

Comparative Life Cycle Assessment of Rankine-based Carnot Batteries and Lithium-Ion Batteries for Grid-Scale Energy Storage

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Highlights

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- Component-wise LCA of Carnot batteries with uncertainty quantification
- Water-based Carnot battery achieves lowest impact in 17 of 18 midpoint categories
- Thermal oil-based Carnot battery has highest impact in 7 midpoint categories
- Thermal energy storage contributes over 50% of total environmental impact
- ORC efficiency most strongly influences environmental impact of Carnot batteries

Comparative Life Cycle Assessment of Rankine-based Carnot Batteries and Lithium-Ion Batteries for Grid-Scale Energy Storage

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Abstract

Carnot batteries are investigated as a potential alternative to electro-chemical batteries for grid-scale electricity storage, which is a crucial element to the decarbonisation of energy systems via variable renewable energy sources. In this work, a comprehensive life cycle assessment of the construction and end-of-life phases of two Rankine-based Carnot battery system configurations is presented, comparing water and thermal oil as hot thermal energy storage fluid. Both are benchmarked against lithium-ion batteries as the most common electro-chemical battery alternative. To enhance the robustness of the analysis, uncertainties in the input parameters and life cycle inventory data are explicitly considered and analysed. The deterministic results show that the Carnot battery using water as hot storage fluid performs best in 17 of 18 environmental impact categories. Thermal energy storage systems are identified as the dominant contributors, accounting for more than 50% of the environmental impact across most categories. The stochastic results considering uncertainty confirm that the Carnot battery with water tends to have the lowest environmental impact, followed by the lithium-ion battery, while the Carnot battery with thermal oil tends to perform the worst.

Keywords: Heat pump, Organic Rankine cycle, Pumped-thermal energy storage, Renewable energy, Thermo-mechanical energy storage, Uncertainty

Nomenclature

Abbreviations

AER	Annual emission reduction
CAES	Compressed-air energy storage
CB	Carnot battery
DALY	Disability-adjusted life years
ESS	Energy storage system
GWP	Global warming potential
HFO	Hydrofluoroolefin
HP	Heat pump
LAES	Liquid-air energy storage
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment

Li-ion	Lithium-ion
ORC	Organic Rankine cycle
PTES	Pumped-thermal electricity storage
TES	Thermal energy storage
TEWI	Total equivalent warming impact
TMES	Thermo-mechanical energy storage

Symbols

η	Efficiency (%)
η_{Carnot}	Carnot efficiency (%)
COP	Coefficient of performance (–)
T	Temperature (K)
x	Recycling credit factor (–)

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1. Introduction

Grid-scale energy storage systems (ESSs) are becoming increasingly valuable with increasing shares of variable renewable energy sources such as wind and solar power in the electricity generation mix. ESSs can help match non-dispatchable generation with inflexible demand, and thus decrease curtailment and increase the share of renewable electricity generation in the overall mix [1]. Historically, grid-scale energy storage was limited to pumped-hydro storage systems, which still account for 94 % of large-scale energy storage capacity installed worldwide, as alternative technologies struggle to compete on scale and cost. However, the limited remaining potential [2] and strongly increasing energy storage demand necessitates the consideration of alternative technologies.

Promising alternatives are electrochemical batteries, especially lithium-ion (Li-ion) batteries and thermo-mechanical energy storage (TMES) systems. The former have experienced an almost 80 % cost reduction from 2010 to 2020 [3] and a more than 95 % cost reduction since the 1990s [4]. This has resulted in a large increase in grid-scale Li-ion battery installations. Globally, the installed battery capacity in the electricity sector has increased from about 1 GW in 2013 to 85 GW in 2023, 40 GW of which were added in 2023 alone. About two-thirds of these are large grid-scale systems, while the others are behind-the-meter ESSs, i.e., typically smaller systems situated at the consumers [5].

TMES systems on the other hand are an emerging technology that offers potentially cost-competitive grid-scale energy storage, though their roundtrip efficiency is typically lower than that of electrochemical batteries [6]. The most common TMES technologies are compressed-air energy storage (CAES) [7], liquid-air energy storage (LAES) [8], and pumped-thermal electricity storage (PTES) systems [9], often called Carnot batteries (CB) [10]. While CAES is likely the least costly of these technologies, it depends on the availability of large (often underground) storage volumes [11]. CBs on the other hand, do not have specific geographical constraints and feature a higher energy density while also having the potential to compete with electrochemical batteries in terms of costs [6].

CBs utilise a heat pump to convert electricity into thermal energy, which is then stored at high temperature. For discharging, the process is reversed, and the thermal energy is converted back into electricity using a heat engine. While various thermodynamic cycles have been proposed — including Brayton cycles with noble gases [12, 13], steam-based Rankine cycles [14], and transcritical CO₂ cycles [15] — this study focuses on Rankine-based systems using organic working fluids. These systems are of particular interest as they leverage mature organic Rankine cycle (ORC) and heat pump technologies already widely deployed in geothermal and waste-heat recovery applications [16], and avoid the high temperatures of Brayton-based systems. This technological maturity not only enhances the near-term commercial viability of Rankine-based CBs but also provides a more robust foundation for life cycle inventory data, as the environmental profiles of the required components are well-documented in industrial databases.

Beyond the choice of thermodynamic cycle and working fluid, the selection of the thermal storage medium represents a critical design decision for CBs. For storage temperatures below 250 °C, latent or liquid sensible heat storage, or a combination of both can be used [10]. The most-used liquid sensible heat storage mediums are pressurized hot water and thermal oil [17, 18]. Water has the advantages of a high specific heat capacity and low costs. However, due to the increasing pressure required to keep it liquid at higher temperatures, it can only be used up to a certain storage temperature. Thermal oil allows for higher storage temperatures while also having higher volumetric storage capacities than steam. Using thermal oil also avoids having to use well-sealed pressure vessels for storage, as it can be stored at ambient pressure even at high temperatures [19].

Most current research on CBs focusses on optimising the system design [20], maximising roundtrip efficiency and/or minimising costs [21, 22, 23], and comparing different energy storage technologies on a technical and economical basis [18, 16]. However, for a holistic technology comparison, it is important to focus not only on technical and economic factors, but also consider the environmental impacts over the entire life cycle.

1.1. Literature on life cycle assessments of Carnot batteries

Research on the environmental impact (especially beyond climate change) of CBs is relatively scarce. Scharrer et al. [24] present a life cycle assessment of a reversible CB working with cyclopentane and a

51 geothermal heat supply. In comparison with Li-ion and lead-acid batteries, the CB consistently exhibits
52 lower environmental impacts. However, the authors limit their analysis to only four environmental impact
53 categories. For their chosen use case (10 hours of constant charging and discharging with a storage capacity
54 of 1 MWh), the water storage tank is by far the most impactful component in terms of environmental impact,
55 while the heat pump compressor is the second-most impactful component. It is unclear if this statement
56 holds for other environmental impact categories or if burden shifting occurs.

57 In the life cycle assessment (LCA) presented by Dumont et al. [25], the environmental impact of the CB
58 is modelled as the sum of the impacts of a heat pump (using R134a as working fluid), and a storage vessel,
59 including its insulation and the storage material. The results vary for different storage materials: Phase
60 change materials were found to have a strong impact on the environment, while for water as storage material,
61 the CB yields better results than an electrochemical battery in 5 out of the 6 considered impact categories.
62 The heat pump dataset is based on a residential 10 kW heat pump. The design of bigger machinery may
63 vary significantly. It is therefore not possible to easily transfer the results to grid-scale CBs.

64 Xia et al. [26] investigate the performance of a cold-storage Rankine-based CB and consider not just the
65 thermodynamic and economic perspective, but also the environmental impact. However, the authors rely
66 on the metrics of annual emission reduction (AER) and total equivalent warming impact (TEWI) for the
67 environmental assessment, rather than performing a full LCA study. While these metrics provide insights
68 into climate change impacts, they do not capture the full spectrum of environmental burdens across multiple
69 impact categories. The results demonstrate that AER and TEWI are significantly affected by the chosen
70 operating point, highlighting the importance of system design on environmental performance. Wang et
71 al. [27] present a more comprehensive approach, performing an LCA for a CB integrated with solar energy,
72 considering five different working fluids. For each configuration, the system is optimised and then assessed
73 using five impact categories. Among the five working fluids, pentane shows the highest and R1336mzz
74 the lowest environmental impact. However, even this study remains limited to only five impact categories,
75 potentially missing important environmental trade-offs in areas such as resource depletion, toxicity, or water
76 use that could influence technology design decisions.

77 The studies presented by Xia et al. [26] and Wang et al. [27] include the operation phase within the
78 system boundaries. While this provides a complete lifecycle view, the resulting environmental profiles are
79 often dominated by the impacts of the charging electricity and depend heavily on the chosen operating
80 point. This 'masking effect' can obscure the specific environmental burdens inherent to the physical plant
81 components and storage media, making it difficult to compare different technology designs independently of
82 the energy system they inhabit.

83 The environmental implications of storage medium selection have received limited attention in CB LCA
84 studies. While Scharrer et al. [24] identified the water storage tank as the dominant contributor to envi-
85 ronmental impacts due to its size and material requirements, no studies have systematically compared the
86 environmental impact of different storage media.

87 Beyond complete CB system assessments, numerous LCA studies on the individual components of CBs
88 are available in the literature: heat pumps [28, 29, 30], thermal energy storages [31, 32], and ORC sys-
89 tems [33]. However, these component-level studies cannot be simply combined to assess complete CB sys-
90 tems, as each study is based on different assumptions and uses different system boundaries and databases.
91 This methodological inconsistency, combined with the limited scope of existing CB LCA studies (assessing
92 no more than six impact categories) and a universal absence of uncertainty analysis, creates significant
93 knowledge gaps regarding the comprehensive environmental performance of CBs. No study to date has
94 quantified the reliability of its results through Monte Carlo simulation or systematic sensitivity analysis,
95 leaving the influence of data variability on the final results unexplored.

96 Furthermore, the existing research is fragmented, with varied impact category coverage (ranging from 2-6
97 categories), inconsistent functional units, and incompatible LCA databases. This makes it difficult to draw
98 definitive conclusions about how CBs compare environmentally to alternative storage technologies such as
99 Li-ion batteries, whose environmental impact is a much-discussed topic in the literature [34], or how different
100 design choices (such as the storage medium selection) affect overall environmental performance.

1.2. Research gap and objectives

The literature review reveals several knowledge gaps in the environmental assessment of CBs: existing studies evaluate no more than six impact categories, employ inconsistent methodologies with varied system boundaries and databases, and have not systematically investigated storage medium selection (water vs. thermal oil) from an environmental perspective. These limitations prevent meaningful comparisons both within CB design variants and against competing technologies such as Li-ion batteries.

Furthermore, existing LCA studies only perform a deterministic assessment of the environmental impacts, despite large uncertainties in both the input parameters, such as characteristics of the CB system, and the environmental impact database. A more robust assessment considering the various uncertainties is yet to be presented. Additionally, the relative environmental burden of the physical infrastructure versus the operational energy losses is frequently confounded by varying assumptions regarding electricity grid mixes. To isolate the impact of technological design and material selection, a focused assessment of the system’s physical lifecycle — independent of specific operational scenarios — is required.

To address these research gaps, this study conducts a comprehensive life cycle assessment of CBs with the following objectives:

1. Comprehensive environmental assessment: Evaluate CB systems across all 18 midpoint and three endpoint impact categories of the ReCiPe method [35] to determine a holistic environmental profile.
2. Robust environmental assessment of system hardware: Consider uncertainties in both the (technology design) input parameters and the environmental impact data.
3. Systematic comparison of storage media: Compare water and thermal oil as storage fluids under consistent assumptions to quantify the environmental trade-offs between these design alternatives.
4. Benchmarking against li-ion batteries: Compare the environmental performance of CBs with Li-ion battery systems (excluding the operational phase) using a standardised LCA framework to support informed technology selection for grid-scale energy storage.

Section 2 details the method and the considered CB systems as well as the assumptions made, Section 3 presents the results, Section 4 provides a brief discussion of the results and highlights limitations of our analysis, and Section 5 concludes this paper.

2. Method

This section outlines the LCA method applied to assess the environmental impacts of CB systems. Section 2.1 describes the CB system considered in this analysis, Section 2.2 details the LCA framework and life cycle inventory data, and Section 2.3 describes the uncertainty quantification.

2.1. Carnot battery system description

This section briefly explains the CB concept investigated in this paper. The investigated system is a Rankine-based CB consisting of four cycles: a heat pump cycle, two thermal energy storage (TES) cycles, and an ORC. The system and its main components are shown in Figure 1.

For charging, an electrical vapour-compression heat pump is used to transfer thermal energy from the cold to the hot storage cycle. The fluid from the cold storage cycle is used to evaporate the working fluid in the heat pump evaporator, cooling down in the process. The fluid from the hot storage cycle is heated in the heat pump condenser and stored in the hot tank. For discharging, the cycles are reversed, and the temperature difference between the hot storage cycle and cold storage cycle is used to power an ORC, which converts the thermal energy back into electricity.

The CB analysed in this study is based on the optimised design proposed by Tillmanns et al. [36], who investigated a case study of daily storage originally proposed by Henchoz et al. [37]. The system is charged at a constant rate for 8 hours, and then discharged, also at a constant rate, for 16 hours. The heat pump cycle operates with isobutene as working fluid, while the ORC uses propane. The cold store uses water as the storage fluid. For the hot store, we investigate two configurations: pressurised water, and thermal oil at ambient pressure. The upper process temperature is about 140 °C, limited by the critical temperatures of

174 aggregated into damage to the three areas of protection, expressed in disability-adjusted life years (DALY)
 175 for human health, species loss ($\text{PDF} \times \text{m}^2 \times \text{yr}$) for ecosystem quality, and surplus cost for resource scarcity.
 176 The Hierarchist perspective was applied, which represents the scientific consensus based on common policy
 177 principles regarding time frame and assumptions of plausible cause-effect relationships [35]. This dual-level
 178 approach allows for both detailed characterization of specific environmental mechanisms (midpoint) and
 179 comprehensive assessment of overall damage (endpoint) within a single, consistent framework.

180 2.2.1. Life cycle inventory

181 All life cycle inventory (LCI) data for materials and energy used to produce the CBs and the Li-ion
 182 battery was obtained from the Ecoinvent database version 3.11 [41], using the cut-off system model. The
 183 cut-off system model applies an attributional approach where recyclable materials are available burden-free
 184 to recycling processes, and only primary production carries environmental burdens. This approach avoids
 185 double-counting of recycling benefits while maintaining mass and energy balances within the system. The
 186 environmental impacts of each material or energy flow needed in this study is scaled by the required amount
 187 to supply the functional unit defined above.

188 The LCA modelling was conducted using the Brightway2 framework version 2.5 [42], an open-source
 189 Python-based software platform for advanced life cycle assessment calculations. The CB is modelled using
 190 a component-wise approach as shown in Figure 2. Each major subsystem (heat pump, ORC plant, hot and
 191 cold TES) is modelled individually.

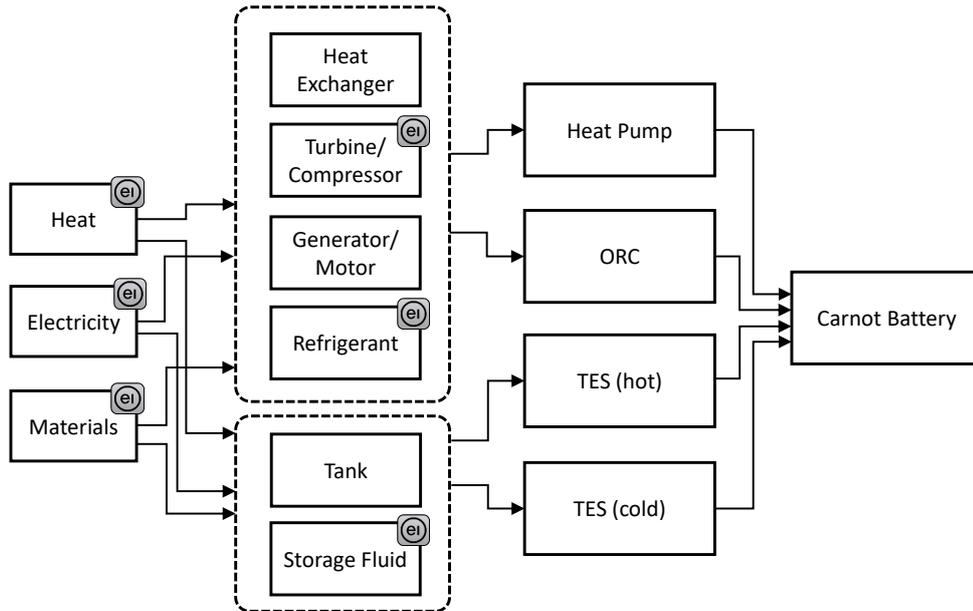


Figure 2: Component-wise CB modelling approach. The components marked with the EI label are modelled directly as Ecoinvent processes, while the others are modelled via their material use (e.g., steel and copper).

192 The heat pump and the ORC plant are modelled based on their primary components: heat exchang-
 193 ers, compressor/turbine, electric generator/motor, and refrigerant. The sizes of the different components
 194 are determined from a thermo-economic optimisation, using a comprehensive Matlab models for thermo-
 195 mechanical energy storage systems [11]. Using the operating conditions specified by Tillmanns et al. [36],
 196 the specific design of the CBs is optimised to maximise the roundtrip efficiency. The model yields results
 197 such as the compressor and turbine power ratings, as well as the sizes of the TES cycles, which are required

198 as inputs to the LCA modelling. Based on the results of the Matlab optimisation model, the heat exchangers
199 are designed as shell-and-tube heat exchangers using the ASPEN Exchanger Design & Rating software. This
200 results in a required mass of low-alloyed steel, which is modelled using the corresponding Ecoinvent market
201 activity.

202 Both the heat pumps compressor as well as the turbine of the ORC plant are modelled using the Ecoinvent
203 dataset of a 10 MW gas turbine, assuming that compressors and turbines have a similar environmental
204 impact. The electric motor of the heat pump compressor and the generator of the ORC plants' turbine are
205 accounted for using a specific copper mass of 1.275 kg kW^{-1} . The value is derived from the 200 kW generator
206 included in the Ecoinvent dataset. The hot and cold stores are modelled based on the mass of low-alloyed
207 steel required for the construction of the storage vessels, and the mass of water or thermal oil required.
208 The required mass of steel is calculated using the method described by Seider et al. [43], accounting for the
209 required pressure resistance. The water and thermal oil are modelled through Ecoinvent market activities,
210 using the market activity for alkylbenzene for the thermal oil.

211 The environmental impacts of the natural refrigerants propane and isobutene are modelled directly from
212 Ecoinvent, using the generic C4 hydrocarbons market activity for the latter. The baseline value of the
213 refrigerant charge is assumed to be 0.15 kg kW^{-1} , based on Sanchez-Moreno Giner [44]. As discussed in
214 Section 2.3, the uncertainty in this value is accounted for in the robust analysis of environmental impacts.
215 The heat pump and ORC plant assembly as well as the manufacturing of the subcomponents is accounted
216 for by using the generic Ecoinvent datasets for metalworking. The lifetime of the Carnot Battery is assumed
217 to be 30 years [6].

218 For the Li-ion battery, we use an Ecoinvent dataset for the entire battery. The dataset's functional unit
219 is 1 kg of battery. We therefore assume a baseline specific gravimetric energy density of 150 Wh kg^{-1} [45] to
220 calculate the required battery mass, as our functional unit is defined based on the discharge energy capacity.
221 As explained in Section 2.3, we also consider uncertainties in this parameter. The lifetime of the Li-ion
222 battery is assumed to 15 years [46]. To account for the shorter lifetime in the LCI, two Li-ion batteries are
223 required for the provision of the functional unit.

224 Besides manufacturing and assembly, we include the end-of-life phase, which is modelled by including
225 recycling processes, recycling efficiencies, and recycling credits per material. The recycling efficiency deter-
226 mines the share of a material that is successfully recovered and reprocessed. Different recycling processes
227 are modelled such as electric arc furnaces for steel recycling and the Ecoinvent copper recycling process.
228 The energy demand and environmental impact of these processes is accounted for. Finally, recycling credits
229 are given for avoiding primary extraction, according to the recycling credit factor. This factor accounts for
230 recycled material already included in the primary process to avoid double-counting, and for the fact that
231 recycled material cannot substitute primary material like-for-like. Both natural refrigerants are assumed to
232 be vented at the end of their life. The analysis accounts for the Global Warming Potential (GWP) of each
233 refrigerant, but other environmental impacts are neglected as no data is available.

234 *2.3. Uncertainty analysis*

235 The CB and Li-ion battery parameters, the LCI data, and the resulting environmental impacts are sub-
236 ject to uncertainties. Following the recommendations of Igos et al. [47] for uncertainty treatment in LCA
237 studies, we conduct a Monte Carlo analysis to account for these uncertainties and quantify their impact
238 on the results. We distinguish two different types of uncertainties according to the classification proposed
239 by Igos et al. [47]: quantity uncertainty (uncertainties in numerical data from Ecoinvent process data) and
240 model structure/context uncertainty (uncertainties in modelling assumptions and methodological choices).
241 Regarding the quantity uncertainty, Ecoinvent processes include uncertainty distributions (typically lognor-
242 mal distributions) characterized using the pedigree matrix approach [48, 49]. We use Brightway's built-in
243 Monte Carlo function to propagate these uncertainties through the LCA calculations. For the model struc-
244 ture and context uncertainties related to our modelling assumptions on the other hand, we have to explicitly
245 define the uncertainty distributions. Due to limited data sources for these assumptions, we consider them
246 to be uniformly distributed, following the approach recommended by Igos et al. [47] for cases with sparse
247 data. The considered assumptions and their bounds are listed in Table 1.

248 We assume that the gravimetric energy density of Li-ion batteries will not reduce in future, while there
 249 is potential for Li-ion batteries to achieve even higher gravimetric energy densities than our baseline as-
 250 sumption. Wherefore, we set the deterministic baseline value as the lower bound, while a doubling of the
 251 gravimetric energy density is chosen as the upper bound for the Monte Carlo analysis.

252 The bounds on the heat pump COP and the ORC efficiency, η_{ORC} are determined based on the Carnot
 253 efficiency, using a typical range of 40 % to 70 % of the Carnot efficiency. The deterministic system presented
 254 in Section 2.1 was optimised for maximum efficiency, thus, it achieves a relatively high ORC efficiency. The
 255 lower and upper bounds of the specific refrigerant charge are set based on the data presented by Sanchez-
 256 Moreno Giner [44]. The recycling credit factor is varied between the deterministic value as optimistic
 257 best-case scenario, and 50 % lower recycling credits as the lower bound.

258 Based on these uncertainty distributions, we perform Latin hypercube sampling to generate the samples
 259 for the Monte Carlo runs. The analysis presented in Section 3 is based on 5000 Monte Carlo samples to
 260 ensure a sufficiently large number of runs.

Table 1: Input parameters for the deterministic LCA and the Monte Carlo analysis. For the Monte Carlo analysis, the parameters are assumed to be uniformly distributed between the lower and the upper bound.

Parameter	Deterministic	Lower Bound	Upper Bound
Gravimetric energy density Li-ion battery in Wh kg^{-1} [45]	150	150	300
COP_{HP}	$0.58 \cdot COP_{Carnot}$	$0.4 \cdot COP_{Carnot}$	$0.7 \cdot COP_{Carnot}$
η_{ORC}	$0.66 \cdot \eta_{Carnot}$	$0.4 \cdot \eta_{Carnot}$	$0.7 \cdot \eta_{Carnot}$
Specific refrigerant charge in g kW^{-1} [44]	150	20	300
Recycling credit factor	x	$0.5 \cdot x$	x

261 3. Results

262 This section presents the results of the comparative life cycle assessment of the two CB configurations
 263 and a Li-ion battery. Section 3.1 shows the comparison of the three technologies in a deterministic analysis.
 264 Section 3.2 extends the comparison by including uncertainties and presents the results of the Monte Carlo
 265 study. Finally, Section 3.3 presents and analysis of the impacts of different uncertain input parameters on
 266 the results.

267 3.1. Results of the deterministic comparative life-cycle assessment

268 The results of the deterministic LCA for both CB configurations and the Li-ion battery are depicted in
 269 Figure 3. The figure shows the environmental impacts for all midpoint impact categories defined by the
 270 ReCiPe method, normalised to the respective impact of the Li-ion battery. Among the 18 midpoint impact
 271 categories, the CB using water as storage fluid achieves the lowest environmental impacts in all but one
 272 impact category. The CB using thermal oil as storage fluid on the other hand achieves lower environmental
 273 impacts than the Li-ion battery in 10 impact categories, but performs worse than the water CB in every
 274 impact category.

275 In comparison to the Li-ion battery, both CBs perform significantly worse in the carcinogenic human tox-
 276 icity impact category. However, this impact category is subject to enormous uncertainties (*cf.* Section 3.2),
 277 which makes it hard to draw meaningful conclusions. The thermal oil CB shows higher environmental im-
 278 pacts than the Li-ion battery in the impact categories of energy resources, climate change, photochemical
 279 oxidant formation, land use, and freshwater ecotoxicity. Thermal oil is petroleum-based, and the production
 280 requires crude oil extraction and an energy intensive refining process. Therefore, the large amount of thermal
 281 oil required for the hot TES cycle of the CB directly contributes to the 3.5 times higher impact than the
 282 Li-ion battery in the energy resources impact category.

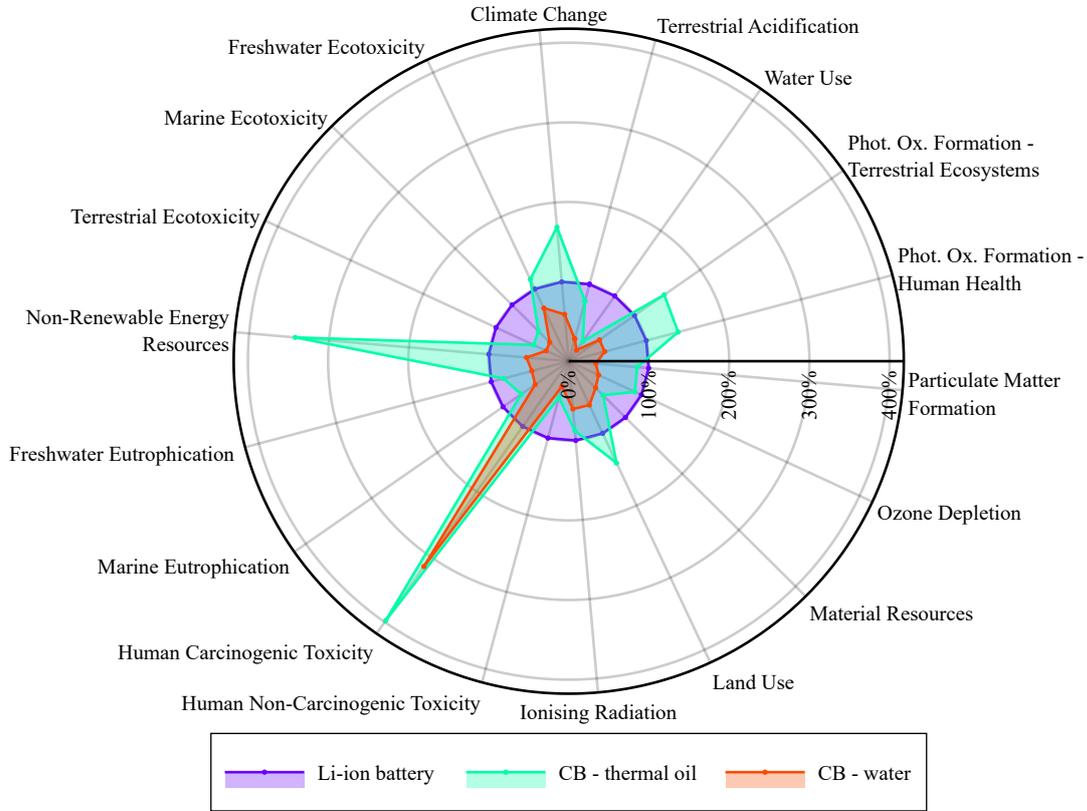


Figure 3: Comparison of the two CBs and the Li-ion battery for all impact categories. The results are normalised to the impacts of the Li-ion battery.

283 Figure 4 shows a component-level breakdown of the environmental impacts across all midpoint impact
 284 categories. For the impact categories where the thermal oil CB shows higher environmental impacts than
 285 the Li-ion battery — most notably in non-renewable energy resources, climate change, phot. ox. formation,
 286 and land use — we see a significant increase in the share of impacts from the hot TES cycle compared to the
 287 water CB. For instance, in the non-renewable energy resources category, the contribution of the hot TES
 288 cycle jumps from approximately 38% in the water-based system to 84% in the thermal oil configuration.
 289 A similar trend is observed for climate change, where the hot TES cycle share increases from roughly 39%
 290 to 63%. This increase can therefore be attributed to the change in storage fluid. Compared to water, the
 291 production and processing of thermal oil is much more energy and resource intensive. Furthermore, thermal
 292 oil has a lower volumetric energy density than water. This is driven by its significantly lower specific heat
 293 capacity ($2.1 \text{ kJ kg}^{-1} \text{ K}^{-1}$ compared to $4.18 \text{ kJ kg}^{-1} \text{ K}^{-1}$ for water) and lower density (800 kg m^{-3}
 294 compared to 1000 kg m^{-3} for water). Consequently, for a given storage capacity, thermal oil requires nearly double the
 295 storage volume of water. This results in significantly larger tanks, which offsets the extra steel required for
 296 water tanks to withstand the high pressure (approx. 10 to 20 bar) needed to maintain the water in a liquid
 297 state at high temperatures.

298 Considering at the component-level breakdown of environmental impacts shown in Figure 4, it becomes
 299 apparent that among all categories, the share of both TES cycles comprises more than 50% of the impacts,
 300 with the exception of human toxicity. The impact of the heat pump makes up most of the remaining impact,
 301 while the share of the ORC plant is the smallest over all categories. Due to the moderate roundtrip efficiency
 302 of only about 30% to 35%, the heat pump is always much larger than the ORC plant, as the compressor

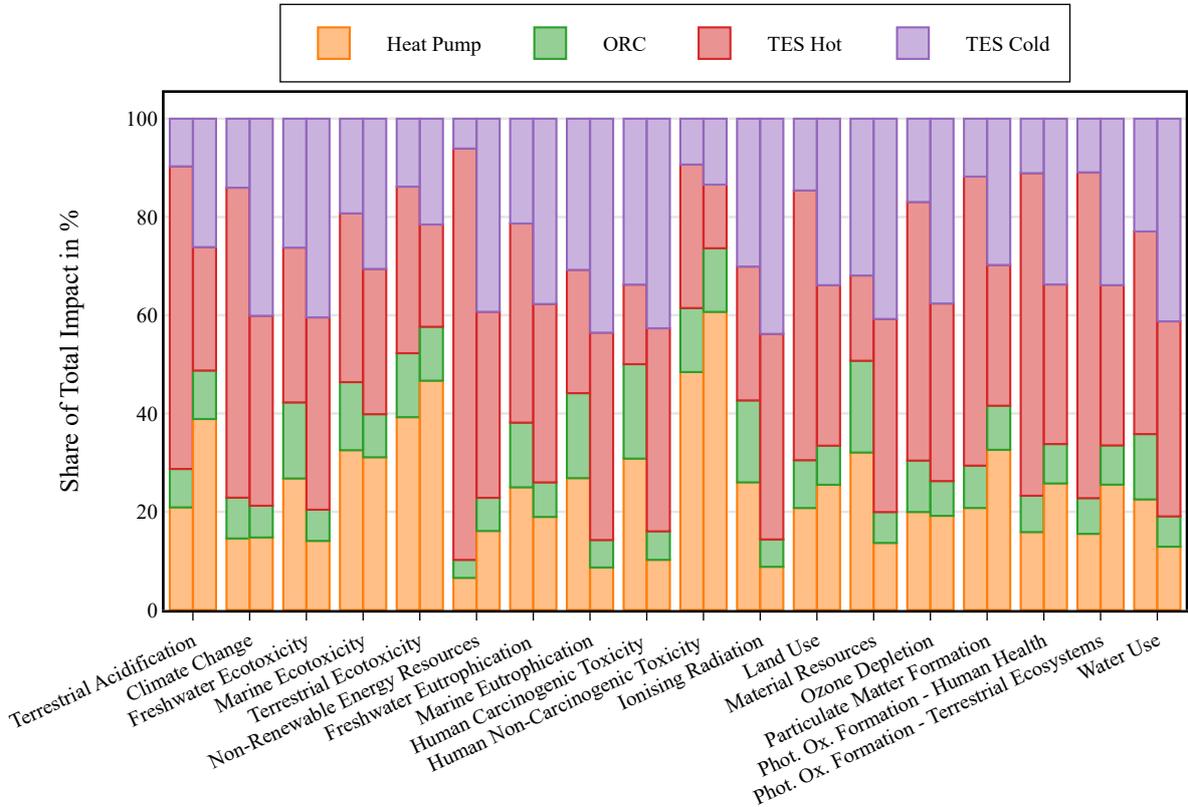


Figure 4: Component contribution per impact category of CBs using thermal oil (left bar) and water (right bar) as hot storage fluid. The total impact per category and type is normalised.

303 power rating is about three times as high as the ORC turbine power rating. Therefore, the impacts of the
 304 heat pump are expected to be higher than those of the ORC plant. This distribution of hardware impacts
 305 — with the storage system as the primary driver — is consistent with the climate change results reported
 306 by Scharrer et al. [24].

307 Between the two CBs there are three major drivers in differences. Firstly, production and processing
 308 of thermal oil is much more energy and resource intensive than the provision of water. Secondly, since the
 309 density and heat capacity of thermal oil are lower than those of water, the thermal oil CB needs larger hot
 310 storage tanks resulting in a higher steel demand. Thirdly, since the heat transfer coefficient within the heat
 311 exchangers of the heat pump and ORC plant are lower due to the thermal oil, the heat exchangers must
 312 be sized larger, resulting in an increase in steel demand. As a result, the share of the hot TES cycle is
 313 smaller for the water CB. The cold TES cycle on the other hand is similar for both CB systems. However, it
 314 accounts for a larger share of total impacts for the water CB, as the absolute impact of the other components
 315 is smaller.

316 Heat pump and ORC plant comprise the biggest share in the categories of marine and terrestrial eco-
 317 toxicity. This is mainly due to heavy metals in electronics. Heat pumps and ORC plants contain significant
 318 amounts of electronic components and copper wiring. The extraction and processing of copper releases
 319 heavy metals like arsenic, lead, and cadmium which are toxic and affect soil and terrestrial life. This effect
 320 is further amplified by the specific background data used in the assessment; the ecoinvent dataset for copper
 321 production reflects a high share of Chinese supply chains. In these regions, copper smelting and refining are

322 primarily powered by lignite-based (brown coal) electricity, leading to substantially higher environmental
323 burdens compared to regions with less carbon-intensive or cleaner energy mixes.

324 For the climate change impact category, Figure 5 breaks down the attribution of impacts to subcom-
325 ponents even further. For the water CB, the main contributor in both storage systems is the storage tank
326 and its steel use, while the impact of the water is negligible ($<1\%$). In contrast, for the thermal oil CB the
327 storage medium is the main contributor in the hot TES cycle, resulting in an increased share of the hot
328 TES cycle at component level. A similar difference is visible for the heat pump and ORC plant. While for
329 the water CB the turbomachines (compressor and turbine) account for the largest share of impacts, for the
330 thermal oil CB the heat exchangers become the largest contributor. Especially the heat pump condenser and
331 evaporator of the ORC plant are much larger to compensate for the lower heat capacity and heat transfer
332 coefficient of the thermal oil. For both CB configurations, the heat pump and ORC refrigerants only account
333 for the smallest share of environmental impacts, as both use low-GWP natural refrigerants.

334 Overall, the deterministic LCA indicates that the water-based CB achieves the lowest environmental
335 impacts in 17 of 18 impact categories. The thermal oil CB performs better than Li-ion batteries in 10
336 categories but worse than the water-based CB in all categories. Component-level analysis reveals that
337 thermal energy storage systems dominate overall impacts ($>50\%$ in most categories), with the choice of
338 storage fluid being the primary differentiator between the two CB configurations.

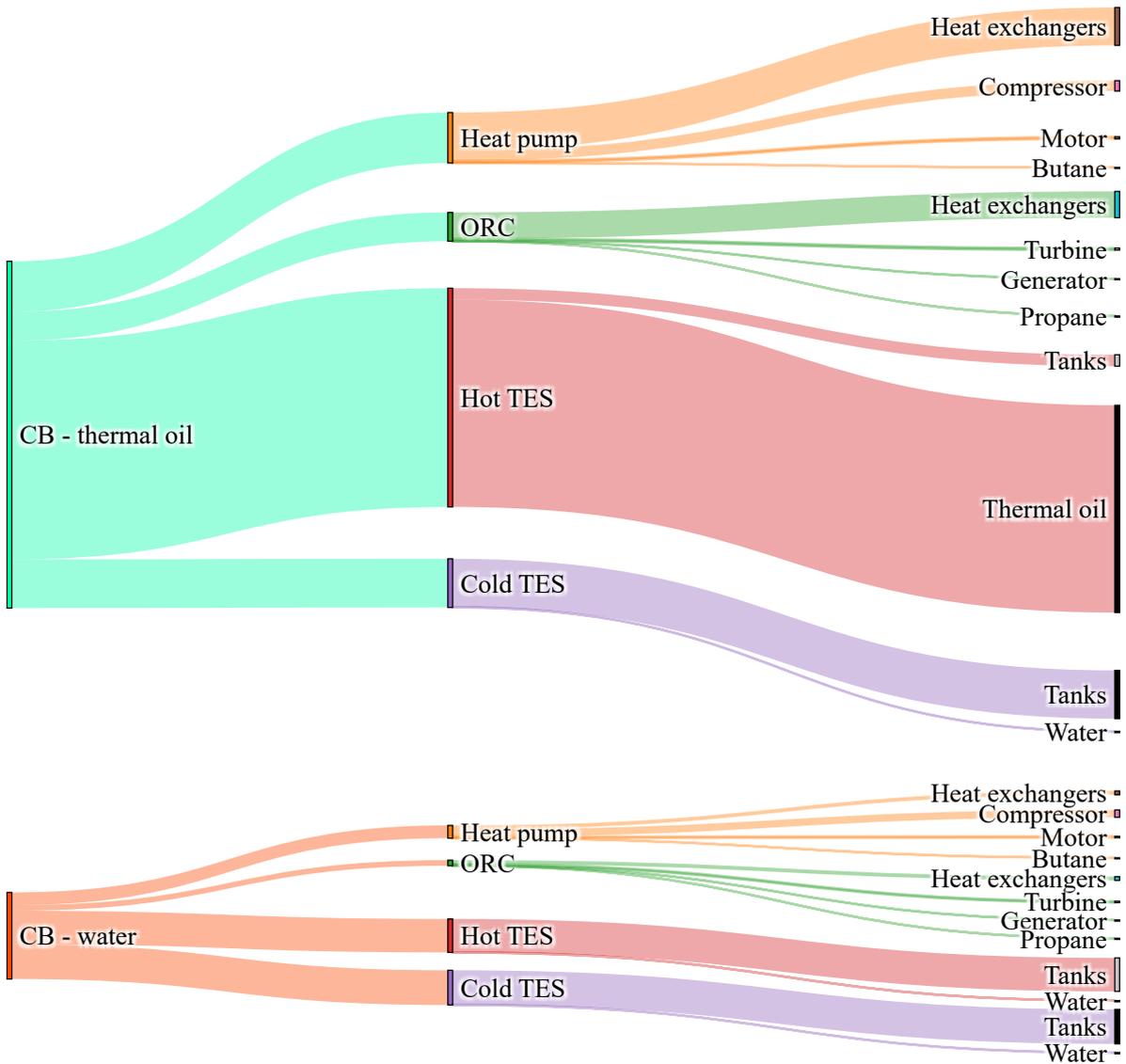


Figure 5: Sankey diagrams showing the system architecture and the environmental impact per component for both CB configurations in the climate change impact category. The widths of the connectors represents the relative contribution of each component (second node) and subcomponent (third node) of the overall system. The height of the first node is scaled to match the absolute impact of the corresponding CB configuration.

3.2. Assessment of life-cycle impacts under uncertainty

As discussed in Section 2.3, the inputs of the LCA analysis are subject to various uncertainties. This applies to both the CB and Li-ion battery process parameters such as efficiencies and specific masses and the life cycle inventories and impact parameters pulled from the Ecoinvent database. Therefore, while a purely deterministic analysis of life cycle impacts can be a useful indication of general trends, for a more robust analysis it is crucial to explicitly consider the uncertainties in the technology comparison. The following figures show the life cycle impacts of the different technologies under uncertainty, determined from the Monte Carlo study described in Section 2.3.

Figure 6 shows the range of environmental impact midpoints of the two CBs and the Li-ion battery determined from the Monte Carlo study, while Figure 7 shows the corresponding endpoints, as defined by the ReCiPe method [35]. In all cases, the impacts are normalised to the mean impact of the Li-ion battery. Note that, as explained above, the mean values of the distributions do not correspond to the deterministic case presented earlier.

The figures highlight the large uncertainties in environmental impacts across all impact categories. In all cases, the ranges of impacts from the different storage systems overlap, meaning that the worst-case impact of the system that performs best on average is higher than the best-case impact of the system that performs worst on average. If the uncertainties across different technologies were independent, no clear conclusion on the comparison between the technologies would be possible. In reality however, the uncertainties are not independent. For example, all technologies require steel and copper and inputs. Thus, if the true environmental impact of steel and copper is at the lower (or upper) end of the uncertainty range, all technologies will be affected in a similar way. Therefore, despite non-linear behaviour and different material compositions of the different technologies, it is implausible that the true environmental impact of one technology will be at the lower end of the ranges shown in Figure 6 and Figure 7 while another technology will be at the upper end. Nonetheless, inputs and processes that are unique to one system, such as Li-ion battery cell manufacturing or the thermal oil, significantly affect the overall environmental impacts, such that conclusions from Figure 6 and Figure 7 have to be drawn very carefully.

Figure 6 shows that the CB with water storage tends to have a lower acidification potential and lower marine and terrestrial ecotoxicities compared to the Li-ion battery, while the climate change impact, freshwater ecotoxicity and energy resource depletion impacts show a similar range between the two technologies. The CB with thermal oil on the other hand tends to have significantly higher climate change and energy resource depletion impacts compared to the other two technologies, with the mean values being about 3 to 5 times higher. The range acidification impacts is also slightly higher compared to the Li-ion battery and significantly higher compared to the CB with water, while the ranges of ecotoxicity impacts are comparable to those of the Li-ion battery. The differences in the ranges of freshwater and marine eutrophication impacts is smaller compared to other impact categories, though the uncertainties especially in the freshwater eutrophication are high. For both eutrophication impacts, CBs with water tend to have lower impacts than Li-ion batteries, while CBs with thermal oil tend to have higher impacts.

The uncertainties in the two human toxicity impacts are so high that it is hard to draw meaningful conclusions. Both CBs tend to have higher carcinogenic impacts than the Li-ion battery, while the ranges of non-carcinogenic toxicity impacts have extremes of $\pm 7000\%$ for the Li-ion battery, $\pm >10\,000\%$ for the CB with thermal oil, and $\pm 3000\%$ for the CB with water. All these ranges include implausible negative values. Note that these distributions are based on the uncertainty information included in the Ecoinvent database.

The CB with water has comparable ionising radiation and land use impacts as the Li-ion battery. It tends to have lower impacts in the remaining midpoint categories shown in Figure 6: material resources, ozone depletion, particulate matter formation, photochemical oxidant formation, and water use. Despite using water as thermal energy storage material, the CB with water tends to have a significantly lower water use than the other technologies, indicating that the main water consumption occurs during raw material production and intermediate processing steps. The CB with thermal oil also tends to have a lower water use than the Li-ion battery. It has a comparable material resource use, but tends to have higher impacts in the other remaining categories.

Considering the ReCiPe endpoint categories shown in Figure 7, the results show that no conclusion can be drawn regarding the comparison of human health impacts of the three technologies due to the aforementioned

391 large uncertainties in human toxicity impacts. The CB with water storage tends to have lower impacts on
392 ecosystem quality than the Li-ion battery, while the average impact of the CB with thermal oil is more than
393 twice as high as the average impact of the Li-ion battery. Regarding natural resources, the Li-ion battery
394 and the CB with water storage have similar impacts, with the CB being marginally lower on average. The
395 CB with thermal oil on the other hand has a five times as high impact on natural resources on average.

396 Overall, the results are broadly in line with the deterministic results presented in Section 3.1: The
397 CB with water storage tends to have lower environmental impacts related to construction and end-of-life
398 than the Li-ion battery, while the CB with thermal oil tends to perform worse. However, the Monte Carlo
399 analysis adds significant additional context, and the conclusions are much less clear-cut as they appear in
400 the deterministic analysis. Especially the ranges of impacts of the CB with water and the Li-ion battery
401 significantly overlap for many impact categories, such that no clear conclusion can be drawn. Depending
402 on the manifestation of the true impacts, either one can have lower environmental impacts than the other.
403 Importantly, uncertain parameters such as the specific weight of the Li-ion battery and the CB efficiency
404 can significantly impact the results, as discussed further below.

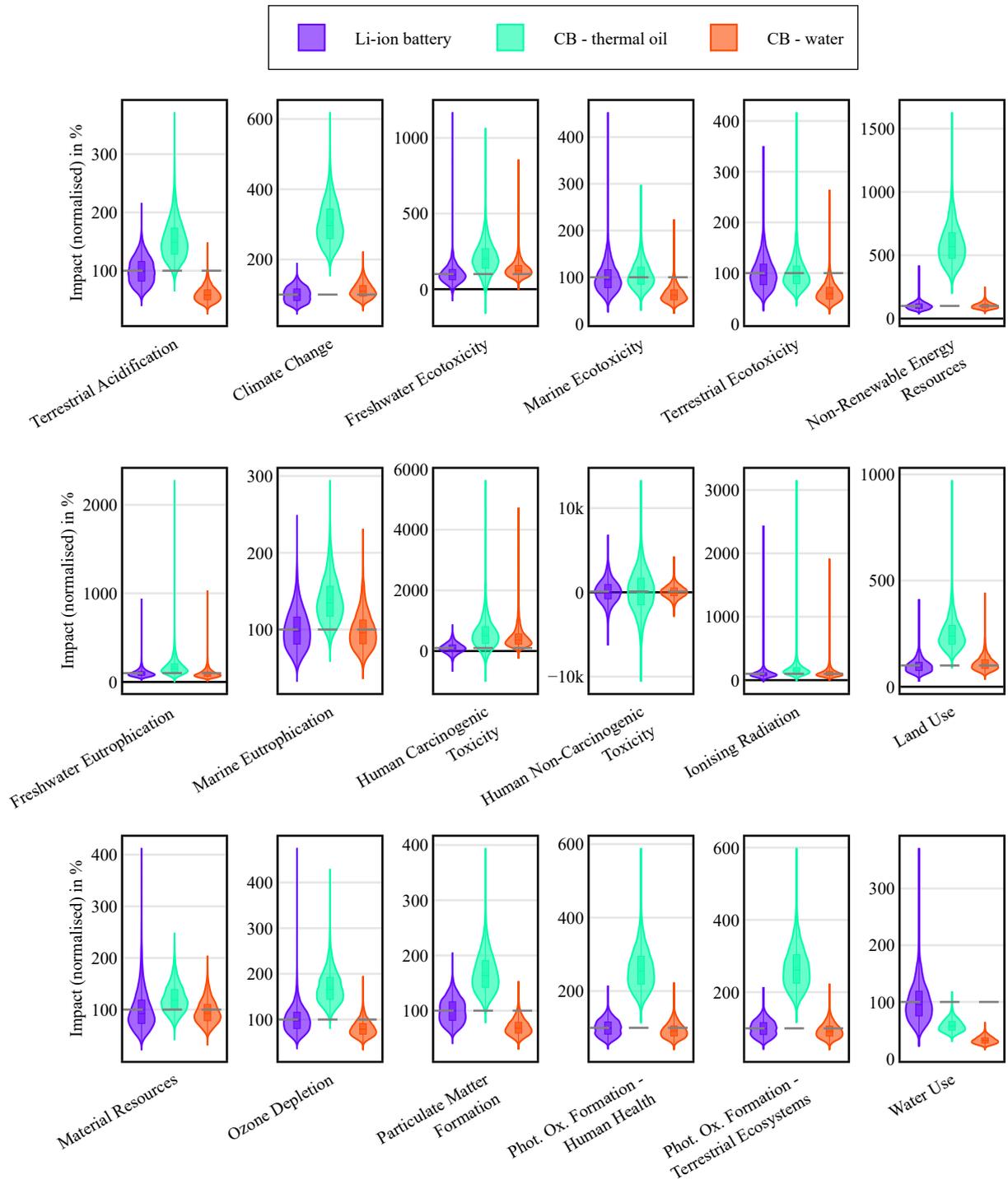


Figure 6: Environmental impacts of Li-ion battery and both CBs for the ReCiPe midpoint categories. The results are normalised to the average impact of the Li-ion battery in each category.

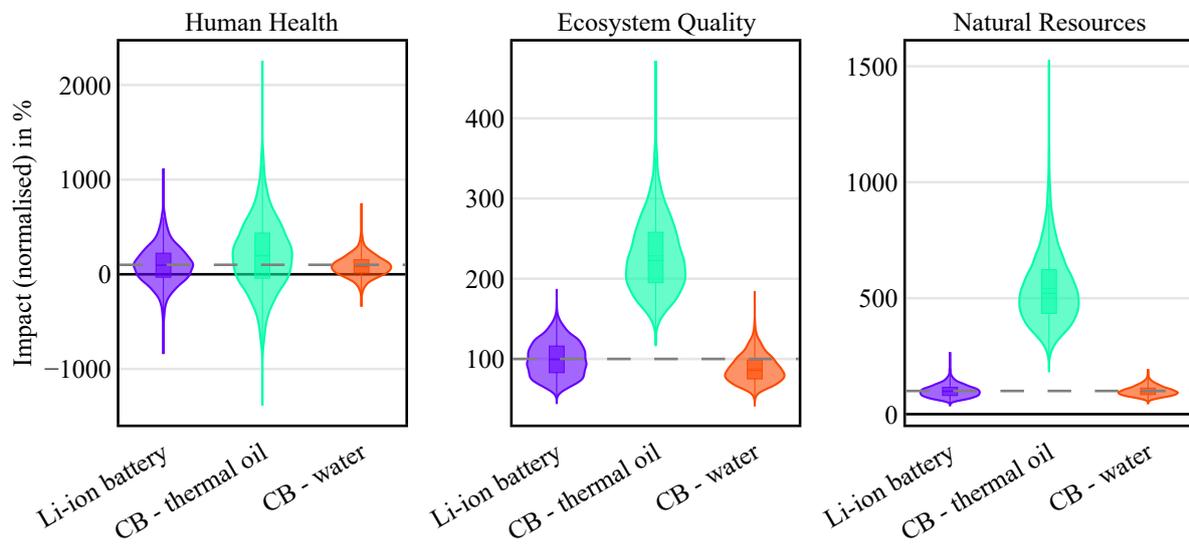


Figure 7: Environmental impacts of Li-ion battery and both CBs for the ReCiPe endpoint categories. The results are normalised to the average impact of the Li-ion battery in each category.

3.3. Impacts of different uncertain input parameters

To quantify the impact of different uncertain input parameters on the resulting environmental impacts, we calculate the Pearson correlation coefficients between the parameters and the impacts in all the different categories. Note that we only analyse the uncertain technical input parameters here (see also Table 1), as these are the parameters that we can directly influence for our technologies, while the uncertainties included in the Ecoinvent database are related to the different required activities such as e.g., steel production, rather than specific to our technologies.

The refrigerant charge is not significantly correlated with any of the ReCiPe midpoint indicators of either CB. As both are using natural refrigerants (hydrocarbons), the environmental impact of the refrigerant is low compared to the other materials used, thus, any change in refrigerant mass only has a minor impact on the overall environmental burden. Our previous analysis showed that that this is different for systems using conventional HFO refrigerants, which have large climate change impacts due to a high GWP [50].

The heat pump *COP* is significantly correlated ($p < 0.015$) with 13 of the 18 ReCiPe midpoint impact categories in case of the CB with water. However, the correlations are quite weak, with a maximum correlation coefficient of -0.19 between the heat pump *COP* and the terrestrial ecotoxicity. As shown in Figure 4 and Figure 5, the heat pump only accounts for a small share of overall environmental impacts. Moreover, unlike the ORC efficiency, the heat pump *COP* does not affect the required TES cycle sizes. A higher *COP* only means that the required thermal energy, determined by the ORC efficiency, is generated more efficiently.

The ORC efficiency is the uncertain input parameters that is the most strongly correlated with the different environmental impacts. A more efficient ORC process results in smaller environmental impacts of the ORC plant itself, but more importantly also reduces the amount of thermal energy that has to be stored, and therefore the size of the TES cycles. Figure 8 shows how the ReCiPe midpoint indicators change with the ORC efficiency, while Figure 9 shows the distributions of the endpoint indicators over the ORC efficiency. The figures show that most environmental impact indicators tend to decrease significantly even with these moderate increases in ORC efficiency, despite the uncertainty in the absolute impacts. For the CB with water storage, the ORC efficiency is strongly negatively correlated with many midpoint indicators such as the terrestrial acidification, climate change, particulate matter formation, and water use, with correlation coefficients of -0.70, -0.78, -0.72, and -0.78, respectively. Consequently, it is also strongly negatively correlated with the endpoints ecosystem quality (-0.78) and natural resources (-0.74). Only the human health shows no strong correlation due to the aforementioned enormous uncertainties in the human toxicity indicators.

Another uncertain input parameter that shows significant correlations ($p < 0.01$) with the environmental impact indicators is the recycling credit factor that determines how much material is recycled and the environmental credits for recycling. However, the correlations are only relatively weakly negative, with a minimum of -0.48 for material resources, and only -0.29 for terrestrial acidification, -0.30 for climate change, and -0.33 for particulate matter formation.

The environmental impacts of the Li-ion battery are most strongly correlated with the specific mass, i.e., the gravimetric energy density. The correlation coefficients are as high as 0.9 for climate change, 0.84 for terrestrial acidification, and 0.85 for particulate matter formation. This results in a correlation coefficient of 0.89 between the specific mass and the ecosystem quality impact of Li-ion batteries, and 0.73 between the specific mass and the natural resources impact. Reducing the specific mass and thus the material use is a very effective way to reduce the environmental impacts of Li-ion batteries.

Of the input parameters considered here, the ORC efficiency has the largest impact on the environmental impacts of the CBs. However, increasing the ORC efficiency is not straightforward and can result in various challenges as discussed in the following Section 4.

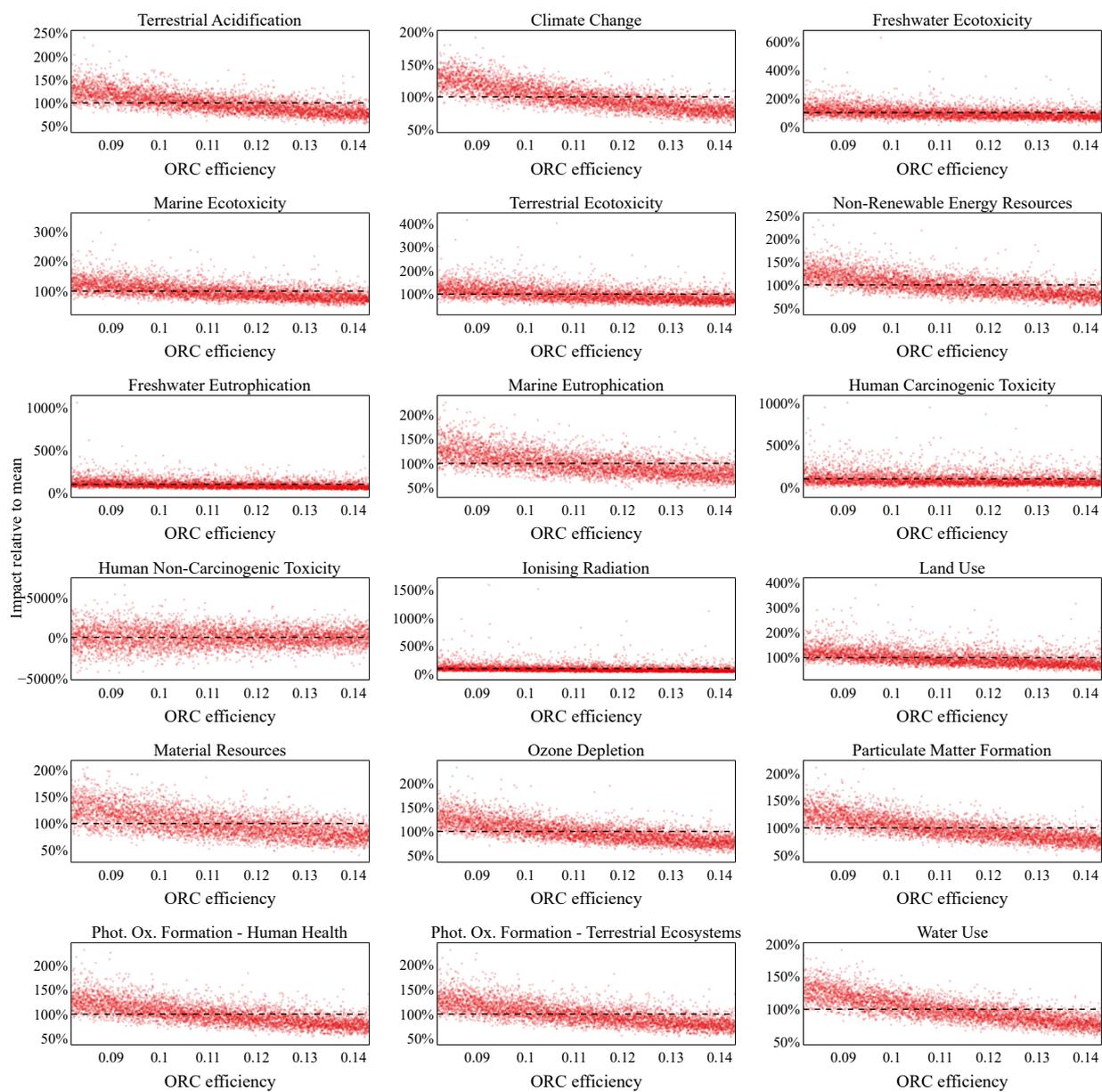


Figure 8: ReCiPe midpoint indicators determined from the Monte Carlo study plotted over the ORC efficiency, which is the most impactful uncertain input parameter considered here. All impacts are normalised to the respective mean impact.

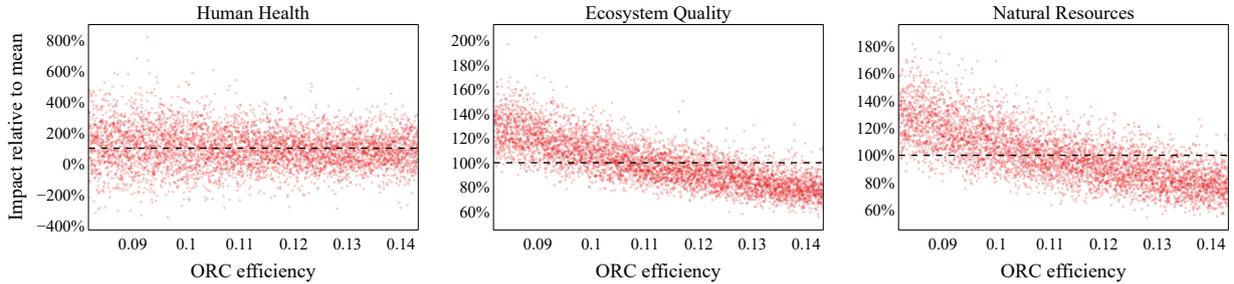


Figure 9: ReCiPe endpoint indicators determined from the Monte Carlo study plotted over the ORC efficiency, which is the most impactful uncertain input parameter considered here. All impacts are normalised to the respective mean impact.

4. Discussion

The deterministic analysis of the environmental impacts of the different electricity storage technologies suggest a clear hierarchy: water-based CBs have the lowest environmental impacts, Li-ion batteries the second lowest, and thermal oil based CBs have by far the highest environmental impact. When considering the various uncertainties in the life cycle analysis, the picture becomes less clear-cut, with overlapping environmental impact ranges between the three technologies. However, the relative ranking of the technologies seems to hold despite the significant uncertainties.

However, several caveats apply to our analysis. Firstly, and perhaps most importantly, this assessment considers only construction and end-of-life impacts. Any environmental impacts from the operational phase are excluded, as they depend significantly on assumptions regarding the electricity generation mix and demand profile, as well as the installed capacities and operational profiles of the electricity storage systems. Therefore, any results including the operational phase will always be specific to the chosen case study and assumptions. Nonetheless, CBs will always have higher environmental impacts than Li-ion batteries in the operational phase due to their poor roundtrip efficiency. The low-temperature CB systems considered here have roundtrip efficiencies in the range of 25 % to 35 %, and even in the best case of high-temperature Joule-Brayton CBs, the predicted roundtrip efficiencies are only in the range of 50 % to 75 % [6]. Li-ion batteries on the other hand reach roundtrip efficiencies of 85 % and higher [46]. Consequently, the energy losses of the CBs are much higher, meaning that more electricity has to be produced in order to achieve the same electricity output after storage. The effect on the storage size is accounted for in our analysis, as we normalise the electricity storage systems according to the discharge power rating. However, the impact of the lower roundtrip efficiency on the required electricity generation capacity and environmental impacts during the operational phase are not quantified here. These effects will disadvantage the CBs and shift the balance in favour of the more efficient Li-ion batteries.

As discussed in Section 3.3, the ORC efficiency has the largest impact on most environmental impact categories. An increase in ORC efficiency leads to significantly lower environmental impacts, mainly due to a reduction in required TES cycle sizes, which account for the largest share of environmental impacts. However, the ORC efficiency is fundamentally limited by the Carnot efficiency, η_{Carnot} , of heat engines:

$$\eta_{\text{Carnot}} = 1 - \frac{T_{\text{cold}}}{T_{\text{hot}}}, \quad (1)$$

with T_{cold} and T_{hot} being the lower and upper process temperature of the heat engine. Therefore, to increase the ORC efficiency, it is necessary to increase the storage temperature. Higher storage temperatures will inevitably lead to lower heat pump $COPs$. However, as discussed in Section 3.3, the positive effect of higher ORC efficiencies dominates, as the heat pump COP does not affect the TES cycle sizes. A much bigger challenge is the impact of higher temperatures on the TES cycle design. Our results show that CBs with water have much lower environmental impacts than CBs with thermal oil. However, to keep the water liquid, the storage pressure has to be increased in line with the temperature, which quickly becomes a difficult

485 engineering challenge and results in much larger wall thicknesses of the storage vessel and increased material
486 use. Beyond the storage vessel itself, these conditions necessitate high-specification auxiliary equipment
487 such as pumps, valves, and sealings. These components must be designed for higher pressure ratings or
488 chemical compatibility with thermal oil, which leads to increased costs and potentially higher environmental
489 burdens due to the use of specialized alloys and complex manufacturing processes. For higher temperatures,
490 the use of alternative storage media such as thermal oils or molten salts becomes inevitable. However, as
491 our analysis has shown, this leads to much higher environmental impacts in most categories. Furthermore,
492 higher storage temperatures may necessitate a shift from natural refrigerants to synthetic alternatives. While
493 this study utilizes natural refrigerants with negligible climate impact, many high-temperature applications
494 require non-natural refrigerants, such as HFOs, to ensure thermal stability and subcritical operation at
495 elevated temperatures. However, as previously noted, the use of conventional refrigerants can significantly
496 increase the climate change impact due to their high GWP, potentially offsetting the efficiency gains of
497 higher process temperatures.

498 The component breakdown analysis reveals that the refrigerant only accounts for a small share of the
499 overall environmental impacts of the CBs. Furthermore, the Monte Carlo analysis shows that the refrigerant
500 charge is not significantly correlated with the environmental impacts of either CB configuration. Our
501 previous analysis has shown that this changes significantly when considering conventional HFO refrigerants
502 as an option [50]. In that case, the refrigerants contribute a large share of the climate change impact due
503 to their high GWP. Natural refrigerants with a low GWP should be the working fluid of choice in any case.

504 The analysis presented here only considers one specific type of CB: a Rankine-based process with liquid
505 thermal energy stores. Many other configurations have been proposed, such as CBs based on Joule-Brayton
506 cycles, steam Rankine cycles, or transcritical CO₂ cycles, using either liquid or solid thermal energy stores.
507 These different configurations should be investigated in future work. Additionally, future work should
508 investigate the operational phase of CBs in comparison to other grid-scale electricity storage technologies.
509 A comprehensive analysis will require a multitude of scenarios considering different power generation mixes
510 and operational profiles of the electricity stores.

511 5. Conclusions

512 A comprehensive life cycle assessment of CBs for large-scale electricity storage has been performed,
513 comparing to commonly-proposed thermal energy storage configurations (water and thermal oil) and bench-
514 marking them against Li-ion batteries as an alternative technology. Initially, the analysis was performed
515 using deterministic input data. Then, to improve the robustness of the conclusions, uncertainties in the
516 input parameters and the life cycle inventory data were considered in a Monte Carlo study. By evaluating
517 these diverse configurations within a single, standardised framework — using consistent system boundaries,
518 functional units, and a comprehensive set of 18 impact categories — this study overcomes the methodological
519 fragmentation and limited scope identified in previous literature.

520 The deterministic results show that the CB using water as hot storage medium has the lowest envi-
521 ronmental impact, performing better than a comparable Li-ion battery in 17 out of 18 ReCiPe midpoint
522 environmental impact indicators. The CB with thermal oil as hot storage medium performs worse than
523 the one with water across all impact categories, due to two effects: firstly, the thermal oil itself has much
524 higher environmental impacts than the water; and secondly, due to its lower density and heat capacity larger
525 storage tanks and heat exchangers are required. Nonetheless, it has lower environmental impacts than the
526 Li-ion battery in 10 impact categories, though for example its climate change and freshwater ecotoxicity
527 impacts are higher. The TESs are the largest contributors to the environmental impacts in both cases.

528 Due to large uncertainties in the parameters, the conclusions from the Monte Carlo study considering
529 uncertainties are less clear-cut, with the ranges of possible impacts of the three different systems overlapping
530 for all 18 midpoint environmental impact categories and the three endpoint categories, human health,
531 ecosystem quality, and natural resources. However, the general trends observed in the deterministic analysis
532 seem to hold: the CB with water storage tends to perform best across most impact categories. Further
533 analysis revealed that, of the considered uncertain parameters, the ORC efficiency has the largest effect on
534 the environmental impacts. It determines not just the dimensioning of the ORC plant, but also the required

535 thermal energy storage capacity. Thus, increasing the ORC efficiency, for example by raising the process
536 temperatures, can be a big lever to reduce environmental impacts. However, higher temperatures also mean
537 higher pressure for the water storage, resulting in a larger steel demand. Moreover, if temperatures become
538 too high, water storage is not feasible any more and thermal oil is required, which, as discussed above,
539 results in much higher environmental impacts.

540 Finally, it is important to note that the operational phase is excluded from the analysis presented here, as
541 its environmental impacts depend heavily on the chosen scenario. However, the environmental impacts of Li-
542 ion batteries during the operational phase will undoubtedly be lower, as they achieve much higher roundtrip
543 efficiencies than CBs. Consequently, CBs require more power to be generated, and thus more low-carbon
544 power generation to be installed, in order to provide the same power output. Given the relatively modest
545 environmental benefits from the construction and the end-of-life phases presented in this work, this raises
546 the question whether CBs are indeed a viable alternative to other large-scale energy storage technologies.

547 **CRedit authorship contribution statement**

548 **Hannah Romberg:** Conceptualization, Methodology, Software, Investigation, Writing - Original Draft,
549 Visualization. **Matthias Mersch:** Methodology, Software, Investigation, Writing - Original Draft, Visu-
550 alization. **Christian Vering:** Conceptualization, Methodology, Writing - Review & Editing, Supervision,
551 Project administration, Funding acquisition. **Christos N. Markides:** Writing - Review & Editing, Supervi-
552 sion, Funding acquisition. **Dirk Müller:** Writing - Review & Editing, Supervision, Project administration,
553 Funding acquisition.

554 **Declaration of generative AI and AI-assisted technologies in the writing process**

555 During the preparation of this work, the authors used Claude Sonnet to refine the language, improve
556 readability, and assist with data visualization. After using this tool, the authors reviewed and edited the
557 content as needed and take full responsibility for the content of the publication.

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