Comparative Life Cycle Assessment of Brayton-Based Carnot 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 a Carnot battery system based on a Brayton cycle utilising argon as working fluid and an alumina-packed bed as thermal energy storage (TES) is presented. Based on a cost-optimised system for grid-scale electricity storage with a round-trip efficiency of $54\,\%$, the environmental impact is evaluated across 18 ReCiPe midpoint categories and compared to the impact of a Rankine-based Carnot battery system and a Lithium-ion battery. The analysis indicates that the Brayton Carnot batteries achieve lowest environmental impacts out of the three storage technologies in 17 out of 18 impact categories. A detailed component analysis identifies the four turbomachines as the main drivers of environmental impact, accounting for over $50\,\%$ of the overall impact.

Keywords:

Energy storage, Environmental impact assessment, Pumped-thermal electricity storage, Renewable energy, Thermo-economic optimisation.

1. Introduction

Decarbonizing energy systems requires robust grid-scale energy storage systems (ESS) to align intermittent renewable power with rigid consumption patterns. Effectively, ESSs act as the key to reducing curtailment and enhancing the utility of wind and solar assets [1]. Although, pumped-hydro storage remains the global benchmark with a $94\,\%$ share of installed capacity, the scarcity of suitable sites necessitates a shift toward more flexible technologies. In this context, lithium-ion (Li-ion) batteries and the nascent field of thermo-mechanical energy storage (TMES) are being investigated ass alternatives for large-scale, cost-effective electricity storage.

While Li-ion batteries have seen significant cost reductions [2] and widespread installation [3], TMES technologies, such as Carnot batteries (CBs), offer potentially cost-competitive and scalable alternatives without specific geographical constraints. CBs store electricity as thermal energy, which is later converted back to electricity via a heat engine. CBs differ in the choice of the thermodynamic cycle, working fluid, and storage media. Two common configurations use Rankine cycles with organic refrigerants [4] or Brayton cycles with noble gases [5]. Due to lower temperature levels, Rankine CBs often use latent or liquid sensible heat storage [6]. Brayton CBs require thermal energy storage at higher temperature levels of up to $1000\,^{\circ}\mathrm{C}$ [6] and are often realised with packed-bed sensible heat storage.

Most current research on CBs focusses on optimising the system design [7], maximising roundtrip efficiency [8] and/or minimising costs [9], and comparing different energy storage technologies on a technical and economical basis [10]. 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. Research on the environmental impact (especially beyond climate change) of CBs is relatively scarce. Existing studies limit their scope in coverage of impact categories [11, 12] and mainly focus on Rankine-based CBs [13, 14], while the environmental impact of Brayton-based CB systems has not yet been studied in detail, although they are predicted to have higher roundtrip efficiencies due to the higher temperature level.

Beyond complete CB system assessments, numerous life cycle assessment (LCA) studies on the individual components of CBs are available in the literature: heat pumps [15], thermal energy stores [16], and ORC systems [17]. However, these component-level studies cannot be simply combined to assess complete CB systems, as each study is based on different assumptions and uses different system boundaries and databases. This methodological inconsistency, combined with the limited scope of existing CB LCA studies (assessing only selected impact categories with focus on Rankine CBs) makes it difficult to draw definitive conclusions about how different CB configurations compare environmentally to alternative storage technologies such as Li-ion batteries.

To adress these research gaps, this study conducts a comprehensive life cycle assessment of a Brayton CB and compares the results to Rankine CBs and Li-ion batteries. Section 2. details the methodology and the specific Brayton CB system under investigation, Section 3. presents the result and Section 4. provides a brief discussion of the results and limitations of our analysis. Finally, Section 5. concludes this paper.

2. Methodology

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 Section 2.3. presents the life cycle inventory data.

2.1. Carnot battery system description

This section briefly explains the CB concept investigated in this paper. The investigated system is a Joule-Brayton cycle with packed bed thermal energy stores modeled based on the work of Zhao et al. [10] and Mersch et al. [18]. A schematic of the process is shown in Figure 1.

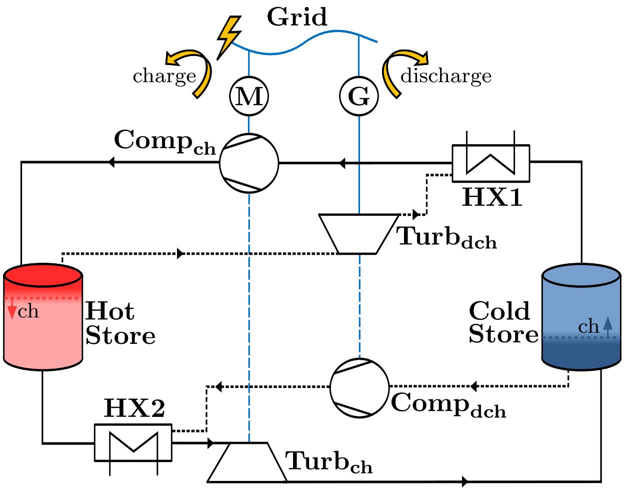

Figure 1: Flow sheet of the investigate Joule-Brayton Carnot battery based on Zhao et al. [10]. The system consists of two packed bed thermal stores, two compressors (comp), two turbines (turb) and two heat exchangers (hx). To charge (ch) the Carnot battery the process runs counterclockwise (solid lines). To discharge (dch) the Carnot battery the process runs clockwise (dotted lines).

During charging, cold working fluid is compressed using grid electricity. The hot compressed working fluid then passes trough the hot store, transferring heat to charge it. Inside the hot store the thermocline moves down as the store is being charged. The working fluid is then cooled against ambient air and expanded in a turbine, reaching temperatures well below the ambient temperature. The cold working fluid then passes through the cold store, cooling it down to charge it. While the cooled store is being charged its thermocline moves upwards. The still cool working fluid is then preheated by gaining heat from the ambient air before it is compressed again. To discharge the Carnot battery, the cycle runs in the other direction. The working fluid is expanded from the upper temperature level and compressed from the colder temperature level, such that the power provided by the expansion of the working fluid is higher than the power needed for the compression, allowing for electricity to be exported to the grid. Due to the different temperature levels and fluid densities, the process requires a total of four turbomachines: a hot compressor and cold turbine for charging, and a cold compressor and hot turbine for discharging.

The CB is designed and investigated for a use case of daily storage originally proposed by Henchoz et al. [19]. The system is charged at a constant rate for 8 hours, and then discharged, also at a constant rate, for 16 hours. In line with Zhao et al. [10], the maximum allowable temperature, which is reached at the compressor outlet during charging, is set to $850\,\mathrm{K}$, while the minimum allowable temperature is $123\,\mathrm{K}$. Argon is used as the working fluid and alumina as the storage medium, since these materials were identified as leading to the best performance of the CB [10].

It should be noted that the case study chosen here is just one example of the broad application range of CB systems, which can strongly vary, for example in power input, capacity or cycle time [20]. While this study focuses on a specific grid-scale use case, the impact of varying operational specifications — such as variable charging/discharging times — on the resulting environmental profile remains a subject for systematic investigation in future work.

2.2. Life cycle assessment of Carnot batteries

This study analyses the environmental impacts of a Brayton CB and compares them to a Rankine CB and a Li-ion battery using the LCA method presented by Romberg et al. [13], which was developed in accordance with ISO 14040 [21]. The system boundaries include the production of CBs components, including upstream processes, *e.g.*, the provision of materials and energy, as well as the end-of-life phase. This study does not include emissions related to the operational phase, as they depend heavily on assumptions on the (future) electricity generation mix and the operating profile of the CB. Focusing on the environmental burden of the physical infrastructure, the functional unit is defined as the provision of $16\,\mathrm{MW\,h}$ of storage capacity over a lifetime of 30 years to allow for an equal comparison between both CB configurations and the Li-ion battery. For the assumed operational profile this equals a discharge power of $1\,\mathrm{MW}$ for the CB. The implications of excluding the operational phase from the LCA are discussed in Section 4..

For the life cycle impact assessment (LCIA), the ReCiPe method was applied at midpoint level, following the recommendations of the International Reference Life Cycle Data System Handbook [22]. The ReCiPe method provides a consistent framework that links midpoint impact categories to endpoint damage categories across three areas of protection: human health, ecosystem quality, and resource availability [23].

2.3. Life cycle inventory

All life cycle inventory (LCI) data for materials and energy used to produce the CBs and the Li-ion battery was obtained from the Ecoinvent database version 3.11 [24], using the cut-off system model. The cut-off system model applies an attributional approach where recyclable materials are available burden-free to recycling processes, and only primary production carries environmental burdens. This approach avoids double-counting of recycling benefits while maintaining mass and energy balances within the system. The environmental impacts of each material or energy flow needed in this study is scaled by the required amount to supply the functional unit defined in Section 2.2..

The LCA modeling was conducted using the Brightway framework version 2.5 [25], an open-source Python-based software platform for advanced life cycle assessment calculations. The Brayton CB is modelled using a component-wise approach as shown in Figure 2. Each major subsystem (charge cycle, discharge cycle, hot and cold TES) is modelled individually.

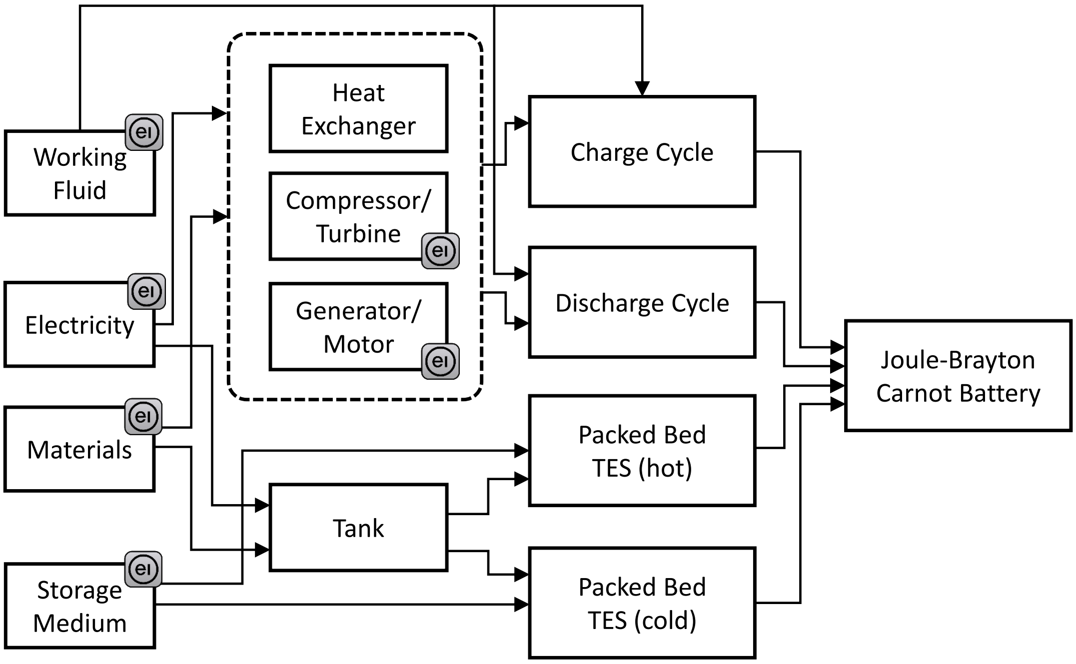

Figure 2: Component-wise CB modelling approach. The components marked with the EI label are modelled directly as Ecoinvent processes, while the others are modelled via their material use (e.g., steel).

The charging and discharging cycles consist of a compressor and a turbine each, for a total of four turbomachines. All of them are modelled using the Ecoinvent dataset of a $10\,\mathrm{MW}$ gas turbine, assuming that compressors and turbines have a similar environmental impact. The electric motors of the compressors and the generators of the turbines are modelled using the Ecoinvent dataset for a $200\,\mathrm{kW}$ generator. Heat exchangers are modelled based on their mass, assume that they are made of low-alloyed steel, while the environmental impact of the working fluid Argon is modelled directly using Ecoinvent. The hot and cold store are also modelled based on their mass, assuming low-alloyed steel construction, and the mass of the storage medium, Alumina, which is modelled via the corresponding Ecoinvent market activity.

The sizes of the different components are determined from a thermo–economic optimisation, using comprehensive Matlab models for TMES systems as described in our previous publications [26, 18]. The optimisation is performed for a $10\,\mathrm{MW}$ storage system to ensure reasonable sizes of the turbomachines. The environmental impacts are then scaled down to match the functional unit defined above. Using quasi steady-state assumptions, consecutive charging and discharging cycles are simulated until stable operation is reached to ensure that the results are independent of the assumptions on the initial state. The design of the process is optimised for maximum roundtrip efficiency subject to technical constraints, as described by Mersch et al. [18].

The model yields results such as the power ratings of all compressors and turbines, as well as the sizes of the packed bed stores, which are required as inputs to the LCA modelling. Based on the results of the Matlab optimisation model, the mass of the heat exchangers is estimated based on the technical specifications of the Güntner GF series for finned-tube heat exchangers [27]. The required mass of low-alloyed steel for the storage vessels is calculated using the method described by Seider et al. [28], accounting for the required wall thicknesses to ensure sufficient pressure resistance. The working fluid mass is estimated from the volume of both storage vessels, with the vessels being the biggest volumina inside the system. The resulting system design is summarised in Table 1. Finally, the plant assembly as well as the manufacturing of the subcomponents is accounted for by using the generic Ecoinvent datasets for metalworking. The lifetime of the CB is assumed to be 30 years [29].

Table 1: Optimised design of the Brayton CB configuration. For the LCA, the impacts are scaled linearly to match the functional unit of a discharge power of $1\,\mathrm{MW}$ over a discharge time of $16\,\mathrm{h}$.

Parameter	**Brayton CB**
Power output	$11.4\,\mathrm{MW}$
Roundtrip efficiency	$54.4\,\%$
Compressor power (ch)	$58.5\,\mathrm{MW}$
Turbine power (ch)	$19.7\,\mathrm{MW}$
Compressor power (dch)	$8.3\,\mathrm{MW}$
Turbine power (dch)	$16.5\,\mathrm{MW}$
Heat exchanger 1 steel mass	$240\,\mathrm{kg}$
Heat exchanger 2 steel mass	$490\,\mathrm{kg}$
Argon mass	$4000\,\mathrm{kg}$
Hot TES steel mass	$805\,000\,\mathrm{kg}$
Hot TES alumina mass	$2\,793\,000\,\mathrm{kg}$
Cold TES steel mass	$135\,000\,\mathrm{kg}$
Cold TES alumina mass	$4\,595\,000\,\mathrm{kg}$

The environmental impact of the Brayton CB is compared to the impacts of a Rankine CB with water storage and a Li-ion battery. Both benchmark systems are modelled as described by Romberg et al. [13]. For the Li-ion battery, the lifecycle impact varies depending on the cathode chemistry, with the two most common ones being Lithium Nickel Manganese Cobalt Oxide (NMC) and Lithium Iron Phosphate (LFP) [30]. Following Romberg et al. [13], we consider LFP batteries for this study due to their generally lower environmental impacts and will refer to them simply as Li-ion battery for the rest of the study. The Li-ion battery is modelled using the corresponding Ecoinvent dataset for the LFP Li-ion battery market. The dataset's functional unit is 1 kg of battery. To convert this to our energy-based functional unit, we assume a gravimetric energy densities of $140\,\mathrm{W\,h\,kg^{-1}}$ for the Li-ion battery [13]. The lifetime of the Li-ion battery is assumed to 15 years [31]. To account for the shorter lifetime, two Li-ion batteries are required for the provision of the functional unit. For a detailed system description and analysis of the Rankine CB we refer to our previous publication [13].

Besides manufacturing and assembly, we include the end-of-life phase, which is modelled by including recycling processes, recycling efficiencies, and recycling credits per material. The recycling efficiency determines the share of a material that is successfully recovered and reprocessed. Steel recycling is modelled using the electric arc furnace Ecoinvent process, while Li-ion battery recycling is modelled using the Ecoinvent market activity for used Li-ion batteries. The energy demands and environmental impacts of these processes are accounted for. Finally, recycling credits are given for avoiding primary extraction, according to the recycling credit factor. This factor accounts for recycled material already included in the primary process to avoid double-counting, and for the fact that recycled material cannot substitute primary material like-for-like.

3. Results

To provide a quantitative scale for the environmental impacts, the absolute results for all three storage systems across the 18 ReCiPe midpoint categories are detailed in Table A1 in the appendix. These values serve as the underlying data for the comparison presented in this section. The normalised results of the LCA for all storage systems are depicted in Figure 3. The figure shows the environmental impacts for all midpoint impact categories defined by the ReCiPe method, normalised to the respective impact of the Li-ion battery.

Among the 18 midpoint impact categories, the Brayton CB achieves the lowest environmental impacts in all but the human non-carcinogenic toxicity impact category, where the Rankine CB achieves a marginally lower environmental impact. However, as noted in the Ecoinvent database documentation, this specific impact category is subject to order-of-magnitude uncertainties, rendering definitive technology rankings unreliable without further characterisation. In comparison to the Li-ion battery, the Brayton CB achieves consistently lower environmental impacts across all impact categories, indicating a significant environmental advantage for the Brayton CB when considering the production and end-of-life phases. For example, the climate change impact of the Brayton CB is 67 % lower compared to the Rankine CB. The main reason for this reduction is the lower steel demand of the storage vessels, which can be explained by two main factors: (1) instead of four storage vessels, only two are required for the Brayton CB due to switch from liquid two-tank systems to packed-bed TESs with a direct heat transfer between the working fluid and the storage material; and (2) smaller storage vessels due to a higher temperature lift resulting in a higher volumetric energy density of the store.

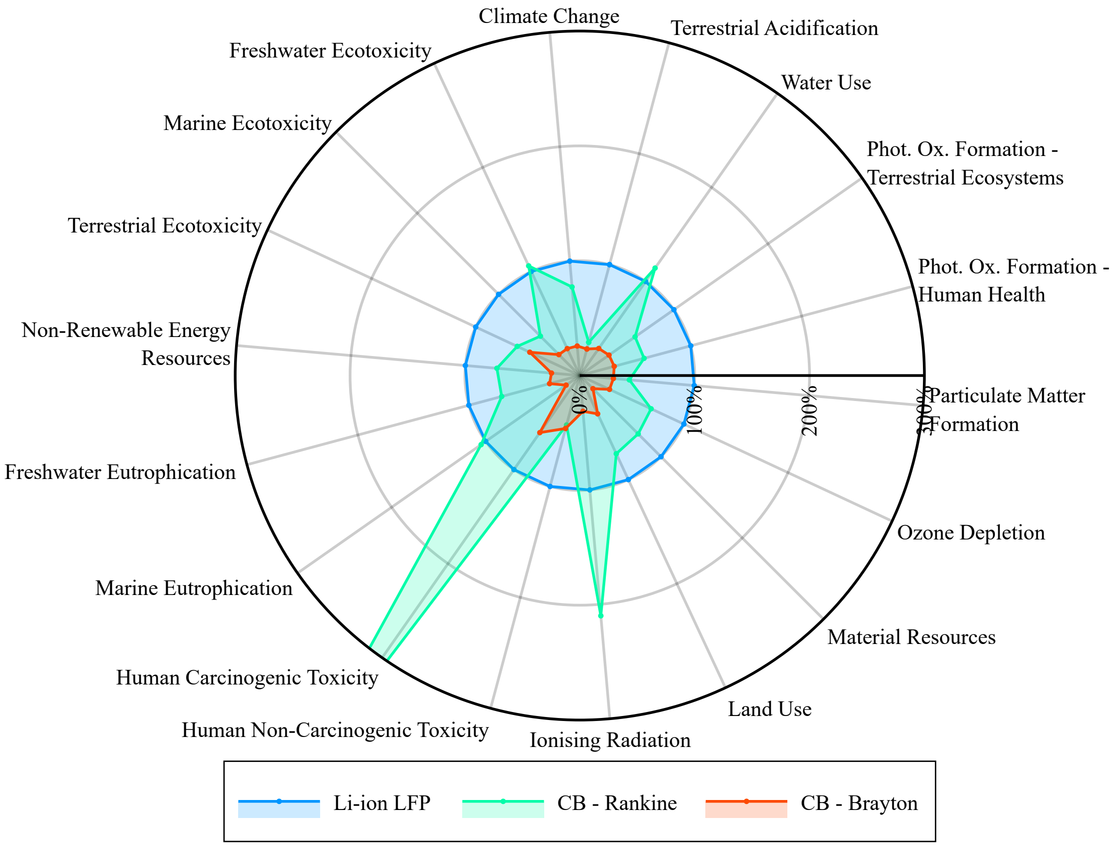

Figure 3: Comparison of the two CB configurations and the Li-ion battery for all midpoint impact categories. The results are normalised to the impacts of the Li-ion battery.

To identify the main causes of environmental impacts, Figure 4 shows a component-level breakdown of the environmental impacts across all midpoint impact categories. The main contributors are the turbomachinery and both packed-bed TESs, while the impacts of both heat exchangers and the working fluid is negligible. For all but two categories, the turbomachines are the main contributors (>50 %), with the turbine and compressor used for charging consistently accounting for a larger share than the machines used for discharging. Since the roundtrip efficiency is below 1, the charging cycle has a higher power rating than the discharging cycle. In the impact categories marine eutrophication and ionising radiation, the cumulative share of both TES systems accounts for roughly 55 % of the total impact. The dominance of the TES units in these categories is directly linked to the high alumina demand and the associated nitrogen emissions.

Comparing the shares of the cold and the hot TES, the share of the cold TES exceeds the share of the hot TES in 16 out of 18 categories. The cold store holds approximately 1.6 times as much alumina as the hot store due to different available temperature lifts and thus different volumetric energy densities. Nevertheless, due to temperature and pressure requirements, the hot storage vessel requires approximately 6 times as much steel as the cold storage vessel. However, the mass of alumina acts as the primary driver of environmental impacts, explaining the bigger share of the cold TES.

The total share of all turbomachinery is the highest for the categories of terrestrial ecotoxocity and human non-carcinogenic toxicity. This is mainly due to the use of copper and electronic components. Electric generators and motors contain significant amounts of electronic components and copper wiring. The extraction and processing of copper releases heavy metals like arsenic, lead, and cadmium which are toxic and affect soil and terrestrial life. This effect is further amplified by the specific background data used in the assessment; the Ecoinvent dataset for copper production reflects a high share of Chinese supply chains. In these regions, copper smelting and refining are primarily powered by lignite-based (brown coal) electricity, leading to substantially higher environmental burdens compared to regions with cleaner energy mixes.

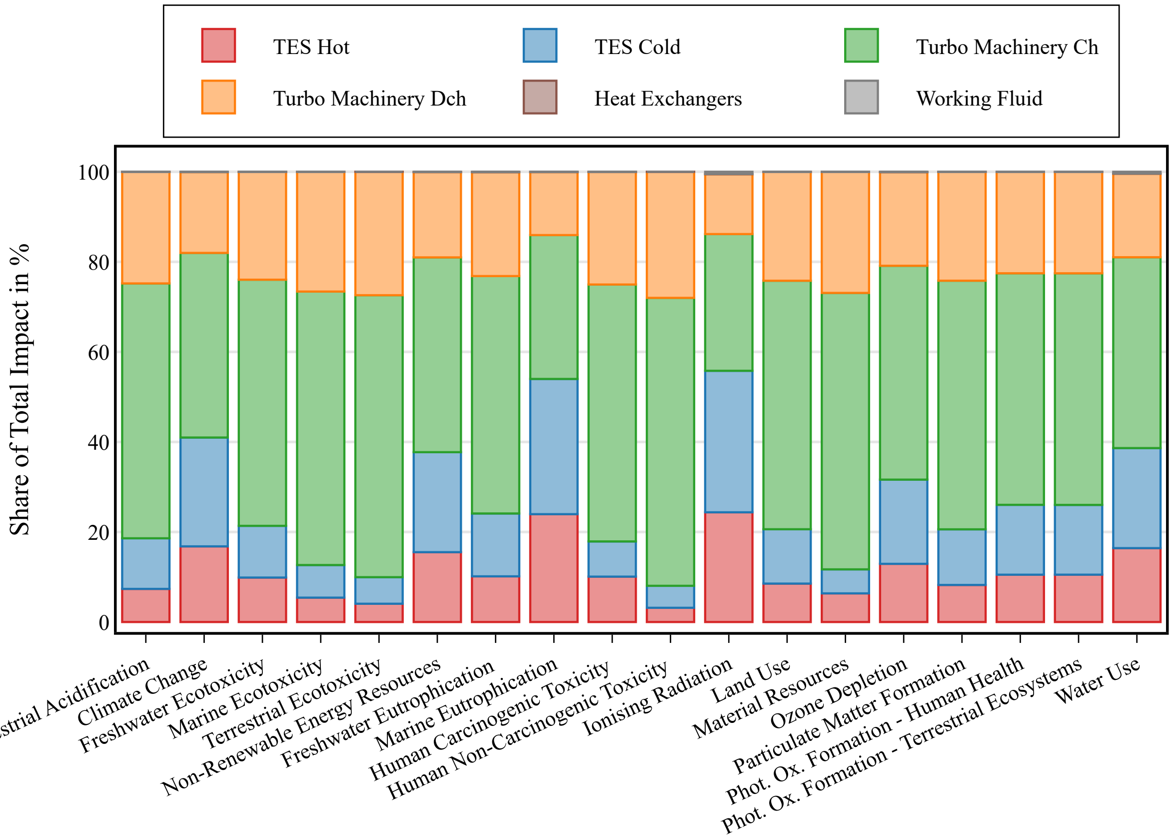

Figure 4: Component-wise breakdown of contributions to each environmental impact category for the Brayton CB, distinguishing between turbomachines for charging (ch) and discharging (dch). The total impact per category is normalised.

For the climate change impact category, Figure 5 breaks down the attribution of impacts to subcomponents even further. The main contributor is the alumina in the cold TES, followed by the hot compressor for the charge cycle. The share of the charge cycle is approximately twice as big as the share of the discharge cycle due two the asynchronous operational profile and the roundtrip efficiency being below 1. Within the charge cycle, the compressor dominates, while the impact of the discharge cycle are dominated by the turbine.

Comparing these results to the results for a Rankine CB presented by Romberg et al. [13], we see that the TES systems, which were the main driver for Rankine CB, become less impactful for Brayton CBs due to the increased volumetric energy density achieved by the higher temperature differences. Overall, the LCA indicates that Brayton CBs outperform Rankine CBs and Li-ion batteries during construction and end-of-life phases from a purely environmental perspective, with the Brayton CB showing the lowest environmental impacts in 17 out 18 impact categories. Component-level analysis reveals that the total turbomachinery impact dominates the overall impact (>50 % in most categories), while the alumina used as storage medium has the biggest individual impact.

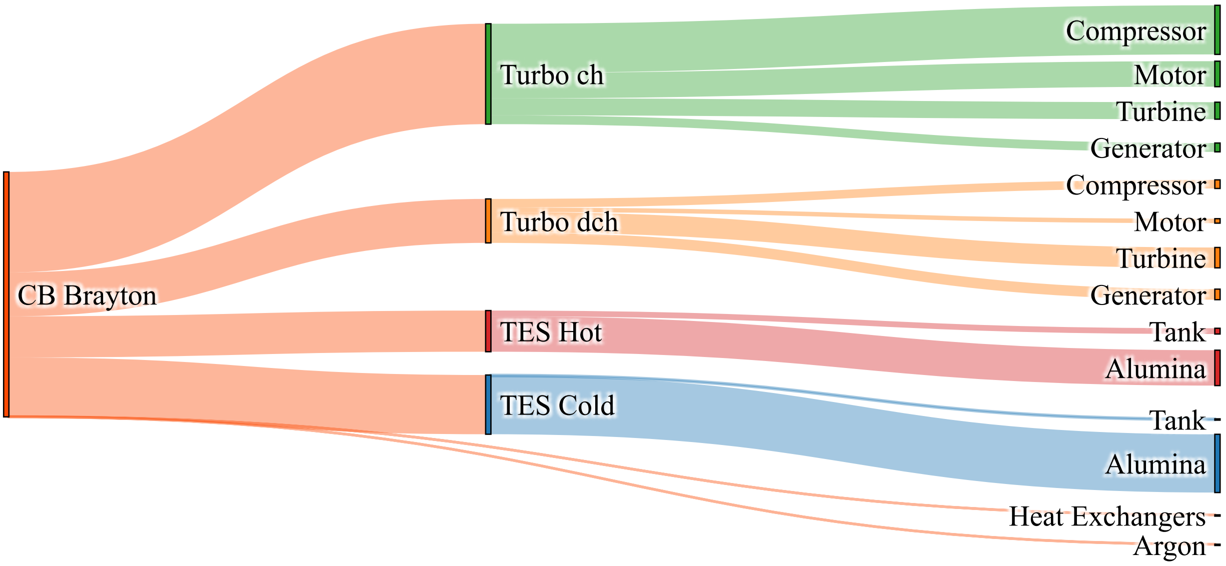

Figure 5: Sankey diagram showing the system architecture and the environmental impact per component for the Brayton CB configurations in the climate change impact category. The widths of the connectors represents the relative contribution of each component (second node) and subcomponent (third node) of the overall system.

4. Discussion

The presented deterministic analysis of the environmental impacts of different electricity storage technologies suggest a clear picture: Brayton CBs have the lowest environmental impacts compared to Rankine CBs and Li-ion batteries. 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 worse roundtrip efficiency. The roundtrip efficiencies of the Brayton CBs considered here are estimated to be in the range of 50 % to 75 % [29], while the roundtrip efficiencies of Rankine CBs fall in the range of 25 % to 35 % [29]. Li-ion batteries on the other hand reach roundtrip efficiencies of 85 % and higher [31]. 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 based on 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. Nonetheless, Brayton CBs will perform better than Rankine CBs, as they can achieve higher roundtrip efficiencies.

Secondly, the parameters of the CBs and the Li-ion battery, as well as the LCI data and the resulting environmental impacts are subject to significant uncertainties. Our previous study on Rankine CBs [13] has demonstrated that overlapping uncertainty intervals — particularly in toxicity and resource-related categories — can significantly diminish the statistical significance of strict technology rankings. According to Igos et al. [32], next to uncertainties in numerical data from Ecoinvent process data, uncertainties in modelling assumptions and methodological choices may play a significant role. In this Brayton CB configuration, several parameters and modelling assumptions could severely influence the results. Firstly, the considered system design results from a theoretical thermo-economic optimisation. Any degradation in turbo machinery performance would impact the component sizing and therefore the resulting environmental impact. Secondly, the steel demand for the high-temperature pressure vessels is calculated based on idealized thermomechanical load. Variations in safety factors or vessel geometries could lead to substantial changes in the total steel mass. Consequently, while the Brayton CB shows a promising deterministic advantage, a comprehensive uncertainty analysis — e.g., using a Monte Carlo approach — would be required to refine and contextualise the findings presented in this work.

5. Conclusion

A comprehensive life cycle assessment of a Brayton CB for large-scale electricity storage is presented. The results are benchmarked against Rankine CBs and Li-ion batteries as alternative technologies. The key findings of the comparison are:

- Brayton CBs show the lowest environmental impact in 17 out of 18 impact categories.
- Turbomachines account for the largest share of environmental impacts of the Brayton CB.
- The storage medium, alumina, has biggest individual impact.
- The impact of the working fluid, argon, and of the heat exchangers are negligible.

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Appendix

Table A1: Absolute impact scores in the 18 ReCiPe midpoint categories for all investigated storage systems.

Impact Category	Unit	Brayton CB	Rankine CB	Li-ion Battery
Terrestrial Acidification	kg SO_2-eq	8.98e+03	1.13e+04	3.75e+04
Climate Change	kg CO_2-eq	8.40e+05	2.52e+06	3.26e+06
Freshwater Ecotoxicity	kg 1,4-DCB-eq	1.54e+03	6.26e+03	5.94e+03
Marine Ecotoxicity	kg 1,4-DCB-eq	1.03e+04	1.93e+04	3.99e+04
Terrestrial Ecotoxicity	kg 1,4-DCB-eq	1.63e+07	2.04e+07	3.39e+07
Non-Renewable Energy Resources	kg oil-eq	2.14e+05	6.26e+05	8.64e+05
Freshwater Eutrophication	kg P-eq	6.24e+01	1.61e+02	2.29e+02
Marine Eutrophication	kg N-eq	2.18e+01	1.57e+02	1.50e+02
Human Carcinogenic Toxicity	kg 1,4-DCB-eq	2.66e+04	1.87e+05	4.38e+04
Human Non-Carcinogenic Toxicity	kg 1,4-DCB-eq	2.31e+06	2.15e+06	4.83e+06
Ionising Radiation	kBq U235-eq	3.45e+03	2.32e+04	1.10e+04
Land Use	$m^2 \cdot$ a crop-eq	4.26e+04	8.71e+04	1.16e+05
Material Resources	kg Cu-eq	1.12e+05	4.97e+05	6.92e+05
Ozone Depletion	kg CFC11-eq	2.99e-01	7.17e-01	1.05e+00
Particulate Matter Formation	kg $PM_{2.5}$-eq	3.29e+03	4.85e+03	1.12e+04
Phot. Ox. Formation - Human Health	kg NMVOC-eq	3.28e+03	6.13e+03	1.06e+04
Phot. Ox. Formation - Terrestrial Ecosystems	kg NMVOC-eq	3.38e+03	6.40e+03	1.09e+04
Water Use	m^3	6.11e+03	2.42e+04	2.12e+04

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