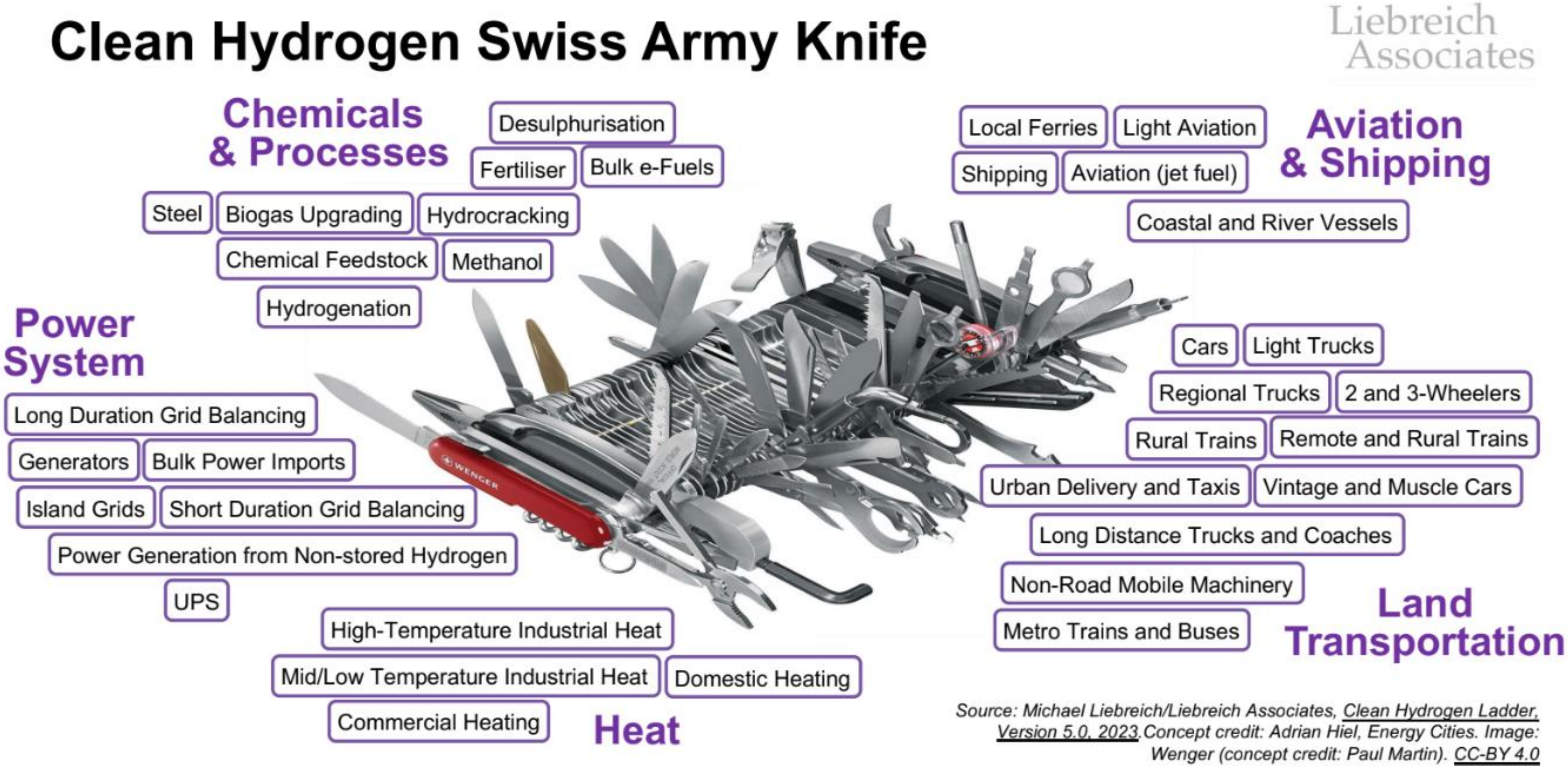
Enabling technologies, transition pathways, issues and controversies

Hydrogen



Clean Hydrogen Swiss Army Knife
Liebreich Associates
Chemicals & Processes
Desulphurisation
Fertiliser
Bulk e-Fuels
Steel
Biogas Upgrading
Hydrocracking
Chemical Feedstock
Methanol
Hydrogenation
Power System
Long Duration Grid Balancing
Generators
Bulk Power Imports
Island Grids
Short Duration Grid Balancing
Power Generation from Non-stored Hydrogen
UPS
High-Temperature Industrial Heat
Mid/Low Temperature Industrial Heat
Domestic Heating
Commercial Heating
Heat
Local Ferries
Light Aviation
Aviation & Shipping
Shipping
Aviation (jet fuel)
Coastal and River Vessels
Cars
Light Trucks
Regional Trucks
2 and 3-Wheelers
Rural Trains
Remote and Rural Trains
Urban Delivery and Taxis
Vintage and Muscle Cars
Long Distance Trucks and Coaches
Non-Road Mobile Machinery
Metro Trains and Buses
Land Transportation
Source: Michael Liebreich/Liebreich Associates, Clean Hydrogen Ladder, Version 5.0, 2023. Concept credit: Adrian Hiel, Energy Cities. Image: Wenger (concept credit: Paul Martin). CC-BY 4.0

Sourcing hydrogen

	Terminology	Technology	Feedstock/ Electricity source	GHG footprint*
PRODUCTION VIA ELECTRICITY	Green Hydrogen	Electrolysis	Wind | Solar | Hydro Geothermal | Tidal	Minimal
	Purple/Pink Hydrogen		Nuclear	
	Yellow Hydrogen		Mixed-origin grid energy	Medium
PRODUCTION VIA FOSSIL FUELS	Blue Hydrogen	Natural gas reforming + CCUS Gasification + CCUS	Natural gas | coal	Low
	Turquoise Hydrogen	Pyrolysis	Natural gas	Solid carbon (by-product)
	Grey Hydrogen	Natural gas reforming		Medium
	Brown Hydrogen	Gasification	Brown coal (lignite)	High
	Black Hydrogen		Black coal	

*GHG footprint given as a general guide but it is accepted that each category can be higher in some cases.

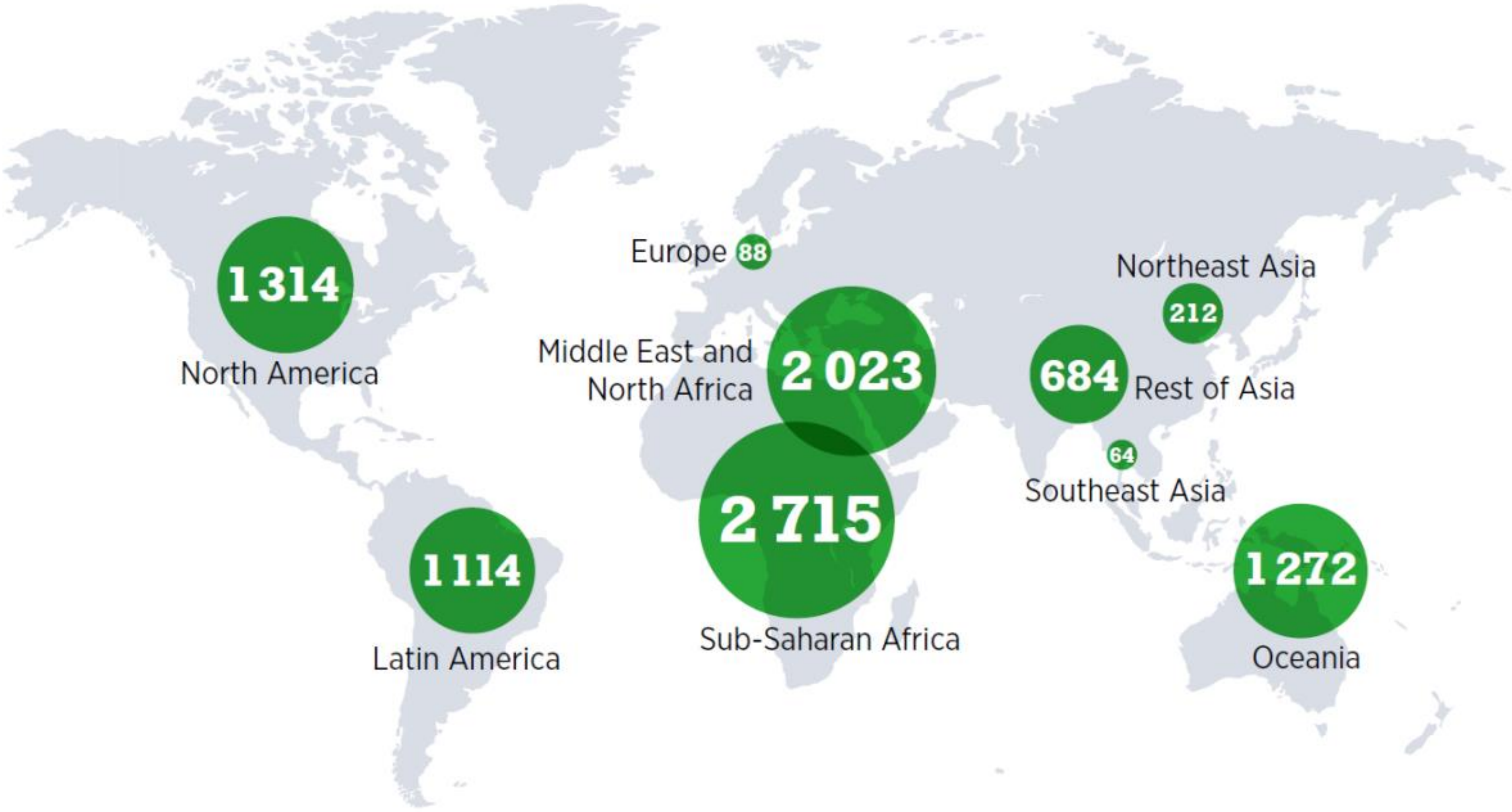
Source: [GEI]

Hydrogen: issues and challenges

- Expensive production
- Expensive transportation

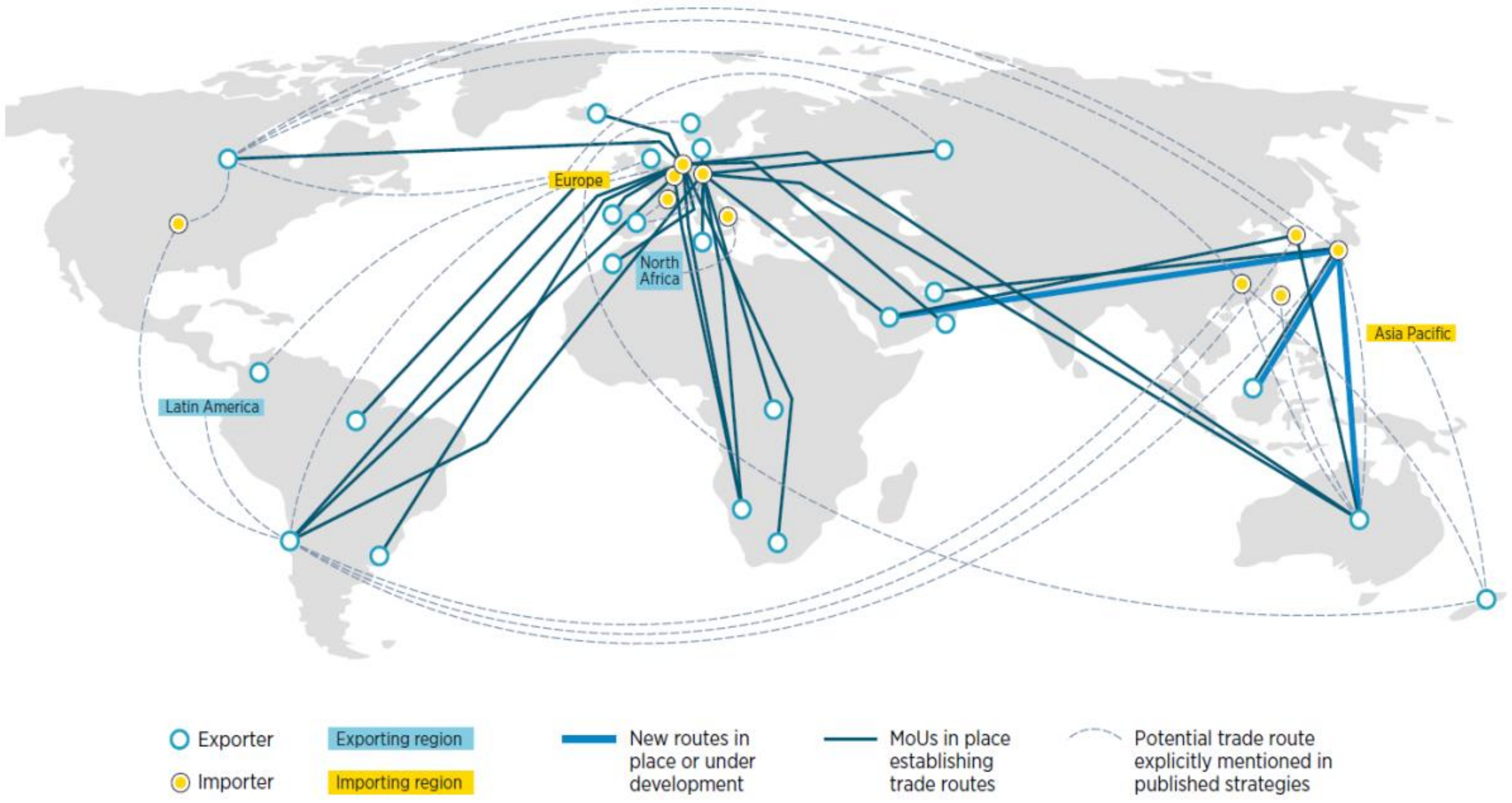
- Additionality
- Diminishing use cases => uncertainty

Sourcing green hydrogen



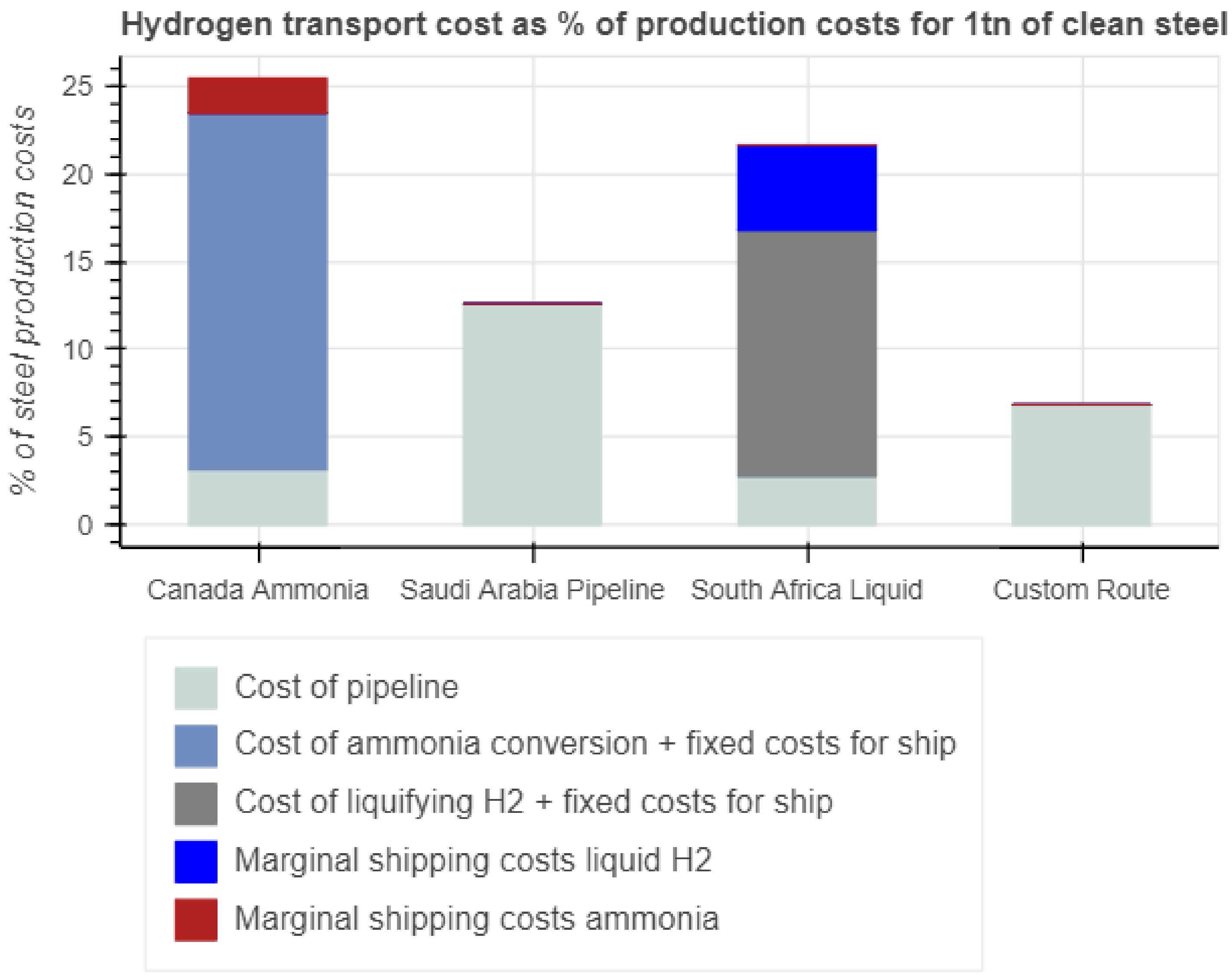
Source:
[IRENA 2022]

Sourcing green hydrogen



Source: [IRENA 2022]

Importing green hydrogen to Europe



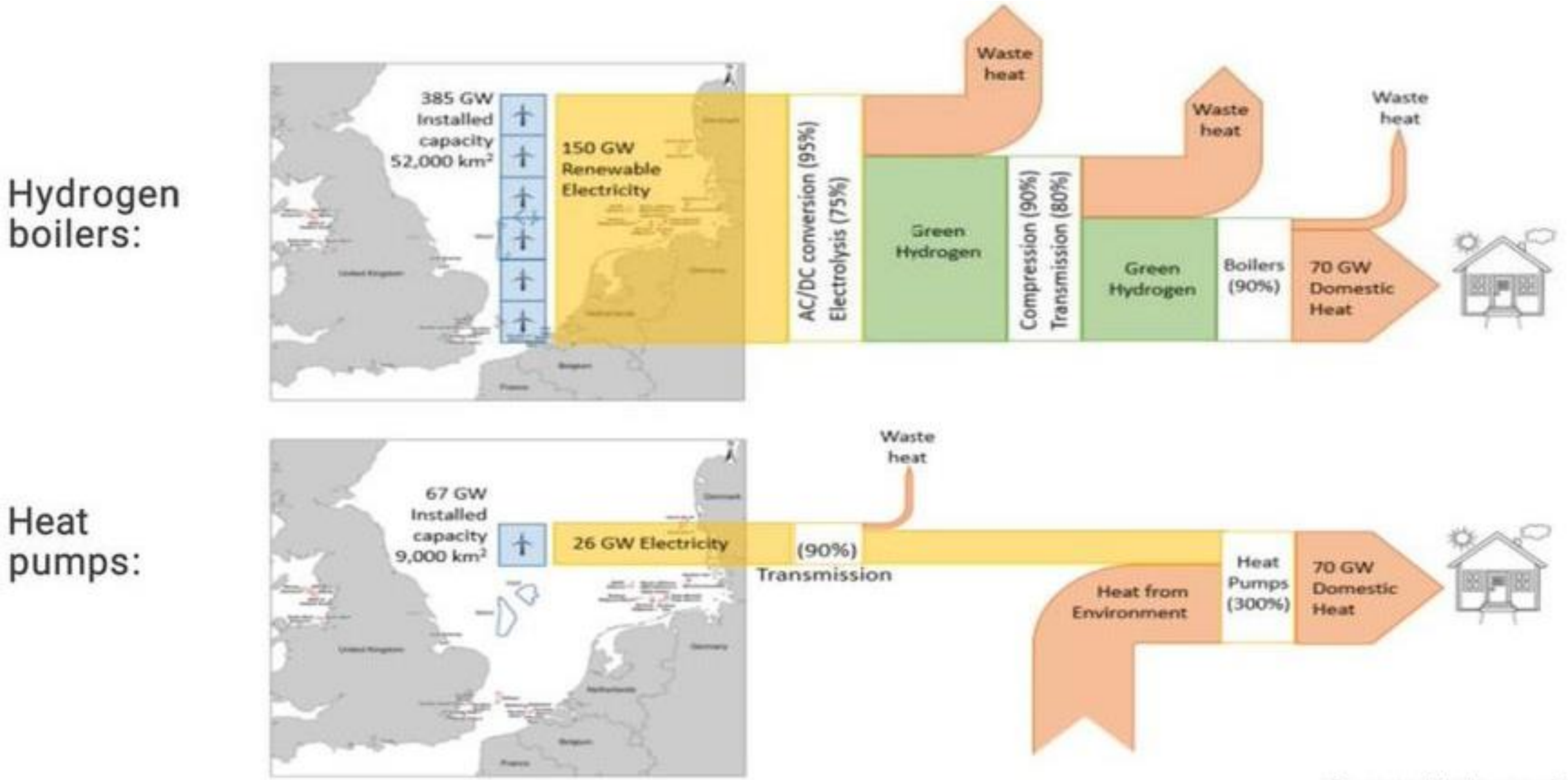
Source: [Hydrogen-model]

Additionality

- Existing H2 production and use: ~90 Mt/y (2022) – 99% is grey
- Producing 90 Mt/y of green H2 <= ~140% of RES installed by 2022

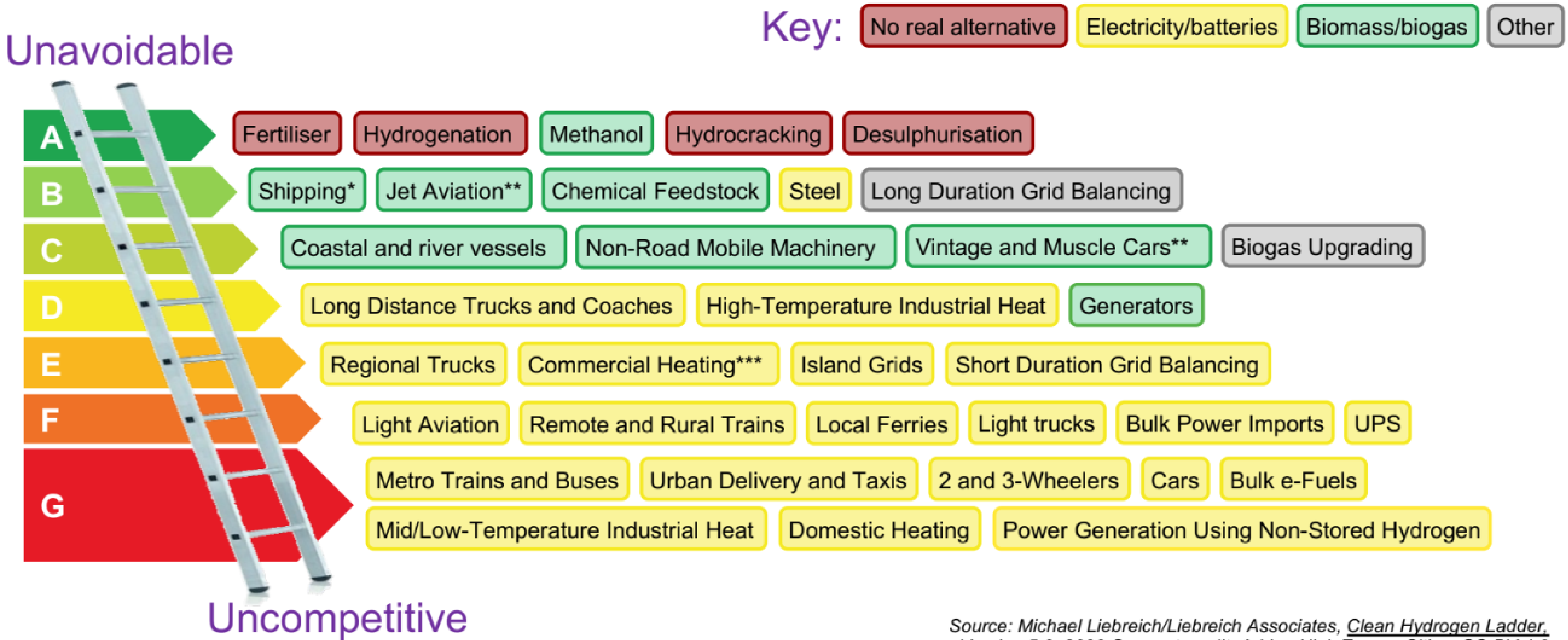
- What electricity shall be allocated to H2 production?

Hydrogen: use cases



Source: Hydrogen Science Coalition

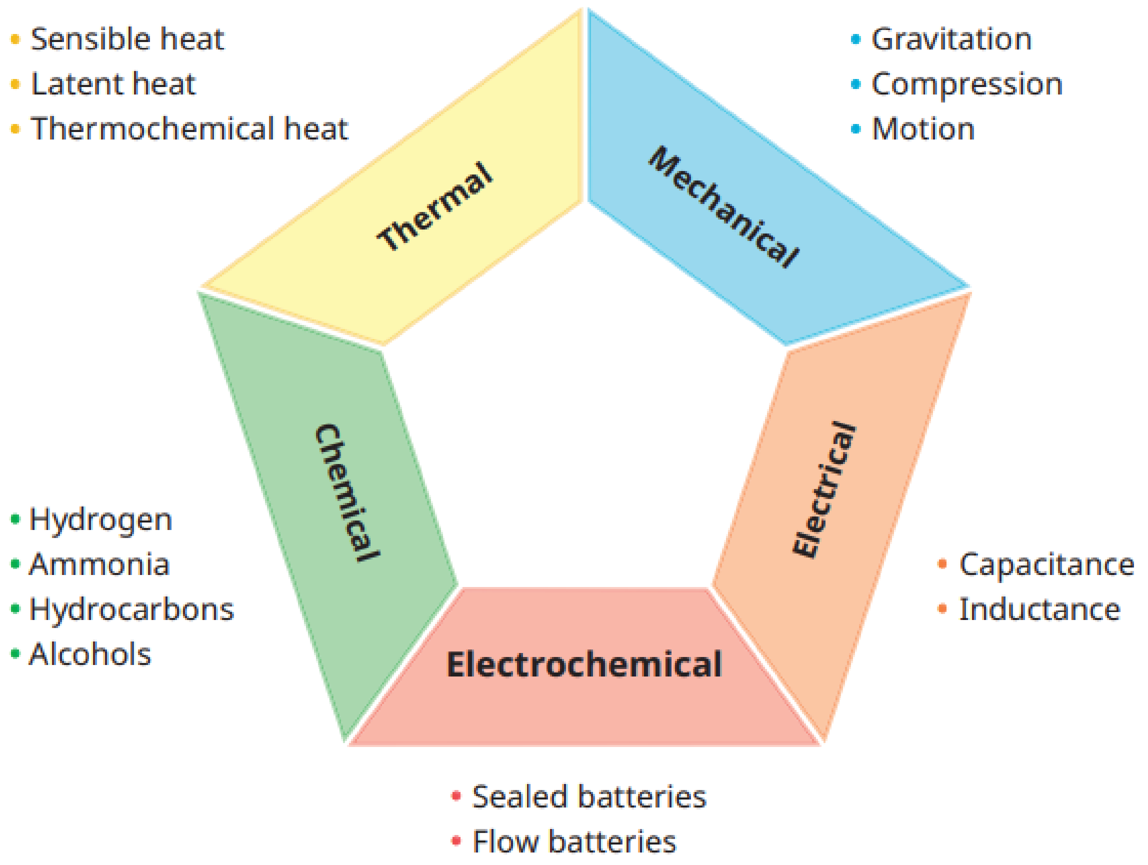
Hydrogen: use cases



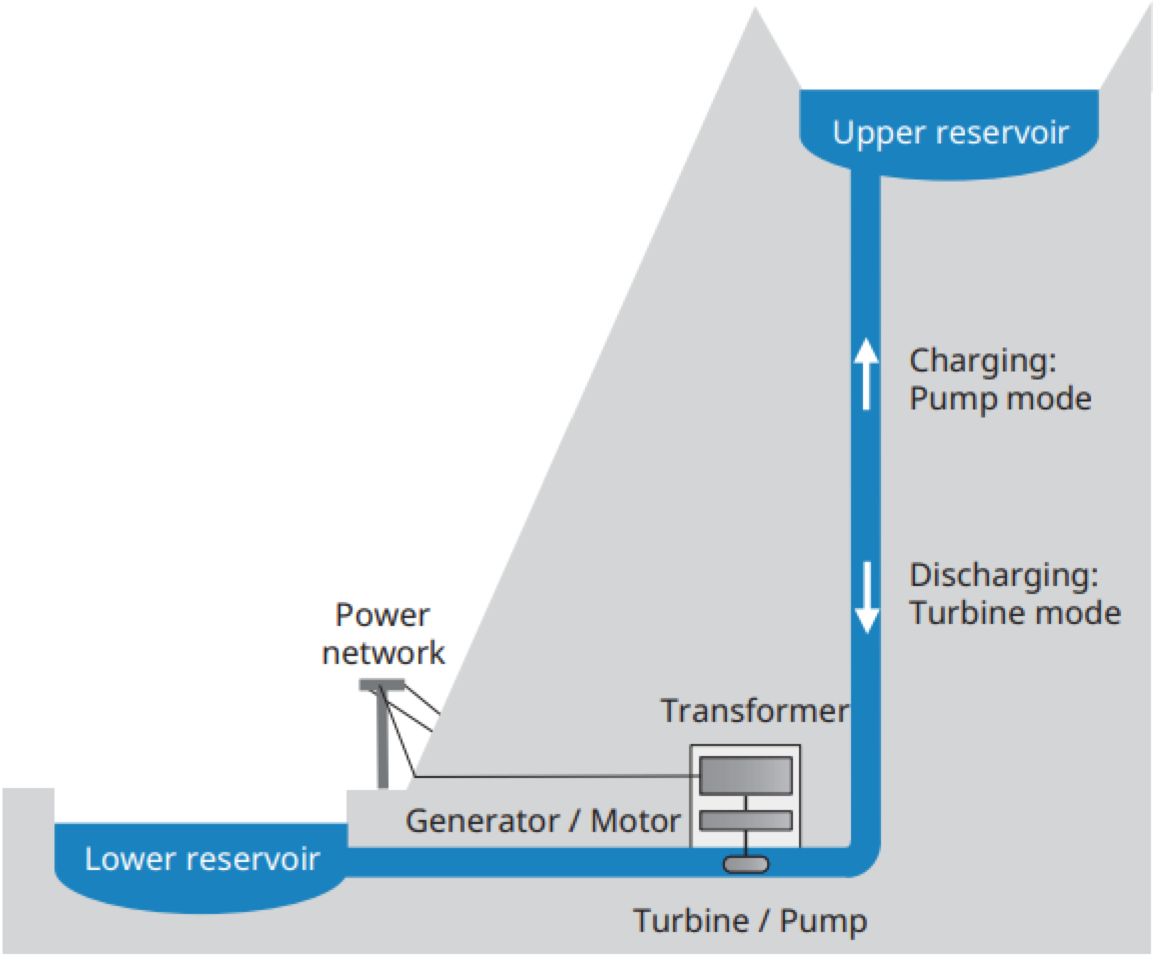
**As ammonia or methanol   **As e-fuel or PBTL   ***As hybrid system*

Source: Michael Liebreich/Liebreich Associates, Clean Hydrogen Ladder, Version 5.0, 2023.Concept credit: Adrian Hiel, Energy Cities.

Storage: it‘s complicated…

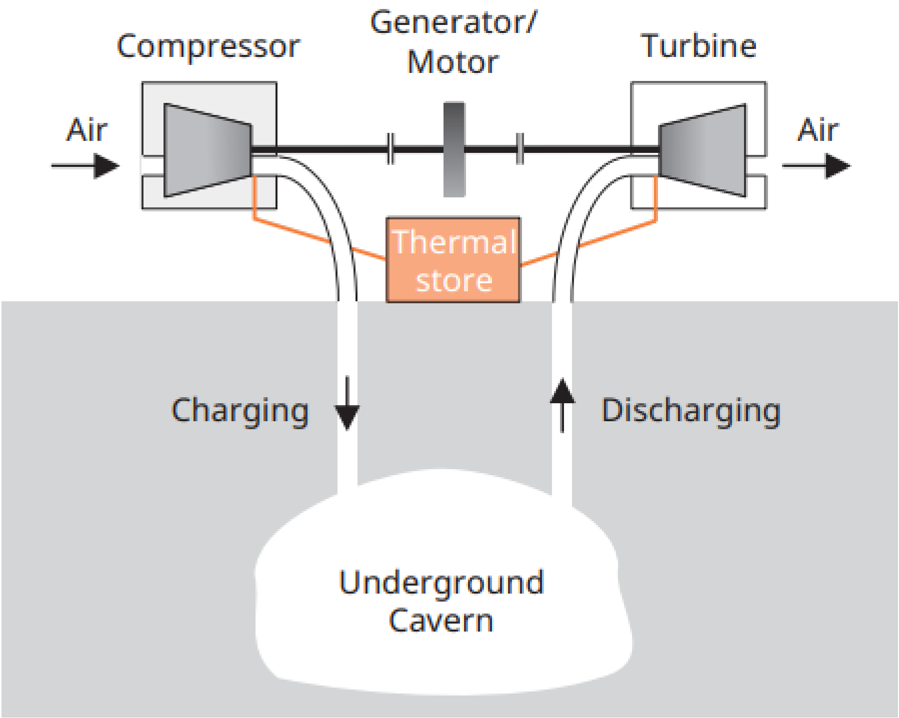


Storage technologies (pumped hydro)



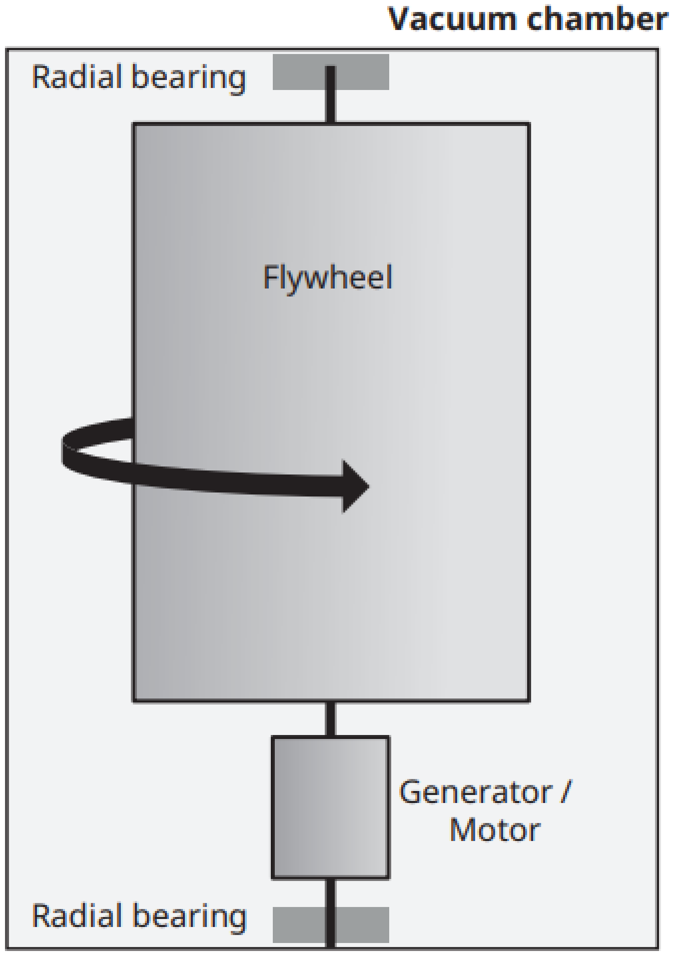
Advantages	+ Technical maturity (~160 GW deployed) + Low specific energy capacity cost (< 50 USD/kWh) + Independent sizing of energy capacity and power capacity + High round-trip efficiency (> 80%) + Long lifetime (> 30,000 cycles)
Disadvantages	– Need for suitable geographical conditions – Long lead-time to build (multiple years) – Low energy density, thus large footprint (< 2 kWh/m^3) – Potential negative environmental and social impacts through creation of water reservoirs – Economical only at large scale (> multiple hundred MW) and long discharge duration (> 4 hours)

Storage technologies (compressed air)



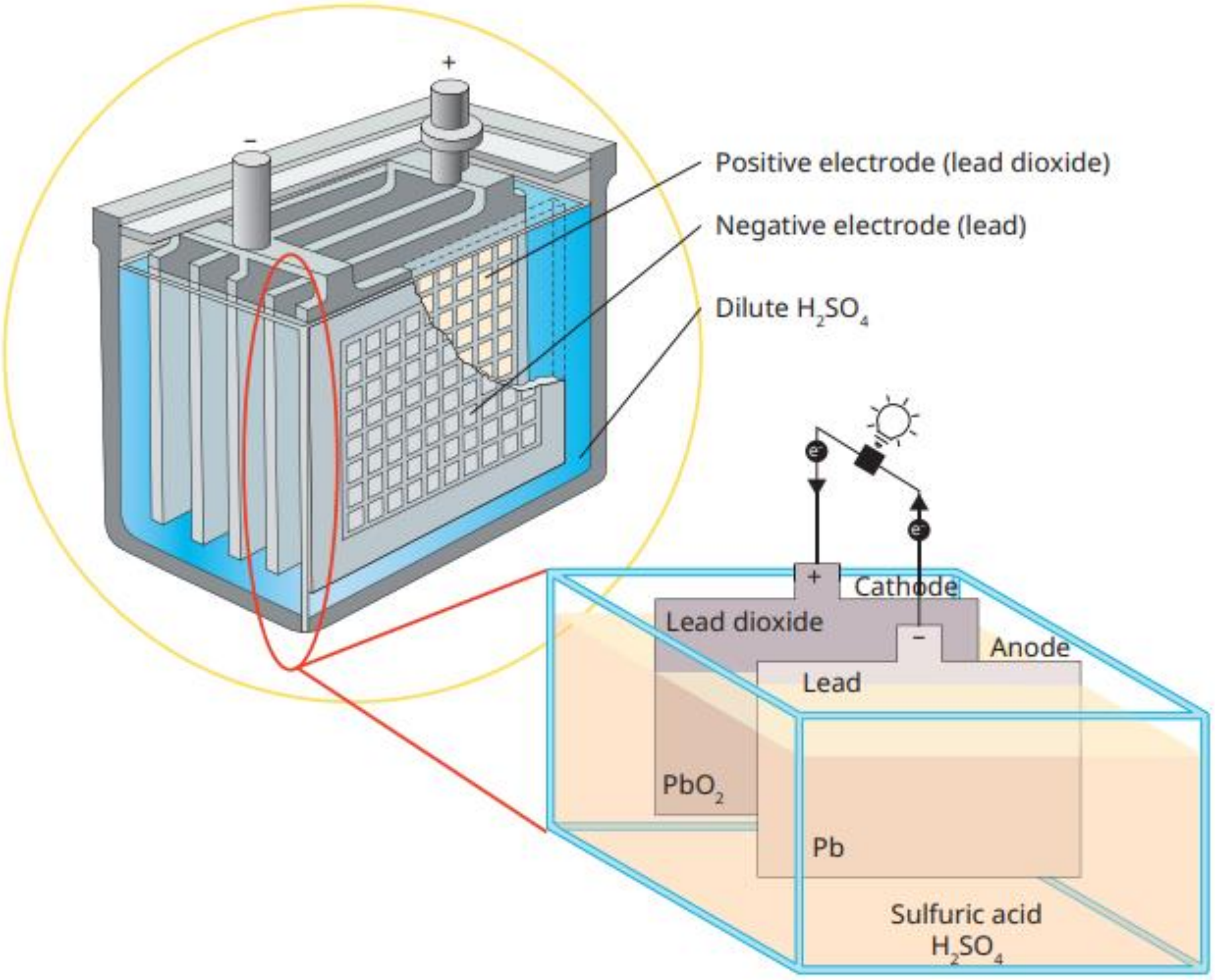
Advantages	+ Low specific energy capacity cost (< 50 USD/kWh) + Independent sizing of energy capacity and power capacity + Long lifetime (> 15,000 cycles) + Modular and location independent when using storage tanks
Disadvantages	– Cost-efficient underground CAES plants are geographically limited by the availability of caverns – Diabatic plants have low round-trip efficiency (< 50%) and require fuel for discharge – Low energy density (~4 kWh/m^3) – Only economic at large scale (> multiple hundred MW) and long discharge duration (> 4 hours)

Storage technologies (flywheel)



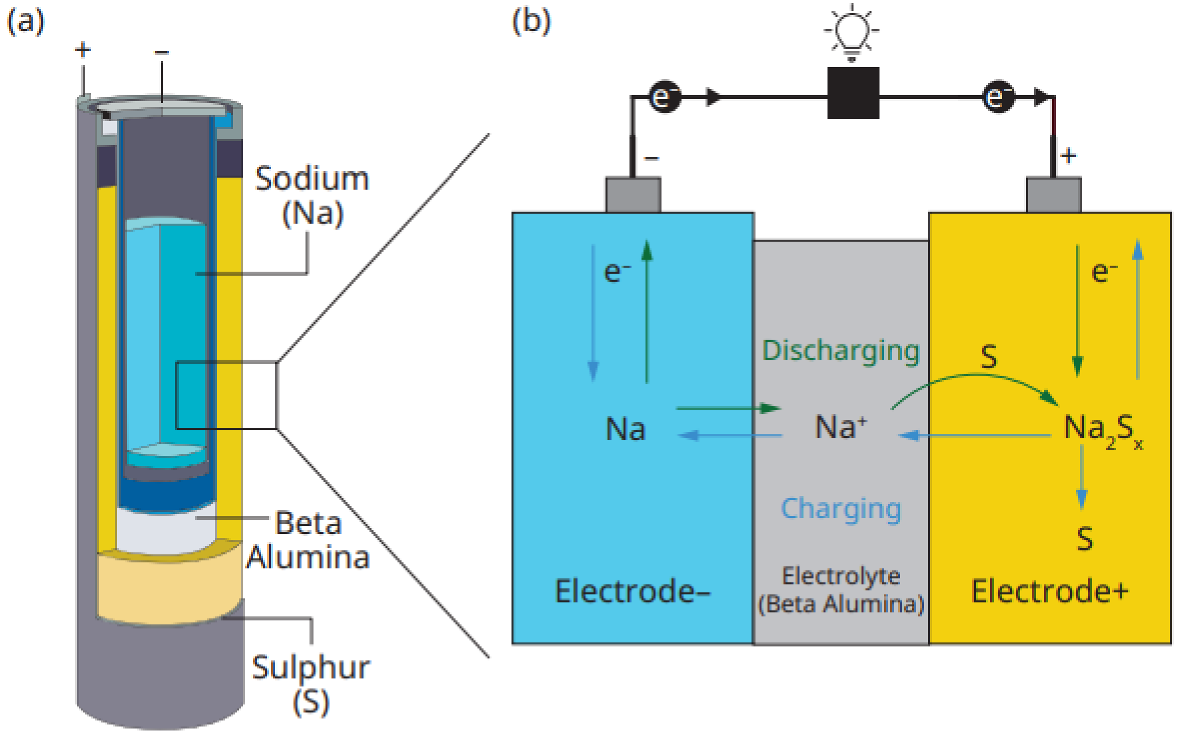
Advantages	+ High round-trip efficiency (~90%) + Rapid response time (< 1 second) + Very long lifetime (> 100,000 cycles) + High power density (1,000–5,000 kW/m³) + Modular capacity sizing (kW–MW size)
Disadvantages	– Low energy density (~50 kWh/m³) – High specific energy capacity cost (> 1,000 USD/kWh) – High self-discharge (up to 20% per idle hour) – Complex engineering to minimize losses and contain the spinning mass in case of a failure

Storage technologies (lead-acid battery)



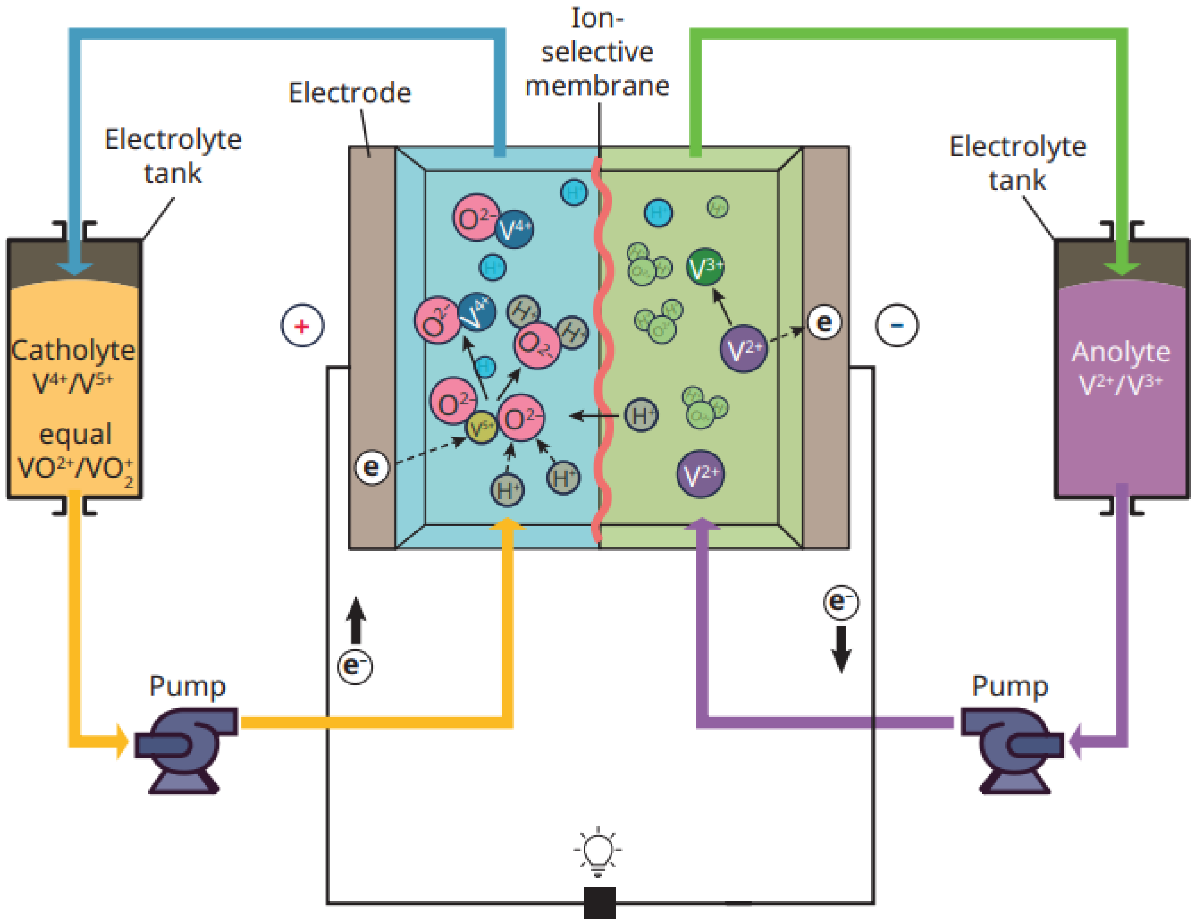
Advantages	+ High technical maturity (commercial since ~1880) + Relatively low cost for battery pack (< 200 USD/kWh) + Capable of high discharge rates + Wide range of sizes and specifications available
Disadvantages	– Low energy density vs other batteries (~70 kWh/m³) – Low depth of discharge for standard systems (30–50%) – Contain toxic materials (lead) – Limited lifetime (< 1,000 cycles)

Storage technologies (sodium-ion battery)



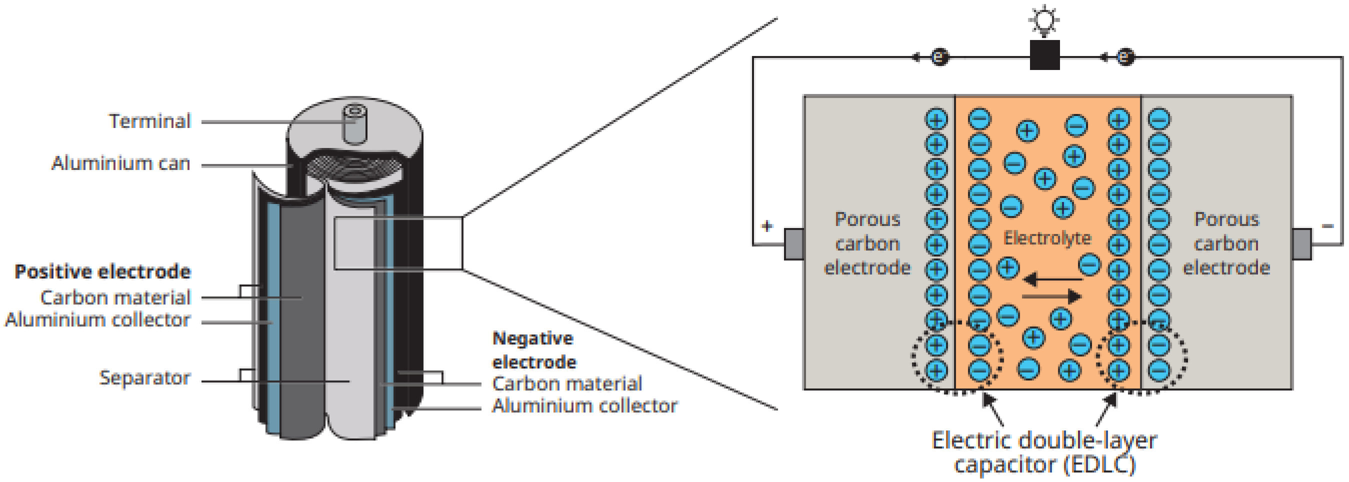
Advantages	+ High energy density (~200 kWh/m³) + Inexpensive, non-toxic raw materials (Na, S) + Wide ambient temperature range (e.g. hot climates) + Long lifetime for a sealed battery (4,500 cycles or 15 years)
Disadvantages	– High self-discharge in idle state due to need to maintain high operating temperature (~300–350 °C) – Relatively low discharge rates (systems are optimized for 6 hours discharge duration) – Safety risk due to high reactivity of sodium with water – Uncertain cost reduction potential with only one leading manufacturer

Storage technologies (redox flow battery)



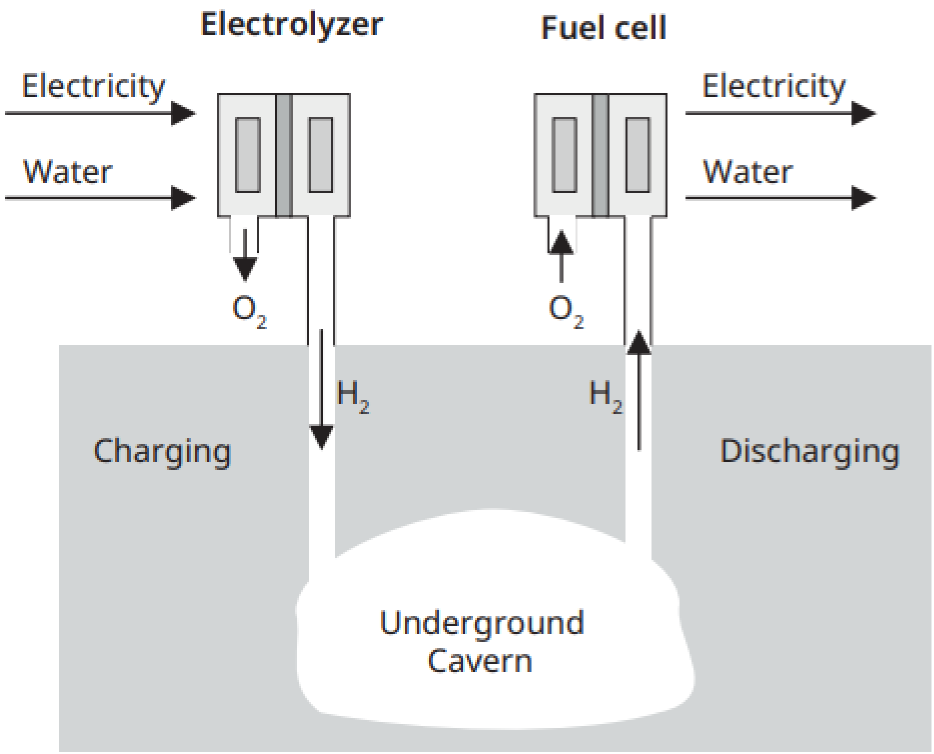
Advantages	+ Independent sizing of energy capacity and power capacity + Long lifetime (~20,000 cycles) + Full depth of discharge (100%) + Limited degradation during operational life + Large operating temperature window (–20–50 °C)
Disadvantages	– Low energy density vs other battery types (~30 kWh/m³) – Relatively immature industry with limited track record – Higher system complexity vs other battery types (e.g. pumps required, risk of electrolyte leakage) – High share of raw material cost in final product creating exposure to volatile raw material prices (e.g. vanadium)

Storage technologies (supercapacitor)



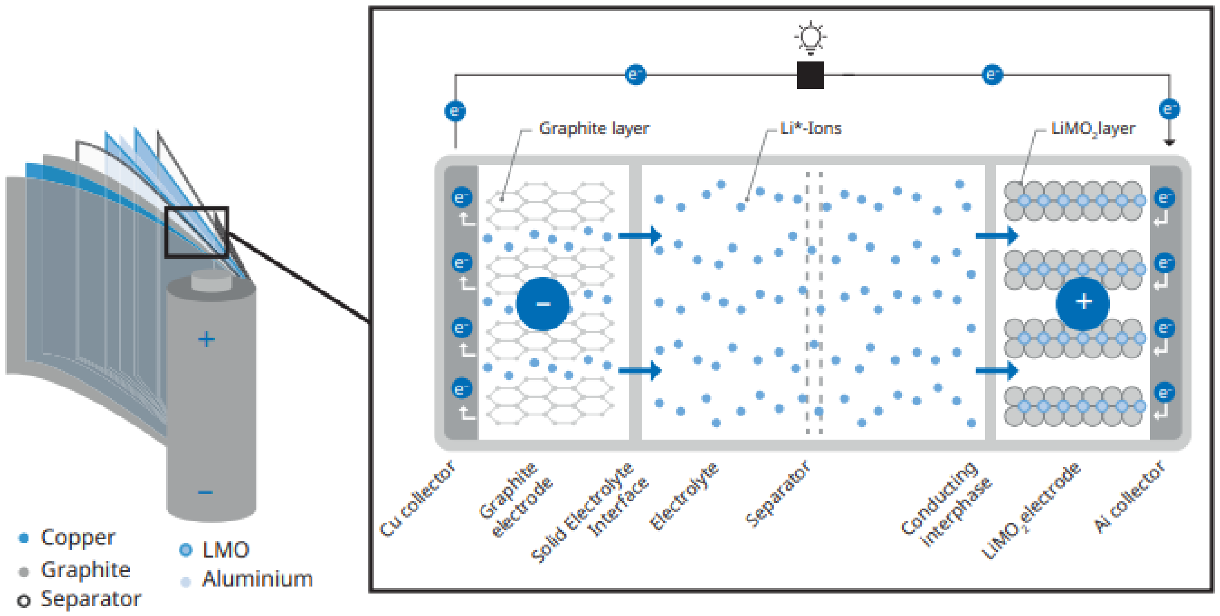
Advantages	+ High power density (~100,000 kW/m³) + High round-trip efficiency (> 90%) + High cycle life (> 100,000 cycles) + Fast response time + Very little or no maintenance required + Wide ambient temperature range (–40–70 °C)
Disadvantages	– Low energy density (~20 kWh/m³) – Short discharge duration (seconds to minutes) – High self-discharge in idle state (~20–40% per day) – Very high energy specific cost (> 10,000 USD/kWh)

Storage technologies (hydrogen)



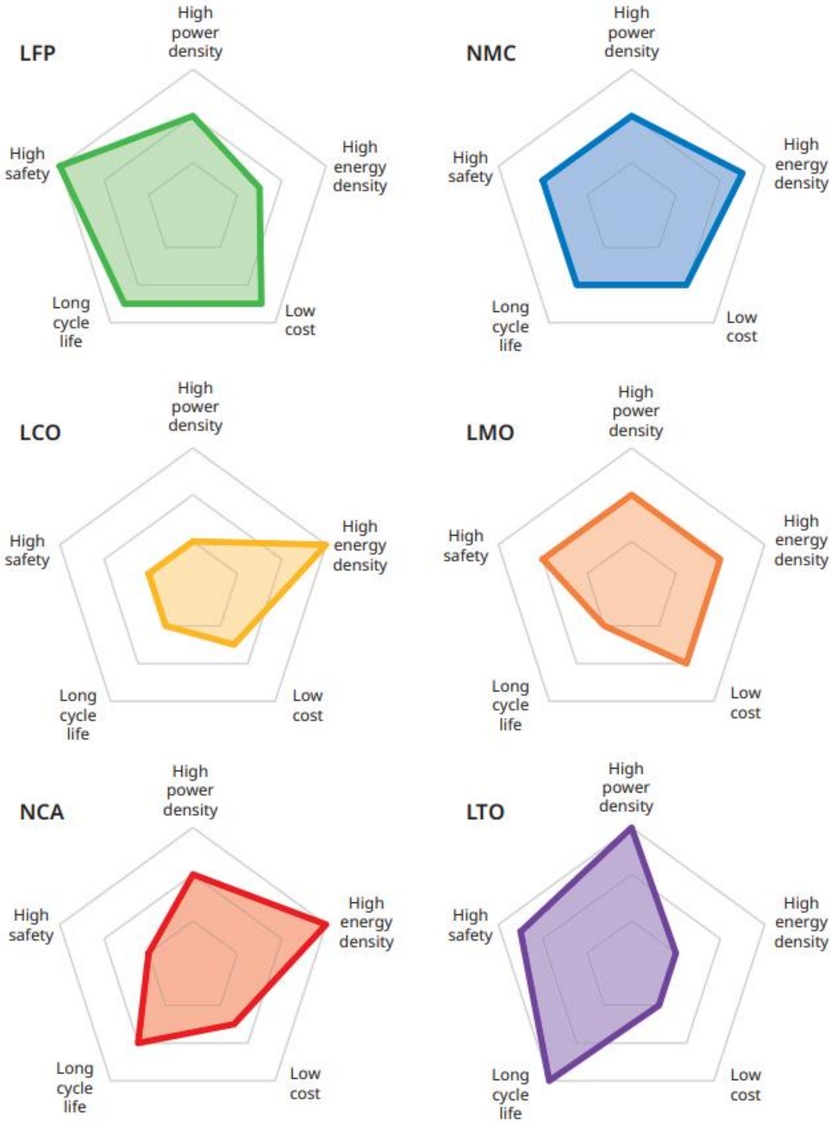
Advantages	+ Fully independent power capacity and energy capacity sizing + Potential to use existing gas network capacity + High energy density (600 kWh/m^3 at 200 bar) + Provision of renewable electricity to other energy sectors
Disadvantages	– Need for compression to reach sufficient energy density – Low round-trip efficiency for re-electrification (< 40%) – Lack of a dedicated hydrogen infrastructure – High investment cost for water electrolyzers – Production of NO_x when burnt in turbine/engine/burner

Storage technologies (lithium-ion battery)



Advantages	+ High energy/power densities (6,000 kW/m^3, 450 kWh/m^3) + High round-trip efficiency (~85%) + Modular sizing + Fast response time (< 1 second) + Strong cost-reduction potential due to several large markets
Disadvantages	– Limited cycle life (~3,500 at 80% depth of discharge) – Degradation throughout operational lifetime – Safety risks through thermal runaway – Potential resource scarcity (e.g. Lithium, Nickel, Cobalt)

Storage technologies (lithium-ion battery)



LFP: Lithium iron posphate

NMC: nickel manganese cobalt

LCO: lithium cobalt oxide

LMO: lithium manganese oxide

NCA: nickel cobalt aluminium

LTO: lithium titanite oxide

Storage: what we‘re looking at?

Parameter	Symbol	Description	Unit
Design parameters			
Nominal power capacity	$Cap_{p, nom}$	Rated amount of power that can be charged and discharged.	kW
Power density—gravimetric	$\rho_{p, gra}$	Nominal power capacity divided by system mass.	kW/kg
Power density—volumetric	$\rho_{p, vol}$	Nominal power capacity divided by system volume.	kW/m^3
Nominal energy capacity	$Cap_{e, nom}$	Rated amount of energy that can be discharged.	kWh
Energy density—gravimetric	$\rho_{e, gra}$	Nominal energy capacity divided by system mass	kWh/kg
Energy density—volumetric	$\rho_{e, vol}$	Nominal energy capacity divided by system volume	kWh/m^3
Depth-of-discharge	DoD	Energy capacity that can be charged/ discharged without severely degrading nominal energy capacity, measured relative to full capacity	$\%_{cap}$

Parameter	Symbol	Description	Unit
Usable energy capacity	$Cap_{e, use}$	Energy capacity that can be discharged accounting for depth of discharge	kWh
Energy-to-power ratio	E/P	Usable energy capacity divided by nominal power capacity	hours
Discharge duration	DD	Time to discharge usable energy capacity at nominal power. *Same as E/P ratio*	hours
Max. C-rate	C	Maximum rate to discharge storage system relative to its usable energy capacity. *Inverse of E/P ratio or minimum DD*	1/hours
Response time	T_{res}	Time between idle state and maximum power	seconds

Operational parameters			
State of charge	SoC	Fraction of energy stored at any moment in time, measured relative to full capacity	$\%_{cap}$
Round-trip efficiency	η_{RT}	Proportion of energy discharged over energy required to charge for a full charge–discharge cycle	%
Self-discharge	η_{self}	Unavoidable loss of state of charge when a storage system is idle (highly dependent on usage profile - can be measured per cycle or averaged across all cycles per year)	$\%_{cap}$
Degradation	Deg_t Deg_c	Rate of loss in usable energy capacity incurred by cycles and/or time lapse due to e.g. changes in state of charge or operating temperature	$\%_{cap}$ per year; $\%_{cap}$ per cycle
Cycle life	$Life_{cyc}$	Number of full charge–discharge cycles before end of usable life	#

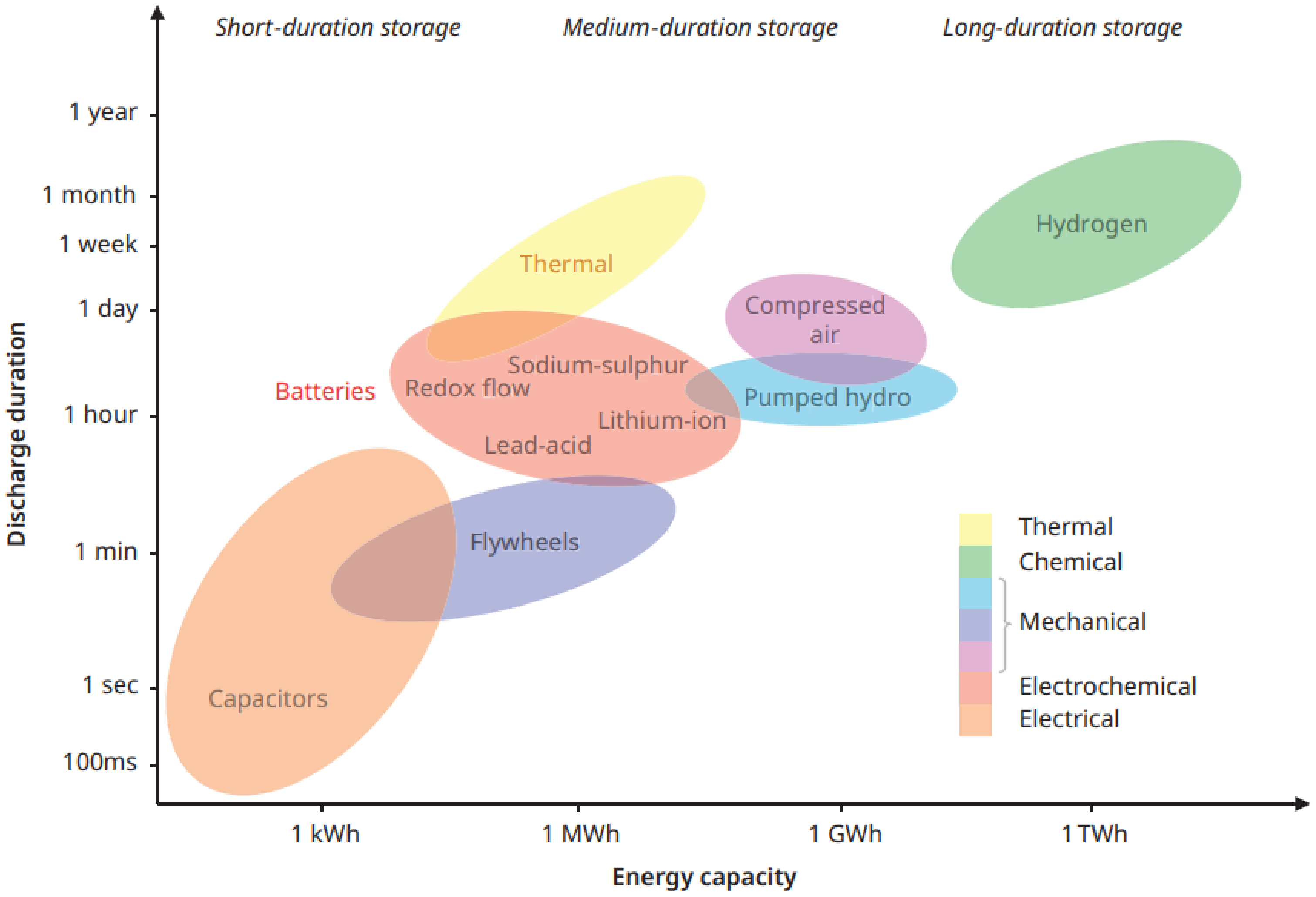
Storage technologies (comparison)

				Pumped hydro	Compressed air	Flywheel	Lithium ion	Sodium sulphur	Lead acid	Vanadium redox flow	Hydrogen	Supercapacitor
Cost parameters	**Investment cost—power**	USD/kW	$C_{p, inv}$	1,100	1,300	600	250	650	300	700	5,000	300
	Investment cost—energy	USD/kWh	$C_{e, inv}$	50	40	3,000	300	450	320	450	30	10,000
	Operation cost—power	USD/ kW-year	$C_{p, om}$	20	14	5	5	5	5	10	30	1
	Operation cost—energy	USD/ MWh_{el}	$C_{e, om}$	0.4	2	2	0.4	0.4	0.4	2	0.4	0
	Replacement cost—power	USD/kW	$C_{p, rep}$	120	100	200	0	0	0	90	0	0
	Replacement cost—energy	USD/kWh	$C_{e, rep}$	0	0	0	0	0	0	0	0	0
	Replacement interval	cycles	Cyc_{rep}	7,300	1,500	20,000	n/a	n/a	n/a	3,500	n/a	n/a
	End-of-life cost—power	USD/kW	$C_{p, eol}$	20	20	20	20	20	20	20	20	20
	End-of-life cost—energy	USD/kWh	$C_{e, eol}$	0	0	0	0	0	0	–100	0	0
	Discount rate	%	r	Depends on technology, use-case, and investor type—sample value: 8% (mature technology, utility investor)								

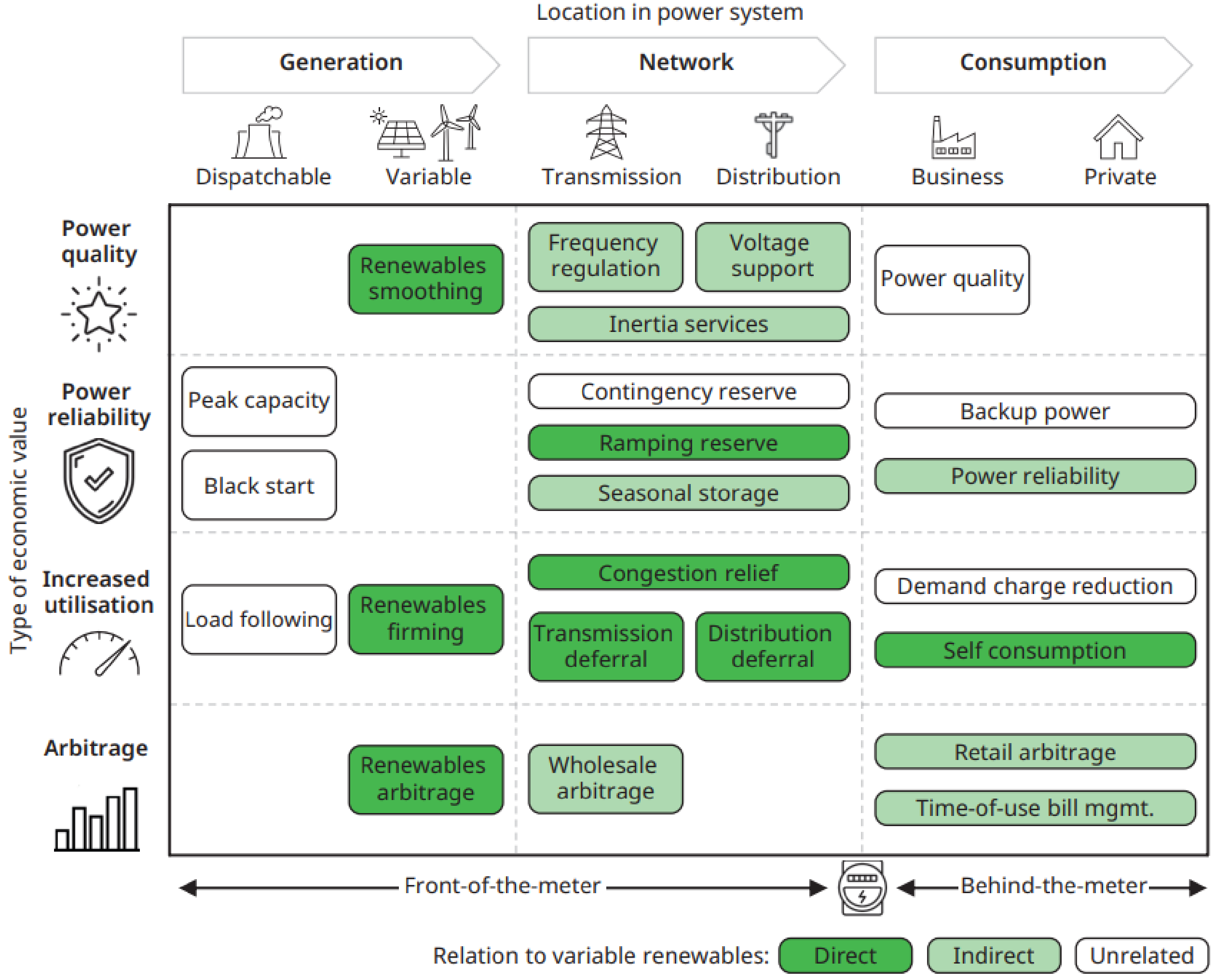
Storage technologies (comparison)

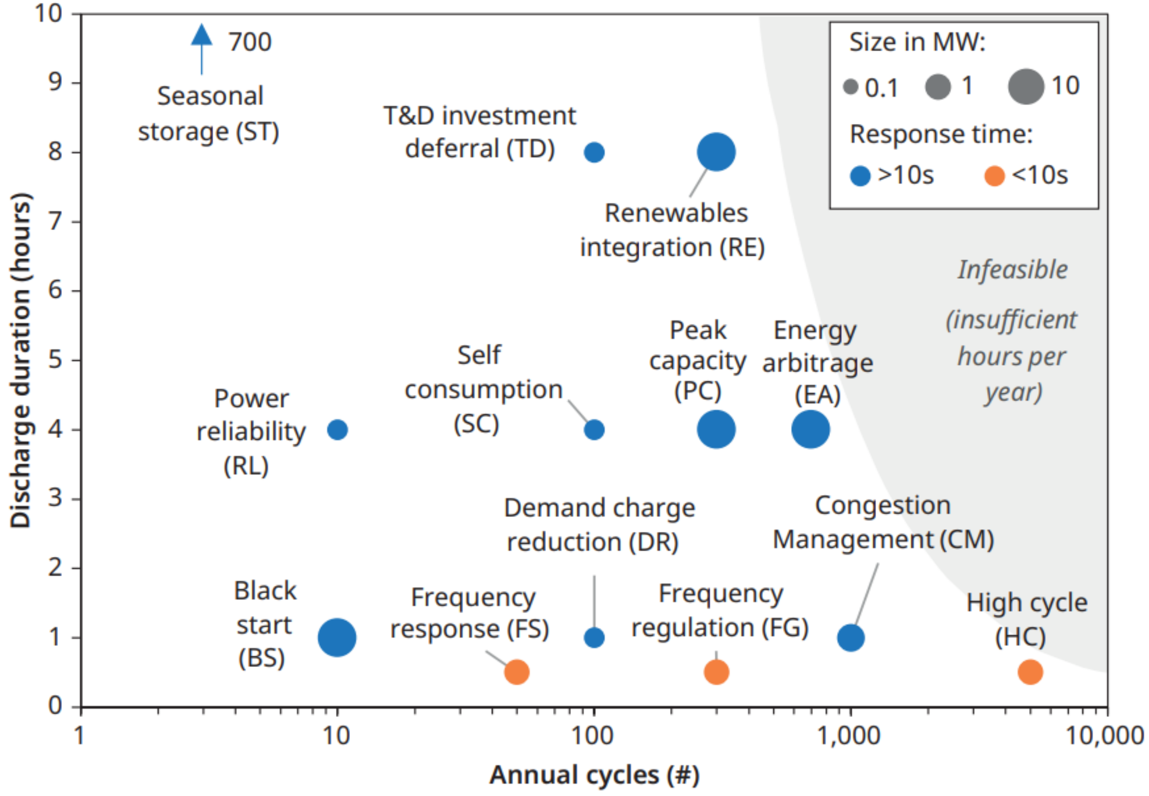
Performance parameters			Pumped hydro	Compressed air	Flywheel	Lithium ion	Sodium sulphur	Lead acid	Vanadium redox flow	Hydrogen	Supercapacitor
Round-trip efficiency	%	η_{RT}	80%	45%	86%	86%	75%	72%	68%	35%	92%
Depth-of-discharge	$\%_{cap}$	DoD	100%	100%	100%	80%	80%	80%	100%	100%	100%
Cycle lifetime	cycles	$Life_{,cyc}$	30,000	15,000	200,000	3,500	4,000	900	20,000	10,000	300,000
Temporal degradation	%/year	Deg_t	0%	0%	0%	1%	1%	1%	0.1%	0%	0%
Self-discharge	$\%_{cap}$	η_{self}	0%	0%	10%	1%	5%	1%	0%	5%	15%
Response time	seconds	T_{res}	> 10	> 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Construction time	years	T_{con}	3	2	1	1	1	1	1	1	1
Power density	kW/m³	-	1	1	3,000	6,000	160	200	5	5	100,000
Energy density	kWh/m³	-	1	4	50	450	200	70	30	600 (at 200 bar)	20

Storage technologies (comparison)



Storage technologies (use cases)





Storage technologies (use cases)

RE / nuclear energy share	Phase	Description	Archetype application	Deployment potential	Discharge duration	Response time
<20%	Pre-2010	Integrated energy market & low-cost nuclear power	Various	low	Mostly 8-12 hours	Minutes
	1	Restructured energy market & reducing system inertia	Frequency regulation	low	< 1 hour	Milliseconds to seconds
	2	Narrowing of peak periods & reducing RE+storage cost	Peak capacity	mid	2-6 hours	Seconds to minutes
	3	RE+storage cost lower than other generators	Renewables integration	high	4-12 hours	Minutes
>80%	4	No fossil fuel generators & very low storage cost	Seasonal storage	uncertain	>12 hours	Minutes to hours

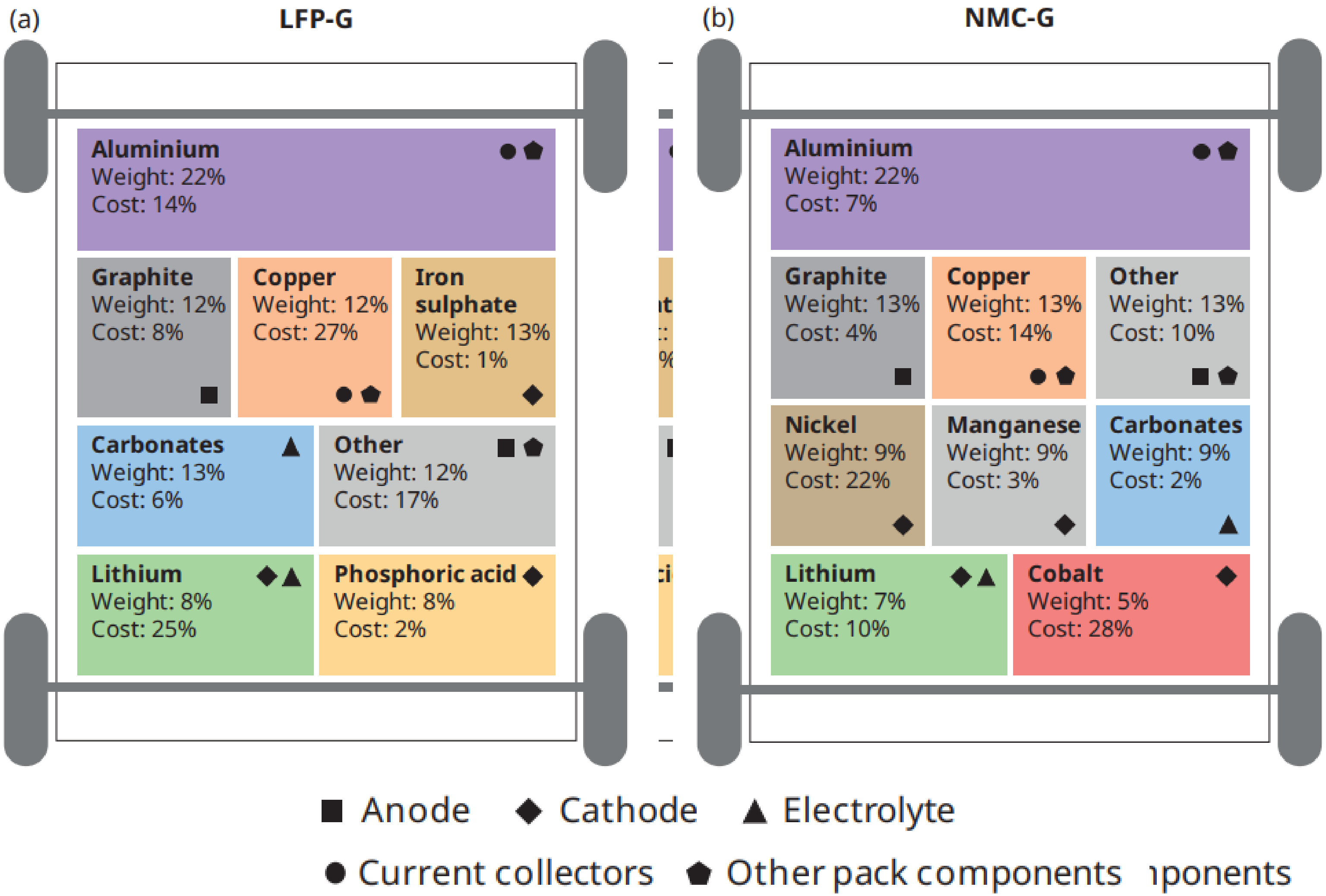
low mid high uncertain

Costs of storage (principles)

Costs = raw materials (incl. energy) + manufacturing

=> We follow: supply chain development + experience curve

Cost of storage (materials)

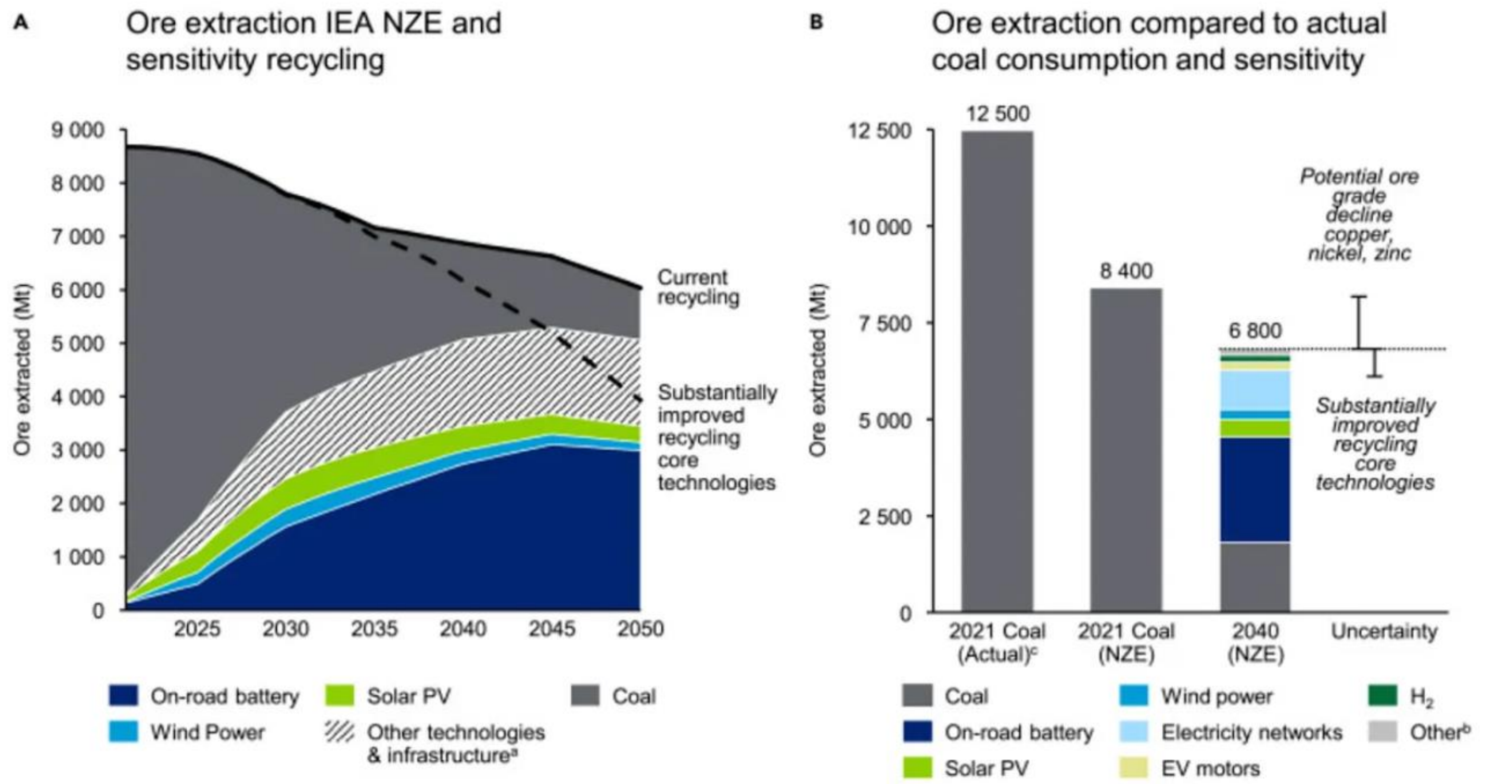


Costs of storage (material availability)

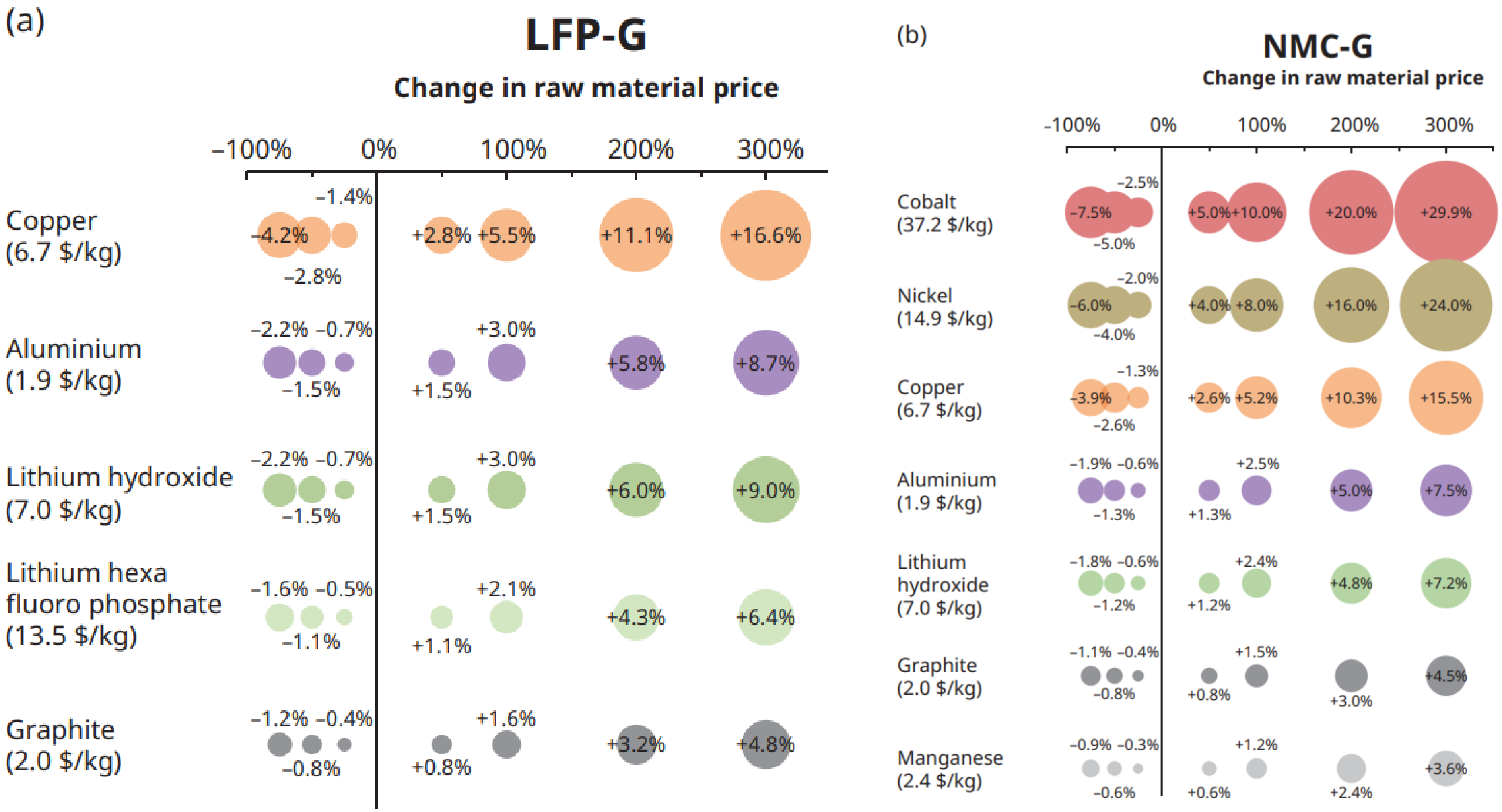
Raw material availability	Unit	Lithium	Cobalt	Nickel	Vanadium
World annual production	Mt	82	140	2500	86
World reserves	Mt	21,000	7,100	94,000	22,000
World resources	Mt	86,000	25,000	300,000	63,000
Production potential (based on resources)	**Unit**	**Lithium**	**Cobalt**	**Nickel**	**Vanadium**
Material intensity in battery	kg/kWh	0.139	0.394	0.392	3.4
Potential electrical energy storage capacity	TWh	619	63	765	19
Number of electric vehicles	bn	12.4	1.3	15.3	n/a
Multiples of stationary capacity projected for 2030	#	619	63	765	19

Costs of storage (material availability)

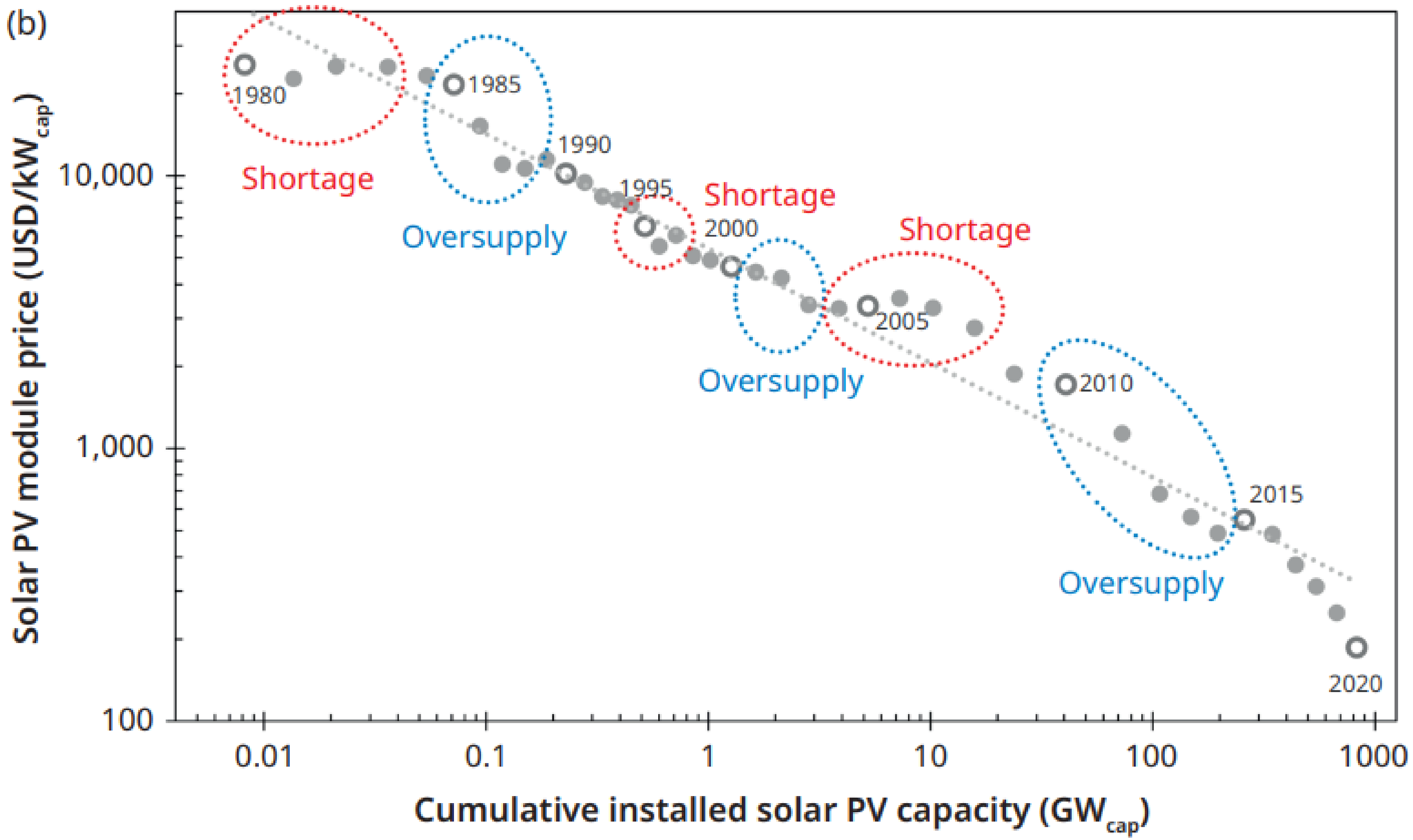
Costs of storage (material availability)



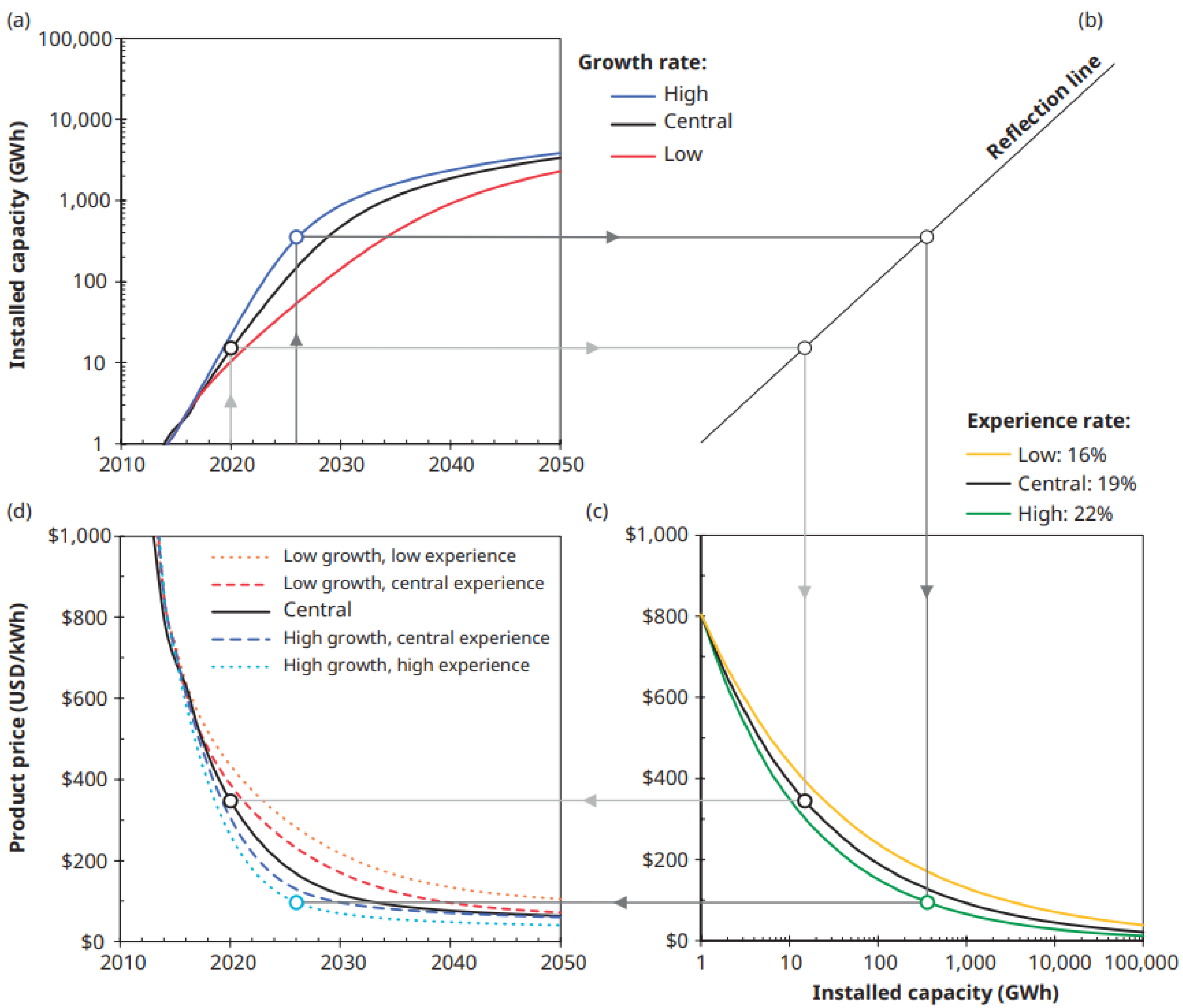
Cost of storage (price sensitivity)



Cost of storage (price sensitivity: the example of PV)



Cost of storage (experience curve)



Costs <= growth in capacity

\+

experience rate

Transition pathways

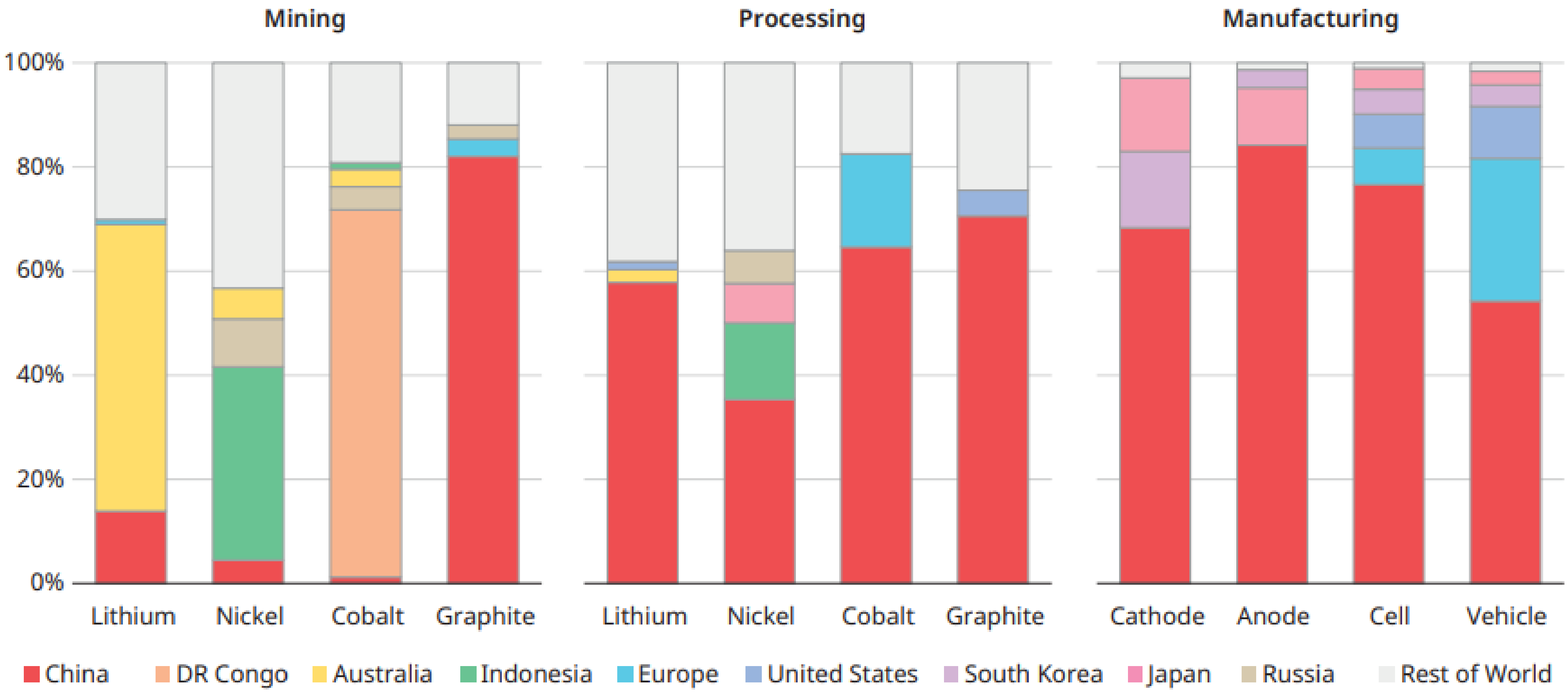
- How much renewable production?
- How much storage capacity?
- What technologies?
- Where they are sourced?
- When? At what sequence?

Political economy

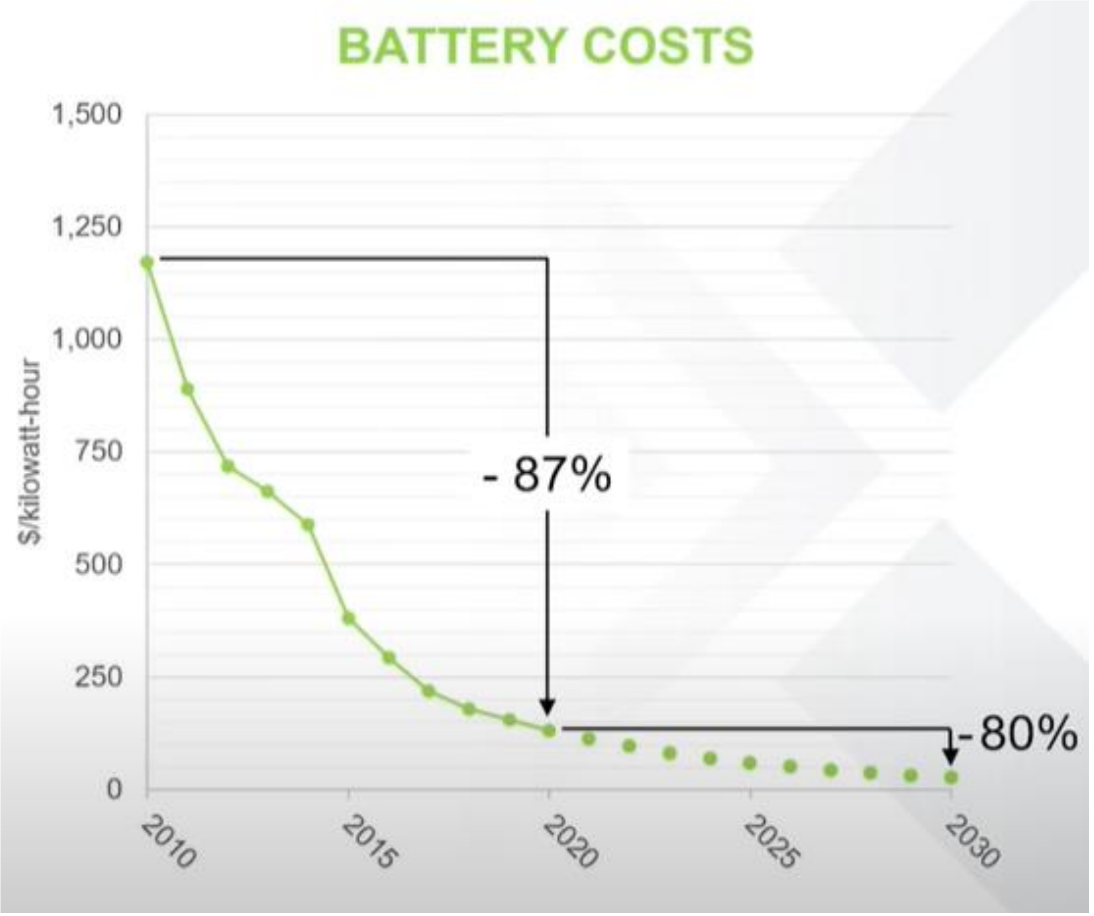
- Who will benefit from the new value chain?

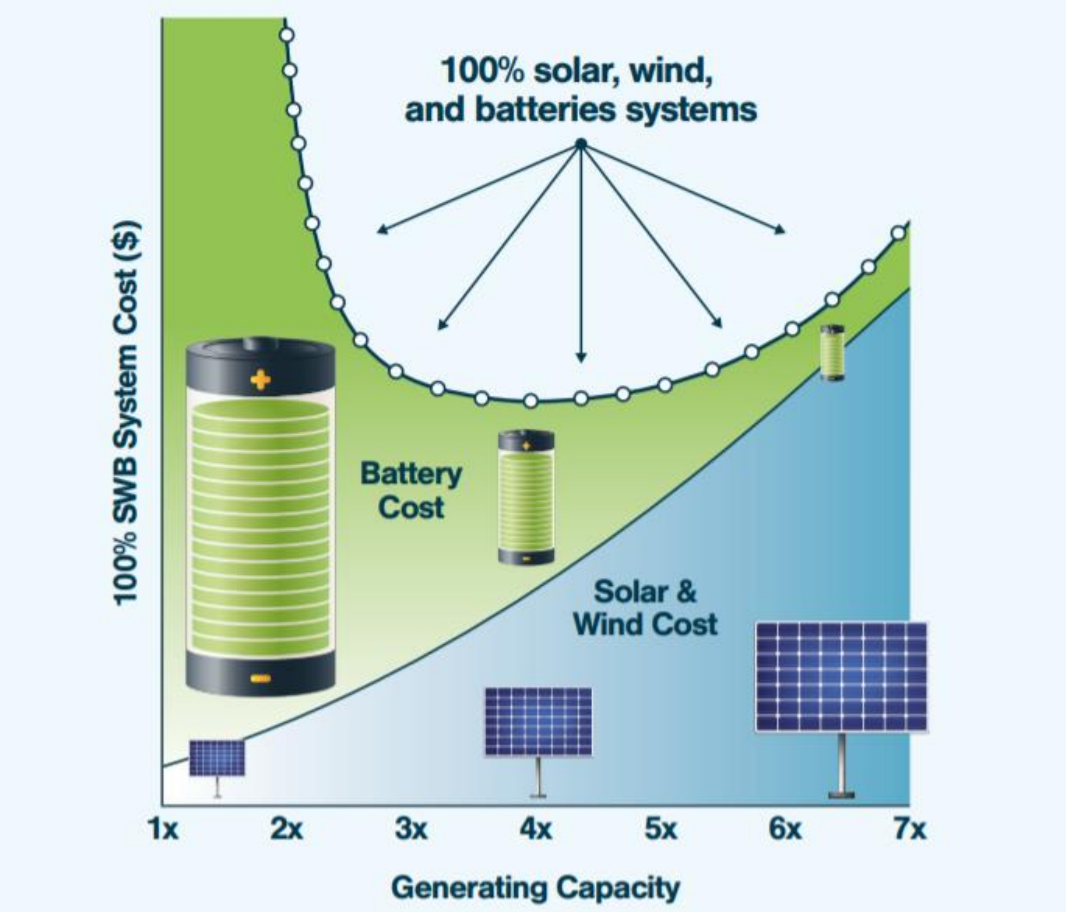
- Who will benefit from the new energy system?

Value chain (geographical distribution)



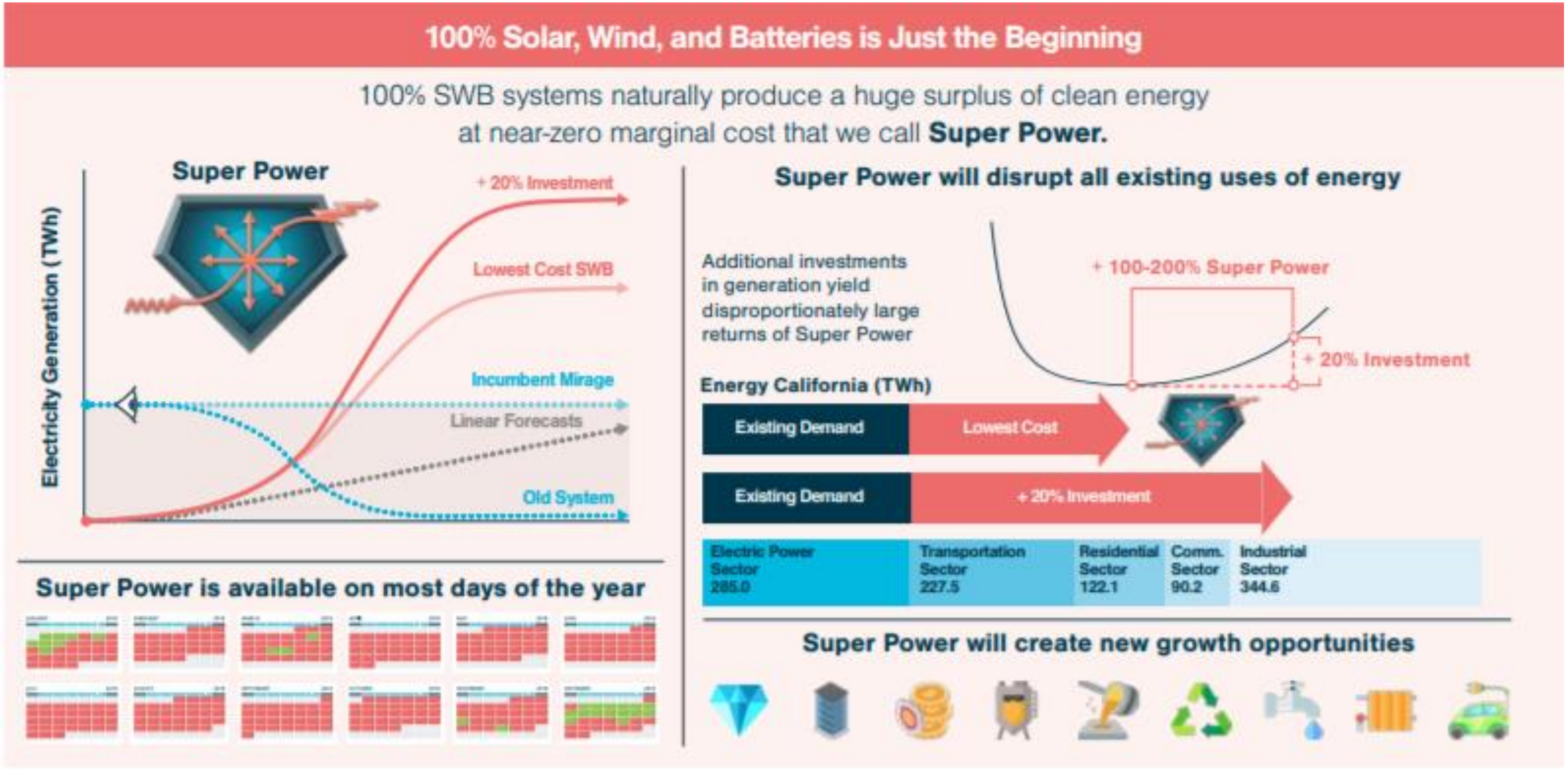
Political economy: who will win the transition?





Source: [RethinkX]

Political economy: who will win the transition?



Source: RethinkX