Towards an energy system with net zero greenhouse gas emissions

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Summer School on Integrated Assessment Models

Villa del Grumello, Como Lake

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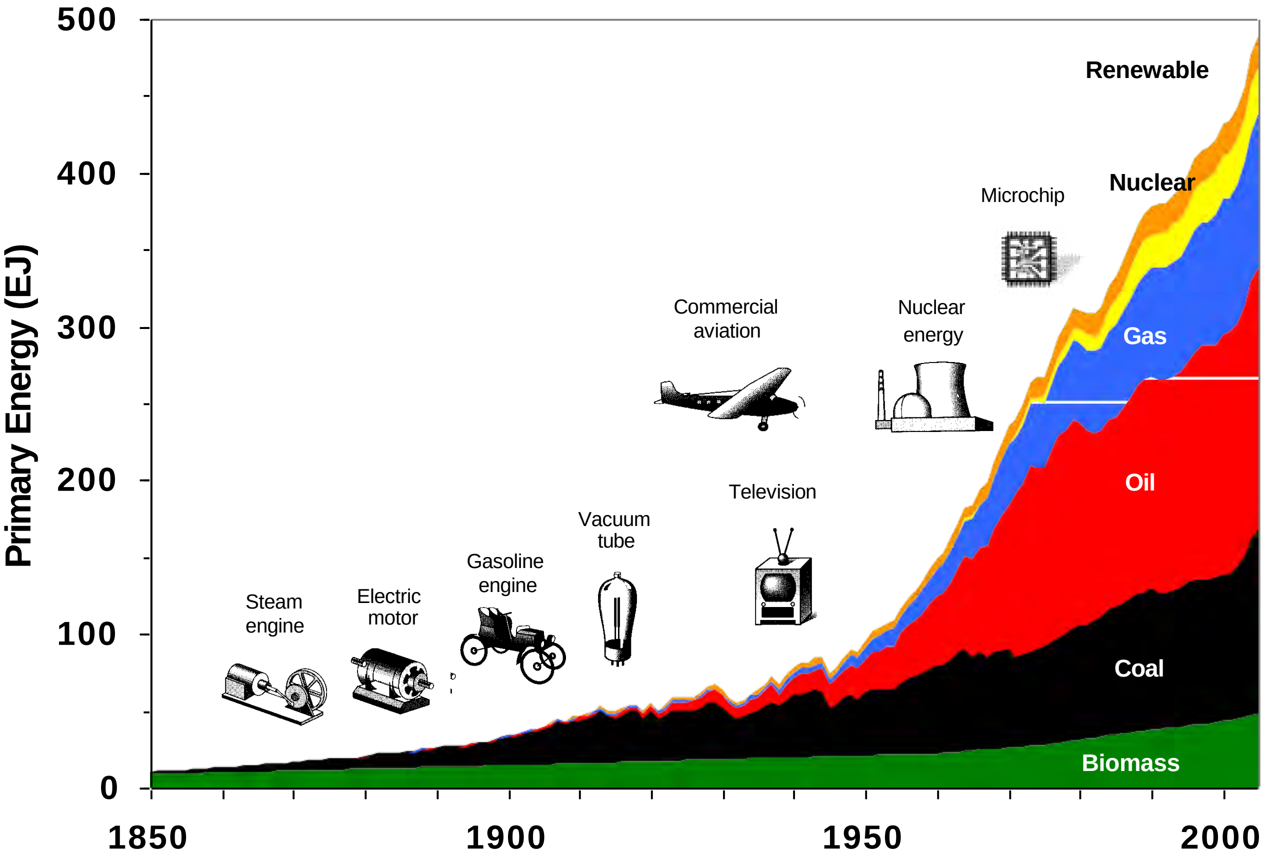
Main Energy Transitions: History

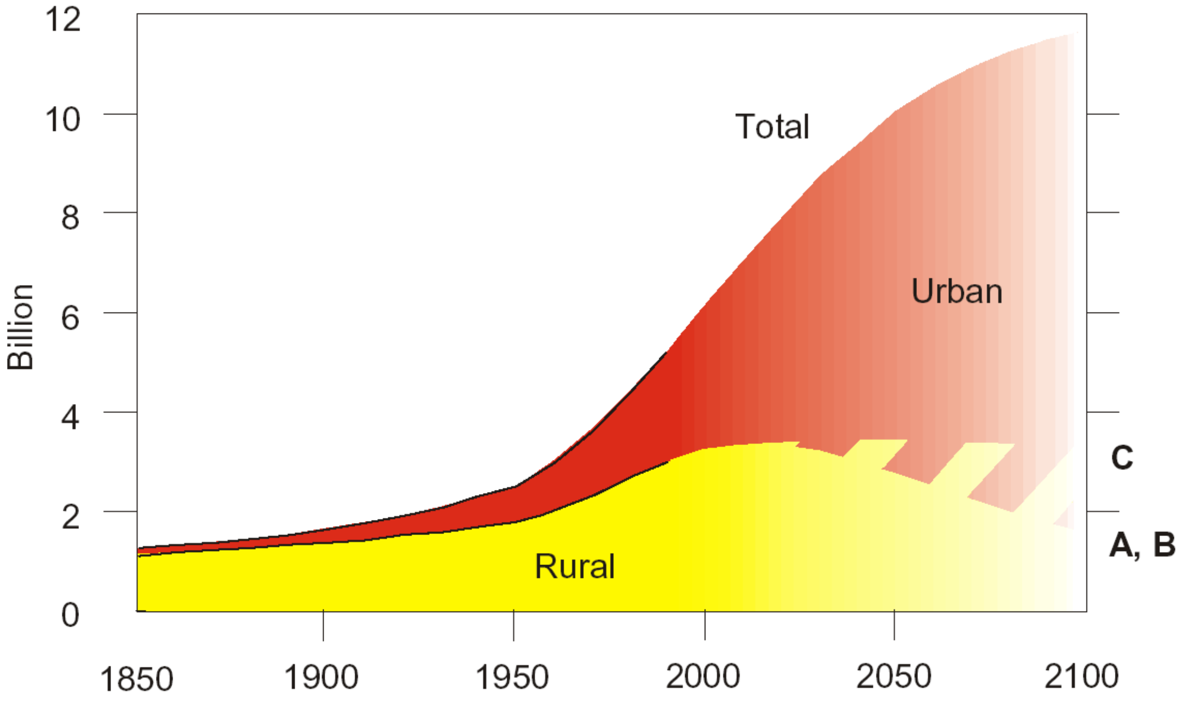
- Non-commercial → commercial
- Renewable → fossil
- Rural → urban
- South → North → South
- Moving to more convenient & flexible fuels
- Improved efficiency/productivity
- Conversion deepening
  (e.g. electrification)
- Increasing supply/demand density
- Desulfurization, Decarbonization

World Primary Energy



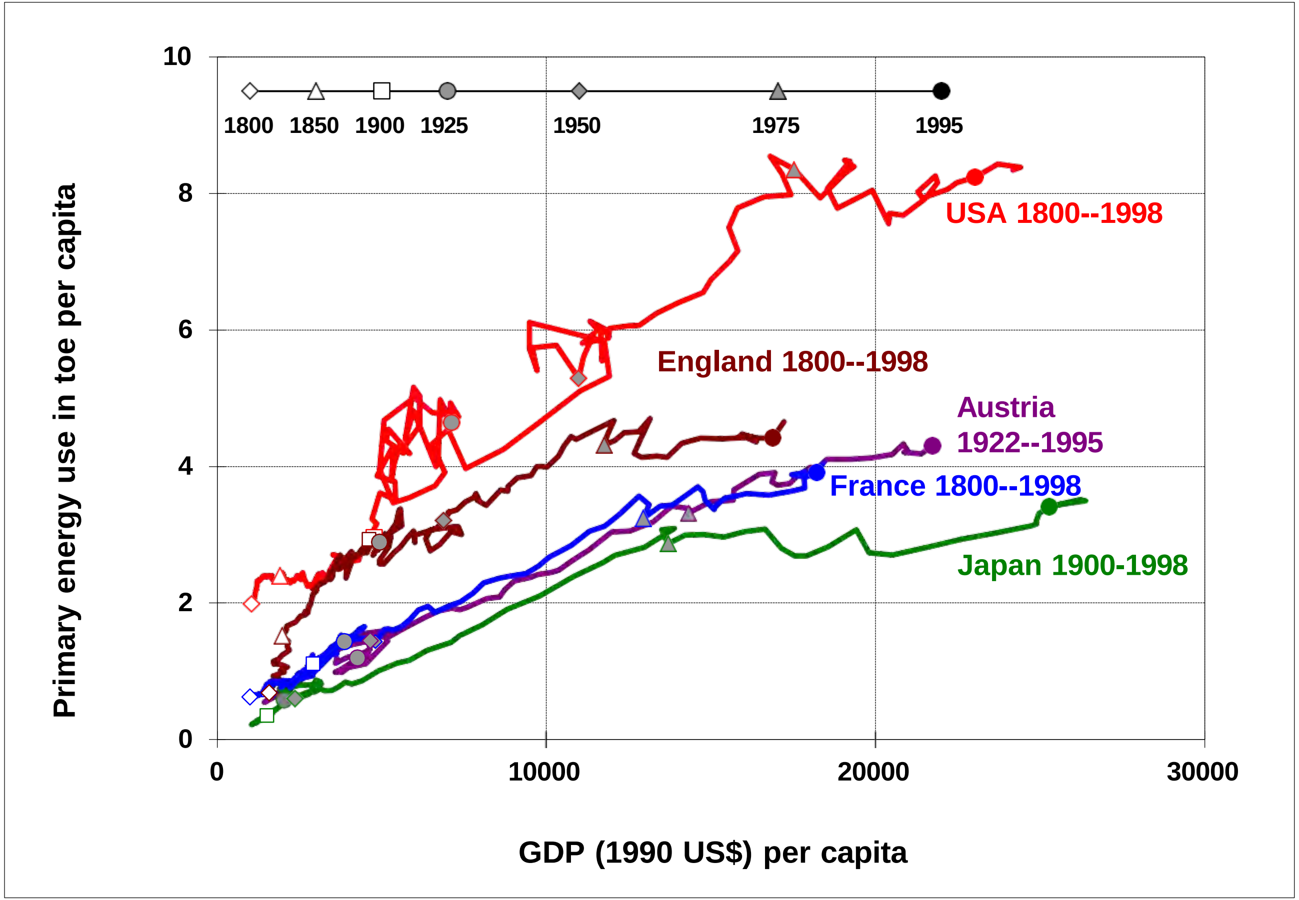
Source: Global Energy Assessment – Grubler et al. (2012)

World Population



Source: IIASA-WEC, 1998

Primary Energy and Wealth



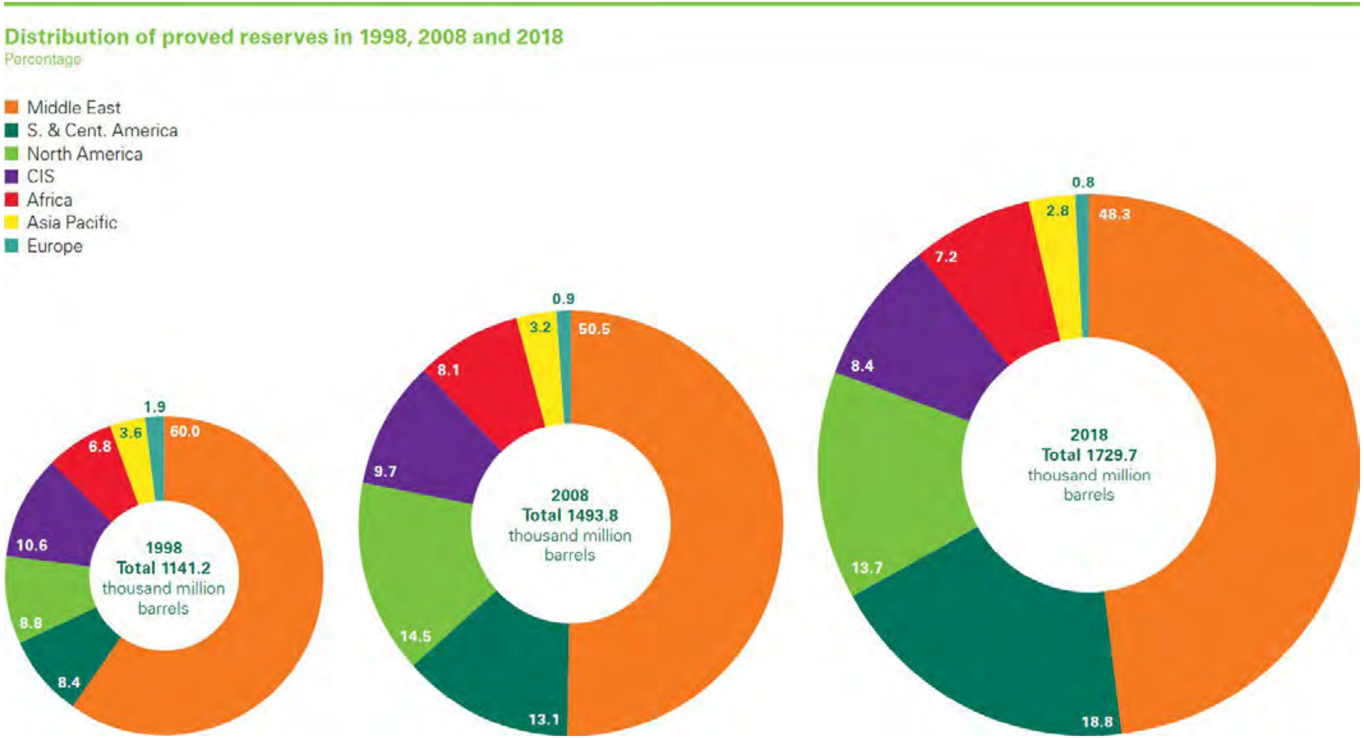
North – South Orders of Magnitude

	1800	1900	2000	2100*
World Primary Energy, EJ	10	40	440	400 - 1600
South as %	60%	30%	40%	44% - 80%
World Population, 10^9	1	1.6	6	7 - 13
South as %	75%	66%	80%	72% - 91%

*Range across the Shared Socioeconomic Pathways (no tails)

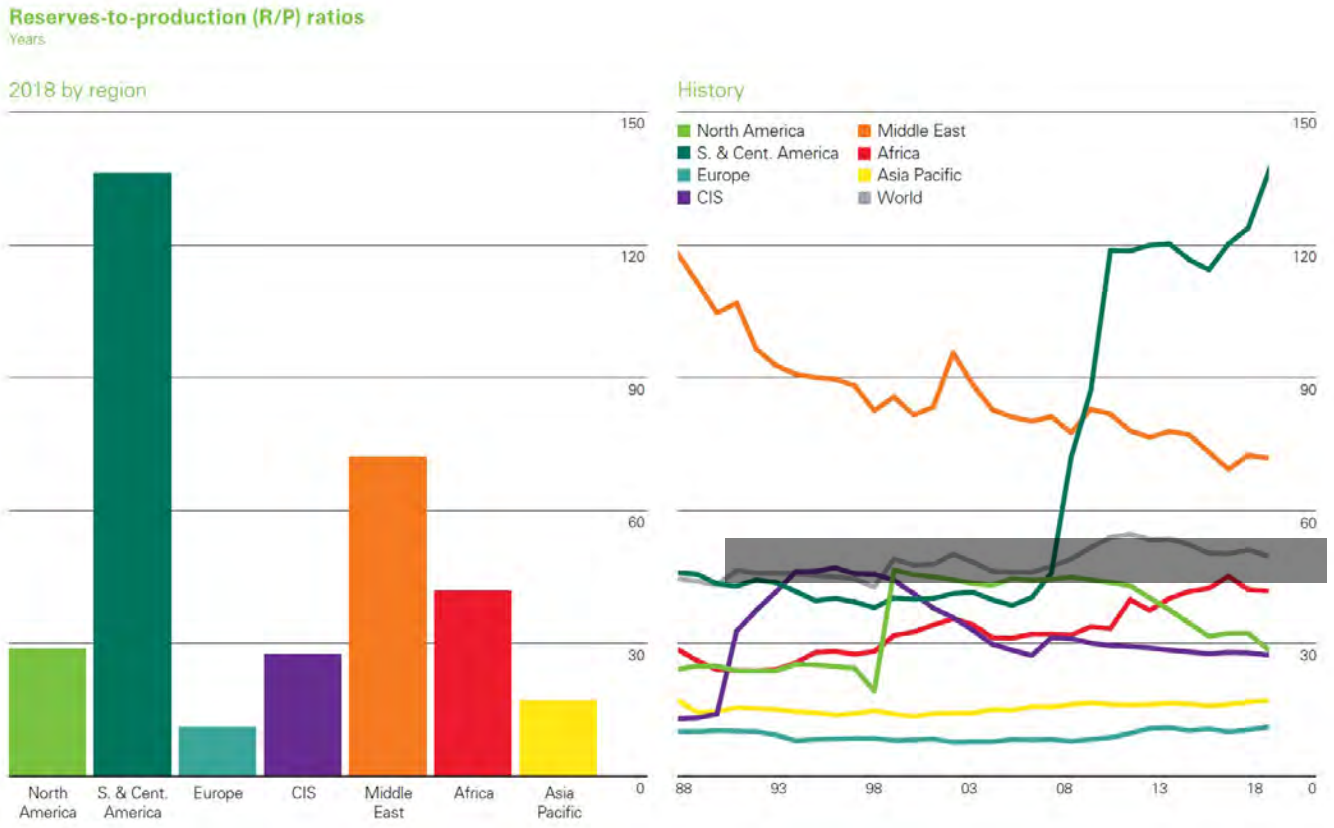
Distribution of proved oil reserves 1998, 2008, 2018

BP Statistical Review, 2019



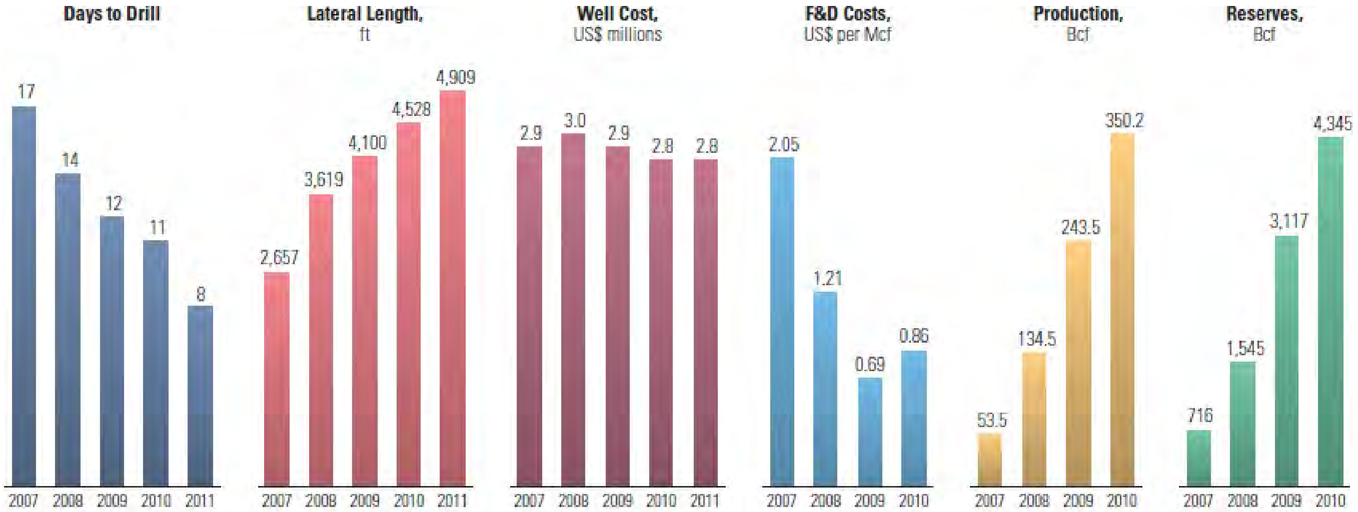
Oil reserves-to-production (R/P) ratios

BP Statistical Review, 2019



The role of technology & innovation – gas shale US

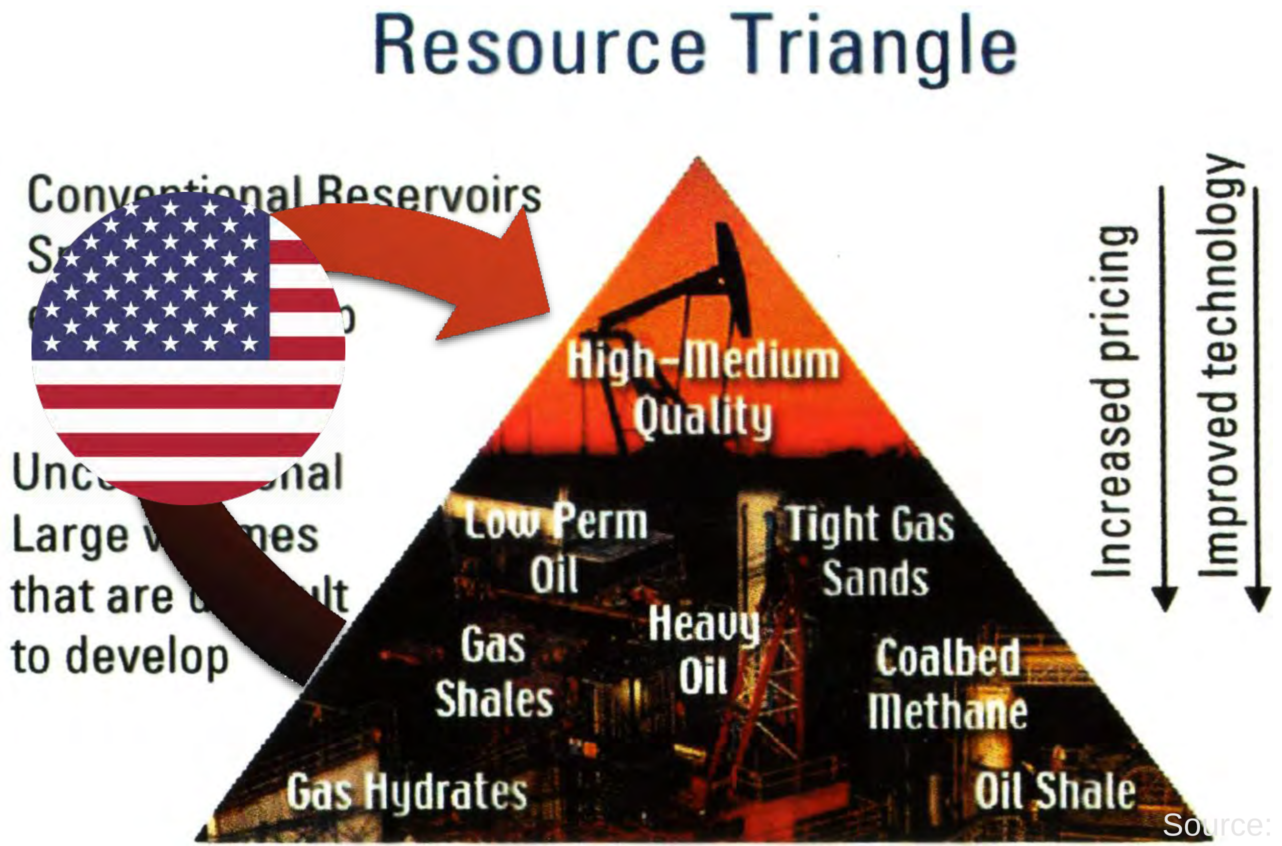
- Shale is the most abundant sedimentary rock on Earth
- No two shale deposits are created equal



^ Continuous process improvement. Over a four-and-a-half year period, from 2007 to 2011, Southwestern Energy reduced days to drill (dark blue) by 52%, even though the lateral length was increased by more than 84% (pink). Well costs (dark red) were flat to slightly lower during the period but the company's finding and development costs (F&D, light blue) were significantly reduced during the period. Production (gold) and reserves (green) greatly increased during the study period. (Data for 2011 are for the first six months of the year.)

Source: Schlumberger, 2011

Hydrocarbon Supply Perspectives

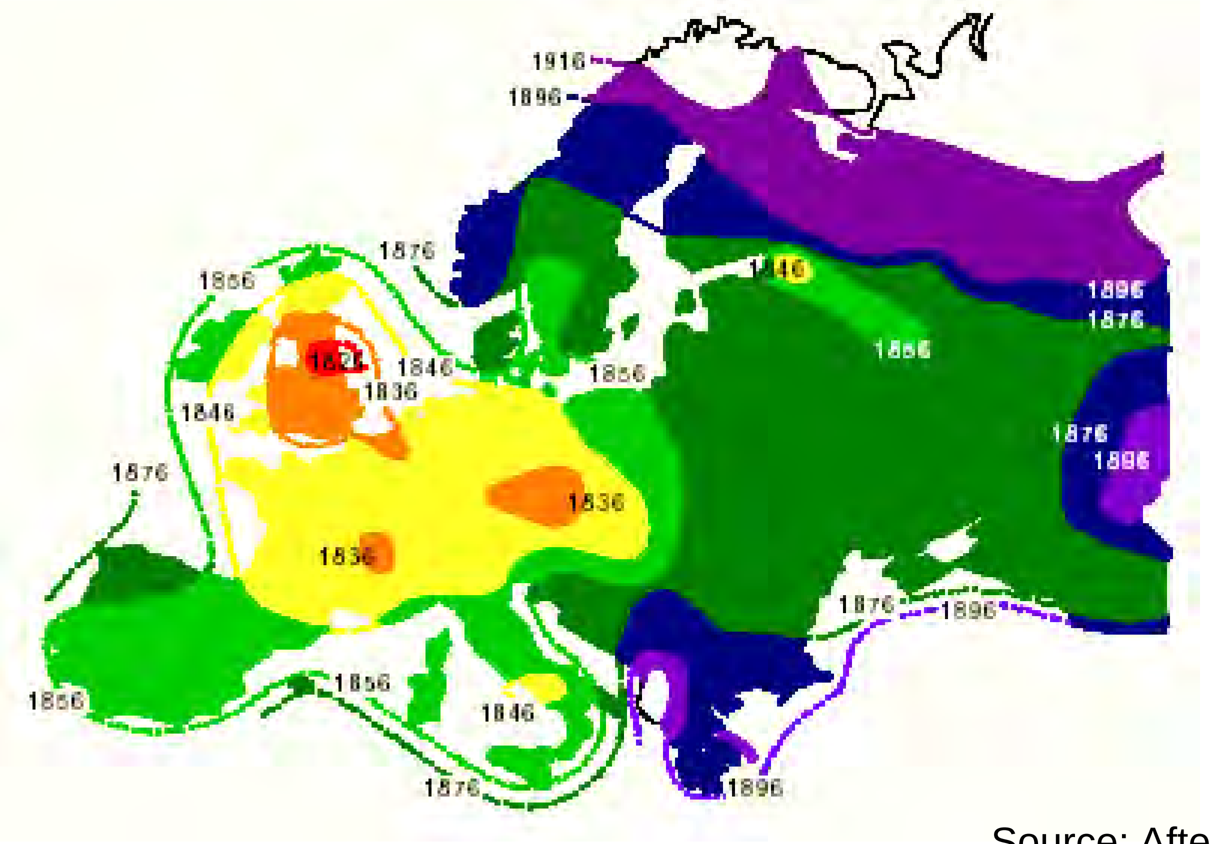


Source: Grohmann, 2005

Changing Mineral Reserves
(Cohen, 1995)

Mineral	Reserves 1950	Production 1950-1980	Reserves 1980
Copper	100	156	494
Iron	19,000	11,040	93,466
Aluminum	1,400	1,346	5,200
Lead	40	85	127

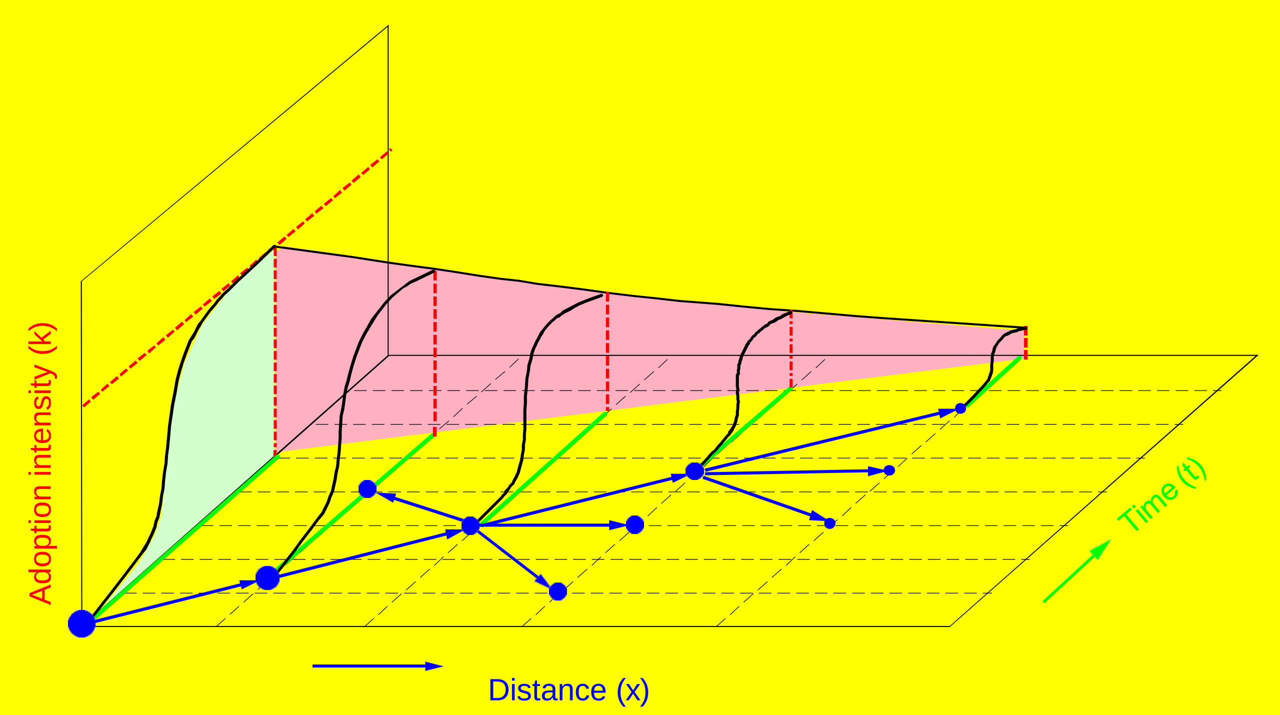
Spatial Diffusion of Railways



Source: After Godlund, 1952

Diffusion in Space and Time

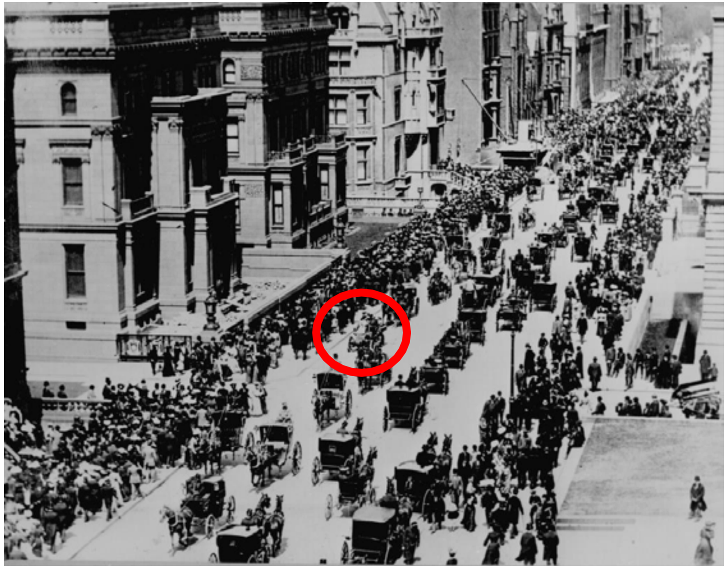
A Simple Conceptual Diffusion Model



Source: Morill, 1968

Easter Parade on Fifth Avenue, New York

1900



Can you spot the car?

1913

Can you spot the horse?

Source (pictures): https://www.inmotionventures.com/movement-disrupted/

Energy Efficiency and Emissions of Horses, Early and Contemporary Automobiles

	Horses	Cars (~1920)	Cars (~1995)
Engine efficiency [%]	4	10	20
Wastes [g/km]			
Solid	400	-	-
Liquid	200	-	-
Gaseous, including			
Carbon (CO_2)*	170	120	70
Carbon (CO)	-	90	2
Nitrogen (NO_x)	-	4	0.2
Hydrocarbons	2+	15	0.2

* total carbon content of fuel

\+ methane

After: Ausubel, 1989

Energy for Sustainable Development

Multiple objectives and complex of interdependencies


Energy Poverty


Energy Security


Biodiversity and Food


Climate Change


Water


Air Pollution

Image sources: NASA, http://www.powernewsnetwork.com/white-house-releases-plan-to-cut-oil-imports-by-13-by-2025/1798/, http://wheresmyamerica.wordpress.com/2007/08/26/i-cant-see-my-america/, http://www.americanprogress.org/issues/green/report/2009/05/14/6142/energy-poverty-101/, http://today.uconn.edu/blog/2010/12/reclaiming-water-a-green-leap-forward/, http://te.wikipedia.org/wiki/%E0%B0%A6%E0%B0%B8%E0%B1%8D%E0%B0%A4%E0%B1%8D%E0%B0%B0%E0%B0%82:Forest_Osaka_Japan.jpg;nationoffuture.org

Energy Systems Transformation

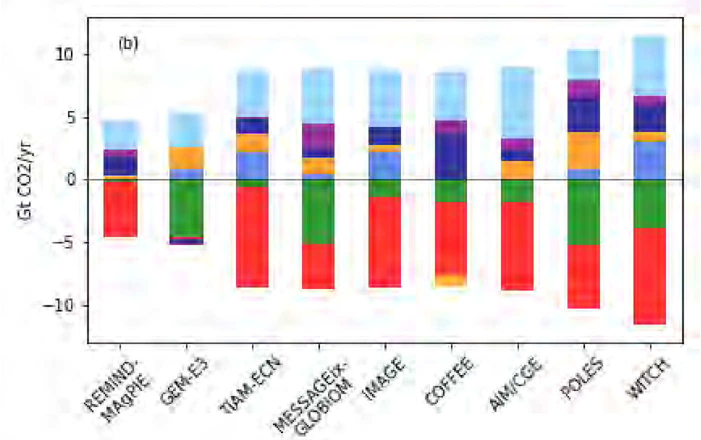
Limiting warming to 1.5C requires changes on an unprecedented scale:

- Rapid and immediate emissions reductions in all sectors
- Reaching net zero emissions (by 2050)
- A range of technologies
- Behavioral change (not sacrifice)
- Increase in investments in low-carbon options

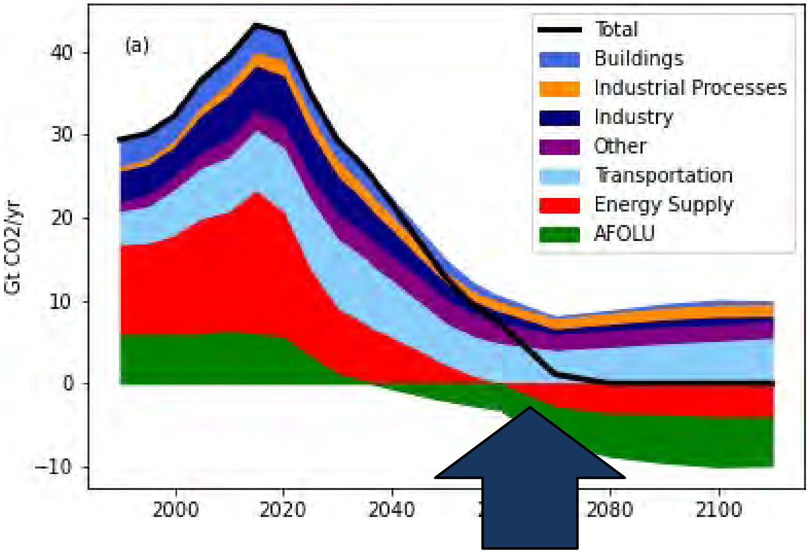
What does carbon neutrality mean?

SECTORAL emissions sources and sinks

Different strategies across models

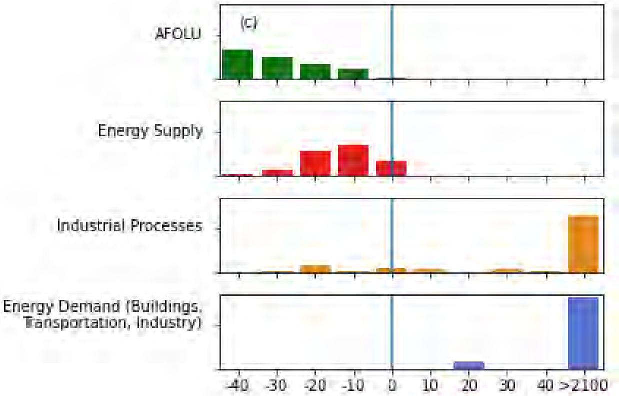


Illustrative zero emissions pathway



Timing of sectors for zero emissions

(compared to the timing of the overall system)



World: Net zero CO2 emissions 2050-2070
EU: Net zero GHG by 2050

Riahi et al, 2022, Nature Climate Change

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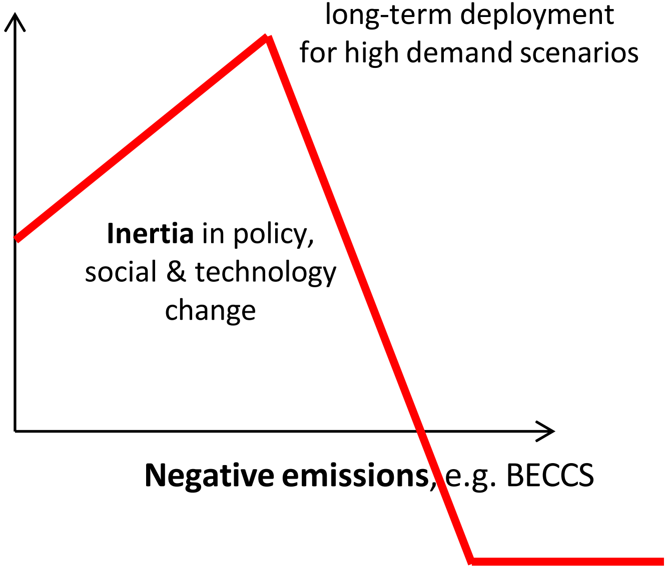
ENGAGE FEASIBILITY OF CLIMATE PATHWAYS

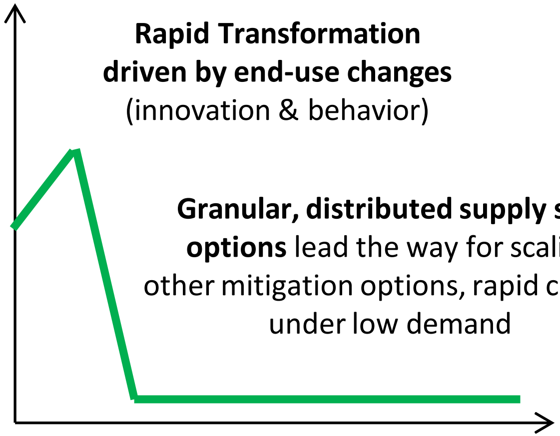
2 Perspectives of the Transformation

GHG Emissions Profiles

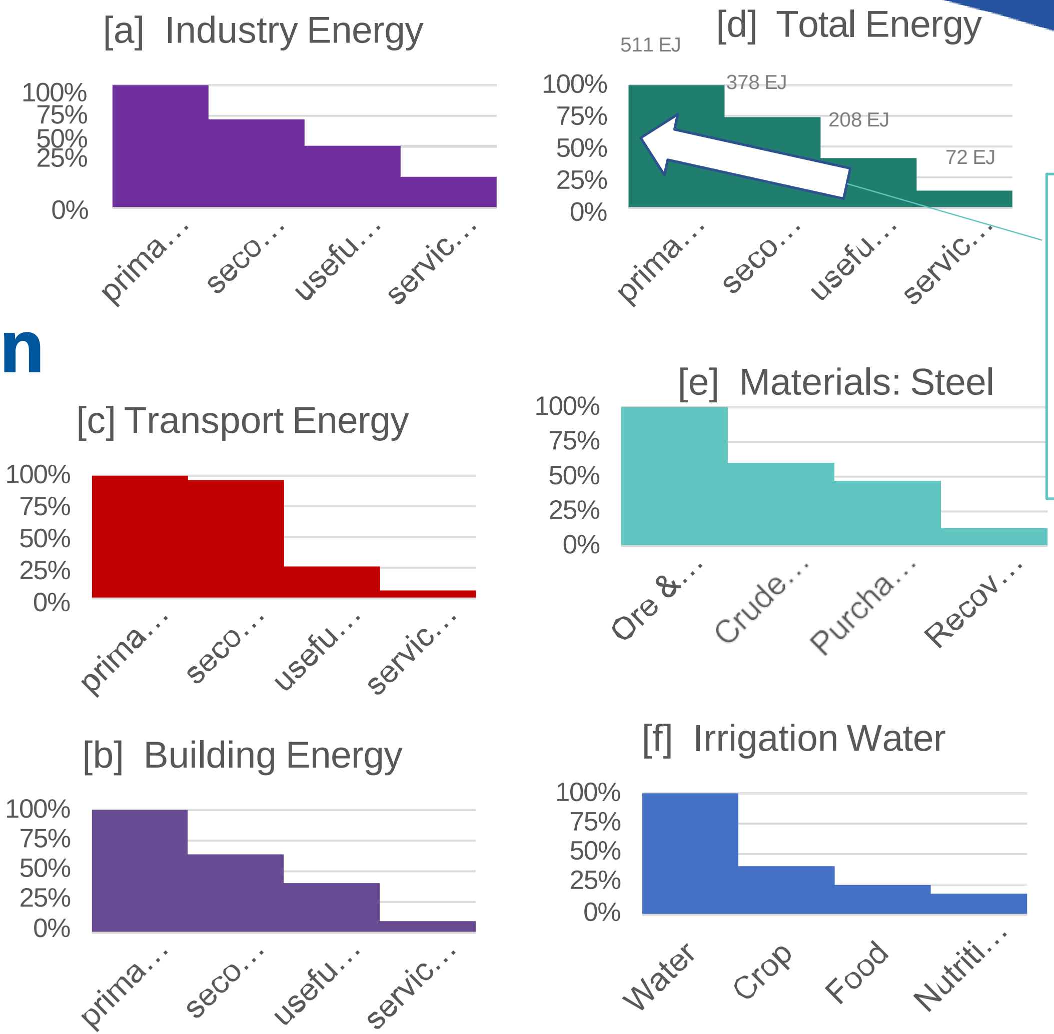
“Conventional” 1.5 C Scenario



Rapid transformation through demand-side solutions and granular technologies



There is an enormous potential for services-led transformation



Service sector has enormous leverage to reduce upstream energy use

“resource conversion cascades”

Source: Wilson, Grubler, and Zimm (2022). Energy-Services Led Transformation. In: *Routledge Handbook of Energy Transitions* (Ed: Araujo).
Data from: Grubler et al. (2018), De Stercke (2014), Nakicenovic et al. (1993), Nakicenovic (1990).

New Trends in Social and Technological Change

- Changing consumer preferences (e.g. diets)
- Generational change in materialism (service rather than ownership)
- New business models (sharing & circular economy)
- Pervasive digitalization and ICT convergence
- Rapid innovation in granular technologies and integrated digital services

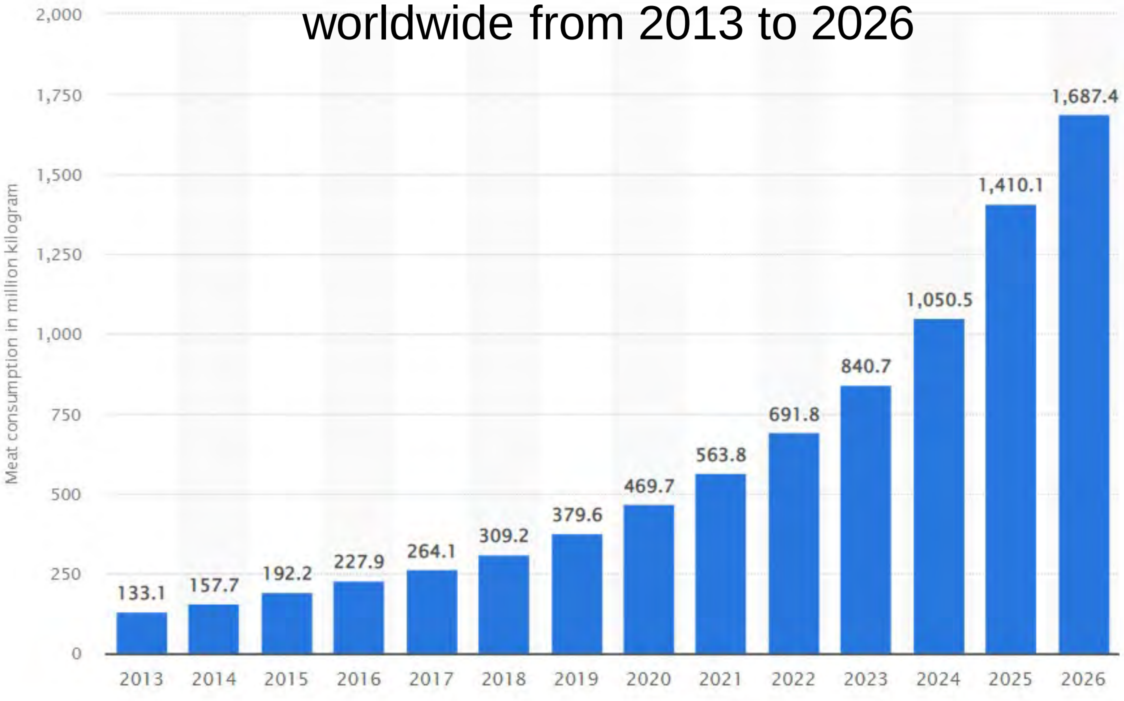
Dietary change

New trends in social and technological change

Changing consumer preferences
(e.g. diets)

July 31, 2017
backpackersguidefortheblondeandtheclueless

Total consumption of meat substitutes worldwide from 2013 to 2026



Source: Statista Market Outlook 2022

Drivers license ownership

New Trends in Social and Technological Change

Generational change in materialism (service rather than ownership)

New business models (sharing & circular economy)

Pervasive digitalization and IC[T] convergence (Society 5.0)

Location	year a	year b	age group	% of age group with drivers license year a	year b	change %-points
Austria 1	2006	2010	17-18	32	39	7
Finland	1983	2008	18-19	37	68	31
Finland	1983	2008	20-29	51	82	31
Israel 1	1983	2008	19-24	42	64	22
Israel 1	1983	2008	25-34	62	78	16
Netherlands	1985	2008	18-19	25	45	20
Netherlands	1985	2008	20-24	64	64	0
Spain	1999	2009	15-24	37	50	13

Data sources: Sivak & Schottle, 2011; Delbosc & Currie, 2013; Nat.Stats, 2017 for Austria, Germany, Israel, Sw

lumpy
large unit size
high unit cost
indivisible
high risk

Technology Unit Size

granular
small unit size
low unit cost
modular
low risk

Source: Grubler, ESA class material

Dublin: shared mobility scenarios

Source: ITF, 2018

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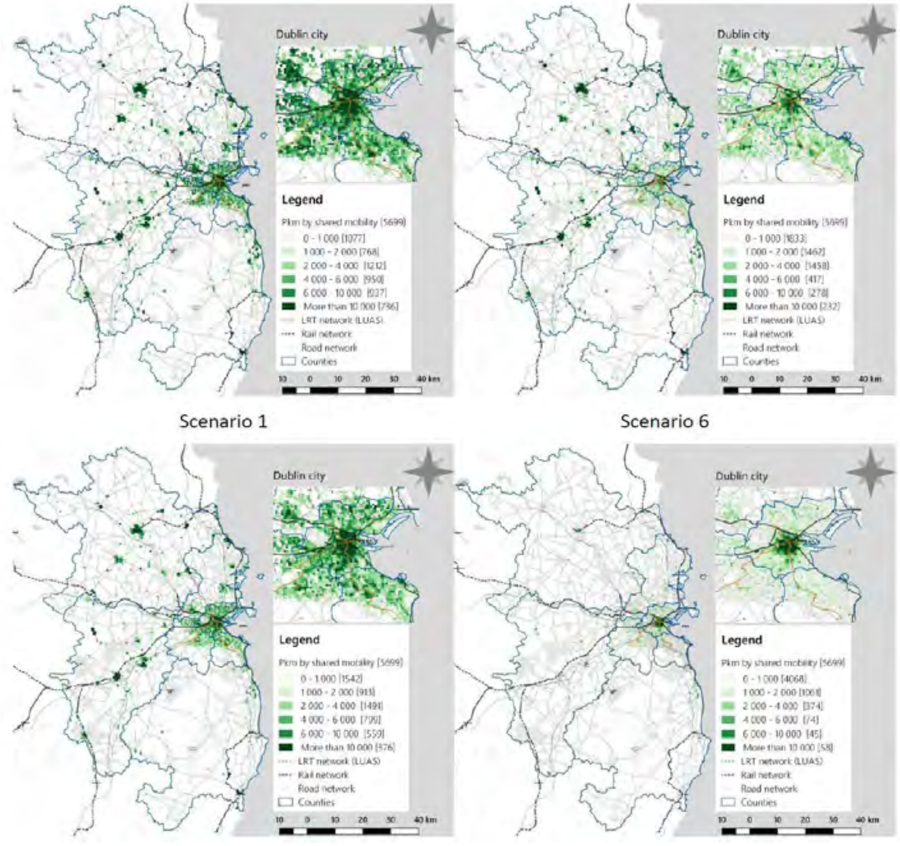
Mobility in the Greater Dublin Area could be delivered with **only 2 %** of the current vehicles!

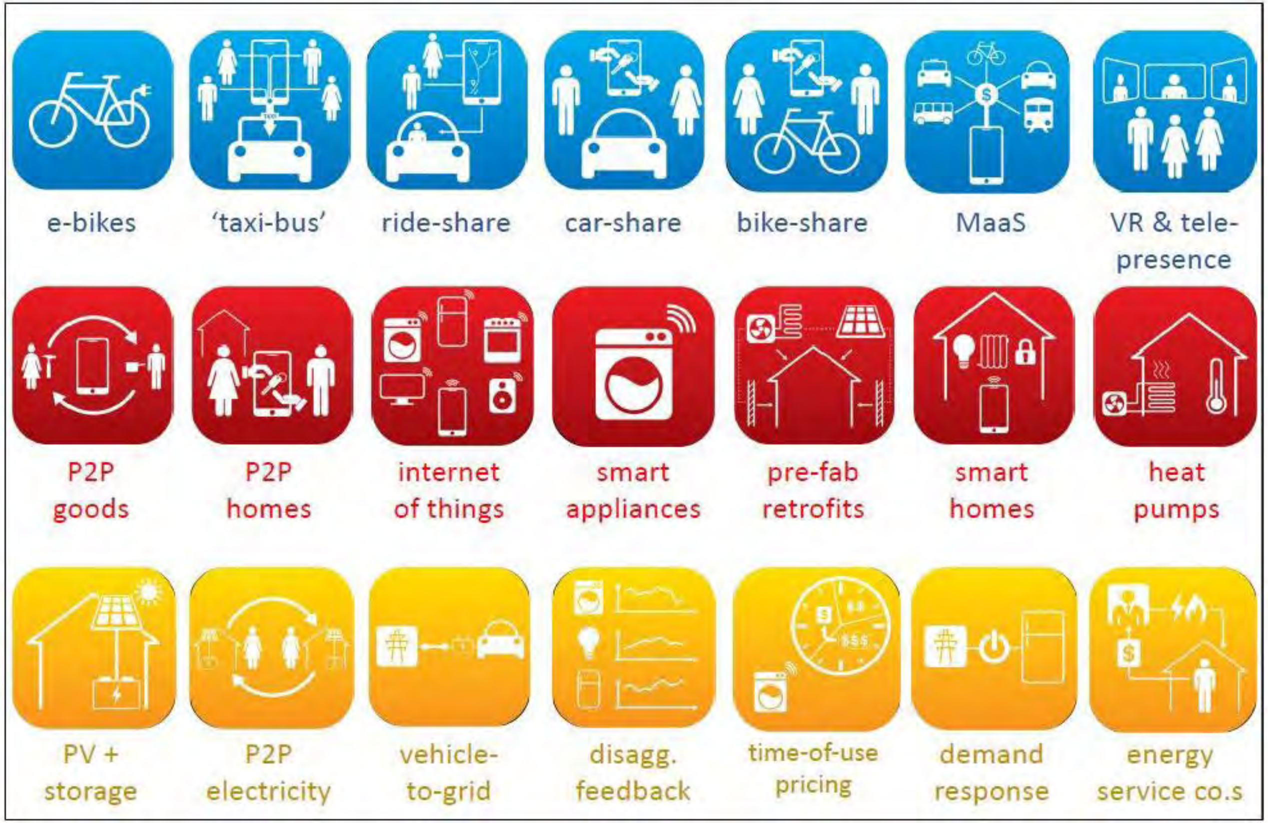
Shared Mobility + existing rail and light-rail transit (LRT).

Pkm: *-38%*
Emissions: *-31%*
Congestion: *-37%*

Better, more convenient, cleaner service at lower costs. Multiple Co-benefits! (congestion, pollution, space)



Disruptive End-user Innovations



Source: Charlie Wilson

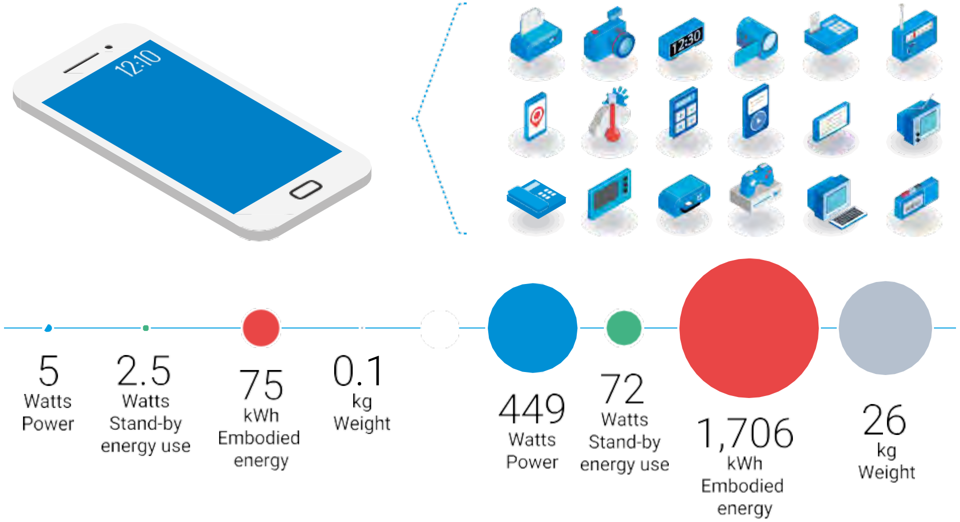
- ✓ Ownership to usership
- ✓ Sharing economy
- ✓ Automized to connected

conversion efficiency

e.g., devices

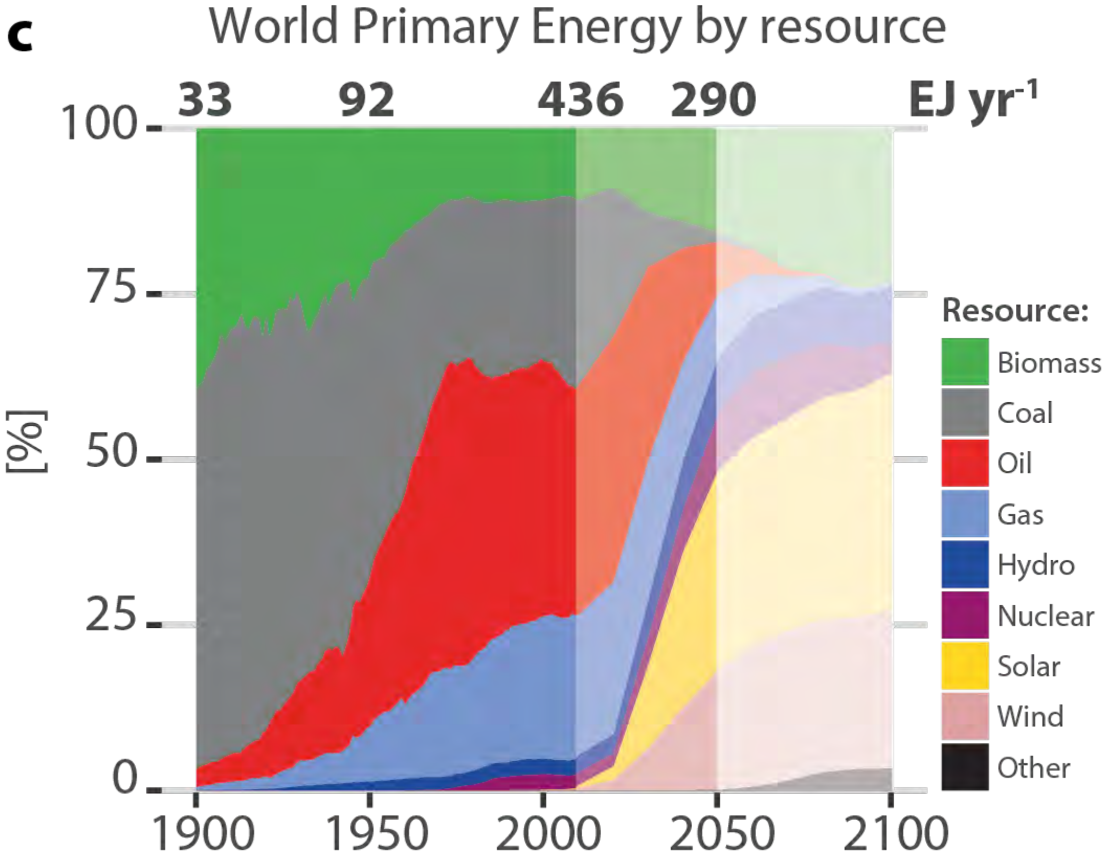
service efficiency

e.g., device convergence



Source: Grubler et al. (2018) *Nature Energy*, based on visualisation by Tupy (2012), and adapted for *UNEP Emissions Gap Report* 2021.

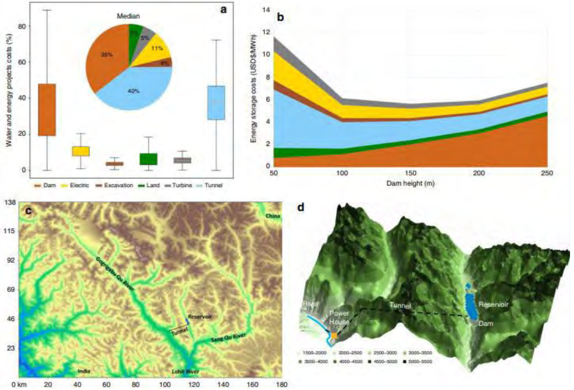
Rapid electrification and diffusion of renewable energy



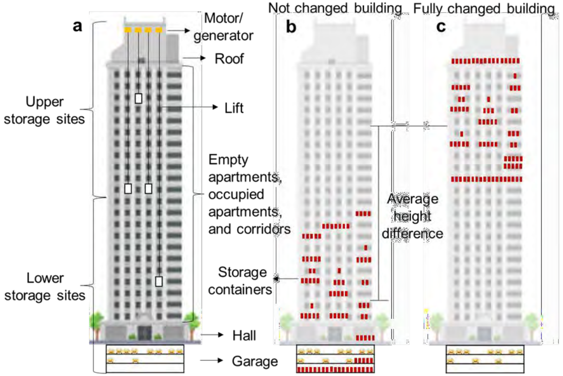
Gruebler et al, 2018

Various energy storage proposals exist and need to be scaled up….

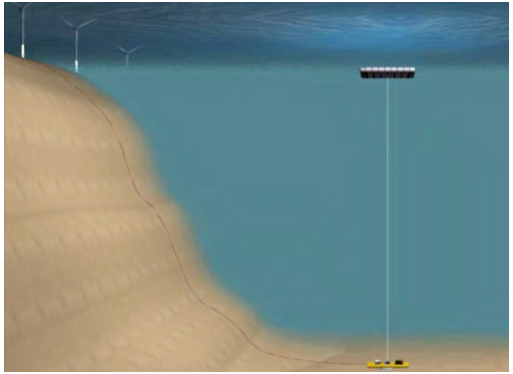
Pumped Hydro



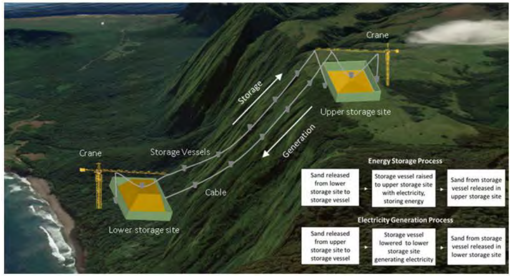
Lift Energy Storage



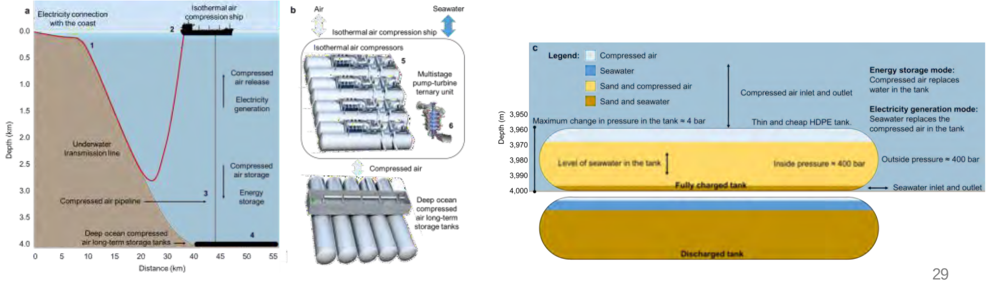
Buoyancy Energy Storage



Gravity Energy Storage



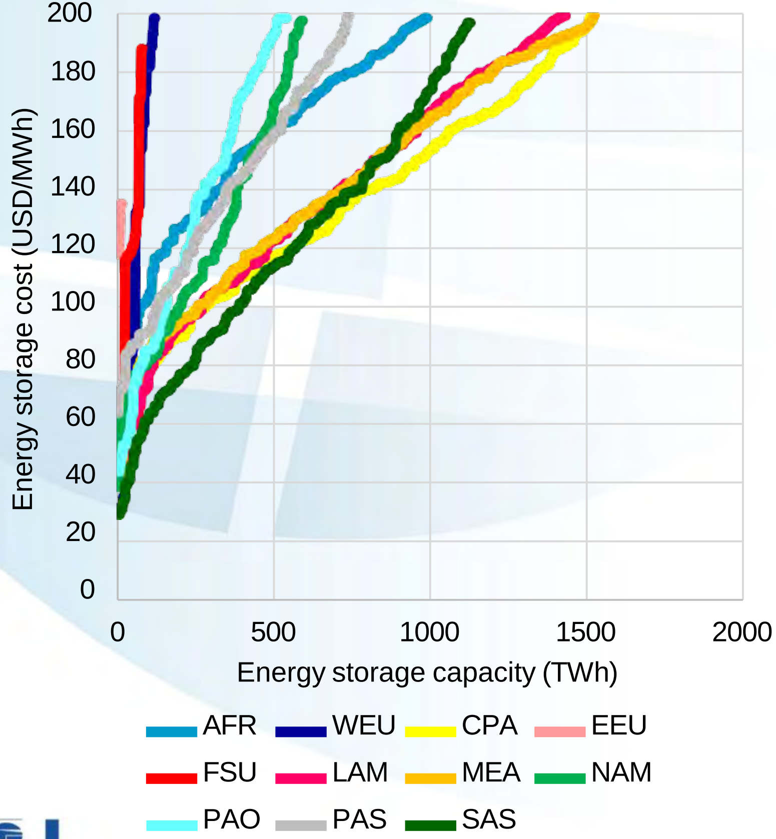
Deep Ocean: Compressed Air or Hydrogen Link:



Hunt et al, forthcoming

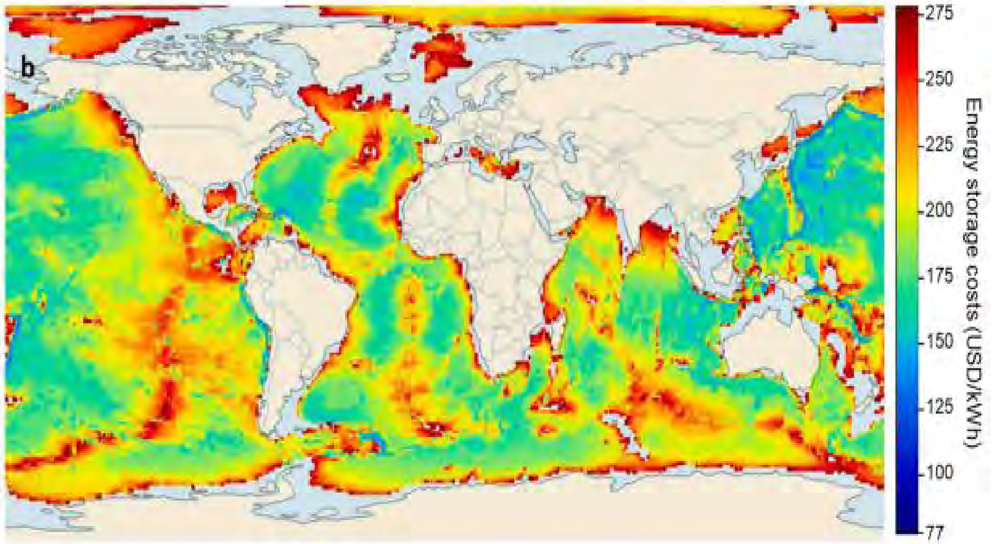
Mountain Gravity Energy Storage

Global potential (TWh)



Buoyancy Energy Storage

Potential >> global electricity needs



Hunt et al, forthcoming

Unconventional Technology Possibilities

Name	Installed capacity cost (USD/KW)	Energy Storage cost (USD/MWh)	Installed capacity per project (MW)	Storage Cycle	Global Potential (TWh)	11 regions
Mountain Gravity Energy Storage (MGES)	200 – 2,000	20 – 200	1 - 20	Seasonal, pluriannual	8.684	Yes
Electric Truck Gravity Energy Storage (ETGES)	1,200	1.2	20 – 100	Monthly, seasonal	5.400	Yes
Lift Energy Storage (LEST)	500 – 1,000	20 – 120	0.02 – 1 (per building)	Ancillary, daily, weekly	0.03 – 0.3	Yes
Seasonal pumped hydropower storage (SPHS)	400 – 600	0.002 – 0.100	100 - 5000	Seasonal, pluriannual	17.300	Yes
Buoyancy Energy Storage Technology (BEST)	4,000 – 8,000	50 – 100	10 - 100	Ancillary, daily, weekly	∞ (deep-sea)	Not yet
Deep hydrogen ocean link (HYDOL)	H2 storage	0.018	H2 storage	Seasonal, pluriannual	∞ (deep-sea)	Not yet
Isothermal deep ocean compressed air energy storage (IDO-CAES)	1,600	1.26	100 – 1000	Monthly, seasonal, pluriannual	∞ (deep-sea)	Not yet

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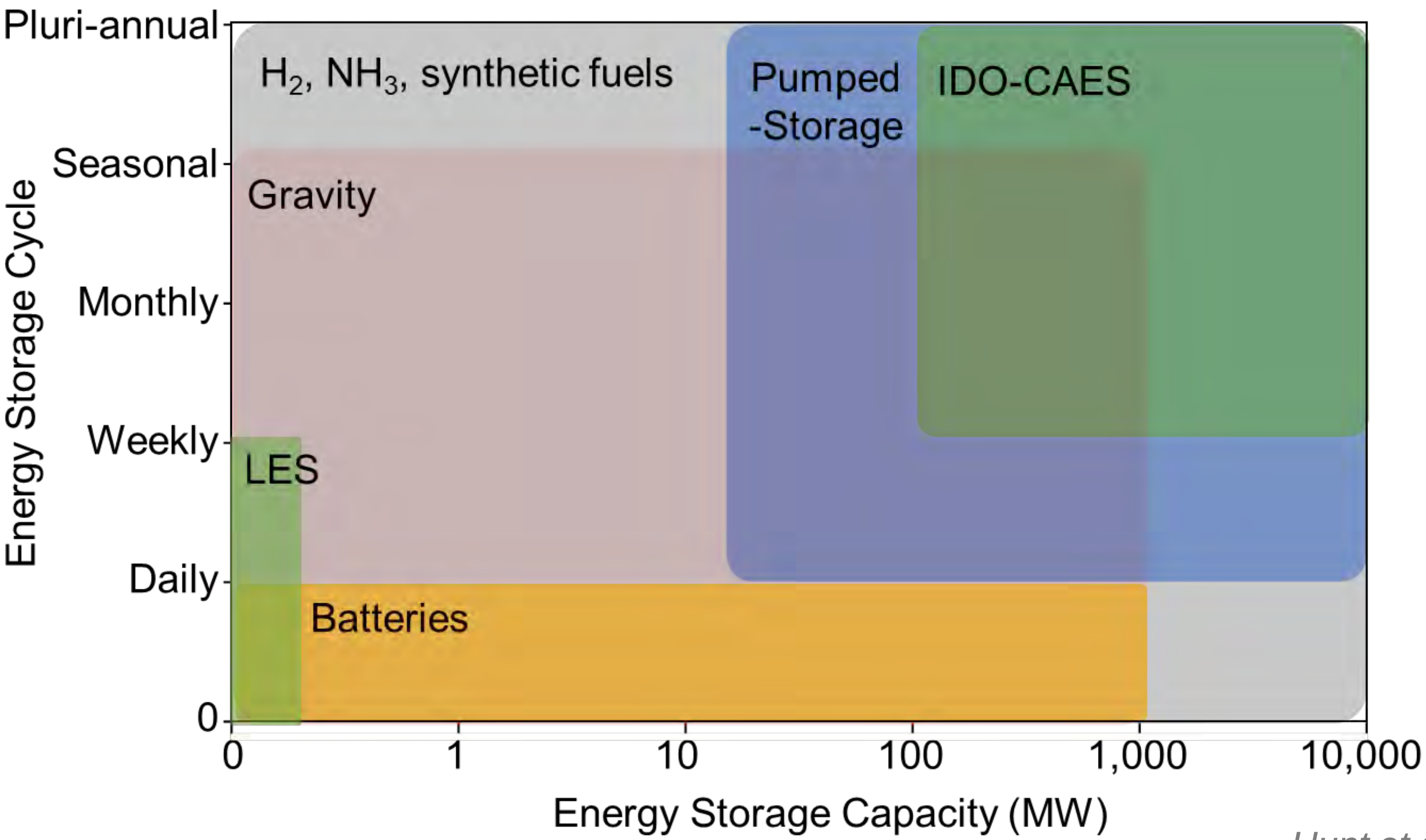
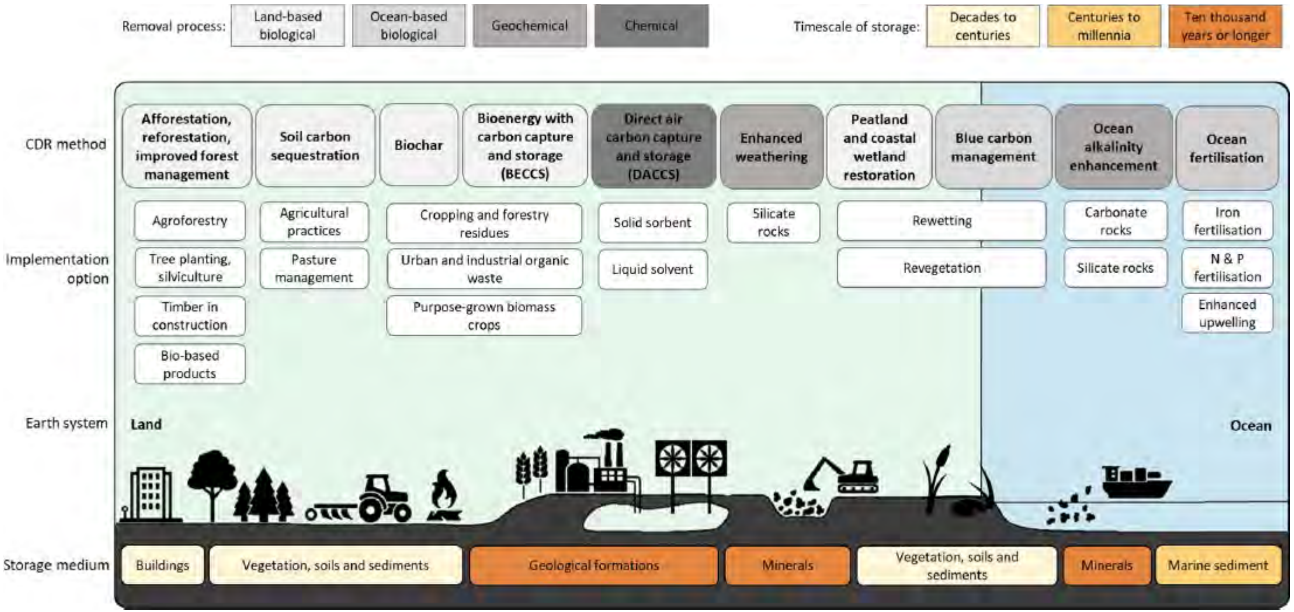
Hunt and Zakeri, forthcoming

Energy storage cycles and storage size



Hunt et al, forthcoming

Carbon dioxide removal (CDR) needed to reach net zero emissions



***Source**: IPCC, 2022, Chapter 12, Cross-Chapter Box 8; based on Minx et al., 2018*

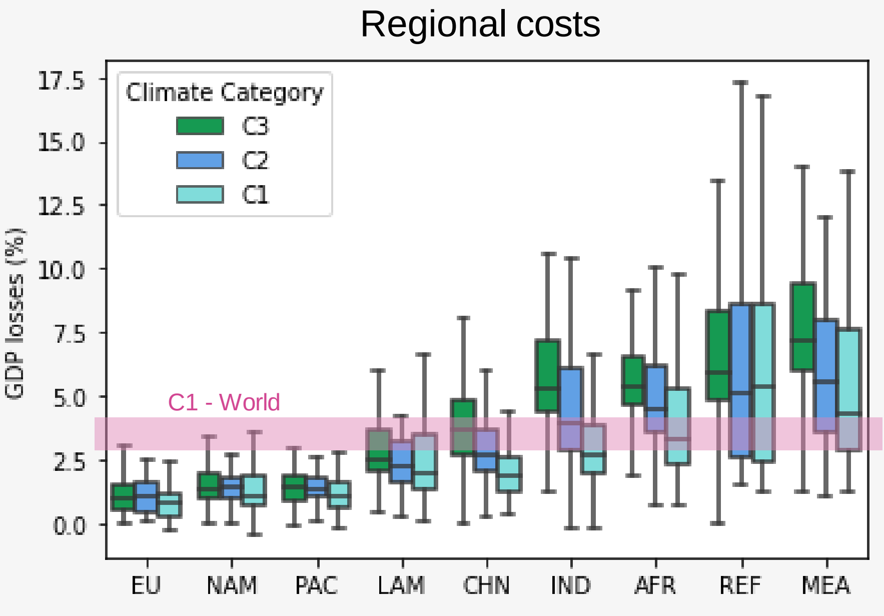
CDR characteristics:

- ✓ Needed to reach net zero
- ✓ Accelerate rate of emissions reductions (early on)
- ✓ "Repair phase" in case target stringency needs to be adjusted over time and temperatures need to reversed.

Wide portfolio

- ➢ Different public perceptions
- ➢ Trade-offs and Synergies
- ➢ Legal framing (permanence and liability)
- ➢ Policy portfolios

Costs of mitigation are modest and on average lower than the avoided costs of impacts (of limiting warming to 2C)



Costs reflect cost-effective allocation of mitigation and does not consider any financial transfers or other equity considerations

- The aggregate global effects of mitigation on global GDP are small compared to global projected GDP growth:

  ➔ 2.6 - 4.2% GDP loss by 2050 for 1.5C

  ➔ 1.3–2.7% GDP loss by 2050 for 2C

  Assuming coordinated global action. The corresponding average reduction in annual global GDP growth over 2020-2050 is 0.04–0.09 percentage points.

- Global GDP is projected to at least double (increase by at least 100%) over by 2050.

- Global cost of limiting warming to 2°C over the 21st century is lower than the global economic benefits of reducing warming, unless: i) climate damages are towards the low end of the range; or, ii) future damages are discounted at high rates

Is it feasible to achieve the climate goals?

Based on IPCC AR6 and Brutschin, E., Pianta, S., Tavoni, M., Riahi, K., Bosetti, V., Marangoni, G., & Ruijven, B. J. van. (2021). A multidimensional feasibility evaluation of low-carbon scenarios. *Environmental Research Letters*, *16*(6), 064069. https://doi.org/10.1088/1748-9326/abf0ce

What is feasibility?

the **plausibility of the transformation** required given a particular **temporal** and **geographical** context

Taken from SOD AR6, Chapter 1.

How can it be evaluated?

at the **“option or sectoral ” level**, i.e. evaluating **a specific mitigation** strategy

at the **“scenario/systemic” level**, i.e. evaluating **a combination of mitigation strategies within a stylized model**

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Assessing the feasibility of archetypal transition pathways towards carbon neutrality – A comparative analysis of European industries

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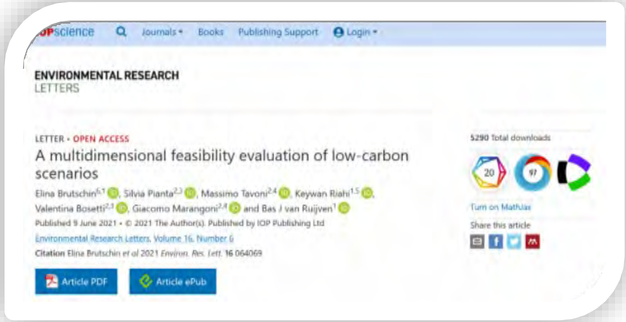

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ENVIRONMENTAL RESEARCH LETTERS

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A multidimensional feasibility evaluation of low-carbon scenarios

Elina Brutschin[6,1], Silvia Pianta[2,3], Massimo Tavoni[2,4], Keywan Riahi[1,5], Valentina Bosetti[2,3], Giacomo Marangoni[2,4] and Bas J van Ruijven[1]

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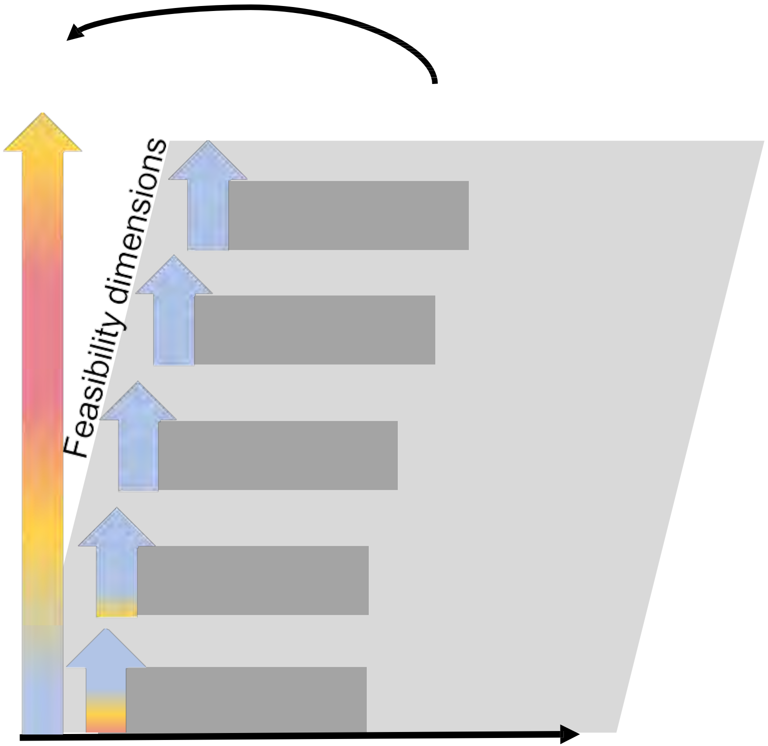


Brutschin et al, 2021

Methods summary

Step 1

Feasibility dimensions

- geophysical
- technological
- economic
- institutional
- socio-cultural

Step 2

Indicators

For each dimension, selection of relevant indicators measuring decadal changes (among indicators available or computable based on scenario set)

Step 3

Thresholds

Categorization of level of feasibility concern for each indicator in each decade based on thresholds defined based on the literature and available empirical data.

- 3 high
- 2 medium
- 1 low

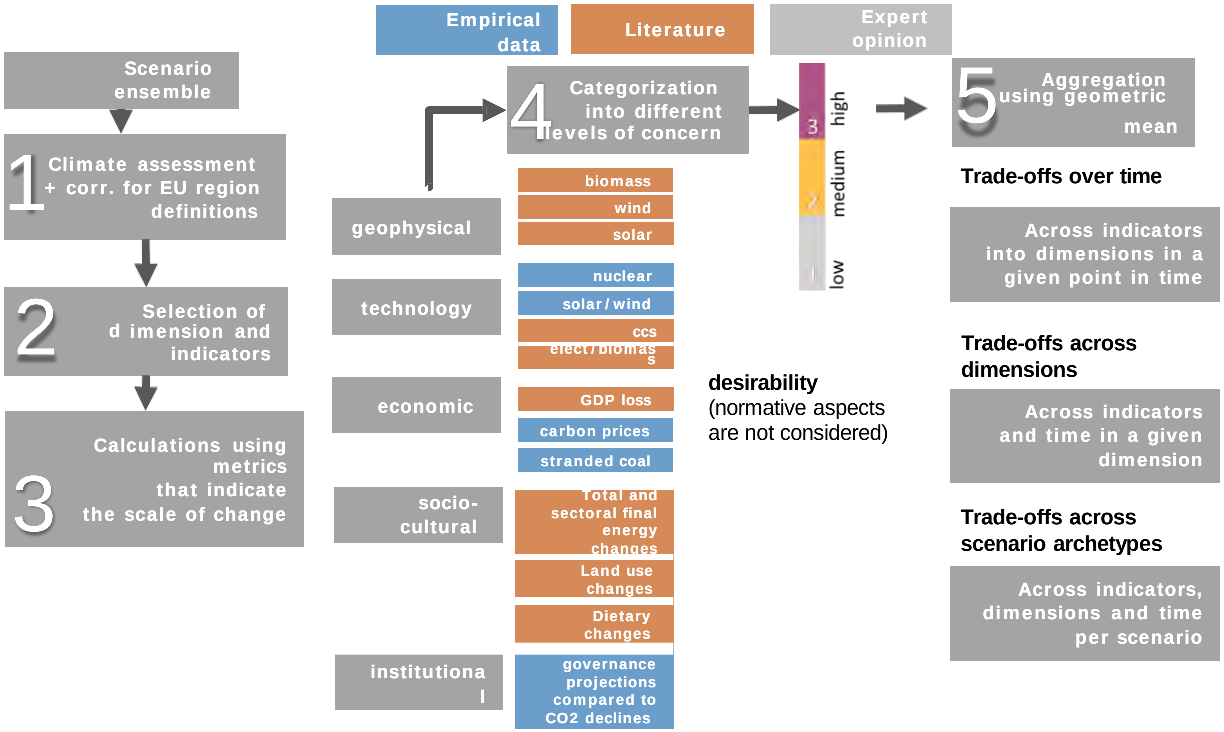
Step 4

Aggregation (geometric mean)

- Aggregation within each dimension → allows assessing **tradeoffs** among feasibility dimensions
- Aggregation across dimensions at different points in time → allows assessing the **timing** and **disruptiveness** of the transformation
- Aggregation across dimensions and across time → allows assessing the **scale** of the transformation

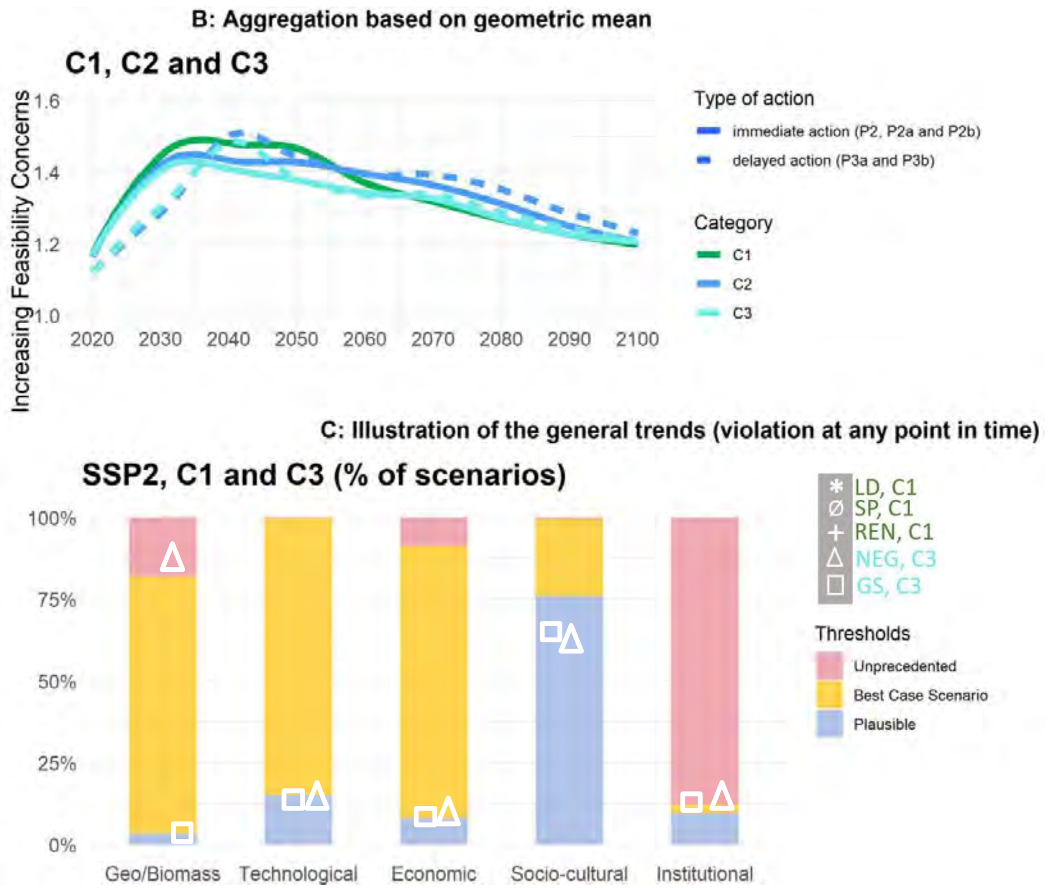
Brutschin et al, 2021

IPCC Methods – pathways level assessment



Brutschin et al, 2021

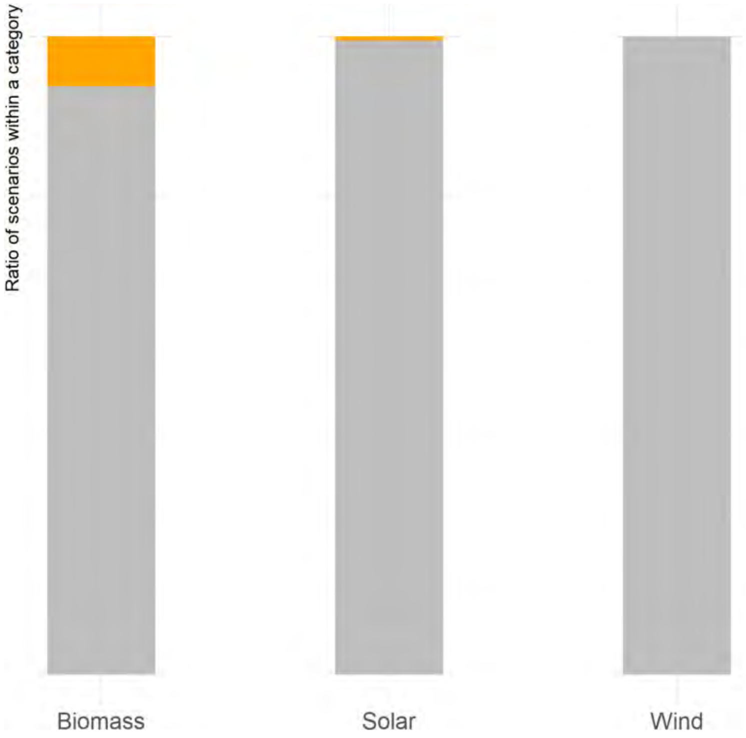
Illustrative results (IPCC AR6)



IPCC Chapter 3, Riahi et al, 2022

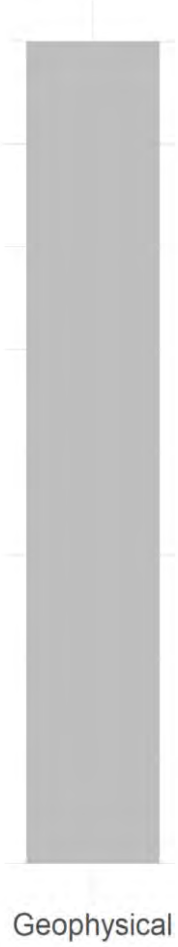
TS – Geophysical dimension

Geophysical dimension (focus on key resources for ambitious climate mitigation):
Some scenarios reach higher concern levels in terms of **global biomass potentials**



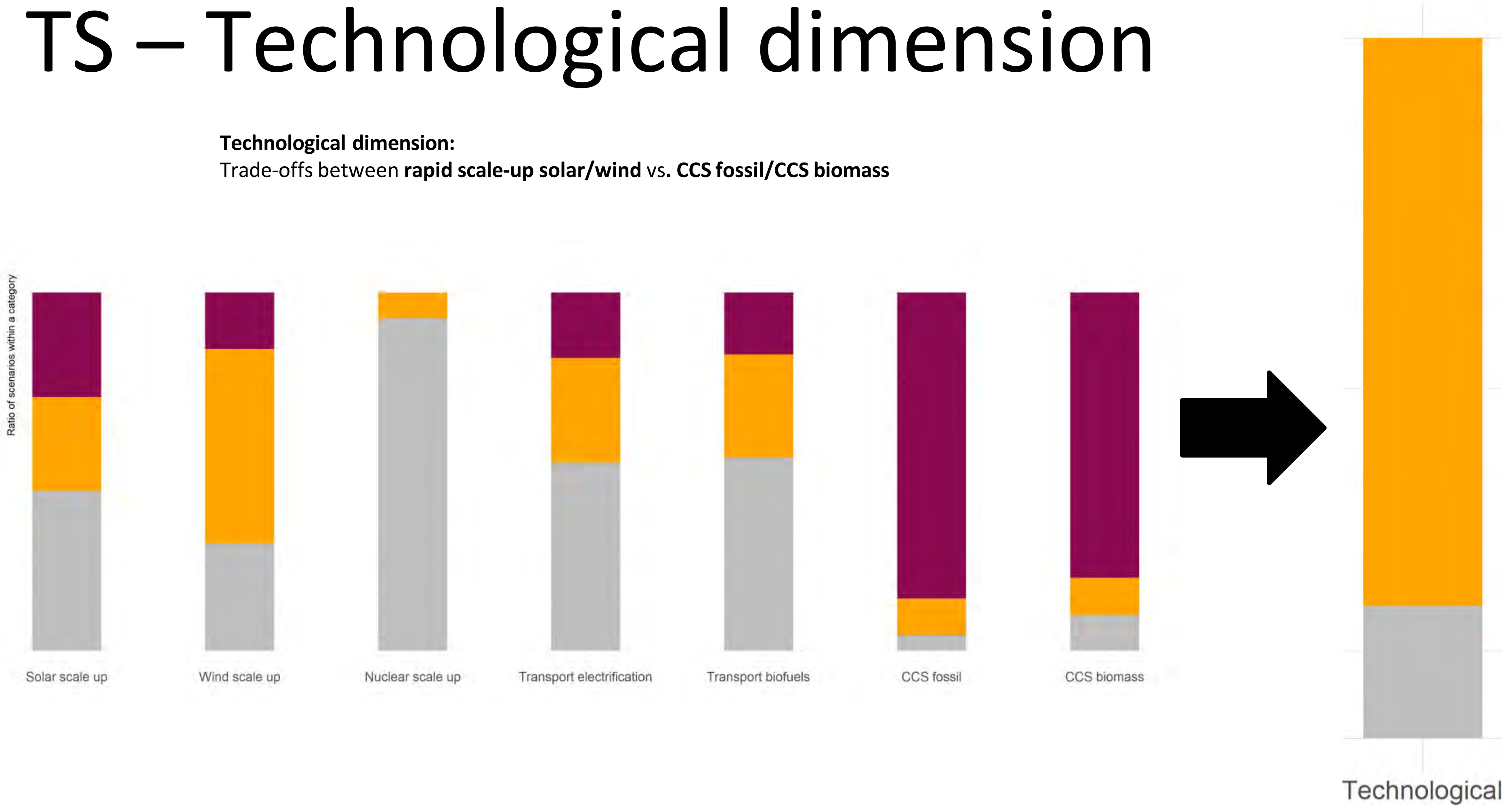
The main aggregation is performed using **geometric mean**

It is a standard procedure to **reduce the level of substitutability** between indicators (employed for instance for the **Human Development Index** and in many other areas (Van Puyenbroeck & Rogge, 2017))



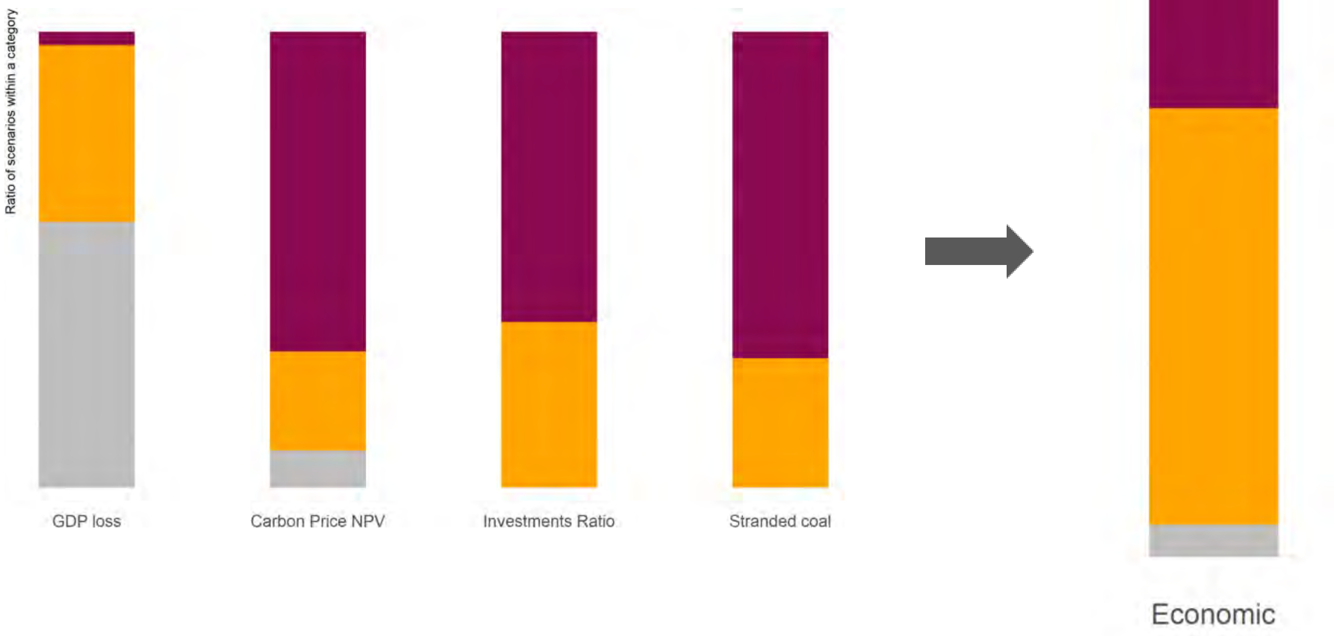
TS – Technological dimension

Technological dimension:
Trade-offs between **rapid scale-up solar/wind** vs. **CCS fossil/CCS biomass**



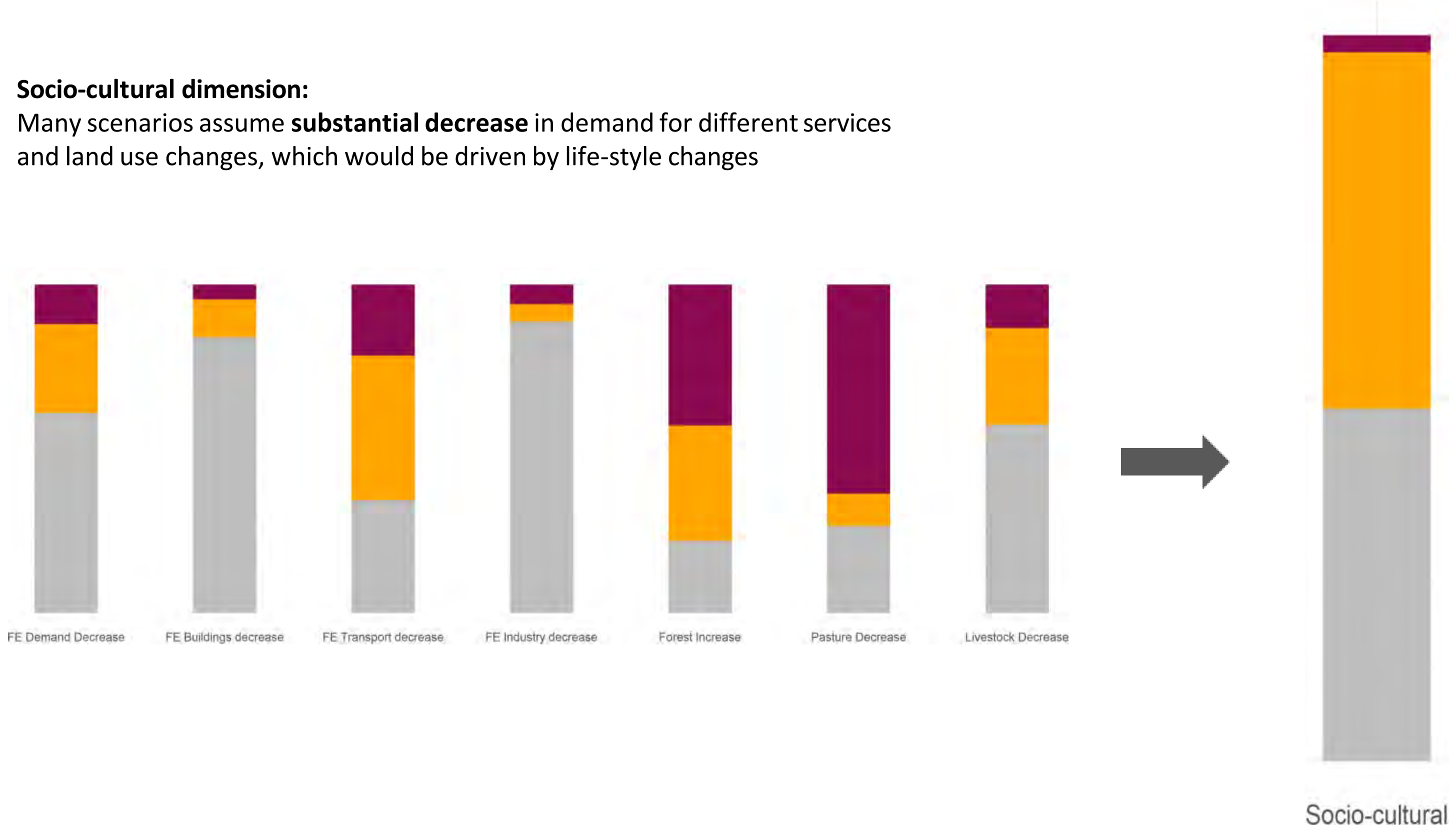
TS – Economic dimension

Economic dimension:
Most scenarios assume a rapid transformation of the energy system which requires **high levels of carbon prices/investments and prematurely retiring coal power plants**



TS – Socio-cultural dimension

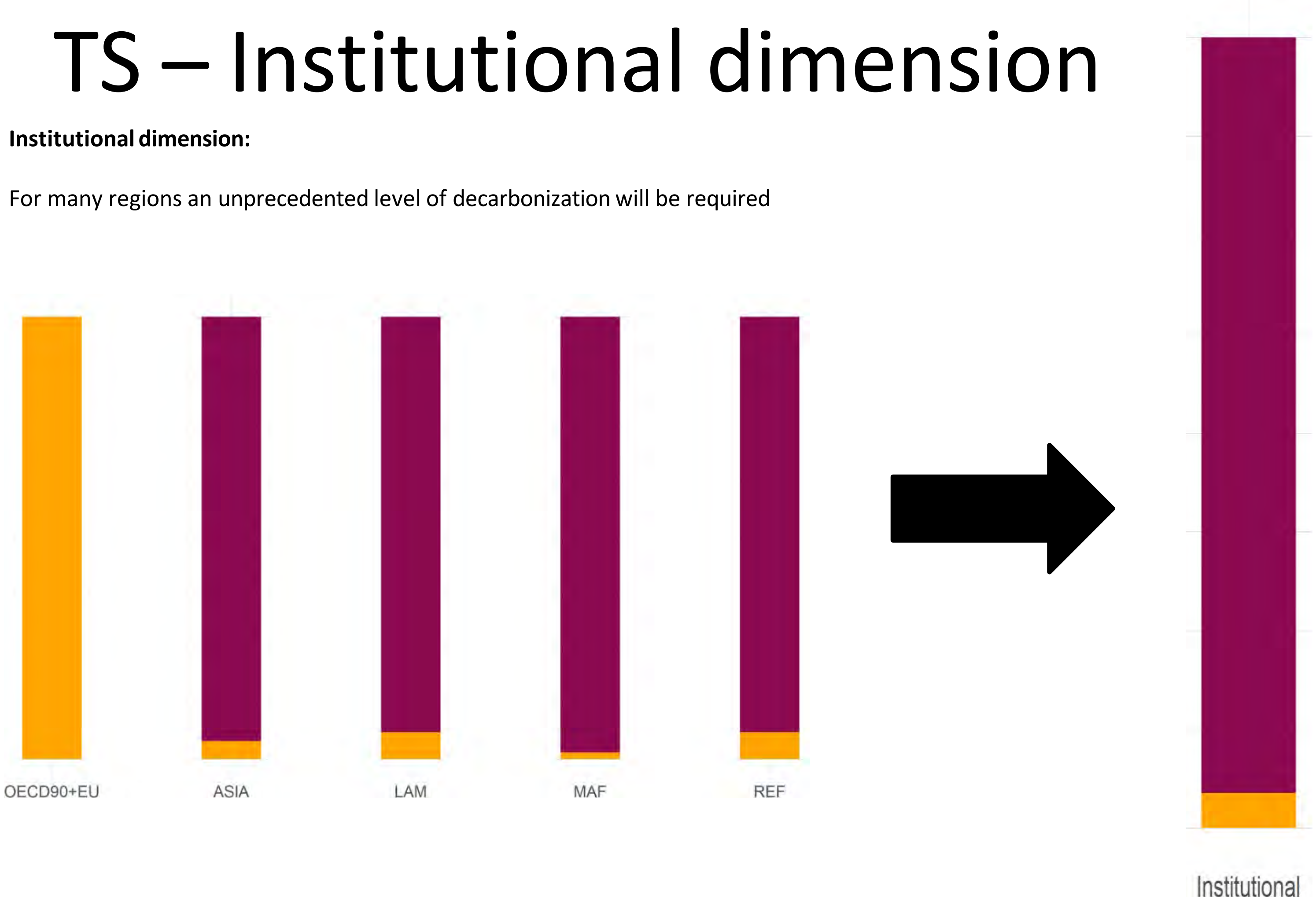
Socio-cultural dimension:
Many scenarios assume **substantial decrease** in demand for different services and land use changes, which would be driven by life-style changes



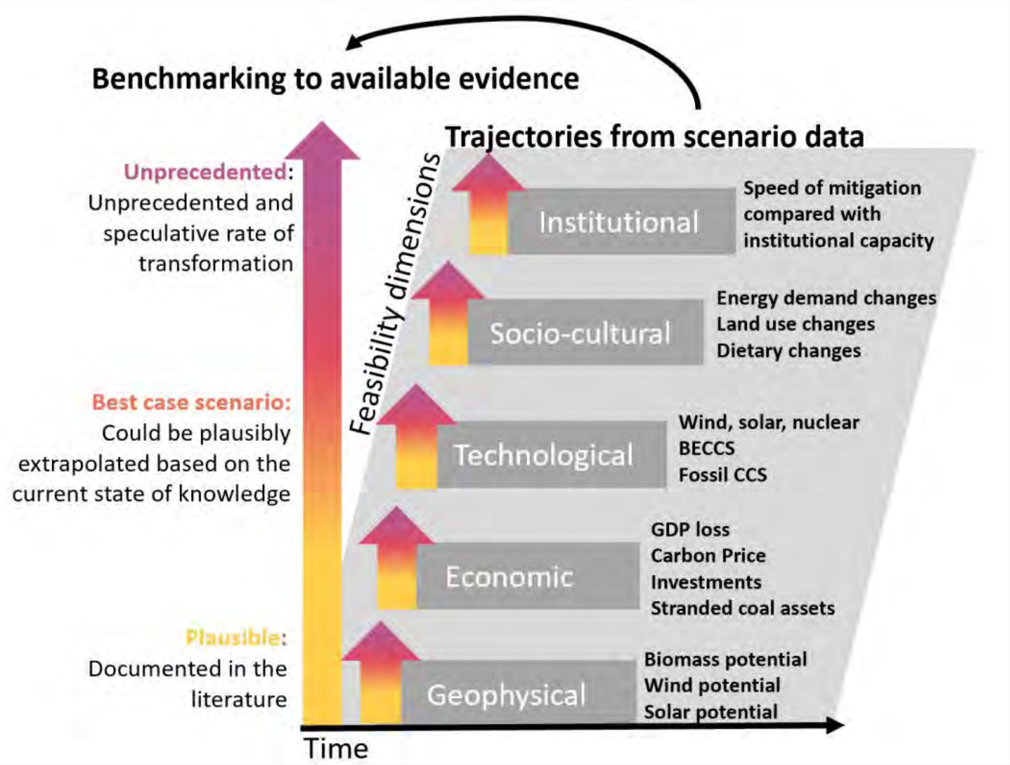
TS – Institutional dimension

Institutional dimension:

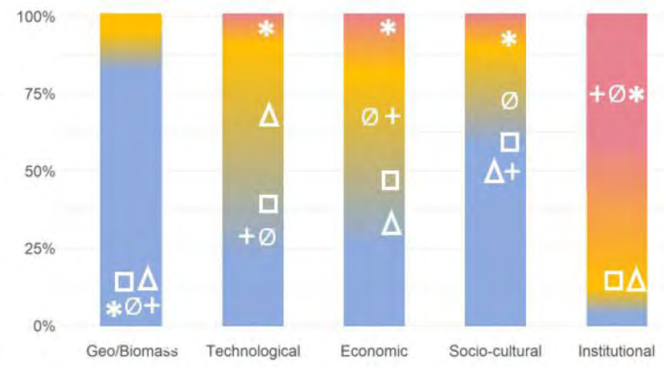
For many regions an unprecedented level of decarbonization will be required



Key challenges comprise governance and institutional dimension in the developing world



Feasibility evaluation of 1.5C and 2C pathways



How can we model governance and institutional change?

Based on Andrijevic et al 2020 and Gidden et al 2023

Government effectiveness in IIASA IAM

(capacity to implement policies) is a relatively good proxy of environmental protection levels

ENVIRONMENTAL RESEARCH
LETTERS

LETTER

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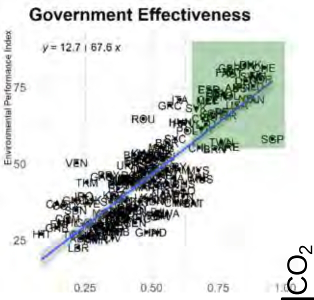
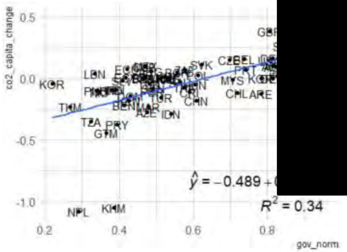
Fairness and feasibility in deep mitigation pathways with novel carbon dioxide removal considering institutional capacity to mitigate

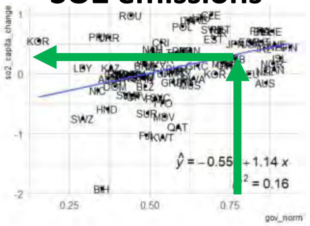
Matthew J Gidden[1,2,*], Elina Brutschin[1], Gaurav Ganti[2,3], Gamze Unlu[1], Behnam Zakeri[1], Oliver Fricko[1], Benjamin Mitterrutzner[1,4], Francesco Lovat[1,5] and Keywan Riahi[1]



CO2 emissions

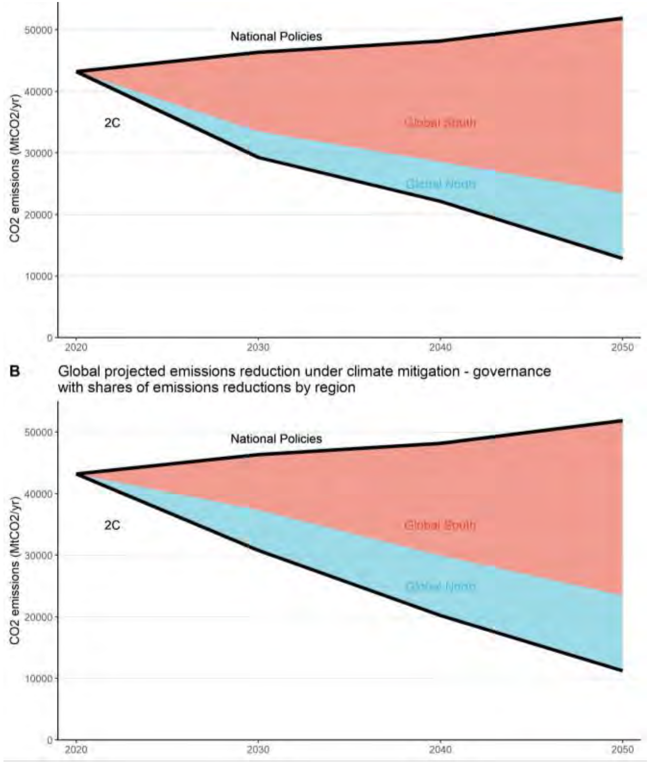


SO2 emissions



840 CO_2

Governance projections along SSPs based on Andrijevic et al. (2020)

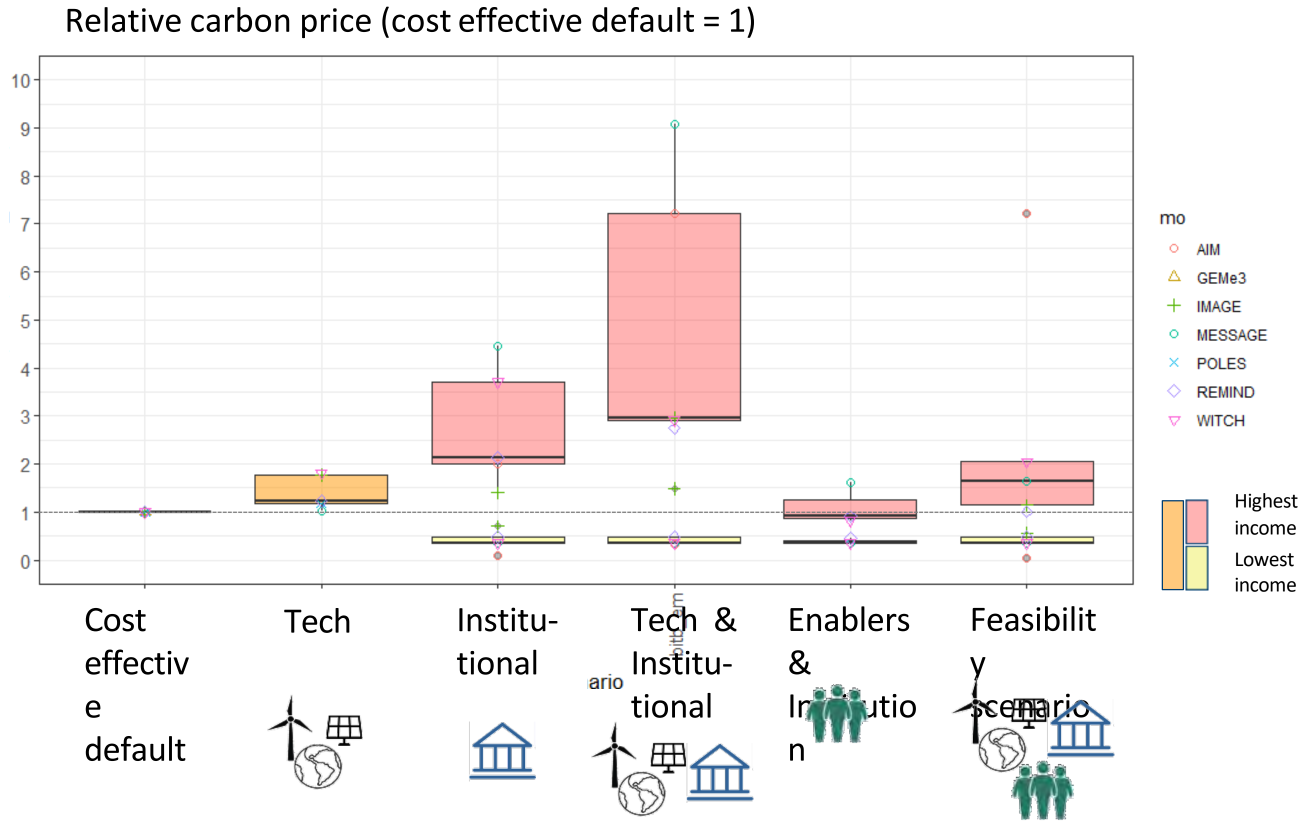


Model Formulation

Governance level	Upper bound on total CO2 emission reductions for a given decade
<0.65	20% (below red)
0.66-0.7	25%
0.71-0.75	40%
0.76	Unconstrained (above green)

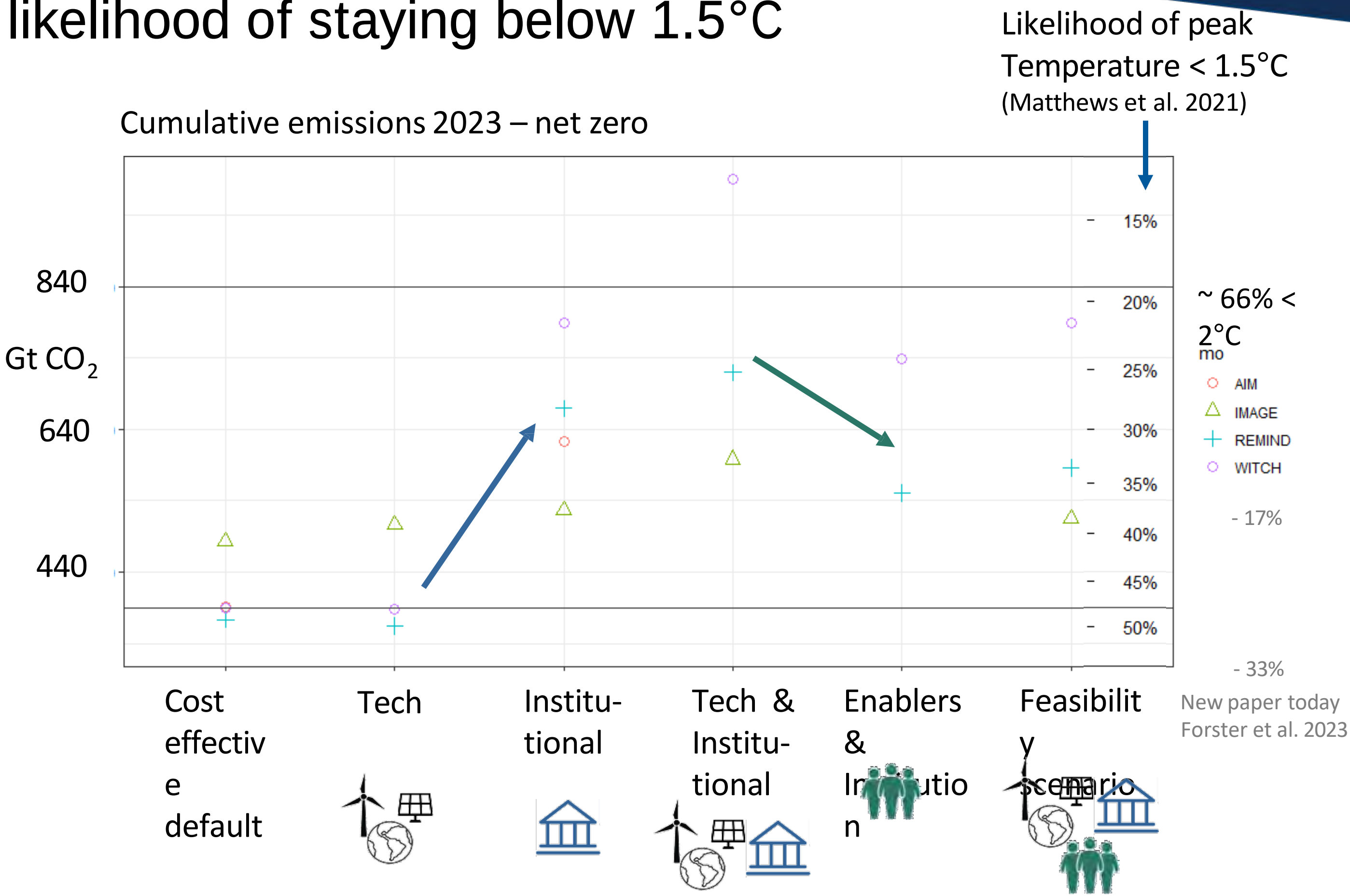
Impact of feasibility concerns on 2°C pathways (66% not-to-exceed)

- Combined constraints most difficult
- Enablers balance institutional feasibility for high-income regions
- Combined constraints and enablers have moderate impact on costs



Lowest achievable net-zero budget –
highest achievable likelihood of staying below 1.5°C

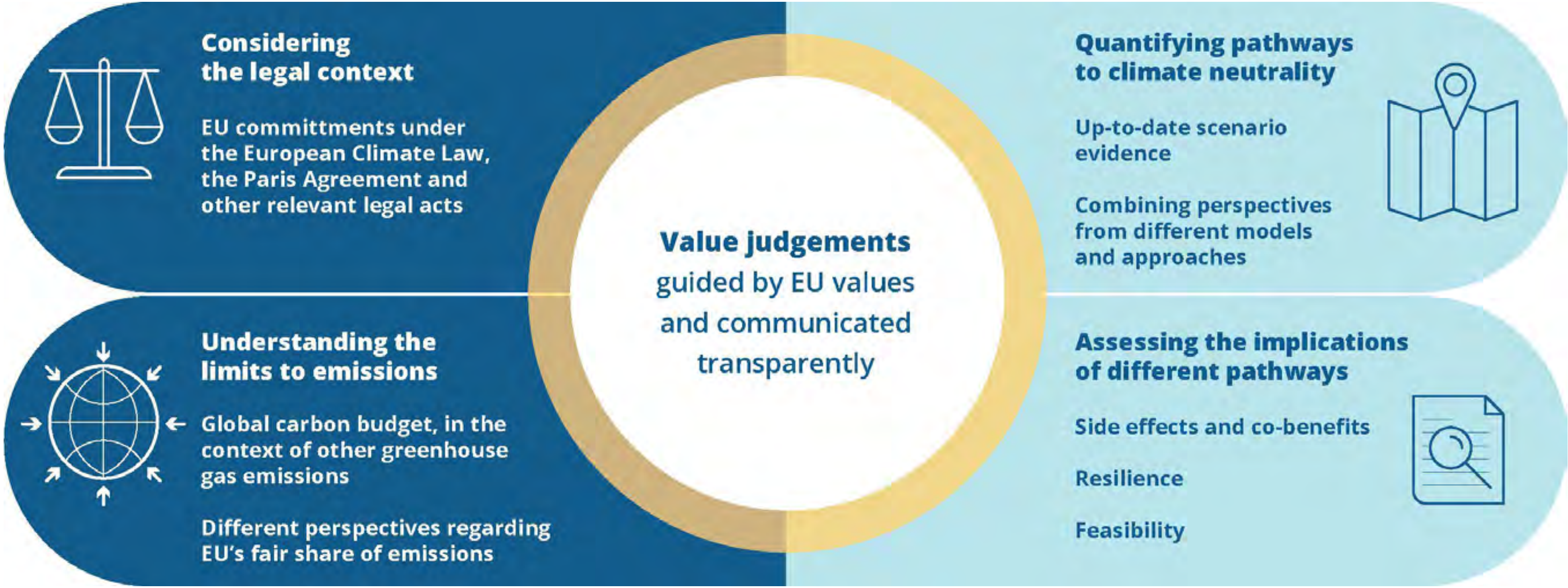
- Without feasibility restrictions, or only with technology restrictions, ~50% likelihood of <1.5 still possible
- Reflecting **institutional constraints** lowers this to max ~15-35%
- **Enablers** only bring it back up to 20-40%



Is this fair?

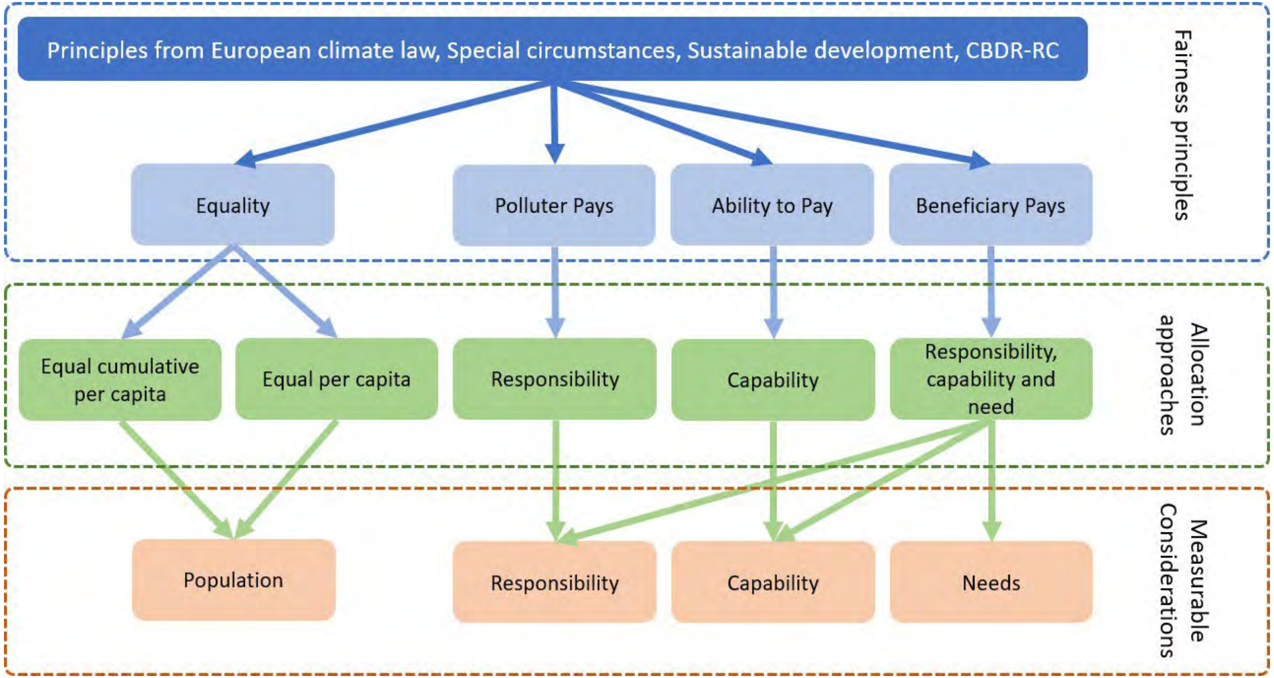
Based on Peltz et al 2023 and the recommendations of the EU Advisory Board on Climate Change, 2023

Recommendations for a fair EU emissions budget - EU Advisory Board on Climate change



https://climate-advisory-board.europa.eu/reports-and-publications/setting-climate-targets-based-on-scientific-evidence-and-eu-values-initial-recommendations-to-the-european-commission

How to operationalise equity and fairness



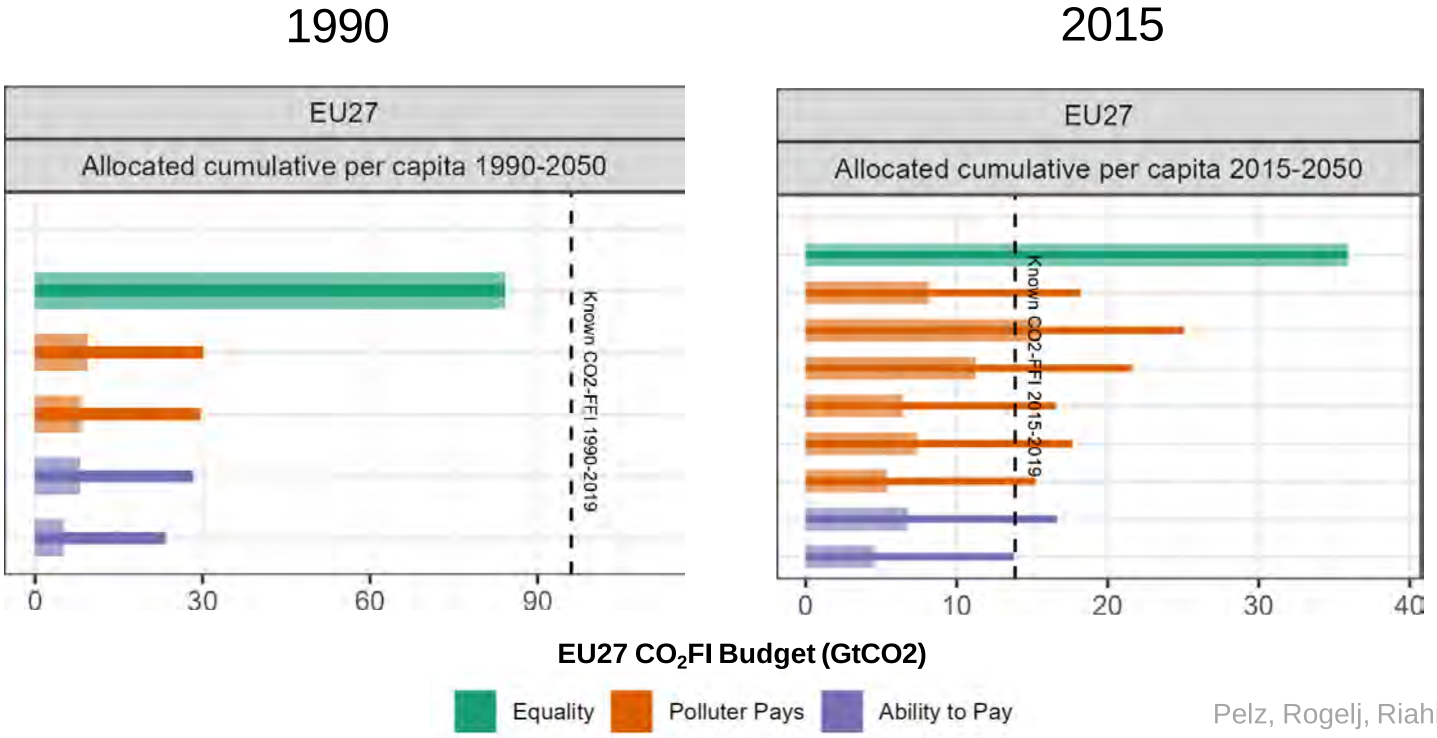
Formal justification underlying
v f ‘w f ’.

Specify how remaining carbon budgets are allocated.

Measurable characteristics of regions, countries, or populations.

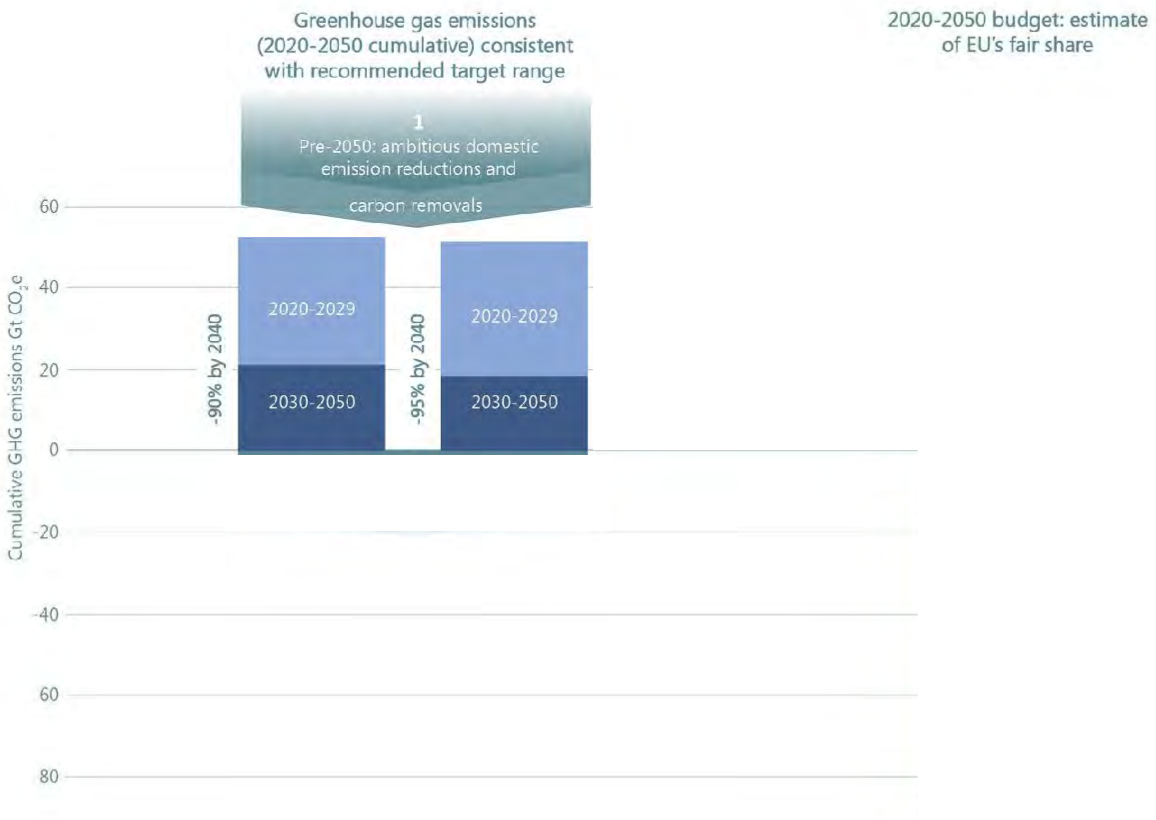
Pelz, Rogelj, Riahi, 2023

A “fair” allocation of the EU budget according to different ethical criteria



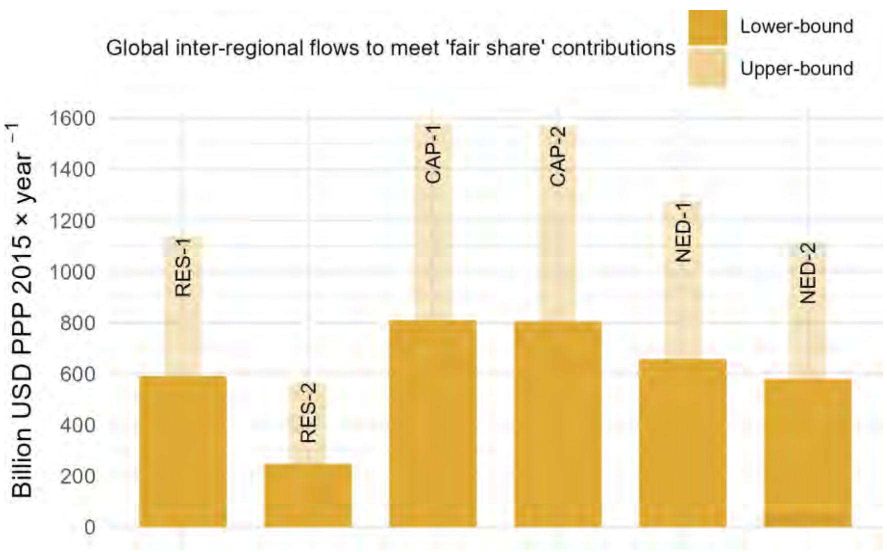
Pelz, Rogelj, Riahi, 2023

EU and its responsibility to support action also internationally



EUAB, 2023

New fair share analysis based on AR6 pathways indicate the need of increasing finance flows



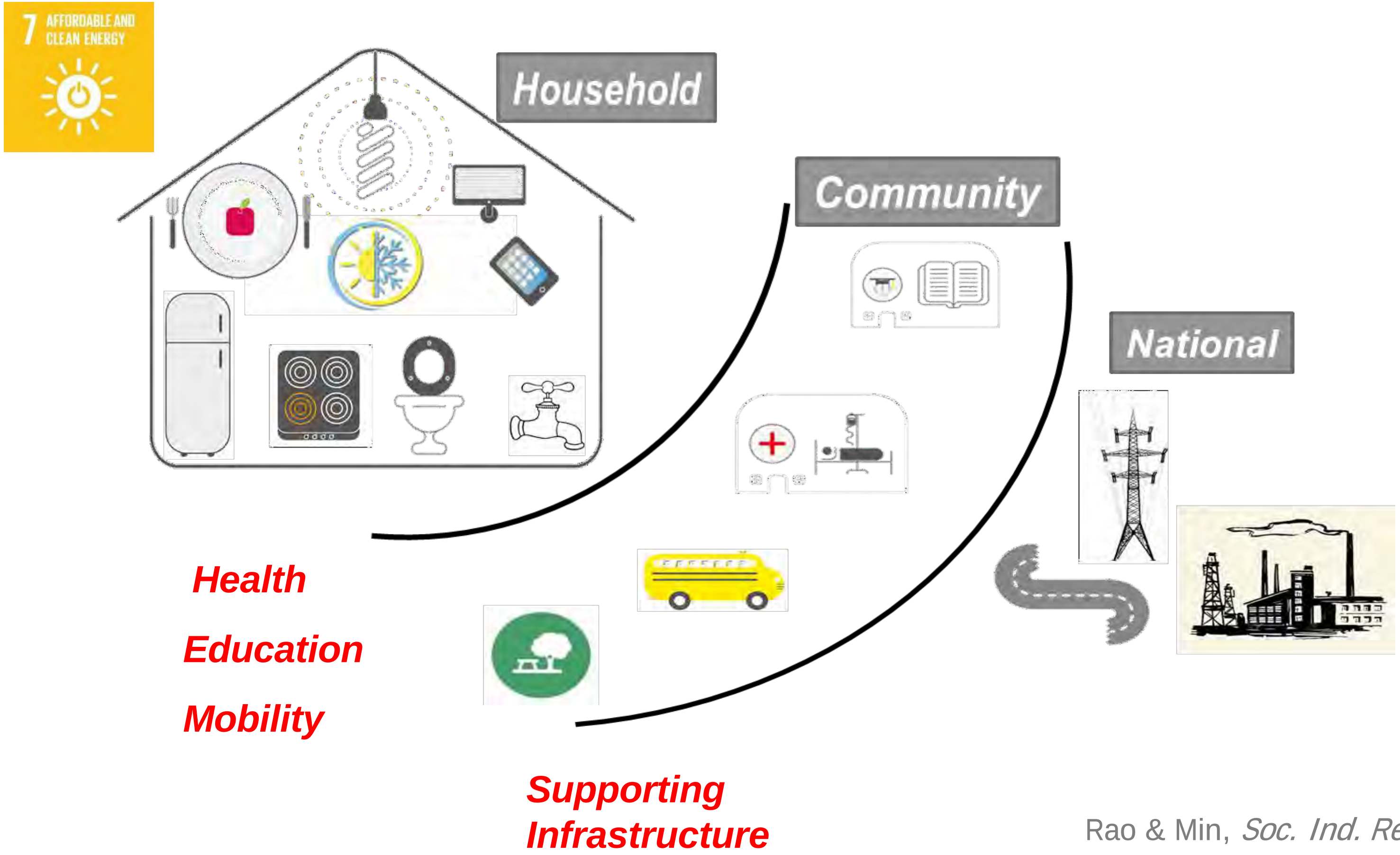
Shonali Pachauri[1], Setu Pelz[1], Christoph Bertram[2], Silvie Kreibiehl[3], Narasimha D. Rao[1,4], Keywan Riahi[1], Youba Sokona[5,6] *(Science, 2022)*

Investments in the AR6 pathways are follow a cost-effectiveness approach (consistent with Article 3 of Paris Agreement)

The pathways, however, do not address the issue of who is financing the regional investments

New assessment of equitable and fair finance (of the investments of the AR6 pathways) suggest a major increase of finance flows from Annex-1 to non-Annex-1 regions

Energy for Poverty Eradication



Rao & Min, *Soc. Ind. Res.*, 2018

Decent Living Standards – Material basis for Well-being

DLS Indicators

Dimension	Unit
Food	kCal, Micronutrition
Shelter Comfort	m^2, Durable (ºC, RH)
Basic appliances	Stove, TV, Fridge
Health/Educ	$$
Clothing	Kg
Water/Sanit	Access, m^3
Mobility	P-km

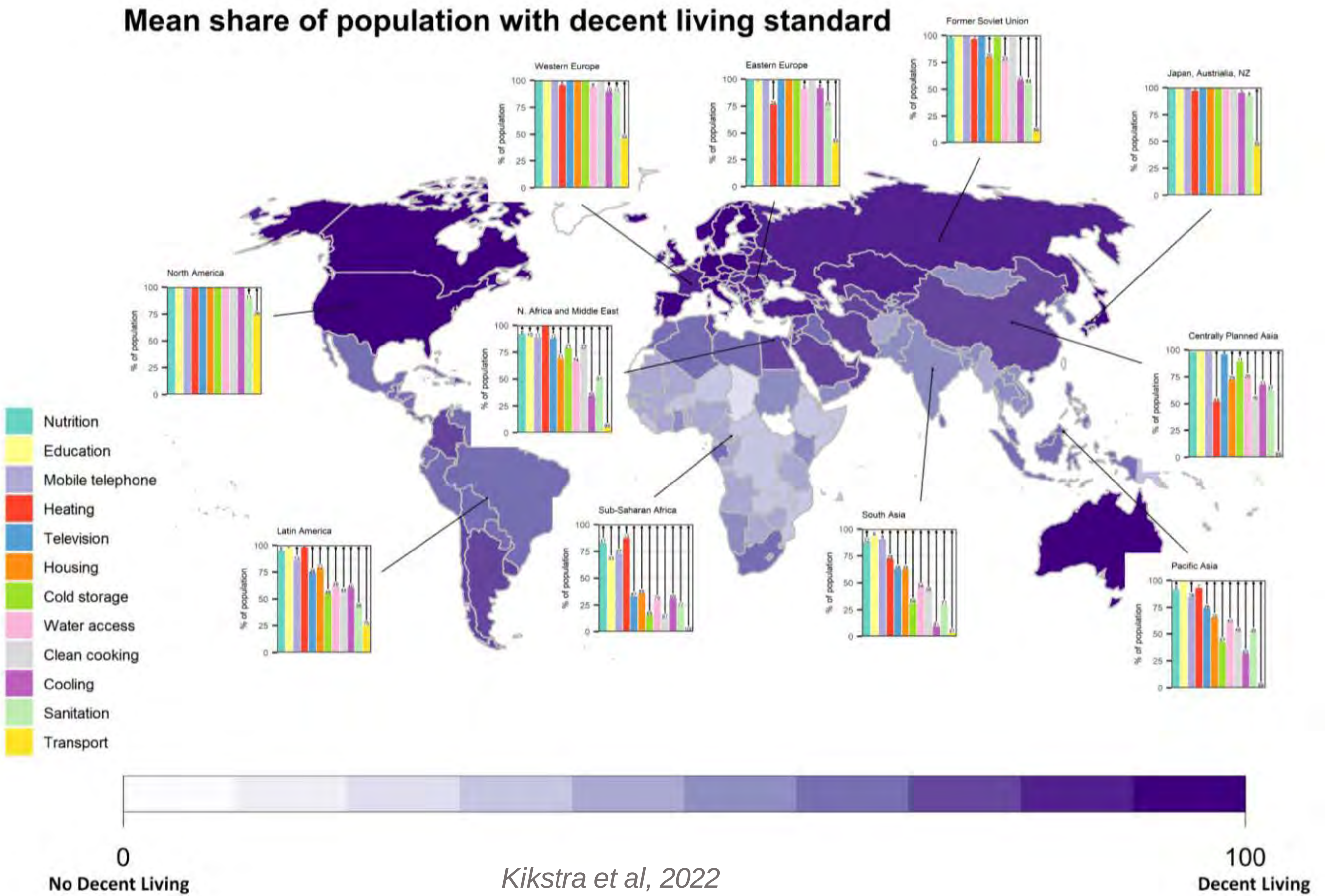
Physical Wellbeing

Dimension	Description/ (Minimum) Thresholds
Housing	Safe, durable (permanent), min space (10 m^2/cap)
Thermal comfort	AC Use (26°C, 60% Humidity), 1 bedroom, nights only. Heating to 18°C
Nutrition	Macro- and micronutrients (protein, zinc, iron, calories)
Clean ckg	LPG or electricity cook stoves
Water	65 l/cap/day, indoor access
Sanitation	Sewage distribution (urban only)
Appliances	Fridge: <200 l; TV; cell phone per adult
Health care	$665 per capita (national)
Education	$1000 -$1500 per student (national)
Mobility Infrastructure	10K p-km motorized; paved roads; public transit

Social Wellbeing

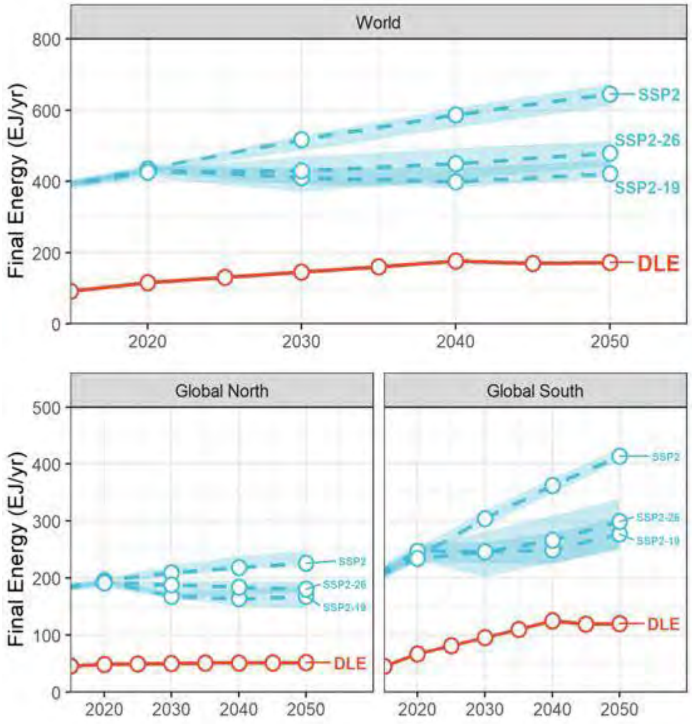
Rao & Min, *Soc. Ind. Res.*, 2018

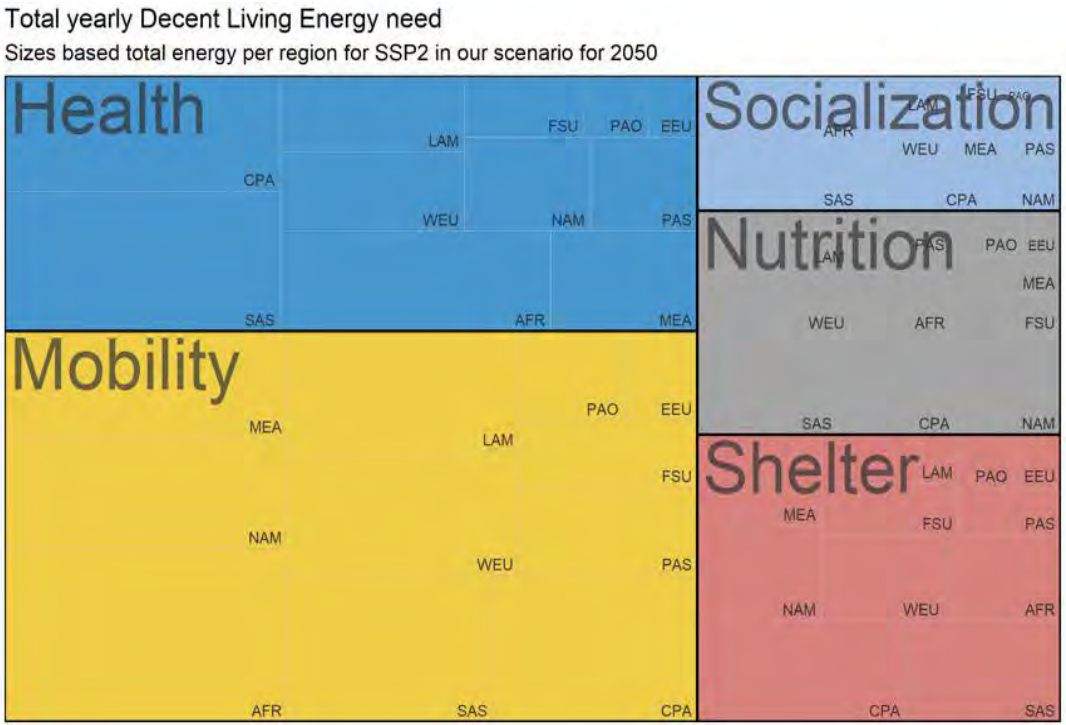
Decent Living Gaps – Today



Kikstra et al, 2022

Energy needs for DLE significantly less than lowest scenarios in the literature





Kikstra et al., 2022

Thank you.

Visit: https://iiasa.ac.at/winners-of-edits-arts-2022-competition-life-in-2050-with-much-less-energy

Role of energy storage in a carbon neutral world

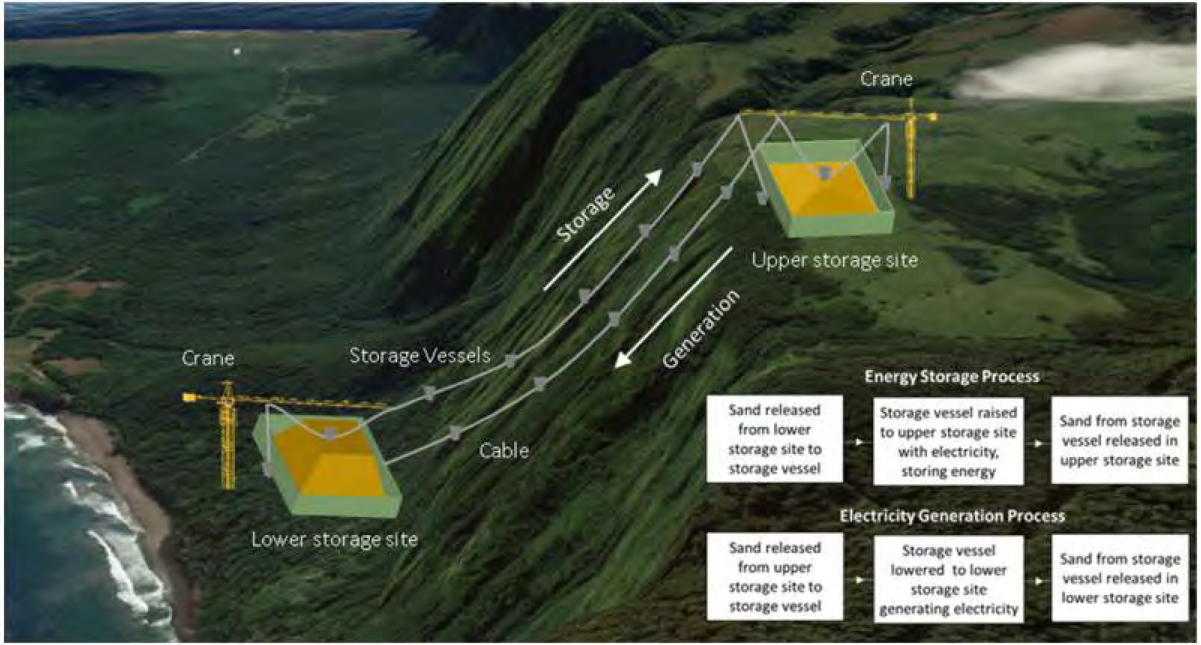
Behnam Zakeri, Julian Hunt, Maarten Brinkerink, (placeholder for other others) Volker Krey, Keywan Riahi

International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

Unconventional Technology Possibilities

Name	Installed capacity cost (USD/KW)	Energy Storage cost (USD/KWh)	Installed capacity per project (MW)	Storage Cycle	Global Potential (TWh)	11 regions
Mountain Gravity Energy Storage (MGES)	200 – 2,000	20 - 200	1 - 20	Seasonal, pluriannual	8.684	Yes
Electric Truck Gravity Energy Storage (ETGES)	1,200	1.2	20 – 100	Monthly, seasonal	5.400	Yes
Lift Energy Storage (LEST)	500 – 1,000	20 - 120	0.02 – 1 (per building)	Ancillary, daily, weekly	0.03 – 0.3	Yes
Seasonal pumped hydropower storage (SPHS)	400 – 600	0.002 – 0.100	100 - 5000	Seasonal, pluriannual	17.300	Yes
Buoyancy Energy Storage Technology (BEST)	4,000 – 8,000	50 – 100	10 - 100	Ancillary, daily, weekly	∞ (deep-sea)	Not yet
Deep hydrogen ocean link (HYDOL)	H_2 storage	0.018	H_2 storage	Seasonal, pluriannual	∞ (deep-sea)	Not yet
Isothermal deep ocean compressed air energy storage (IDO-CAES)	1,600	1.26	100 – 1000	Monthly, seasonal, pluriannual	∞ (deep-sea)	Not yet

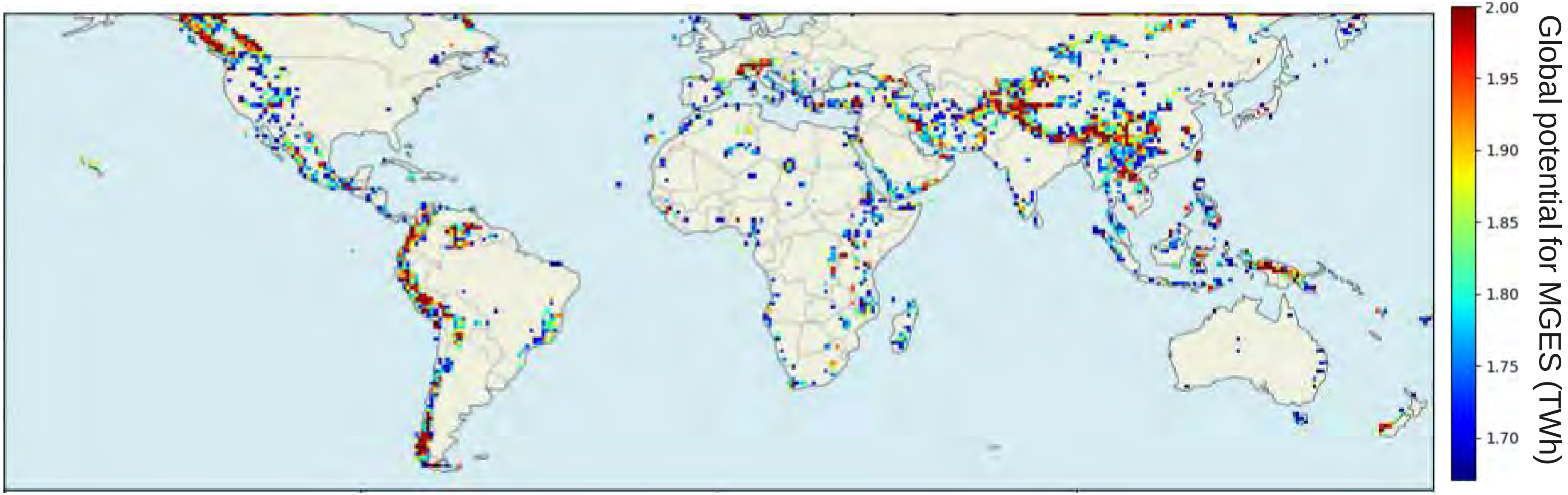
Mountain Gravity Energy Storage



Innovative technologies: Seasonal Storage

Mountain Gravity Energy Storage

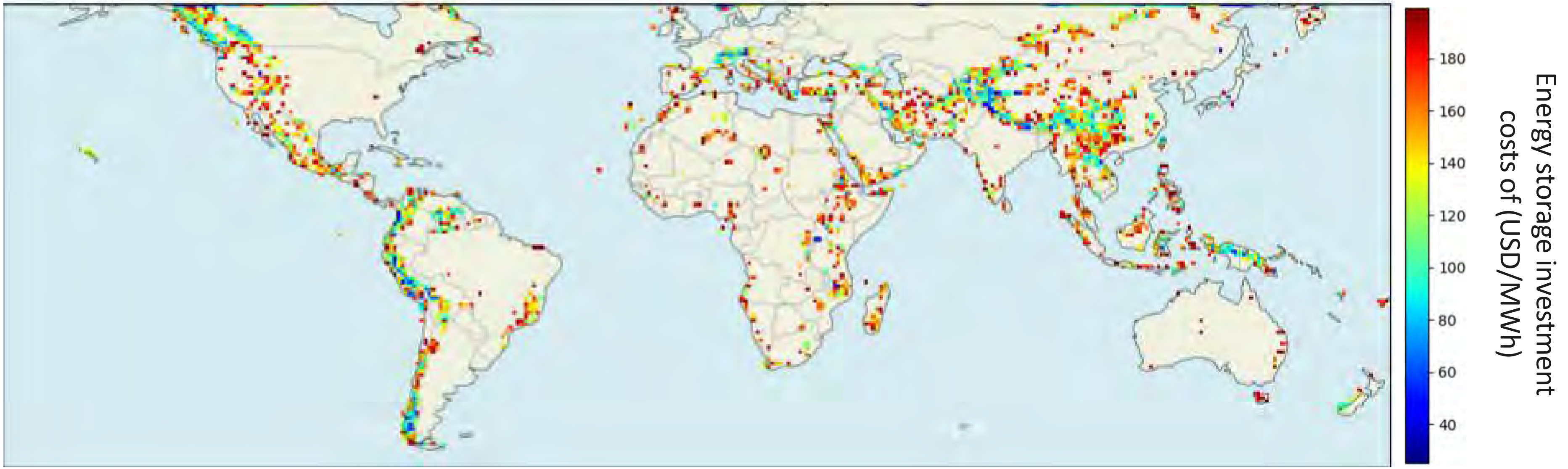
Global potential (TWh)



Innovative technologies: Seasonal Storage

Mountain Gravity Energy Storage

Energy storage investment costs (USD/MWh)



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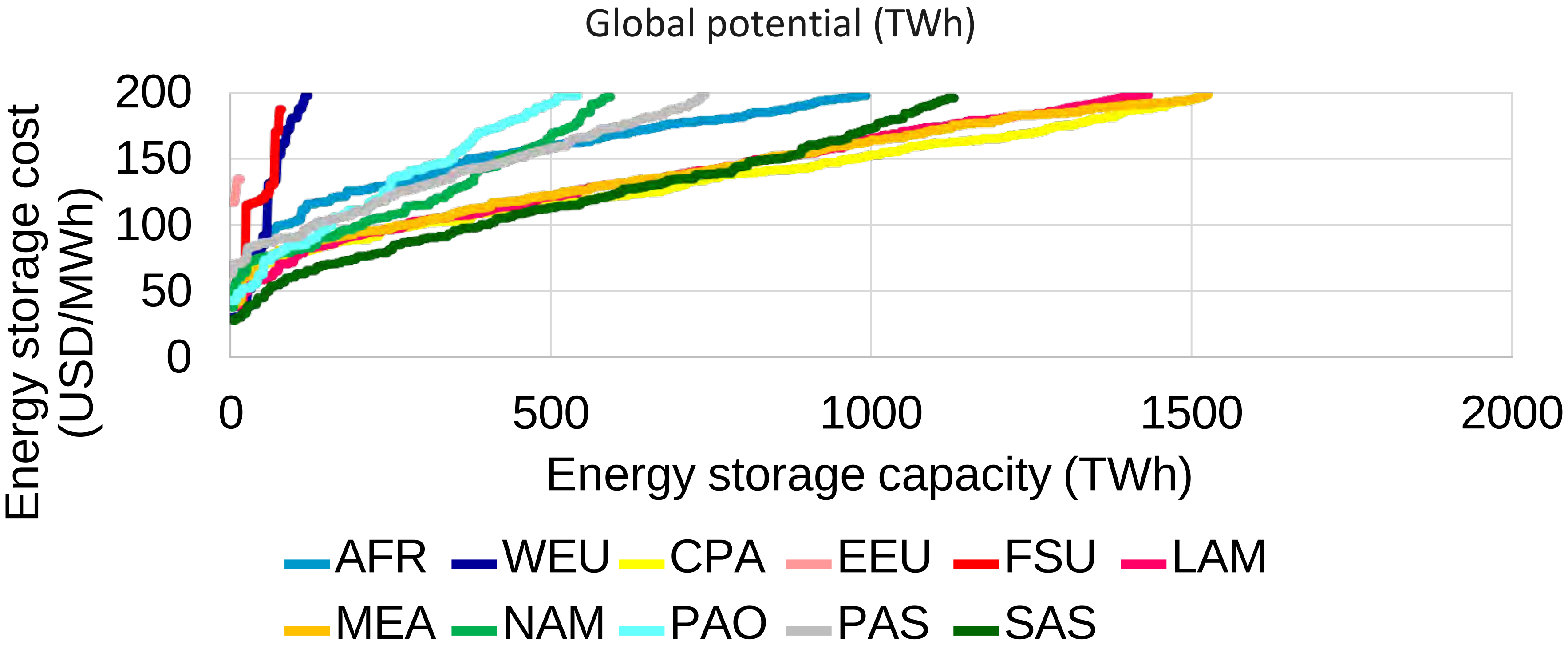
Mountain Gravity Energy Storage



Technologies

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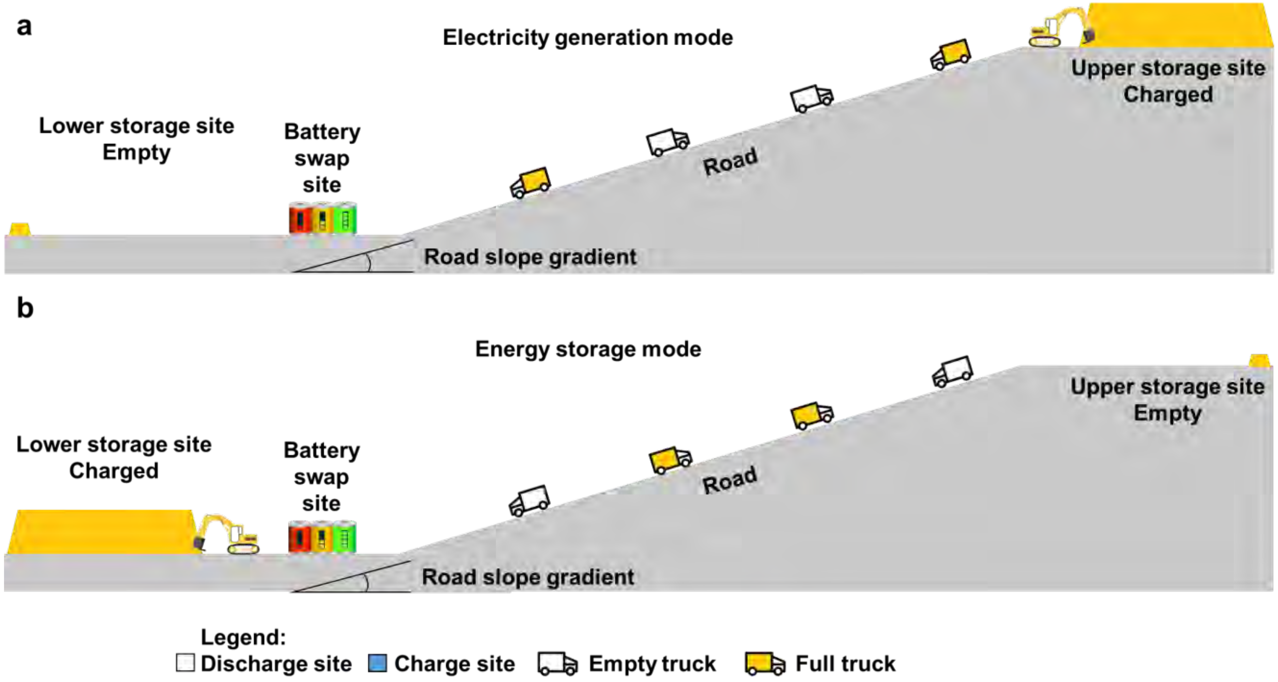
Electric Truck Gravity Energy Storage, a solution for long-term energy storage



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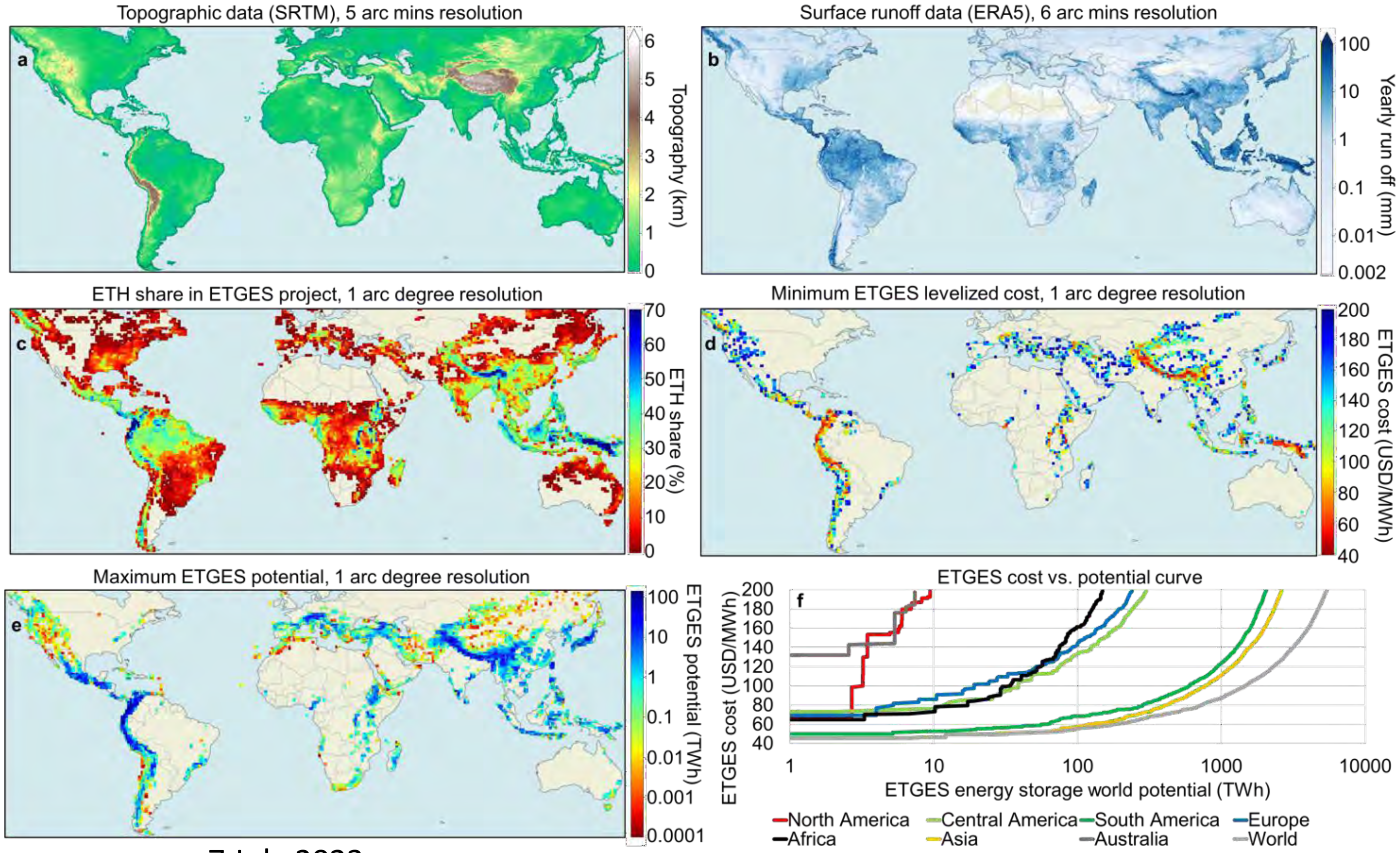
Topographic data (SRTM), 5 arc mins resolution
a
Topography (km)
0
1
2
3
4
5
6
Surface runoff data (ERA5), 6 arc mins resolution
b
Yearly run off (mm)
100
10
1
0.1
0.01
0.002
ETH share in ETGES project, 1 arc degree resolution
c
ETH share (%)
70
60
50
40
30
20
10
0
Minimum ETGES levelized cost, 1 arc degree resolution
d
ETGES cost (USD/MWh)
200
180
160
140
120
100
80
60
40
Maximum ETGES potential, 1 arc degree resolution
e
ETGES potential (TWh)
100
10
1
0.1
0.01
0.001
0.0001
ETGES cost vs. potential curve
f
ETGES cost (USD/MWh)
ETGES energy storage world potential (TWh)
1
10
100
1000
10000
North America
Central America
South America
Europe
Africa
Asia
Australia
World

7 July 2023

Technologies

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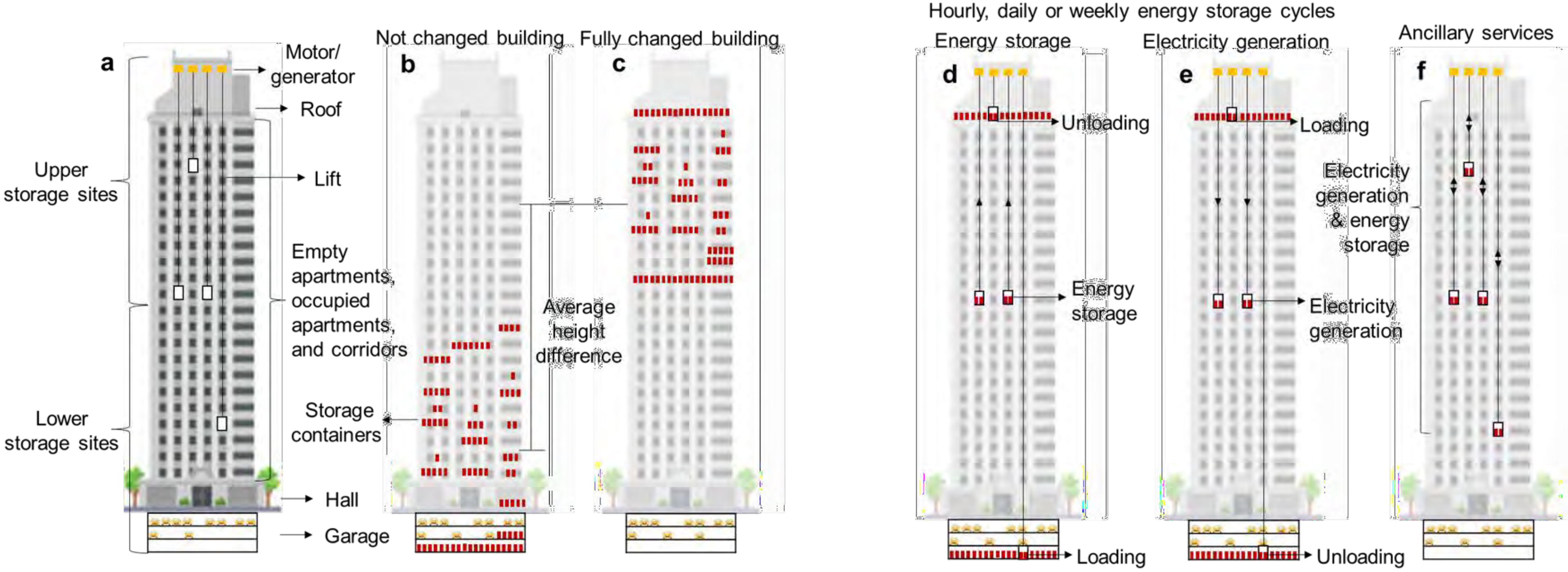
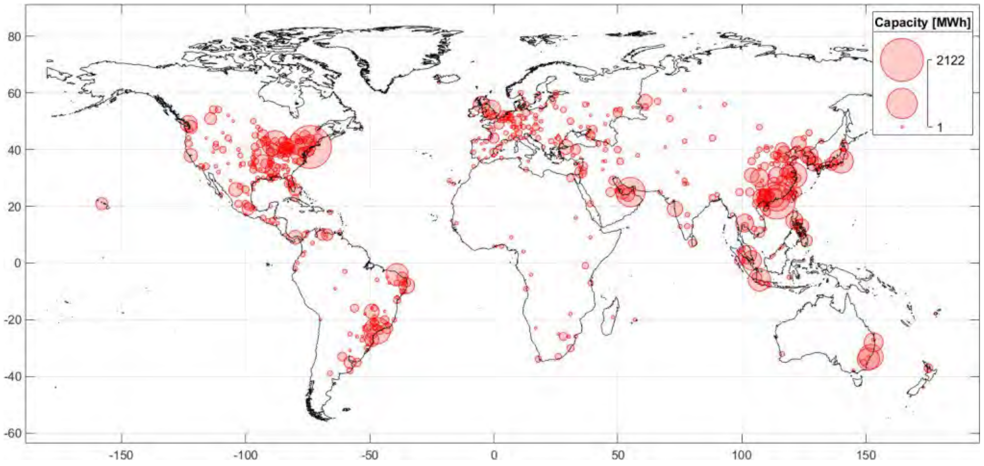
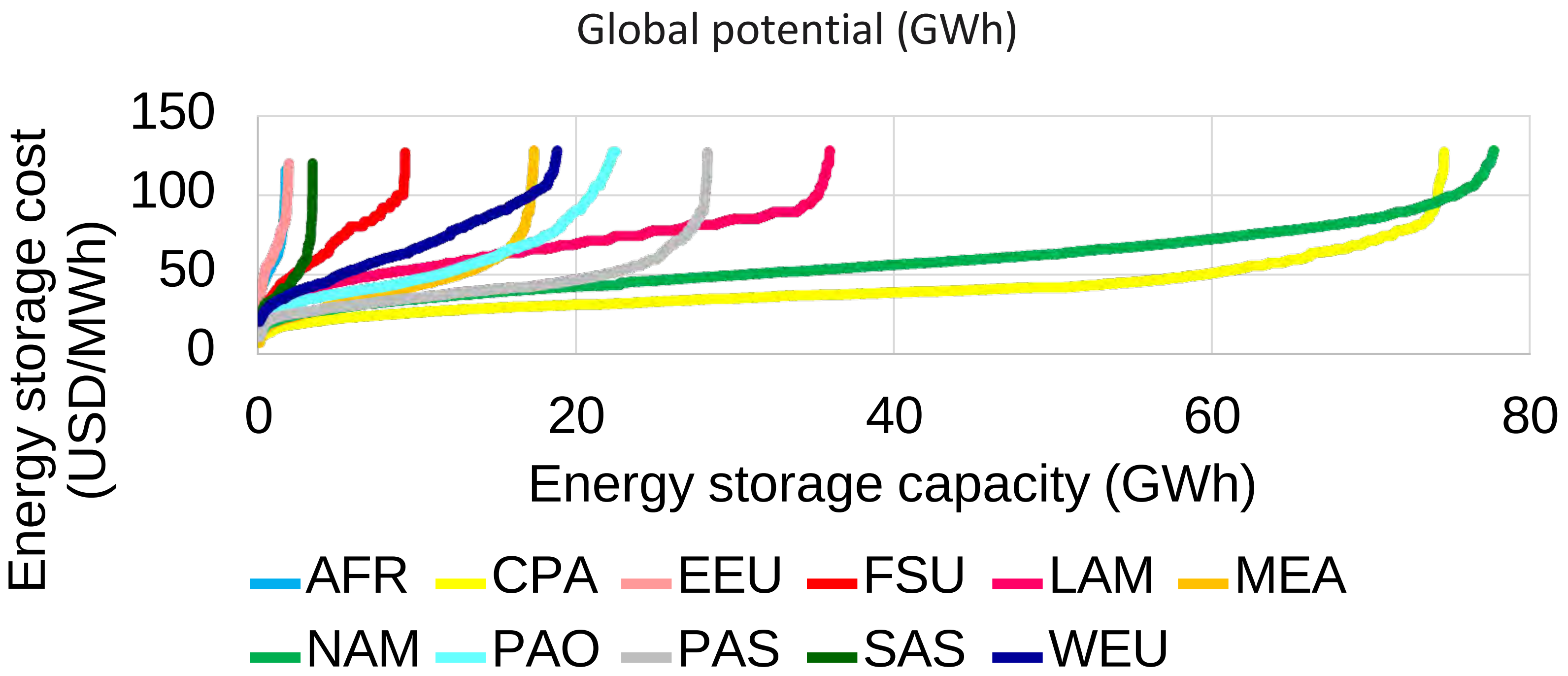
Lift Energy Storage Technology: a solution for decentralized urban energy storage



Global potential

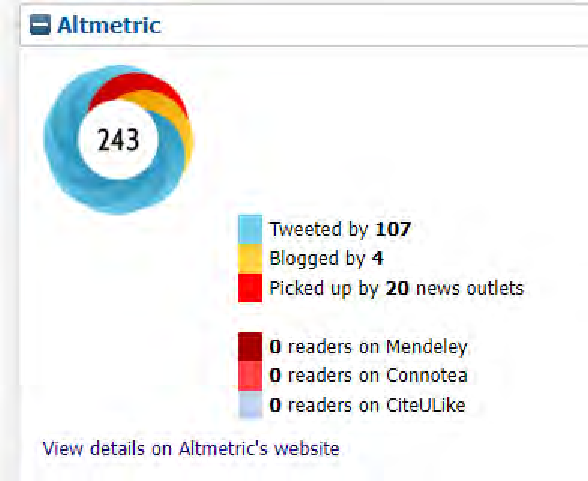


North America	3152	2396	670	178	44	17	8
Western Europe	1191	464	121	23	7	1	0
Pacific OECD	857	575	295	60	14	2	
Central and Eastern Europe	113	57	7	3	0		
Former Soviet Union	616	218	40	8			
Centrally Planned Asia and China	912	1241	152[illegible]				
South Asia	38	92					
Other Pacific Asia	326						
Middle East and North Afric							
Latin America and the							


Global potential (GWh)
Energy storage cost (USD/MWh)
150
100
50
0
0
20
40
60
80
Energy storage capacity (GWh)
AFR
CPA
EEU
FSU
LAM
MEA
NAM
PAO
PAS
SAS
WEU

Lift Energy Storage Technology: a solution for decentralized urban energy storage

Press release



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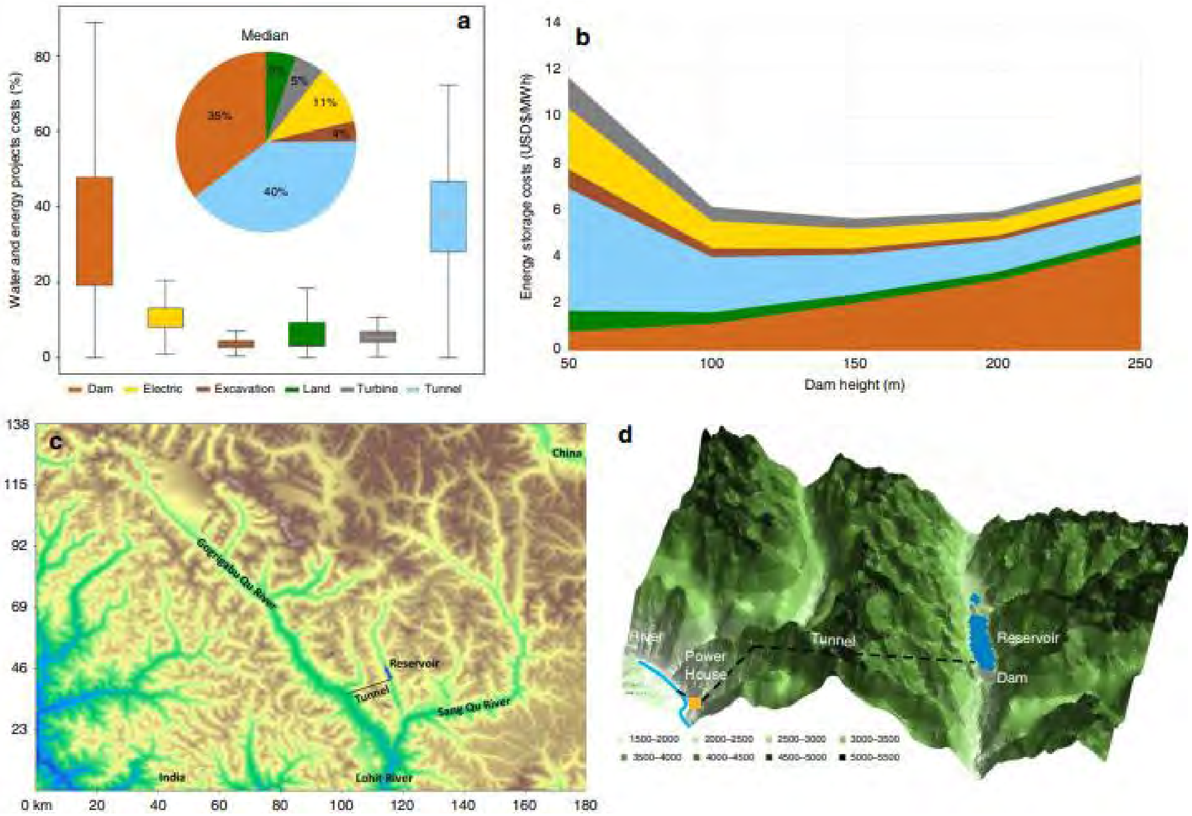
Global resource potential of seasonal pumped hydropower storage for energy and water storage



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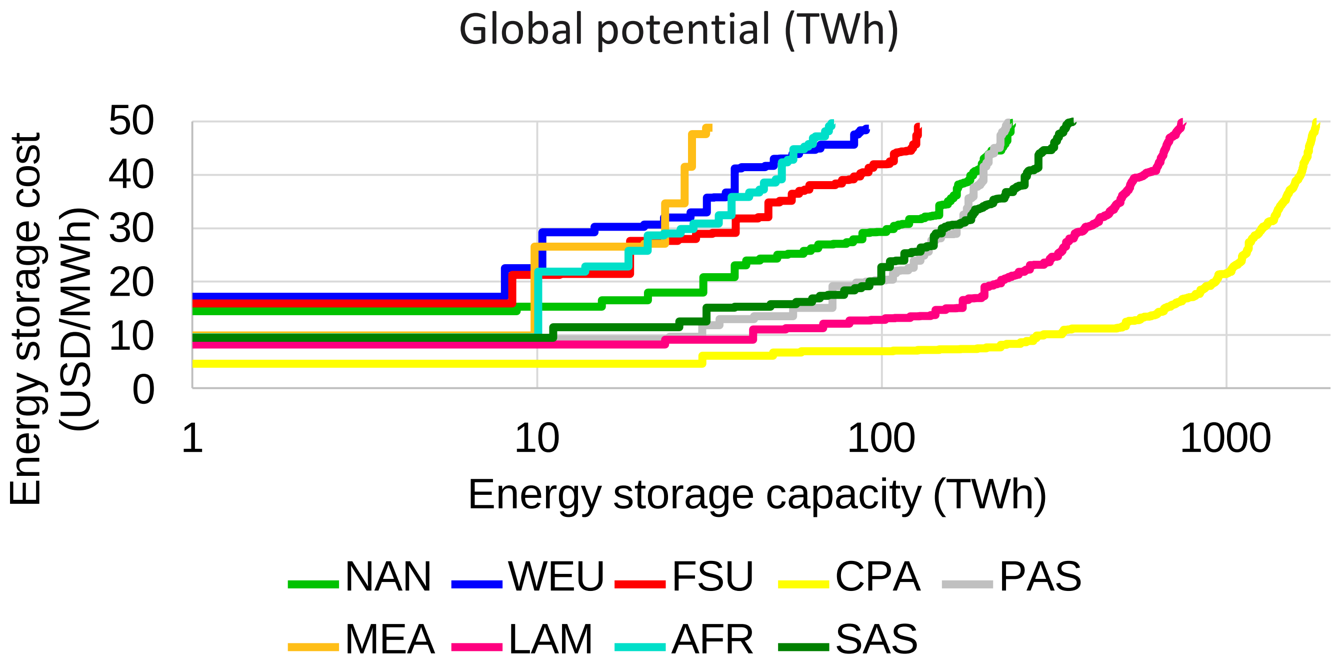

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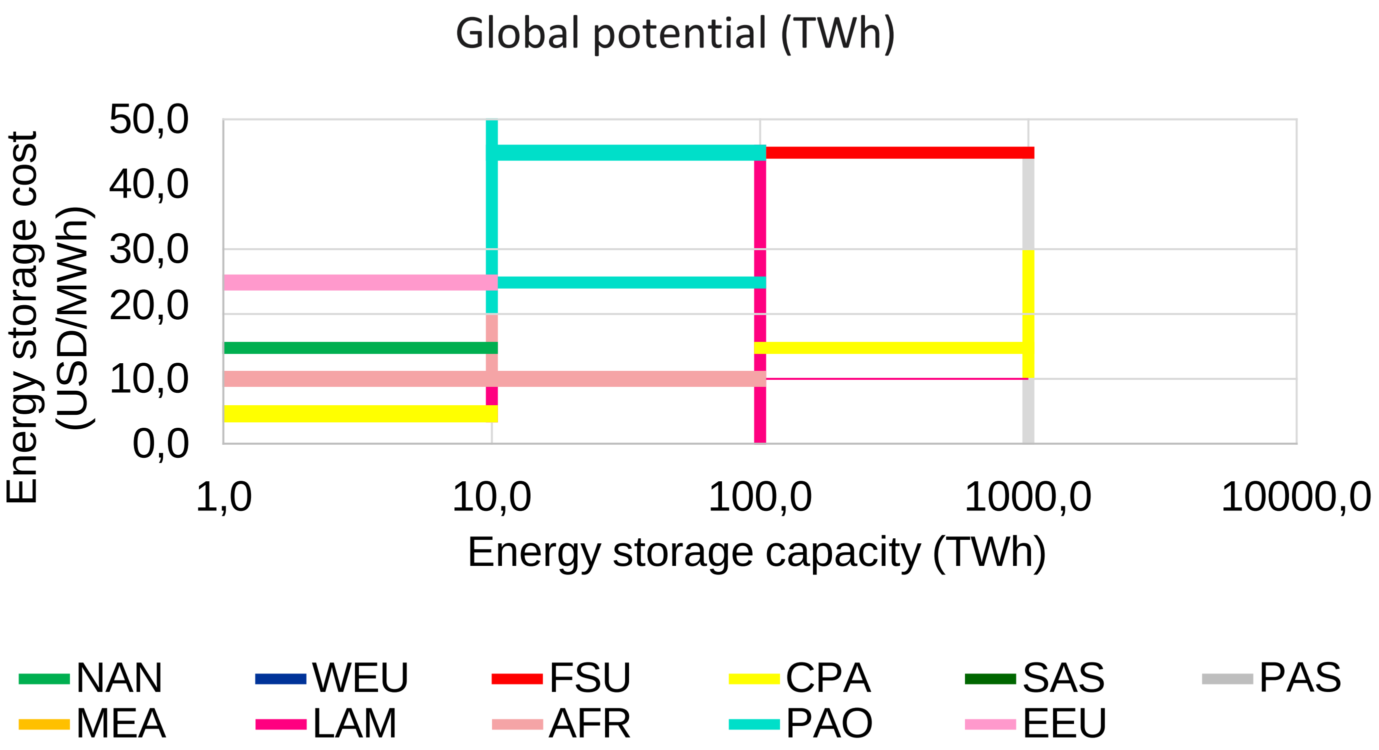

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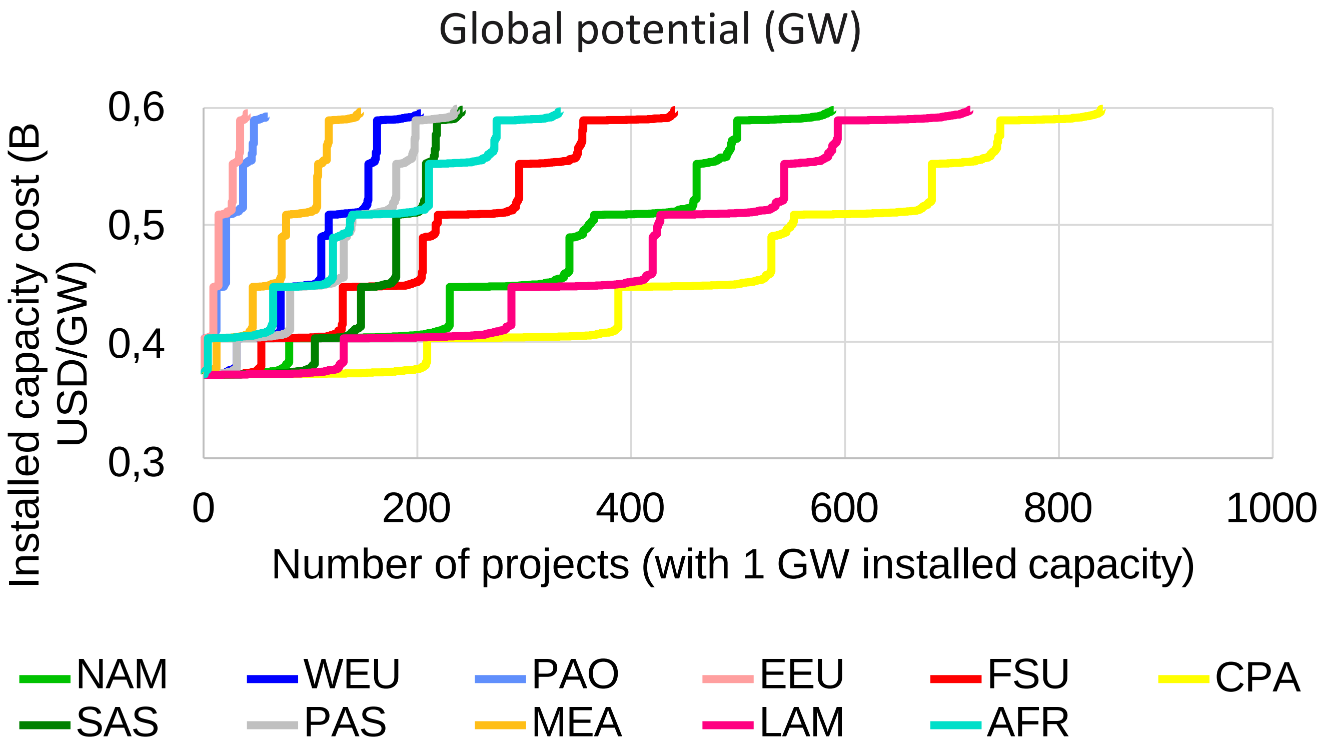

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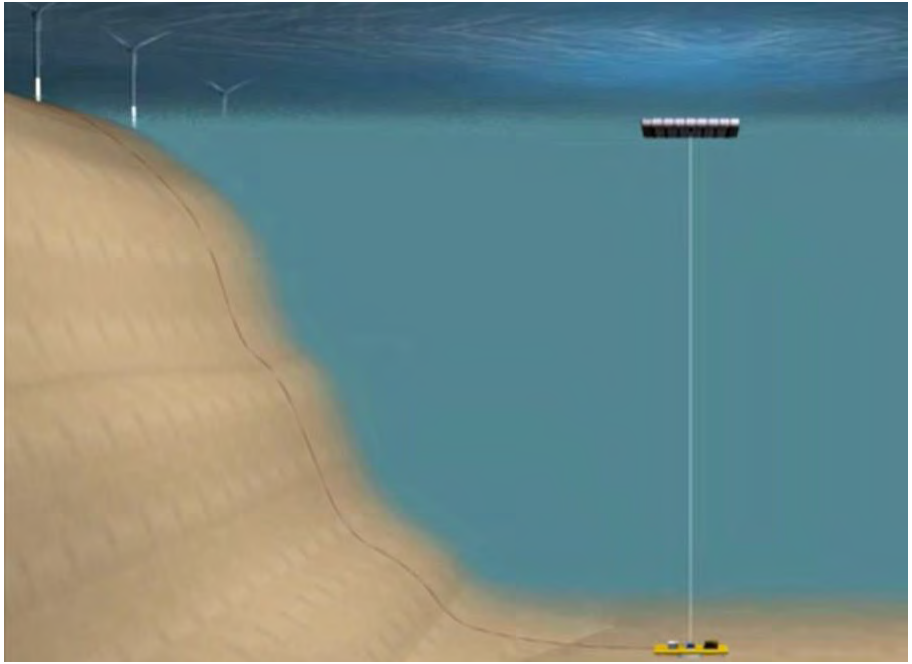
Buoyancy Energy Storage Technology: An energy storage solution for islands, coastal regions, offshore wind power and hydrogen compression



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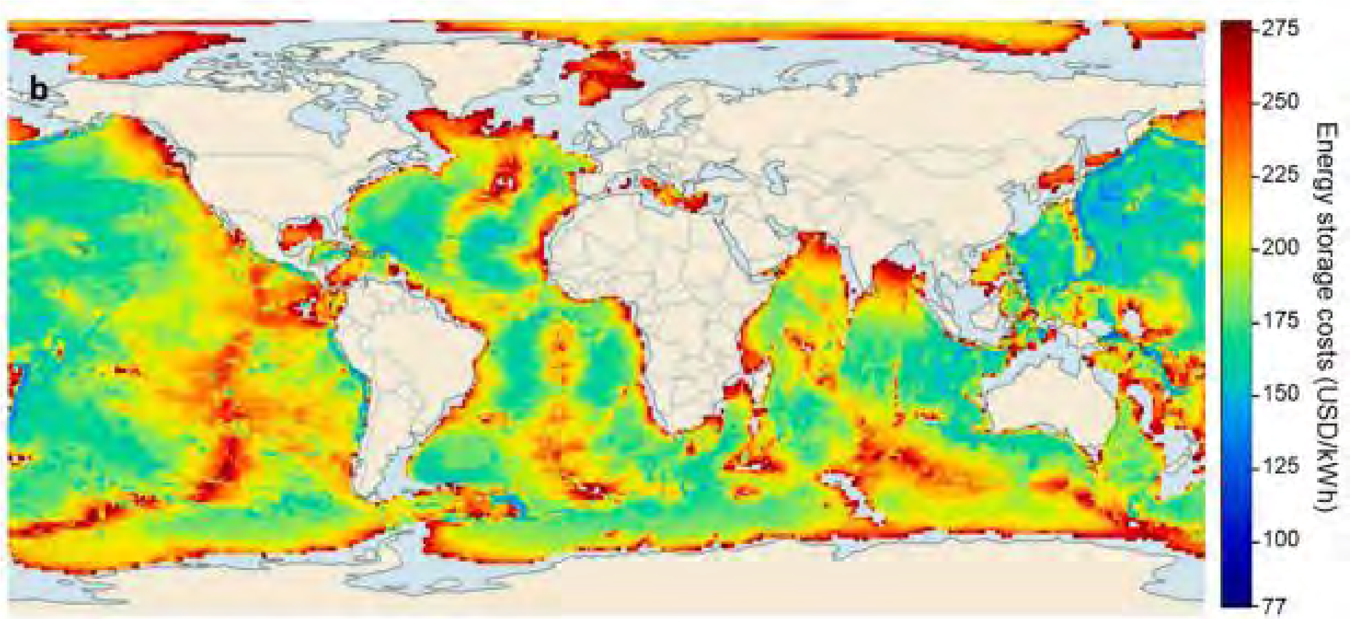

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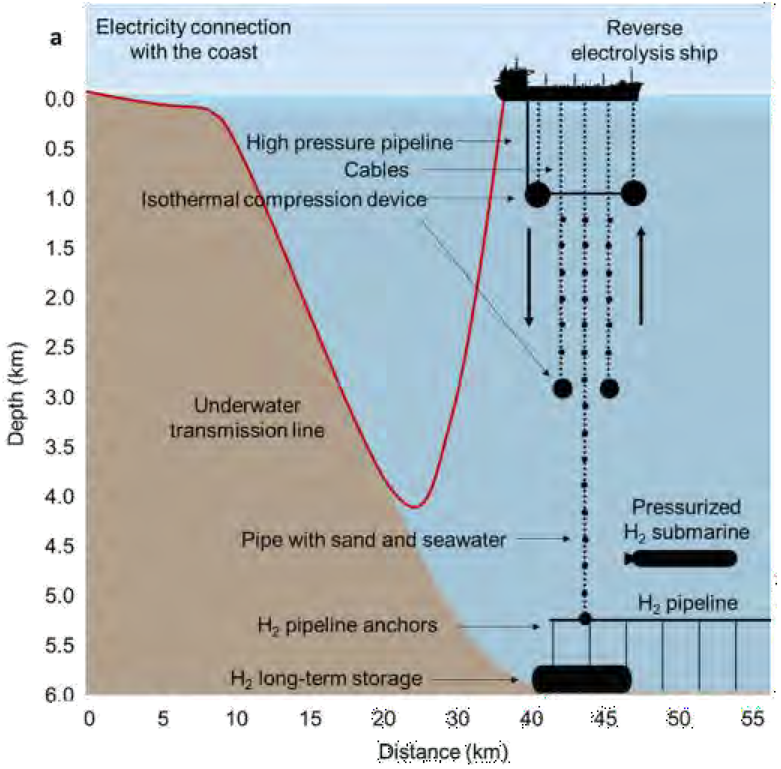
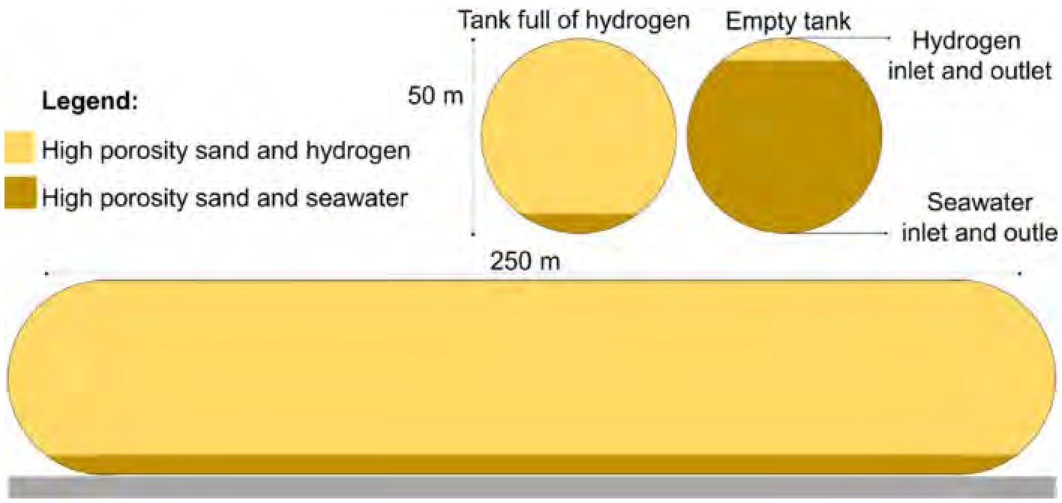
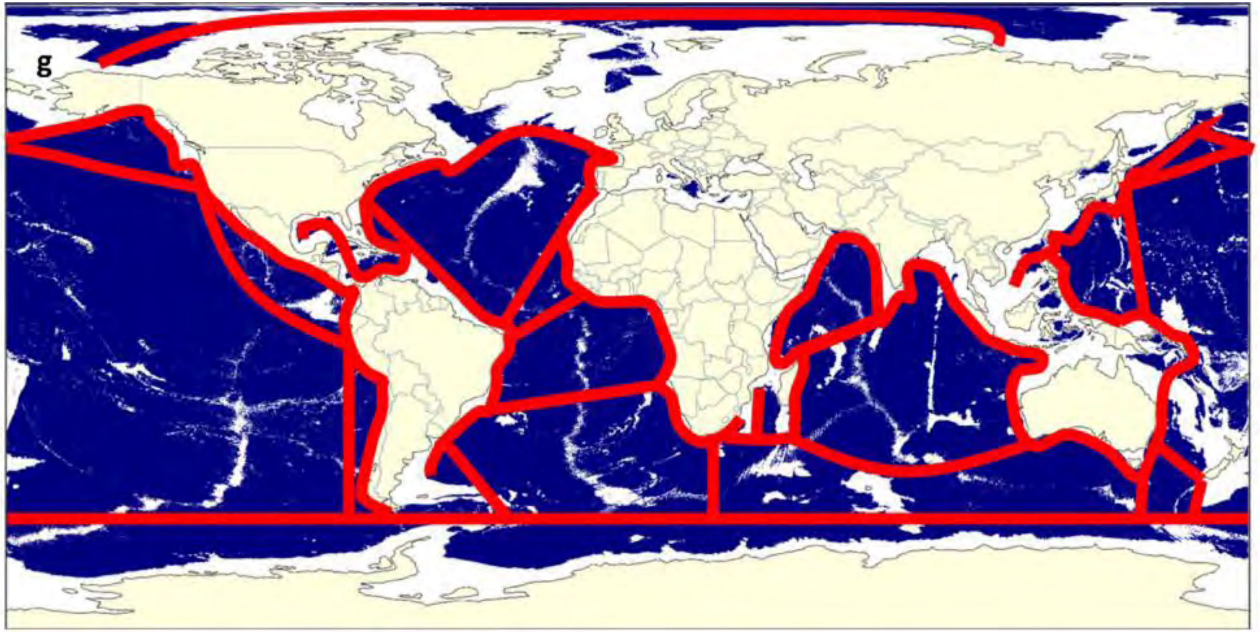
Deep hydrogen ocean link (HYDOL)	H_2 storage	0.018	H_2 storage	Seasonal, pluriannual	∞ (deep-sea)	Not yet
Isothermal deep ocean compressed air energy storage (IDO-CAES)	1,600	1.26	100 – 1000	Monthly, seasonal, pluriannual	∞ (deep-sea)	Not yet

Hydrogen Deep Ocean Link:
A global sustainable interconnected energy grid





Hydrogen Deep Ocean Link:
A global sustainable interconnected energy grid



Energy storage technologies

Different storage technologies and their respective storage cycles.

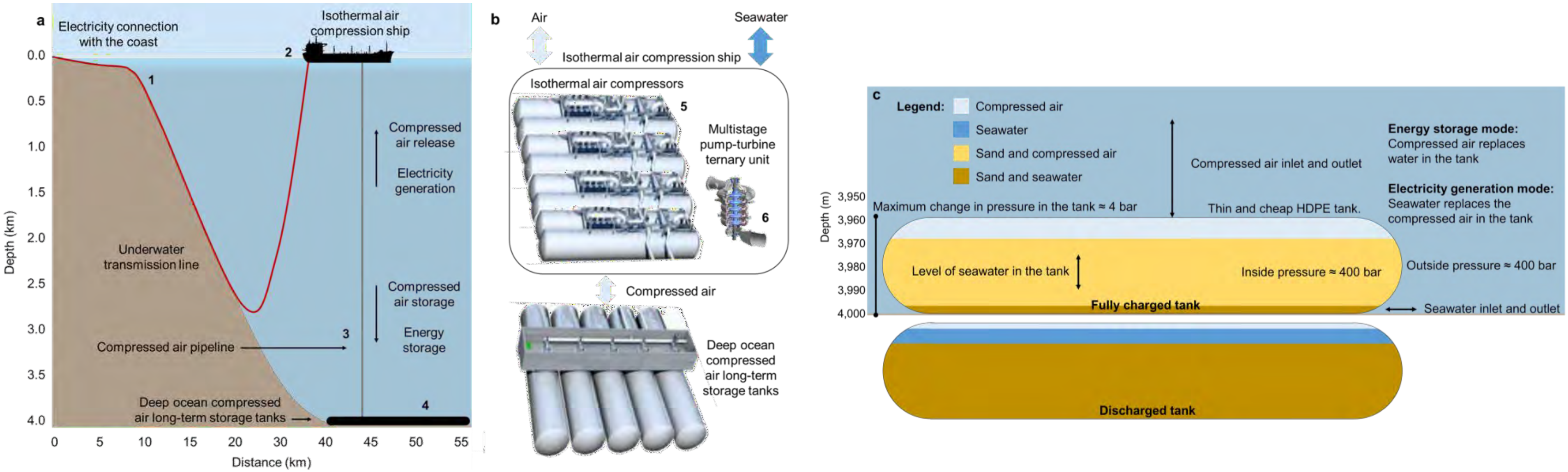
Storage type	Storage technologies	Details	Storage cycles
Mechanical	Pumped hydro	Daily, weekly, seasonal	Daily, weekly, seasonal
	Gravity storage	Energy Volt	Daily
		Gravitricity	Daily
		Mountain gravity	Daily, weekly, seasonal
		Lift energy storage	Daily, weekly
		Electric truck hydropower	Daily, weekly, seasonal
	Compressed air/H2	Adiabatic storage	Daily, weekly
		AirBattery (isothermal)	Daily, weekly
		Buoyancy (isothermal)	Daily, weekly
	Flywheels	Flywheels	Hourly
Eletrochemical	Batteries	Batteries (many)	Daily, weekly
	Hydrogen	Power-to-power	Daily, weekly, seasonal
		Power-to-fuel	Daily, weekly, seasonal
Thermal	Sensible heat	Pit storage	Seasonal
		Underground thermal	Seasonal
		Hot water tanks	Daily, weekly
		Molten salt	Daily, weekly
	Latent heat	Ice storage	Daily, weekly, seasonal
	Thermochemical	Thermal chemical	Daily, weekly, seasonal
Electrical	Capacitors	Ultra-capacity	Hourly

Legend: we have published or under review   we have not published

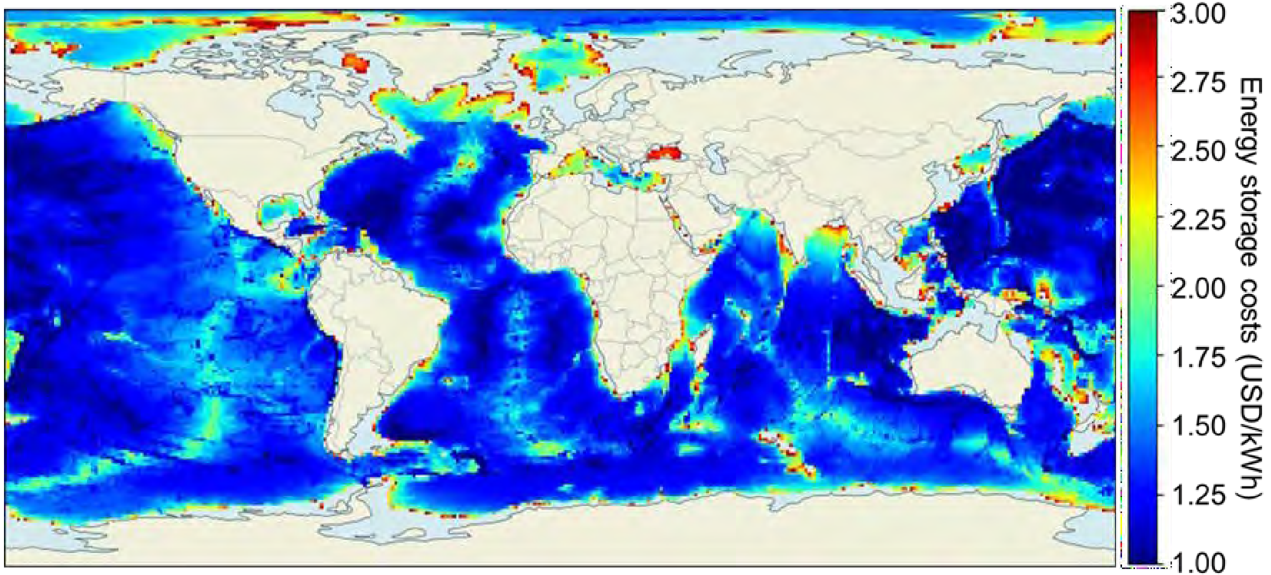
Technologies

Name	Installed capacity cost (USD/KW)	Energy Storage cost (USD/KWh)	Installed capacity per project (MW)	Storage Cycle	Global Potential (TWh)	11 regions
Mountain Gravity Energy Storage (MGES)	1000 - 2000	50 - 100	1 - 20	Seasonal, pluriannual	8.684	Yes
Electric Truck Gravity Energy Storage (ETGES)	1,200	1.2	20 – 100	Monthly, seasonal	5.400	Yes
Lift Energy Storage (LEST)	500 – 1,000	20 - 120	0.02 – 1 (per building)	Ancillary, daily, weekly	0.03 – 0.3	Yes
Seasonal pumped hydropower storage (SPHS)	400 – 600	0.002 – 0.100	100 - 5000	Seasonal, pluriannual	17.300	Yes
Buoyancy Energy Storage Technology (BEST)	4,000 – 8,000	50 – 100	10 - 100	Ancillary, daily, weekly	∞ (deep-sea)	Not yet
Deep hydrogen ocean link (HYDOL)	H_2 storage	0.018	H_2 storage	Seasonal, pluriannual	∞ (deep-sea)	Not yet
Isothermal deep ocean compressed air energy storage (IDO-CAES)	1,000 – 2,000	1 – 3	100 – 1000	Monthly, seasonal, pluriannual	∞ (deep-sea)	Not yet

Isothermal deep ocean compressed air energy storage: an affordable solution for long-term energy storage



Isothermal deep ocean compressed air energy storage: an affordable solution for long-term energy storage



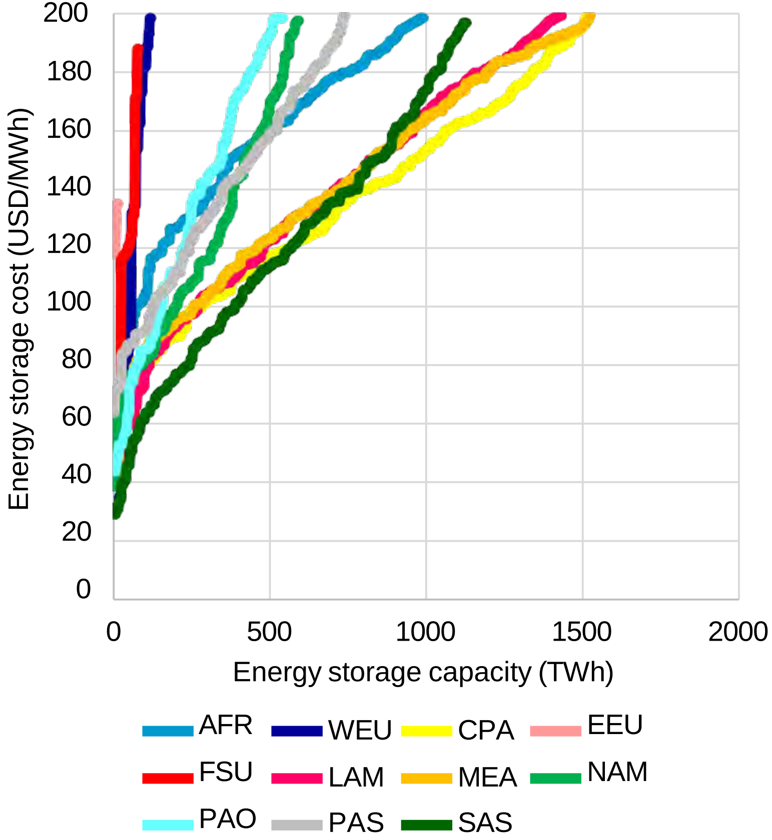
Energy storage options

Storage type	Storage technologies	Details	Storage cycles
Mechanical	Pumped hydro	Daily, weekly, seasonal	Daily, weekly, seasonal
	Gravity storage	Energy Volt	Daily
		Gravitricity	Daily
		Mountain gravity	Daily, weekly, seasonal
		Lift energy storage	Daily, weekly
		Electric truck hydropower	Daily, weekly, seasonal
	Compressed air/H2	Adiabatic storage	Daily, weekly
		AirBattery (isothermal)	Daily, weekly
		Buoyancy (isothermal)	Daily, weekly
	Flywheels	Flywheels	Hourly
Eletrochemical	Batteries	Batteries (many)	Daily, weekly
	Hydrogen	Power-to-power	Daily, weekly, seasonal
		Power-to-fuel	Daily, weekly, seasonal
Thermal	Sensible heat	Pit storage	Seasonal
		Underground thermal	Seasonal
		Hot water tanks	Daily, weekly
		Molten salt	Daily, weekly
	Latent heat	Ice storage	Daily, weekly, seasonal
	Thermochemical	Thermal chemical	Daily, weekly, seasonal
Electrical	Capacitors	Ultra-capacity	Hourly

Legend: we have published or under review   we have not published

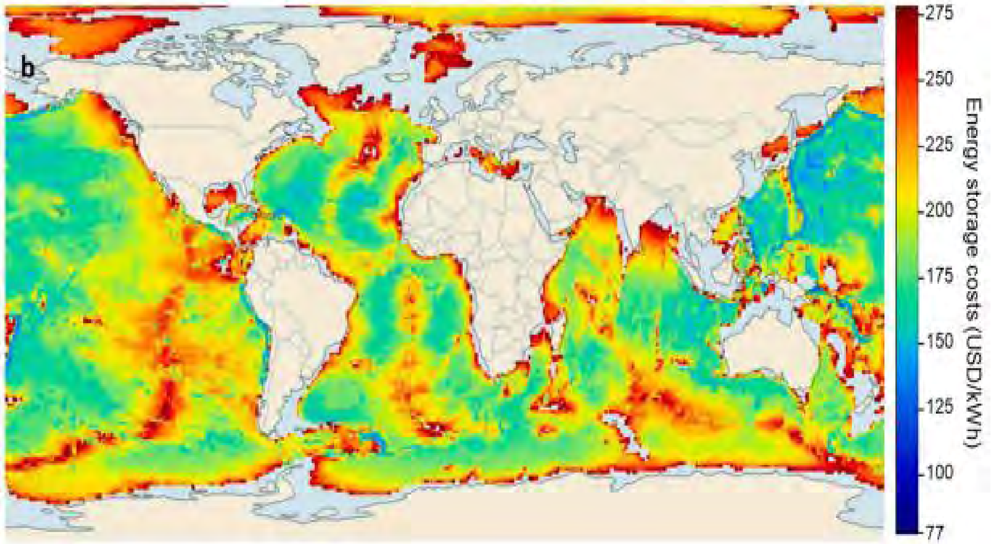
Mountain Gravity Energy Storage

Global potential (TWh)



Buoyancy Energy Storage

Potential >> global electricity needs



Hunt et al, 2020, 2021

Unconventional Technology Possibilities

Name	Installed capacity cost (USD/KW)	Energy Storage cost (USD/MWh)	Installed capacity per project (MW)	Storage Cycle	Global Potential (TWh)	11 regions
Mountain Gravity Energy Storage (MGES)	200 – 2,000	20 – 200	1 - 20	Seasonal, pluriannual	8.684	Yes
Electric Truck Gravity Energy Storage (ETGES)	1,200	1.2	20 – 100	Monthly, seasonal	5.400	Yes
Lift Energy Storage (LEST)	500 – 1,000	20 – 120	0.02 – 1 (per building)	Ancillary, daily, weekly	0.03 – 0.3	Yes
Seasonal pumped hydropower storage (SPHS)	400 – 600	0.002 – 0.100	100 - 5000	Seasonal, pluriannual	17.300	Yes
Buoyancy Energy Storage Technology (BEST)	4,000 – 8,000	50 – 100	10 - 100	Ancillary, daily, weekly	∞ (deep-sea)	Not yet
Deep hydrogen ocean link (HYDOL)	H2 storage	0.018	H2 storage	Seasonal, pluriannual	∞ (deep-sea)	Not yet
Isothermal deep ocean compressed air energy storage (IDO-CAES)	1,600	1.26	100 – 1000	Monthly, seasonal, pluriannual	∞ (deep-sea)	Not yet

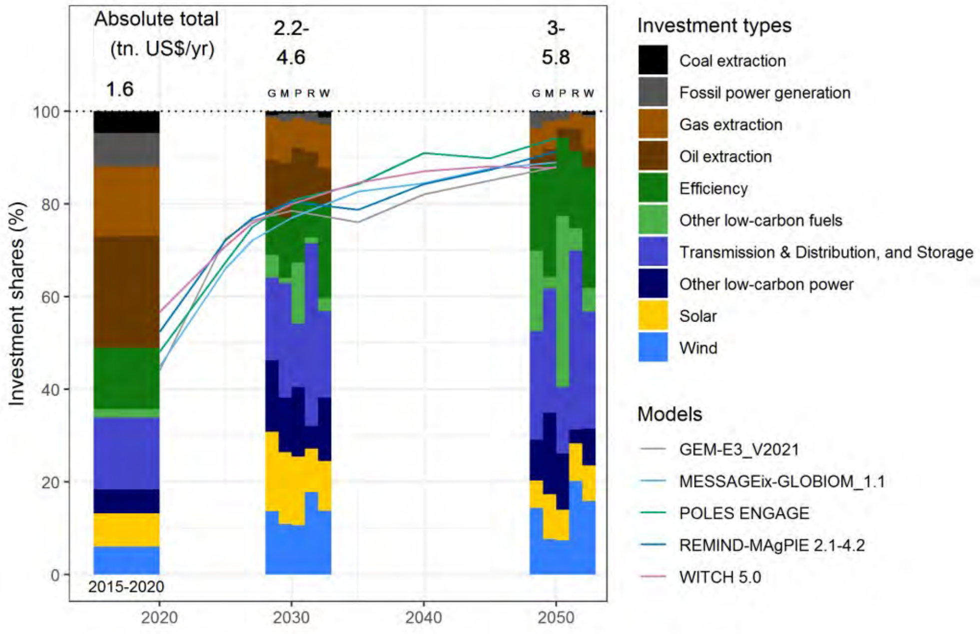
Hunt and Zakeri, forthcoming

Energy investment needs

1.5°C require rapid shift and scale-up of energy investments:

- ✓ **By 2030 80% of all investments need to be carbon-neutral**
- ✓ In the next decade, investments into decarbonizing power are dominating, especially solar and wind, plus "system" investments into **transmission & distribution and storage**
- ✓ **Coal**, and fossil power generation investments are **eliminated nearly immediately**, and gas and oil investments strongly reduced

Share of investments 1.5°C scenarios



Bertram et al, 2021