

Current and Future Environmental Costs and Impacts of Grid-Scale Battery and Mechanical Electricity Storage

This poster is based on the authors MSc thesis in Industrial Ecology at Leiden University and TU Delft

Intro

Storage is essential to match variable renewable generation with demand and limit warming [1]. Lithium-Ion Batteries (LIBs) dominate current storage (97 GWh in 2023 [3]) due to 97% cost declines since 1991 [2] and could meet 2050 needs of up to 19.2 TWh [4–7]. Yet LIB supply chains cause major environmental [8] and social impacts. Existing LCAs are fragmented, GHG-centric, and lack harmonisation or long-term scope [9]. Non-GHG harms are rarely monetised [6,10], and while True Cost Accounting (TCA) can internalise them [11], it hasn't been applied to storage.

Research question

What are the current and future specific (A) environmental impacts (LCA), (B) environmental costs (TCA), and (C) environmentally adjusted Levelized Costs of Storage (TCA-LCOS) of storing 1 kWh electricity of 16x battery chemistries and mechanical electricity storage technologies?

Methods

- Method-stacking:** hybrid LCA-TCA [12]
 - Attributional static (prospective) **Life-Cycle Assessment (LCA):**
 - LCA: Activity Browser, ISO 14044:2006 [13], Ecoinvent v3.9.1, ReCiPe2016
 - Data collection: Foreground processes based on literature [6], [14], [15], ecoinvent v3.9.1 (ei391) [16], and Siemens Energy AG [17].
 - Background scenarios: SSPs from REMIND [19] & PREMISE [20]
 - True Cost Accounting (TCA):** Environmental externality pricing via CE Delft [18]

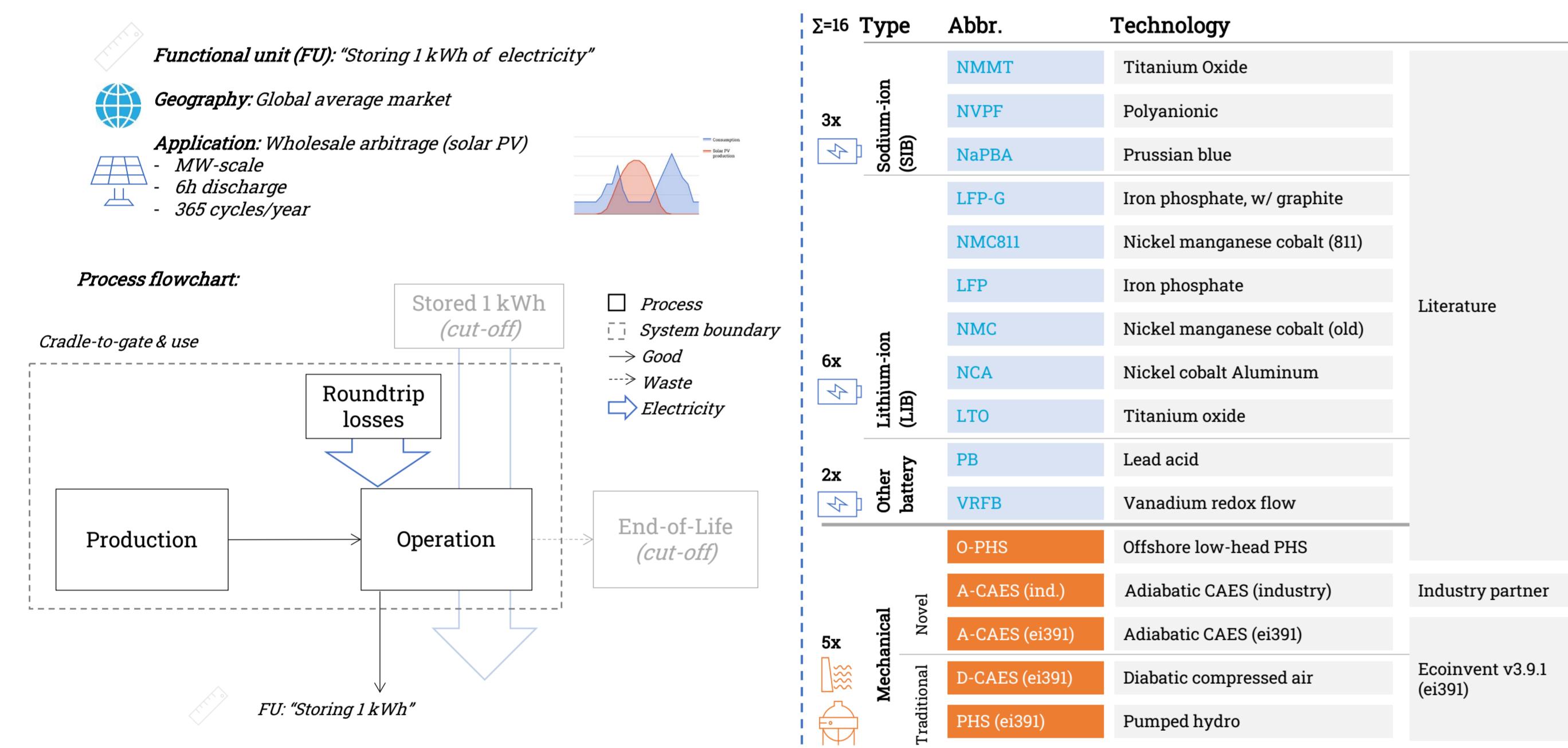


Figure 1. Goal and scope definition as well as covered technologies (incl. used abbreviations)

(A) Results – Environmental impacts: LCA

LCA results show storing 1 kWh photovoltaic (PV) electricity can, depending on technology, amplify impacts: Climate impacts (GWP100) between +40-400% (+34-340 gCO₂/kWh-storing), and others between +10-1,100% compared to direct solar PV electricity use (Table 1). Nevertheless, all storage technologies have significantly lower climate impacts than alternative natural gas peaking plants. While selected (historic, current, promising market dominance) mechanical storage and batteries show currently similar low-impact levels, future scenarios show “A-CAES” with lower across impacts, except “land use” (LOP). This is across impact categories driven by material-intensive battery production processes (>85% contribution), contrasting with the operational losses that dominate mechanical storages (>90% contribution). Focusing solely on (current) climate impacts, like most previous research, risks environmental problem shifting, as ecological hotspots vary by technology (Fig. 2). Key trade-offs include climate change (GWP), water use (WCP), metals/minerals resource depletion (SOP), land use (LOP), and marine eutrophication (MEP).

Table 1. LCA results (current), ReCiPe2016 v1.03 midpoint (H), data bars scaled to per column.

Technology name	Resource Depletion																Human Toxicity										Other			
	TAP	GWP100	ETFP	MEP	TETP	FFP	FEP	MEP	HTPnc	HTPpc	IRP	LOP	SOP	ODPinf	PMFP	HOFP	EOFP	WCP	Land	Ozone	Particulate Matter	Smog, human health	Smog, terrestrial eco-systems	Water use						
NMNT	2.41E-04	4.32E-02	8.45E-03	1.11E-02	6.43E-01	1.08E-02	2.99E-05	2.50E-05	8.70E-03	1.44E-01	6.64E-03	3.01E-03	2.97E-03	2.11E-08	9.51E-05	1.34E-04	1.39E-04	9.14E-04												
NVPF	3.89E-04	5.91E-02	9.22E-03	1.22E-02	6.14E-01	1.55E-02	3.44E-05	2.74E-05	1.60E-02	1.52E-01	7.08E-03	3.63E-03	3.17E-03	2.38E-08	1.56E-04	1.61E-04	7.06E-04													
NaPBA	2.49E-04	5.46E-02	9.25E-03	1.21E-02	6.09E-01	1.32E-02	3.64E-05	3.56E-05	1.09E-02	1.64E-01	7.61E-03	3.48E-03	2.89E-03	2.67E-08	1.03E-04	1.52E-04	1.58E-04	6.70E-04												
LFP-G	3.62E-04	4.28E-02	1.46E-02	1.91E-02	1.74E+00	1.04E-02	2.44E-05	2.14E-05	8.95E-03	2.67E-01	5.46E-03	3.33E-03	2.06E-02	1.98E-08	1.34E-04	1.20E-04	1.25E-04	5.75E-04												
NMC811	3.99E-04	4.68E-02	1.62E-02	2.13E-02	2.05E+00	1.19E-02	1.66E-05	1.43E-05	8.01E-03	2.96E-01	6.63E-03	4.36E-03	1.26E-02	2.29E-08	1.50E-04	1.30E-04	1.36E-04	1.76E-03												
LFP	4.25E-04	6.94E-02	2.25E-02	2.91E-02	1.97E+00	1.86E-02	1.18E-05	6.98E-06	1.24E-02	3.43E-01	3.19E-03	6.10E-03	2.47E-02	2.06E-08	1.74E-04	1.77E-04	1.85E-04	8.98E-04												
NMC	4.03E-04	6.76E-02	2.88E-02	3.74E-02	2.75E+00	1.87E-02	1.54E-05	7.39E-06	1.13E-02	4.98E-01	6.86E-03	5.37E-03	1.85E-02	2.58E-08	1.97E-04	1.72E-04	1.80E-04	2.82E-03												
NCA	1.68E-03	9.85E-02	3.33E-02	4.35E-02	3.88E+00	2.78E-02	6.13E-05	8.91E-06	1.34E-02	5.28E-01	6.32E-03	5.87E-03	2.67E-02	4.80E-08	5.64E-04	1.48E-03	1.50E-03	2.65E-03												
LTO	1.24E-03	8.65E-02	2.36E-02	3.09E-02	2.65E+00	2.33E-02	4.79E-05	8.60E-06	1.39E-02	3.79E-01	5.23E-03	4.99E-03	2.51E-02	3.99E-08	4.24E-04	1.10E-03	1.12E-03	2.09E-03												
PB	1.29E-03	1.93E-01	6.24E-02	8.40E-02	3.99E+00	5.09E-02	1.37E-04	1.26E-05	6.52E-02	2.26E+00	3.47E-02	1.67E-02	1.94E-02	6.77E-08	4.98E-04	4.75E-04	4.96E-04	3.03E-03												
VRFB	1.28E-03	1.59E-01	8.57E-02	1.11E-01	7.28E+00	4.28E-02	1.51E-04	1.21E-05	3.56E-02	1.29E+00	1.12E-02	2.00E-02	1.04E-02	1.01E-07	5.06E-04	4.71E-04	3.00E-04	2.42E-03												
O-PHS	1.199E-04	4.64E-02	9.08E-03	1.19E-02	1.01E+00	1.05E-02	2.23E-05	3.42E-06	1.21E-02	1.10E-01	2.92E-03	1.26E-02	7.78E-03	1.49E-08	9.57E-05	1.21E-04	1.27E-04	1.23E-03												
A-CAES (ind.)	1.96E-04	4.75E-02	9.58E-03	1.26E-02	1.11E+00	1.15E-02	2.24E-05	3.49E-06	9.09E-03	1.13E-01	3.05E-03	1.55E-02	2.45E-03	1.63E-08	9.44E-05	1.22E-04	1.29E-04	1.50E-03												
A-CAES (ei391)	1.37E-04	3.40E-02	6.68E-03	8.79E-03	7.70E-01	8.48E-03	1.55E-05	2.42E-06	5.44E-03	7.85E-02	2.15E-03	1.10E-02	1.47E-03	1.15E-08	6.54E-05	8.72E-05	9.31E-05	1.06E-03												
D-CAES	2.98E-04	3.40E-01	8.54E-03	1.13E-02	9.64E-01	1.72E-01	2.23E-05	3.37E-06	1.06E-02	1.04E-01	3.27E-03	1.34E-02	3.54E-03	8.12E-08	1.30E-04	3.85E-04	4.27E-04	1.42E-03												
PHS	1.65E-04	6.52E-02	7.68E-03	1.01E-02	8.93E-01	9.89E-03	1.86E-05	2.86E-06	7.82E-03	9.35E-02	2.82E-03	1.25E-02	1.95E-03	1.49E-08	8.09E-05	1.11E-04	1.17E-04	3.04E-02												
Solar PV	3.53E-04	8.49E-02	1.73E-02	2.28E-02	2.01E+00	2.06E-02	4.02E-05	6.26E-06	1.38E-02	2.04E-01	5.55E-03	2.88E-02	3.76E-03	2.96E-08	1.68E-04	2.18E-04	2.31E-04	2.76E-03												
Wind onshore	5.94E-05	1.54E-02	6.50E-03	8.05E-03	2.13E-01	4.04E-03	6.63E-06	1.11E-06	1.08E-02	3.59E-02	6.13E-04	1.08E-03	2.16E-03	4.56E-09	3.10E-05	4.45E-05	4.73E-05	1.38E-04												
Natural gas	3.45E-04	6.76E-01	2.47E-03	3.31E-03	2.19E-01	2.56E-01	7.52E-06	1.18E-06	6.76E-03	3.89E-02	5.14E-04	7.73E-04	2.68E-03	1.36E-07	1.26E-04	6.78E-04	7.79E-04	1.17E-03												

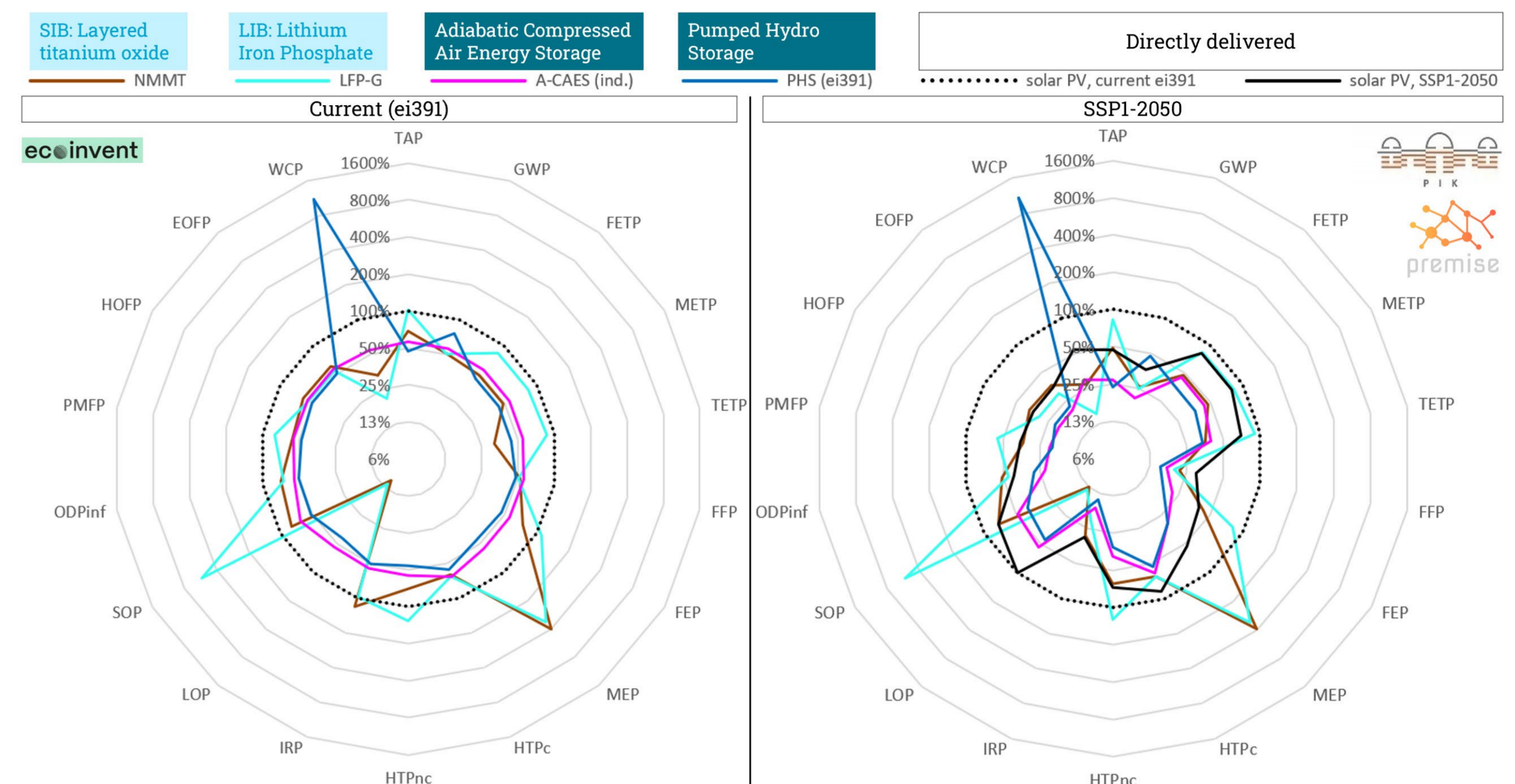


Figure 2. LCA result spider diagrams selected tech. normalised to 1 kWh directly delivered solar PV, spikes indicate trade-offs.

(B) & (C) Results – Environmental Costs: TCA(-LCOS)

(B) Environmental costs: TCA results range between 0.05-0.60 €/2024/kWh-storing (Fig. 3). Non-climate impacts account for >90% of TCA costs, dominated by human health-damaging impacts: “(Non-)carcinogenic human toxicity” (HTPnc/HTPpc), and “particulate matter formation” (PMFP). The contribution analysis identified technology-specific hotspots, with steel and lead processing dominating HTPpc, copper and lead-related mining activities driving HTPnc, electricity consumption, and metal-specific inputs like nickel, lithium, and lead, being key contributors to PMFP.

(C) Environmentally adjusted Levelized Costs of Storage: TCA increases LCOS by >100% for most batteries and by +50–80% for mechanical storages, making several batteries costlier than the best mechanical storages (Fig. 3). Future TCA reduces for mechanical storages by up to -4 ct €/2024(-30%), triple that of batteries (Table 2).

Table 3. Absolute and relative change of total TCA-LCOS/-LCOE reduction between current (ei391) and future (SSP1-2050).

	NMNT	NVPF	NaPBA	LFP-G	NMC811	LFP	NMC	NCA	LTO	PB	VRFB	O-PHS (ind.)	A-CAES (ei391)	D-CAES (ei391)	PHS (ei391)	Solar PV	Wind onshore	Natural gas	
Δ_{TCA}	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02	-0.02	-0.02	+0.04	-0.03	-0.02	-0.02	-0.01	-0.04	-0.04	+0.003	-0.02	
%	-12%	-9%	-12%	-11%	-12%	-10%	-11%	-9%	-7%	7%	-7%	-17%	-25%	-29%	-32%	-18%	-30%	5%	-10%

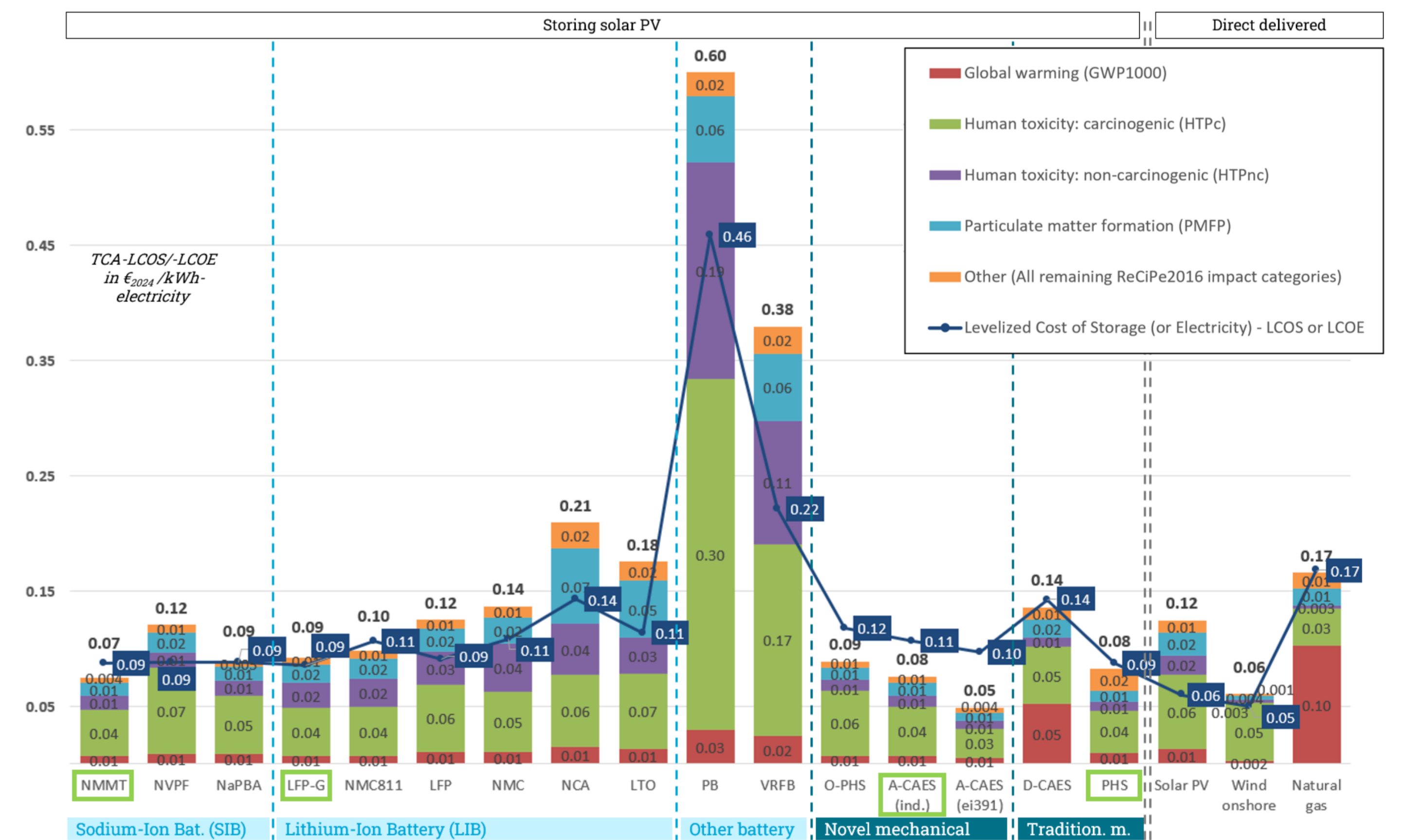


Figure 3. Current (2022) environmental costs (TCA) for storing 1 kWh, for comparison, LCOS (calculated via [21]) and LCOE [22] for direct delivered electricity sources.

Conclusion

Recommendations for practitioners are to investigate impacts beyond climate to avoid (future) problem-shifting via rigorous (prospective) LCAs. Internalising environmental costs via TCA simplifies complex multi-criteria environmental trade-off analysis and thus decision making from a societal welfare perspective. To better reflect societal costs, future policies should update carbon taxes/prices and extend schemes to other impact categories. Or at least include TCA-LCOS in energy storage tenders, similar to Dutch environmental shadow prices for construction projects. Re-source-efficient (more circular) mechanical storages should be prioritised over batteries where geographically feasible due to mostly lower (future) impacts. To reduce mechanical storage impacts, optimise round-trip efficiency and choose low-impact charging electricity (e.g., wind over solar). Prioritise batteries for high cycle applications (>1/day) to maximise material utilisation and for renewable sources with high impacts (e.g., solar PV) to leverage higher round-trip efficiency. To further reduce battery impacts, clean-up production processes, lower material usage, and increase lifetime-stored electricity through longer (calendaric) lifetimes. Future research should expand this work by adding an End-of-Life stage, more technologies, as well as simultaneous economic (LCOS) as well as environmental cost and impact modelling for different geographic and temporal granularities.

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