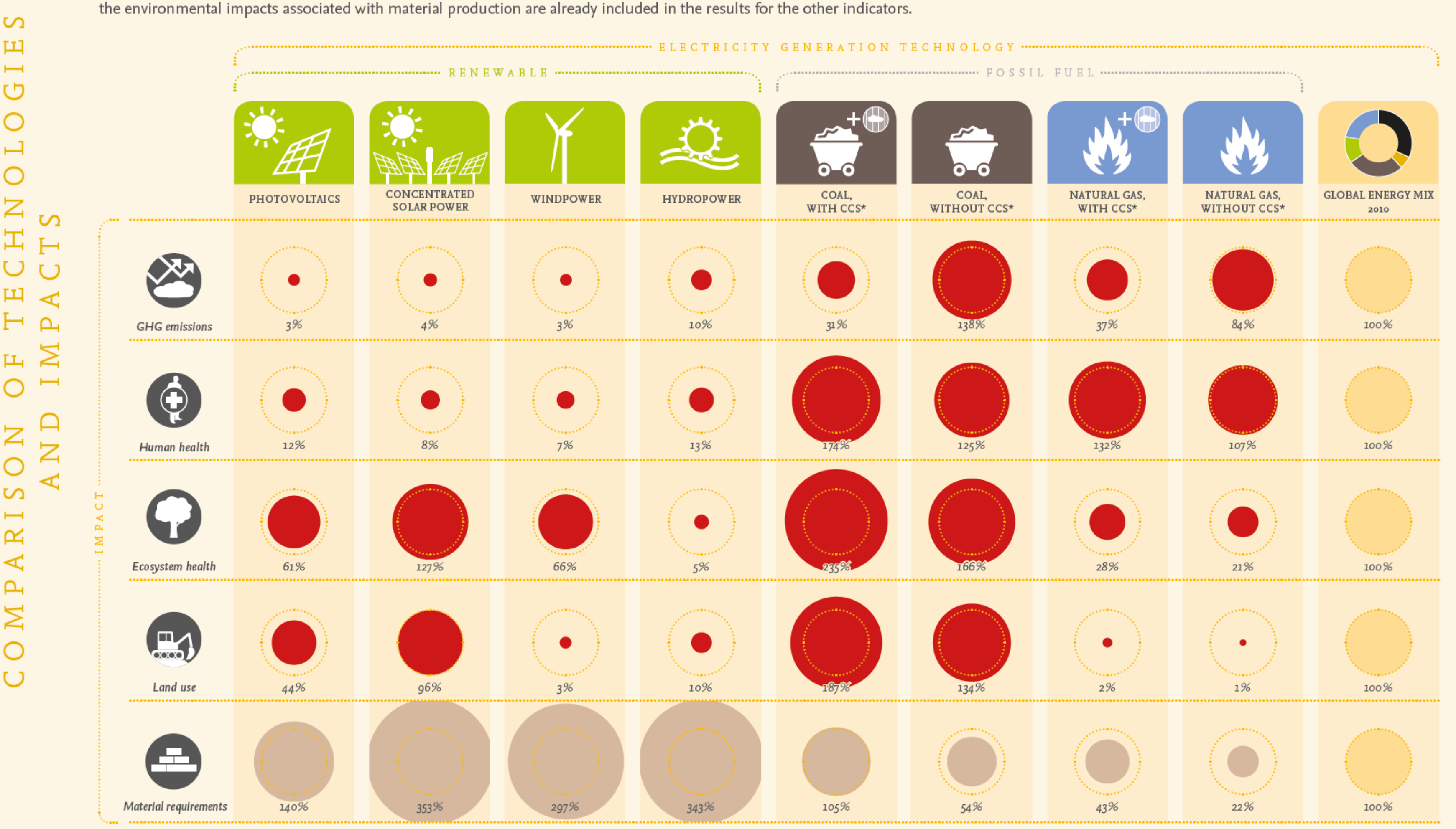
Results aggregation
Endpoint indicators

This infographic compares electricity generation technologies and highlights the environmental benefits, and trade-offs of each technology. The graphic presents an overview over the life cycle impacts and material requirements per unit of electricity produced by different technology groups compared to the global electricity generation mix in the year 2010. Indicators for materials are shown for reference; the environmental impacts associated with material production are already included in the results for the other indicators.



* Carbon capture storage (CCS) technology entails the capture of CO_2 from large anthropogenic sources, transport of the CO_2 to an underground storage reservoir and long-term isolation from the atmosphere.

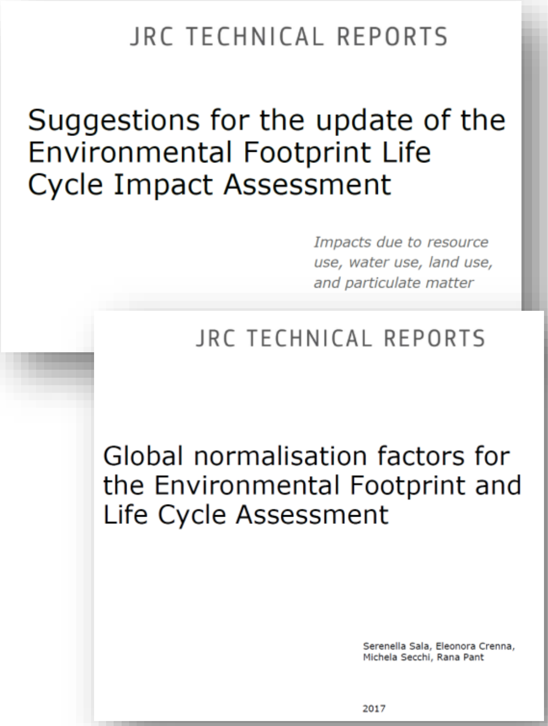
Results aggregation – Option 2

Normalisation and weighting

Table 1. Global normalisation factors for emissions and resource extraction in 2010, based on EF 2017 method (Sala et al 2017). The attributed score is from I-highest to III-lowest

Impact category	Model	Unit	global NF for EF	global NF for EF per person *	Inventory coverage completeness	Inventory robustness	Recommendation level of EF impact assessment
Climate change	IPCC (2013)	kg CO_2 eq	5.79E+13	8.40E+03	II	I	I
Ozone depletion	WMO (1999)	kg CFC-11 eq	1.61E+08	2.34E-02	III	II	I
Human toxicity, cancer	USEtox (Rosenbaum et al., 2008)	CTU_h	2.66E+05	3.85E-05	III	III	II/III
Human toxicity, non-cancer	USEtox (Rosenbaum et al., 2008)	CTU_h	3.27E+06	4.75E-04	III	III	II/III
Particulate matter	Fantke et al., 2016	disease incidences	4.95E+06 [(a)]	7.18E-04	I/II	I/II	I
Ionising radiation	Frischknecht et al., 2000	kBq U-235 eq.	2.91E+13	4.22E+03	II	III	II
Photochemical ozone formation	Van Zelm et al., 2008 as applied in ReCiPe (2008)	kg NMVOC eq.	2.80E+11	4.06E+01	III	I/II	II
Acidification	Posch et al., 2008	mol H^+ eq	3.83E+11	5.55E+01	II	I/II	II
Eutrophication, terrestrial	Posch et al., 2008	mol N eq	1.22E+12	1.77E+02	II	I/II	II
Eutrophication, freshwater	Struijs et al., 2009	kg P eq	5.06E+09	7.34E-01	II	III	II
Eutrophication, marine	Struijs et al., 2009	kg N eq	1.95E+11	2.83E+01	II	II/III	II
Land use	Bos et al., 2016 (based on)	pt	9.64E+15 [(b)]	1.40E+06	II	II	III
Ecotoxicity freshwater	USEtox (Rosenbaum et al., 2008)	CTUe	8.15E+13	1.18E+04	III	III	II/III
Water use	AWARE 100 (based on; UNEP, 2016)	m^3 water eq of deprived water	7.91E+13 [(b)]	1.15E+04	I	II	III
Resource use, fossils	ADP fossils (van Oers et al., 2002)	MJ	4.50E+14	6.53E+04	I	II	III
Resource use, minerals and metals	ADP ultimate reserve (van Oers et al., 2002)	kg Sb eq	4.39E+08	6.36E-02	I	II	III

* World population used to calculate the NF per person: 6895889018 people. Source: UNDESA (2011)
(a) NF calculation takes into account the emission height, in both the inventory and the impact assessment
(b) The NF is built by means of regionalised CFs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Suggestions for the update of the Environmental Footprint Life Cycle Impact Assessment

Impacts due to resource use, water use, land use, and particulate matter

JRC TECHNICAL REPORTS

Global normalisation factors for the Environmental Footprint and Life Cycle Assessment

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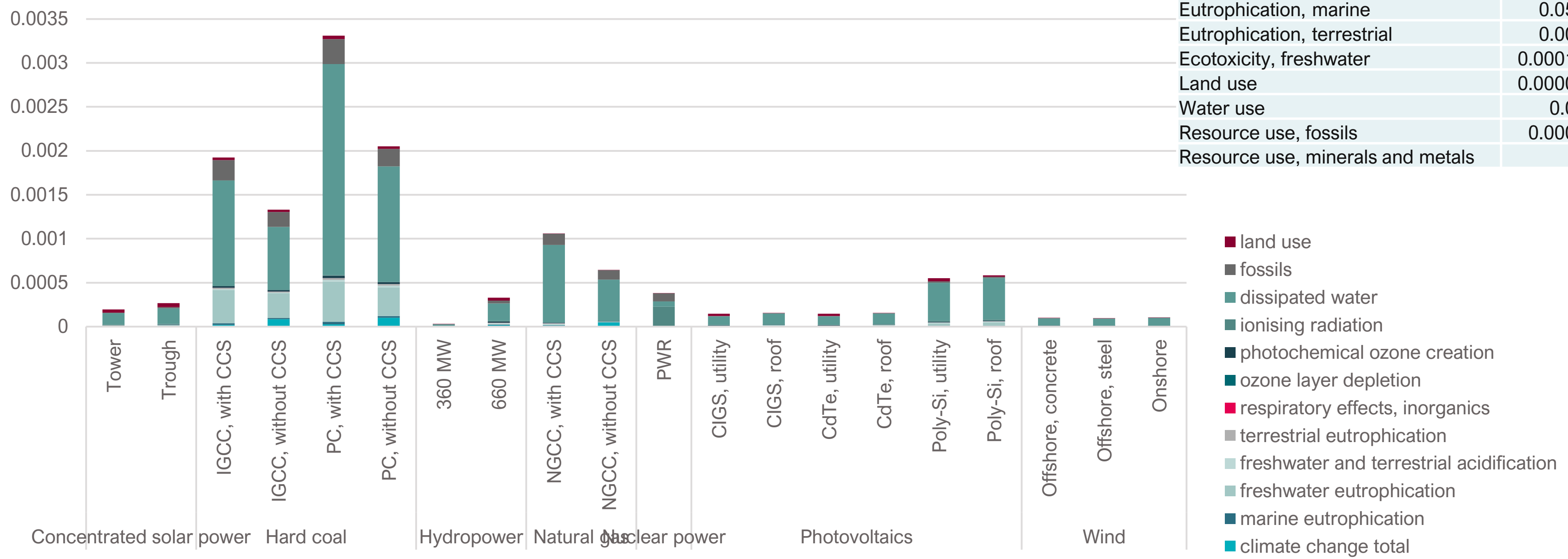
Results aggregation – Option 2

Results normalized, Europe EU region
(“how much of an average EU28 citizen’s footprint”)

Normalization	EU28
Climate change	0.00010846
Ozone depletion	46.2963
Ionising radiation	0.000884956
Photochemical ozone formation	0.0315457
Particulate matter	0.263158
Human toxicity, non-cancer	1876.17
Human toxicity, cancer	27100.3
Acidification	0.0211416
Eutrophication, freshwater	0.6756576
Eutrophication, marine	0.0591716
Eutrophication, terrestrial	0.0056818
Ecotoxicity, freshwater	0.000114416
Land use	0.000013369
Water use	0.012285
Resource use, fossils	0.00001538
Resource use, minerals and metals	9.901



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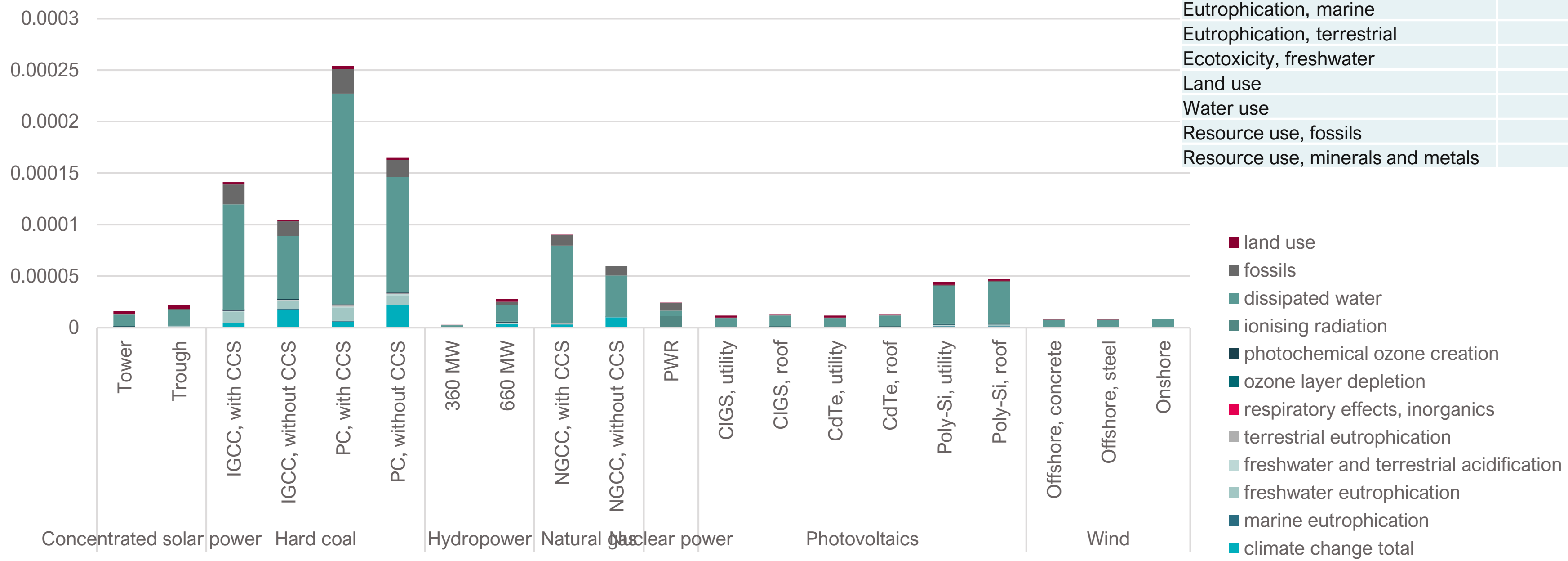
Results aggregation – Option 2

Weighting	Factor
Climate change	0.2106
Ozone depletion	0.0631
Ionising radiation	0.0501
Photochemical ozone formation	0.0478
Particulate matter	0.0896
Human toxicity, non-cancer	0.0184
Human toxicity, cancer	0.0213
Acidification	0.0620
Eutrophication, freshwater	0.0280
Eutrophication, marine	0.0296
Eutrophication, terrestrial	0.0371
Ecotoxicity, freshwater	0.0192
Land use	0.0794
Water use	0.0851
Resource use, fossils	0.0832
Resource use, minerals and metals	0.0755

Results normalized & weighted, Europe EU region (*highly subjective*)



"Weighting is the optional fourth and final step in Life Cycle Impact Assessment (LCIA), after classification, characterization and normalization. This final step is perhaps the most debated. Weighting entails multiplying the normalized results of each of the impact categories with a weighting factor that expresses the relative importance of the impact category." https://pre-sustainability.com/articles/weighting-applying-a-value-judgement-to-lca-results/