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Summer School 2022

Effective Mitigation of Climate Change: Modelling Advances and Priorities for AR7

September 6, 2022

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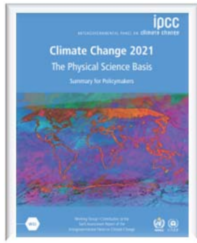
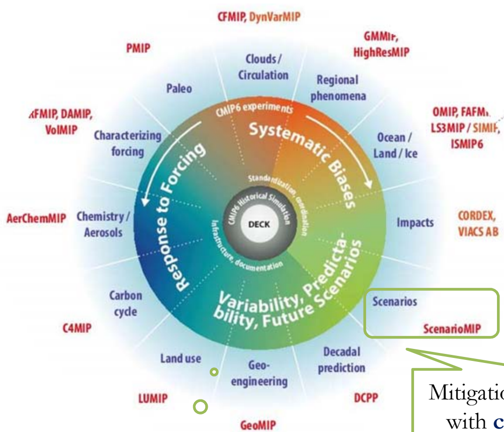
Existing Status of Models and Scenarios in CMIP6

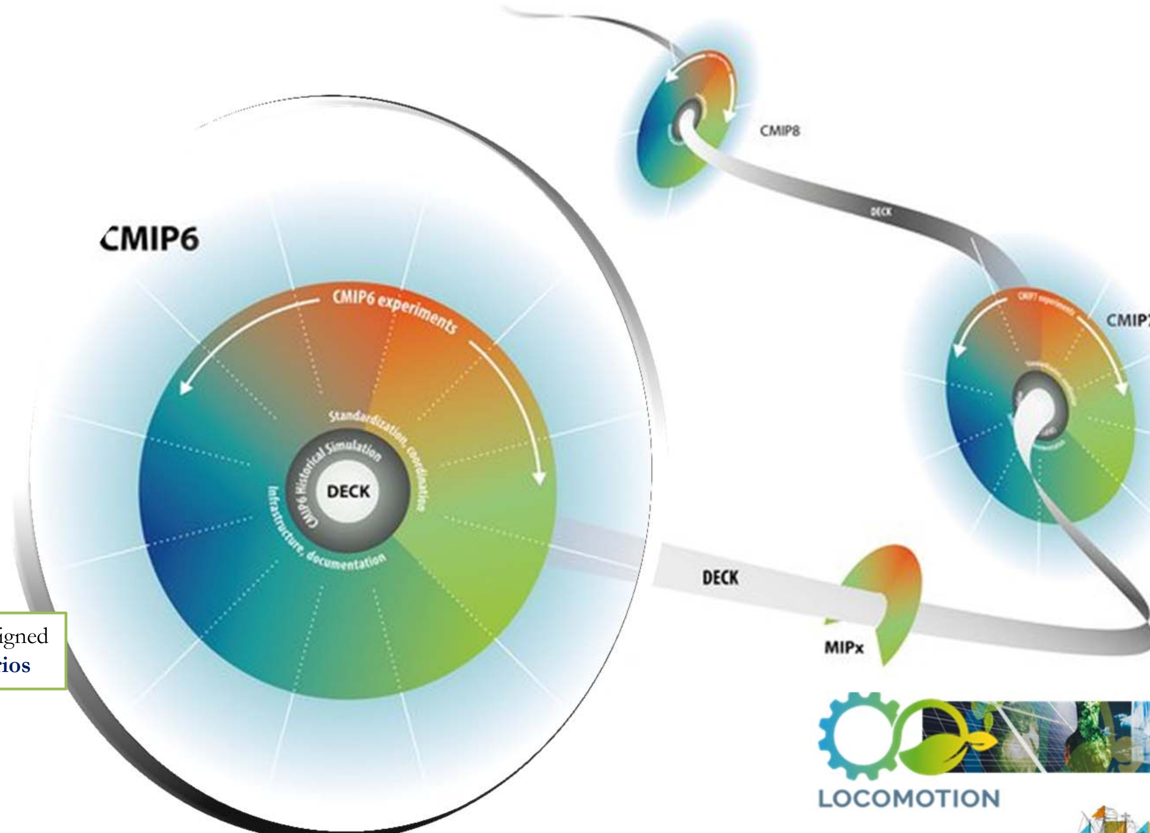
Climate science and mitigation scenarios continued to advance in AR6 with still important needs ahead in AR7





Mitigation scenarios aligned with **climate scenarios**

The **complexity** of feedbacks also require greater modelling capability (e.g. carbon sinks)



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Picture Source: The Evolution Of Climate Modelling <https://climate.esa.int/de/neuigkeiten-und-veranstaltungen/cmip-the-evolution-of-climate-modelling/>

Existing Status of Models and Scenarios in CMIP6

Advances in earth system models enable better benchmarking results while key interactions still require attention

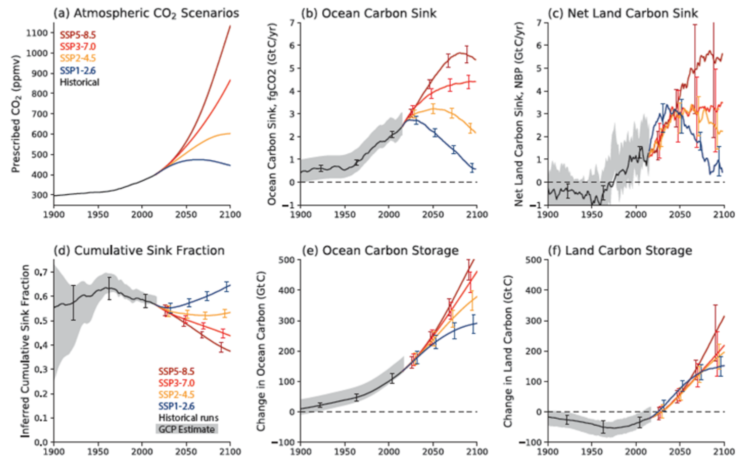
(a) Land Benchmarking Results

	CMIP5 ESMs: bcc-csm1-1	CanESM2	CESM1-BGC	GFDL-ESM2G	IPSL-CM5A-LR	MIROC-ESM	MPI-ESM-LR	NorESM1-ME	HadGEM2-ES	CMIP6 ESMs: BCC-CSM2-MR	CanESM5	CESM2	GFDL-ESM4	IPSL-CM6A-LR	MIROC-ES2L	MPI-ESM1.2-LR	NorESM2-LM	UKESM1-0-LL	Mean CMIP5	Mean CMIP6
Land Ecosystem & Carbon Cycle	-0.72	-0.93	-1.55	-1.51	-0.13	0.60	-0.43	-1.31	0.19	-0.43	0.66	0.48	-1.09	0.22	0.60	-0.07	1.00	0.49	1.63	2.30
Biomass	0.20	-0.45	-1.52	-0.40	-1.26	-0.26	-1.07	-1.77	0.92	1.39	0.74	-0.20	-0.54	0.16	0.93	-0.96	-0.01	1.04	1.23	1.82
Burned area			-0.87				0.10	-0.83				1.60								
Leaf Area Index	-0.20	-0.64	-1.30	-2.53	-0.01	0.30	0.01	-1.85	-0.16	0.27	0.08	0.34	-0.70	1.19	0.82	0.46	0.37	0.69	1.04	1.81
Soil Carbon	0.27	1.26	-1.46	0.07	0.75	0.47	-0.03	-1.14	0.07	0.23	1.35	-0.99	-2.04	-1.55	0.90	-0.75	-0.17	0.24	1.01	1.48
Gross Primary Productivity	0.59	-1.23	0.01	-1.81	-1.40	0.29	-0.53	-0.24	-1.04	0.77	0.04	0.59	-0.38	1.17	-1.02	-0.37	0.73	0.09	1.51	2.22
Net Ecosystem Exchange	-0.42	-1.81	-0.21	-0.65	1.10	-0.24	0.80	0.02	-1.03	-1.02	-1.19	0.59	1.69	-0.42	0.63	-0.21	1.08	-1.43	1.28	1.43
Ecosystem Respiration	0.90	-0.56	-0.86	-0.24	-1.35	0.99	-0.01	-0.94	-1.54	0.81	0.59	0.51	-0.79	0.90	-0.21	-1.24	0.43	-0.94	1.34	2.21
Carbon Dioxide		-1.54	-0.36	-2.92	-0.74	1.53	-0.00	0.37	0.85		0.42	0.26	0.39	0.59	1.10	-0.87	0.21	0.69	0.09	-0.07
Global Net Carbon Balance		-1.64	-0.88	-1.13	0.17	-0.31	-0.38	-0.50	0.24		-0.23	1.34	-1.70	0.17	-0.74	1.45	1.56	0.26	0.92	1.40
Land Hydrology Cycle	-2.65	-0.42	0.44	-0.18	-0.49	-0.52	-0.57	0.17	0.70	0.15	-0.47	1.51	-1.24	0.58	-0.72	-0.83	0.97	0.87	1.00	1.70
Evapotranspiration	-0.82	-0.99	-0.27	-1.02	0.64	-1.14	-0.62	-0.60	0.28	0.39	-1.08	1.09	0.65	0.43	-1.40	-1.01	0.82	1.05	1.41	2.20
Evaporative Fraction	-0.34	0.74	0.74	-0.14	-0.85	0.21	-1.98	0.22	-0.34	0.10	0.11	1.25	-0.88	1.29	-1.65	-1.81	1.11	-0.06	0.98	1.29
Runoff	-3.66	-0.35	0.47	0.06	-0.67	-0.57	0.12	0.44	1.33	-0.07	-0.23	0.96	-0.17	-0.19	0.02	-0.05	0.47	0.99	-0.03	1.13
Latent Heat	-0.02	-0.39	-0.38	-0.93	0.24	-0.98	-0.73	-0.71	-0.21	0.66	-1.20	1.60	0.12	0.42	-1.52	-1.24	1.40	0.40	1.49	1.99
Sensible Heat	-0.85	-0.20	0.80	-0.28	-1.12	-1.23	-1.67	0.45	0.65	-1.04	0.37	1.02	-0.39	1.19	-0.54	-1.63	0.63	0.92	1.48	1.45
Terrestrial Water Storage Anomaly	-2.79	-0.45	0.47	0.50	-0.38	0.34	0.35	0.43	0.58	0.15	-0.08	0.95	-2.91	0.43	0.37	0.15	0.39	0.51	0.49	0.50
Permafrost	-0.88	-2.26	0.01	0.13	0.83	0.69	0.56	0.69	-0.56	-0.11	-3.02	0.83	0.74	-0.18	0.49	0.42	0.89	0.43	0.06	0.23

Relative Scale: Worse Value … Better Value; Missing Data or Error

Response of ocean carbon sinks

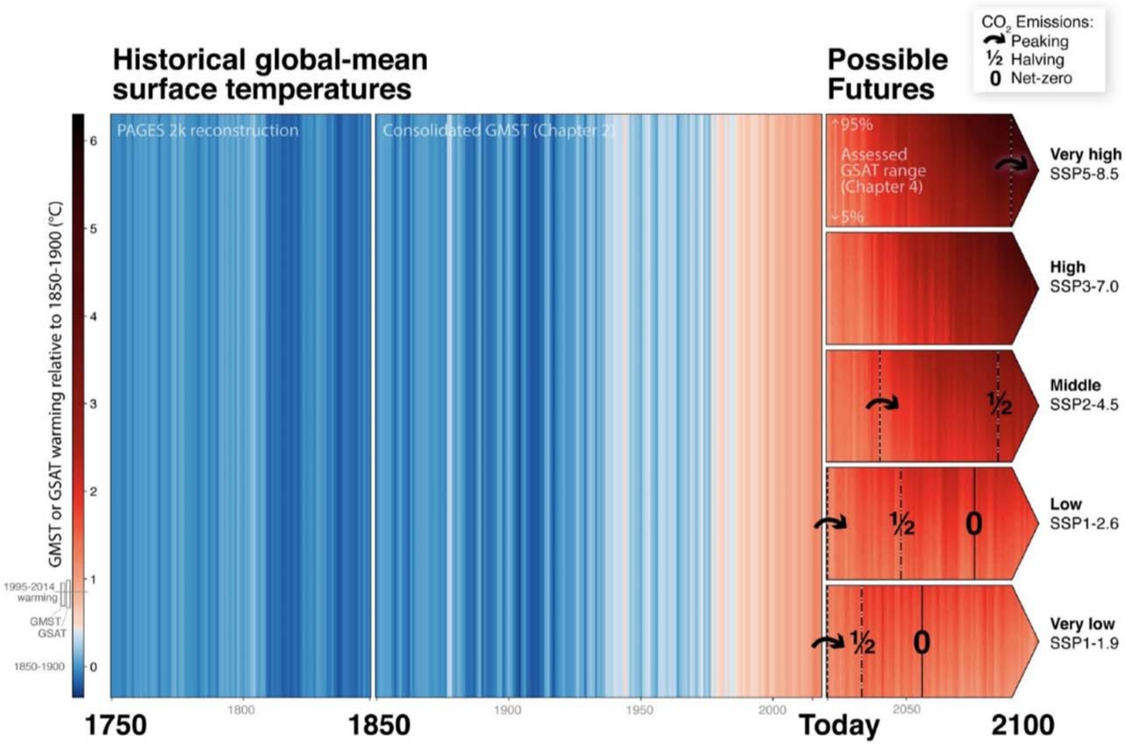
Response of land carbon sinks

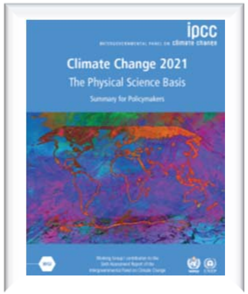


Source: Canadell et al. (2021), Global Carbon and Other Biogeochemical Cycles and Feedbacks (Chapter 5), in: IPCC (2021), Climate Change 2021: The Physical Science Basis

Acting Quickly and More Integratively Is Urgent

CO_2 emissions need to be halved globally from present levels by 2030 for any chance of remaining within 1.5°C





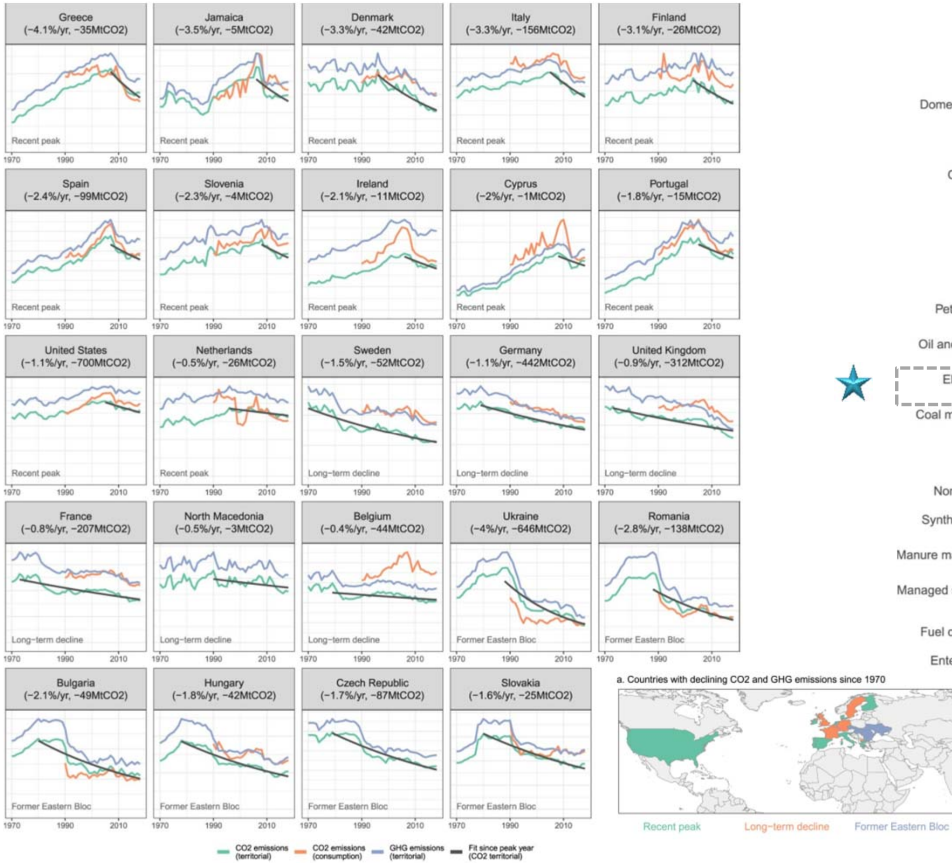
Or else 1.5°C will be beyond reach

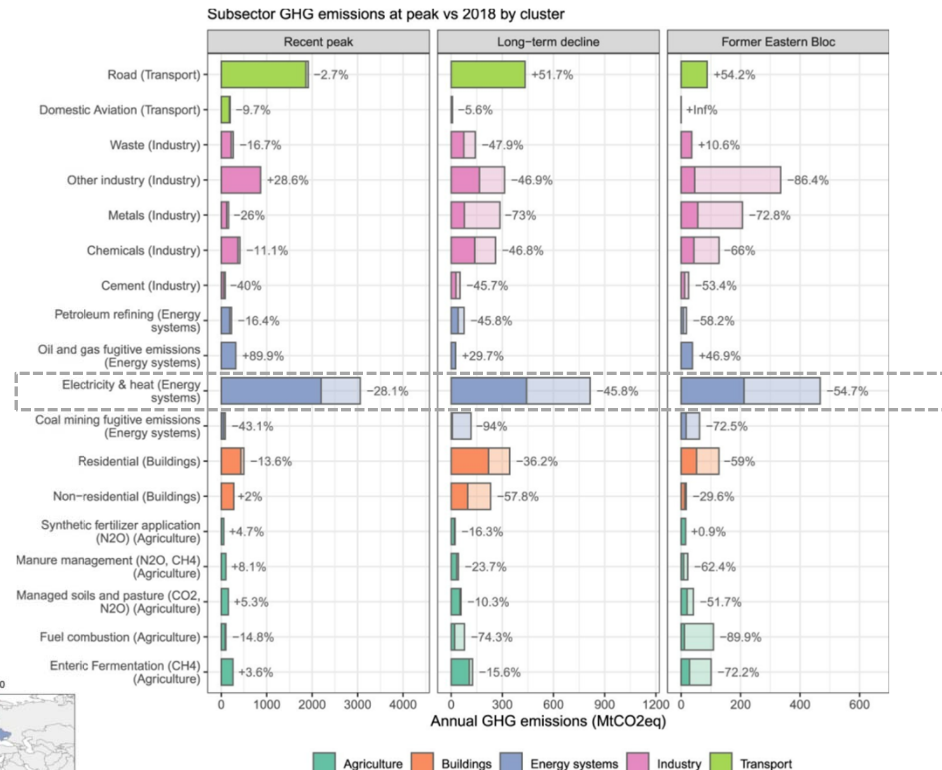
Scenario	Best Estimates	*Very Likely* Range (2021-2100)
SSP1-2.6 (Low)	1.5°C (2021-2040), 1.7°C (2041-2060), 1.8°C (2081-2100)	1.2 °C to 2.4°C
SSP1-1.9 (Very Low)	1.5°C (2021-2040), 1.6°C (2041-2060), 1.4°C (2081-2100)	1.2 °C to 1.8°C

Source: IPCC (2021), Climate Change 2021: The Physical Science Basis <https://www.ipcc.ch/report/ar6/wg1/>

Decoupling of Emissions in 24 Countries and Counting

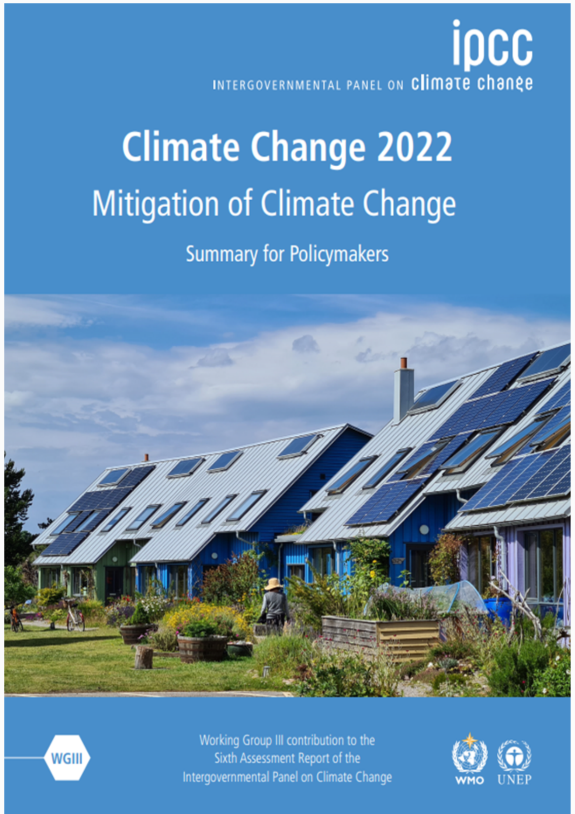
About 24 countries have already recorded sustained reductions in CO_2 and GHG emissions in the last decades





Source: Lamb et al. (2022), Countries with sustained greenhouse gas emissions reductions: an analysis of trends and progress by sector, Climate Policy 22(1):1-17.

Sixth Assessment Report – Mitigation of Climate Change

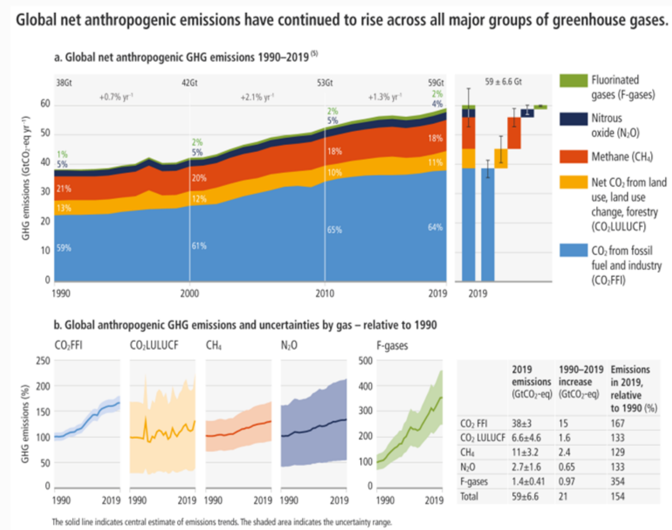


Recent developments and current trends

System transformations to limit global warming

Linkages between mitigation, adaptation, and **sustainable development**

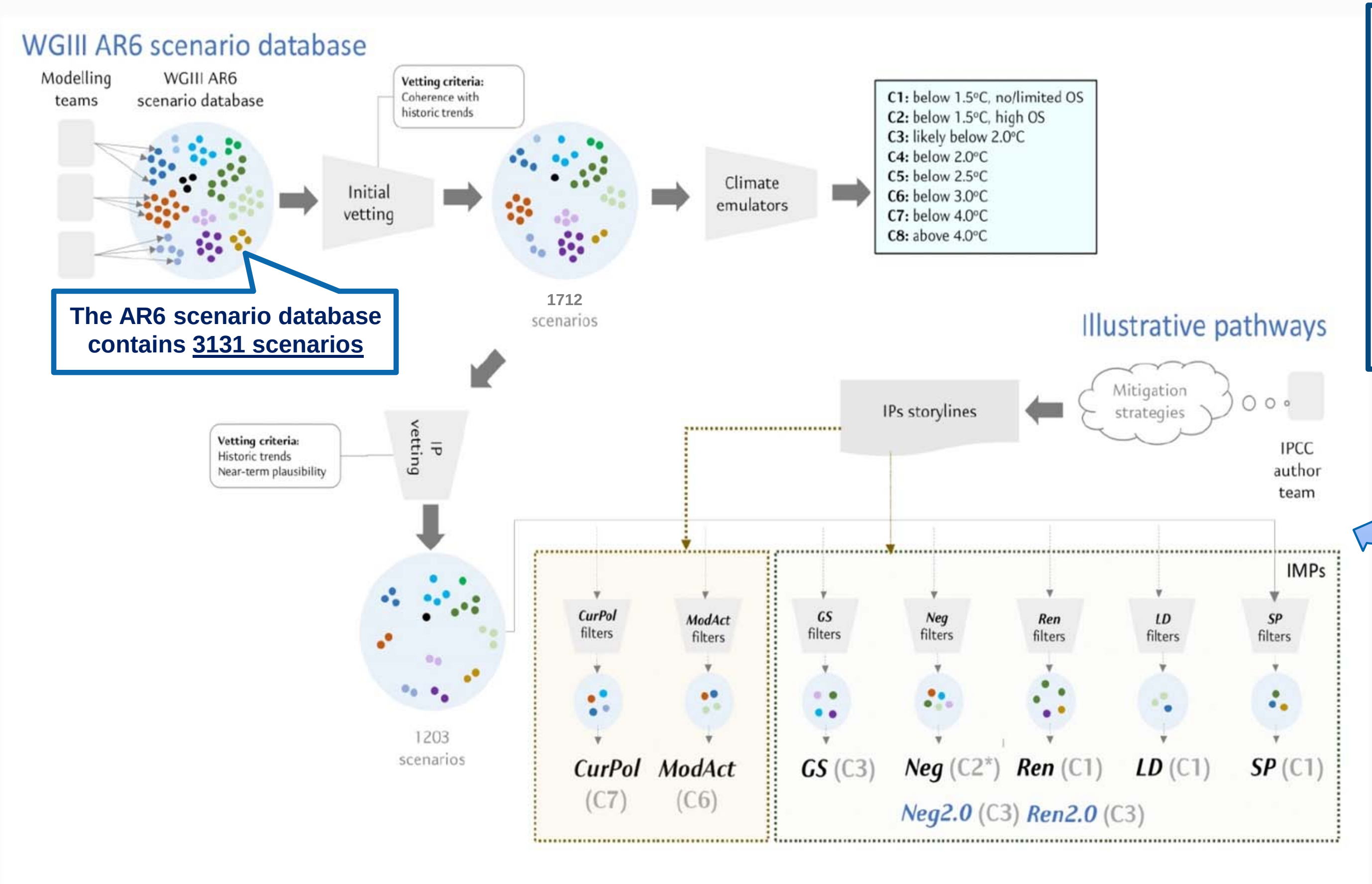
Strengthening the response

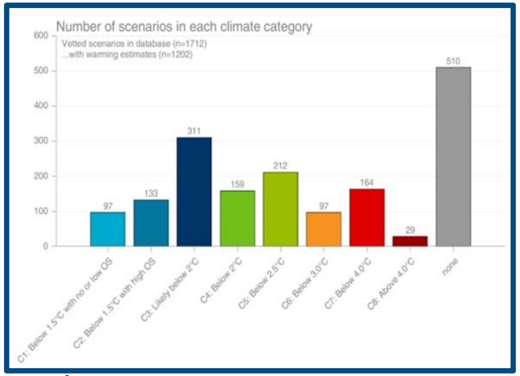


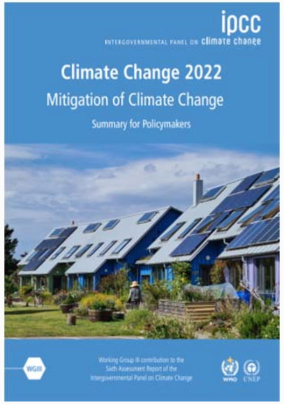
	2019 emissions ($GtCO_2$-eq)	1990–2019 increase ($GtCO_2$-eq)	Emissions in 2019, relative to 1990 (%)
CO_2 FFI	38±3	15	167
CO_2 LULUCF	6.6±4.6	1.6	133
CH_4	11±3.2	2.4	129
N_2O	2.7±1.6	0.65	133
F-gases	1.4±0.41	0.97	354
Total	59±6.6	21	154

IPCC (2022) <https://www.ipcc.ch/report/ar6/wg3/>

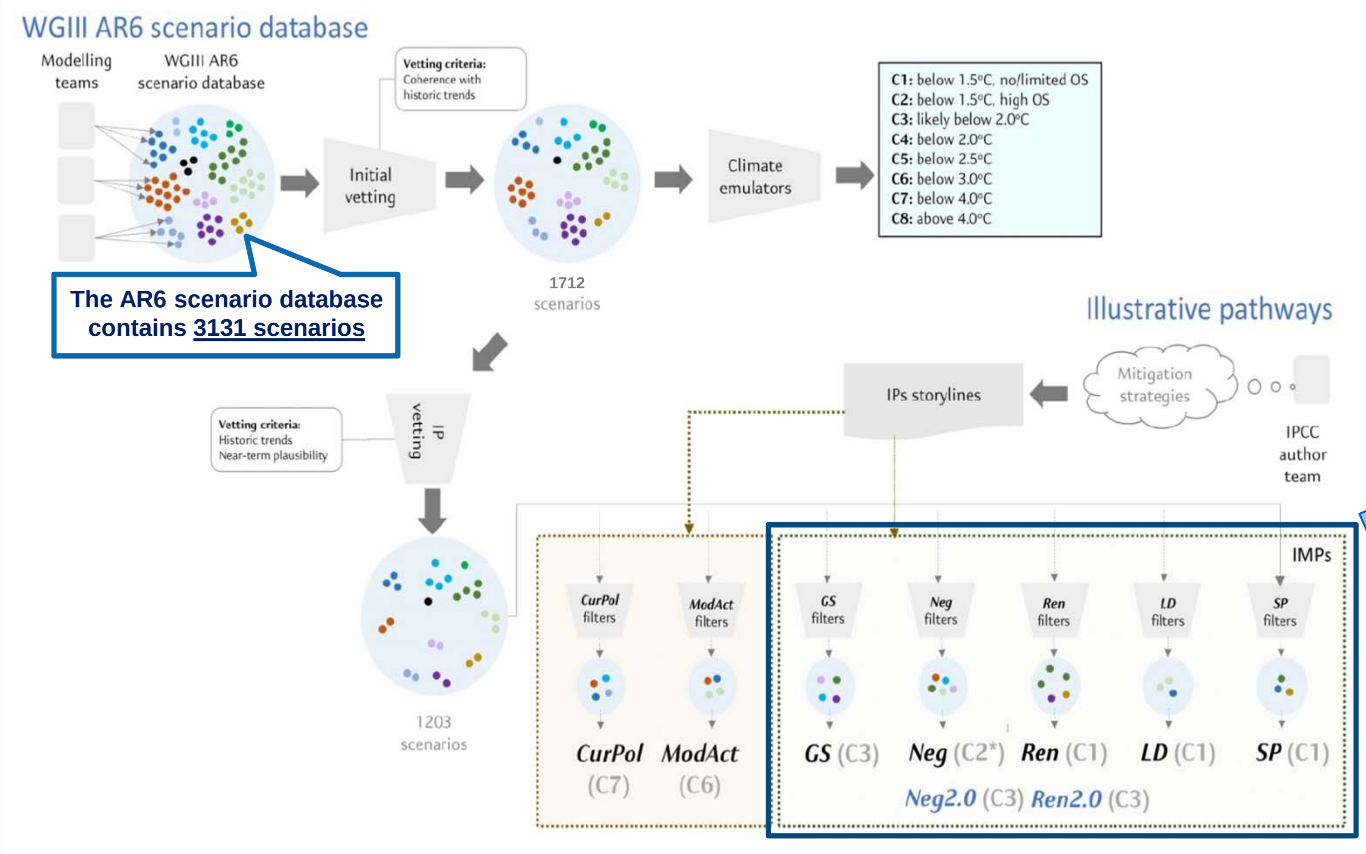
Shifting from unsustainable energy, land and resource use



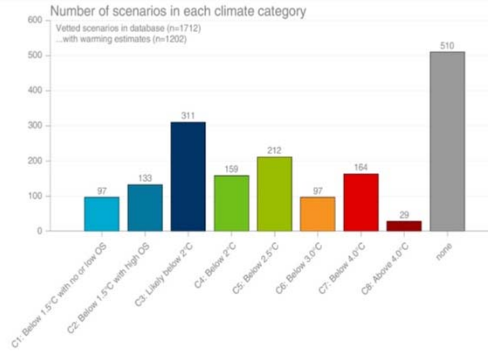


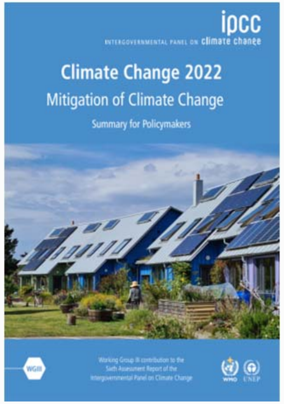


Shifting from unsustainable energy, land and resource use



The AR6 scenario database contains <u>3131 scenarios</u>



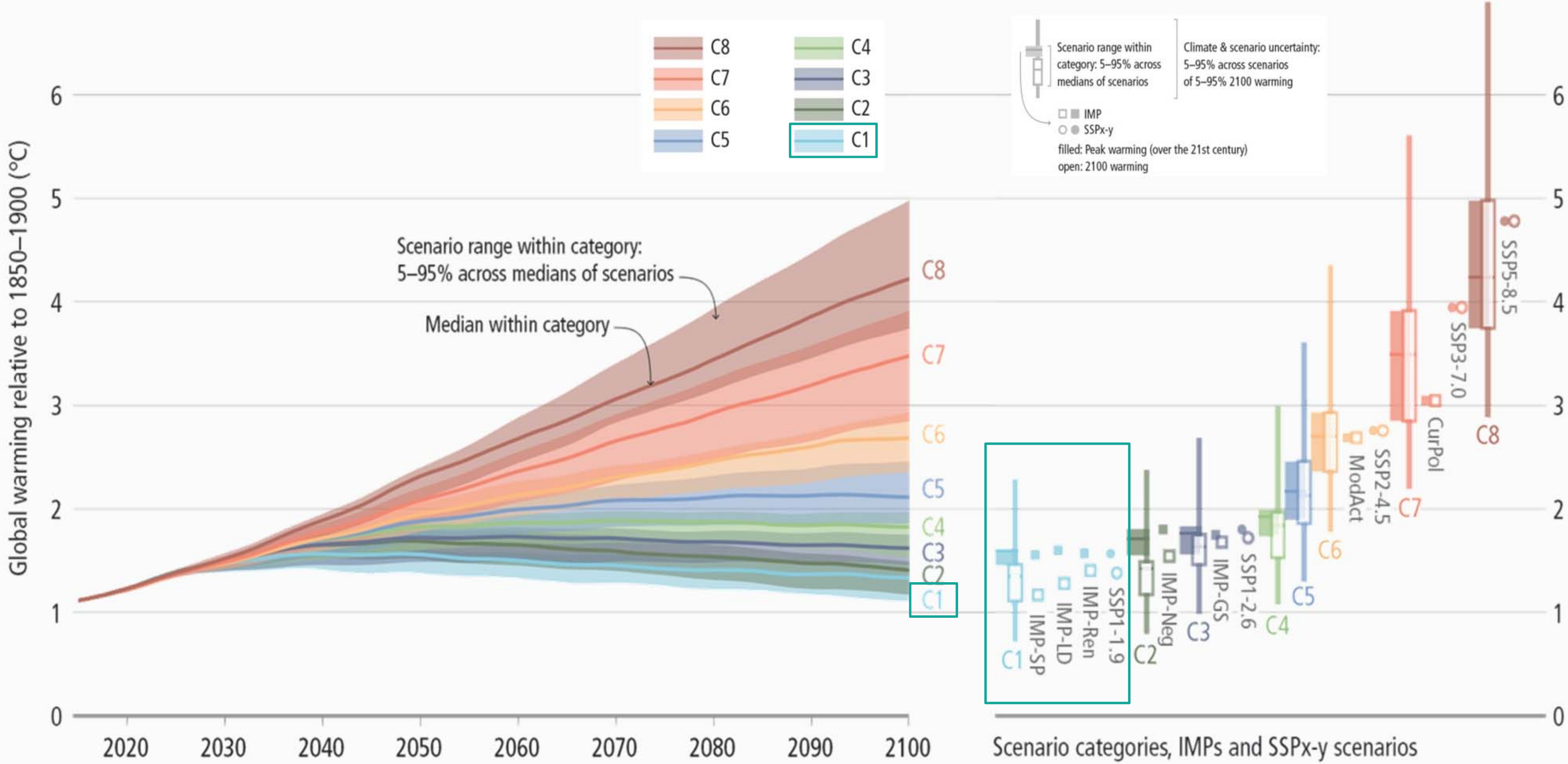


Key characteristics of the modelled global emissions pathways

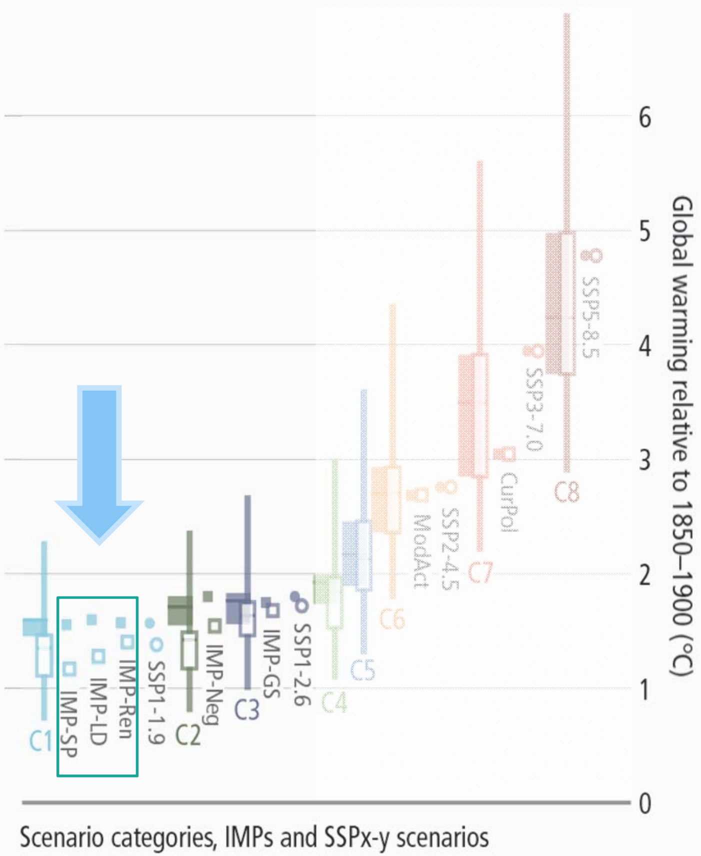
p50 [p5-p95] [1]			GHG emissions Gt CO_2-eq/yr [7]			GHG emissions reductions from 2019, % [8]			Emissions milestones [9,10]				Cumulative CO_2 emissions Gt CO_2 [13]		Cumulative net-negative CO_2 emissions Gt CO_2	Global mean temperature change 50% probability [14] °C		Likelihood of peak global warming staying below (%) [15]		
Category [2, 3, 4] (# pathways)	Category / subset label	WG I SSP & WG III IPs/IMPs alignment [5, 6]	2030	2040	2050	2030	2040	2050	Peak CO_2 emissions (% peak before 2100)	Peak GHG emissions (% peak before 2100)	Net-zero CO_2 (% net-zero pathways)	Net-zero GHGs [11, 12] (% net-zero pathways)	2020 to net-zero CO_2	2020-2100	Year of net-zero CO_2 to 2100	At peak warming	2100	<1.5°C	<2.0°C	<3.0°C
Modelled global emissions pathways categorised by projected global warming levels (GWL). Detailed likelihood definitions are provided in SPM Box 1. The five illustrative scenarios (SSPx-y) considered by AR6 WGI and the Illustrative (Mitigation) Pathways assessed in WGIII are aligned with the temperature categories and are indicated in a separate column. Global emission pathways contain regionally differentiated information. This assessment focuses on their global characteristics.			*Projected median annual GHG emissions in the year across the scenarios, with the 5th-95th percentile in brackets. Modelled GHG emissions in 2019: 55 [53-58] $GtCO_2$-eq*			*Projected median GHG emission reductions of pathways in the year across the scenarios compared to modelled 2019, with the 5th-95th percentile in brackets. Negative numbers indicate increase in emissions compared to 2019.*			*Median 5-year intervals at which projected CO_2 & GHG emissions peak, with the 5th-95th percentile interval in brackets. Percentage of peaking pathways is denoted in round brackets. Three dots (...) denotes emissions peak in 2100 or beyond for that percentile.*		*Median 5-year interval at which projected CO_2 & GHG emissions of pathways in this category reach net-zero, with the 5th-95th percentile interval in square brackets. Percentage of net-zero pathways is denoted in round brackets. Three dots (...) denotes net-zero not reached for that percentile.*		*Median cumulative net CO_2 emissions across the projected scenarios in this category until reaching net-zero or until 2100, with the 5th-95th percentile interval in square brackets.*		*Median cumulative net-negative CO_2 emissions between the year of net-zero CO_2 and 2100. More net-negative results in greater temperature declines after peak*	*Projected temperature change of pathways in this category (50% probability across the range of climate uncertainties), relative to 1850-1900, at peak warming and in 2100, for the median value across the scenarios and the 5th-95th percentile interval in square brackets.*		*Median likelihood that the projected pathways in this catgeory stay below a given global warming level, with the 5th-95th percentile interval in square brackets*		
C1 (97)	Limit warming to 1.5°C (>50%) with no or limited overshoot		31 [21-36]	17 [6-23]	9 [1-15]	43 [34-60]	69 [58-90]	84 [73-98]				2095-2100 (52%) [2050-...]	510 [330-710]	320 [-210-570]	-220 [-660--20]	1.6 [1.4-1.6]	1.3 [1.1-1.5]	38 [33-58]	90 [86-97]	100 [99-100]
C1a (50)	... with net-zero GHGs	SSP1-1.9, SP, LD	33 [22-37]	18 [6-24]	8 [0-15]	41 [31-59]	66 [58-89]	85 [72-100]	2020-2025 (100%) [2020-2025]		2050-2055 (100%) [2035-2070]	2070-2075 [100%) [2050-2090]	550 [340-760]	160 [-220-620]	-360 [-680--140]	1.6 [1.4-1.6]	1.2 [1.1-1.4]	38 [34-60]	90 [85-98]	100 [99-100]
C1b (47)	... without net-zero GHGs	Ren	29 [21-36]	16 [7-21]	9 [4-13]	48 [35-61]	70 [62-87]	84 [76-93]				...-... (0%) [...-...]	460 [320-590]	360 [10-540]	-60 [-440-0]	1.6 [1.5-1.6]	1.4 [1.3-1.5]	37 [33-56]	89 [87-96]	100 [99-100]
C2 (133)	Return warming to 1.5°C (>50%) after a high overshoot	Neg	42 [31-55]	25 [17-34]	14 [5-21]	23 [0-44]	55 [40-71]	75 [62-91]	2020-2025 (100%) [2020-2030]	[2020-2025]	2055-2060 (100%) [2045-2070]	2070-2075 (87%) [2055-...]	720 [530-930]	400 [-90-620]	-360 [-680--60]	1.7 [1.5-1.8]	1.4 [1.2-1.5]	24 [15-42]	82 [71-93]	100 [99-100]
C3 (311)	Limit warming to 2°C (>67%)		44 [32-55]	29 [20-36]	20 [13-26]	21 [1-42]	46 [34-63]	64 [53-77]	2020-2025 (100%) [2020-2030]	[2020-2025]	2070-2075 (93%) [2055-...]	...-... (30%) [2075-...]	890 [640-1160]	800 [510-1140]	-40 [-290-0]	1.7 [1.6-1.8]	1.6 [1.5-1.8]	20 [13-41]	76 [68-91]	99 [98-100]
C3a (204)	... with action starting in 2020	SSP1-2.6	40 [30-49]	29 [21-36]	20 [14-27]	27 [13-45]	47 [35-63]	63 [52-76]	2020-2025 (100%) [2020-2025]		2070-2075 (91%) [2055-...]	...-... (24%) [2080-...]	860 [640-1180]	790 [480-1150]	-30 [-280-0]	1.7 [1.6-1.8]	1.6 [1.5-1.8]	21 [14-42]	78 [69-91]	100 [98-100]
C3b (97)	... NDCs until 2030	GS	52 [47-56]	29 [20-36]	18 [10-25]	5 [0-14]	46 [34-63]	68 [56-82]			2065-2070 (97%) [2055-2090]	...-... (41%) [2075-...]	910 [720-1150]	800 [560-1050]	-60 [-300-0]	1.8 [1.6-1.8]	1.6 [1.5-1.7]	17 [12-35]	73 [67-87]	99 [98-99]
C4 (159)	Limit warming to 2°C (>50%)		50 [41-56]	38 [28-44]	28 [19-35]	10 [0-27]	31 [20-50]	49 [35-65]	2020-2025 (100%) [2020-2030]		2080-2085 (86%) [2065-...]	...-... (31%) [2075-...]	1210 [970-1490]	1160 [700-1490]	-30 [-390-0]	1.9 [1.7-2.0]	1.8 [1.5-2.0]	11 [7-22]	59 [50-77]	98 [95-99]
C5 (212)	Limit warming to 2.5°C (>50%)		52 [46-56]	45 [37-53]	39 [30-49]	6 [-1-18]	18 [4-33]	29 [11-48]			...-... (41%) [2080-...]	...-... (12%) [2090-...]	1780 [1400-2360]	1780 [1260-2360]	0 [-160-0]	2.2 [1.9-2.5]	2.1 [1.9-2.5]	4 [0-10]	37 [18-59]	91 [83-98]
C6 (97)	Limit warming to 3°C (>50%)	SSP2-4.5 Mod-Act	54 [50-62]	53 [48-61]	52 [45-57]	2 [-10-11]	3 [-14-14]	5 [-2-18]	2030-2035 (96%) [2020-2090]	2020-2025 (97%)				2790 [2440-3520]			2.7 [2.4-2.9]	0 [0-0]	8 [2-18]	71 [53-88]
C7 (164)	Limit warming to 4°C (>50%)	SSP3-7.0 Cur-Pol	62 [53-69]	67 [56-76]	70 [58-83]	-11 [-18-3]	-19 [-31-1]	-24 [-41--2]	2085-2090 (57%) [2040-...]	2090-2095 (56%)	No net-zero		No net-zero	4220 [3160-5000]	No net-zero	Temperature does not peak by 2100	3.5 [2.8-3.9]	0 [0-0]	0 [0-2]	22 [7-60]
C8 (29)	Exceed warming of 4°C (>=50%)	SSP5-8.5	71 [69-81]	80 [78-96]	88 [82-112]	-20 [-34--17]	-35 [-65--29]	-46 [-92--36]	2080-2085 (90%) [2070-...]					5600 [4910-7450]			4.2 [3.7-5.0]	0 [0-0]	0 [0-0]	4 [0-11]

a. Median global warming across scenarios in categories C1 to C8

b. Peak and 2100 global warming across scenario categories, IMPs and SSPx-y scenarios considered by AR6 WG1



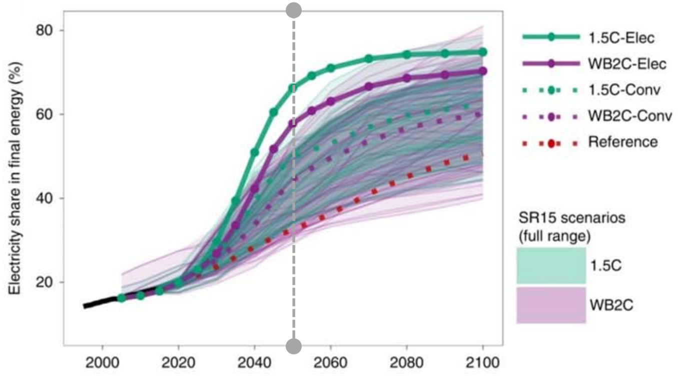
System transformations in the Illustrative Mitigation Pathways

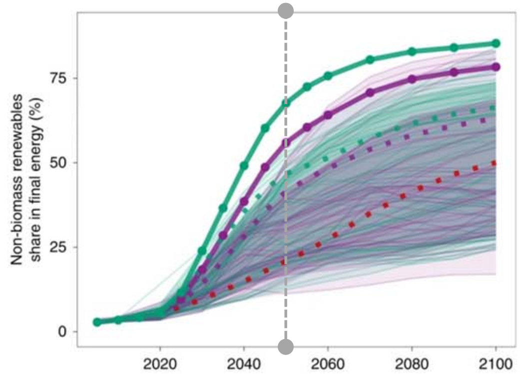


Illustrative Mitigation Pathways (IMPs)		General characteristics
IMPs in C1	Renewable energy (IMP-RE)	Rapid deployment and technology development of **renewables; electrification**
	Low demand (IMP-LD)	**Reduced demand** leads to early emission reductions
	Shifting pathways (IMP-SP)	**Major transformations shift development towards sustainability** and reduced inequality, including deep GHG emissions reduction

Illustrative Mitigation Pathway for Renewable Energy

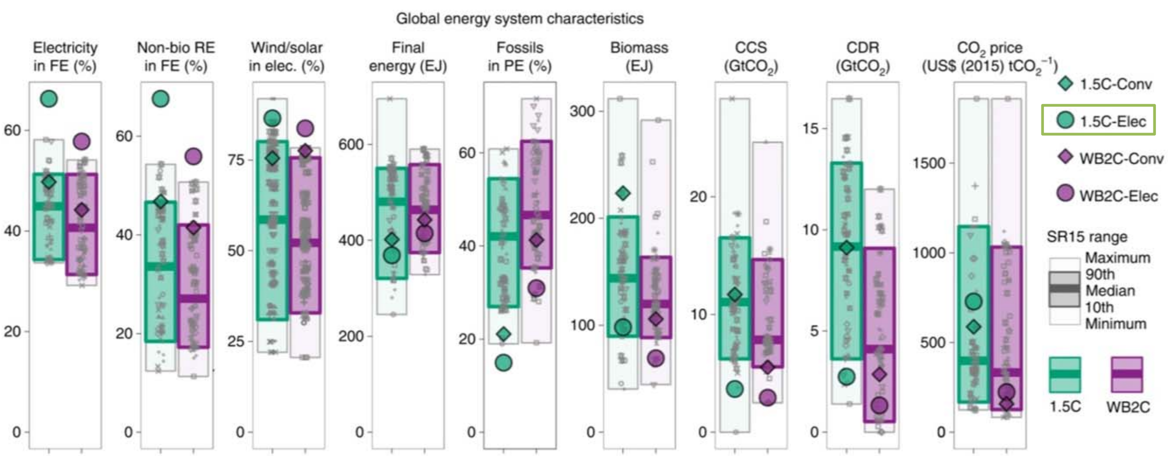
The IMP for renewable energy comes to about 66% non-biomass renewable energy share in final energy in 2050





1.5C-Elec Scenario

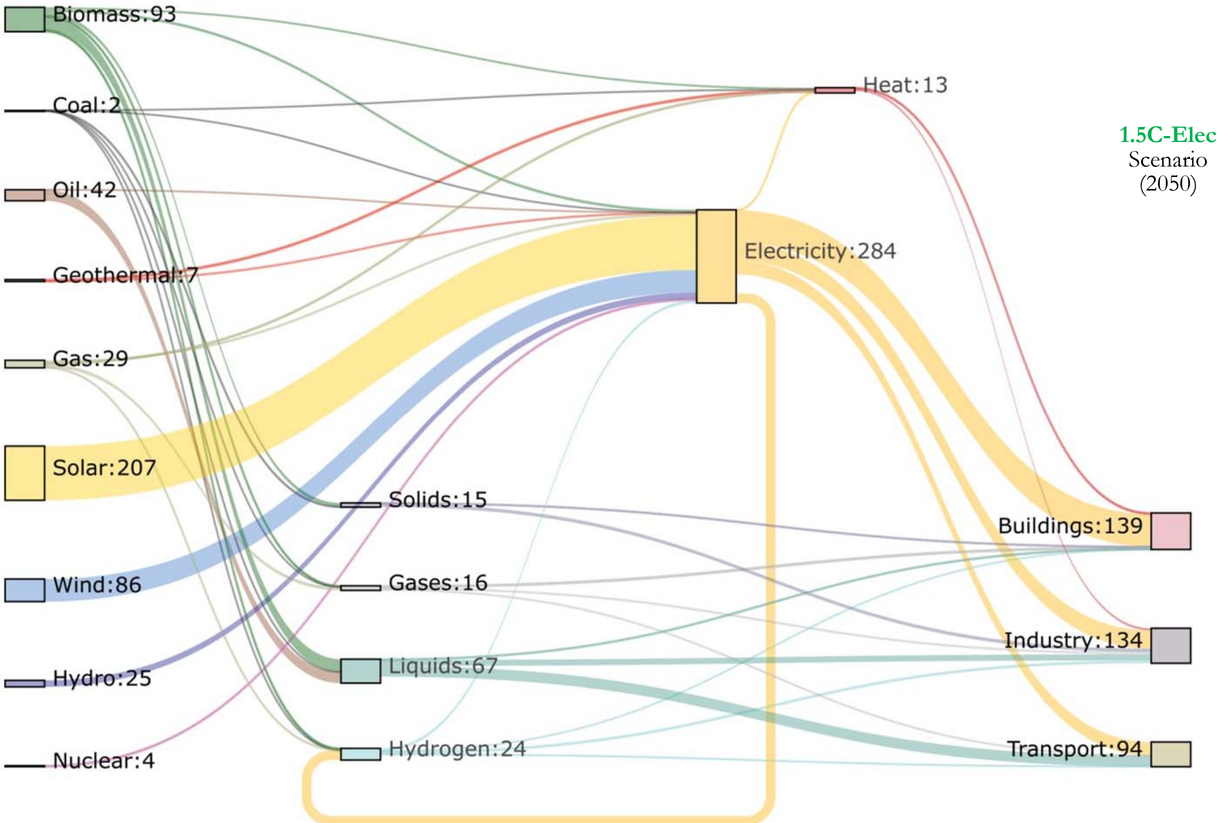
- Continued **fast cost decreases in wind, solar and battery technology**
- Learning rate of solar PV of **25% per doubling of cumulative capacity**
- Integration of VRE via battery storage, H_2 generation and demand flexibilization



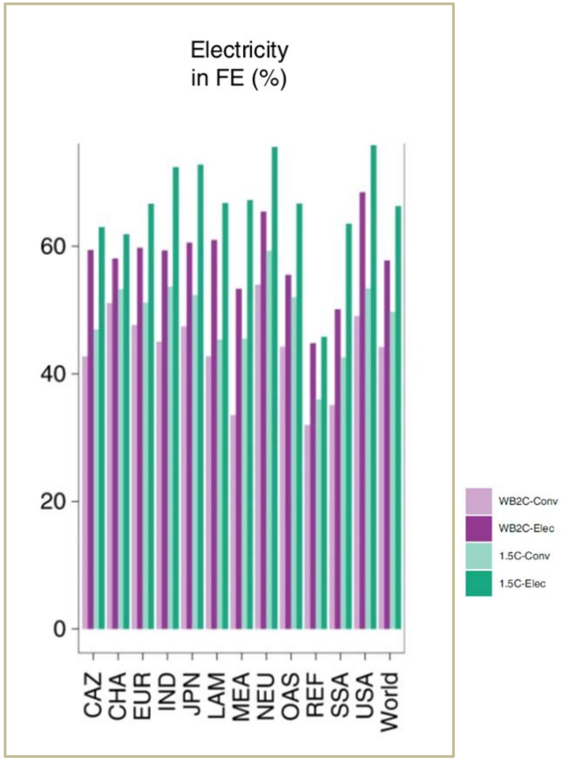
Source: Luderer et al. (2022), Impact of declining renewable energy costs on electrification in low-emission scenarios, *Nature Energy* 7: 32–42

Illustrative Mitigation Pathway for Renewable Energy

Solar, wind, geothermal, hydro, biomass have shares in primary energy of 42%, 17%, 5%, 1% and 19% in 2050 (84.4%)



1.5C-Elec
Scenario
(2050)

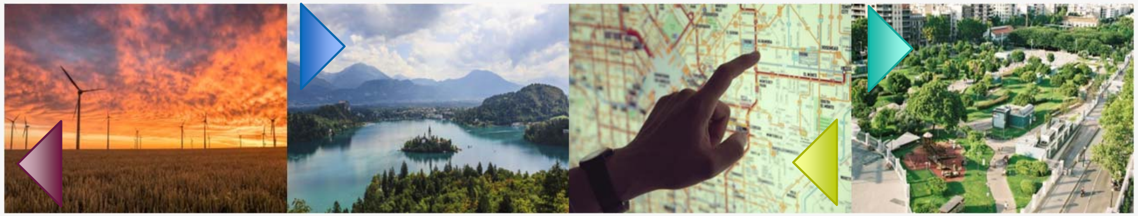


Source: Luderer et al. (2022), Impact of declining renewable energy costs on electrification in low-emission scenarios, *Nature Energy* 7: 32–42

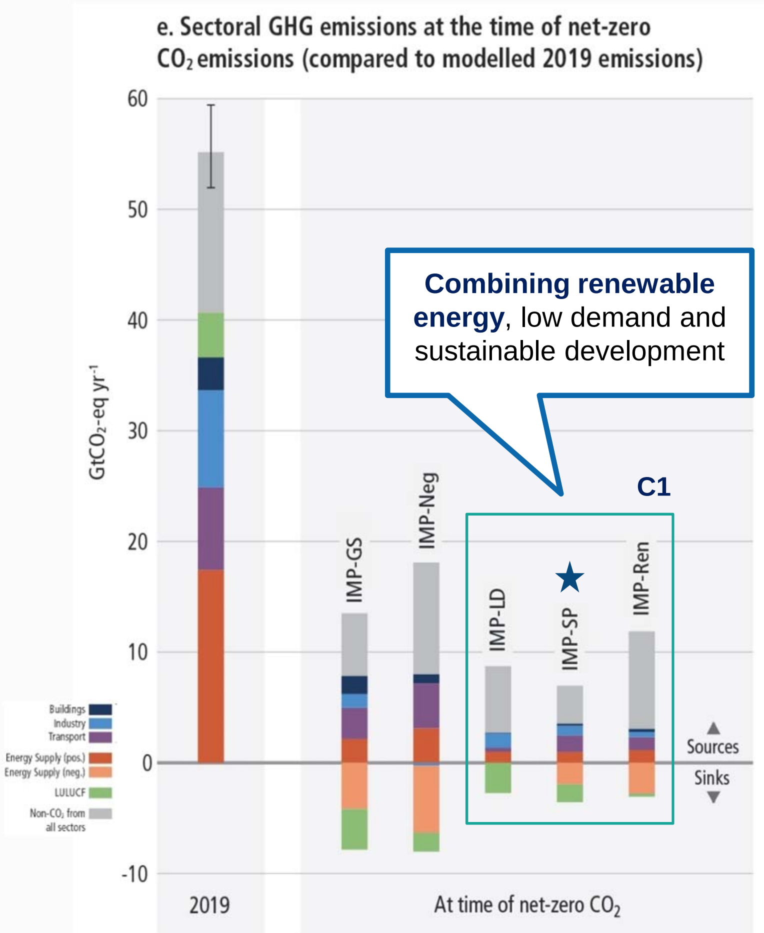
System transformations in the Illustrative Mitigation Pathways

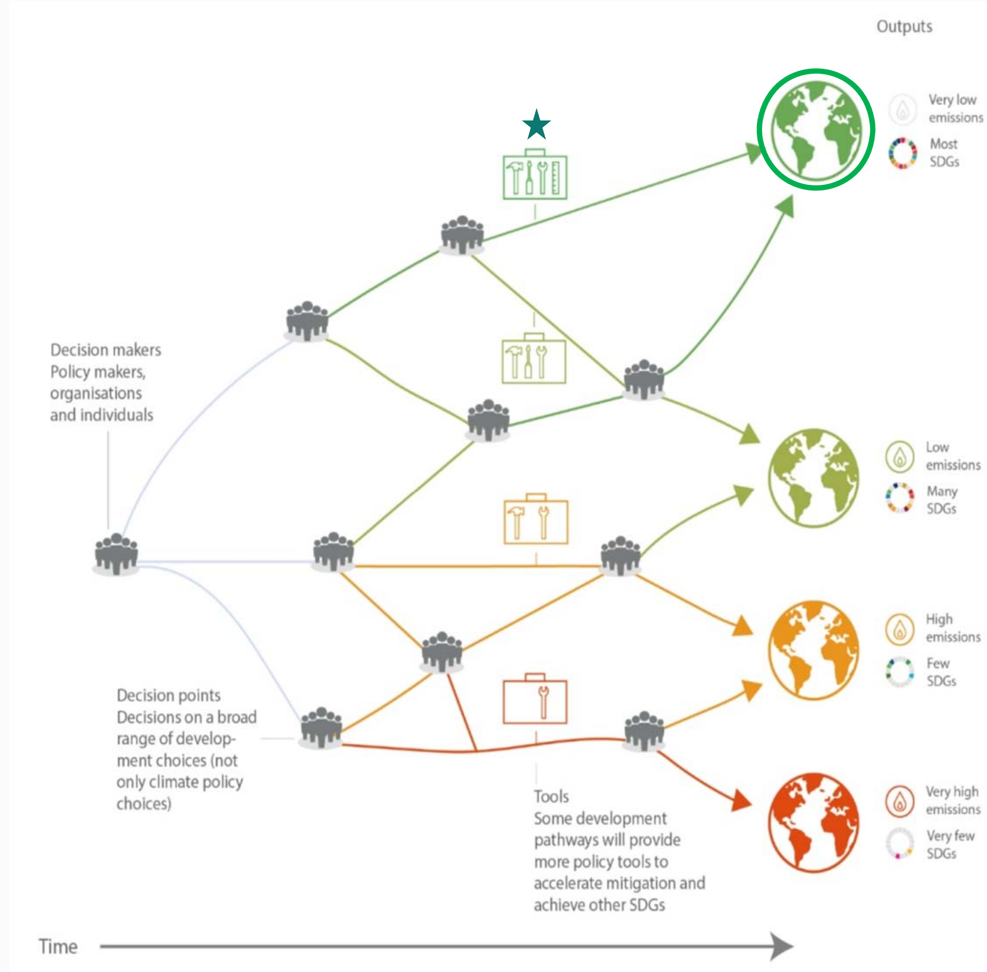
Illustrative Mitigation Pathways (IMPs)		General characteristics	Policy	Innovation	Energy	Land use, food biodiversity	Lifestyle
IMPs in C1	Renewable energy (IMP-RE)	Rapid deployment and technology development of **renewables; electrification**	Successful international climate policy regime; policies and financial incentives favouring the **rapid upscaling of renewable energy**	**Rapid further development** of innovative renewable electricity technologies and policy regimes	**Renewable energy, electrification**; sector coupling; storage or power-to-X technologies; better interconnections		Service provisioning and demand changes to better adapt to **high renewable energy supply**
	Low demand (IMP-LD)	**Reduced demand** leads to early emission reductions		**Social innovation; efficiency;** across all sectors	**Demand reduction**; modal shifts in transport; rapid diffusion of BAT in buildings and industry	**Lower food and agricultural waste**; less meat-intensive lifestyles	**Service provisioning and demand changes**; behavioural changes
	Shifting pathways (IMP-SP)	**Major transformations shift development towards sustainability** and reduced inequality, including deep GHG emissions reduction	**SDG policies in addition to climate policy** (poverty reduction; environmental protection		**Demand reduction; renewable energy (IMP-RE + IMP-LD)**	Lower food and agricultural waste; less meat-intensive lifestyles; afforestation.	Service provisioning and demand changes

Role of renewable energy and low demand in net-zero pathways and shifting development towards sustainability



System transformations across energy, land use, innovation, lifestyle and policy

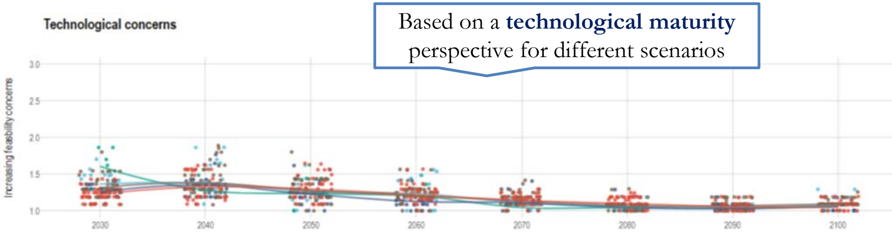

e. Sectoral GHG emissions at the time of net-zero CO_2 emissions (compared to modelled 2019 emissions)
GtCO$_2$-eq yr^{-1}
60
50
40
30
20
10
0
-10
2019
At time of net-zero CO_2
IMP-GS
IMP-Neg
IMP-LD
IMP-SP
IMP-Ren
C1
Combining renewable energy, low demand and sustainable development
Sources
Sinks
Buildings
Industry
Transport
Energy Supply (pos.)
Energy Supply (neg.)
LULUCF
Non-CO₂ from all sectors


Outputs
Very low emissions
Most SDGs
Low emissions
Many SDGs
High emissions
Few SDGs
Very high emissions
Very few SDGs
Decision makers
Policy makers, organisations and individuals
Decision points
Decisions on a broad range of development choices (not only climate policy choices)
Tools
Some development pathways will provide more policy tools to accelerate mitigation and achieve other SDGs
Time

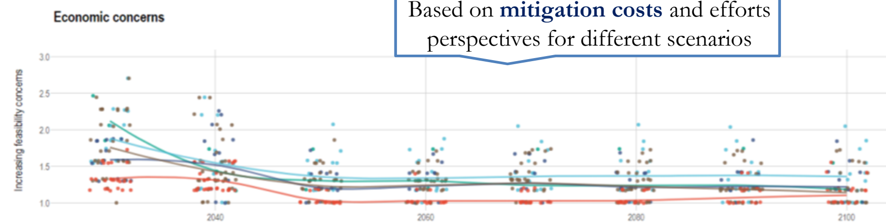
Multi-Dimensional Feasibility Assessment of Scenarios

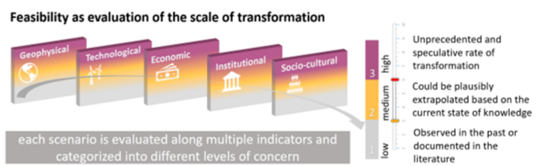
A multi-dimensional approach to assessing the feasibility of scenarios across time was also initiated during AR6

Based on a **technological maturity** perspective for different scenarios

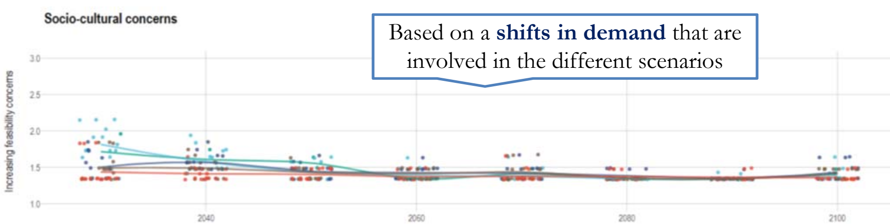


Based on **mitigation costs** and efforts perspectives for different scenarios

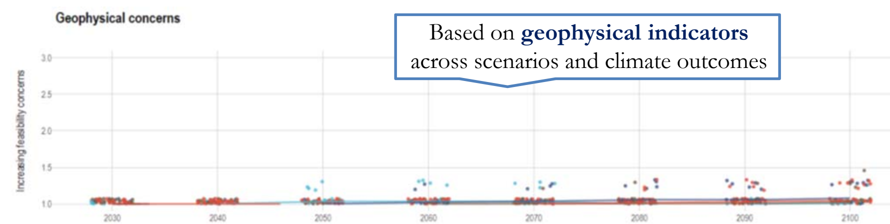




Based on a **shifts in demand** that are involved in the different scenarios



Based on **geophysical indicators** across scenarios and climate outcomes

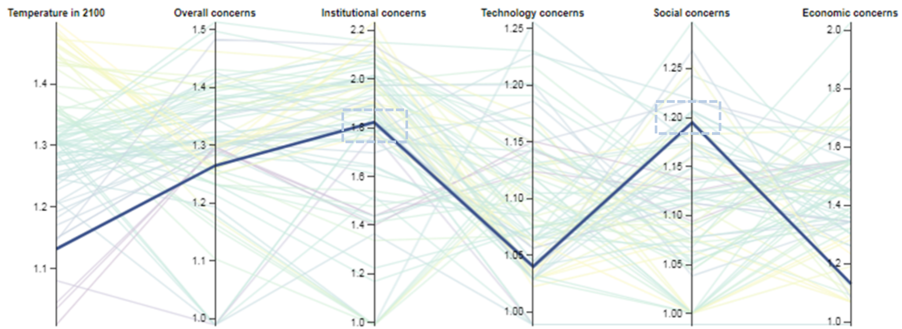


Sources: Brutschin et al. (2021), A multidimensional feasibility evaluation of low-carbon scenarios, *Environ. Res. Lett.* 16: 064069; IIASA Multidimensional Feasibility Dashboard <https://data.ece.iiasa.ac.at/climate-action-feasibility-dashboard/>

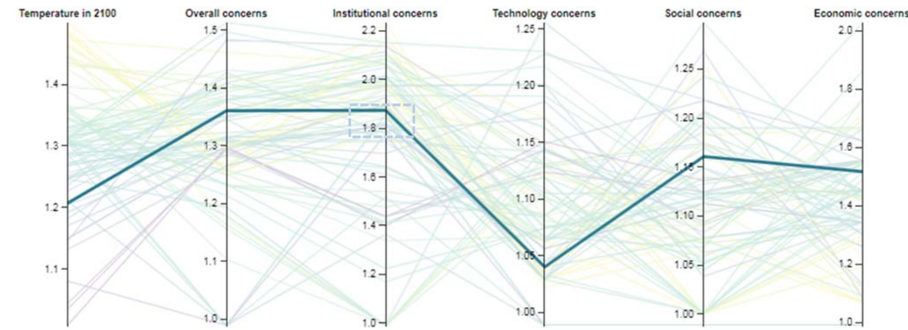
Multi-Dimensional Feasibility Assessment of Scenarios

A multi-dimensional approach to assessing the feasibility of scenarios across time was also initiated during AR6

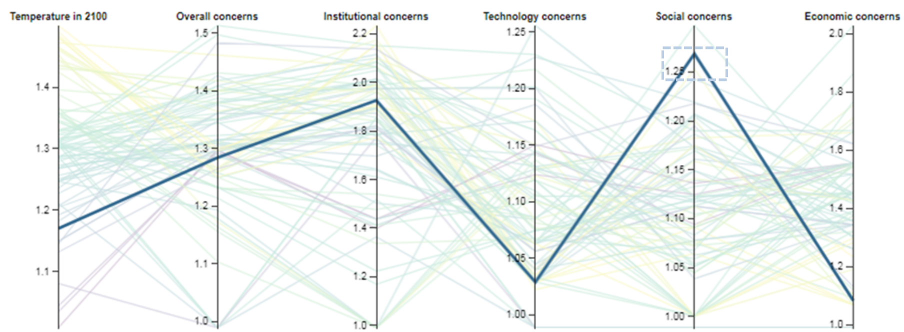
REMIND-MAgPIE 1.7-3.0 (**SMP_1p5C_Sust**)



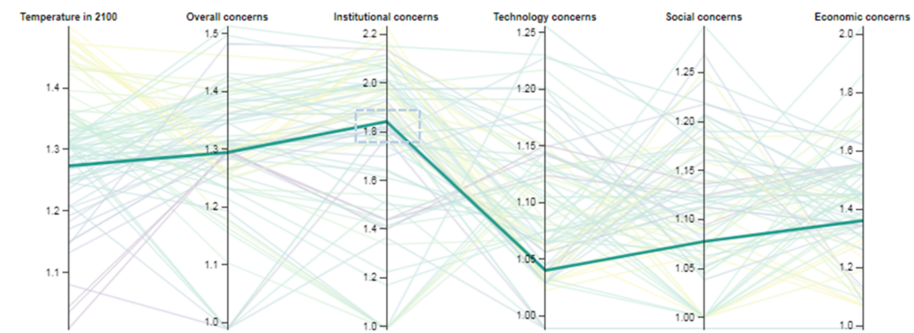
REMIND-MAgPIE 1.7-3.0 (**SMP_1p5C_regul**)



REMIND-MAgPIE 1.7-3.0 (**SMP_1p5C_lifesty**)



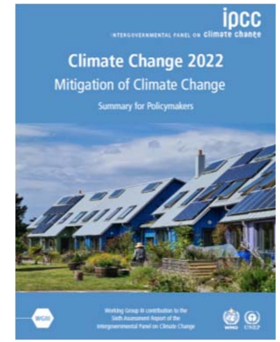
REMIND-MAgPIE 1.7-3.0 (**SMP_1p5C_early**)



Sources: Brutschin et al. (2021), A multidimensional feasibility evaluation of low-carbon scenarios, *Environ. Res. Lett.* 16: 064069;
IIASA Multidimensional Feasibility Dashboard <https://data.ece.iiasa.ac.at/climate-action-feasibility-dashboard/>

Additional Possibilities for Improvement Beyond AR6

In addition to modelling 100% renewable energy scenarios, other areas for improvement include material efficiency



C.5 **Net zero CO_2 emissions from the industrial sector are challenging but possible. Reducing industry emissions will entail coordinated action throughout value chains to promote all mitigation options, including demand management, energy and materials efficiency, circular material flows, as well as abatement technologies and transformational changes in production processes. Progressing towards net zero GHG emissions from industry will be enabled by the adoption of new production processes using low- and zero-GHG electricity, hydrogen, fuels, and carbon management. (*high confidence*) {11.2, 11.3, 11.4, Box TS.4}**

C.5.1 The use of steel, cement, plastics, and other materials is increasing globally, and in most regions. There are many sustainable options for demand management, materials efficiency, and circular material flows that can contribute to reduced emissions, but how these can be applied will vary across regions and different materials. These options have a potential for being more used in industrial practice and would need more attention from industrial policy. These options, as well as new production technologies, are generally not considered in recent global scenarios nor in national economy-wide scenarios due to relative newness. As a consequence, the mitigation potential in some scenarios is underestimated compared to bottom-up industry-specific models. (*high confidence*) {3.4, 5.3, Figure 5.7, 11.2, Box 11.2, 11.3, 11.4, 11.5.2, 11.6}

SPM

"Demand management, materials efficiency and circular material flows – are generally not considered in recent global scenarios nor in national economy-wide scenarios **due to relative newness**."

Material efficiency and global pathways towards 100% renewable energy systems – system dynamics findings on potential and constraints

Source: IPCC, Climate Change 2022: Mitigation of Climate Change Summary for Policymakers <https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SPM.pdf>

LOCOMOTION

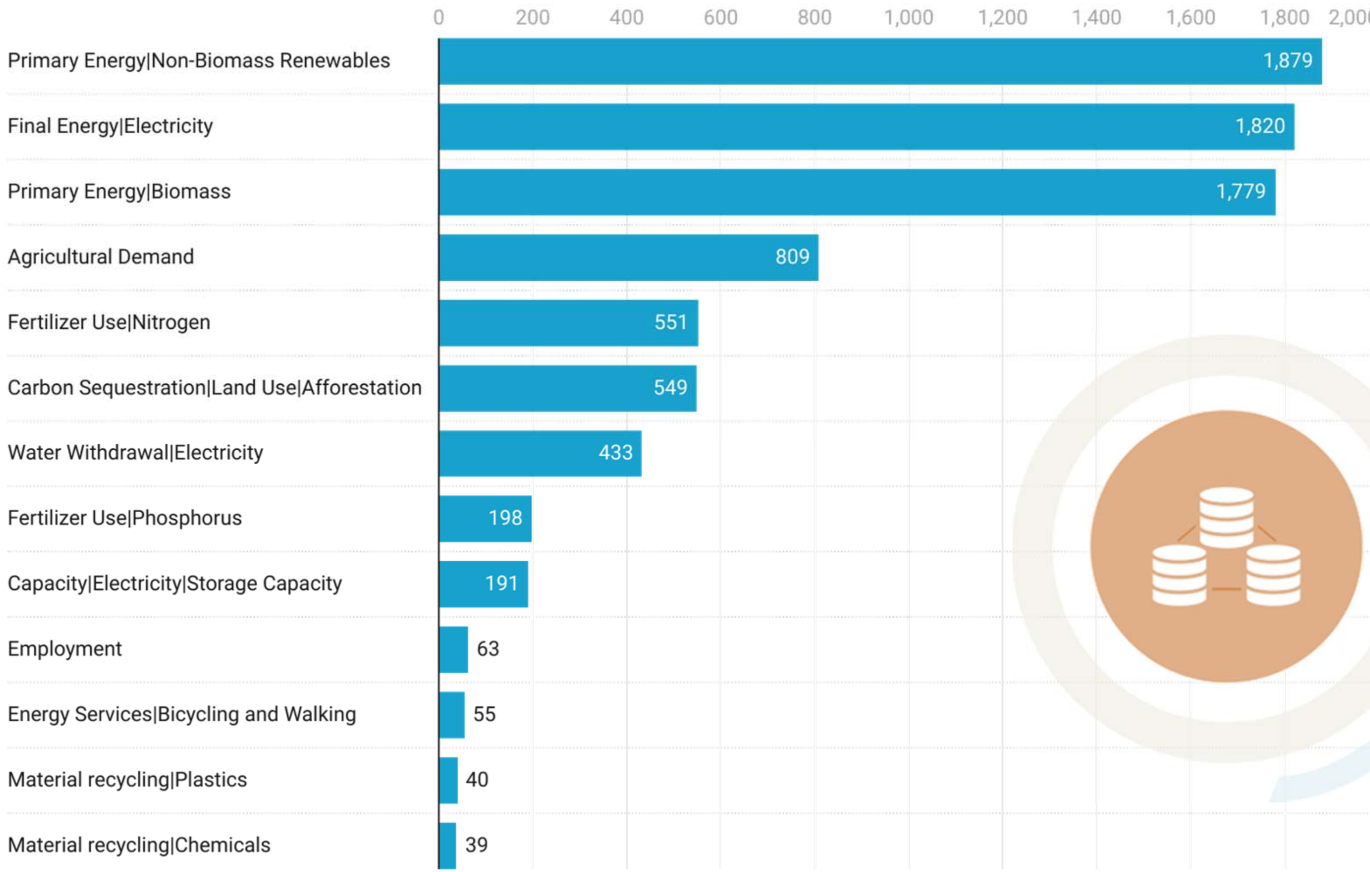
AR6 Scenario Explorer and Database – Indicators

The existing models and scenarios represent different coverage of aspects that are important for effective mitigation

AR6 Scenario Explorer and Database hosted by IIASA

IAMC

IIASA International Institute for Applied Systems Analysis www.iiasa.ac.at

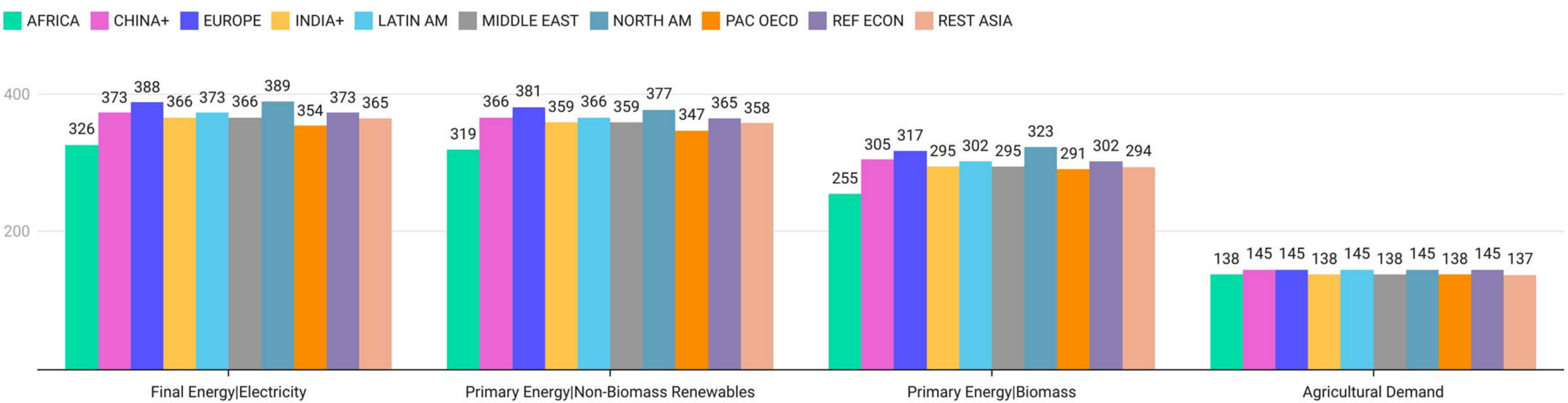


Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

AR6 Scenario Explorer and Database – Indicators

At the level of 10 regions, there is a similar scene with key differences, also representing modelling capabilities

AR6 Scenario Explorer and Database hosted by IIASA



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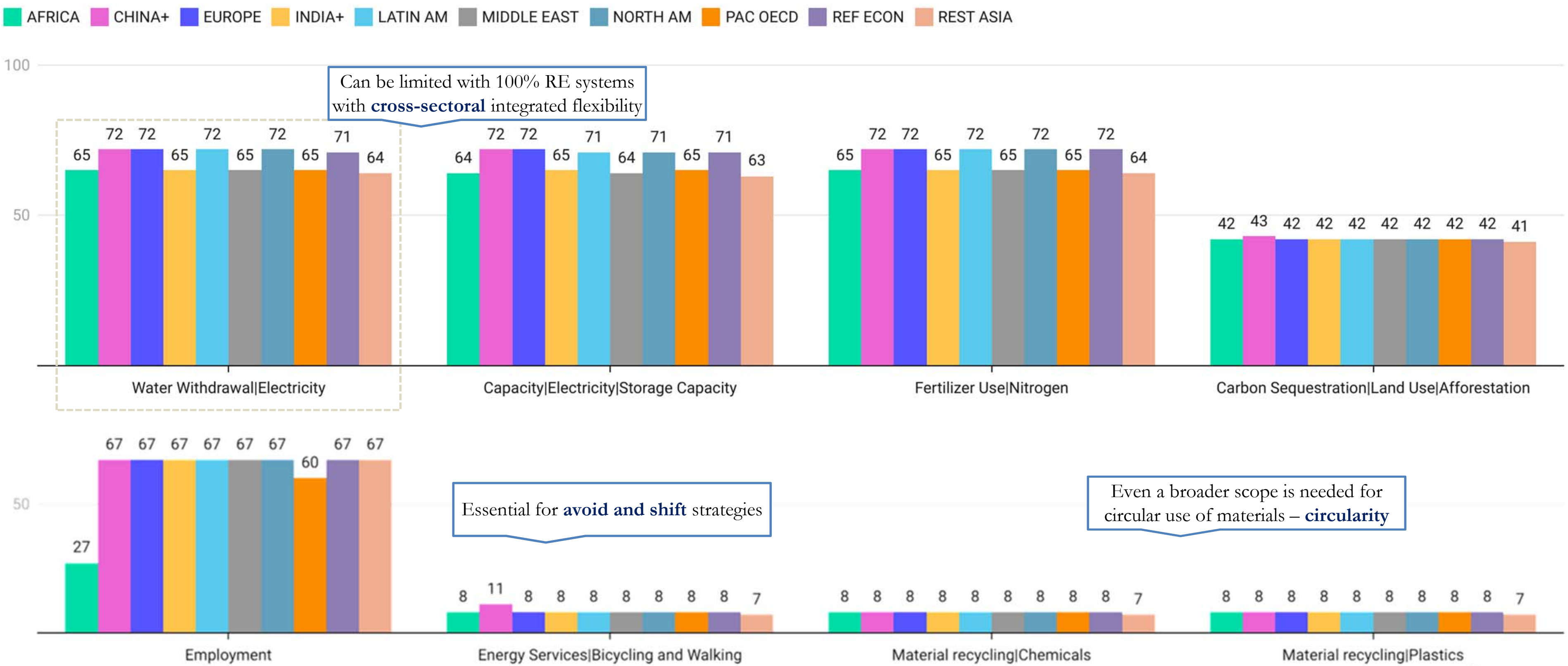
AR6 Scenario Explorer and Database – Indicators

At the level of 10 regions, there is a similar scene with key differences, also representing modelling capabilities



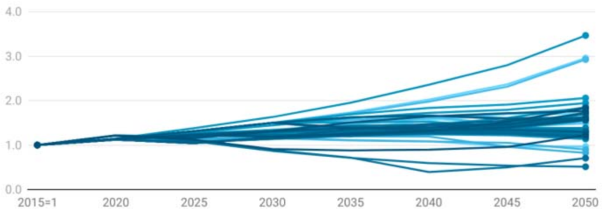
Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

Regional Perspectives – Within Planetary Boundaries?

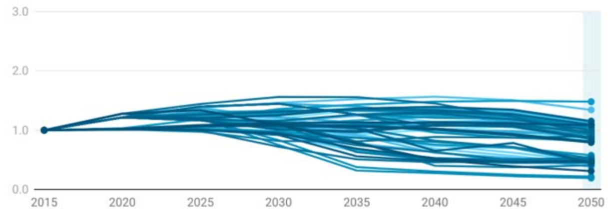
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – Water Withdrawal for Electricity (km^3/yr, normalized with 2015 values = 1)

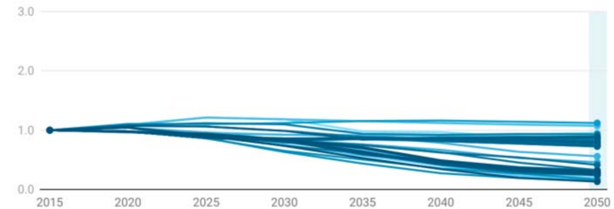
Region 1 – Africa



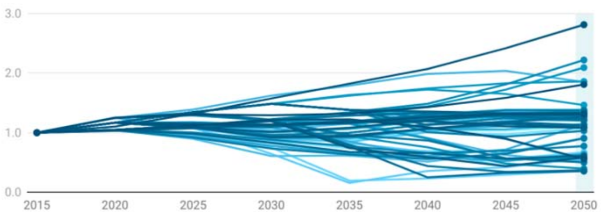
Region 2 – Eastern Asia (China+)



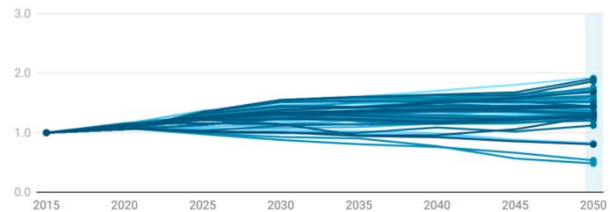
Region 3 – Europe



Region 4 – Southern Asia (India+)



Region 5 – Latin America and Caribbean



Minimum	Average	Maximum
North America 0.03 times: 152.48 → 5.25 km^3/yr	**Actoss Regions** 0.91 times from 2015 values	**Africa** 3.47 times: 18.69 → 64.76 km^3/yr
SSP1-1.9 Scenario		No Policy Scenario

n = 64-72 scenarios for different regions;
This sample of scenarios is kept for the other indicators and included when data is available.

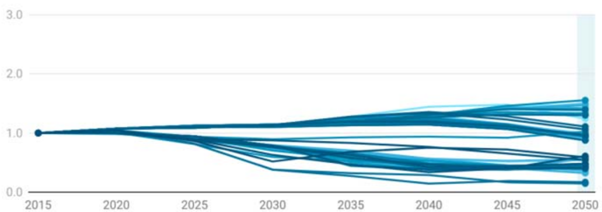
Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>; The scale of the y-axis is different for regions when necessary.

Regional Perspectives – Within Planetary Boundaries?

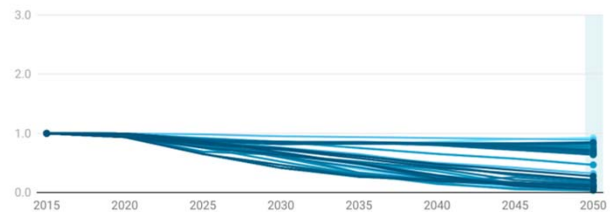
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – Water Withdrawal for Electricity (km^3/yr, normalized with 2015 values = 1)

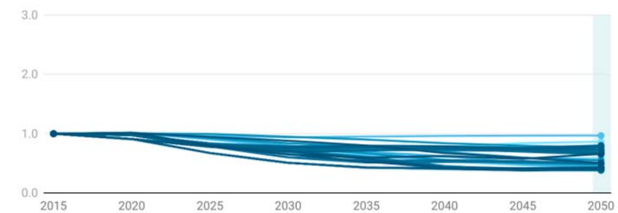
Region 6 – Middle East



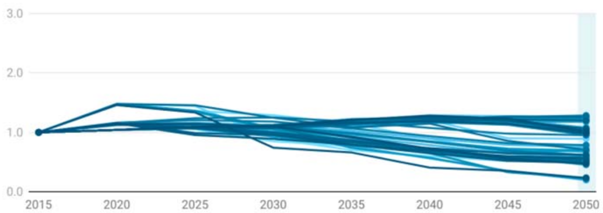
Region 7 – North America



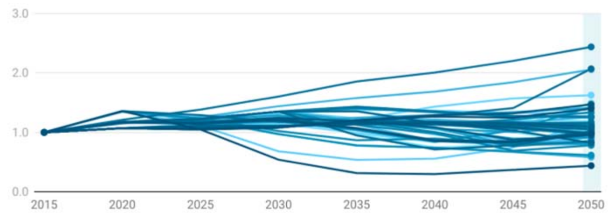
Region 8 – Asia-Pacific Developed (Pacific OECD)



Region 9 – Eastern Europe and West-Central Asia (Ref Econ)



Region 10 – South-East Asia & Developing Pacific (Rest Asia)



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SSP1-1.9 Scenario		No Policy Scenario

n = 64-72 scenarios for different regions;
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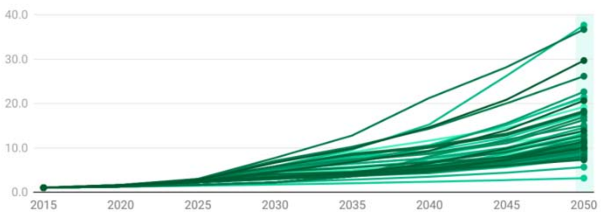
LOCOMOTION

Regional Perspectives – Within Planetary Boundaries?

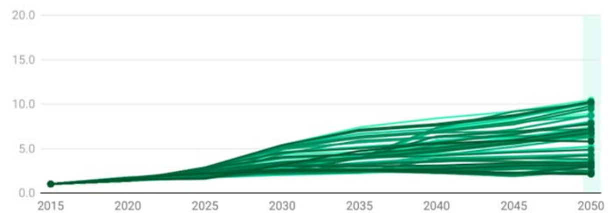
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – Primary Energy from Non-Biomass Renewables (EJ/yr, normalized with 2015 values = 1)

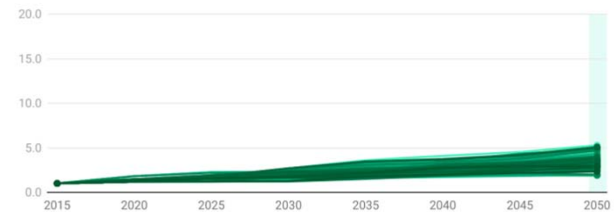
Region 1 – Africa



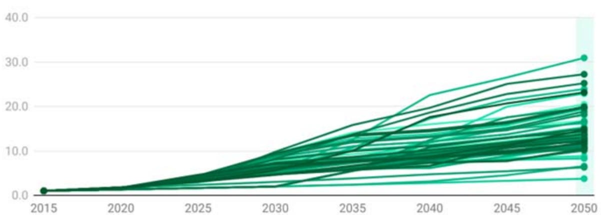
Region 2 – Eastern Asia (China+)



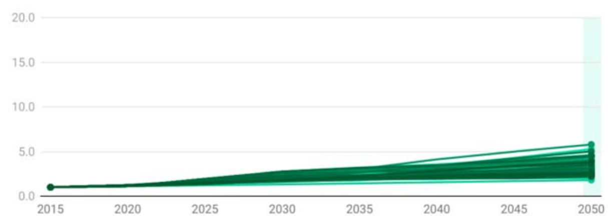
Region 3 – Europe



Region 4 – Southern Asia (India+)



Region 5 – Latin America and Caribbean



Minimum	Average	Maximum
Ref Econ 1.66 times: 1.80 → 2.98 EJ/yr	**Actoss Regions** 10.78 times from 2015 values	**Middle East** 160.62 times: 0.07 → 11.22 EJ/yr

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>; The scale of the y-axis is different for regions when necessary.

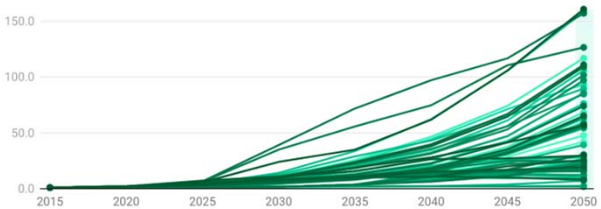
LOCOMOTION

Regional Perspectives – Within Planetary Boundaries?

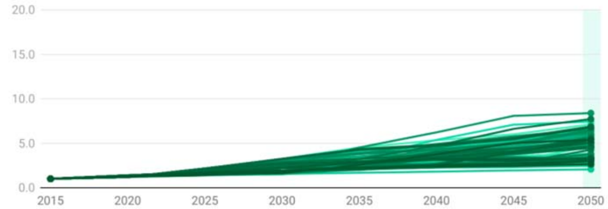
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – Primary Energy from Non-Biomass Renewables (EJ/yr, normalized with 2015 values = 1)

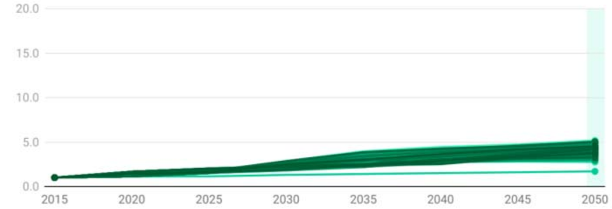
Region 6 – Middle East



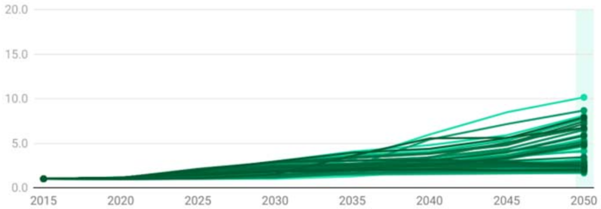
Region 7 – North America



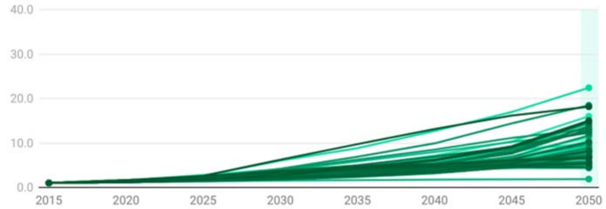
Region 8 – Asia-Pacific Developed (Pacific OECD)



Region 9 – Eastern Europe and West-Central Asia (Ref Econ)



Region 10 – South-East Asia & Developing Pacific (Rest Asia)



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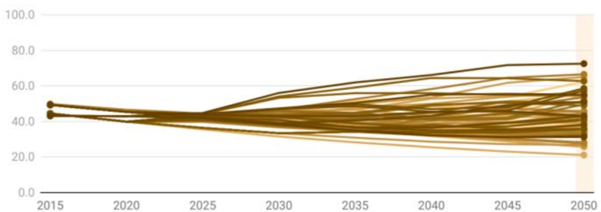
Regional Perspectives – Within Planetary Boundaries?

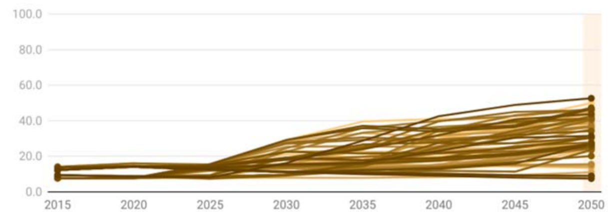
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – Total Renewable Energy Share in Primary Energy (%)

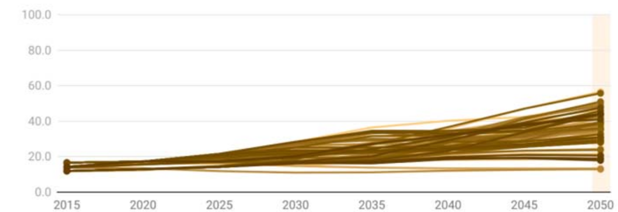
Region 1 – Africa



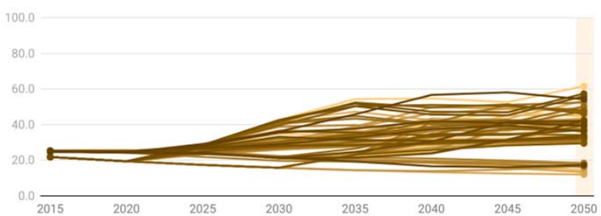
Region 2 – Eastern Asia (China+)



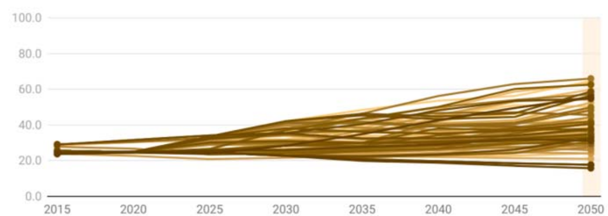
Region 3 – Europe



Region 4 – Southern Asia (India+)



Region 5 – Latin America and Caribbean



Minimum	Average	Maximum
Middle East 0.80% (Stable from 0.58%)	**Actoss Regions and Scenarios** Only 30.66% in 2050	**Africa** 72.49% (Up from 43.18%)

SSP1-1.9-LIRE_LB (Lifestyle and RE)

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

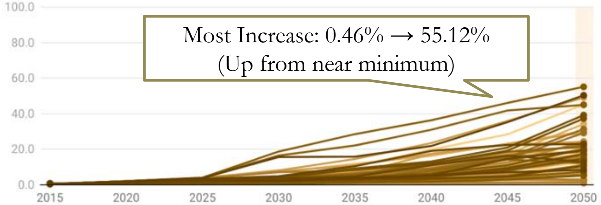
LOCOMOTION

Regional Perspectives – Within Planetary Boundaries?

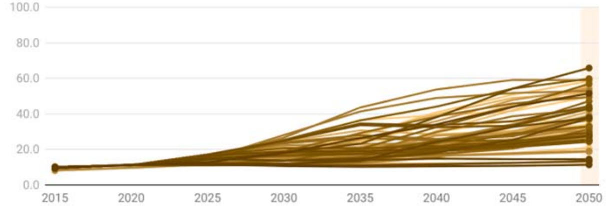
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – Total Renewable Energy Share in Primary Energy (%)

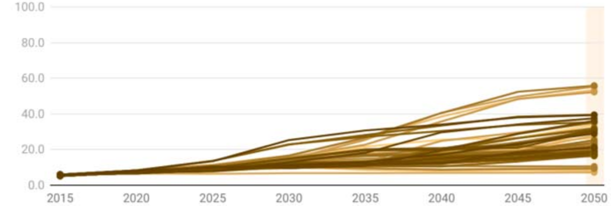
Region 6 – Middle East



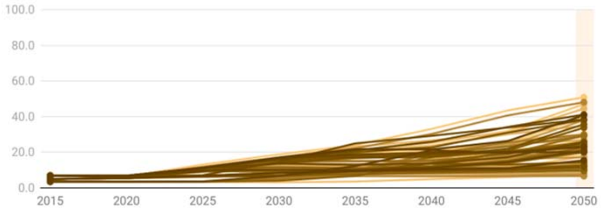
Region 7 – North America



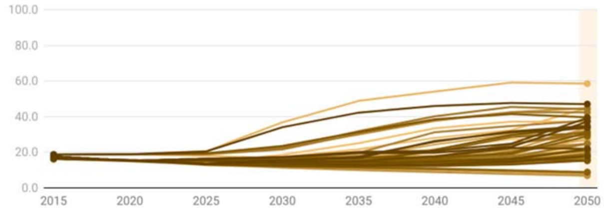
Region 8 – Asia-Pacific Developed (Pacific OECD)



Region 9 – Eastern Europe and West-Central Asia (Ref Econ)



Region 10 – South-East Asia & Developing Pacific (Rest Asia)



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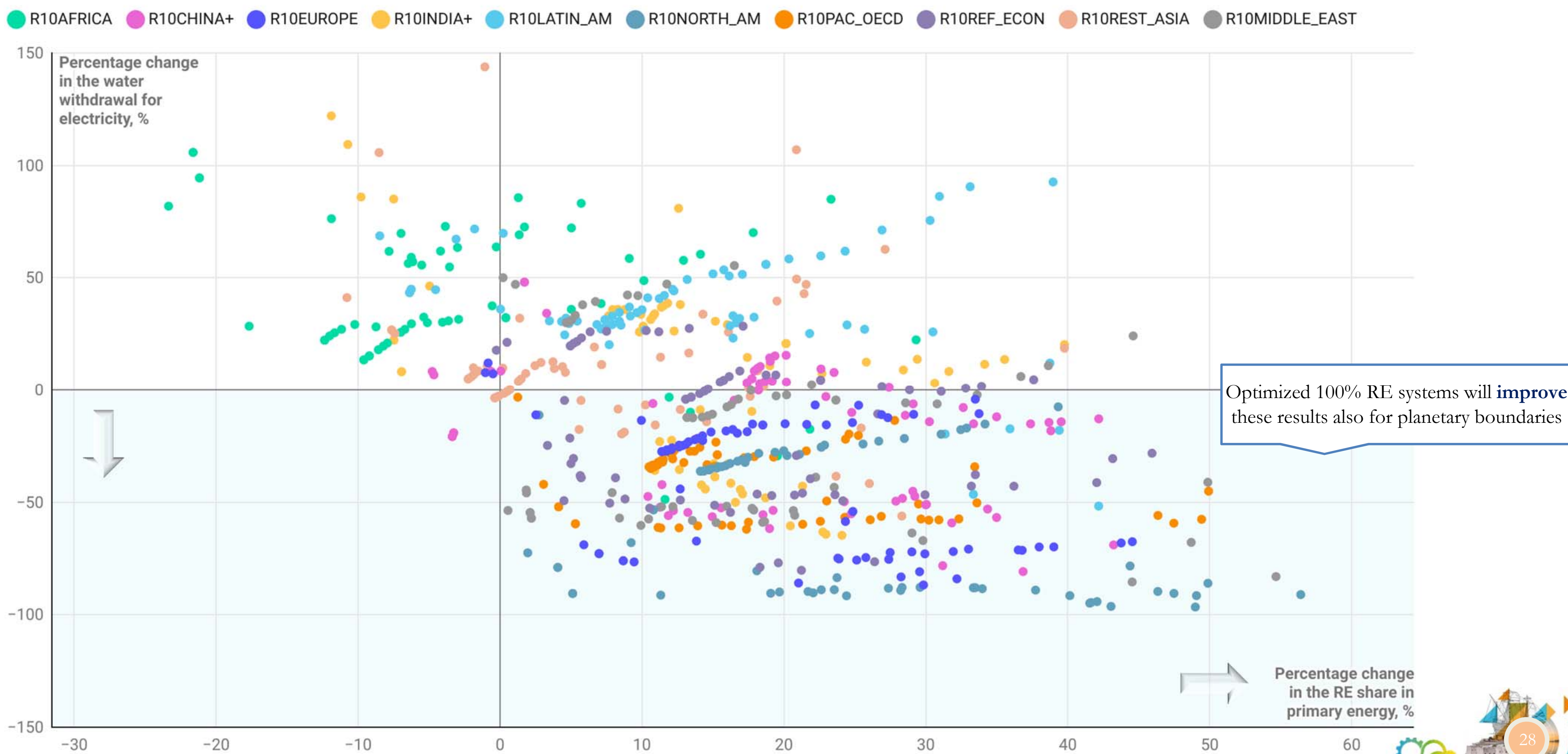
SSP1-1.9-LIRE_LB

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

LOCOMOTION

Cross-Comparison: Water Withdrawal and RE Share

Synergies between reducing water withdrawal for electricity and increasing RE share in primary energy is crucial

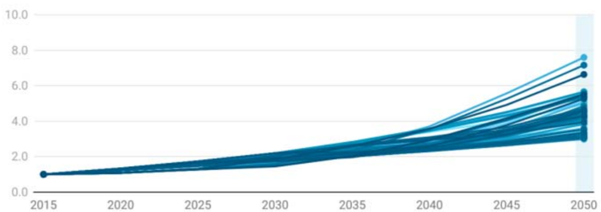


Regional Perspectives – Within Planetary Boundaries?

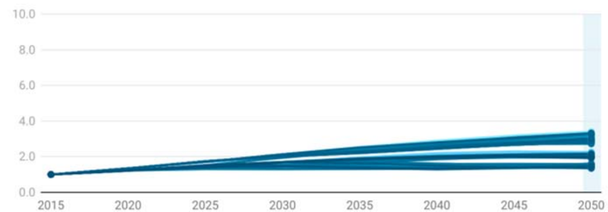
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – <u>Final Energy|Electricity</u> (EJ/yr, normalized with 2015 values = 1)

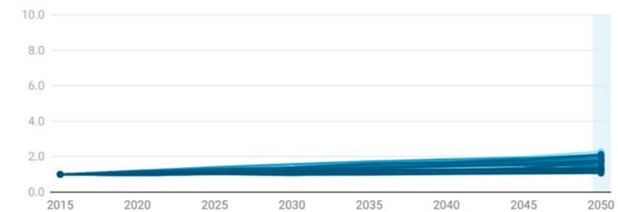
Region 1 – Africa



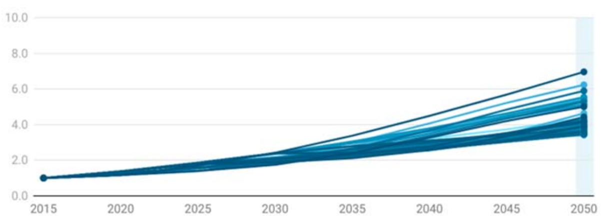
Region 2 – Eastern Asia (China+)



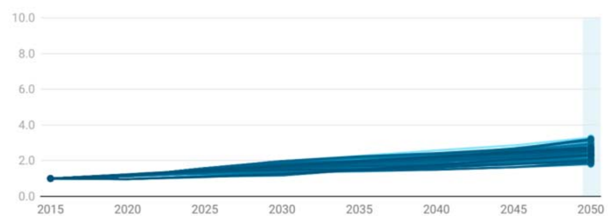
Region 3 – Europe



Region 4 – Southern Asia (India+)



Region 5 – Latin America and Caribbean



Minimum	Average	Maximum
Pacific OECD 0.97 times: 4.48 → 4.33 EJ/yr	**Actoss Regions** 2.46 times from 2015 values	**<u>Africa</u>** 7.59 times: 2.25 → 17.11 EJ/yr

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

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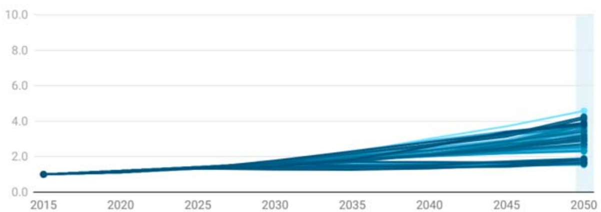
Regional Perspectives – Within Planetary Boundaries?

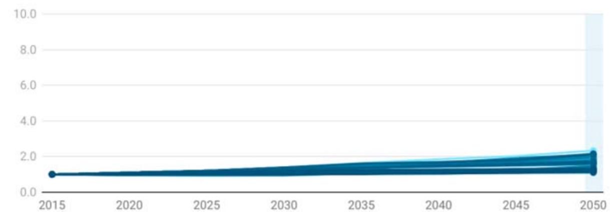
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – Final Energy|Electricity (EJ/yr, normalized with 2015 values = 1)

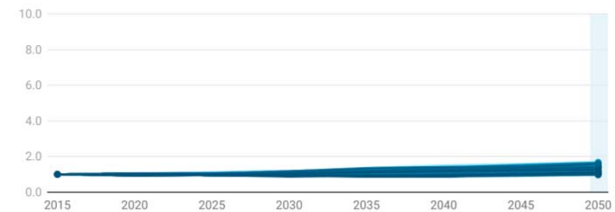
Region 6 – Middle East



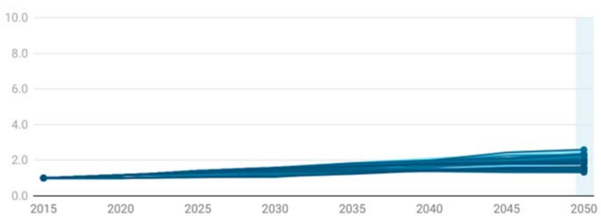
Region 7 – North America



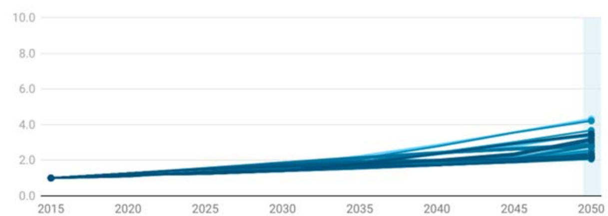
Region 8 – Asia-Pacific Developed (Pacific OECD)



Region 9 – Eastern Europe and West-Central Asia (Ref Econ)



Region 10 – South-East Asia & Developing Pacific (Rest Asia)



Minimum	Average	Maximum
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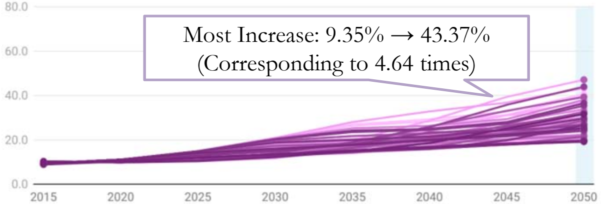
Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

Regional Perspectives – Within Planetary Boundaries?

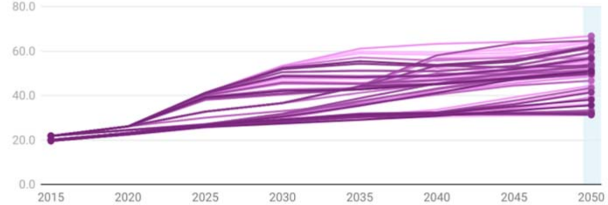
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – Electricity Share in Final Energy (%)

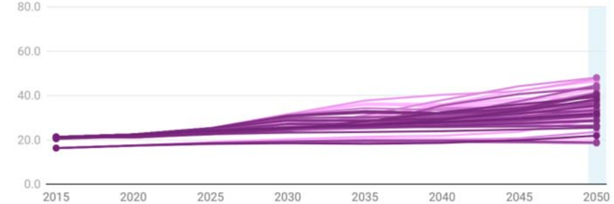
Region 1 – Africa



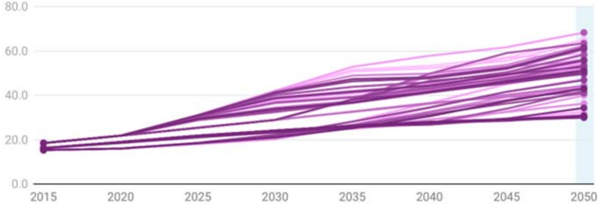
Region 2 – Eastern Asia (China+)



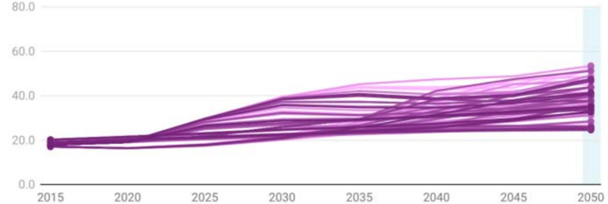
Region 3 – Europe



Region 4 – Southern Asia (India+)



Region 5 – Latin America and Caribbean



Minimum	Average	Maximum
Europe 18.50% (Down from 16.27%)	**Actoss Regions and Scenarios** Only 35.51% in 2050	**India+** 68.28% (Up from 18.45%)

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

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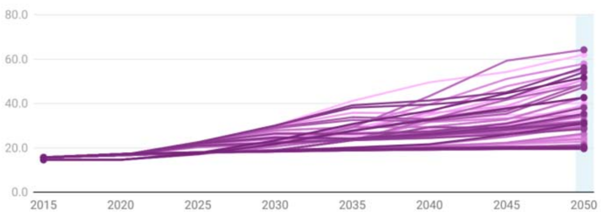
Regional Perspectives – Within Planetary Boundaries?

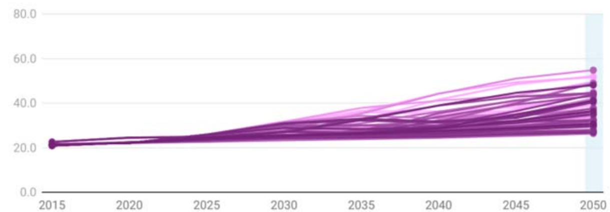
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – Electricity Share in Final Energy (%)

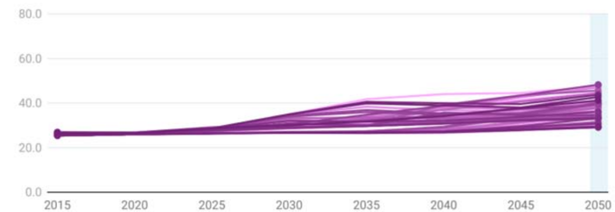
Region 6 – Middle East



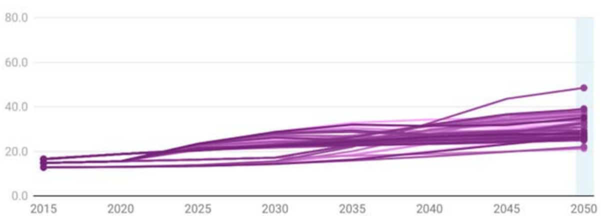
Region 7 – North America



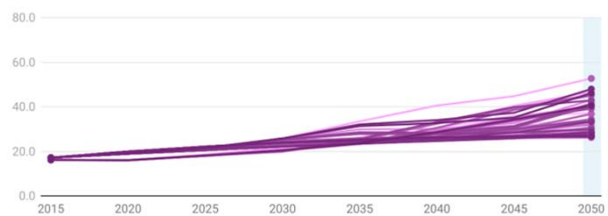
Region 8 – Asia-Pacific Developed (Pacific OECD)



Region 9 – Eastern Europe and West-Central Asia (Ref Econ)



Region 10 – South-East Asia & Developing Pacific (Rest Asia)



Minimum	Average	Maximum
Europe 18.50% (Down from 16.27%)	**Actoss Regions and Scenarios** Only 35.51% in 2050	**India+** 68.28% (Up from 18.45%)

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

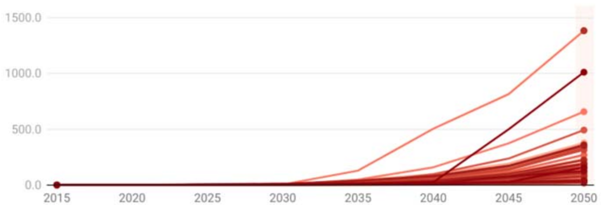
LOCOMOTION

Regional Perspectives – Within Planetary Boundaries?

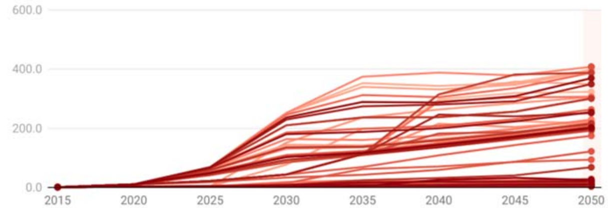
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – Electricity Storage Capacity (GWh, normalized with 2015 values = 1)

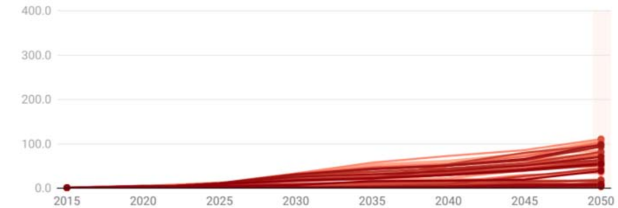
Region 1 – Africa



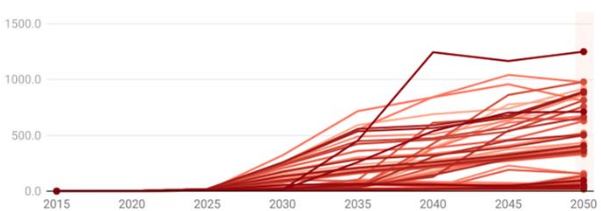
Region 2 – Eastern Asia (China+)



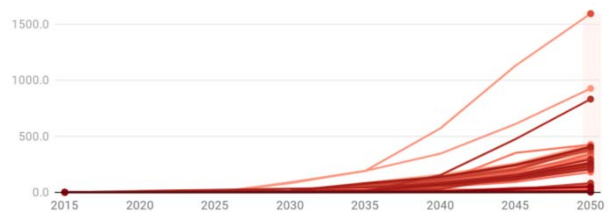
Region 3 – Europe



Region 4 – Southern Asia (India+)



Region 5 – Latin America and Caribbean



Minimum	Average	Maximum
Ref Econ 0.83 times: 3.45 → 2.87 GWh	**Actoss Regions** 140.00 times from 2015 values	**Latin America** 1592.60 times: 1.83 → 2913.96 GWh

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>; The scale of the y-axis is different for regions when necessary; Any zero values in the reference year are given the average

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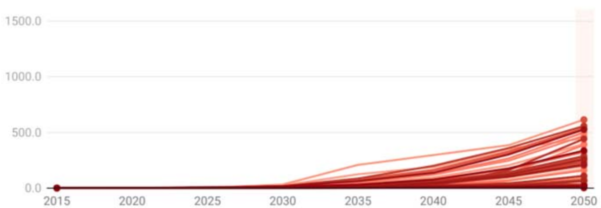
Regional Perspectives – Within Planetary Boundaries?

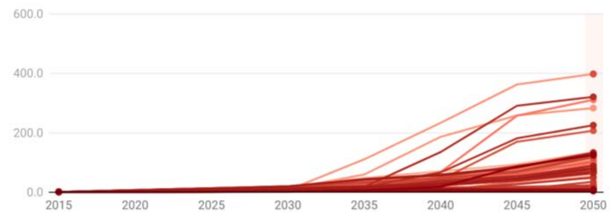
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – Electricity Storage Capacity (GWh, normalized with 2015 values = 1)

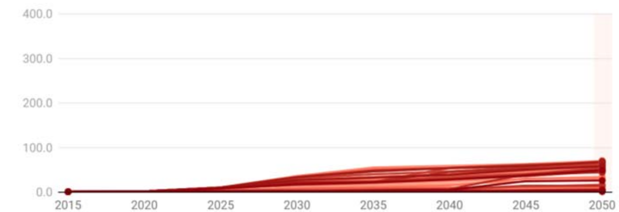
Region 6 – Middle East



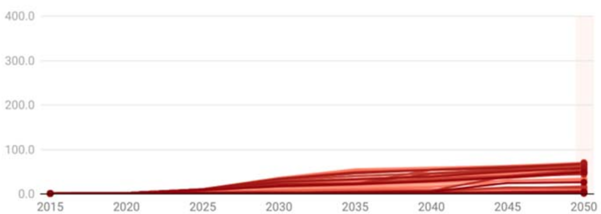
Region 7 – North America



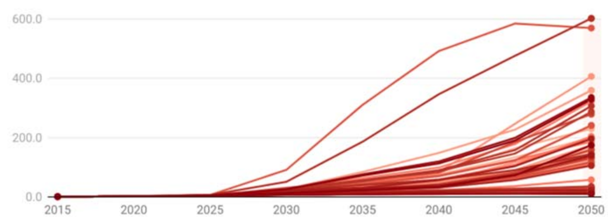
Region 8 – Asia-Pacific Developed (Pacific OECD)



Region 9 – Eastern Europe and West-Central Asia (Ref Econ)



Region 10 – South-East Asia & Developing Pacific (Rest Asia)



Minimum	Average	Maximum
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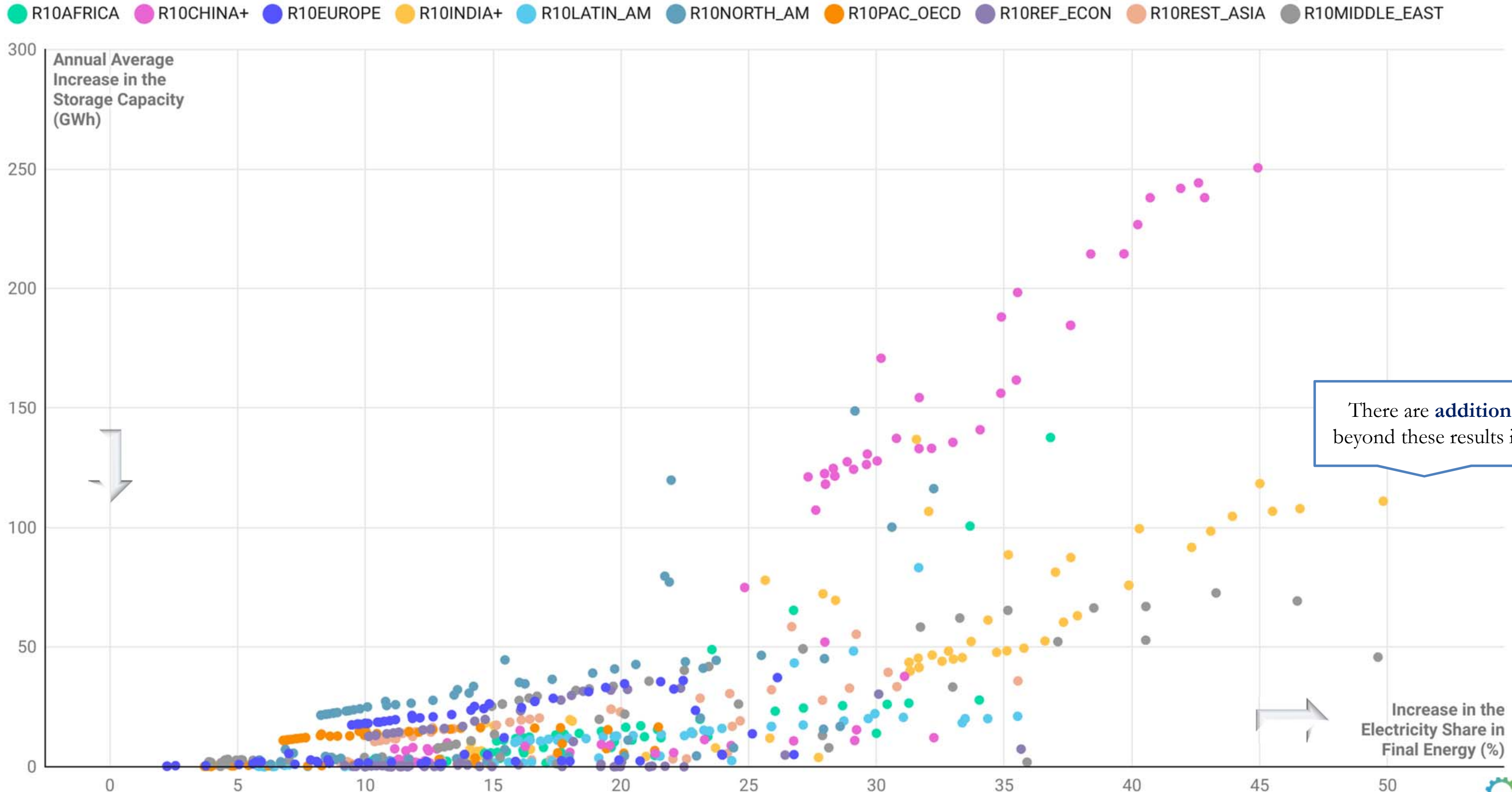
Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>; The scale of the y-axis is different for regions when necessary; Any zero values in the reference year are given the average

Cross-Comparison: Storage and Electricity Share

Enabling a representation of smart energy systems in IAMs can support improvements in both of these dimensions



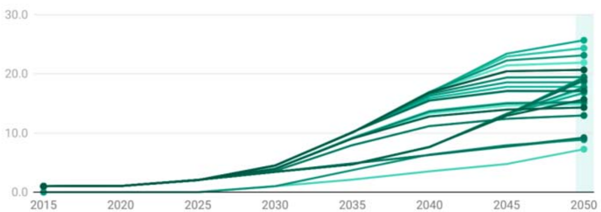
There are **additional opportunities** beyond these results in both dimensions

Regional Perspectives – Within Planetary Boundaries?

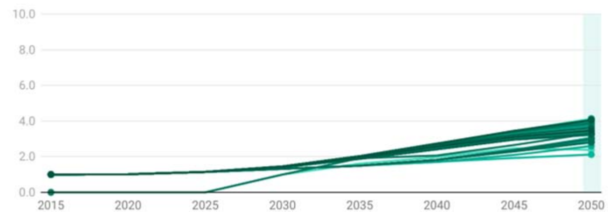
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – Land Use Afforestation (Mt CO_2/yr , normalized with 2015 values = 1)

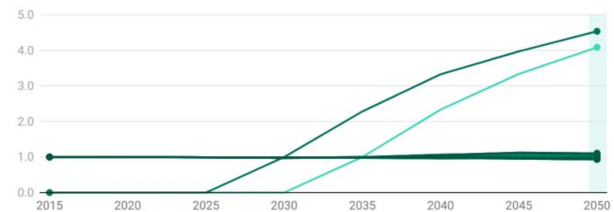
Region 1 – Africa



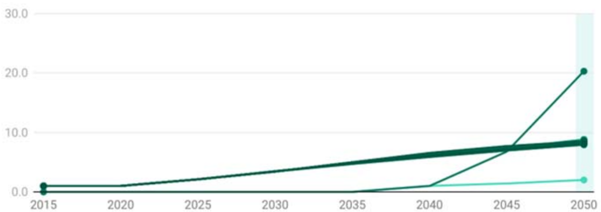
Region 2 – Eastern Asia (China+)



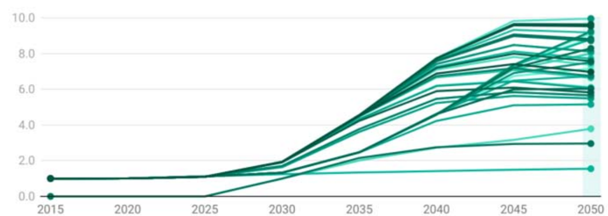
Region 3 – Europe



Region 4 – Southern Asia (India+)



Region 5 – Latin America and Caribbean



Minimum	Average	Maximum
India+ 2.01 times: 4.12 → 8.28 Mt CO_2/yr	**Actoss Regions** 11.16 times from 2015 values	**North America** 109.51 times: 2.23 → 244.26 Mt CO_2/yr

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>; The scale of the y-axis is different for regions when necessary; Non-zero values for some scenarios start in 2030

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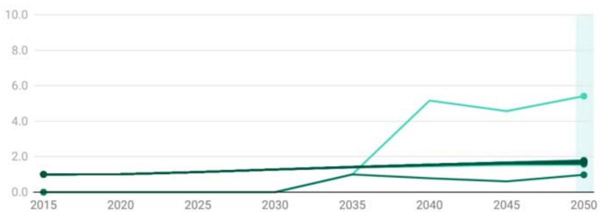
Regional Perspectives – Within Planetary Boundaries?

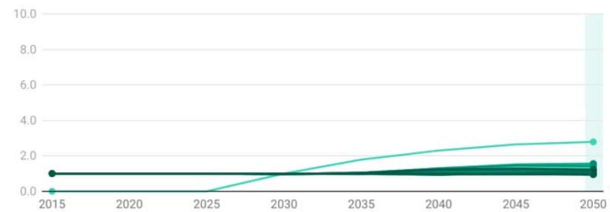
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – <u>Land Use Afforestation</u> (Mt CO_2/yr , normalized with 2015 values = 1)

Region 6 – Middle East

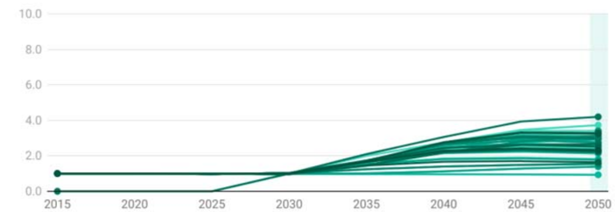


Region 7 – North America

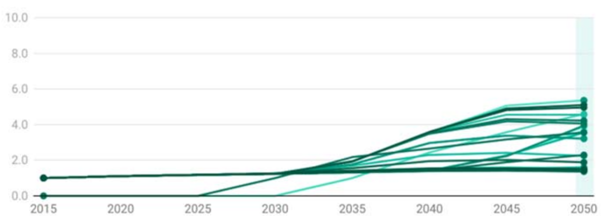


The scenario with the maximum value is not included in this graph

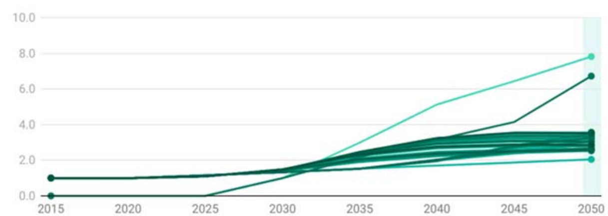
Region 8 – Asia-Pacific Developed (Pacific OECD)



Region 9 – Eastern Europe and West-Central Asia (Ref Econ)



Region 10 – South-East Asia & Developing Pacific (Rest Asia)



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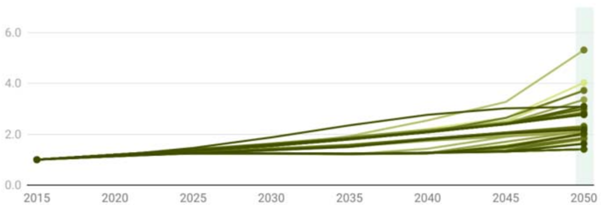
Regional Perspectives – Within Planetary Boundaries?

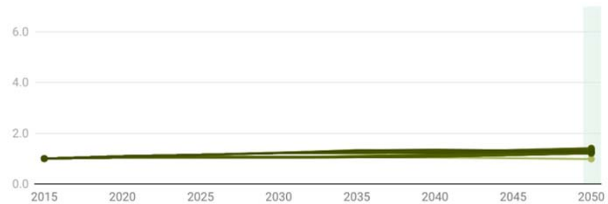
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – Agricultural Demand (million t DM/yr, normalized with 2015 values = 1)

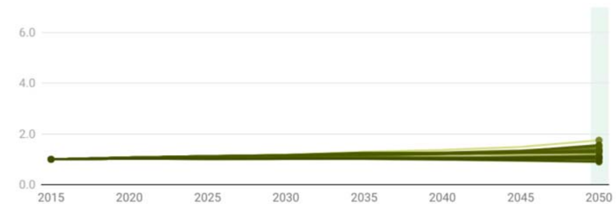
Region 1 – Africa



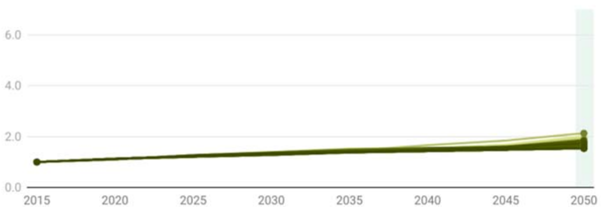
Region 2 – Eastern Asia (China+)



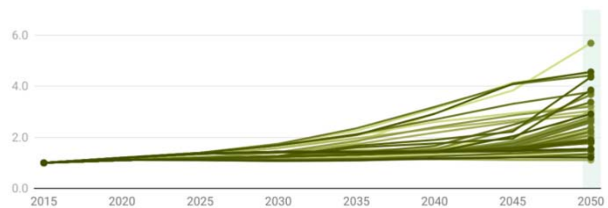
Region 3 – Europe



Region 4 – Southern Asia (India+)



Region 5 – Latin America and Caribbean



Minimum	Average	Maximum
North America 0.86 times: 542.03→ 464.59 mt DM/yr	**Actoss Regions** 1.79 times from 2015 values	**Pacific OECD** 6.25 times: 66.78 → 417.64 mt DM/yr

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

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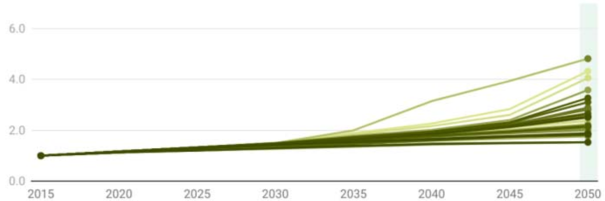
Regional Perspectives – Within Planetary Boundaries?

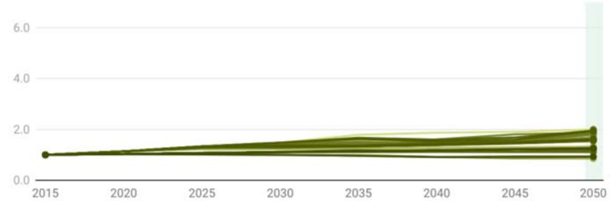
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – Agricultural Demand (million t DM/yr, normalized with 2015 values = 1)

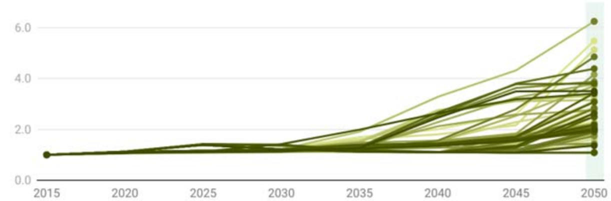
Region 6 – Middle East



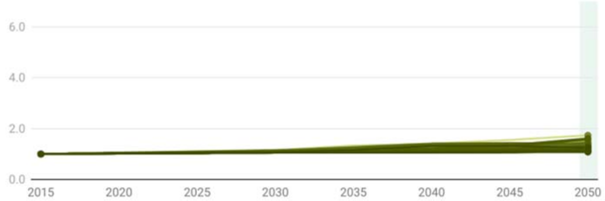
Region 7 – North America



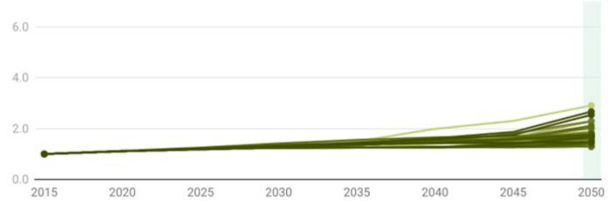
Region 8 – Asia-Pacific Developed (Pacific OECD)



Region 9 – Eastern Europe and West-Central Asia (Ref Econ)



Region 10 – South-East Asia & Developing Pacific (Rest Asia)



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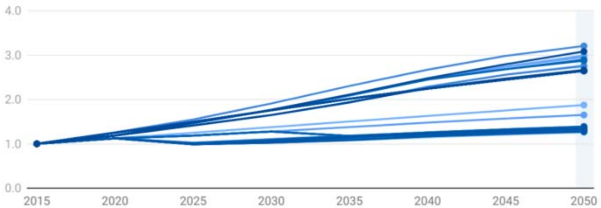
Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

Regional Perspectives – Within Planetary Boundaries?

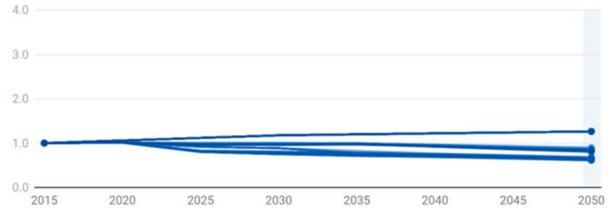
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – Fertilizer Use|Nitrogen (Tg N/yr, normalized with 2015 values = 1)

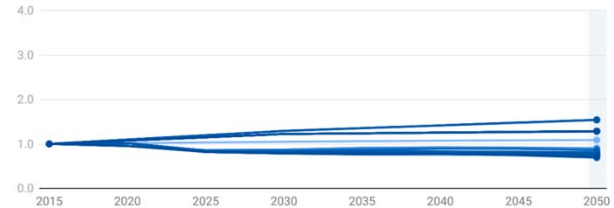
Region 1 – Africa



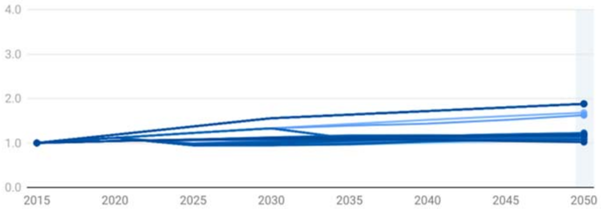
Region 2 – Eastern Asia (China+)



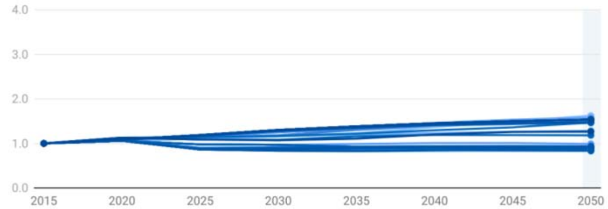
Region 3 – Europe



Region 4 – Southern Asia (India+)



Region 5 – Latin America and Caribbean



Minimum	Average	Maximum
China+ 0.61 times: 29.75 → 18.02 Tg N/yr	Actoss Regions 1.28 times from 2015 values	Africa 3.21 times: 3.32 → 10.65 Tg N/yr

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

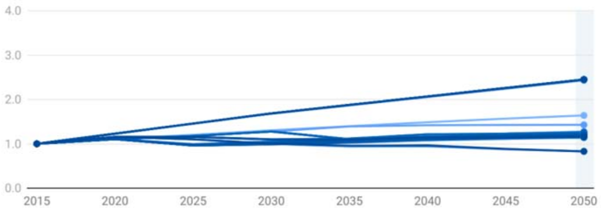
LOCOMOTION

Regional Perspectives – Within Planetary Boundaries?

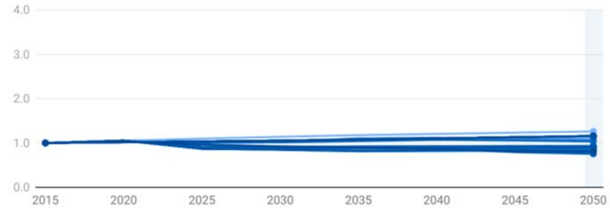
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – Fertilizer Use|Nitrogen (Tg N/yr, normalized with 2015 values = 1)

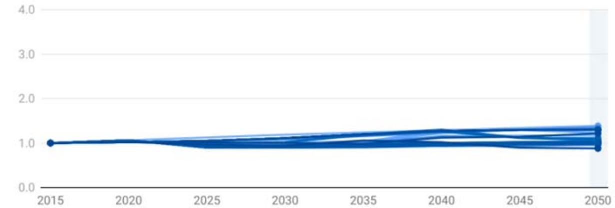
Region 6 – Middle East



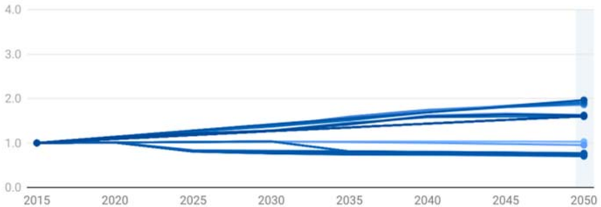
Region 7 – North America



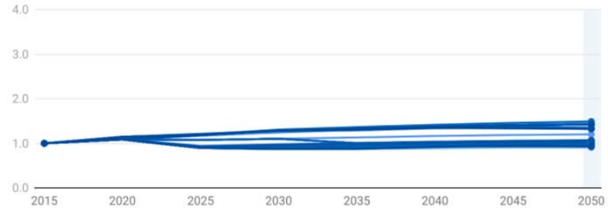
Region 8 – Asia-Pacific Developed (Pacific OECD)



Region 9 – Eastern Europe and West-Central Asia (Ref Econ)



Region 10 – South-East Asia & Developing Pacific (Rest Asia)

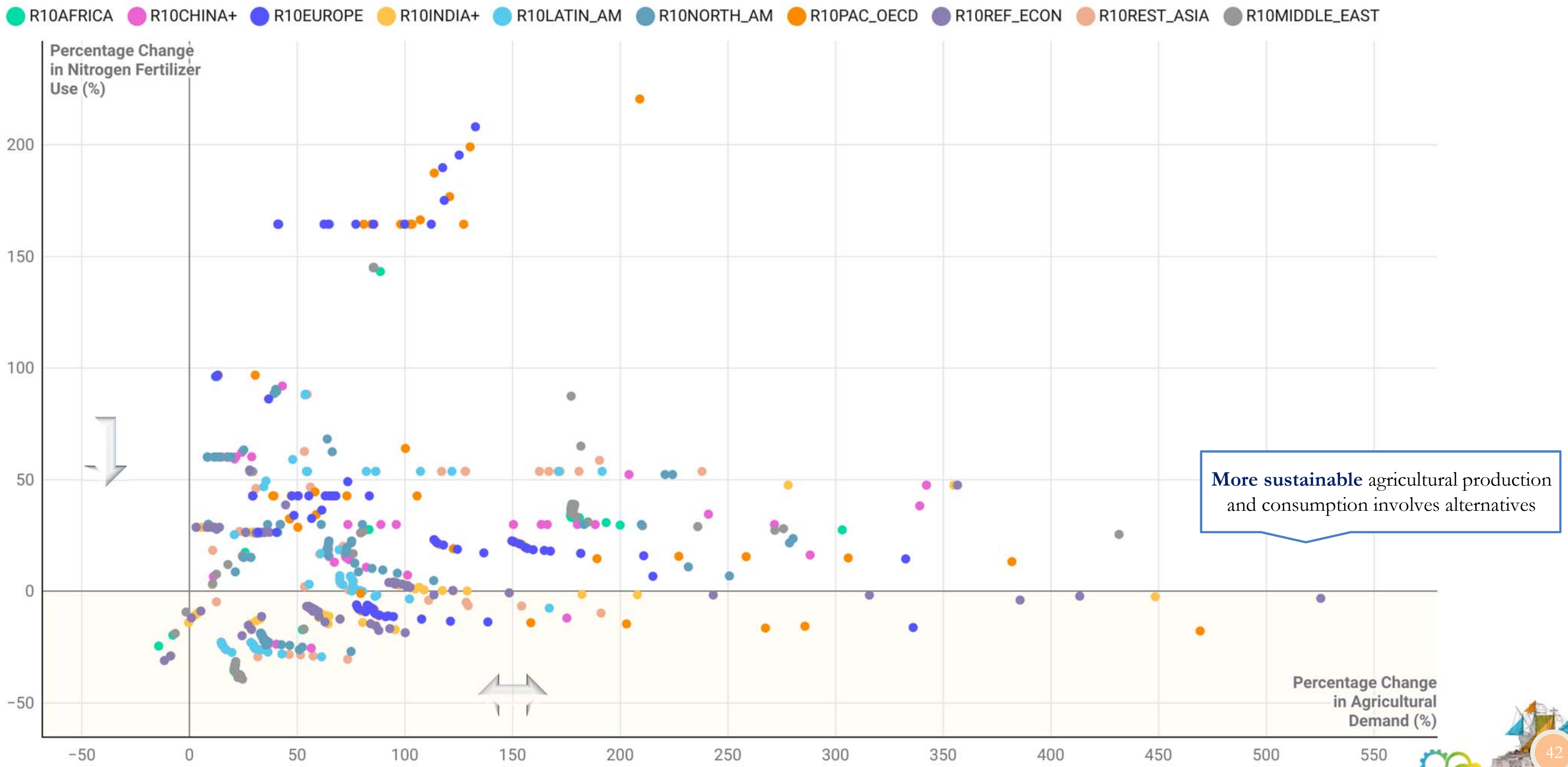


Minimum	Average	Maximum
China+ 0.61 times: 29.75 → 18.02 Tg N/yr	**Actoss Regions** 1.28 times from 2015 values	**Africa** 3.21 times: 3.32 → 10.65 Tg N/yr

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

Cross-Comparison: Fertilizer and Agricultural Demand

Reducing changes in nitrogen fertilizer use while allowing agricultural demand to satisfy food security is crucial



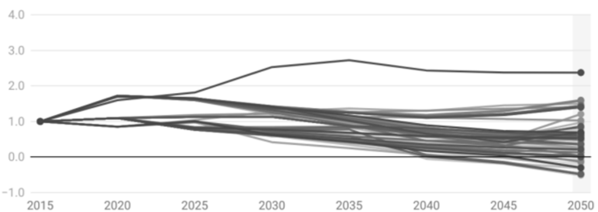
LOCOMOTION

Regional Perspectives – Within Planetary Boundaries?

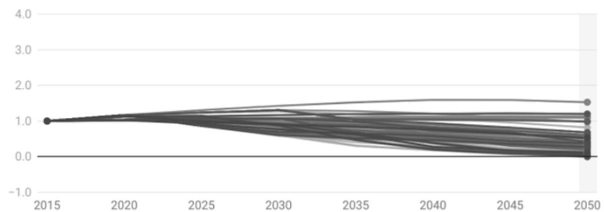
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – <u>CO_2 Emissions in 2050</u> (Mt CO_2/yr, normalized with 2015 values = 1)

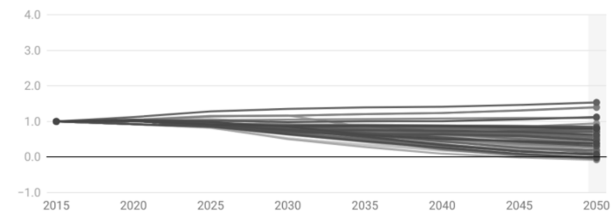
Region 1 – Africa



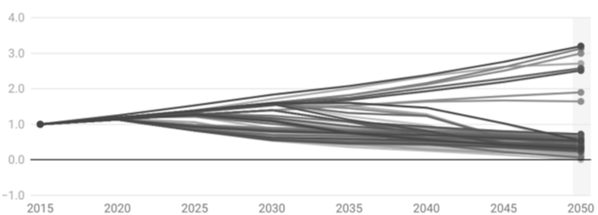
Region 2 – Eastern Asia (China+)



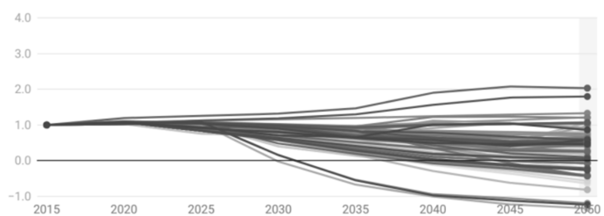
Region 3 – Europe



Region 4 – Southern Asia (India+)



Region 5 – Latin America and Caribbean



Minimum	Average	Maximum
<u>Latin America</u> -1.34 times: 3055 → -4080 Mt CO_2/yr	**Actoss Regions** 0.53 times from 2015 values	**<u>India+</u>** 3.20 times: 2481 → -7933 Mt CO_2/yr

No Policy Scenario

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

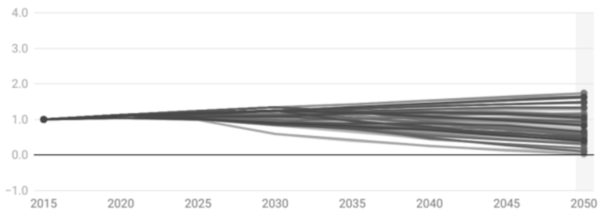
LOCOMOTION

Regional Perspectives – Within Planetary Boundaries?

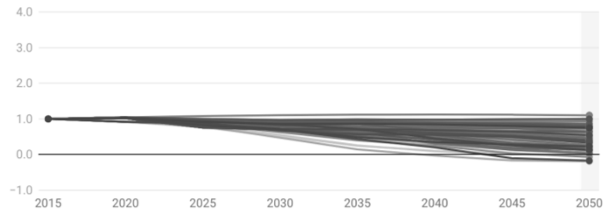
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – <u>CO_2 Emissions in 2050</u> (Mt CO_2/yr, normalized with 2015 values = 1)

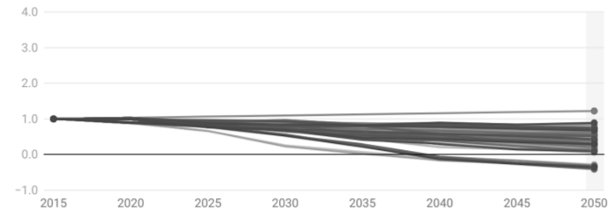
Region 6 – Middle East



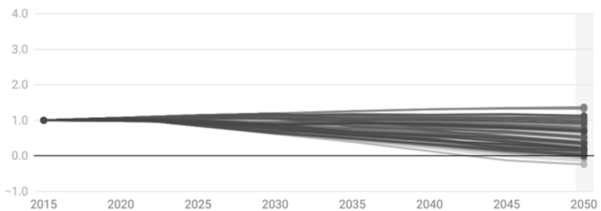
Region 7 – North America



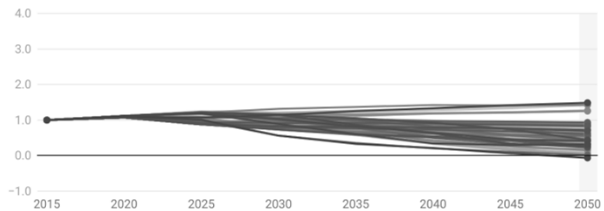
Region 8 – Asia-Pacific Developed (Pacific OECD)



Region 9 – Eastern Europe and West-Central Asia (Ref Econ)



Region 10 – South-East Asia & Developing Pacific (Rest Asia)



Minimum	Average	Maximum
Latin America -1.34 times: 3055 → -4080 Mt CO_2/yr	**<u>Actoss Regions</u>** 0.53 times from 2015 values	**India+** 3.20 times: 2481 → -7933 Mt CO_2/yr

No Policy Scenario

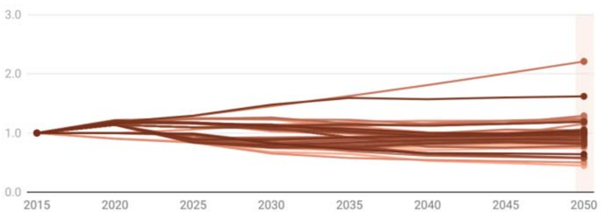
Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

Regional Perspectives – Within Planetary Boundaries?

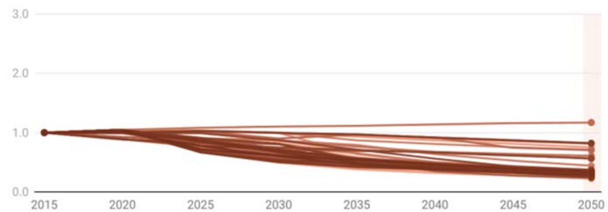
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – <u>CH_4 Emissions in 2050</u> (Mt CH_4/yr, normalized with 2015 values = 1)

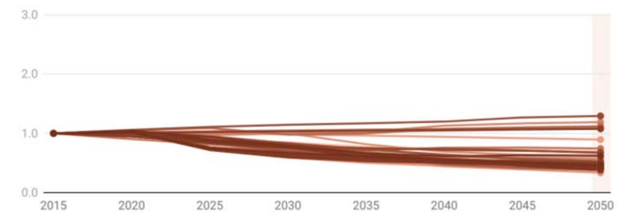
Region 1 – Africa



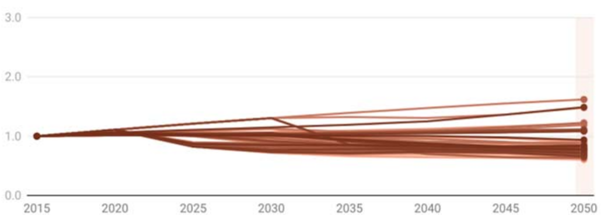
Region 2 – Eastern Asia (China+)



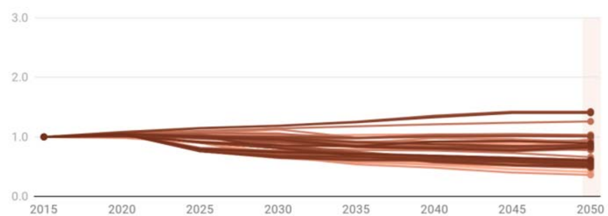
Region 3 – Europe



Region 4 – Southern Asia (India+)



Region 5 – Latin America and Caribbean



Minimum	Average	Maximum
Middle East 0.16 times: 30.07 → 4.86 Mt CH_4/yr	**Actoss Regions** 0.62 times from 2015 values	**<u>Africa</u>** 2.21 times: 50.57 → 111.73 Mt CH_4/yr

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

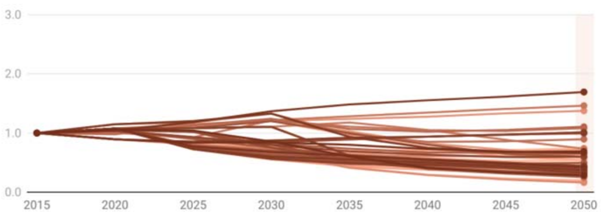
LOCOMOTION

Regional Perspectives – Within Planetary Boundaries?

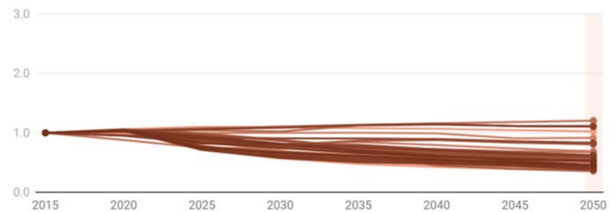
Another crucial aspect is determining whether various trajectories are within the planetary boundaries or not

Selected Indicator – <u>CH_4 Emissions in 2050</u> (Mt CH_4/yr, normalized with 2015 values = 1)

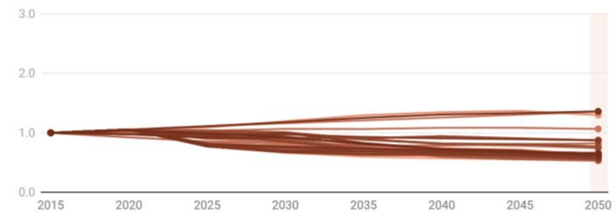
Region 6 – Middle East



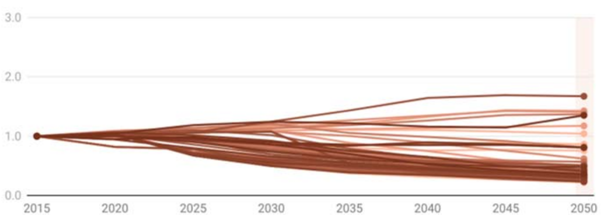
Region 7 – North America



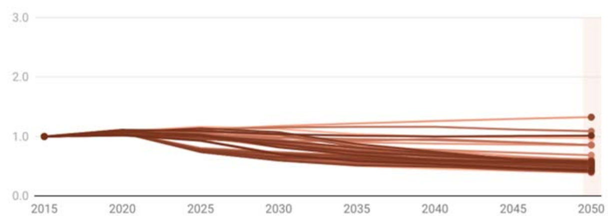
Region 8 – Asia-Pacific Developed (Pacific OECD)



Region 9 – Eastern Europe and West-Central Asia (Ref Econ)



Region 10 – South-East Asia & Developing Pacific (Rest Asia)



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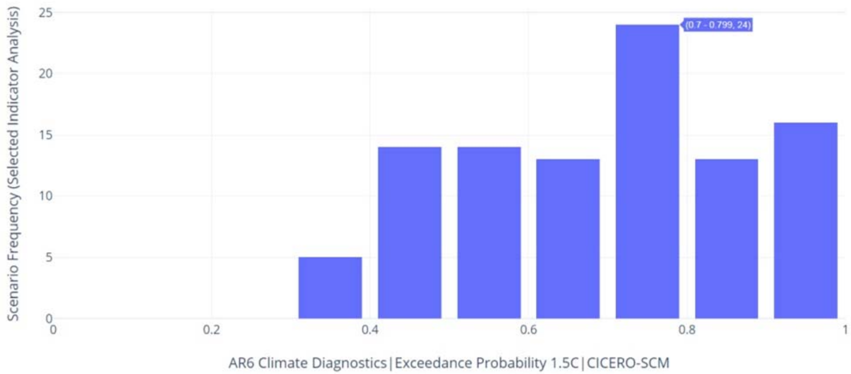
Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

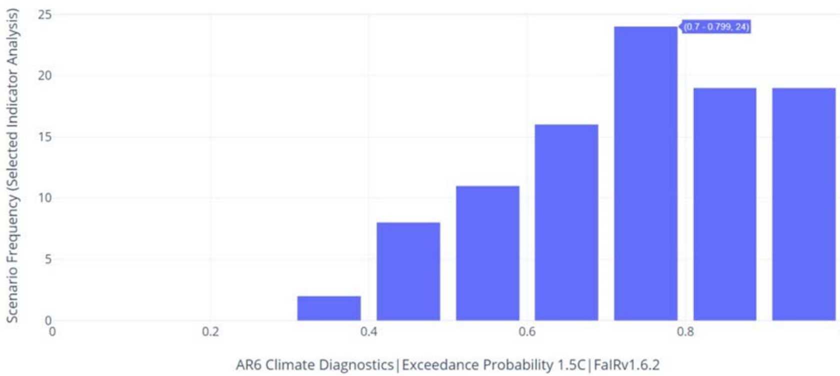
Consequences for the Exceedance Probability of 1.5°C

Some of the scenario inefficiencies are also embedded in the consequence for the probability of exceeding 1.5°C

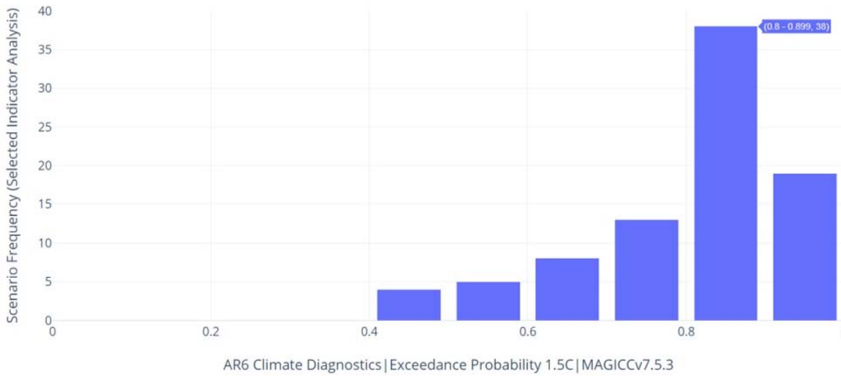
Climate Emulators: Cicero Simple Climate Model (CICERO-SCM)



Finite Amplitude Impulse Response (FaIR) Simple Climate Model



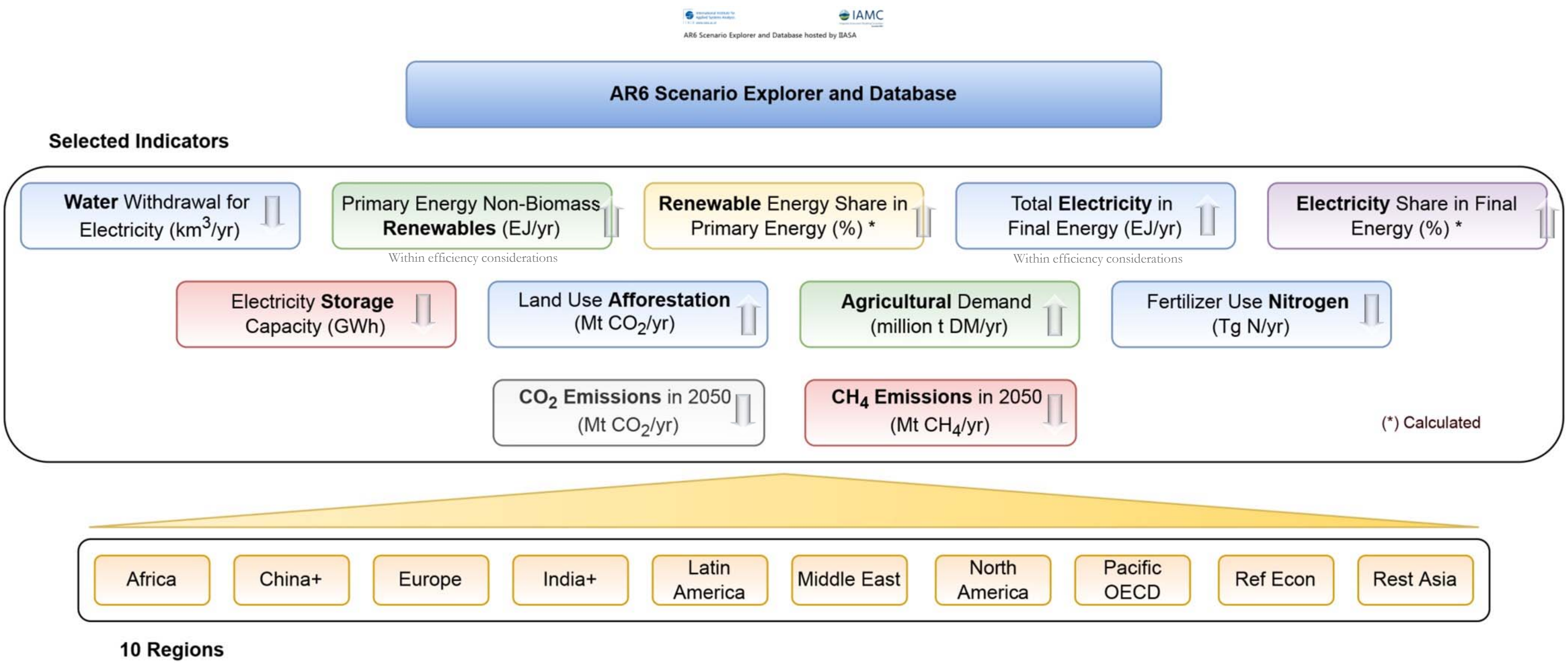
Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC)



Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

Comparison of the Different Scenarios by 10 Regions

Comparing how different outcomes are reached across regions can show additional opportunities for improvement



Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/>

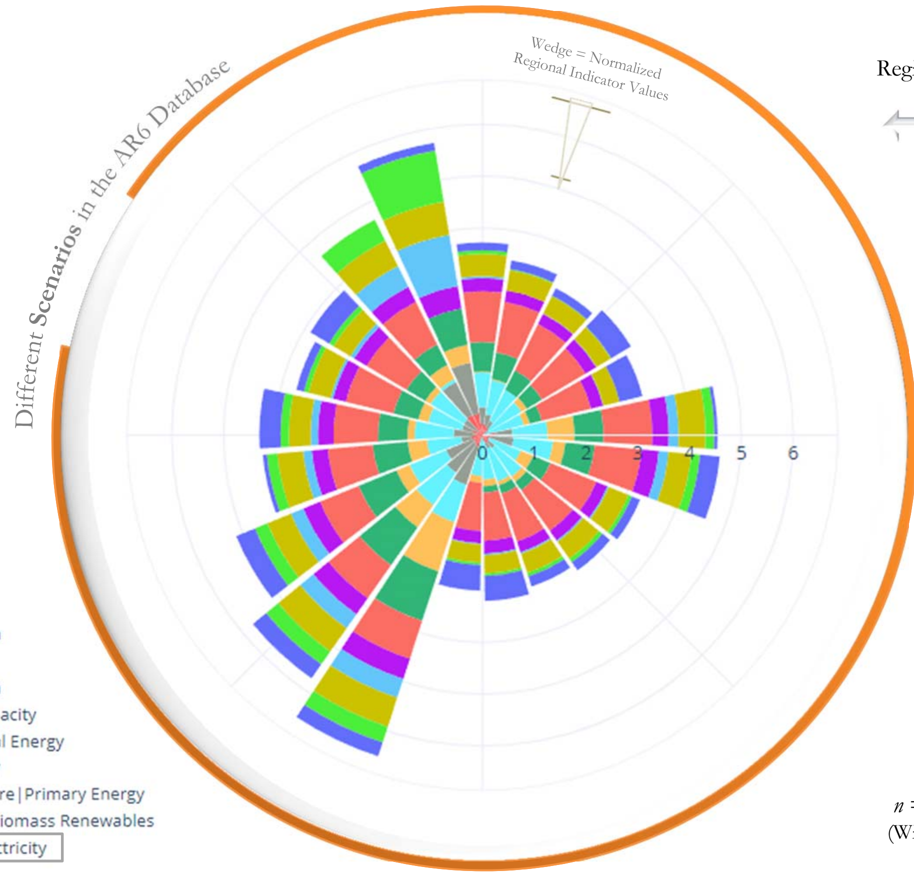
Comparison of the Different Scenarios by 10 Regions

Comparing how different outcomes are reached across regions can show additional opportunities for improvement

Best value
among scenarios

Per indicator
and per region

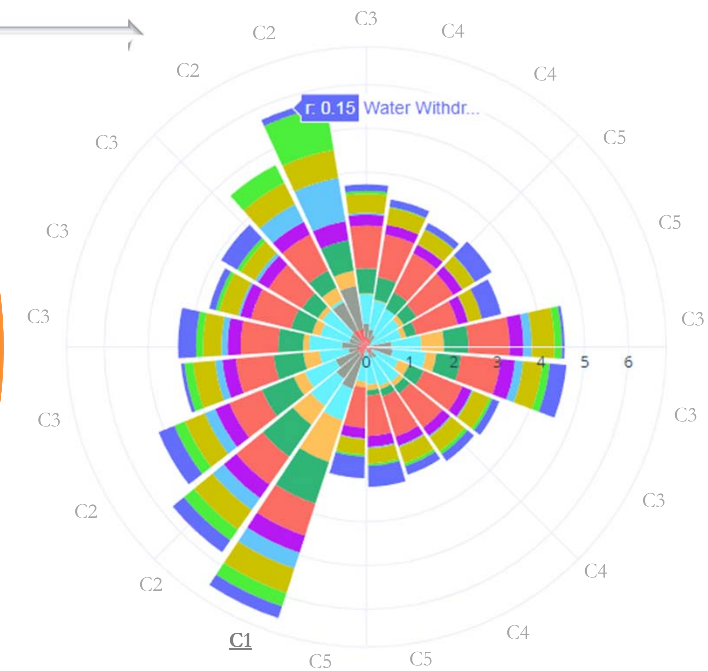
Worst value
among scenarios



Legend

- CH4 Emissions | 2050
- CO2 Emissions | 2050
- Fertilizer Use | Nitrogen
- Agricultural Demand
- Land Use Afforestation
- Electricity | Storage Capacity
- Electricity Share in Final Energy
- Final Energy | Electricity
- Renewable Energy Share | Primary Energy
- Primary Energy | Non-Biomass Renewables
- Water Withdrawal | Electricity

Region 1 – **Africa**



n = 21 scenarios
(With all indicators)

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/> with labelling according to the categories

LOCOMOTION

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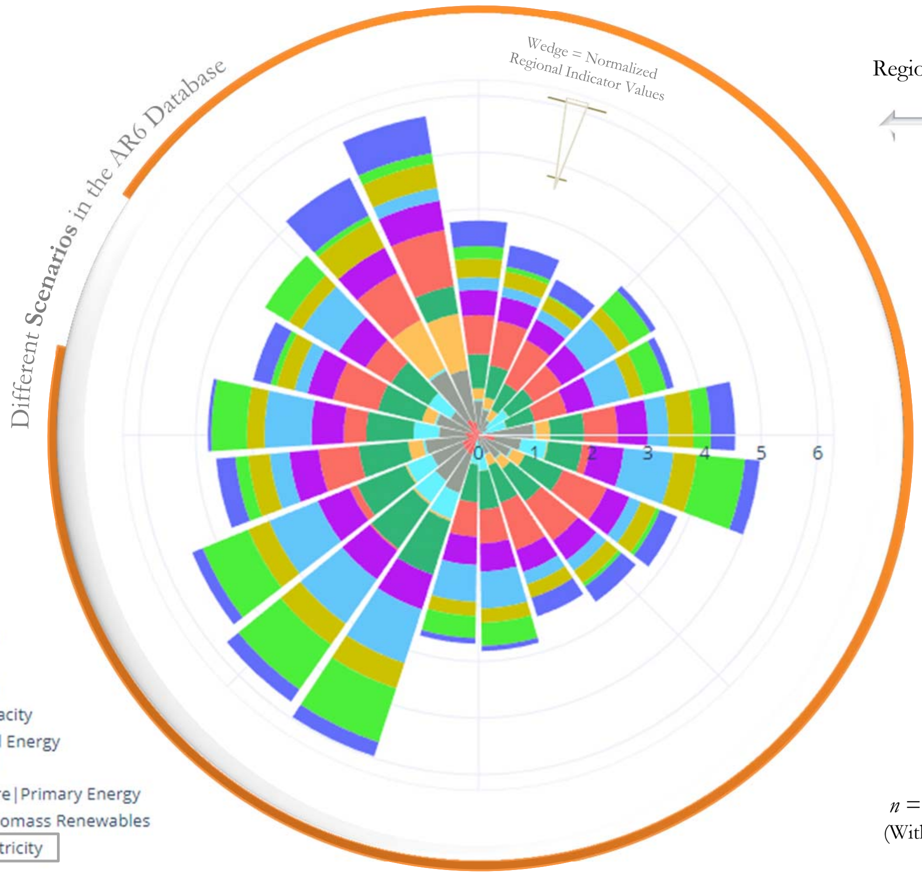

Legend

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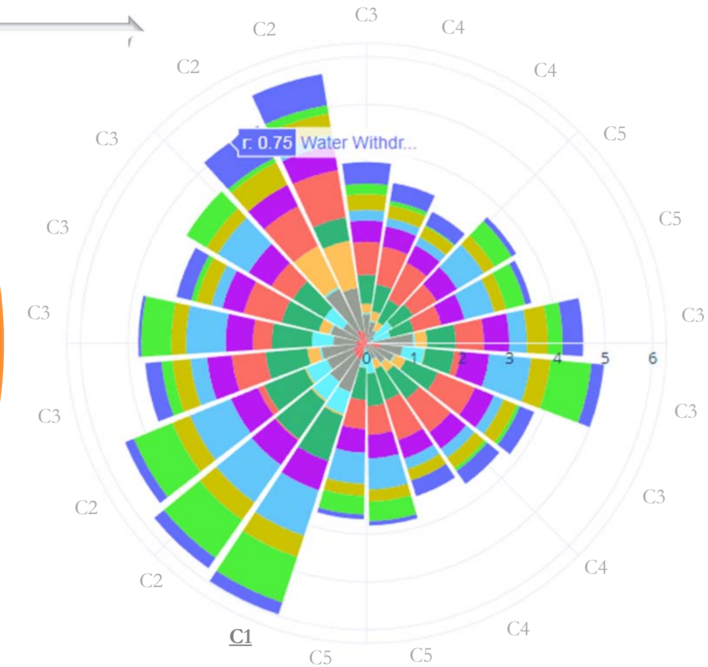
Region 2 – **Eastern Asia (China+)**



n = 21 scenarios
(With all indicators)

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LOCOMOTION

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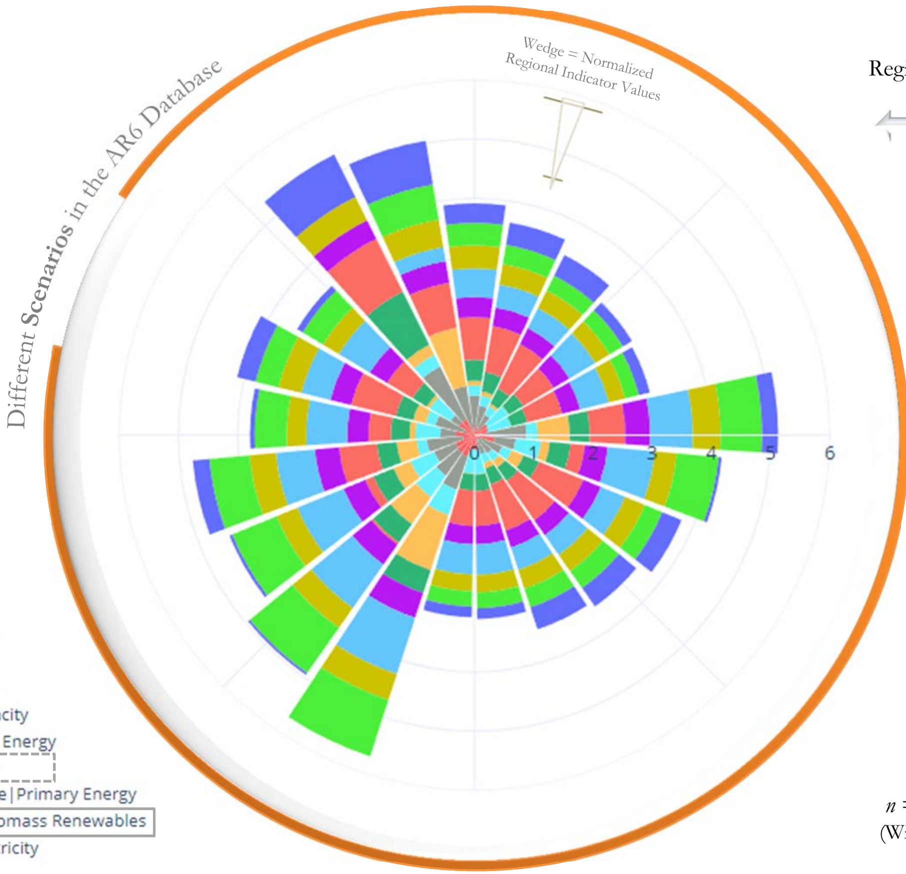
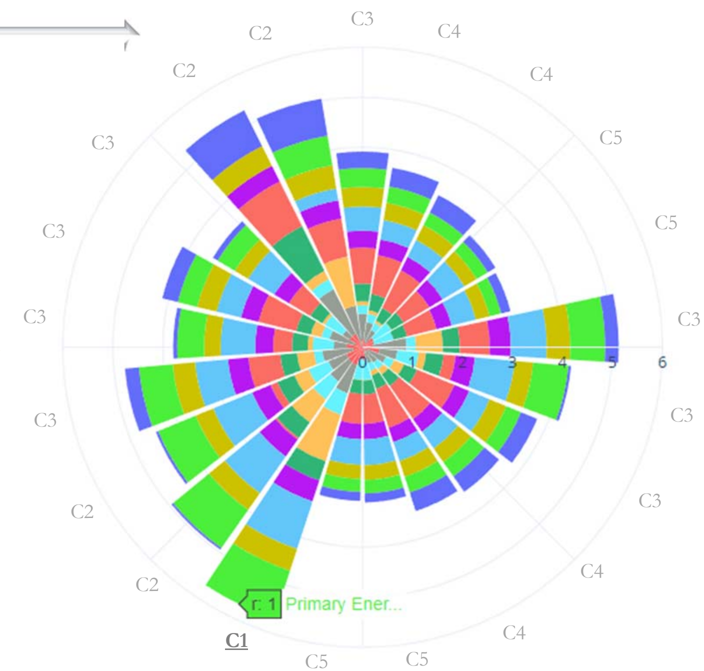


Region 3 – **Europe**



Legend

- CH4 Emissions | 2050
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- Fertilizer Use | Nitrogen
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- Electricity | Storage Capacity
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n = 21 scenarios
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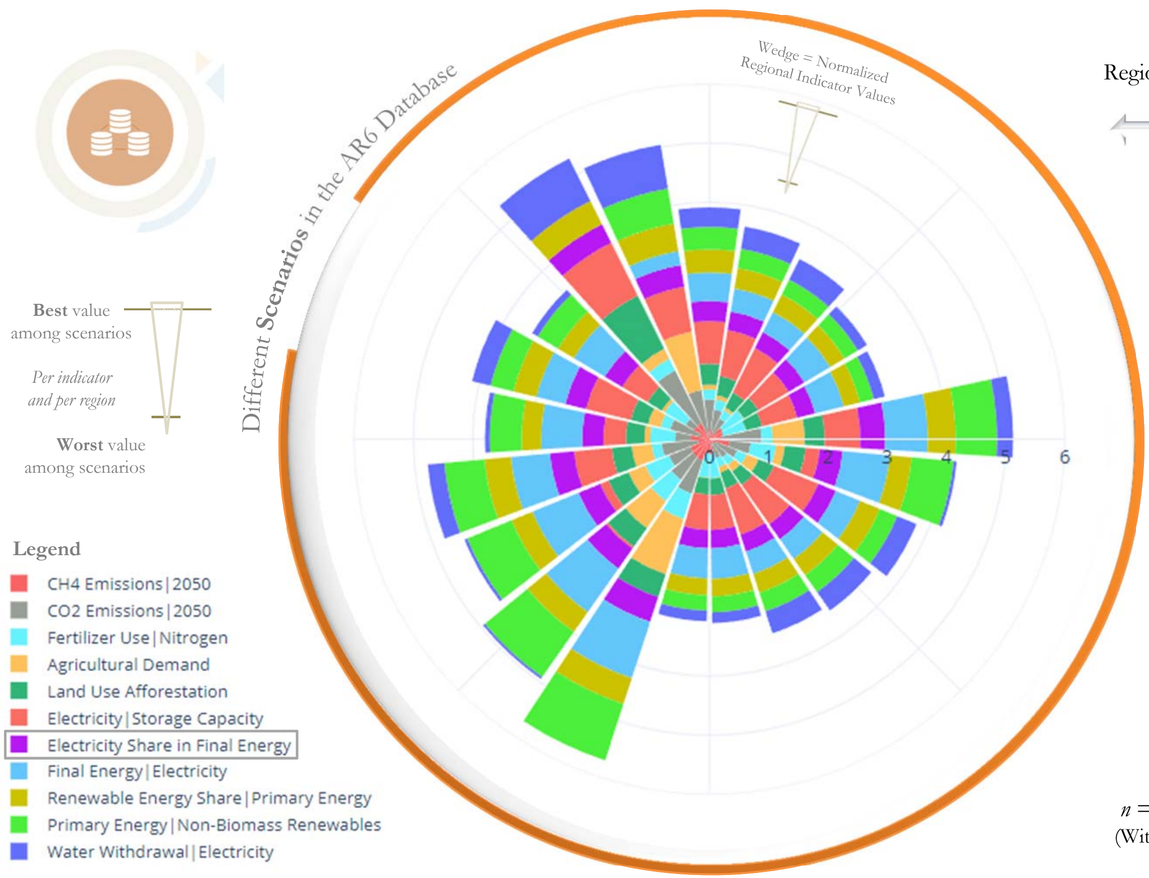

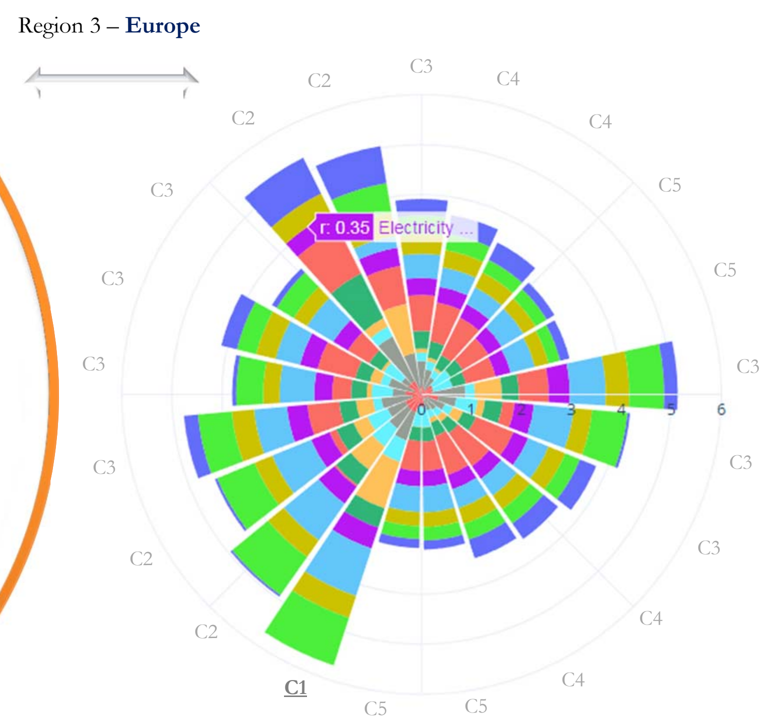

n = 21 scenarios
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LOCOMOTION

Comparison of the Different Scenarios by 10 Regions

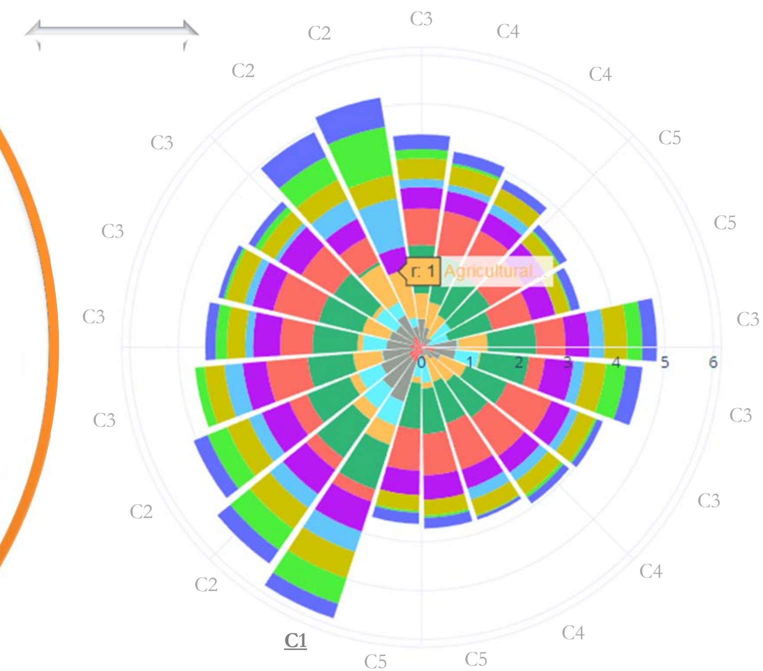
Comparing how different outcomes are reached across regions can show additional opportunities for improvement

Best value
among scenarios

Per indicator
and per region

Worst value
among scenarios

Region 4 – **Southern Asia (India+)**



Legend

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- Electricity Share in Final Energy
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n = 21 scenarios
(With all indicators)

Source: Original analysis for the invited lecture
based on <https://data.ene.iiasa.ac.at/ar6/>
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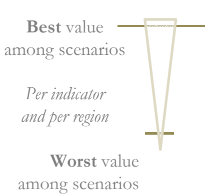
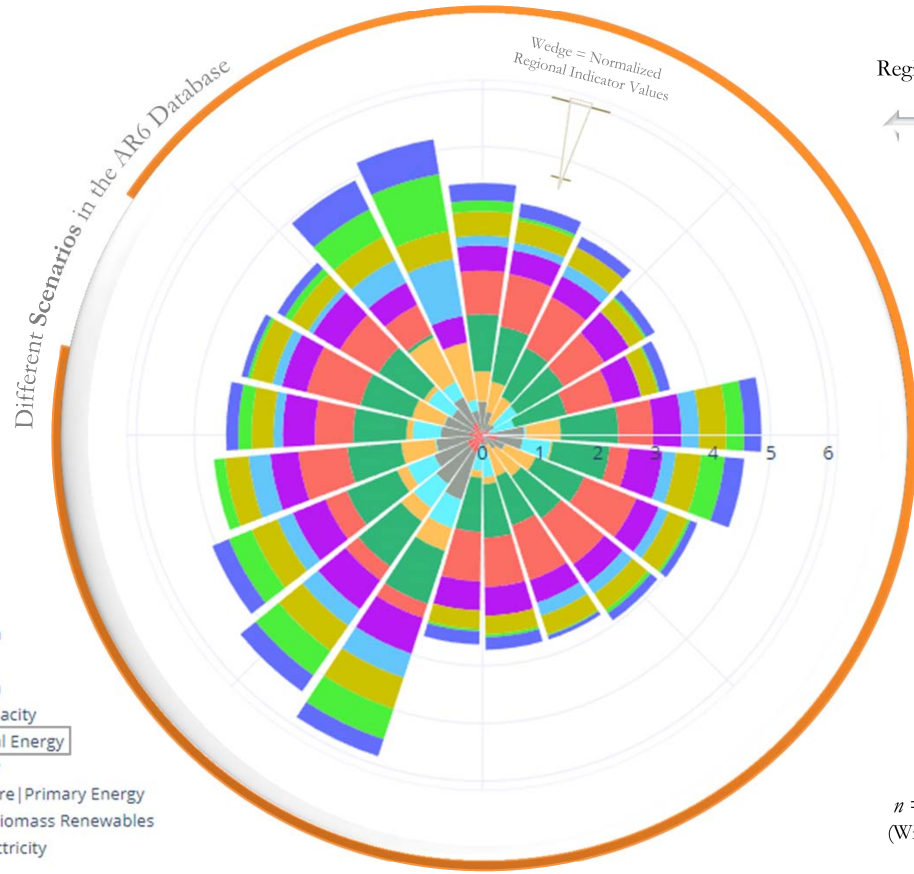
LOCOMOTION

Comparison of the Different Scenarios by 10 Regions

Comparing how different outcomes are reached across regions can show additional opportunities for improvement





Legend

- CH4 Emissions|2050
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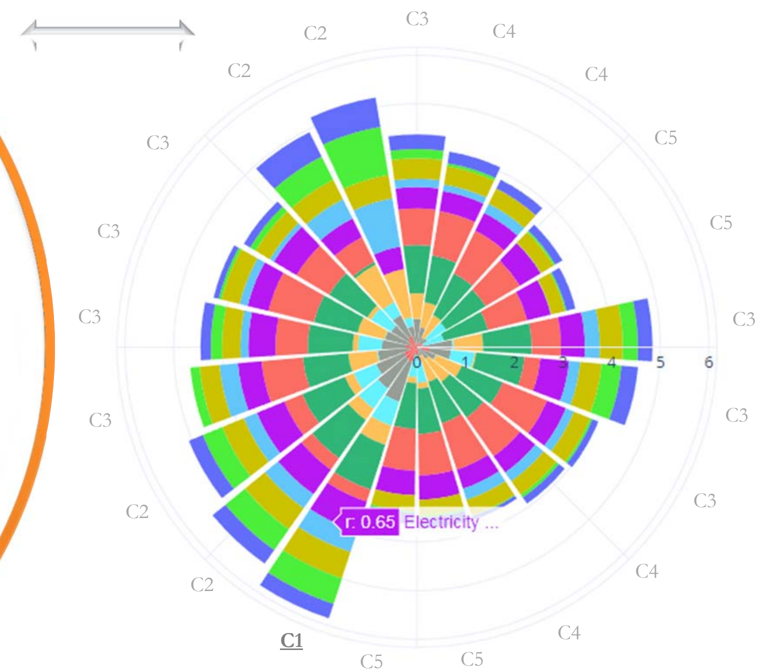
Region 4 – **Southern Asia (India+)**



n = 21 scenarios
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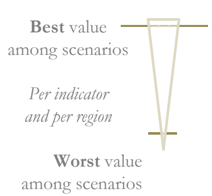
Comparing how different outcomes are reached across regions can show additional opportunities for improvement



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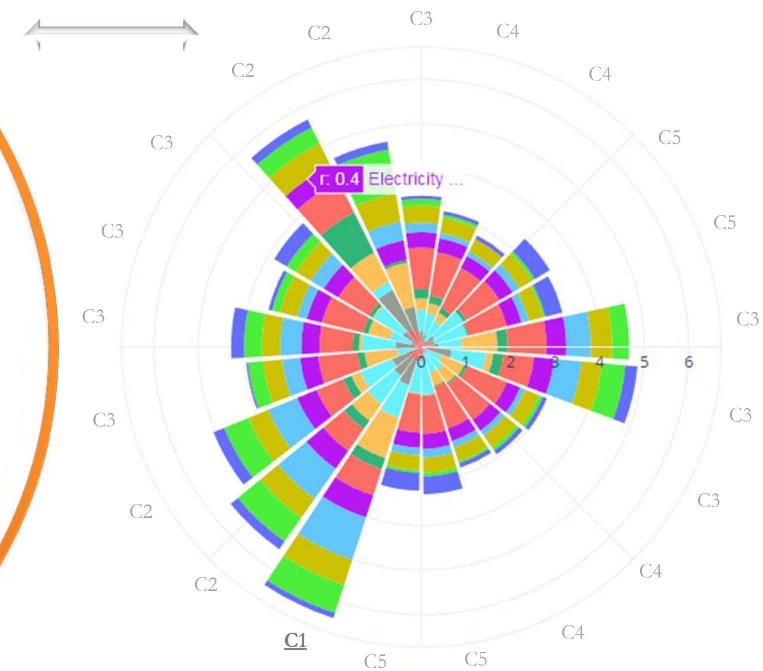
Region 5 – **Latin America and Caribbean**



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(With all indicators)

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LOCOMOTION

Comparison of the Different Scenarios by 10 Regions

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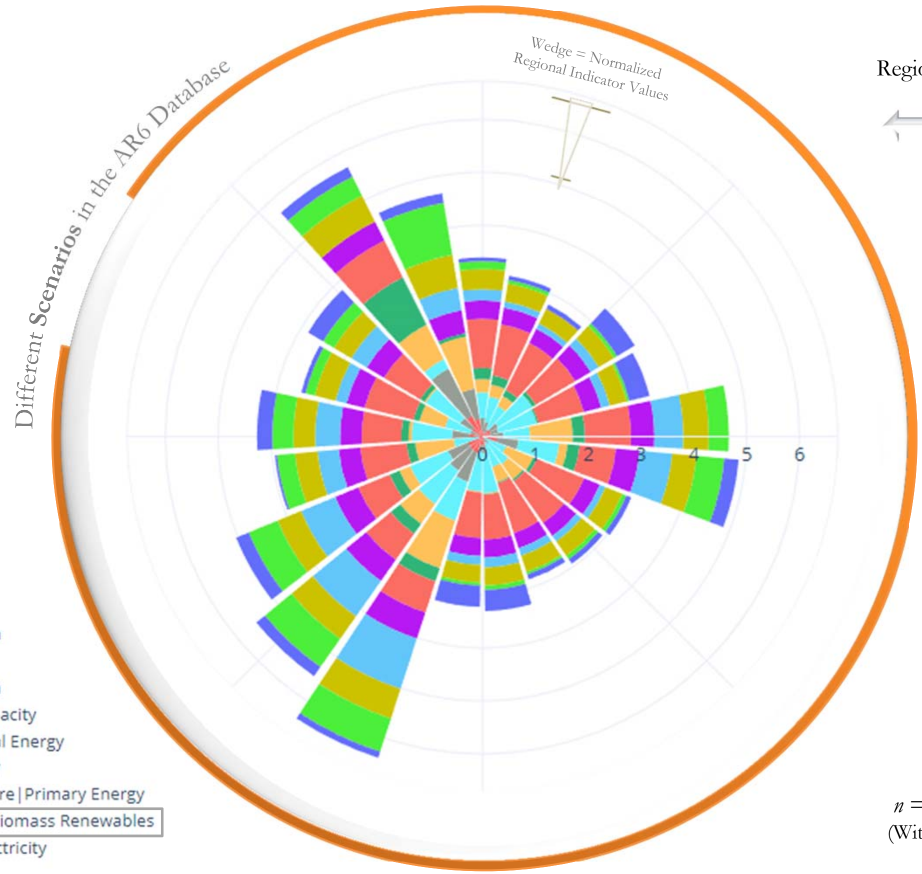

Legend

- CH4 Emissions | 2050
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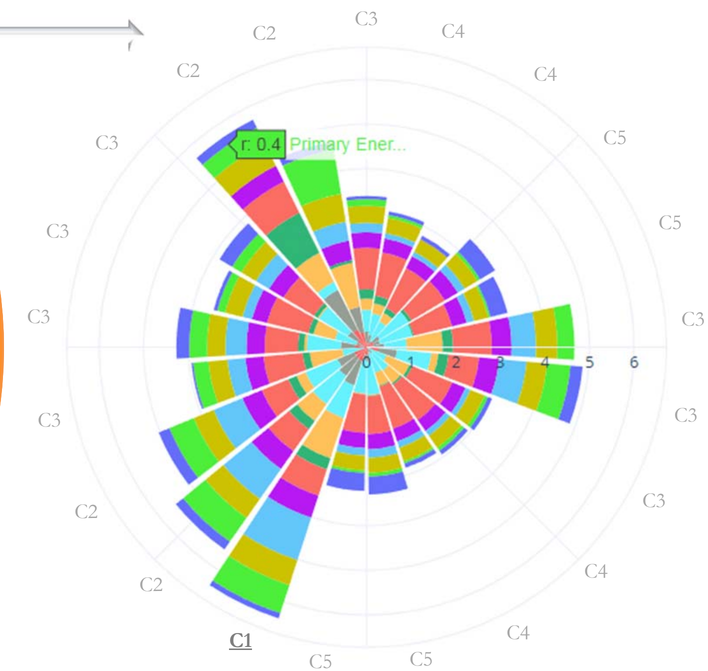
Region 5 – **Latin America and Caribbean**



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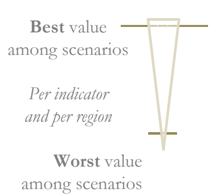
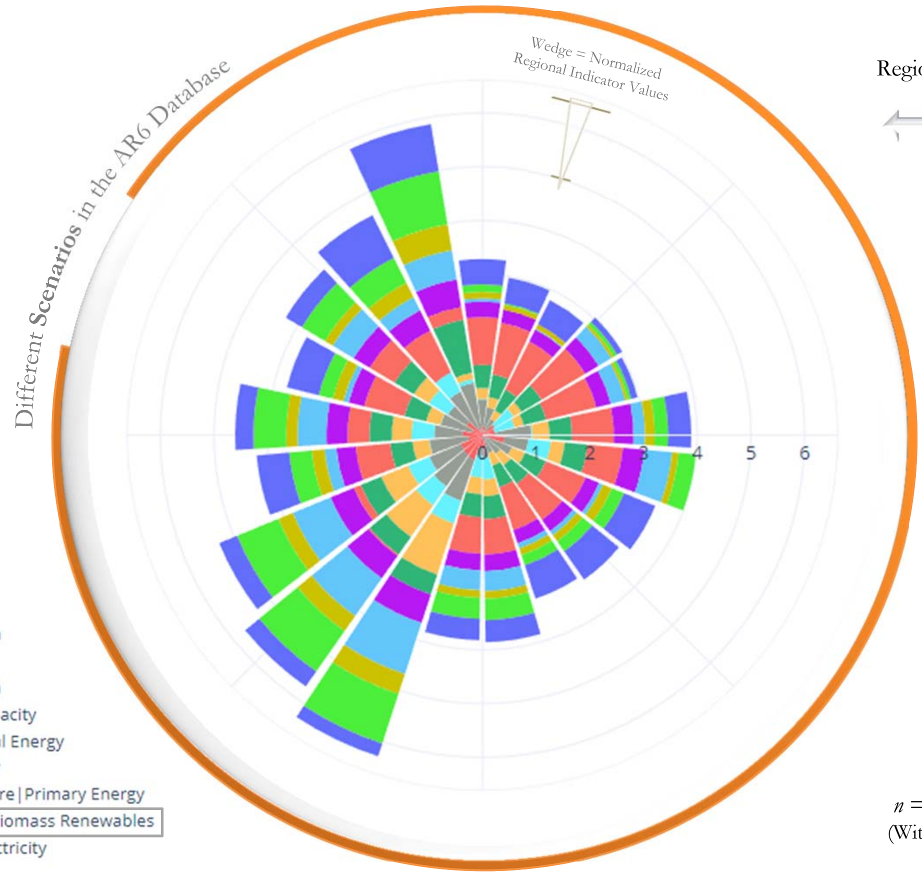
Comparing how different outcomes are reached across regions can show additional opportunities for improvement





Legend

- CH4 Emissions | 2050
- CO2 Emissions | 2050
- Fertilizer Use | Nitrogen
- Agricultural Demand
- Land Use Afforestation
- Electricity | Storage Capacity
- Electricity Share in Final Energy
- Final Energy | Electricity
- Renewable Energy Share | Primary Energy
- Primary Energy | Non-Biomass Renewables
- Water Withdrawal | Electricity

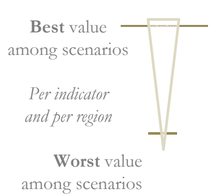
Region 6 – **Middle East**

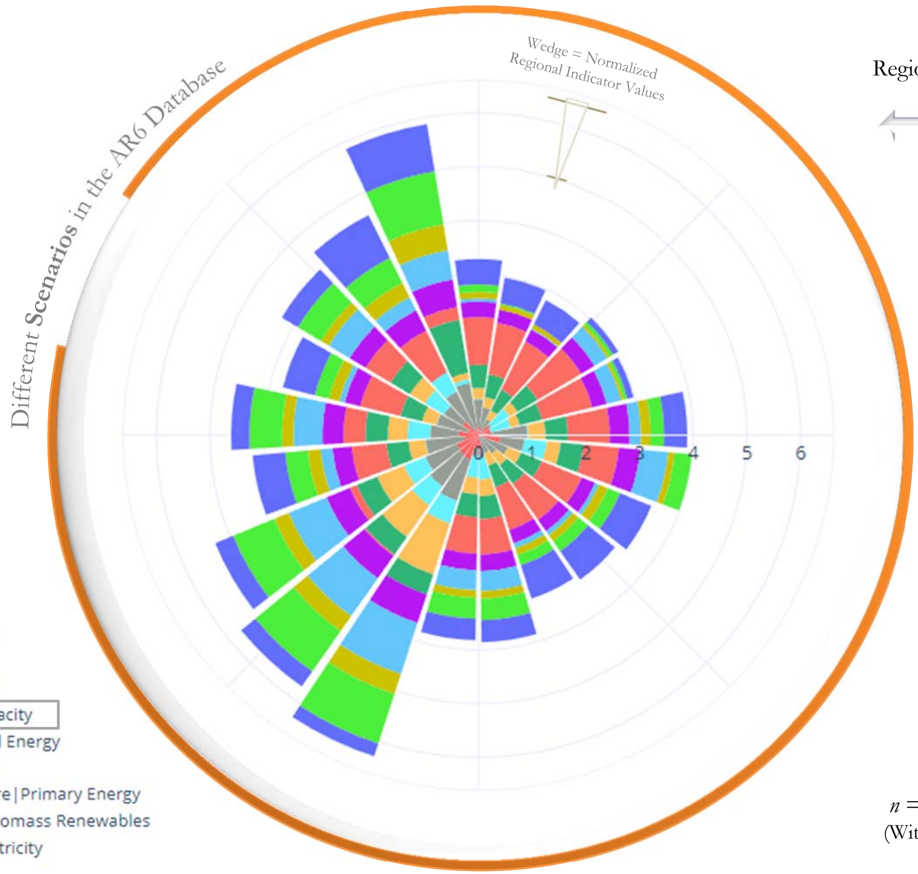
n = 21 scenarios
(With all indicators)

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/> with labelling according to the categories

Comparison of the Different Scenarios by 10 Regions

Comparing how different outcomes are reached across regions can show additional opportunities for improvement





Legend

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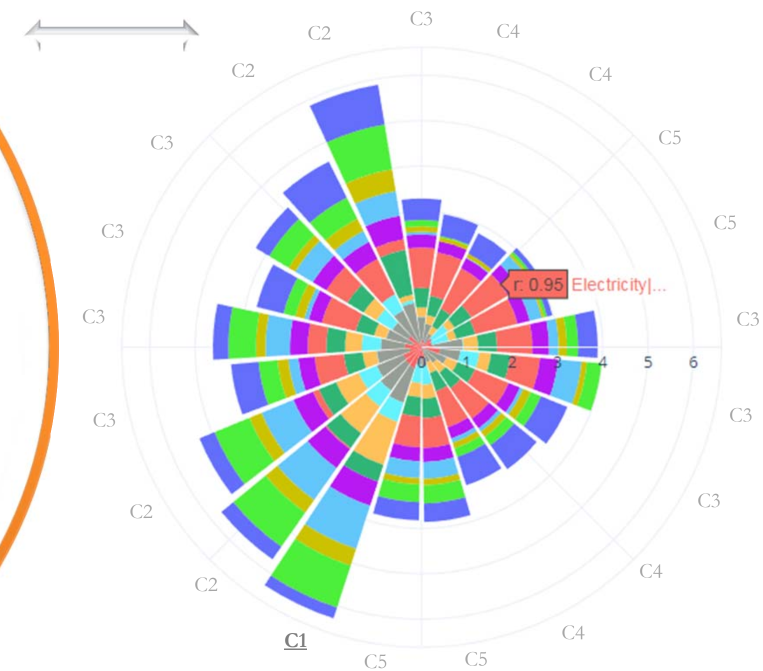
Region 6 – **Middle East**



n = 21 scenarios
(With all indicators)

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/> with labelling according to the categories

Comparison of the Different Scenarios by 10 Regions

Comparing how different outcomes are reached across regions can show additional opportunities for improvement

Best value
among scenarios

*Per indicator
and per region*

Worst value
among scenarios

Legend

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- Fertilizer Use | Nitrogen
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- Electricity | Storage Capacity
- Electricity Share in Final Energy
- Final Energy | Electricity
- Renewable Energy Share | Primary Energy
- Primary Energy | Non-Biomass Renewables
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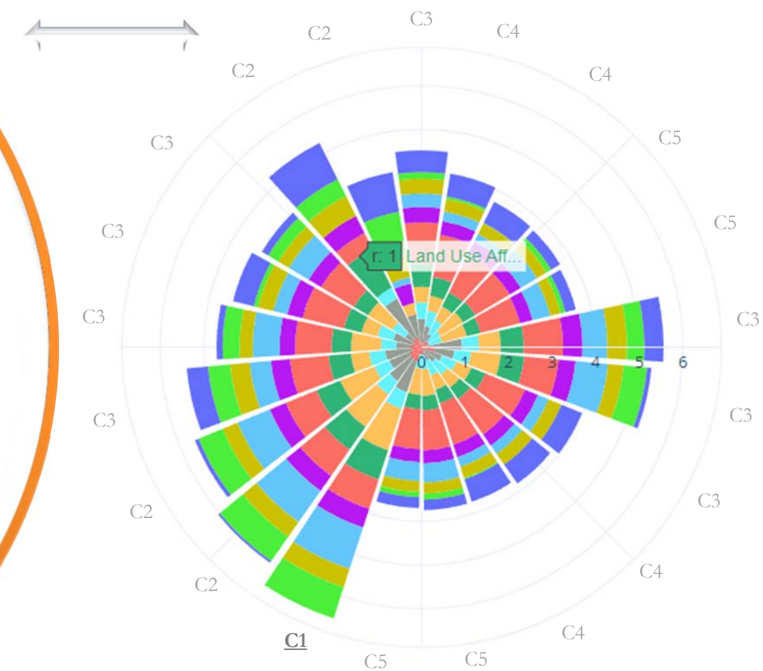
Region 7 – **North America**



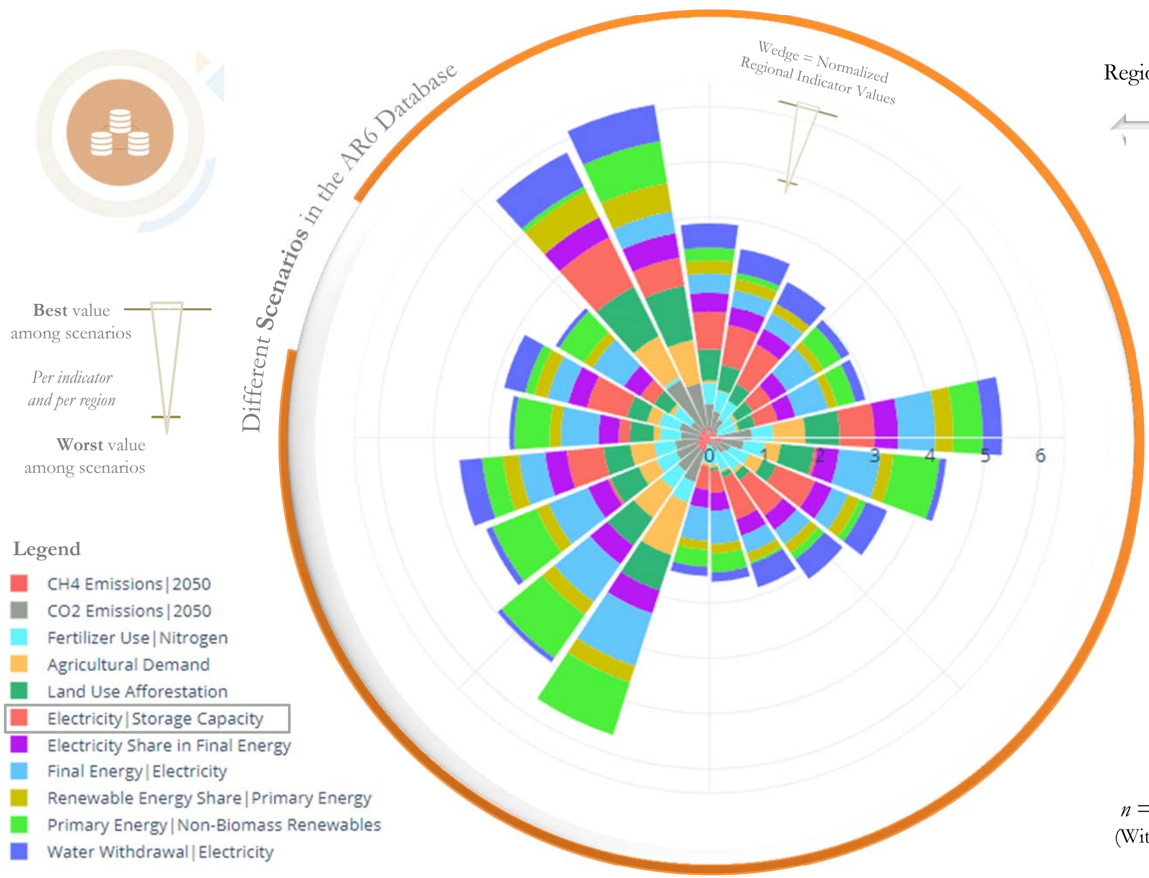
n = 21 scenarios
(With all indicators)

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/> with labelling according to the categories

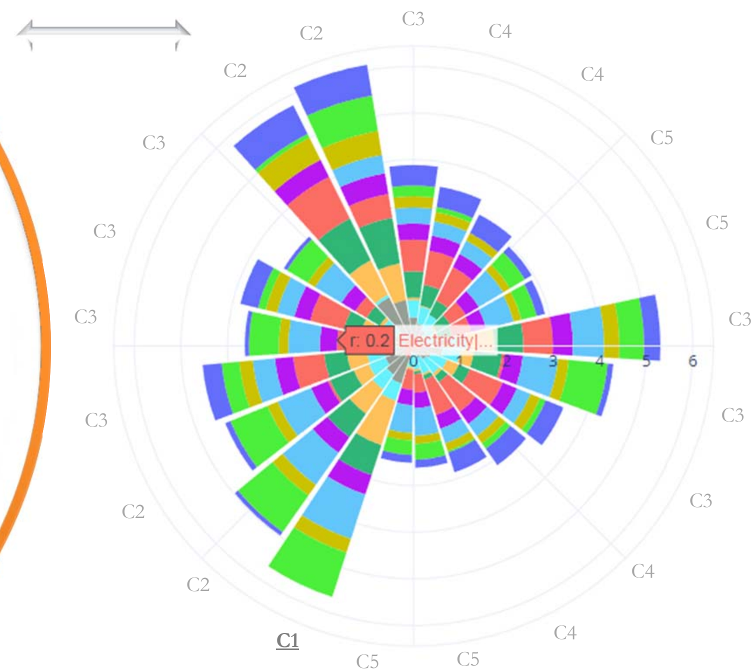
LOCOMOTION

Comparison of the Different Scenarios by 10 Regions

Comparing how different outcomes are reached across regions can show additional opportunities for improvement



Region 8 – **Asia-Pacific Developed**



n = 21 scenarios
(With all indicators)

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/> with labelling according to the categories

Comparison of the Different Scenarios by 10 Regions

Comparing how different outcomes are reached across regions can show additional opportunities for improvement

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among scenarios

Per indicator
and per region

Worst value
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Legend

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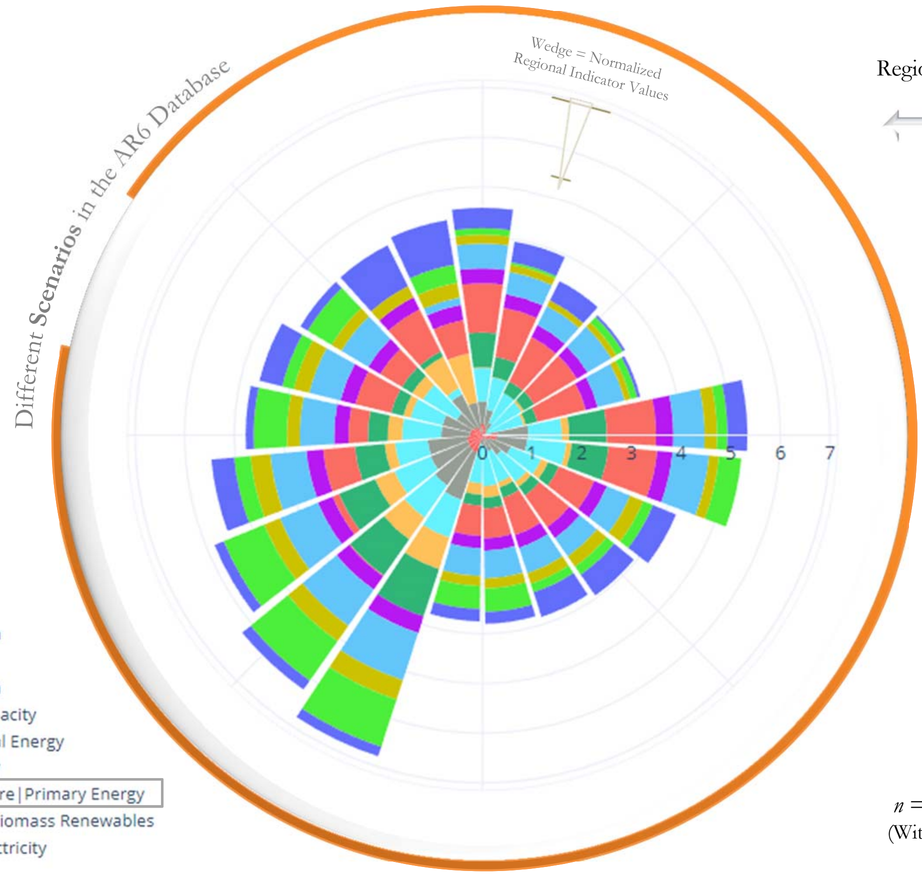
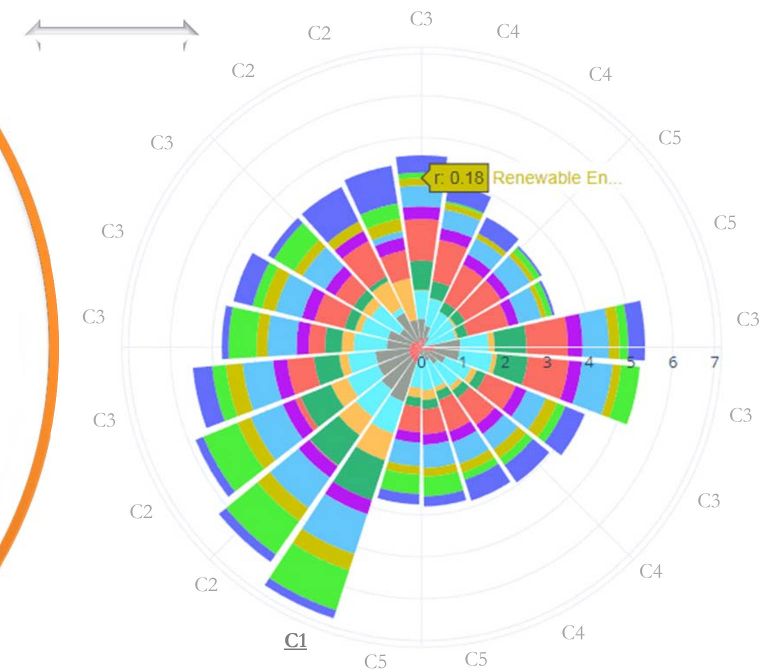


Region 9 – **Eastern Europe and West-Central Asia**



n = 21 scenarios
(With all indicators)

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/> with labelling according to the categories

Comparison of the Different Scenarios by 10 Regions

Comparing how different outcomes are reached across regions can show additional opportunities for improvement

Best value
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*Per indicator
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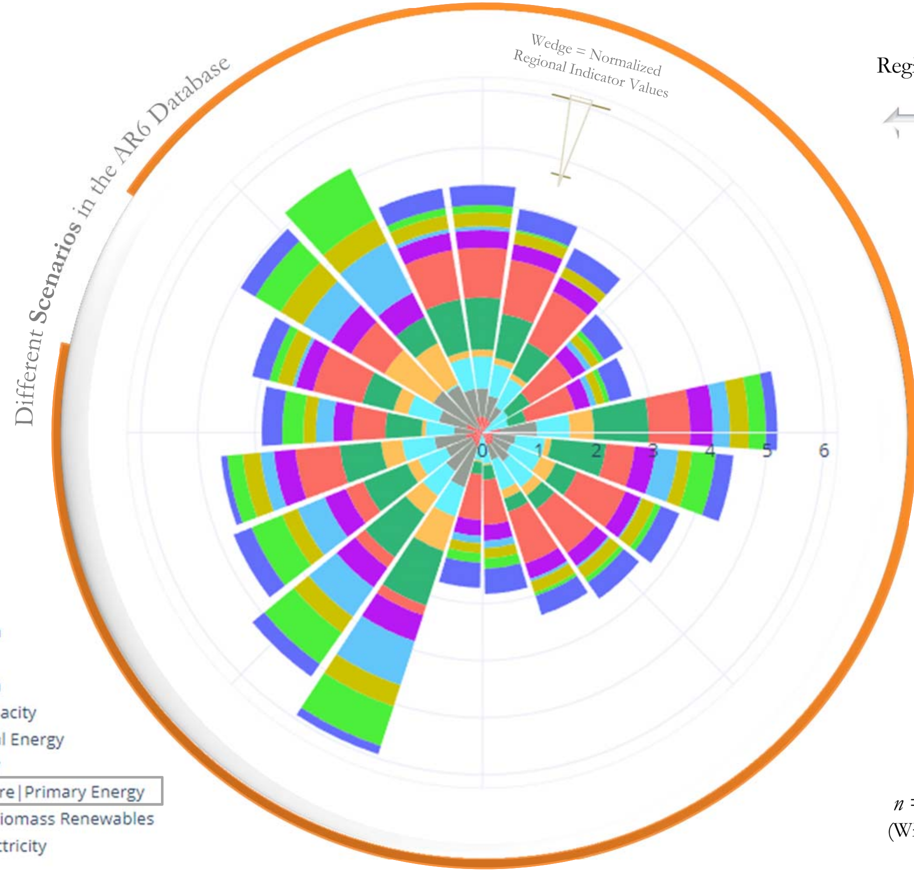
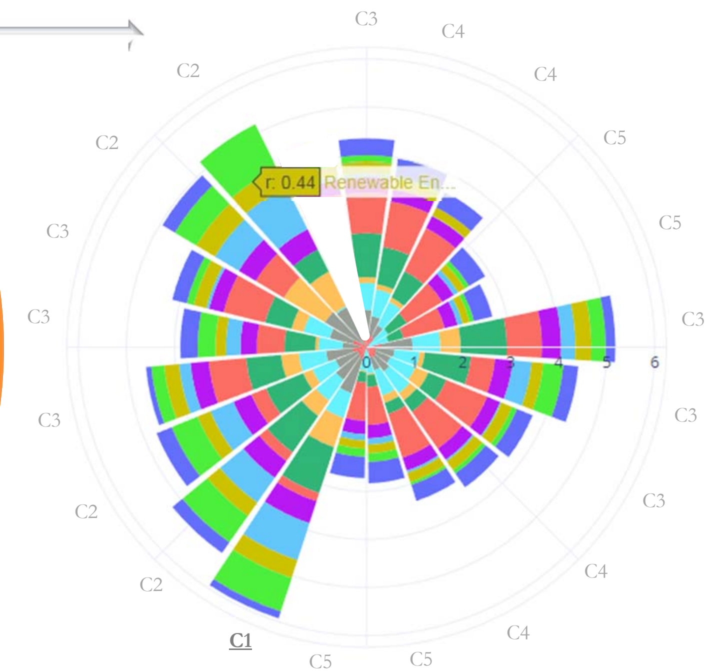


Region 10 – **South-East Asia and Developing Pacific**



Legend

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- Final Energy | Electricity
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- Primary Energy | Non-Biomass Renewables
- Water Withdrawal | Electricity

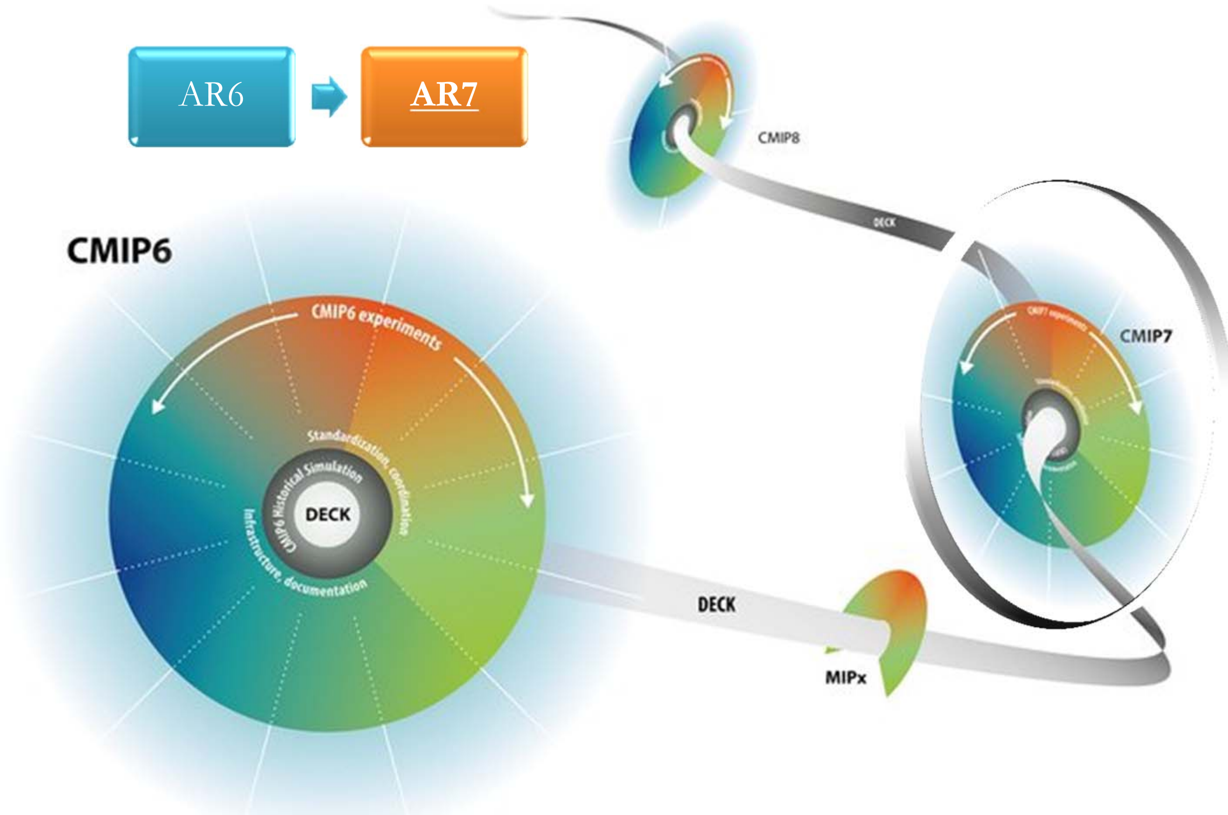
n = 20 scenarios
(With all indicators)

Source: Original analysis for the invited lecture based on <https://data.ene.iiasa.ac.at/ar6/> with labelling according to the categories

LOCOMOTION

Possible Priorities for Models and Scenarios for AR7

Possible priorities for models/scenarios interacting with the next Coupled Model Intercomparison Project (CMIP7)



Possible Priorities

1. Ensuring **Cross-Sectoral Integration** in Modelling
2. Utilizing More **Granular Inputs** Across Systems
3. Being Explicit on the **Urban Share of Emissions**
4. Better Linking Scenarios with Various **Co-Benefits**
5. Comparability with the **Earth System Boundaries**

Picture Source: The Evolution Of Climate Modelling <https://climate.esa.int/de/neuigkeiten-und-veranstaltungen/cmip-the-evolution-of-climate-modelling/>

1) Ensuring Cross-Sectoral Integration in Modelling

Cross-sectoral integration in modelling will increase energy system flexibility for 100% renewable energy systems

Model	Coverage	Methodological Approach	Resolution
Dispa-SET	Power and heat sectors	Optimization (MIP)	Hourly
LUT Energy System Transition Model	**Energy sector**	**Optimization (LP)**	**Hourly**
EnergyPlan	**Energy sector**	**Simulation**	**Hourly**
H2RES	**Energy sector**	**Optimization (LP)**	**Hourly/Multi-Year Investment**
ETSAP-TIAM	Energy sector and links	IAM optimization (LP)/partial equilibrium	Yearly (seasonal time slices)
GCAM	Energy sector and links	IAM/partial equilibrium	Yearly (5 years)
HOMER	Power sector	Simulation	Minutes
LEAP	Energy sector	Simulation	Yearly
MARKAL	Energy sector	IAM/optimization (LP)	Yearly (seasonal time slices)
MESSAGE	Energy sector	IAM/optimization (LP)	Yearly (5 years)
NEMS	Energy sector	Optimization (LP)/partial equilibrium	Yearly
OSeMOSYS	**Energy sector**	**Optimization (LP)**	**Hourly (time slices)**
PLEXOS	Power sector	Optimization (MIP)	Minutes to Hourly
DIETER	Power sector (integration with P2Heat and EV)	Optimization (LP)	Hourly
GenX	Power sector (alternatively heat sector)	Optimization (MIP)	Flexible degree of resolution
REMix	Power sector (alternatively heat, H2, others)	Optimization (LP)	Hourly
PyPSA-Eur-Sec-30	**Energy sector**	**Optimization (MIP)**	**Hourly (single year)**
PRIMES	Energy sector	Optimization (LP - EPEC)/partial equilibrium	Yearly
ReEDS	Power sector	Optimization	Hourly (time slices)
ReMIND	Energy sector and links	IAM	Yearly (5–10 years)
TIMES	Energy sector and links	IAM	Yearly (time slices)
WITCH	Energy sector and links	IAM	Yearly (5 years)
SWITCH	Power sector	Optimization (MIP)	Hourly Dispatch/Decadal Investment

Source: Feijoo, Pfeifer, Herc, Groppi, Duić (2022), A long-term capacity investment and operational energy planning model with power-to-X and flexibility technologies, *Renewable and Sustainable Energy Reviews* 167: 112781

LOCOMOTION

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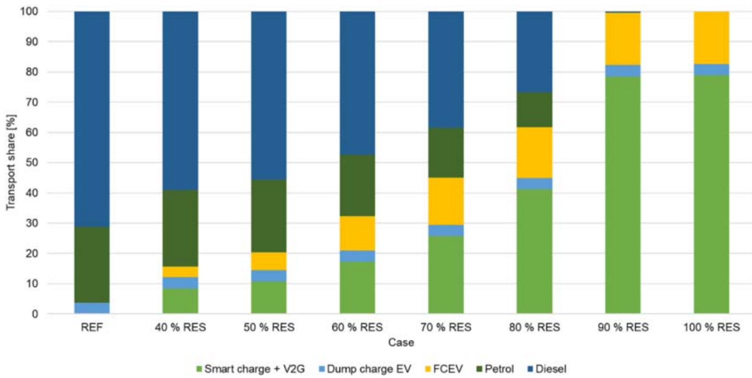
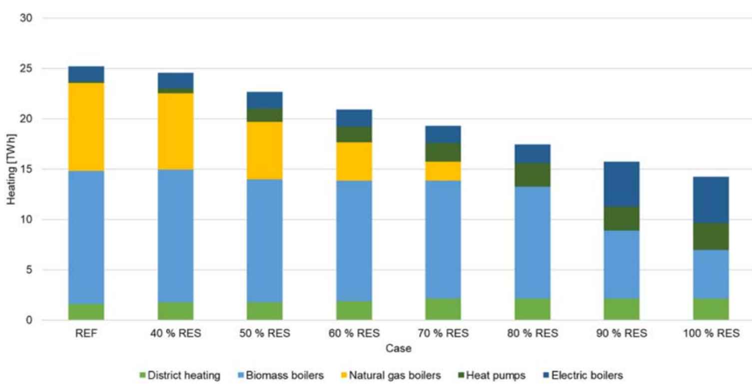
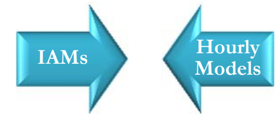
Cross-sectoral integration in modelling will increase energy system flexibility for 100% renewable energy systems

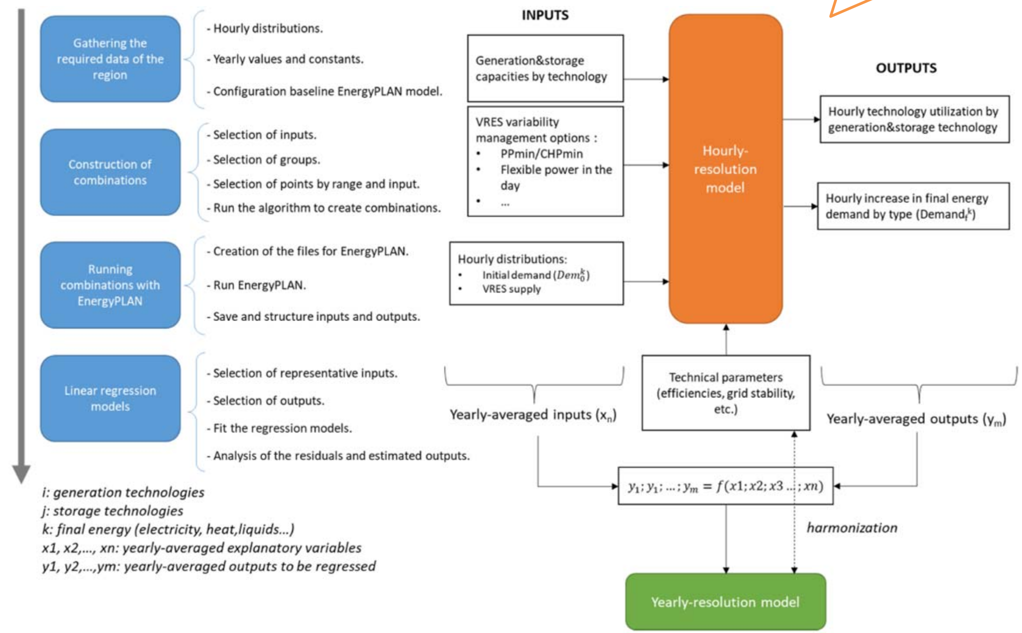




Source: Herc, Pfeifer, Duić (2022), Optimization of the possible pathways for gradual energy system decarbonization, *Renewable Energy* 193: 617-633



New generation of IAMs require **hourly modelling integration**

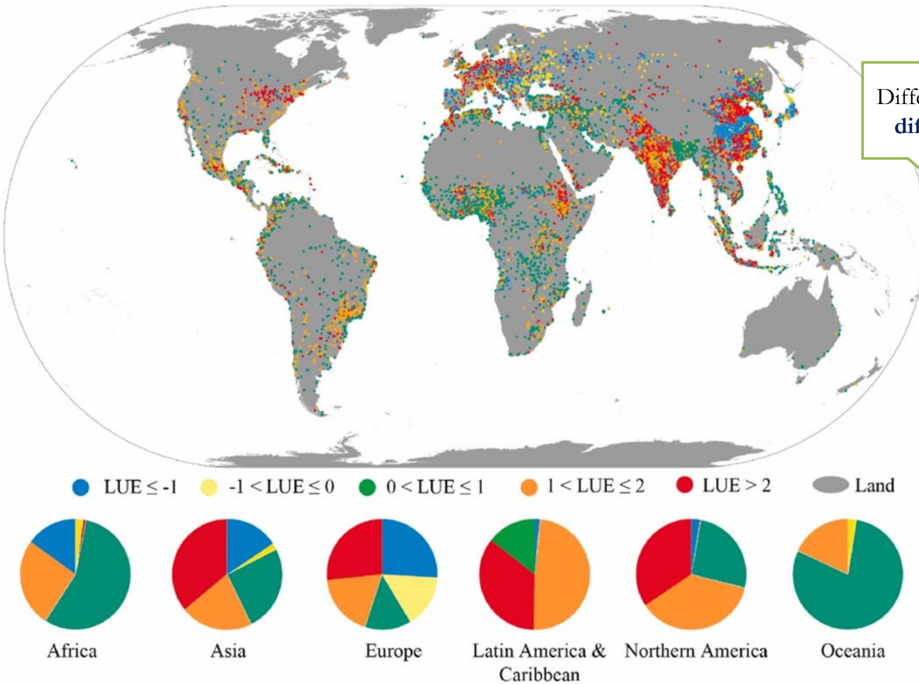


Source: Parrado-Hernando et al. (2022), Capturing features of hourly-resolution energy models through statistical annual indicators, *Renewable Energy*

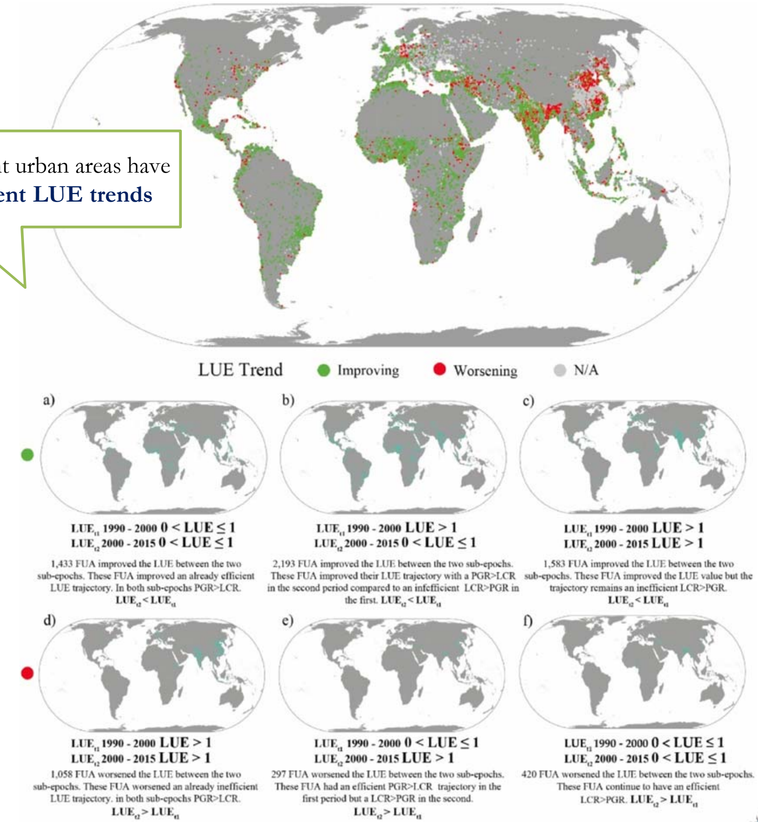
LOCOMOTION

2) Utilizing More Granular Inputs Across Systems

More granular inputs related to land, water and socio-ecological systems will increase the applicability of scenarios



Different urban areas have **different LUE trends**



Source: Schiavina et al. (2022), Land use efficiency of functional urban areas: Global pattern and evolution of development trajectories, *Habitat International* 123: 102543

LOCOMOTION

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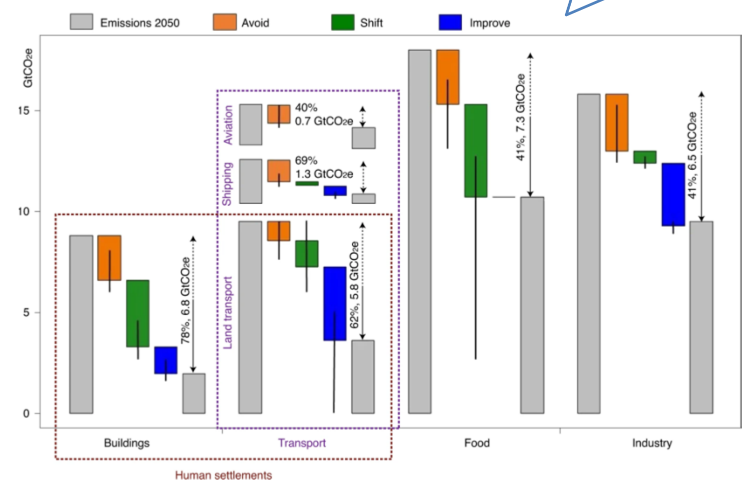
More granular inputs related to land, water and socio-ecological systems will increase the applicability of scenarios

Vehicle	Type	Unit	2015	2020	2025	2030	2035	2040	2045	2050
LDV	ICE	kWh_{th}/p-km	0.485	0.456	0.413	0.368	0.336	0.308	0.260	0.211
	BEV	kWh_{el}/p-km	0.113	0.101	0.089	0.078	0.072	0.067	0.061	0.055
	PHEV	kWh_{th}/p-km	0.145	0.114	0.091	0.081	0.074	0.068	0.057	0.046
	PHEV	kWh_{el}/p-km	0.079	0.075	0.069	0.061	0.056	0.052	0.048	0.043
	FCEV	kWh_{H2}/p-km	0.172	0.164	0.136	0.130	0.119	0.118	0.097	0.091
2W/3W	ICE	kWh_{th}/p-km	0.126	0.126	0.126	0.126	0.125	0.125	0.125	0.125
	BEV	kWh_{el}/p-km	0.044	0.044	0.044	0.044	0.044	0.044	0.044	0.044
BUS	ICE	kWh_{th}/p-km	0.233	0.224	0.210	0.210	0.205	0.199	0.193	0.189
	BEV	kWh_{el}/p-km	0.107	0.101	0.095	0.091	0.087	0.083	0.079	0.076
	PHEV	kWh_{th}/p-km	0.116	0.112	0.105	0.105	0.102	0.100	0.097	0.095
	PHEV	kWh_{el}/p-km	0.053	0.050	0.048	0.045	0.043	0.041	0.039	0.038
	FCEV	kWh_{H2}/p-km	0.178	0.166	0.156	0.147	0.139	0.132	0.124	0.118
MDV	ICE	kWh_{th}/t-km	1.334	1.229	1.132	1.043	0.961	0.885	0.815	0.751
	BEV	kWh_{el}/t-km	0.549	0.479	0.419	0.367	0.333	0.302	0.275	0.251
	PHEV	kWh_{th}/t-km	0.801	0.737	0.679	0.626	0.576	0.531	0.489	0.450
	PHEV	kWh_{el}/t-km	0.220	0.191	0.168	0.147	0.133	0.121	0.110	0.101
	FCEV	kWh_{H2}/t-km	0.801	0.737	0.679	0.626	0.576	0.531	0.489	0.450
HDV	ICE	kWh_{th}/t-km	0.445	0.403	0.365	0.330	0.299	0.271	0.246	0.222
	BEV	kWh_{el}/t-km	0.237	0.207	0.181	0.159	0.144	0.130	0.119	0.108
	PHEV	kWh_{th}/t-km	0.311	0.282	0.255	0.231	0.210	0.190	0.172	0.156
	PHEV	kWh_{el}/t-km	0.071	0.062	0.054	0.048	0.043	0.039	0.036	0.032
	FCEV	kWh_{H2}/t-km	0.267	0.242	0.219	0.198	0.180	0.163	0.147	0.133

Source: Khalili et al. (2019), Global Transportation Demand Development with Impacts on the Energy Demand and Greenhouse Gas Emissions in a Climate-Constrained World, *Energies* 12: 3870;

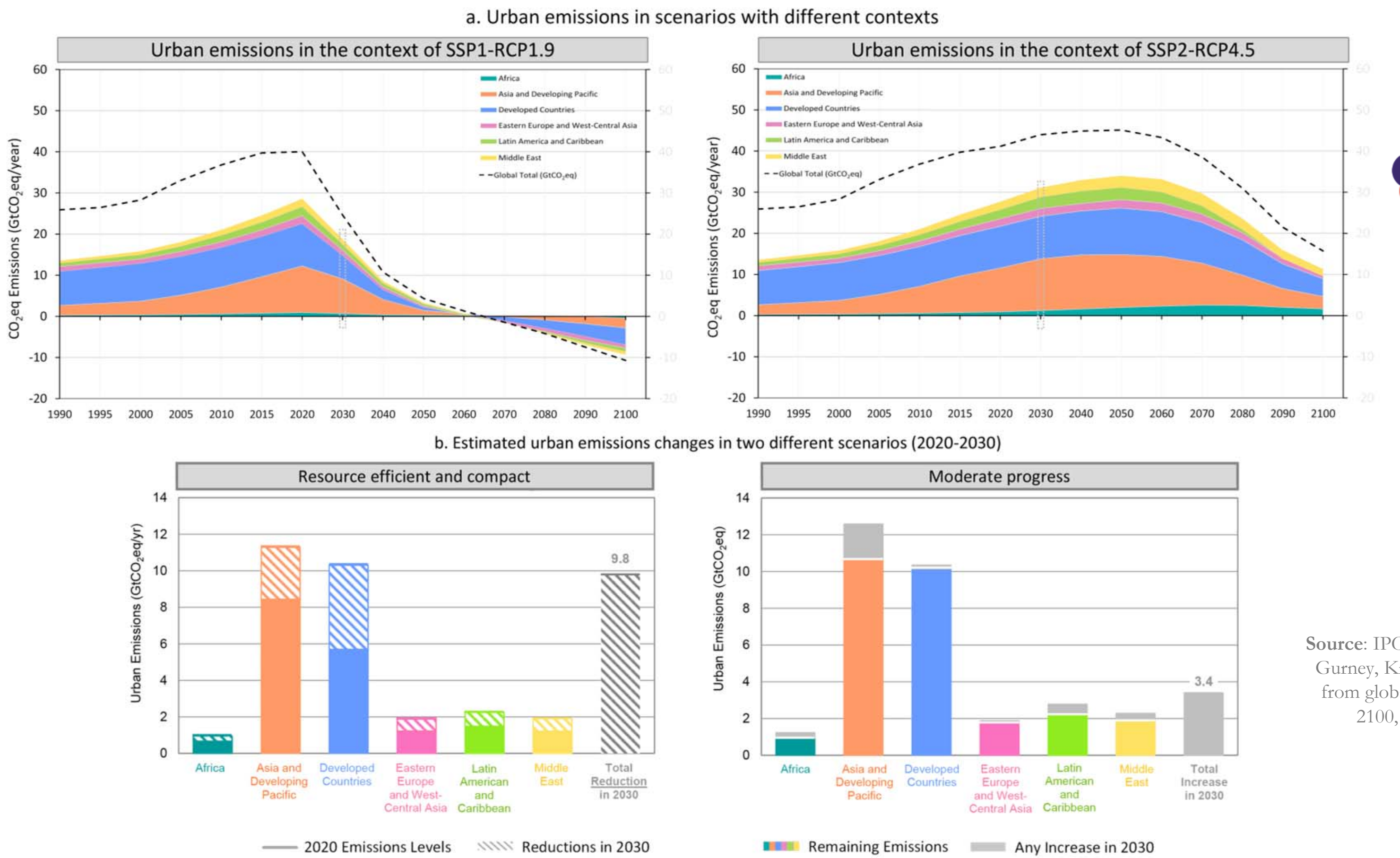
Avoid, shift and improve aspects from **bottom-up studies only**



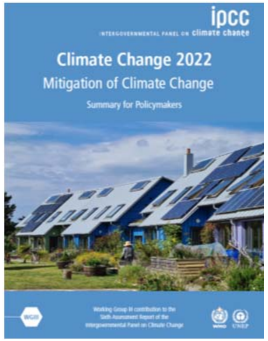
Source: Creutzig et al. (2022), Demand-side solutions to climate change mitigation consistent with high levels of well-being, *Nature Climate Change* 12: 36–46

3) Being Explicit on the Urban Share of Emissions

After AR6, it may become a common standard in IPCC reports to provide the urban share of emissions in scenarios



SCENARIOS FORUM 2022



Source: IPCC (2022), Technical Summary; adapted from Gurney, Kılkış et al. (2022), Greenhouse gas emissions from global cities under SSP/RCP scenarios, 1990 to 2100, *Global Environmental Change* 73: 102478

LOCOMOTION

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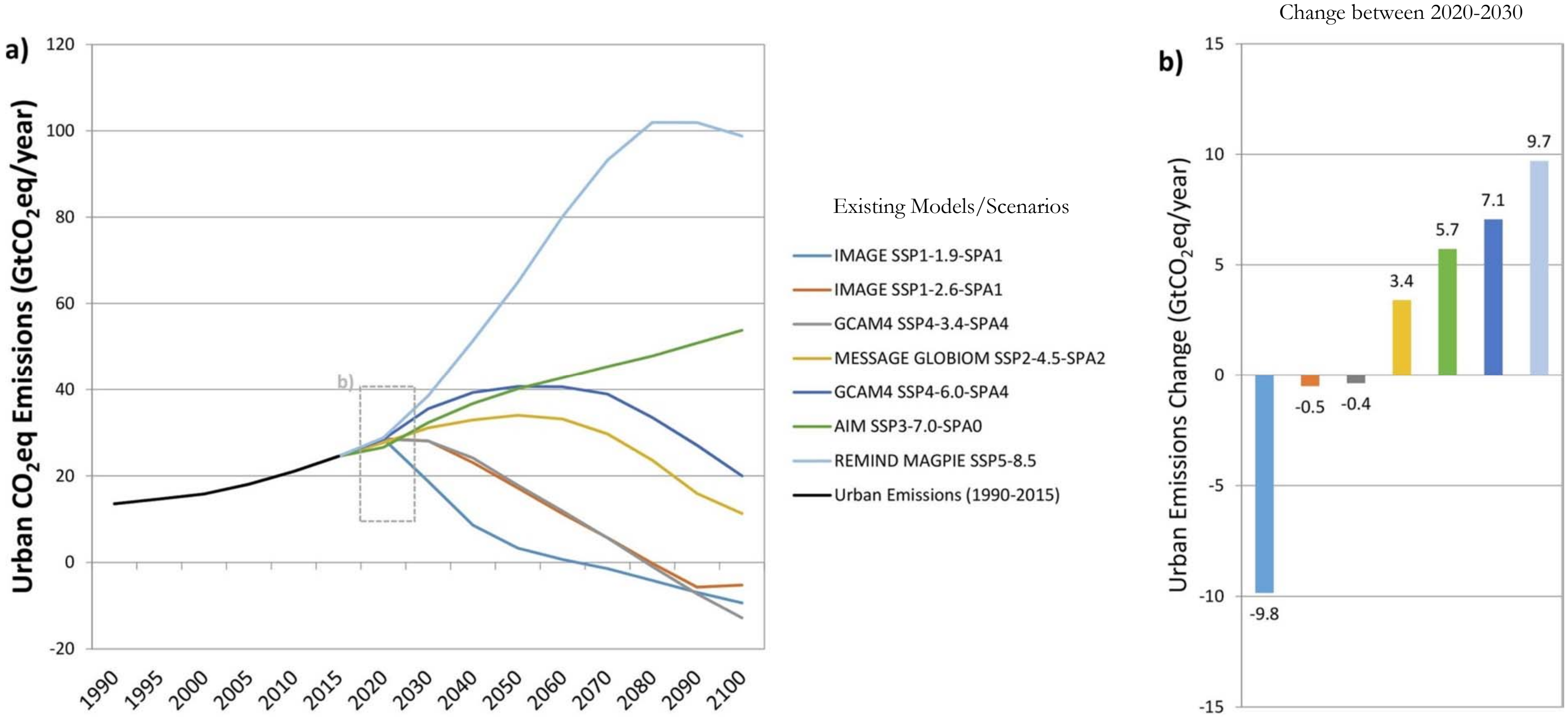

Source: Gurney, Kılkış et al. (2022), Greenhouse gas emissions from global cities under SSP/RCP scenarios, 1990 to 2100, *Global Environmental Change* 73: 102478

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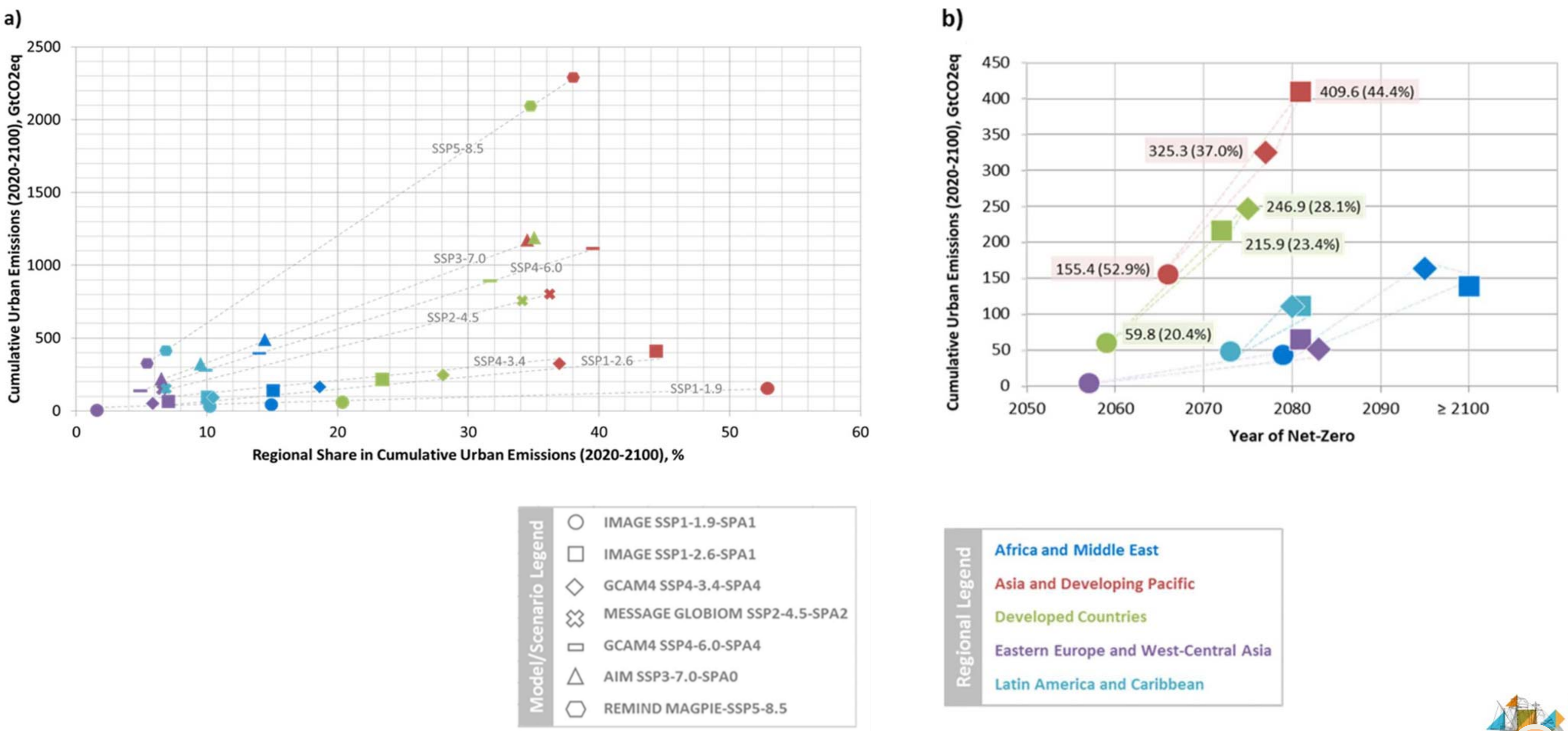

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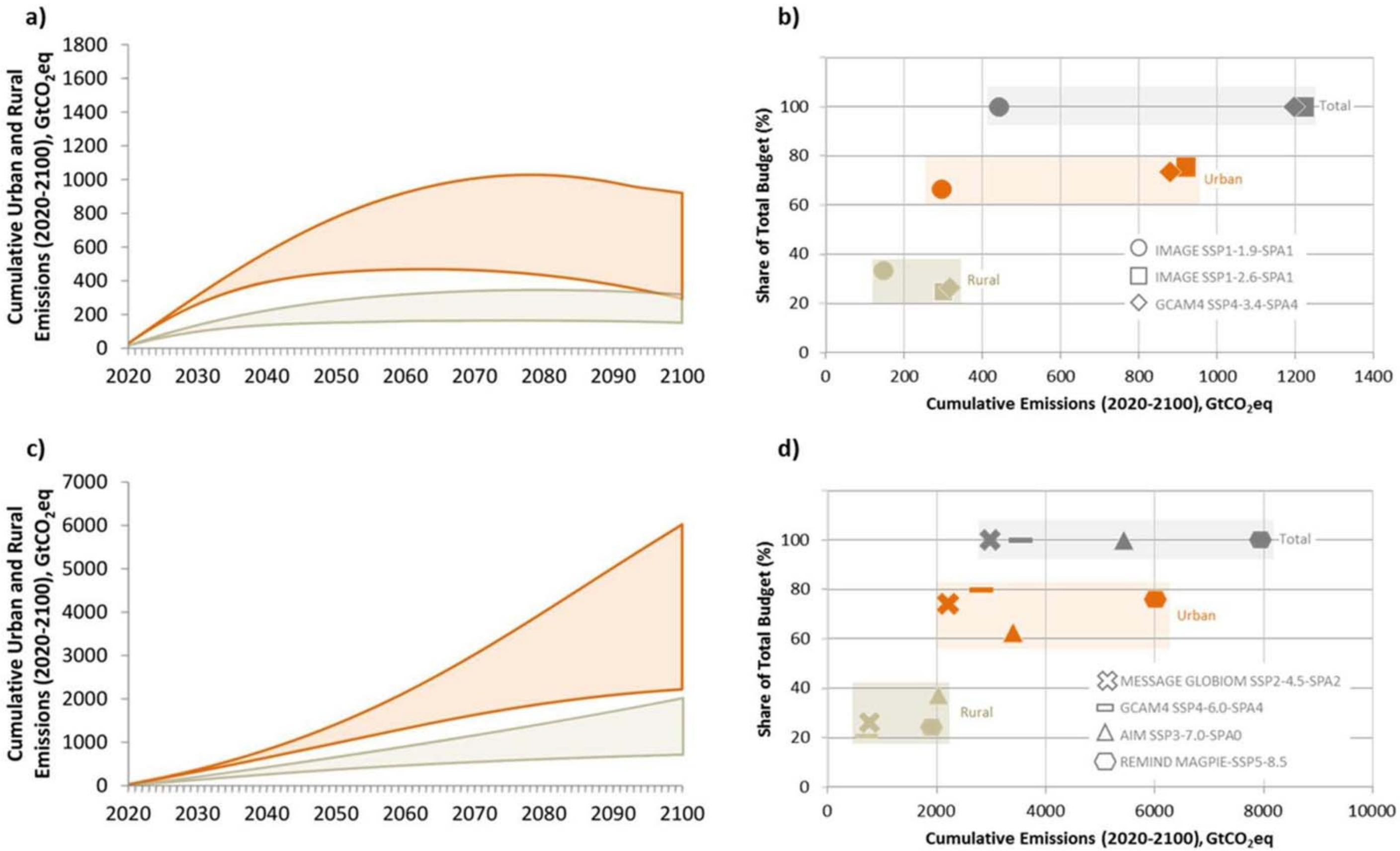
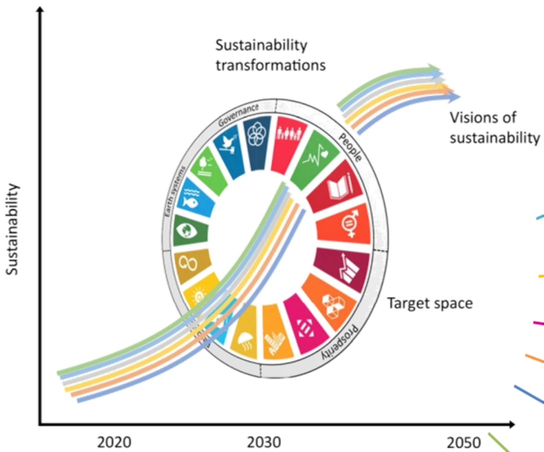


Source: Gurney, Kılkış et al. (2022), Greenhouse gas emissions from global cities under SSP/RCP scenarios, 1990 to 2100, *Global Environmental Change* 73: 102478

LOCOMOTION

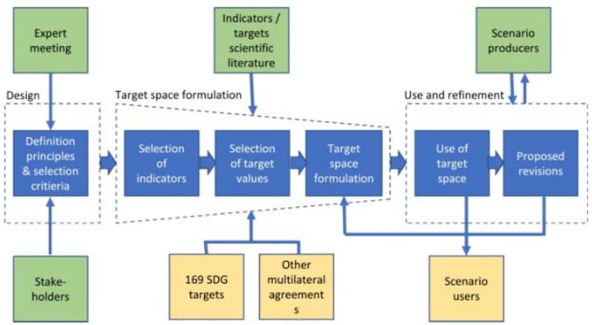
4) Better Linking Scenarios with Various Co-Benefits

Better linking climate scenarios with co-benefits will support accelerating the mitigation effort across all regions



2015 → 2030 → 2050

Sample SDGs	Normative Goal	Indicator	2015	2030	2050
Clean water and sanitation	Universal access to clean water	Population without access to improved water source piped	660 million	0	0
	End water scarcity	The area under water stress (water stress index for most water scarce month/season)	11%	No increase	No increase
Affordable and clean energy	Universal modern energy services for all	Population without basic electricity access	1.1 billion	0	0
Reduced inequalities	Decrease relative Poverty	Number of people below 50% of median national daily income	>1.4 billion	15%	10%
Sustainable cities and communities	Improve air quality in Cities	Population exposed to annual average $PM_{2.5}$ > 25 mg/m^3	65%	20%	10%
Life below water	Balance phosphorus in oceans	P flow from freshwater systems into the ocean	22 Tg P y^{-1}	11 Tg P y^{-1}	11 Tg P y^{-1}
	Halt land-system change	Global (biome): area of forested land as % of original forest cover (potential forest)	4,000 ha	No further loss of primary forest	Global: 75%, specified by forest type
Life on land	Balance nitrogen in soils	Industrial and intentional biological fixation of N	150 Tg N y^{-1}	62 Tg N y^{-1}	62 Tg N y^{-1}
	Protect biodiversity	Protect biodiversity	BII	No degradation from 2020 onward	



Source: van Vuuren et al. (2022), Defining a sustainable development target space for 2030 and 2050, *One Earth* 142-156.

LOCOMOTION

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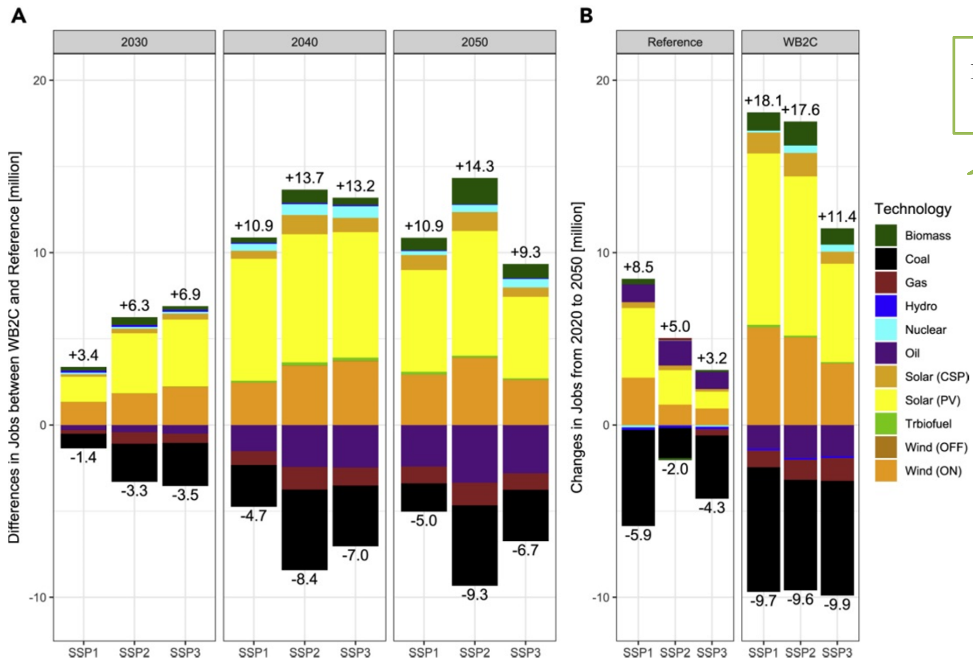
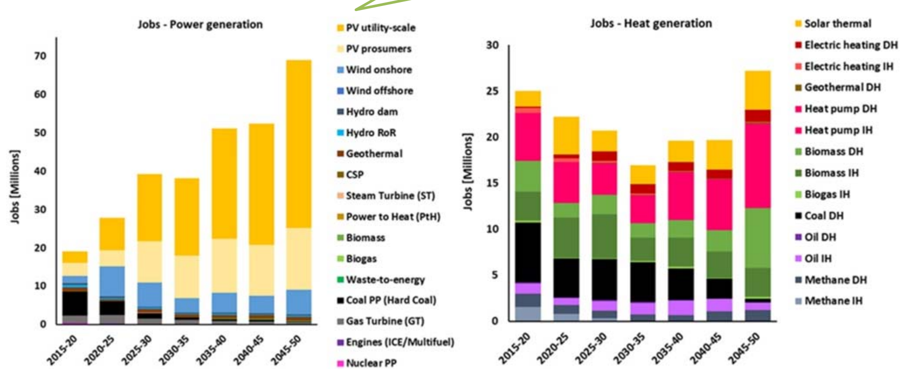


Source: Pai et al. (2022), Meeting well-below 2°C target would increase energy sector jobs globally, *One Earth* 4(7): 1026-1036

Energy system jobs shift to >10 million new jobs in **renewable energy led by solar and wind**

Total jobs in power, heat, transport, and desalination in a 100% RE scenario is about **134 million in 2050**



Source: Ram et al. (2022), Job creation during a climate compliant global energy transition across the power, heat, transport, and desalination sectors by 2050, *Energy* 238: 121690

LOCOMOTION

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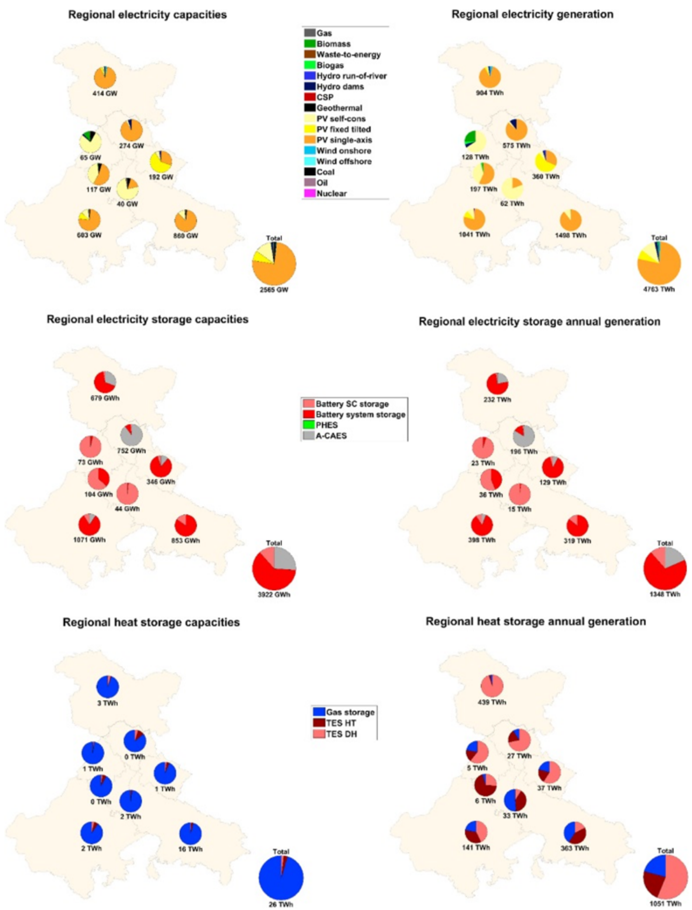
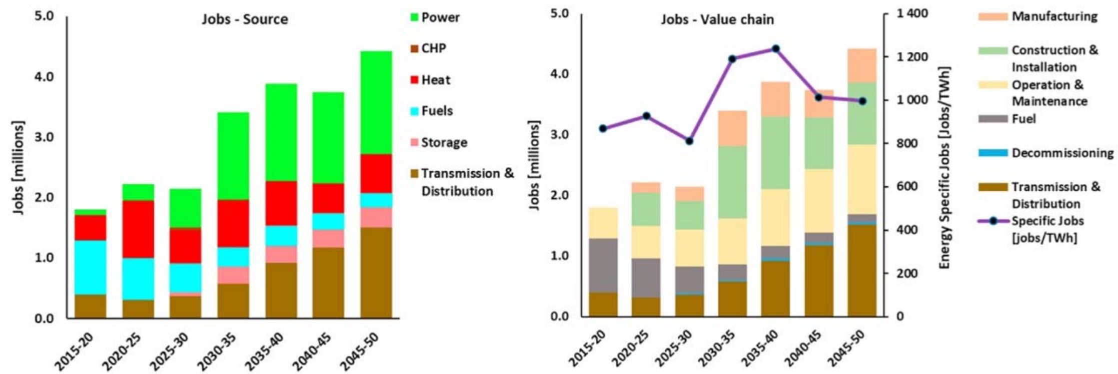


A 100% renewable energy scenario for North India will increase energy jobs from about 1.8 million in 2020 to **4.4+ million by 2050**



Source: Ram et al. (2022), Energy transition in megacities towards 100% renewable energy: A case for Delhi, *Renewable Energy* 195: 578-589

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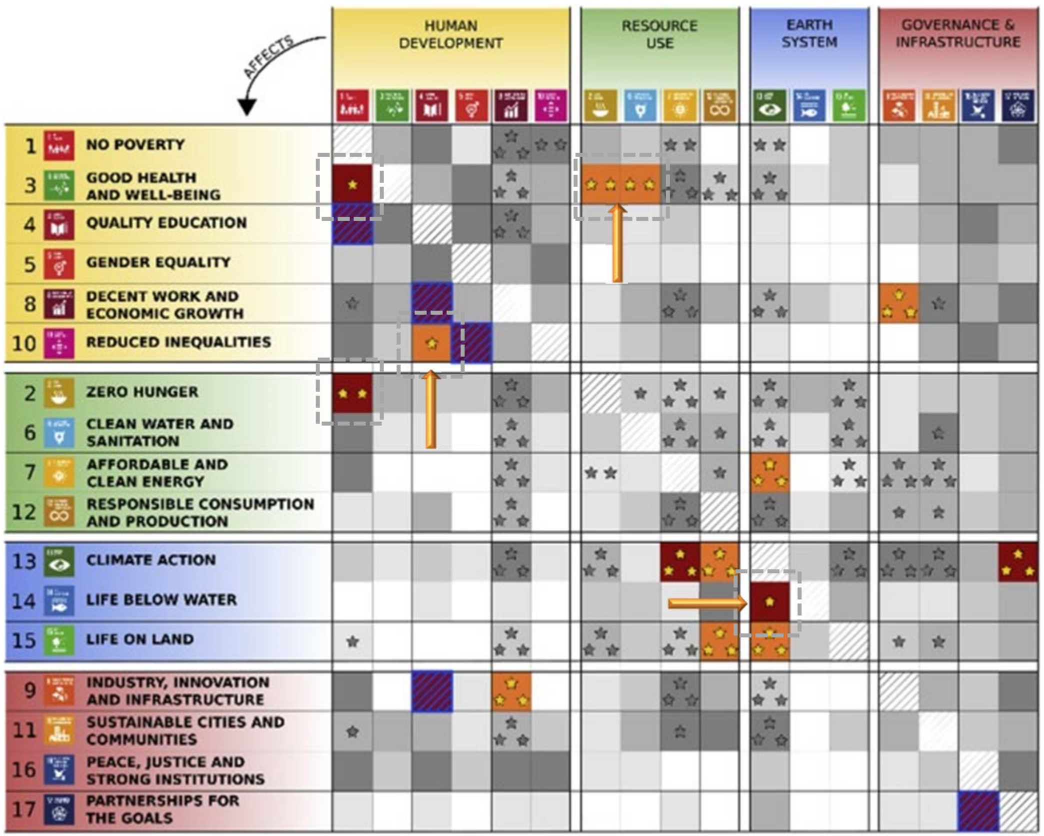
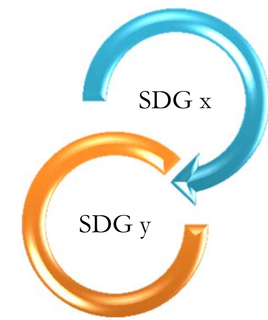
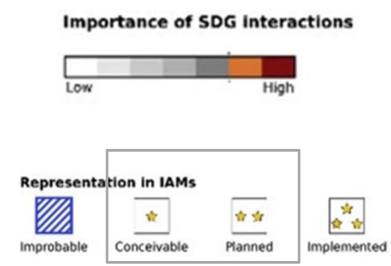


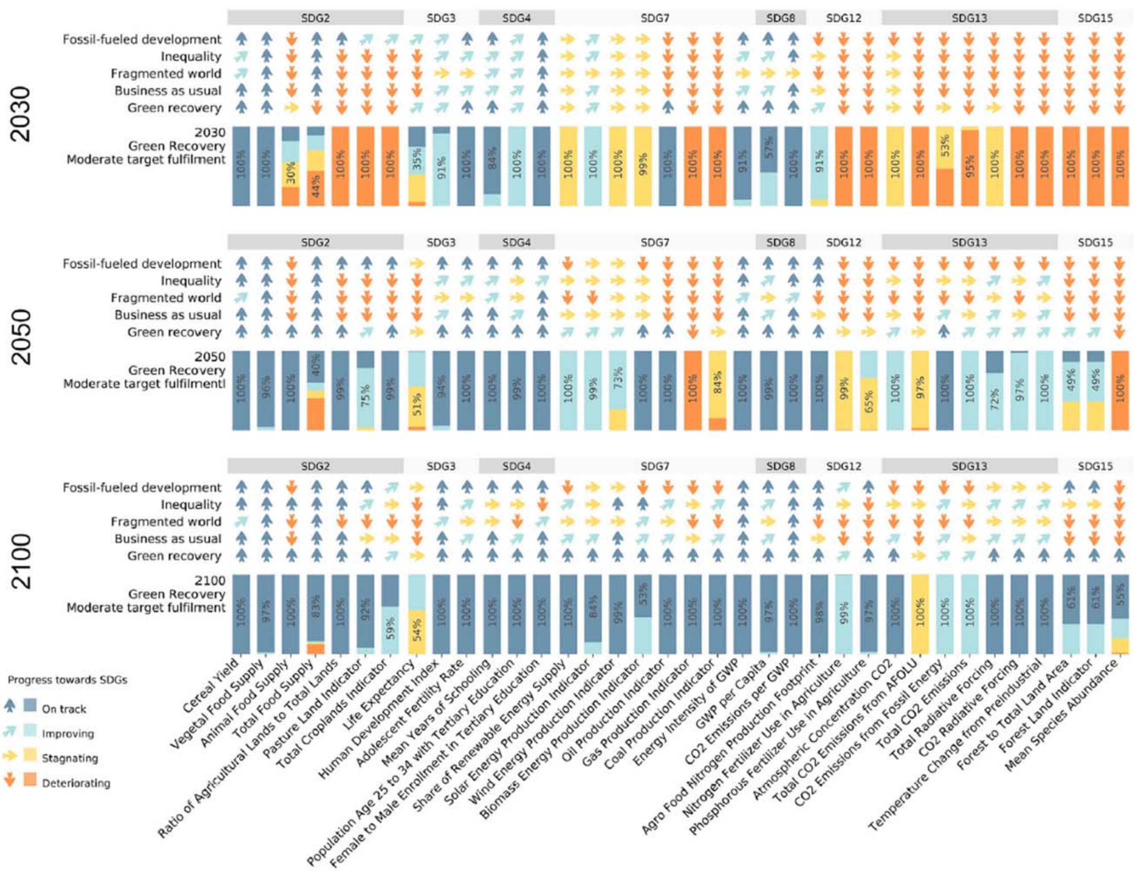




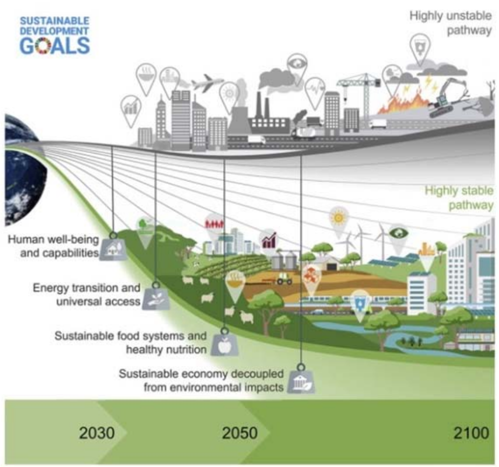
Source: van Soest (2019), Analysing interactions among Sustainable Development Goals with Integrated Assessment Models, *Global Transitions* 1: 210-225

4) Better Linking Scenarios with Various Co-Benefits

Better linking climate scenarios with co-benefits will support accelerating the mitigation effort across all regions



Still a way to go for the SDG benefits of 100% renewable energy scenarios



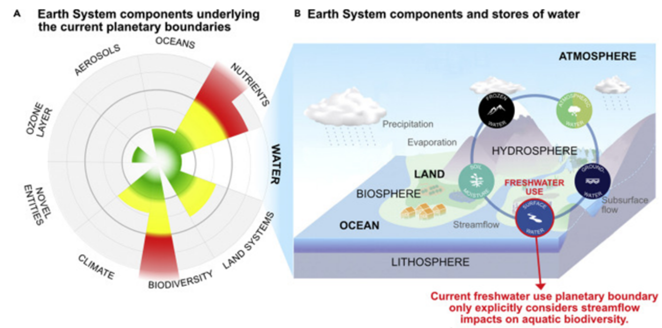
Source: Moallemi et al. (2022), Early systems change necessary for catalyzing long-term sustainability in a post-2030 agenda, *One Earth* 5: 1-20

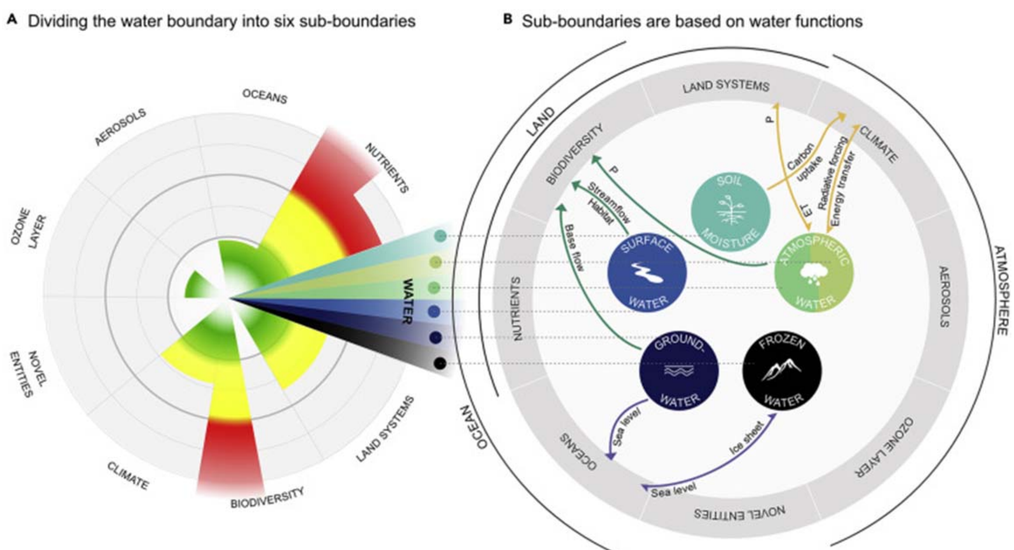
5) Comparability with the Earth System Boundaries

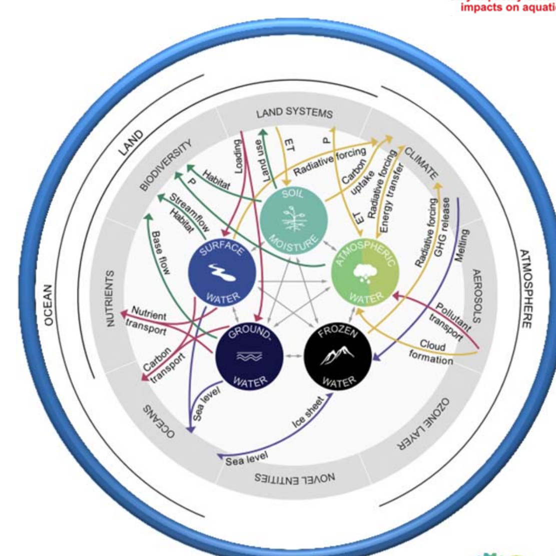
Vetting criteria should determine scenarios that are and are not within the earth system boundaries across domains

Earth System Boundary Domain	Upper Boundaries in Safer Operating Space
Nitrogen (Schulte-Uebbing et al., In Review)	43 Mt N yr^{-1} of agricultural surplus or 57 TgN yr^{-1} (closing yield gaps)
Phosphorus	4.5-9.0 TgP yr^{-1} soil surplus
Blue Water (Gleeson et al., 2020)	**<20%** alteration of monthly surface water flows for all rivers globally

Source for Nitrogen: Schulte-Uebbing et al. From planetary to regional boundaries for agricultural nitrogen pollution (In Review)





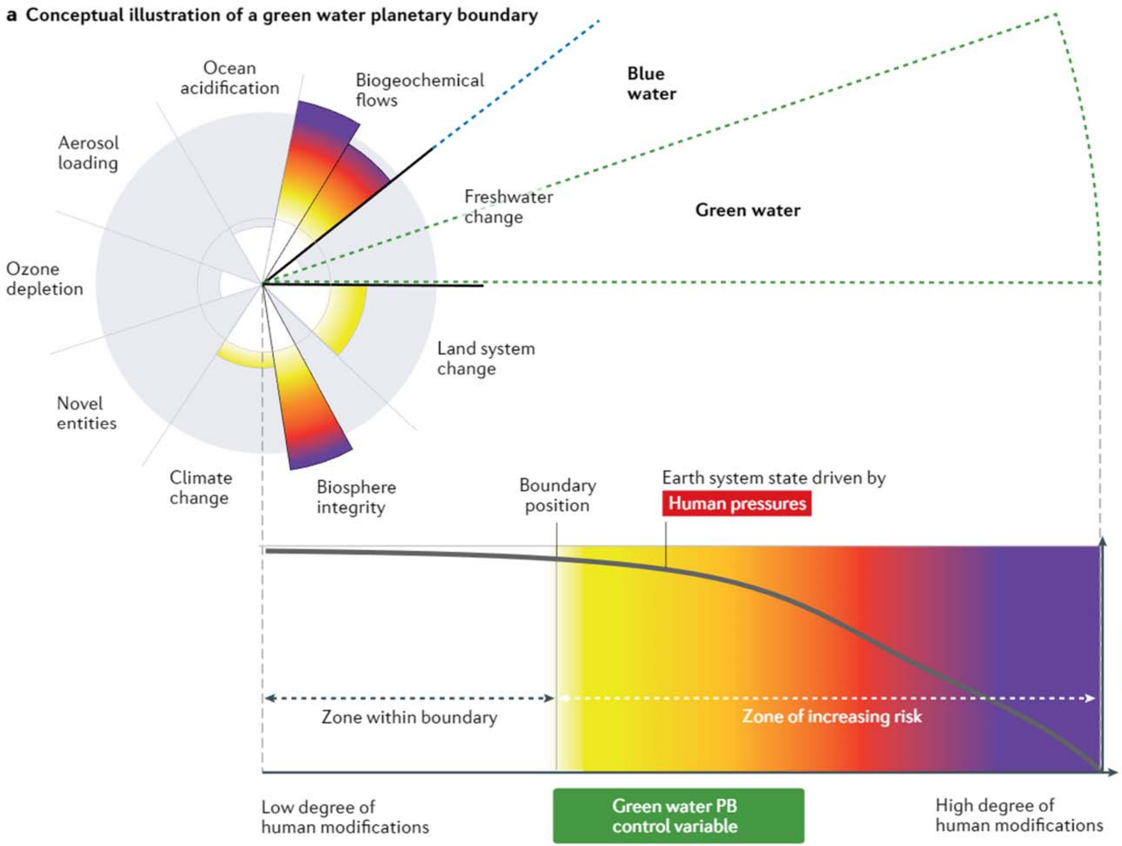


Source: Gleeson et al. (2020), The Water Planetary Boundary: Interrogation and Revision, *One Earth* 2: 223-234.

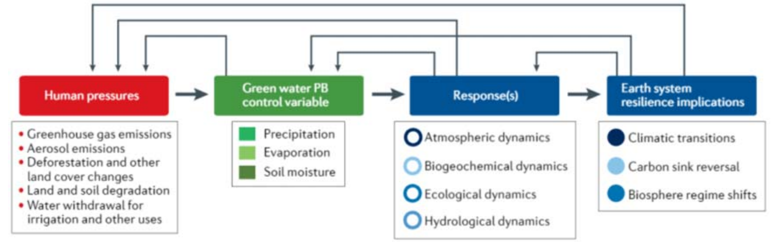
LOCOMOTION

5) Comparability with the Earth System Boundaries

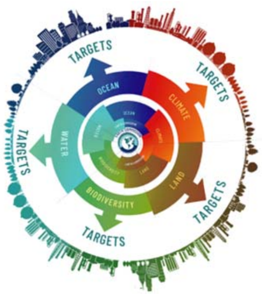
Vetting criteria should determine scenarios that are and are not within the earth system boundaries across domains



EARTH COMMISSION
GLOBAL COMMONS ALLIANCE



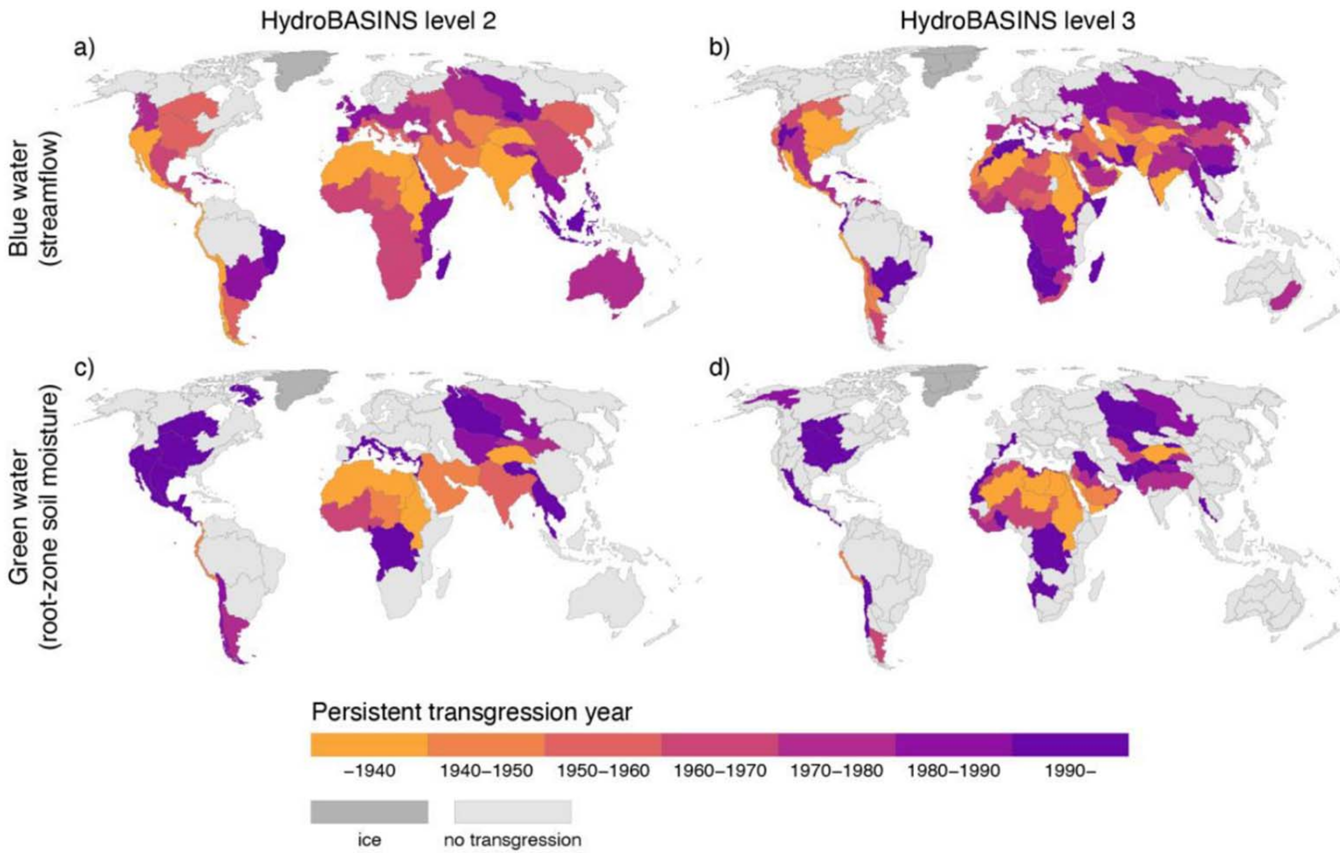
Source: Wang- Erlandsson et al. (2022), A planetary boundary for green water, *Nature Reviews Earth & Environment* 3: 380-392.

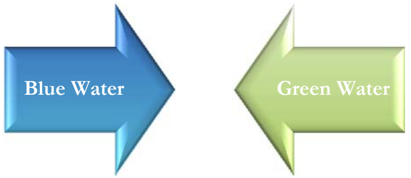


LOCOMOTION

5) Comparability with the Earth System Boundaries

Vetting criteria should determine scenarios that are and are not within the earth system boundaries across domains

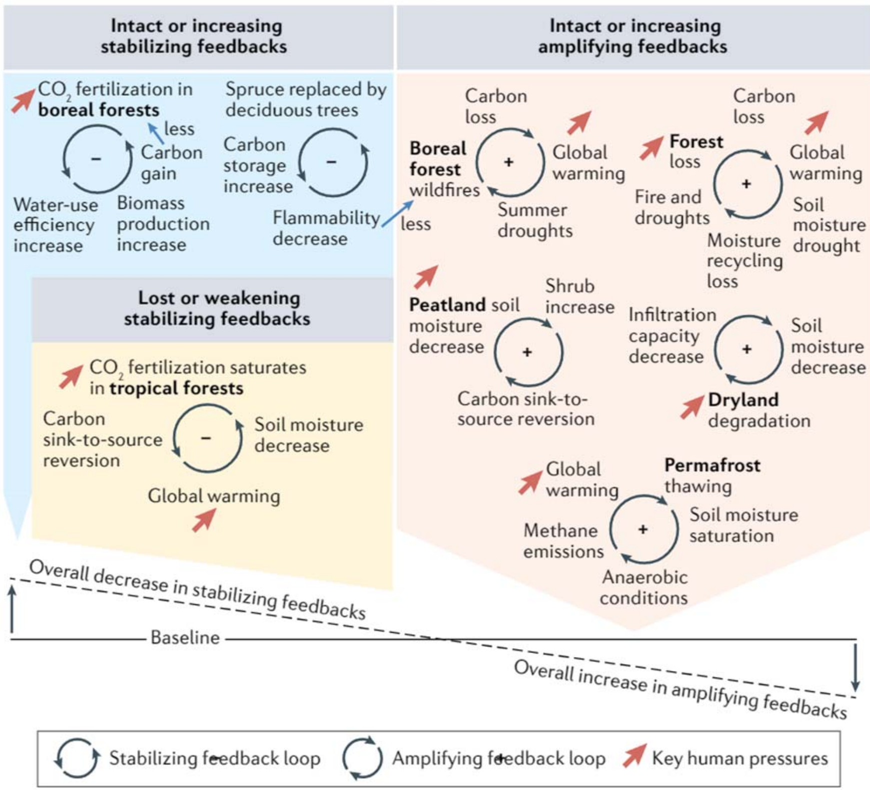


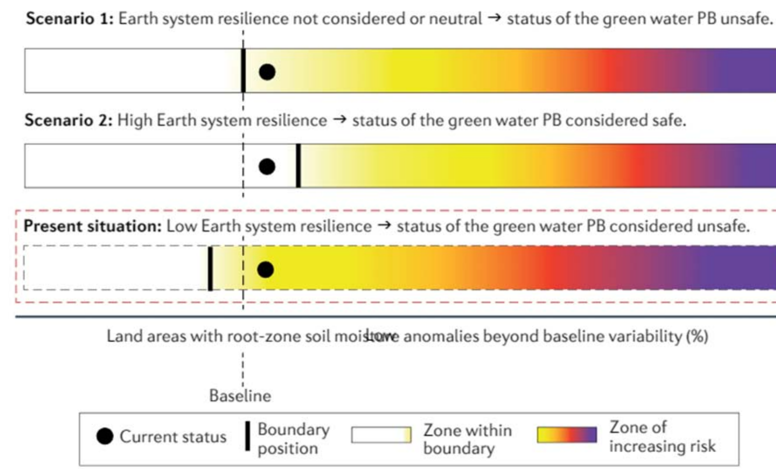


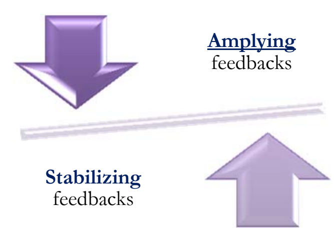
Source: Porkka et al., Global water cycle shifts substantially beyond stable pre-industrial conditions, Earth ArXiv

5) Comparability with the Earth System Boundaries

Vetting criteria should determine scenarios that are and are not within the earth system boundaries across domains



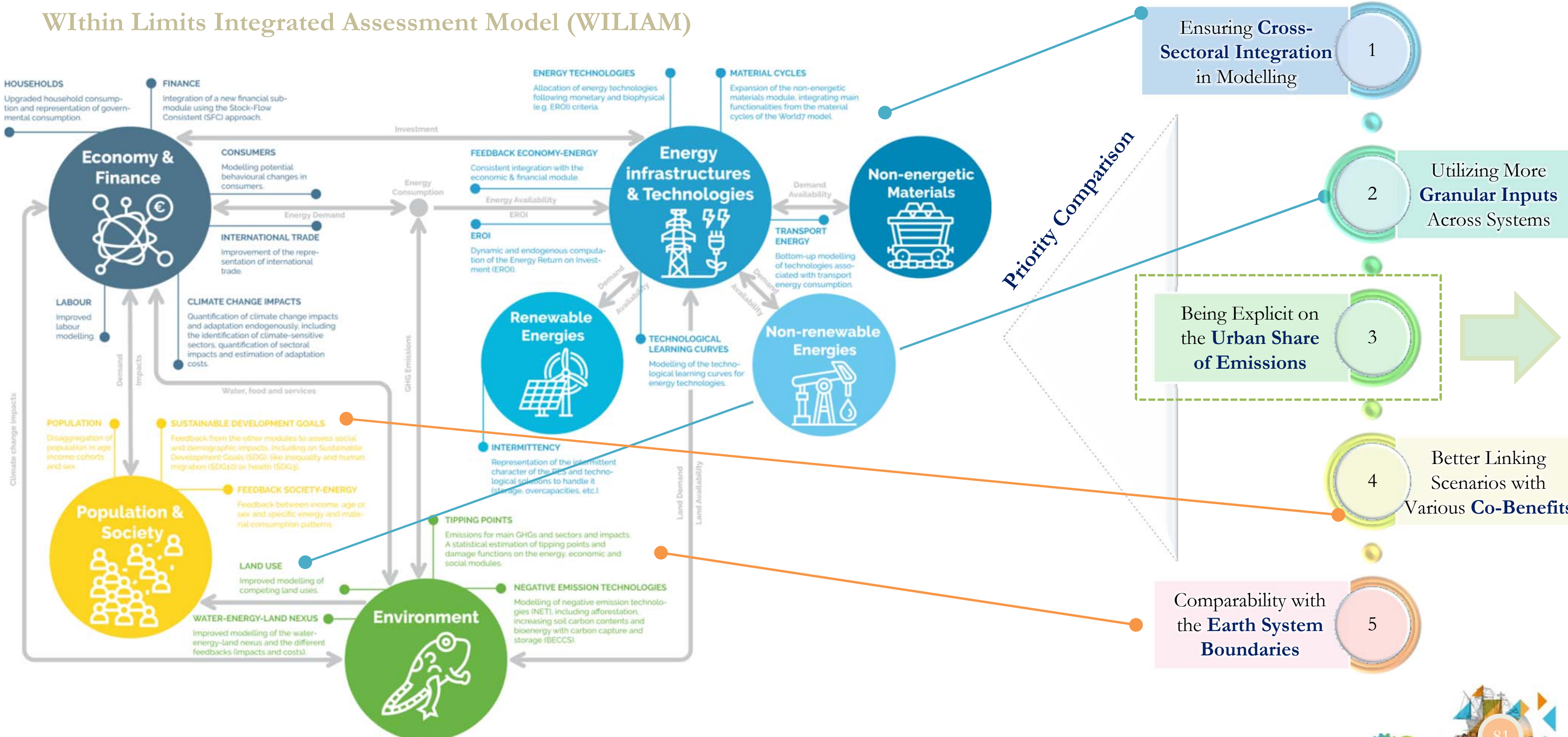




Source: Wang- Erlandsson et al. (2022), A planetary boundary for green water, *Nature Reviews Earth & Environment* 3: 380-392.

Overall Comparison of these Priorities with WILIAM

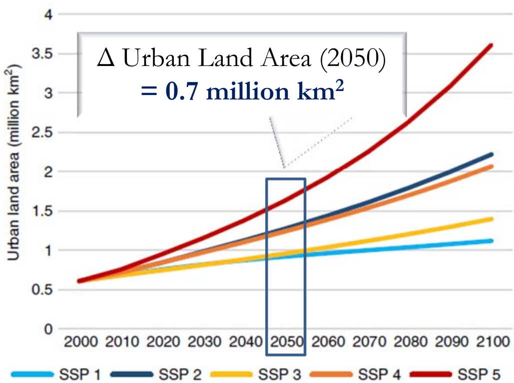
Most priorities are being addressed by WILIAM also with a very good basis to provide synergies among priorities



Source: Locomotion Project <https://www.locomotion-h2020.eu/locomotion-models/locomotion-iams/>

What Will It Take to Transform Urban Systems?

The way cities continue to be planned, interact with the energy system and utilize resources will be essential

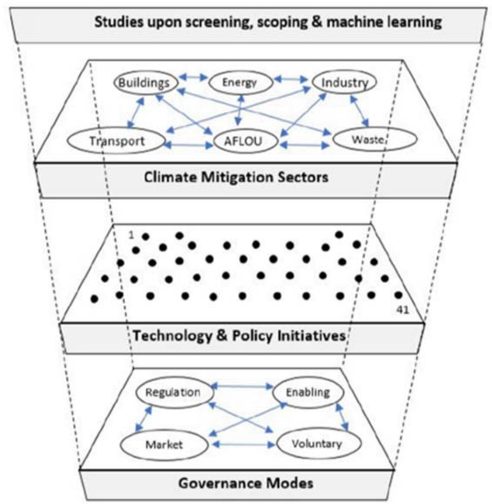


Source: Gao and O'Neill (2020), *Nature Communications* 11:2302

Modifying emerging urbanization

- 20–25% reduction of future urban energy use until 2050

Source: Creutzig et al. (2016); Creutzig et al. (2015)



Source: Sethi et al (2020), Climate change mitigation in cities: a systematic scoping of case studies, *Environ. Res. Lett.* 15 093008

Reducing urban resource use

- Continuing to build cities the same way may require nearly 90 billion tonnes of materials by 2050

Source: Swilling et al. (2018), The Weight of Cities: Resource Requirements of Future Urbanization

Integrating measures across urban sectors realizes synergies in GHG emission reductions

Urban land use and spatial planning, urban energy planning and resource efficiency


Energy 236 (2021) 121394

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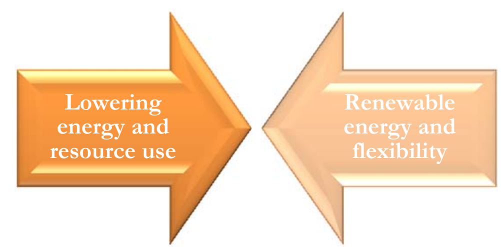
Transition towards urban system integration and benchmarking of an urban area to accelerate mitigation towards net-zero targets

Şiir Kılkış

The Scientific and Technological Research Council of Turkey, Atatürk Bulvarı No: 221, 06100, Kavaklıdere, Ankara, Turkey

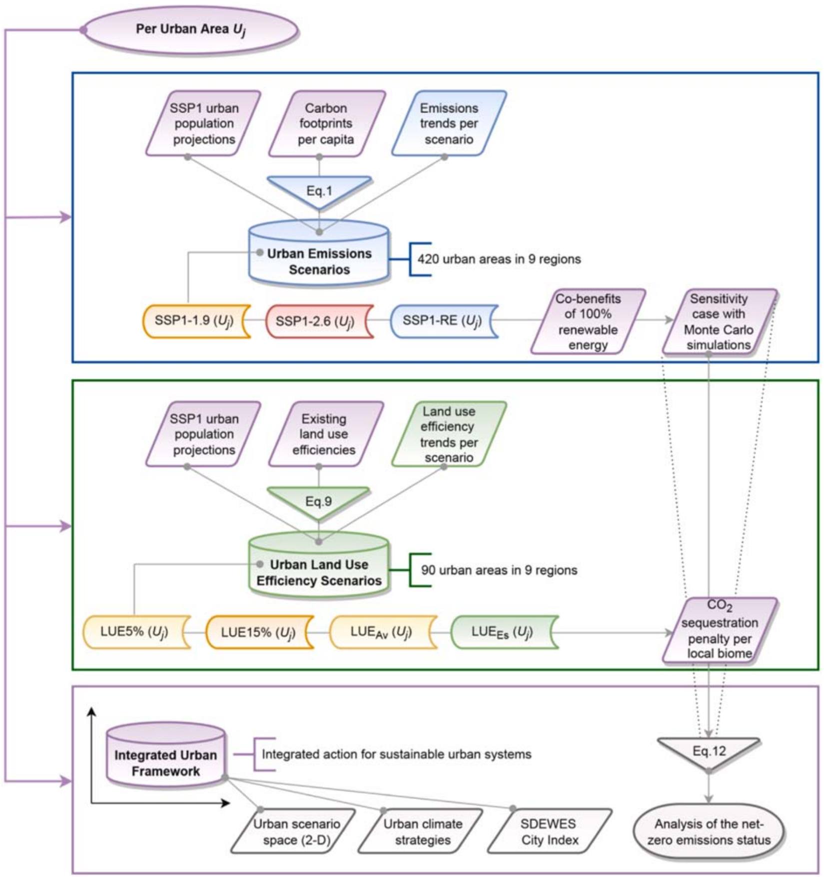
Source: Kılkış (2021), *Energy* 236:121394

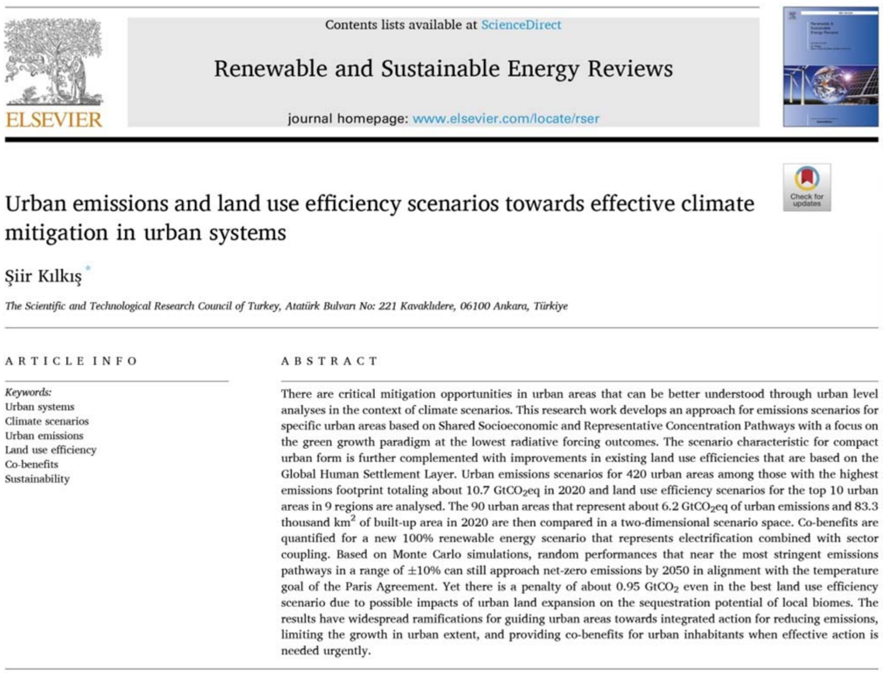
New opportunities



Urban Emissions and Land Use Efficiency Scenarios

Critical mitigation opportunities in urban areas can be guided through urban emissions and LUE scenarios





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ELSEVIER

Urban emissions and land use efficiency scenarios towards effective climate mitigation in urban systems

Şiir Kılkış *

The Scientific and Technological Research Council of Turkey, Atatürk Bulvarı No: 221 Kavaklıdere, 06100 Ankara, Türkiye

ARTICLE INFO

Keywords:
Urban systems
Climate scenarios
Urban emissions
Land use efficiency
Co-benefits
Sustainability

ABSTRACT

There are critical mitigation opportunities in urban areas that can be better understood through urban level analyses in the context of climate scenarios. This research work develops an approach for emissions scenarios for specific urban areas based on Shared Socioeconomic and Representative Concentration Pathways with a focus on the green growth paradigm at the lowest radiative forcing outcomes. The scenario characteristic for compact urban form is further complemented with improvements in existing land use efficiencies that are based on the Global Human Settlement Layer. Urban emissions scenarios for 420 urban areas among those with the highest emissions footprint totaling about 10.7 $GtCO_2eq$ in 2020 and land use efficiency scenarios for the top 10 urban areas in 9 regions are analysed. The 90 urban areas that represent about 6.2 $GtCO_2eq$ of urban emissions and 83.3 thousand km^2 of built-up area in 2020 are then compared in a two-dimensional scenario space. Co-benefits are quantified for a new 100% renewable energy scenario that represents electrification combined with sector coupling. Based on Monte Carlo simulations, random performances that near the most stringent emissions pathways in a range of ±10% can still approach net-zero emissions by 2050 in alignment with the temperature goal of the Paris Agreement. Yet there is a penalty of about 0.95 $GtCO_2$ even in the best land use efficiency scenario due to possible impacts of urban land expansion on the sequestration potential of local biomes. The results have widespread ramifications for guiding urban areas towards integrated action for reducing emissions, limiting the growth in urban extent, and providing co-benefits for urban inhabitants when effective action is needed urgently.

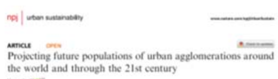
Source: Kılkış (2022), Urban emissions and land use efficiency scenarios towards effective climate mitigation in urban systems, *Renewable and Sustainable Energy Reviews* 167: 112733

Urban Emissions Scenarios in the SSP-RCP Framework

Multiple datasets are integrated for SSP1 population projections per urban area and 100% renewable energy trends

Data inputs – Urban emissions and trends
- Global Gridded Model of Carbon Footprints
- Global Human Settlement Layer GHSL-UCDB
- Urban population by SSP per urban cluster (*)

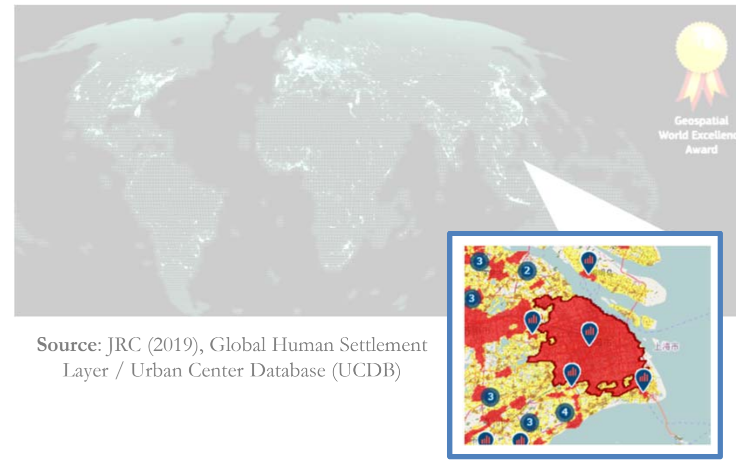
(*) Source: Kii (2021), npj *Urban Sustainability* 1:10


npj | urban sustainability

ARTICLE OPEN

Projecting future populations of urban agglomerations around the world and through the 21st century

The focus is on the top 500 urban areas with the highest footprint, 420 being harmonized across urban datasets



Source: JRC (2019), Global Human Settlement Layer / Urban Center Database (UCDB)

Scenario	Urbanization Qualities	Electrification and flexibility	Renewable energy deployment	Energy and material efficiency	Technology development / innovation	Behavioral and lifestyle responses	Afforestation and re-forestation
★ **SSP1-RE**	**Rapid / Compact**	**Highest**	**Highest**	**Highest**	**Highest**	**Highest**	**Higher**
SSP1-1.9	Rapid / Compact	Higher	Higher	Higher	Higher	Higher	Higher
SSP1-2.6	Rapid / Compact	High	High	High	High	High	High

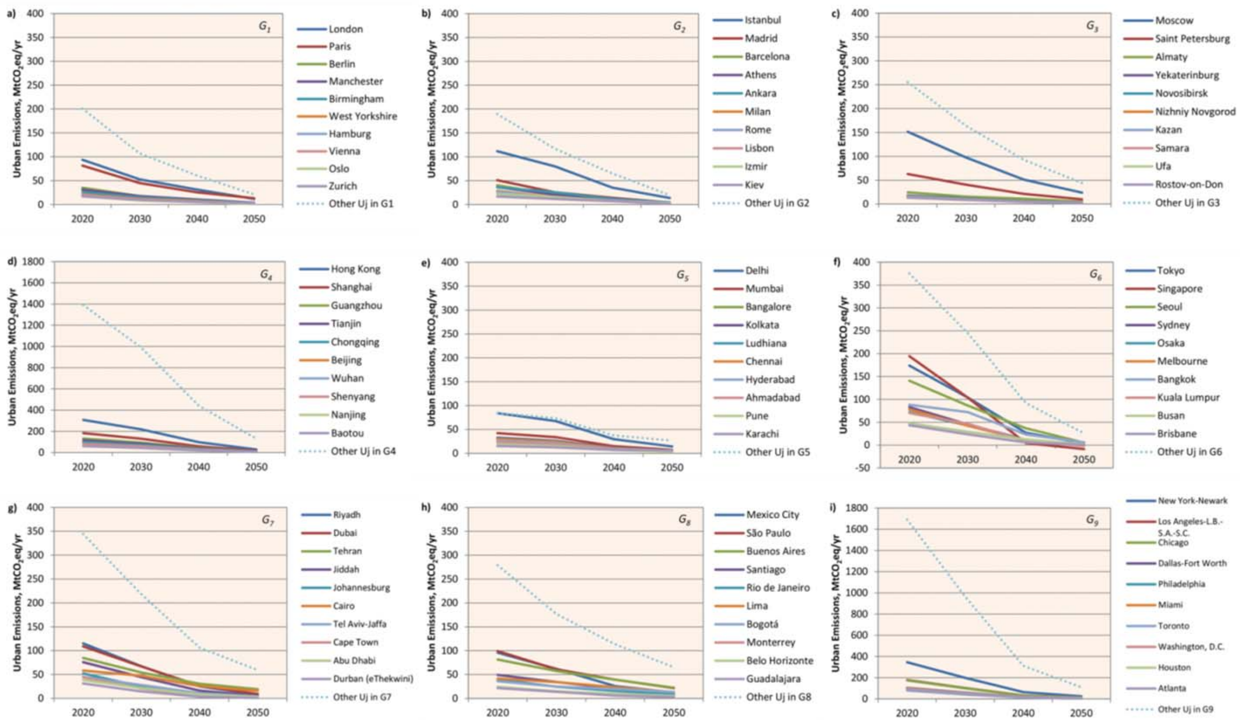
Climate scenario inputs
- Additional SSP1 scenario involving 100% renewable energy based on regional GHG emission trends

Additional Source: Bogdanov et al. (2021), Low-cost renewable electricity as the key driver of the global energy transition towards sustainability, *Energy* 227 <https://doi.org/10.1016/j.energy.2021.120467>

Urban Emissions Scenarios for 420 Urban Areas

Each SSP1 scenario has different implications for mitigation efforts involving the 420 urban areas and the outcomes

Urban emissions scenarios for 420 urban areas by region - **SSP1-1.9**



Urban implications:
Compact urban form with **wide-spread electrification and efficiency**

• Electrification of end uses	Higher
• Renewable energy deployment	Higher
• Energy and material efficiency	Higher
• Technology development / innovation	Higher
• Behavioral and lifestyle responses	Higher
• Afforestation and re-forestation	Higher

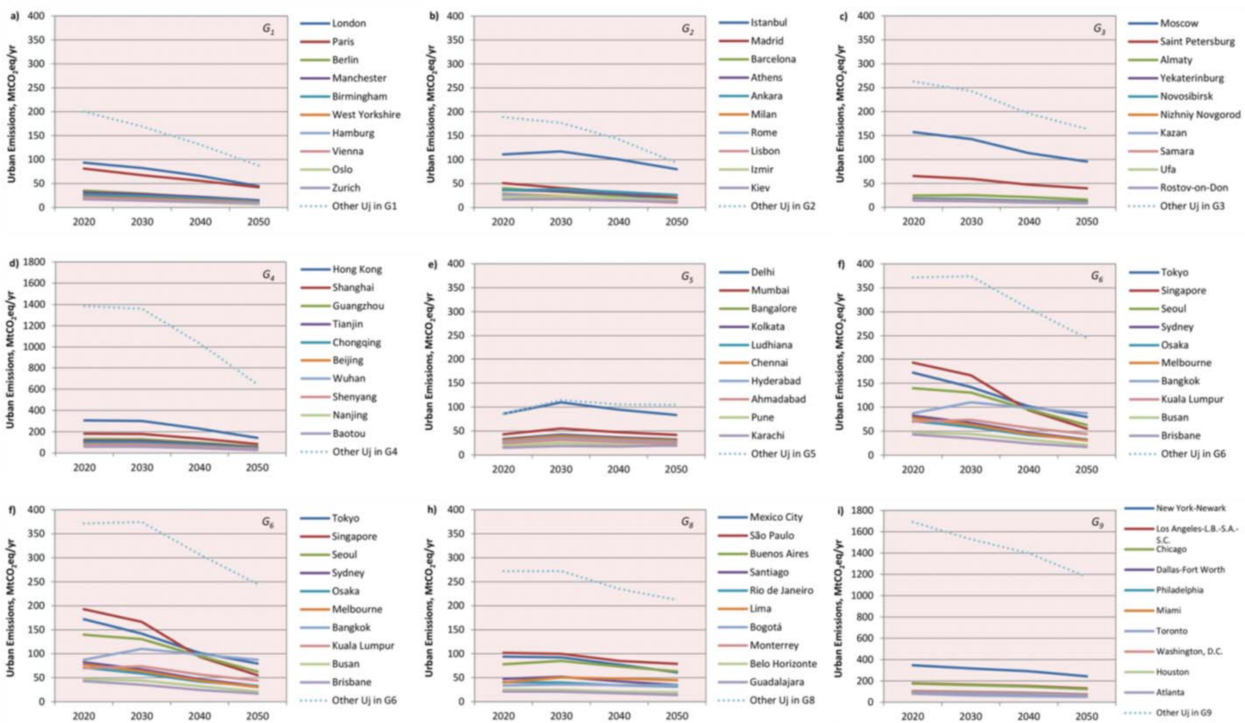
Mitigation solutions, e.g.
- Electric mobility
- Large-scale heat pumps
- Renewable energy
- Material efficiency

Source: Kılkış (2022), Urban emissions and land use efficiency scenarios towards effective climate mitigation in urban systems, *Renewable and Sustainable Energy Reviews* 167: 112733

Urban Emissions Scenarios for 420 Urban Areas

Each SSP1 scenario has different implications for mitigation efforts involving the 420 urban areas and the outcomes

Urban emissions scenarios for 420 urban areas by region - **SSP1-2.6**



Urban implications:
Same principles with relatively slower progress **in urban areas**

• Electrification of end uses	High
• Renewable energy deployment	High
• Energy and material efficiency	High
• Technology development / innovation	High
• Behavioral and lifestyle responses	High
• Afforestation and re-forestation	High

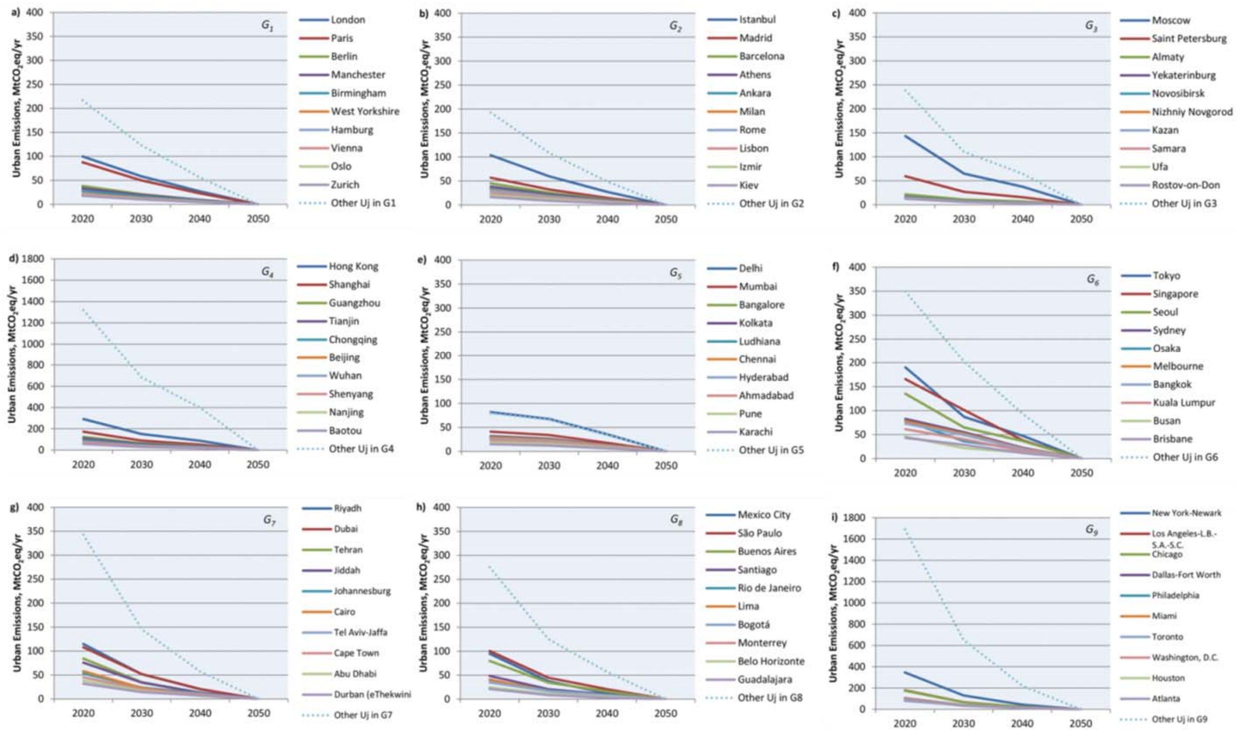
Mitigation solutions, e.g.
- Electric mobility
- Large-scale heat pumps
- Renewable energy
- Material efficiency

Source: Kılkış (2022), Urban emissions and land use efficiency scenarios towards effective climate mitigation in urban systems, *Renewable and Sustainable Energy Reviews* 167: 112733

Urban Emissions Scenarios for 420 Urban Areas

Each SSP1 scenario has different implications for mitigation efforts involving the 420 urban areas and the outcomes

Urban emissions scenarios for 420 urban areas by region - **SSP1-RE**



Urban implications:
Support for system flexibility for **100% renewable energy penetration**

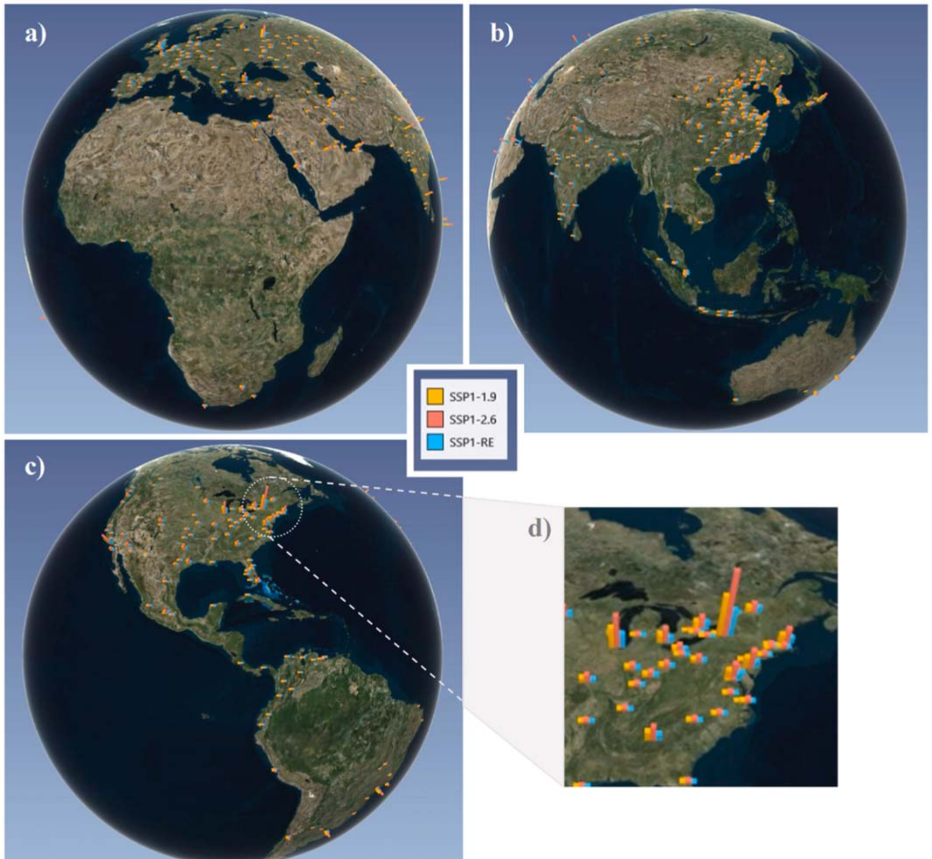
• Electrification and flexibility	Highest
• Renewable energy deployment (100%)	Highest
• Energy and material efficiency	Highest
• Technology development / innovation	Highest
• Behavioral and lifestyle responses	Highest
• Afforestation and re-forestation	Higher

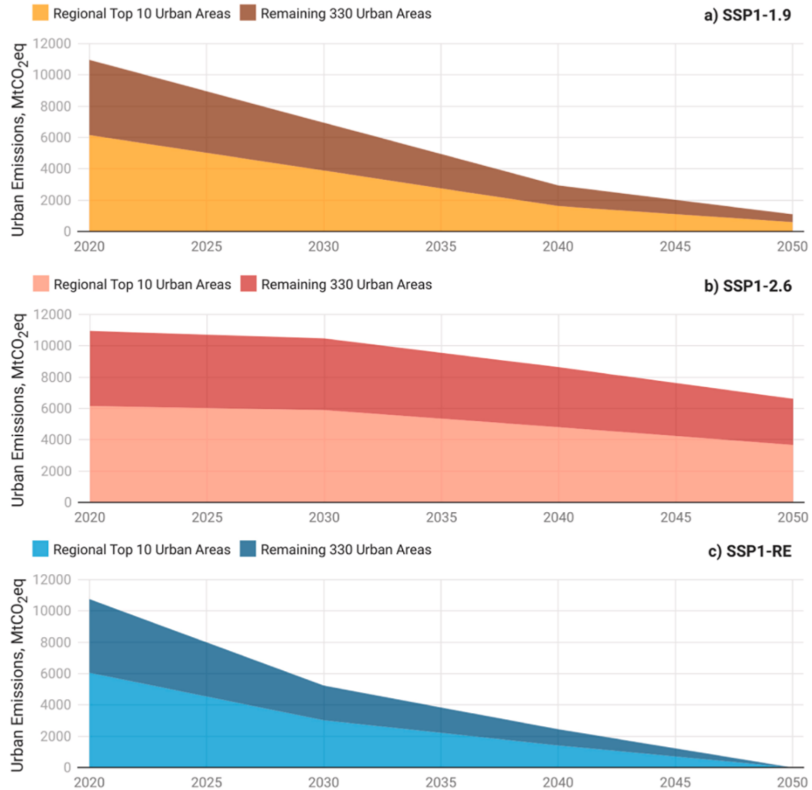
Mitigation solutions, e.g.
- Vehicle-to-grid (V2G)
- Power-to-heat (P2H)
- Smart energy systems
- Material efficiency

Source: Kılkış (2022), Urban emissions and land use efficiency scenarios towards effective climate mitigation in urban systems, *Renewable and Sustainable Energy Reviews* 167: 112733

Urban Emissions Scenarios for 420 Urban Areas

The results have widespread ramifications for guiding urban areas towards integrated action for reducing emissions

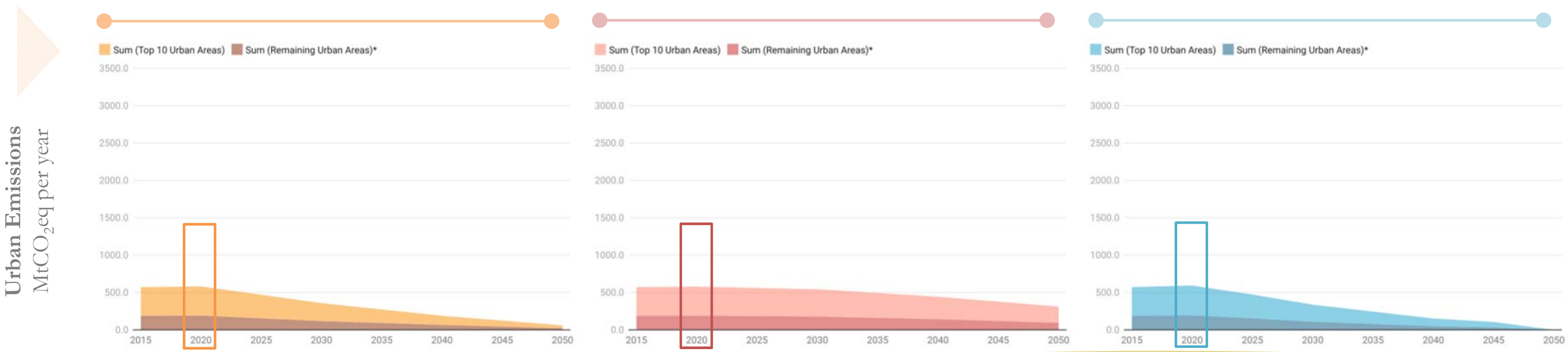




Source: Kılkış (2022), Urban emissions and land use efficiency scenarios towards effective climate mitigation in urban systems, *Renewable and Sustainable Energy Reviews* 167: 112733

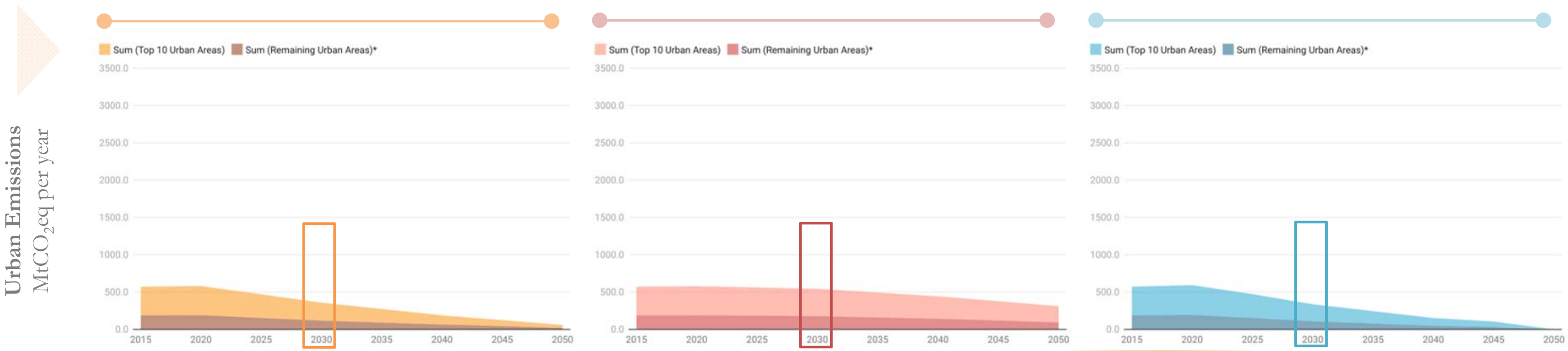
Future Outlook of Emissions for 420 Urban Areas

In Southern and Eastern Europe, urban emissions for 32 of the top 420 urban areas are 585.9 ± 7.0 $MtCO_2eq$ in 2020



Future Outlook of Emissions for 420 Urban Areas

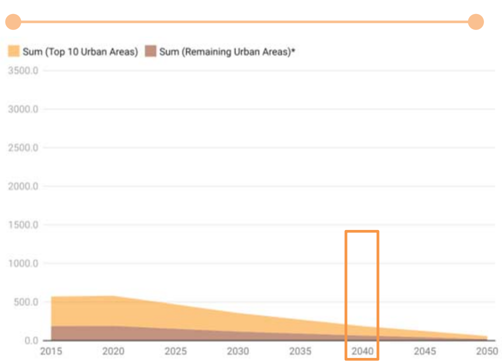
Across the SSP1 scenarios, urban emissions pathways can lead to 357.6, 543.5 or 336.6 $MtCO_2eq$ in 2030

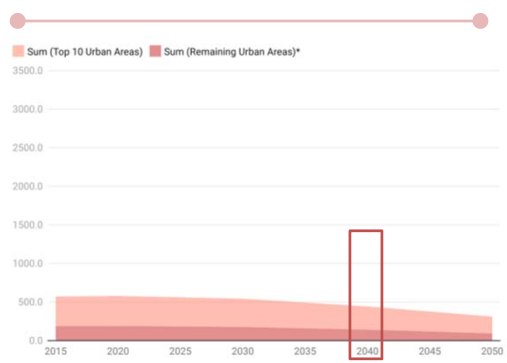


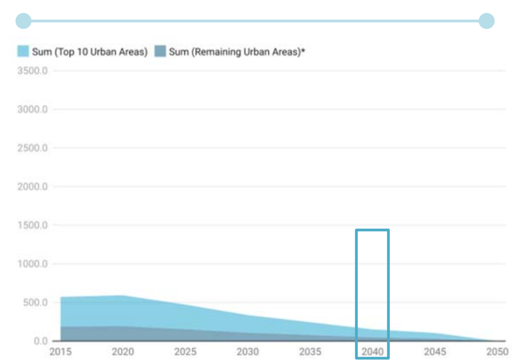
Future Outlook of Emissions for 420 Urban Areas

Across the SSP1 scenarios, urban emissions pathways can lead to 187.9, 442.8 or 151.8 $MtCO_2eq$ in <u>2040</u>

Urban Emissions
$MtCO_2eq$ per year

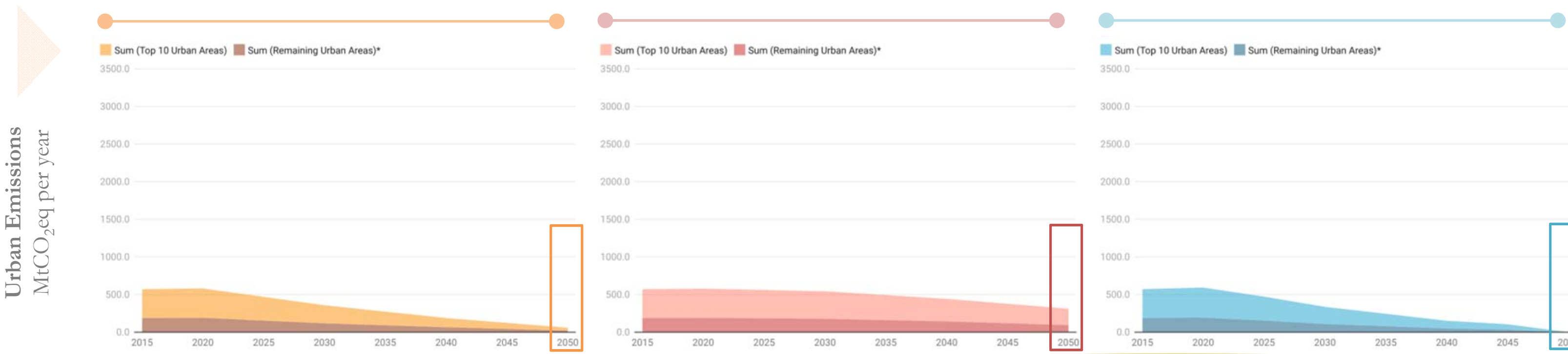






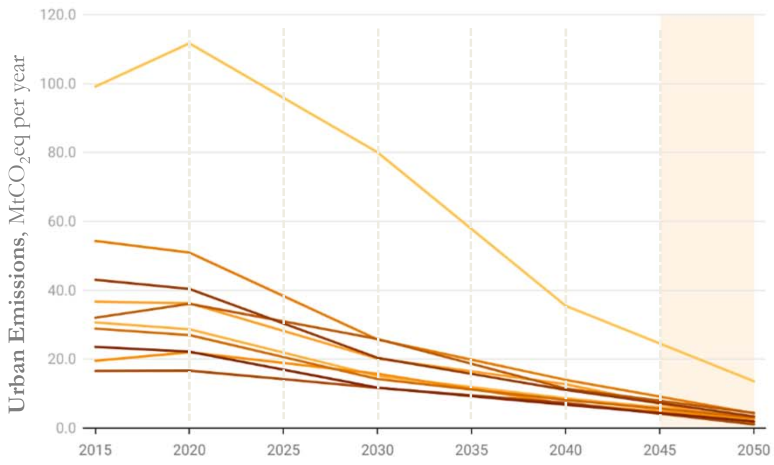
Future Outlook of Emissions for 420 Urban Areas

Across the SSP1 scenarios, urban emissions pathways can lead to 58.7, 311.3 or ~0.0 $MtCO_2eq$ in <u>2050</u>



Top 10 Emitting Areas – Southern and Eastern Europe

Under SSP1-1.9, the top 10 urban areas in this region will need to reduce their total footprint by 352.7 $MtCO_2eq$ by 2050



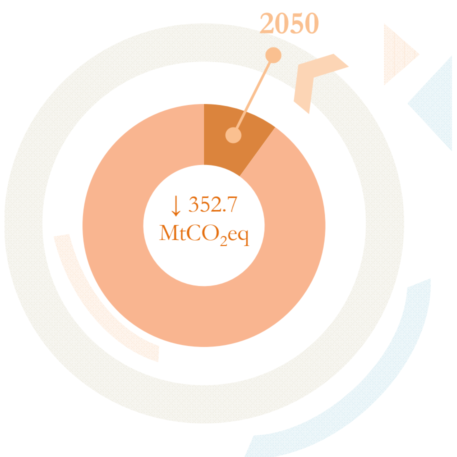
Search in table

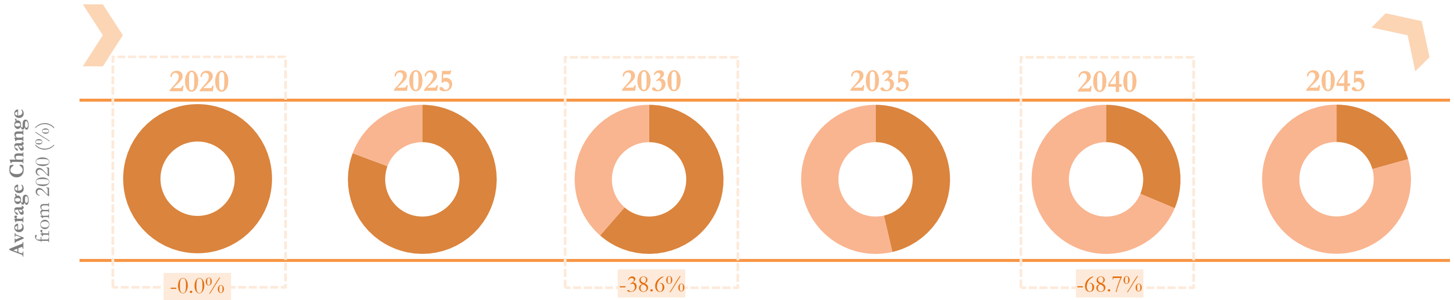
Region → Southern and Eastern Europe

0.3 111.7

Uj	2015	2020	2025	2030	2035	2040	2045	2050
Istanbul	99.1	111.7	95.9	80.0	57.8	35.5	24.5	13.6
Madrid	54.3	50.9	38.3	25.7	19.8	14.0	9.1	4.3
Barcelona	43.1	40.4	30.4	20.4	15.7	11.1	7.2	3.4
Athens	36.7	36.2	28.2	20.2	16.5	12.7	7.1	1.4
Ankara	32.0	36.1	31.0	25.9	18.7	11.5	7.9	4.4
Milan	30.7	28.7	21.9	15.1	11.9	8.7	6.0	3.3
Rome	28.9	27.0	20.6	14.2	11.2	8.2	5.6	3.1
Lisbon	23.6	22.2	17.0	11.7	9.3	6.8	4.4	1.9
Izmir	19.5	22.0	18.9	15.8	11.4	7.0	4.8	2.7
Kiev	16.6	16.7	14.2	11.7	9.5	7.3	4.2	1.1

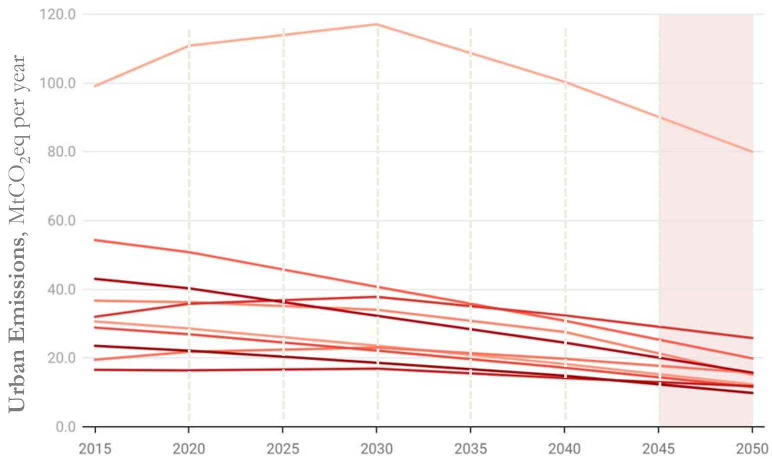
In units of $MtCO_2eq$ per year including CO_2 and CH_4.





Top 10 Emitting Areas – Southern and Eastern Europe

Reductions in SSP1-2.6 remain less than half in 2050 at 171.9 $MtCO_2eq$, again forgoing a missed 1.5°C target



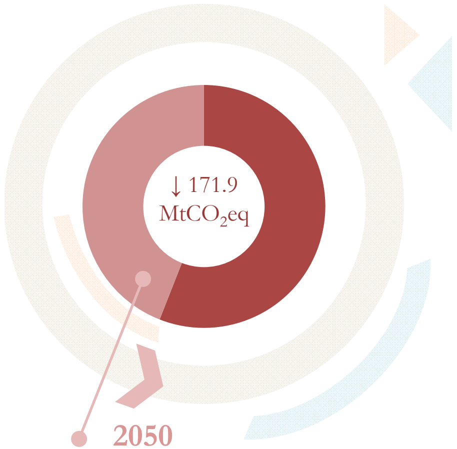
Search in table

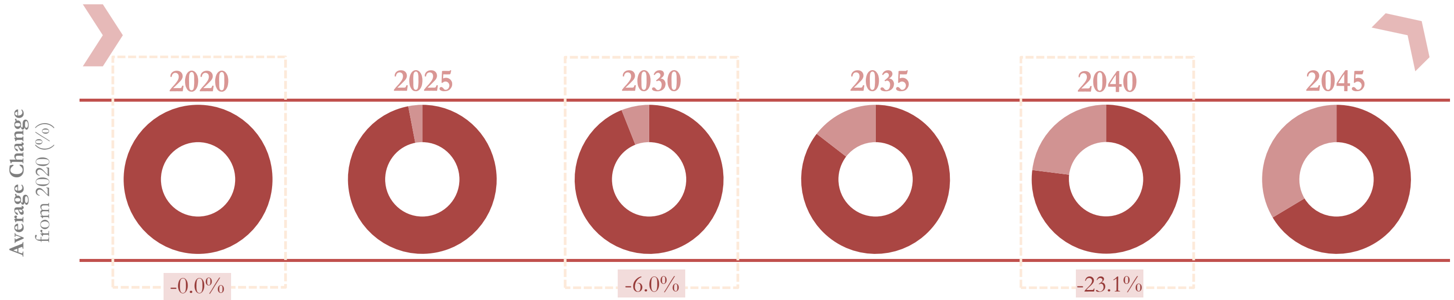
Region → Southern and Eastern Europe

1.1 – 117.1

Uj	2015	2020	2025	2030	2035	2040	2045	2050
Istanbul	99.1	110.8	114.0	117.1	108.7	100.3	90.2	80.0
Madrid	54.3	50.8	45.8	40.7	35.8	30.9	25.4	19.9
Barcelona	43.1	40.3	36.3	32.3	28.4	24.5	20.1	15.8
Athens	36.7	36.3	35.2	34.1	30.8	27.6	21.4	15.2
Ankara	32.0	35.8	36.8	37.8	35.1	32.4	29.1	25.8
Milan	30.7	28.6	26.1	23.6	20.9	18.3	15.3	12.4
Rome	28.9	26.9	24.6	22.2	19.7	17.2	14.4	11.6
Lisbon	23.6	22.2	20.4	18.6	16.8	14.9	12.4	9.9
Izmir	19.5	21.8	22.5	23.1	21.4	19.8	17.8	15.8
Kiev	16.6	16.4	16.7	16.9	15.6	14.2	13.0	11.9

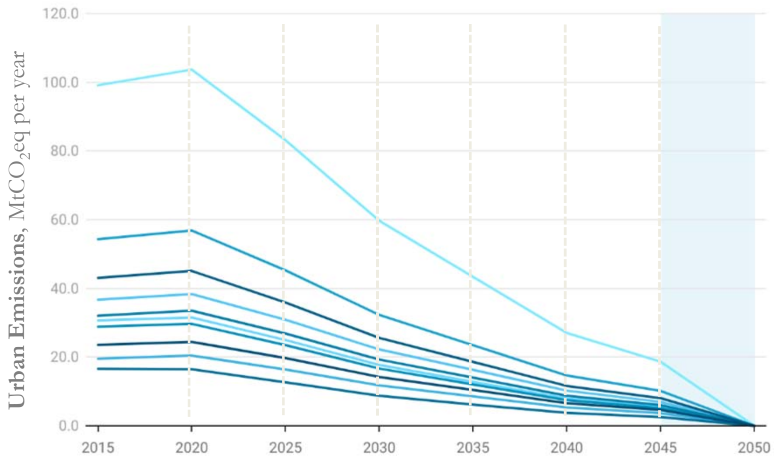
In units of $MtCO_2eq$ per year including CO_2 and CH_4.





Top 10 Emitting Areas – Southern and Eastern Europe

For these areas, 100% RE scenarios provide opportunities to eliminate 400.0 $MtCO_2eq$ of urban emissions in 2050



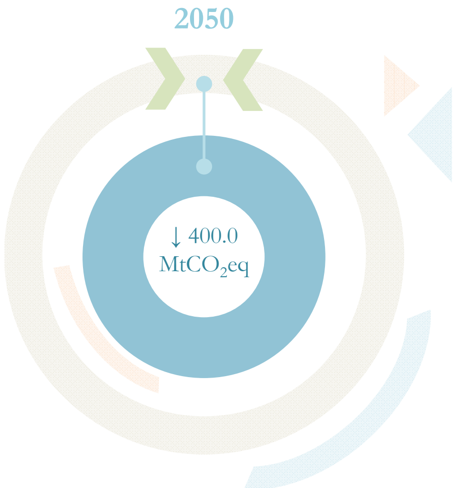
Search in table

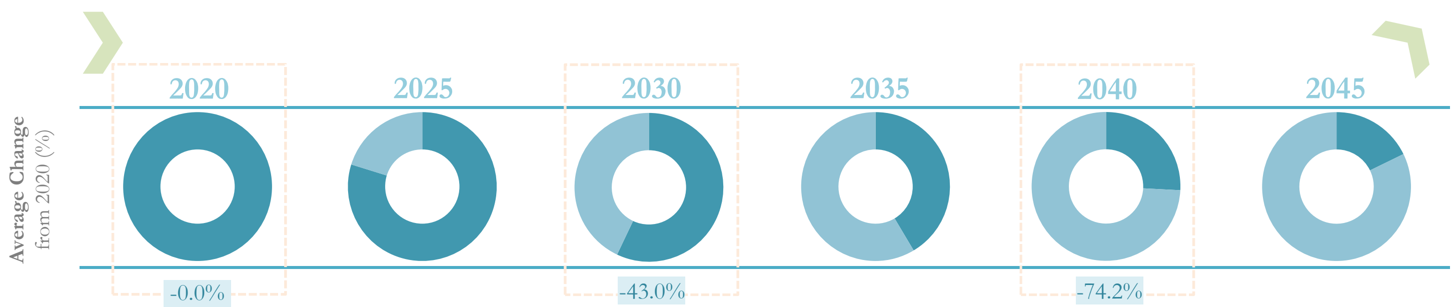
Region → Southern and Eastern Europe

0.0 103.7

Uj	2015	2020	2025	2030	2035	2040	2045	2050
Istanbul	99.1	103.7	83.1	59.7	43.4	27.0	18.7	0.0
Madrid	54.3	56.8	45.3	32.3	23.5	14.6	10.2	0.0
Barcelona	43.1	45.1	35.9	25.6	18.6	11.6	8.0	0.0
Athens	36.7	38.4	30.9	22.2	16.3	10.2	6.9	0.0
Ankara	32.0	33.5	26.9	19.3	14.0	8.7	6.0	0.0
Milan	30.7	31.5	25.0	17.7	12.8	7.9	5.5	0.0
Rome	28.9	29.7	23.5	16.7	12.0	7.5	5.1	0.0
Lisbon	23.6	24.4	19.7	14.2	10.4	6.6	4.6	0.0
Izmir	19.5	20.4	16.4	11.8	8.5	5.3	3.7	0.0
Kiev	16.6	16.5	12.7	8.7	6.2	3.8	2.5	0.0

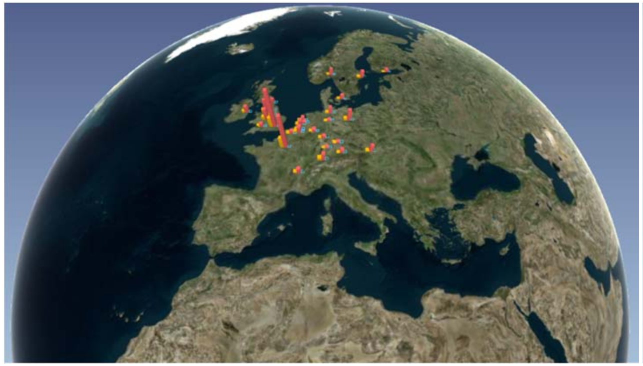
In units of $MtCO_2eq$ per year including CO_2 and CH_4.

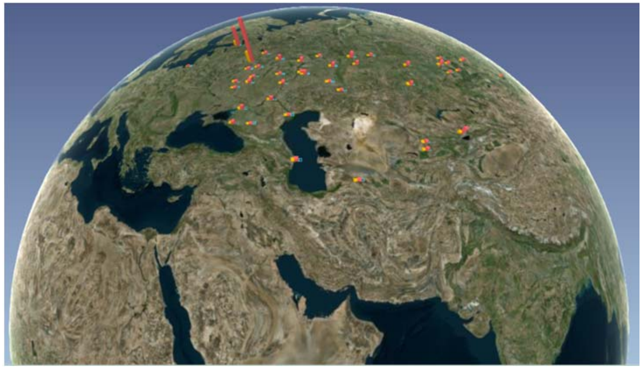


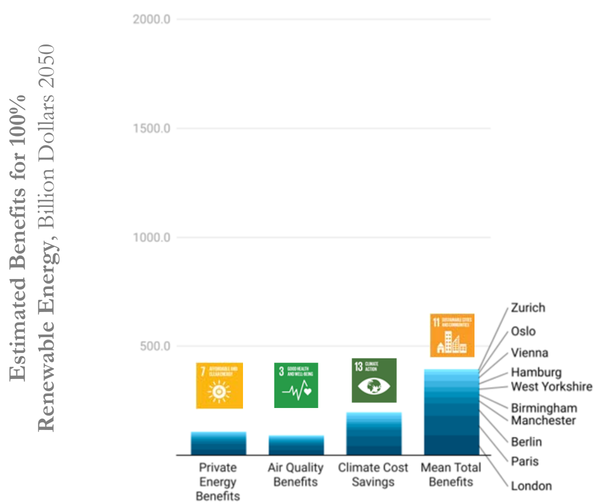


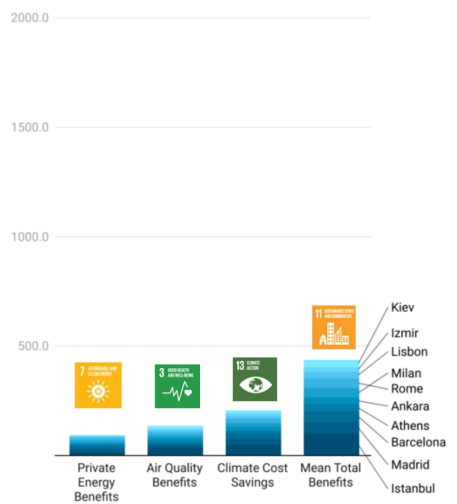
What Kind of Urban Areas Do We Want to See in 2050?

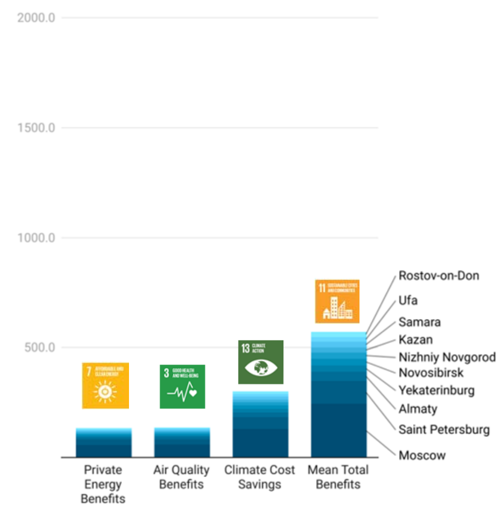
Urban areas that are providing energy, health and climate related benefits for urban inhabitants are possible











Calculated based on local per capita values in Jacobson et al.(2020) with harmonized SSP1 urban population in 2050 based on Kii et al. (2021)

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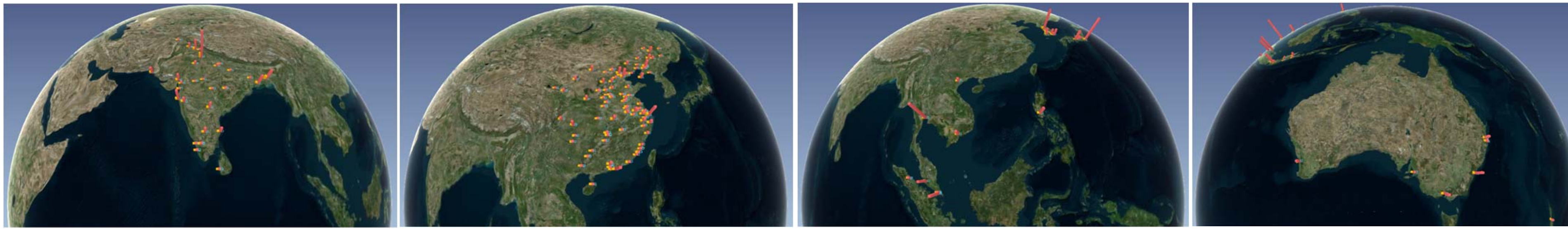
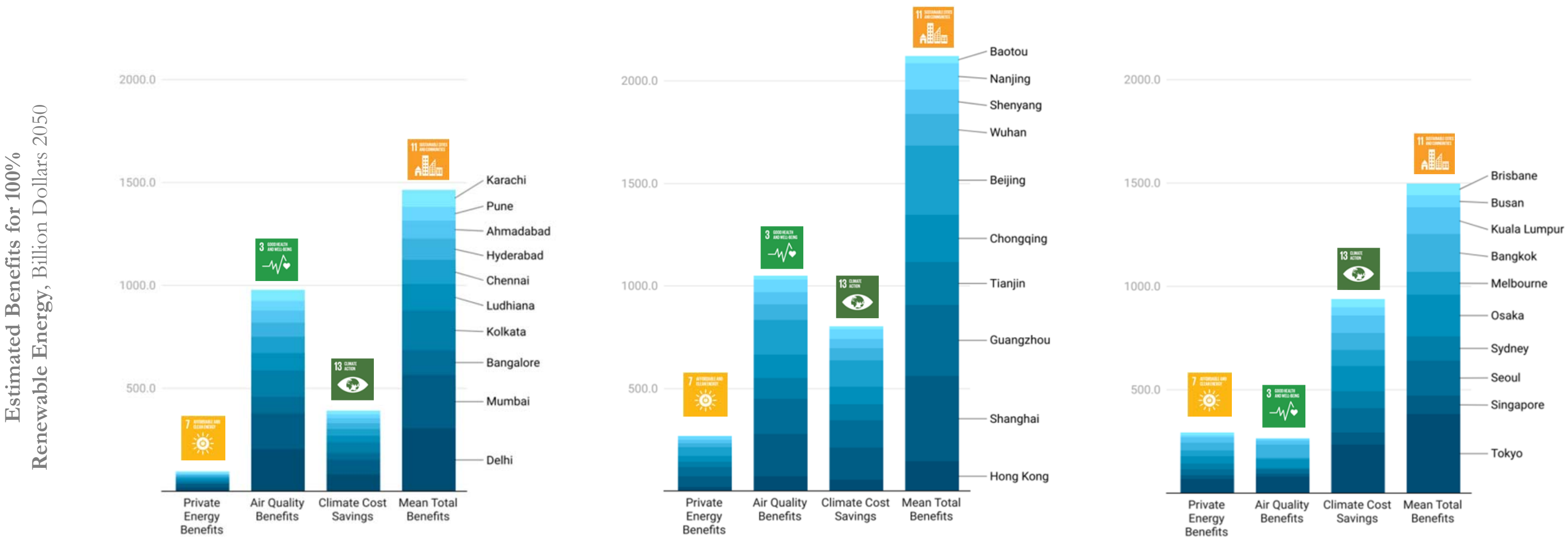


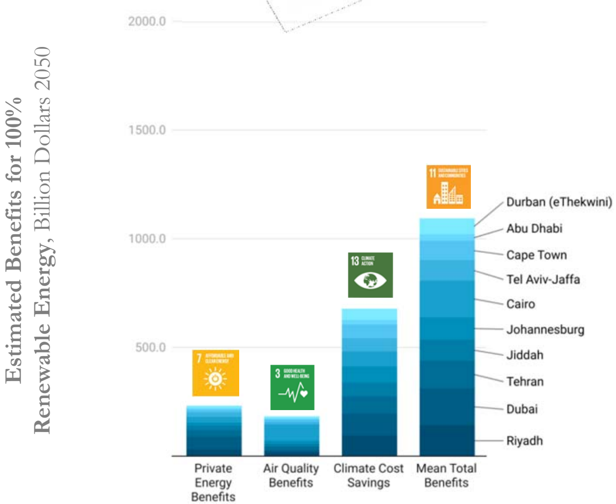


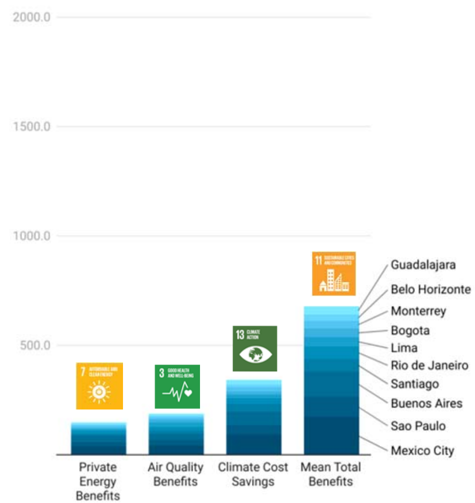
Calculated based on local per capita values in Jacobson et al.(2020) with harmonized SSP1 urban population in 2050 based on Kii et al. (2021)

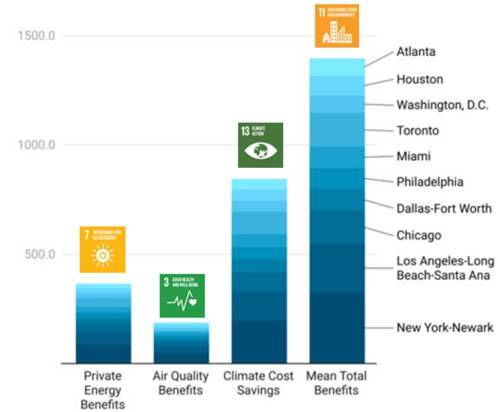
What Kind of Urban Areas Do We Want to See in 2050?

Urban areas that are providing <u>energy, health and climate related benefits for urban inhabitants are possible</u>

Contributions to sustainable development based on the SDGs will continue after 2030



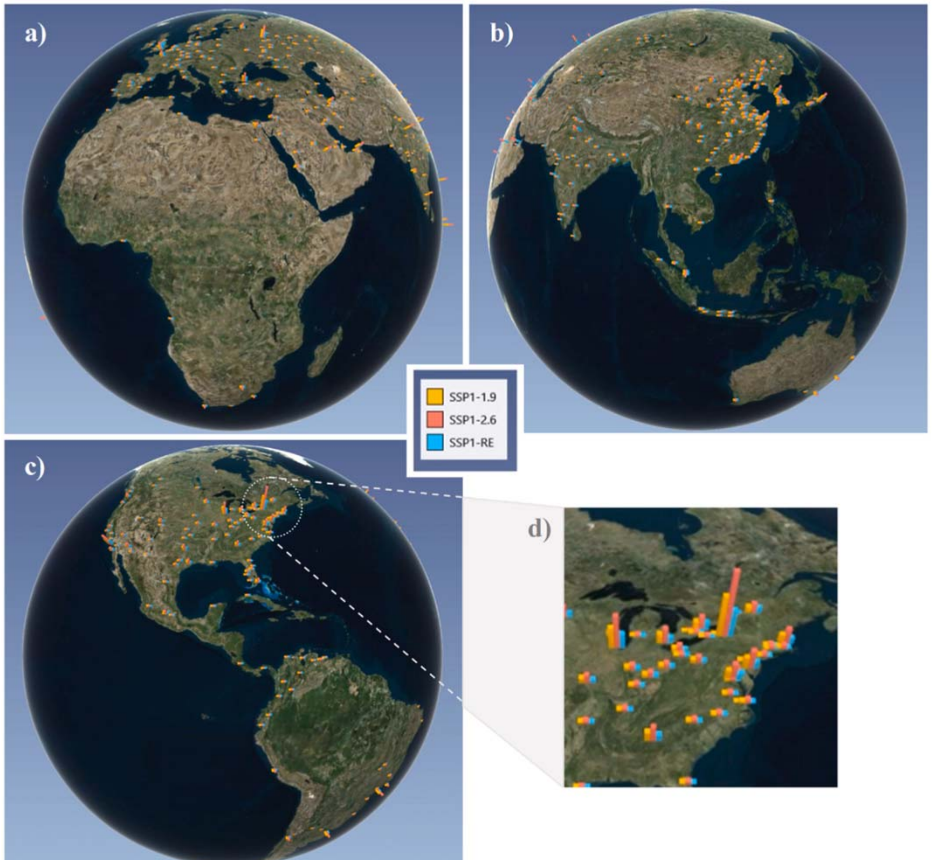


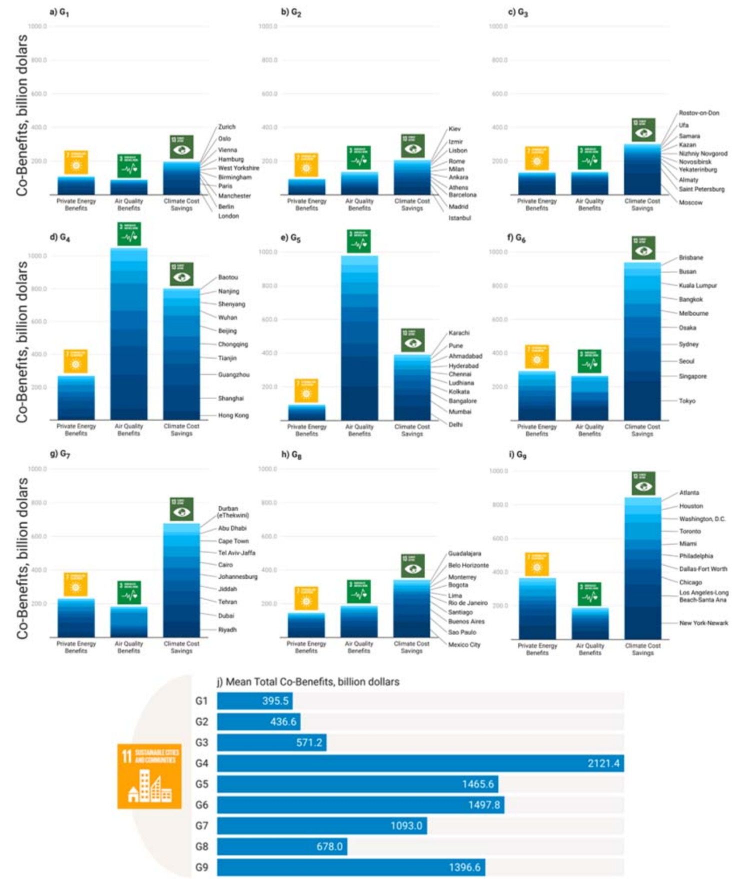


Calculated based on local per capita values in Jacobson et al.(2020) with harmonized SSP1 urban population in 2050 based on Kii et al. (2021)

What Kind of Urban Areas Do We Want to See in 2050?

The total estimated co-benefits for 90 urban areas under SSP1-RE amounts to about 9.7 trillion USD in 2050





Calculated based on local per capita values in Jacobson et al.(2020) with harmonized SSP1 urban population in 2050 based on Kii et al. (2021)

Integrated Scenarios Utilizing Land Use Efficiency

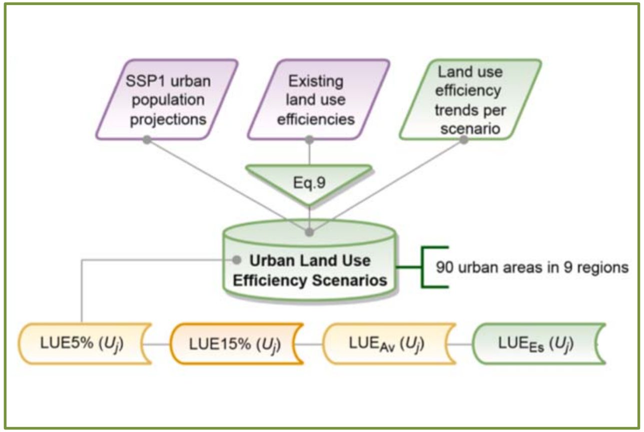
The three SSP1 scenarios for urban emissions are further coupled with scenarios considering land use efficiency

Data inputs – Urban emissions and trends

- Global Gridded Model of Carbon Footprints
- Global Human Settlement Layer GHSL-UCDB
  → **Land use efficiency (LUE) per urban cluster**
- Urban population by SSP per urban cluster

Land use efficiency is tracked per urban area for SDG11.3 (*) and is here used for extended scenarios

11 SUSTAINABLE CITIES AND COMMUNITIES



Overall method based on **original research work**

(*) SDG11.3: "By 2030, enhance inclusive and sustainable urbanization and capacity for participatory, **integrated and sustainable human settlement planning and management** in all countries"

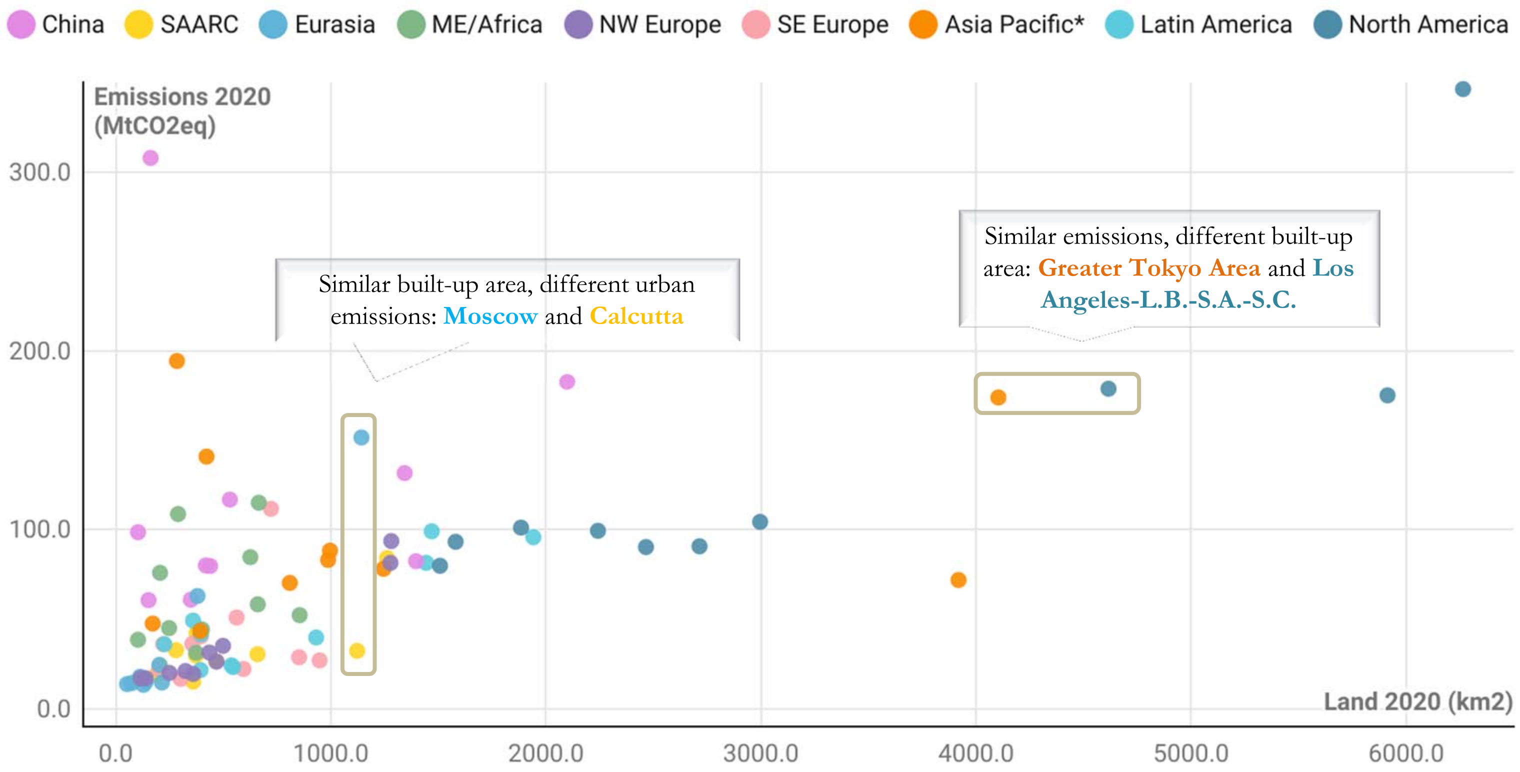
Scenario	Urbanization Qualities
SSP1-RE	Rapid / Relatively Compact
SSP1-1.9	Rapid / Relatively Compact
SSP1-2.6	Rapid / Relatively Compact

Scenario	Land Use Efficiency
LUE 5%	5% improvement every 5 years
LUE 15%	15% improvement every 10 years
LUE Av	Convergence to regional average LUE
LUE Best	**Transition to the best regional LUE**

11 SUSTAINABLE CITIES AND COMMUNITIES

2-Dimensional Scenario Space – Emissions and Land

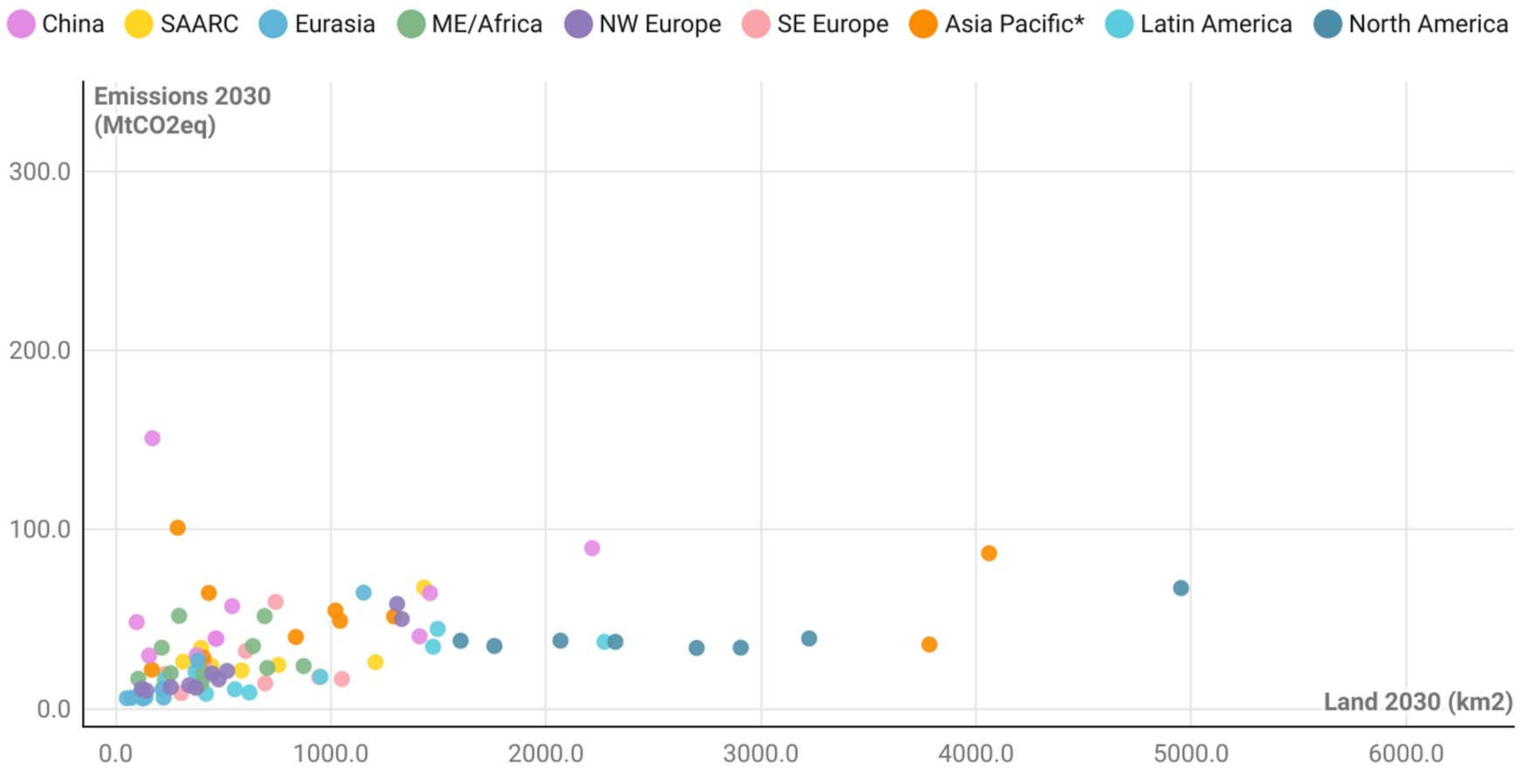
In 2020, 90 urban areas were responsible for 5.9 ± 0.3 $GtCO_2$eq of emissions, covering 83.3 x 10^3 km^2 of built-up area



Source: Kılkış (2022), Urban emissions and land use efficiency scenarios towards effective climate mitigation in urban systems, *Renewable and Sustainable Energy Reviews* 167: 112733

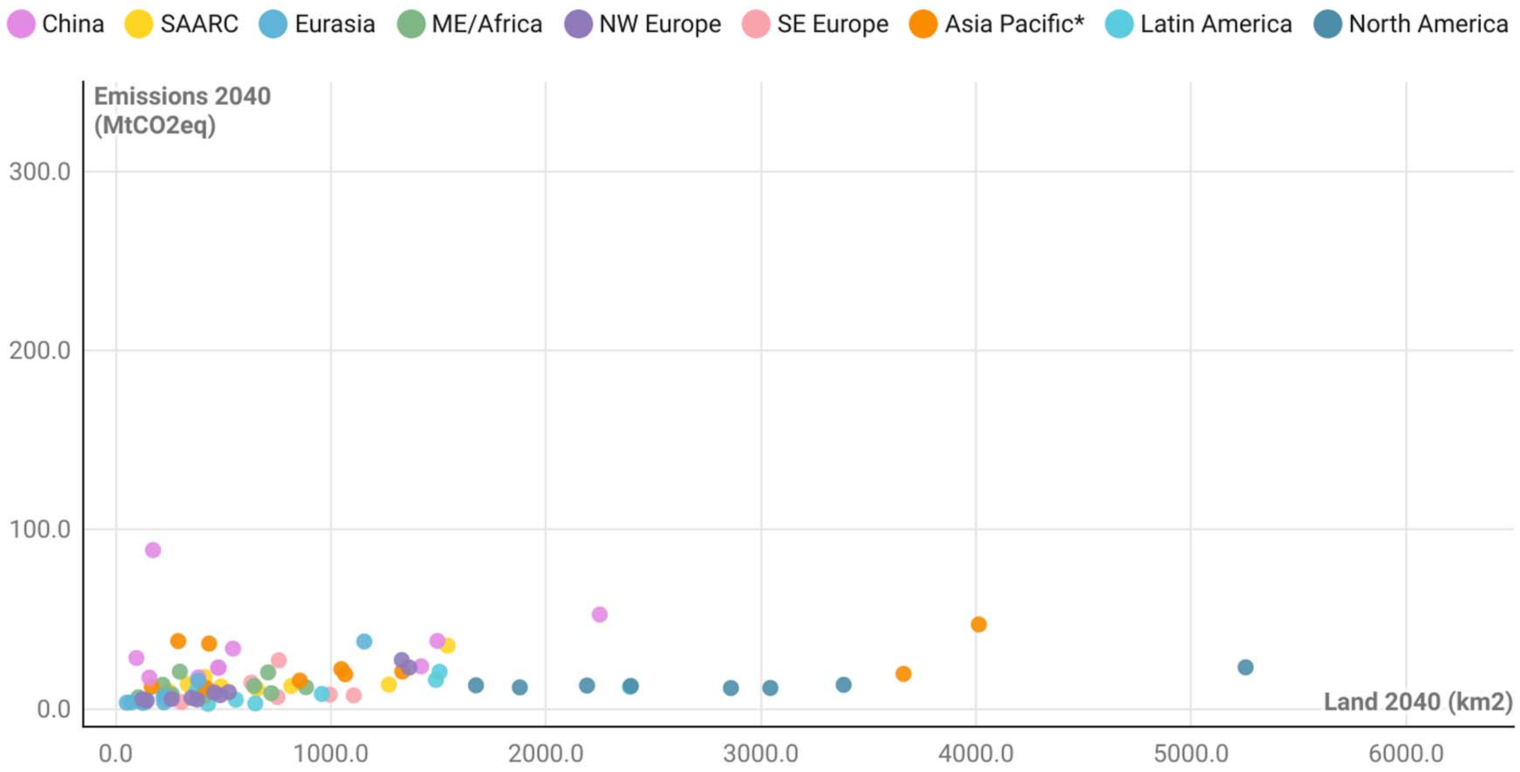
2-Dimensional Scenario Space – Emissions and Land

In 2030, the 90 urban areas progress toward 100% RE while limiting growth in built-up area to about 6.3 x 10^3 km^2



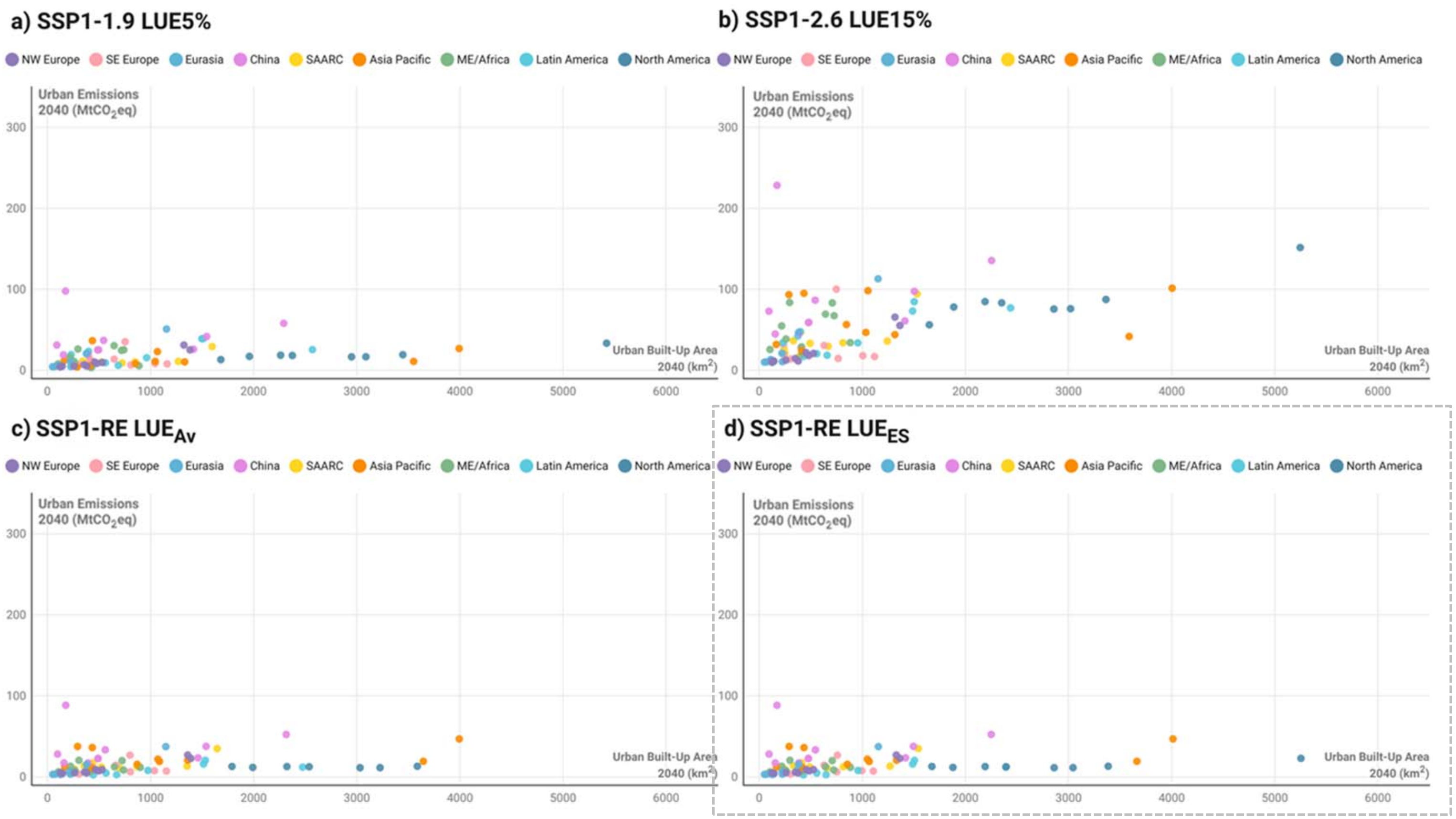
2-Dimensional Scenario Space – Emissions and Land

In 2040, the 90 urban areas progress toward 100% RE while limiting growth in built-up area to about 10.1 x 10^3 km^2



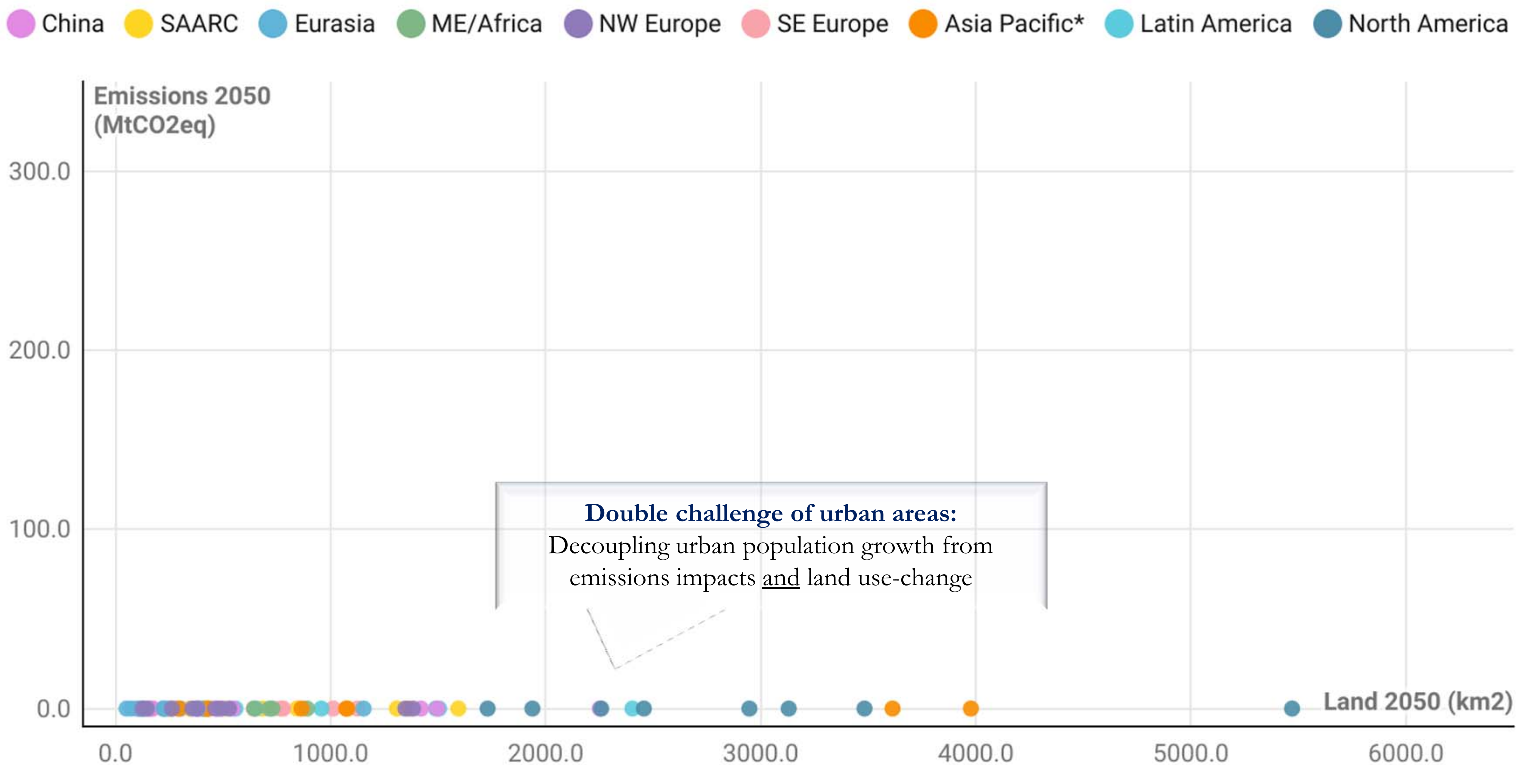
2-Dimensional Scenario Space – Emissions and Land

Different combinations of urban emissions and urban built-up area represent different implications for mitigation



2-Dimensional Scenario Space – Emissions and Land

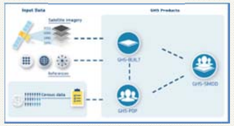
In 2050, the 90 urban areas reach the 100% RE target while limiting growth in built-up area to about $\underline{11.9 \times 10^3\ km^2}$



Cumulative Emissions from Urban Land Use Change

Even in the scenario with the best LUE, land use change in local biomes will have <u>cumulative emissions penalties</u>

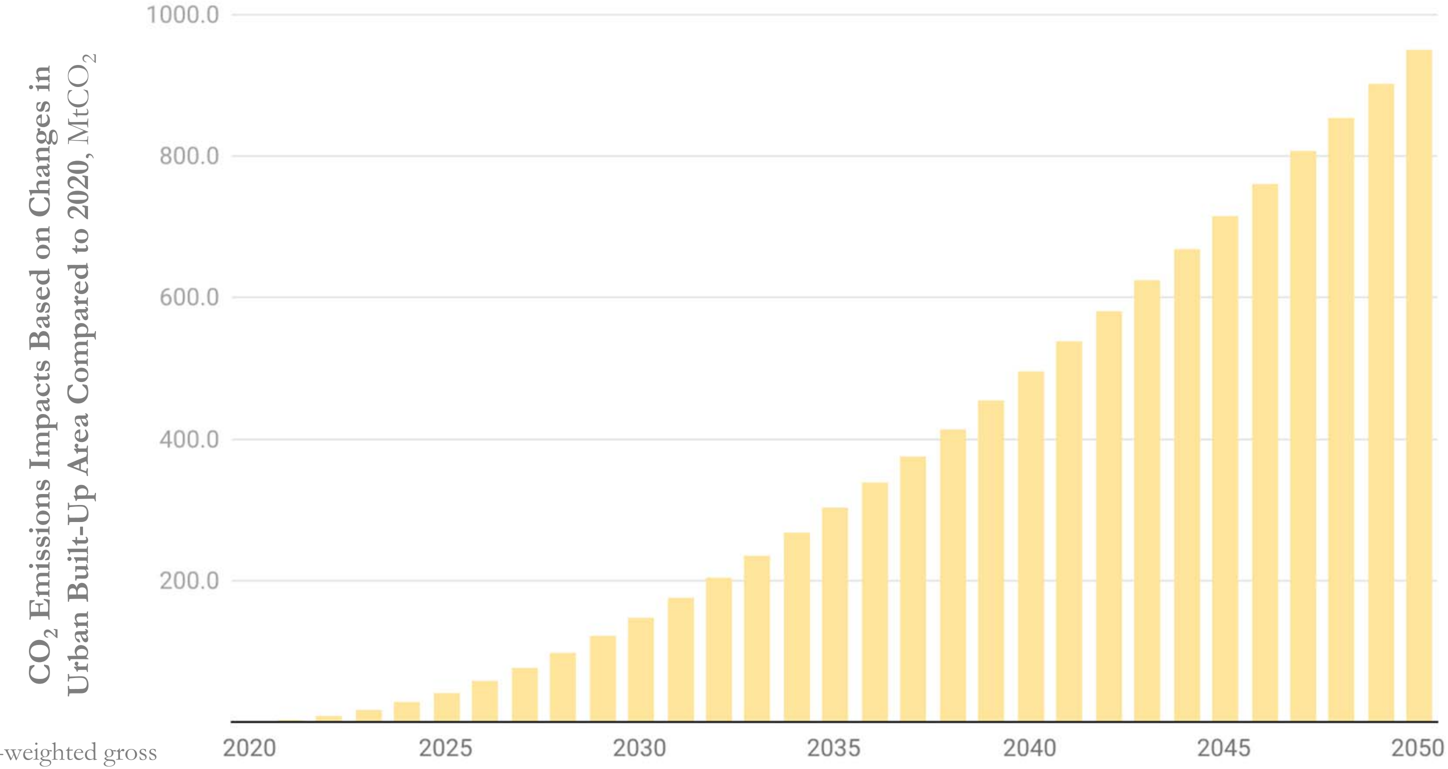
GHSL



Local Biomes (U_j)

CO_2 Sequestration Potential per Year

Impact in 2050



Source: Based on area-weighted gross primary productivity per biome in Harper et al. (2016) using in JULES model.

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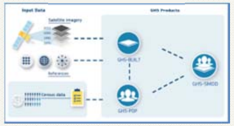

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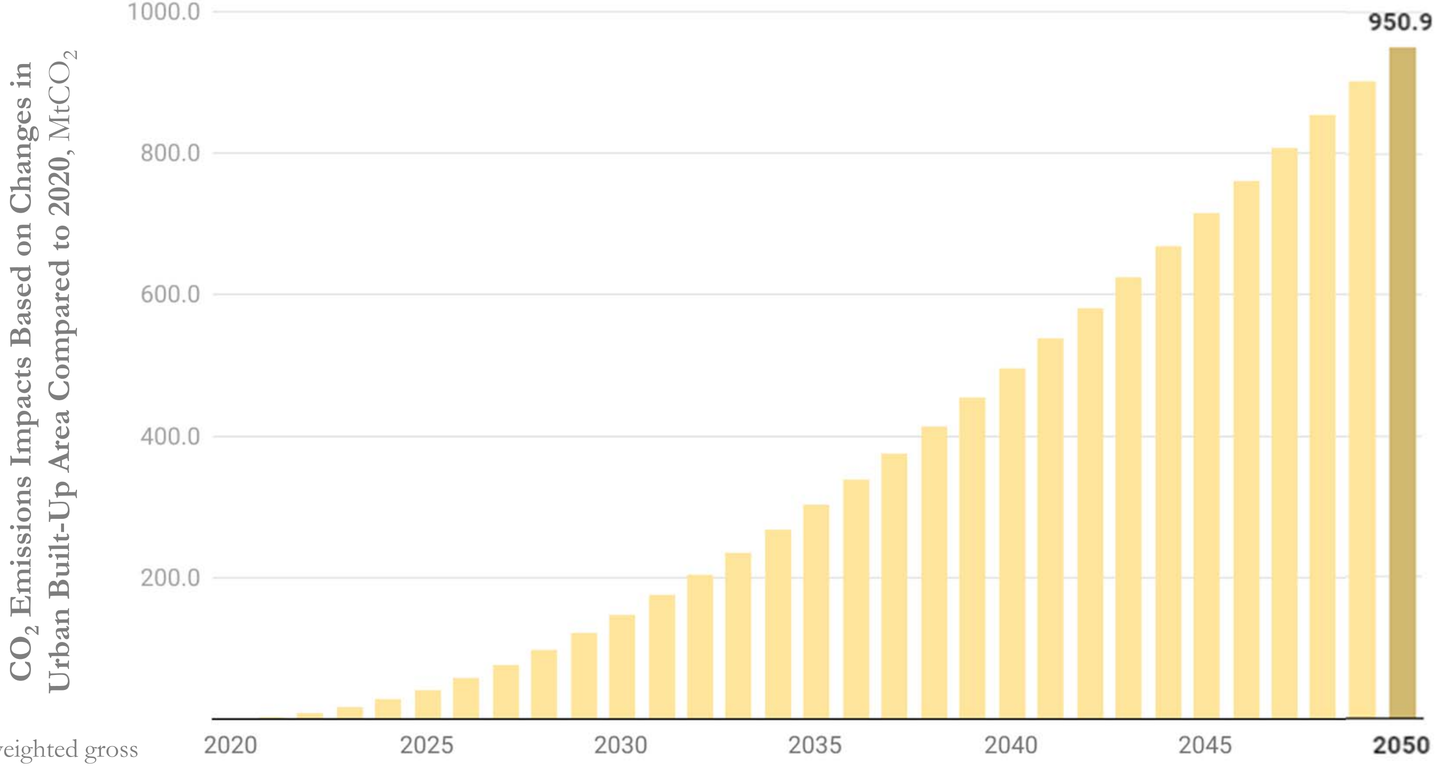
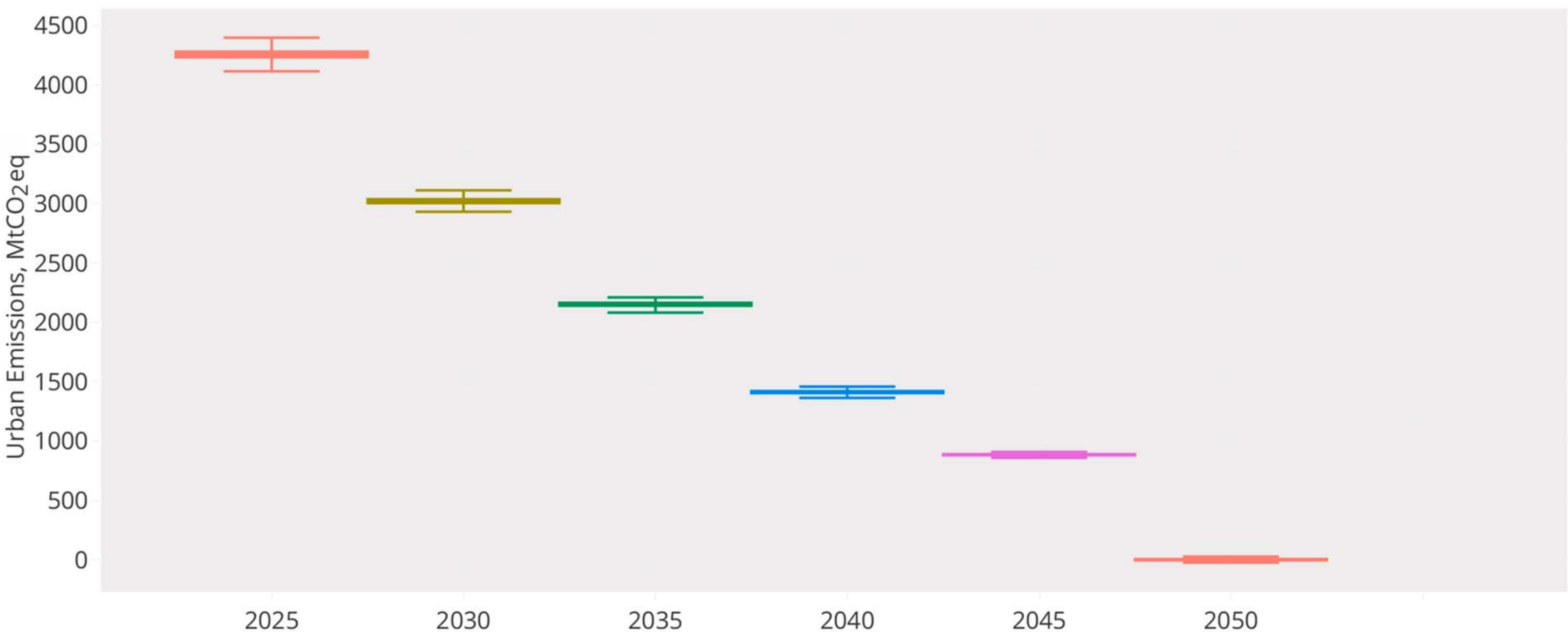


Source: Based on area-weighted gross primary productivity per biome in Harper et al. (2016) using in JULES model.

Importance of the Success of Urban Governance

If each urban area reaches SSP1-RE values <u>within ±10% randomly</u>, progress towards net-zero can be still within sight

Sum of the Emissions of 90 Urban Areas with 10,000 Monte Carlo Simulations for Each Urban Area, $MtCO_2eq$

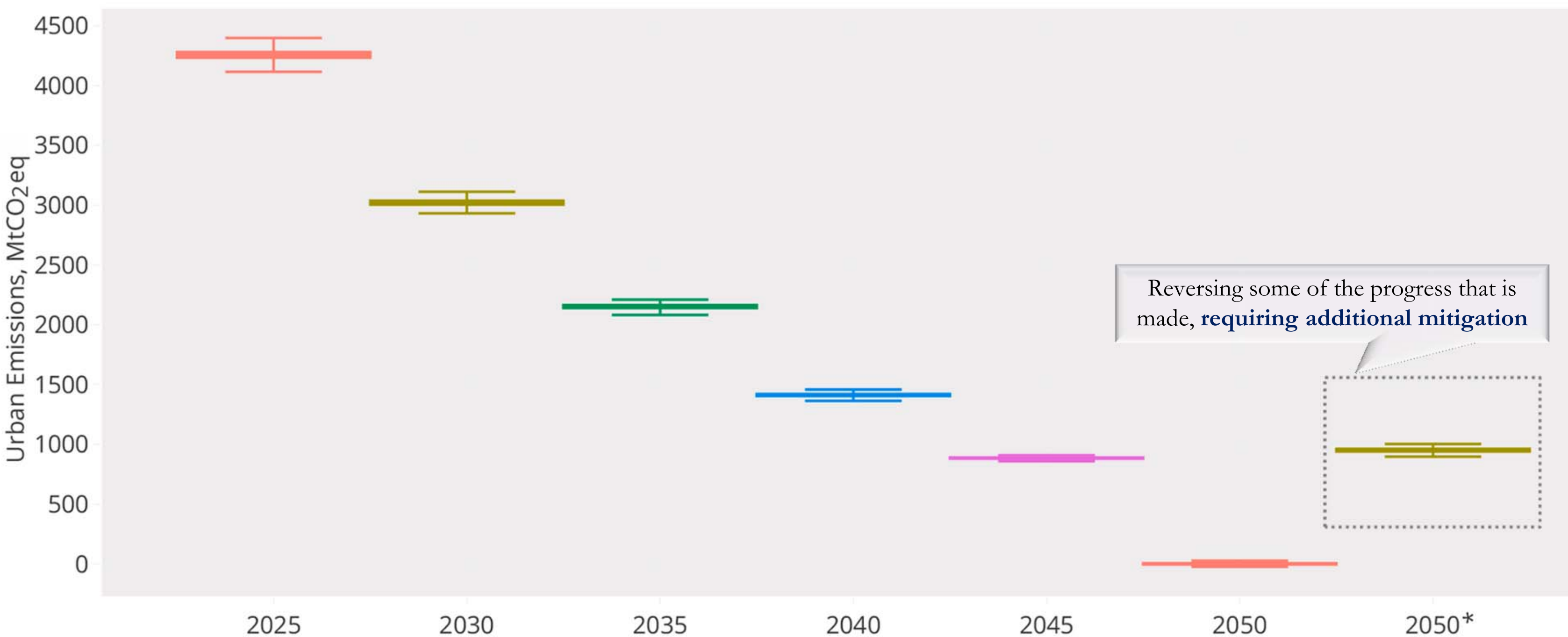


Source: Kılkış (2022), Urban emissions and land use efficiency scenarios towards effective climate mitigation in urban systems, *Renewable and Sustainable Energy Reviews* 167: 112733

Cumulative Emissions from Urban Land Use Change

Cumulative emissions from land use change can alter a net-zero status in 2050 by ~1 $GtCO_2eq$ for the 90 urban areas

Sum of the Emissions of 90 Urban Areas with 10,000 Monte Carlo Simulations for Each Urban Area, $MtCO_2eq$

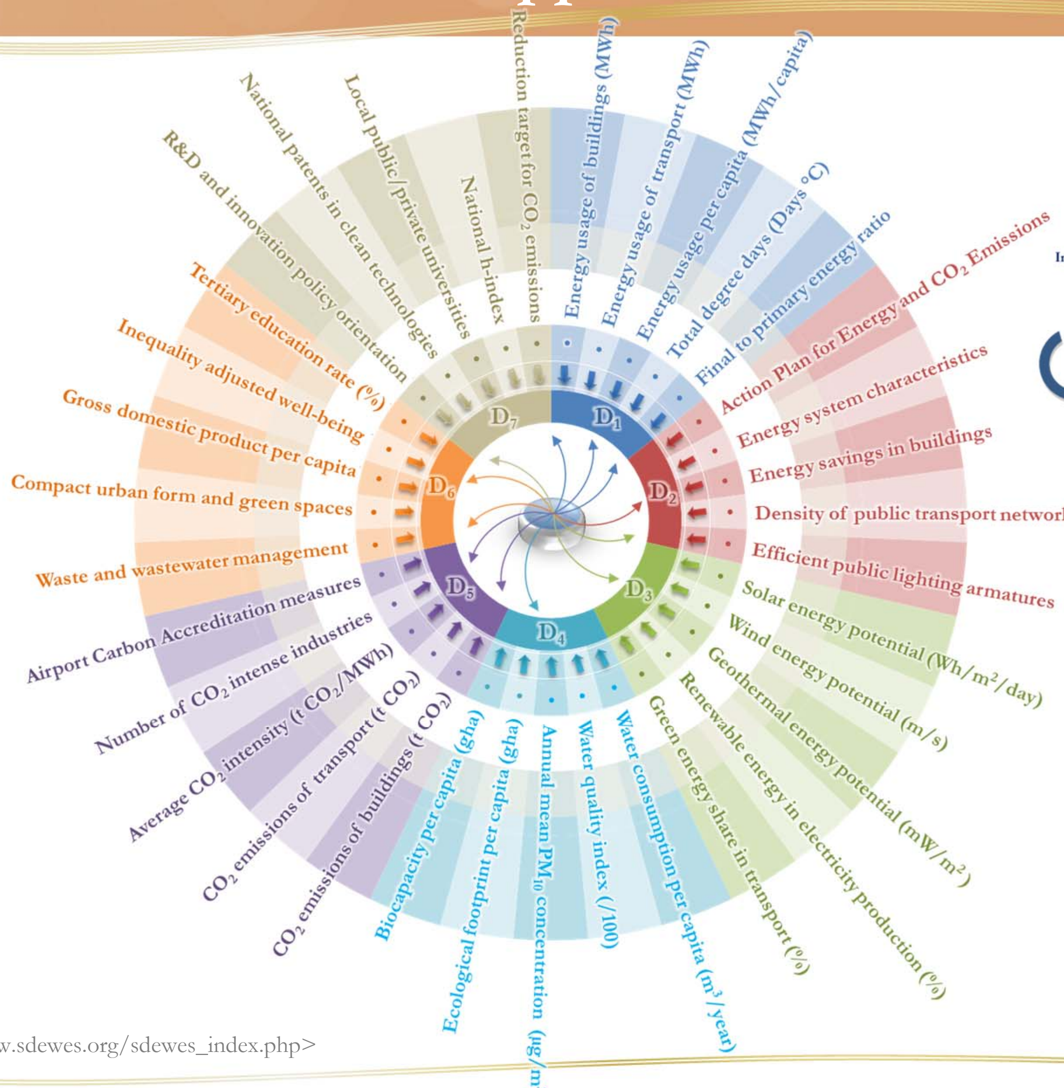


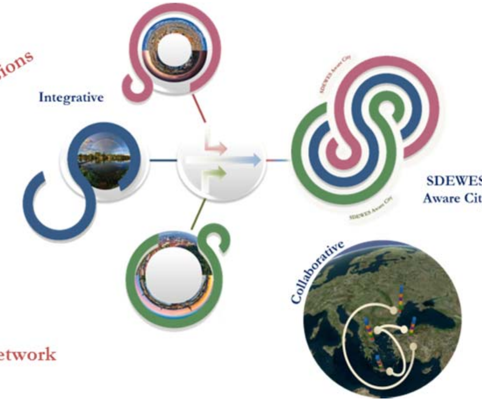
Source: Kılkış (2022), Urban emissions and land use efficiency scenarios towards effective climate mitigation in urban systems, *Renewable and Sustainable Energy Reviews* 167: 112733

Multi-Dimensional Approach of the SDEWES Index

SDEWES Index

- D_1: Energy Usage and Climate
- D_2: Penetration of Energy and CO_2 Saving Measures
- D_3: Renewable Energy Potential and Utilization
- D_4: Water Usage and Environmental Quality
- D_5: CO_2 Emissions and Industrial Profile
- D_6: Urban Planning and Social Welfare
- D_7: R&D, Innovation and Sustainability Policy



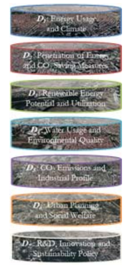


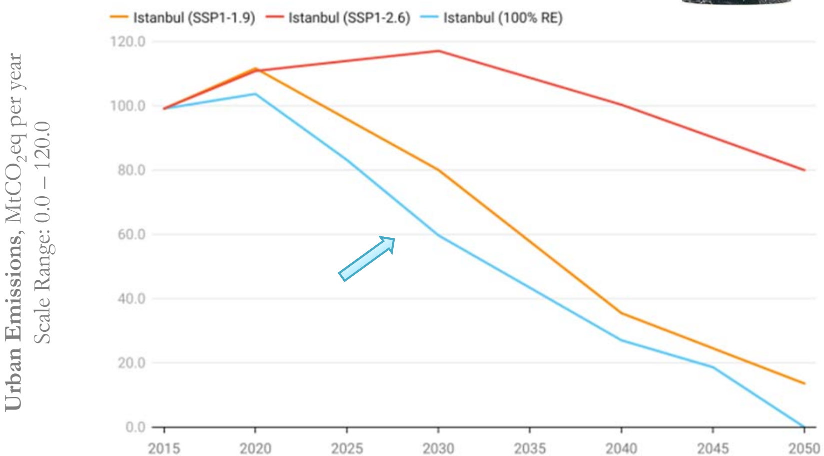
- Supporting **renewable energy penetration**
- Integration of **urban and energy planning**
- **Decoupling** of emissions from greater wellbeing

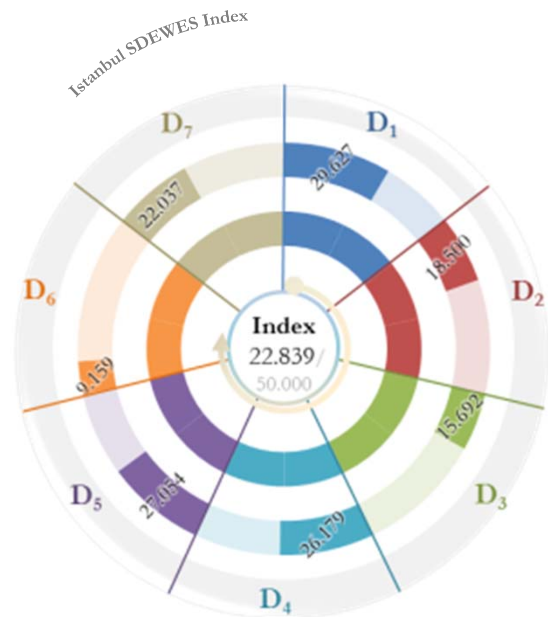
Source: SDEWES Index <https://www.sdewes.org/sdewes_index.php>

Actions Urban Areas Are Taking and Opportunities

- Can learn from other urban areas and **plan for realizing higher reduction targets**
- National strategy for smart and sustainable cities that are adding value to welfare
- → SDEWES Index: Challenged City







Making the complete shift for the urban energy system and beyond

Co-benefits of 100% RE in the urban area:

Energy, air quality and climate cost savings in 2050

Monetary units in USD

Source: Calculated based on local per capita values for 2050 in Jacobson et al.(2020) with SSP1 urban population projection

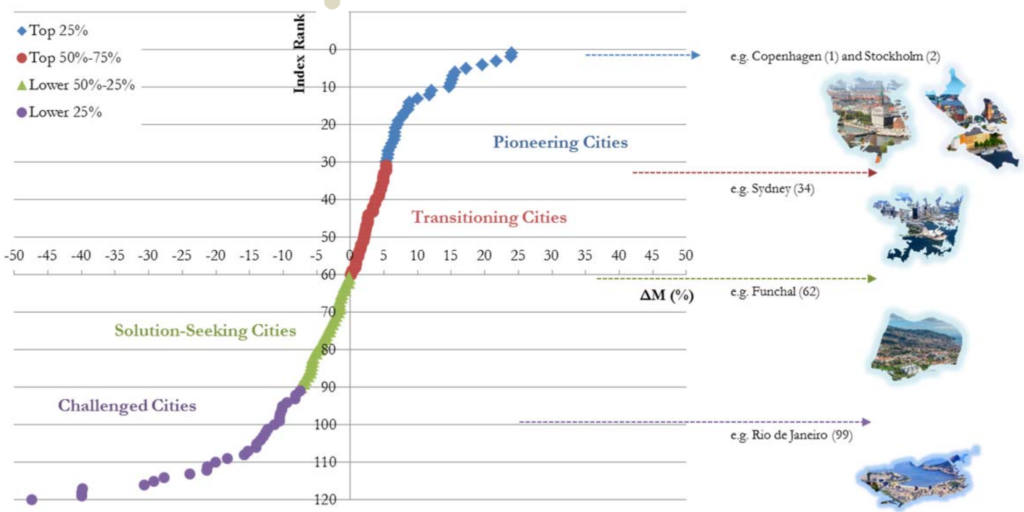
Sources: Ministry of Environment and Urbanization; Barcelona's Climate Plan 2018 – 2030

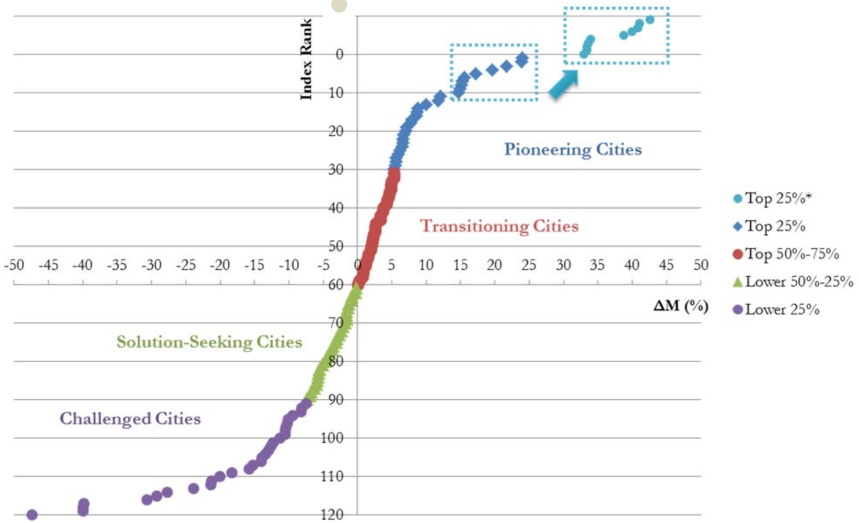
Even Pioneers Can Improve – Advancing Together

All urban areas can improve their performances and even the pioneers can improve by advancing urban integration

- Zeroing energy emissions
- 100% renewable electricity
- All cities with lowest PM_{10}
- Low ecological footprint
- Additional urban planning

Achieving collectively, even the pioneers



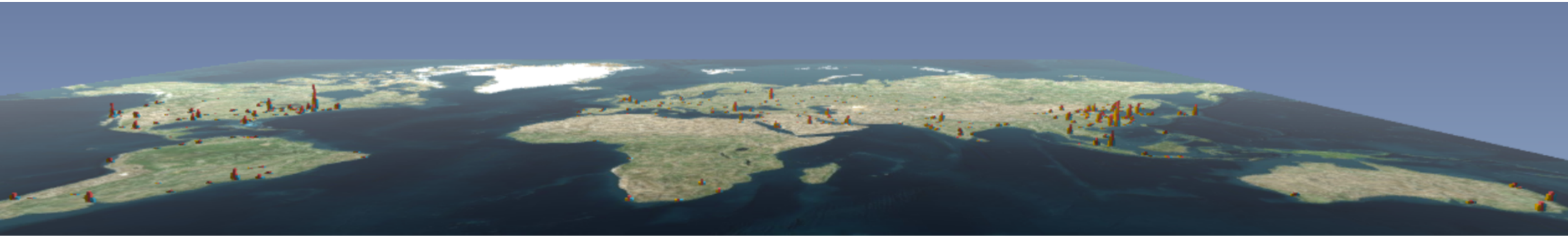


Source: Kılkış (2019), Benchmarking the sustainability of urban energy, water and environment systems and envisioning a cross-sectoral scenario for the future, *Renewable and Sustainable Energy Reviews* 103: 529-545

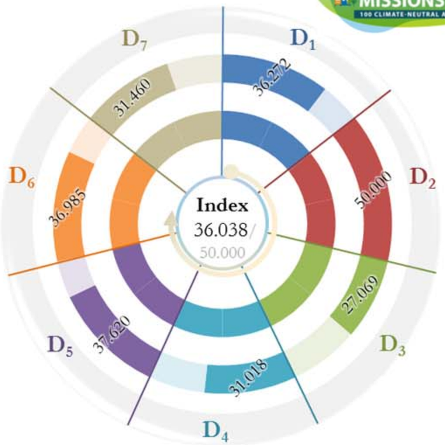
Source: Kılkış (2020), Integrated approach for climate neutrality in urban areas with correct timing and response, *Climate Neutrality in Cities Panel*

Urban Enablers of Action for Smart Energy Systems

Beyond the top emitting 420 urban areas, other urban areas can be pioneers for net-zero emissions much earlier



SDEWES Index for Copenhagen (Rank 1 / 120)



Urban Enablers of Smart Energy Systems

- Emphasis on carbon-neutral district heating by 2025 and **energy system flexibility** based on integration for future energy systems with heat pumps and power-to-X
- **Partnerships** for flexible electricity use at large scale

Sources: SDEWES Centre (2018); Kılkış (2019) <https://www.sdewes.org/sdewes_index.php>

Source: Copenhagen 2025 Climate Plan Roadmap 2021-2025

Integrated Approach for Net-Zero GHG Emissions

The mission on climate-neutral cities with 112 cities will involve an integrated approach for net-zero GHG emissions

System flexibility options will allow reaching **much higher shares of RE in the broader European energy system**

Resource Utilization

Energy Transition

- **Reducing the amount of total waste generated** and halving the amount of residual (non-recycled) municipal waste by 2030

- **Coordinated planning and operation of the energy system as a whole**, across multiple energy carriers, infrastructures, and consumption sectors

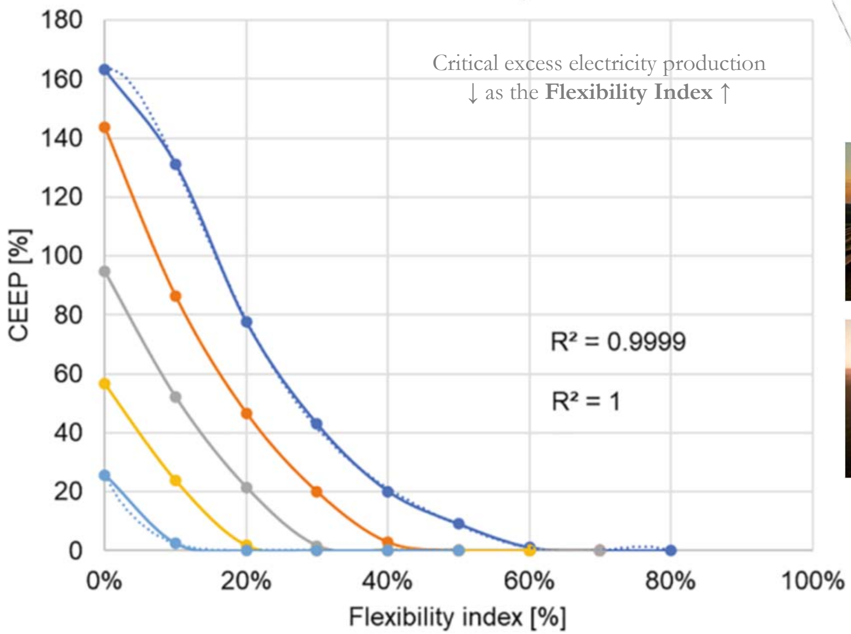
- Modern, renewable based **smart district heating and cooling systems**
- **Twin green and digital transitions**, new forms of cooperation
- Systemic adaptation beyond sectors and **nature-based solutions**

Sources: EC (2019); EC (2020); EC (2021)

Beyond Scenarios – Time to Realize the Pathways

Enhancing system flexibility for the highest penetration of renewable energy requires urban level contributions

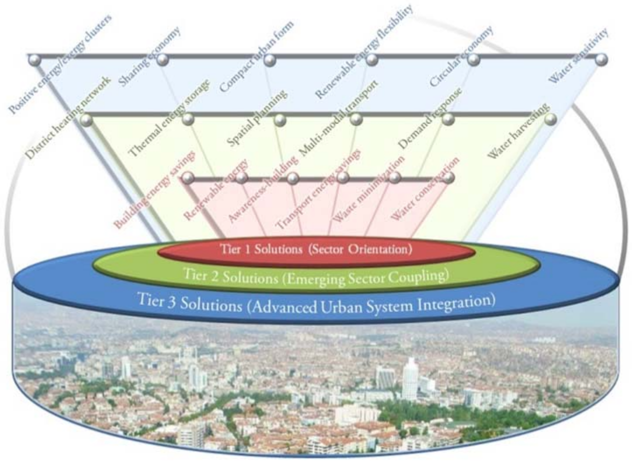
Demand flexibilization as an enabler, e.g. vehicle to grid and power to heat



Source: Pfeifer et al. (2021), Flexibility index and decreasing the costs in energy systems with high share of renewable energy, *Energy Conversion and Management* 240: 114258

The 420 urban areas **can mobilize** to realize the pathways with wider views of integrated action!

Advancing from sector orientation to emerging sector coupling and **urban system integration**

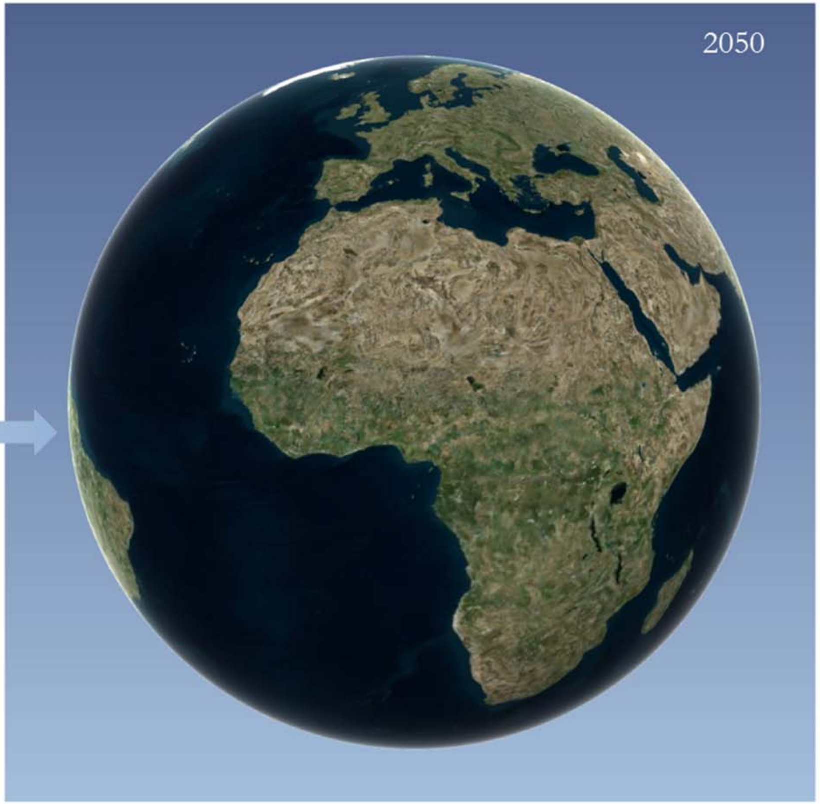


Source: Kılkış (2021), *Energy* 236:121394

* Due to the time dimension of balancing supply and demand, can also **save exergy from being destroyed in the overall system**

No Other Time to Act and Scale Up Than Now

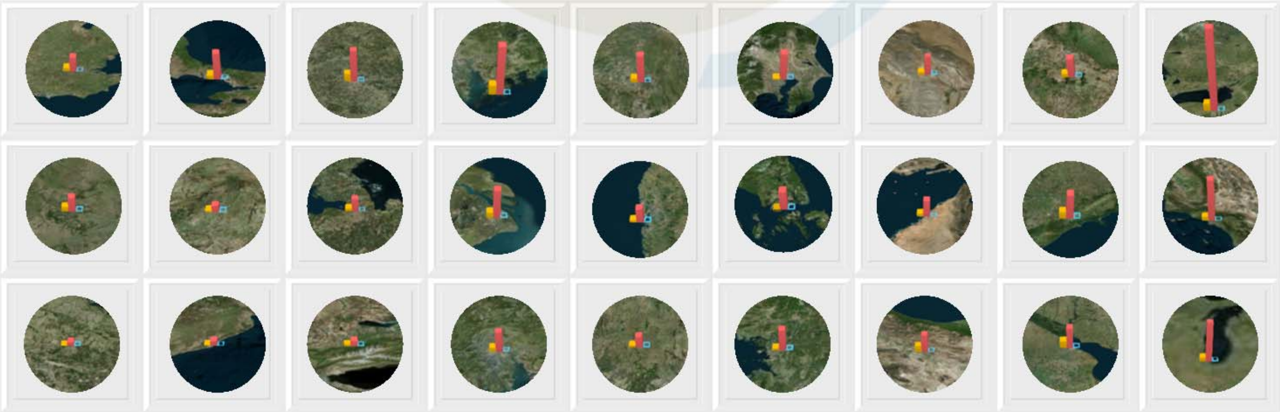
Outcomes will depend on <u>enabling a shift to sustainability</u>



Represents **original data analysis** that is included in Kılkış (2022)

Targeting Sustainable Urban Systems Across the World

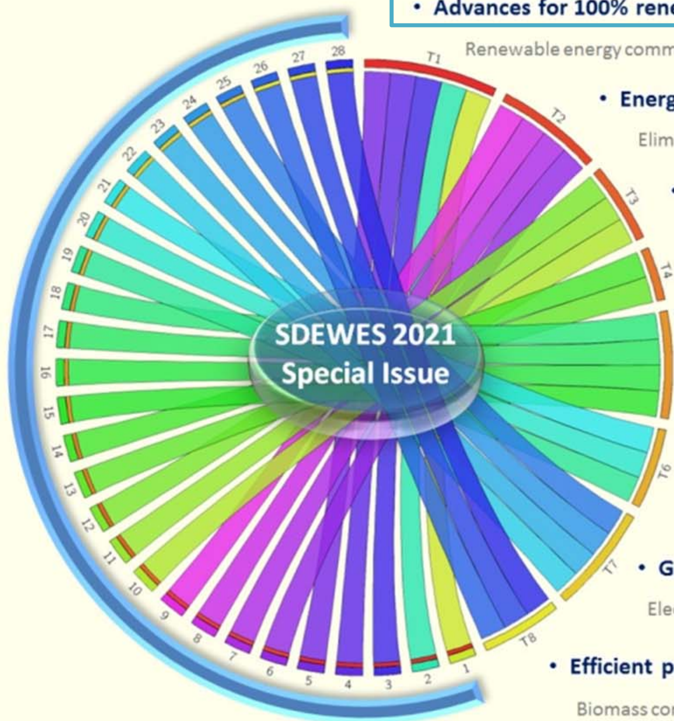
Collective action across all regions for more sustainable urban systems can support making a world of a difference!



2050 Scenario Comparisons for the Top 3 in Each Region

Effective Climate Mitigation with System Integration

Mitigating climate change requires an effective approach that involves integrated, coordinated, and synergistic action



- **Advances for 100% renewable energy systems**
  Renewable energy communities, energy planning, district heating and cooling networks, sharing energy resources
- **Energy security with sustainable energy solutions**
  Eliminating natural gas use for space heating, thermal zoning, sustainable cooling, kinetic facades
- **Transforming transport for energy transition solutions**
  Electrified transport in smart energy networks, decarbonization of the maritime sector
- **New frontiers in renewable energy technologies**
  Accurate forecasting of marine energy, renewable energy for monitoring water quality
- **System restructuring for the energy transition**
  Electricity markets, flexibilisation, deep geothermal from abandoned drilling sites
- **Upgrading of biomass for biofuel production**
  Catalytic pyrolysis for the circular economy, efficient conversion of lignocellulosic biomass
- **Green hydrogen innovations and heat transfer**
  Electrocatalysts, optimization, waste heat utilization, high performance heat exchangers
- **Efficient processes for sustainable combustion**
  Biomass combustion, pressurized oxy-combustion, supercritical combustion of biomass resources


Renewable Energy

Capturing features of hourly-resolution energy models through statistical annual indicators

Highlights

- IAMs are yearly-resolution models with difficulties to capturing dynamics generated from variable renewables.
- Different methods for introducing sub-annual information are being used in IAMs.
- Novel method to translate dynamics of hourly-resolution into yearly-resolution models.
- Test for the current European region, robust, flexible and easily generalizable to other countries.

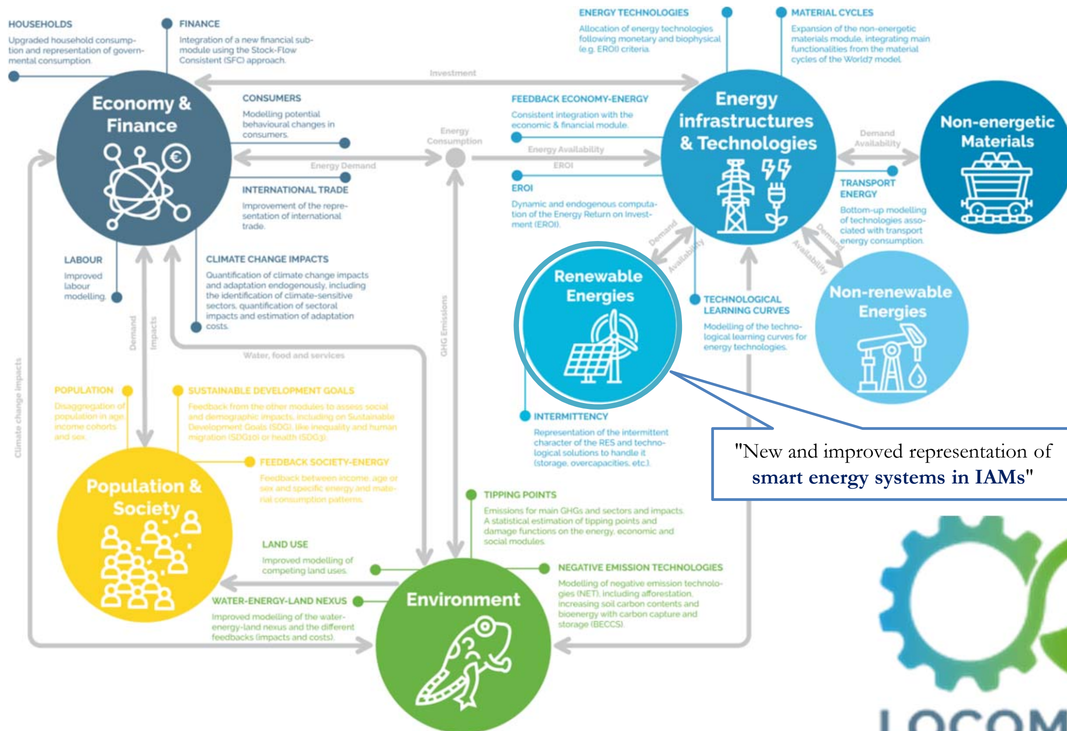
LOCOMOTION

Source: Effective mitigation of climate change with sustainable development of energy, water and environment systems, SDEWES 2021 Special Issue in *Energy Conversion and Management* (ECM) <https://doi.org/10.1016/j.enconman.2022.116146>

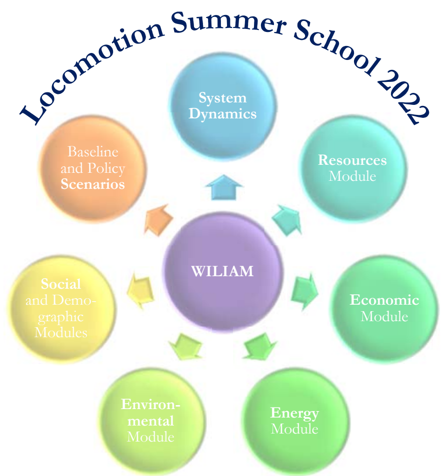
Overall Comparison of the Priorities with WILIAM

WILIAM is addressing important and essential areas of improvement opportunities for the next cycle AR7

WIthin Limits Integrated Assessment Model (WILIAM)



"New and improved representation of **smart energy systems in IAMs**"



Source: Locomotion Project <https://www.locomotion-h2020.eu/locomotion-models/locomotion-iams/>