Comparative life cycle assessment of lithium-ion battery chemistries for residential storage

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Abstract

Residential storage deployment is expected to grow dramatically over the coming decade. Several lithium-ion chemistries are employed, but the relative environmental impacts of manufacturing them is poorly understood. This study presents a cradle-to-gate life cycle assessment to quantify the environmental impact of five prominent lithium-ion chemistries, based on the specifications of 73 commercially-available battery modules used for residential applications. Three impact categories are analysed (global warming potential, cumulative energy demand and mineral resource scarcity) across two functional units (storage capacity and lifetime energy delivered). Environmental impact depends more on cycling frequency than chemistry choice, and none of the battery chemistries convincingly outperforms the others. Cells only constitute a third to a half of the environmental impact, which is comparable to the inverter. Routes to making residential lithium-ion battery systems more environmentally benign include reducing the reliance on cobalt, nickel and copper, increasing the specific useable energy, developing comprehensive recycling initiatives, and maximising the utilisation (cycle frequency) once in operation.

Highlights:

- Life cycle assessment of five lithium-ion battery chemistries for residential storage
- Cycling frequency matters more than choice of chemistry for lifetime impacts
- Frequent cycling substantially reduces environmental impact per energy delivered
- If cycled more than twice a day, NCO-LTO achieves lowest environmental impact
- The inverter accounts for 25-46% of the battery system's global warming potential

Glossary

BMS:	Battery management system
CED:	Cumulative energy demand
EDOEI:	Energy delivered on energy invested
GWP:	Global warming potential
CO_2e:	CO_2 equivalent
LCI:	Life cycle inventory
LFP-C:	Lithium iron phosphate ($LiFePO_4$) cathode active material with graphite anode active material
LMO-C:	Lithium manganese oxide ($LiMn_2O_4$) cathode active material with graphite anode active material
MRS:	Mineral resource scarcity which represents the surplus cost potential in USD
NCA-C:	Lithium nickel cobalt aluminium oxide ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$) cathode active material with graphite anode active material
NCO-LTO:	Lithium nickel cobalt oxide ($LiNi_{0.8}Co_{0.2}O_2$) cathode active material with lithium titanite oxide ($Li_4Ti_5O_{12}$) anode active material
NMC-C:	Lithium nickel manganese cobalt oxide ($LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$) cathode active material with graphite anode active material

1 Introduction

Lithium-ion batteries formed four-fifths of newly announced energy storage capacity in 2016, and residential energy storage is expected to grow dramatically from just over 100,000 systems sold globally in 2018 to more than 500,000 in 2025[1]. The increasing prominence of lithium-ion batteries for residential energy storage[2-4] has triggered the need for comparison in terms of the environmental impact potential of the different chemistries in use. Batteries can maximise the use of intermittent renewable energy by storing the excess of production and redelivering it when needed. High specific power and energy[5] make lithium-ion one of the most promising technologies currently available for residential energy storage along with other contexts such as businesses and renewable power plants[6,7]. There is a range of lithium-ion battery chemistries, using different active materials in the cathodes and anodes. This study focuses on the most commonly used in residential energy storage, namely: LFP-C, NMC-C, NCA-C, LMO-C and NCO-LTO.

In the past decade, life cycle inventories have been developed for the manufacturing of lithium-ion batteries which has facilitated the modelling of their environmental impacts. Most notably, Zackrisson et al.[8] and Majeau-Bettez et al.[9] produced LCIs for the LFP-C, Notter et al.[10] for the LMO-C, Bauer[11] for the NCA-C and LFP-LTO and Majeau-Bettez et al.[9] and Ellingsen et al.[12] for the NMC-C. Most current research focuses on batteries used in electric vehicles[13], with relatively few studies looking at their environmental performance in stationary applications. For example, Hiremath et al. showed a general lithium-ion battery has a better lifetime global warming potential than other electrochemical technologies[14]. No studies appear to have considered the environmental performance of residential lithium-ion batteries using the specifications of commercially-available systems.

Peters et al.'s meta-analysis[13] has shown the wide range in results obtained by previous lithium-ion LCAs which used different values for the specific energy and cycle life. Later work has attempted to make these LCAs more comparable by standardising impact assessment methods, system boundaries, and assumptions around the composition of the batteries and their manufacturing[15]. Many other features have often been neglected though, such as the influence of the calendar life, the number of times the batteries are cycled each day, self-consumption, capacity retention, and the necessity of – and uncertainty around – a battery inverter. Furthermore, the environmental impacts of high cycle life batteries using an LTO negative electrode is rarely investigated[13].

Barnhart and Benson[16] investigated the primary energy demand of a range of energy storage technologies. Their metric of energy stored on energy invested could be further developed by including the energy used to charge the batteries during their lifetime.

The objective of the study is to explore the relative environmental impacts of the most commonly used chemistries in residential energy storage across a range of cycling intensities which reflect realistic operational requirements. Chemistries with lower environmental impacts should be identified, as they may warrant privileged support levels as investments in residential energy storage scale up. Differences in technical performance may mean that no one chemistry is 'best', and their relative environmental impacts will be application-specific. This study also aims to highlight the pollution hotspots common to all chemistries in current residential battery systems and assess the energy efficiency of those systems.

After this introduction and literature review, the next section summarises our methodology, covering the scope, data sources, assumptions and functional units used in this LCA. Section 3 presents and discusses our results, focusing in turn on the three metrics we consider: the global warming potential (GWP) and mineral resource scarcity (MRS) per unit of storage capacity and per unit of lifetime energy delivered, and the energy delivered on energy invested (EDOEI). Finally, section 4 summarises the main conclusions of the study.

2 Methodology

2.1 Scope definition

The focus of the study is on lithium-ion battery systems used for residential application. The nominal capacity of these products usually ranges from 1 to 15 kWh, but modules are stackable and can be scaled up to hundreds of kWh using either many regular-sized inverters or fewer larger ones[17].

This study adapts the best-available LCIs for lithium-ion batteries to the manufacture of commercially-available residential battery modules. These LCIs are predominantly for electric vehicles which do not require the same cooling mechanism as batteries used in households, among other differences. Residential battery modules include cells containing the positive and negative electrodes, the electrolyte, a separator and the cell container. A battery management system and the module casing are then added to form the battery module. A liquid cooling system, a fan, an LCD

screen and a cabinet are outside the scope of this study, because only some manufacturers include these components (see Supplementary material B section 1).

A cradle-to-gate approach was chosen (Figure 1), taking into account the materials input, energy input, infrastructure requirements, transportation and waste outputs[18]. Battery maintenance was accounted for but the impact of the electricity feeding the batteries was not, since this could be generated from a range of sources and varies significantly around the world and over time[19]. This allows our results to be applied internationally, regardless of regional electricity mix. Total environmental burdens of providing storage services are then the sum of our results plus the impacts of the electricity used to charge the cells. The end-of-life stage is not modelled because the field of recycling lithium-ion batteries is still nascent. It is unclear whether pyrometallurgy, hydrometallurgy, biometallurgy or more mechanical treatments will become dominant[20-22]. Furthermore, the absence of detailed life cycle inventories for the recycling of each chemistry means the end-of-life stage cannot be modelled with confidence.

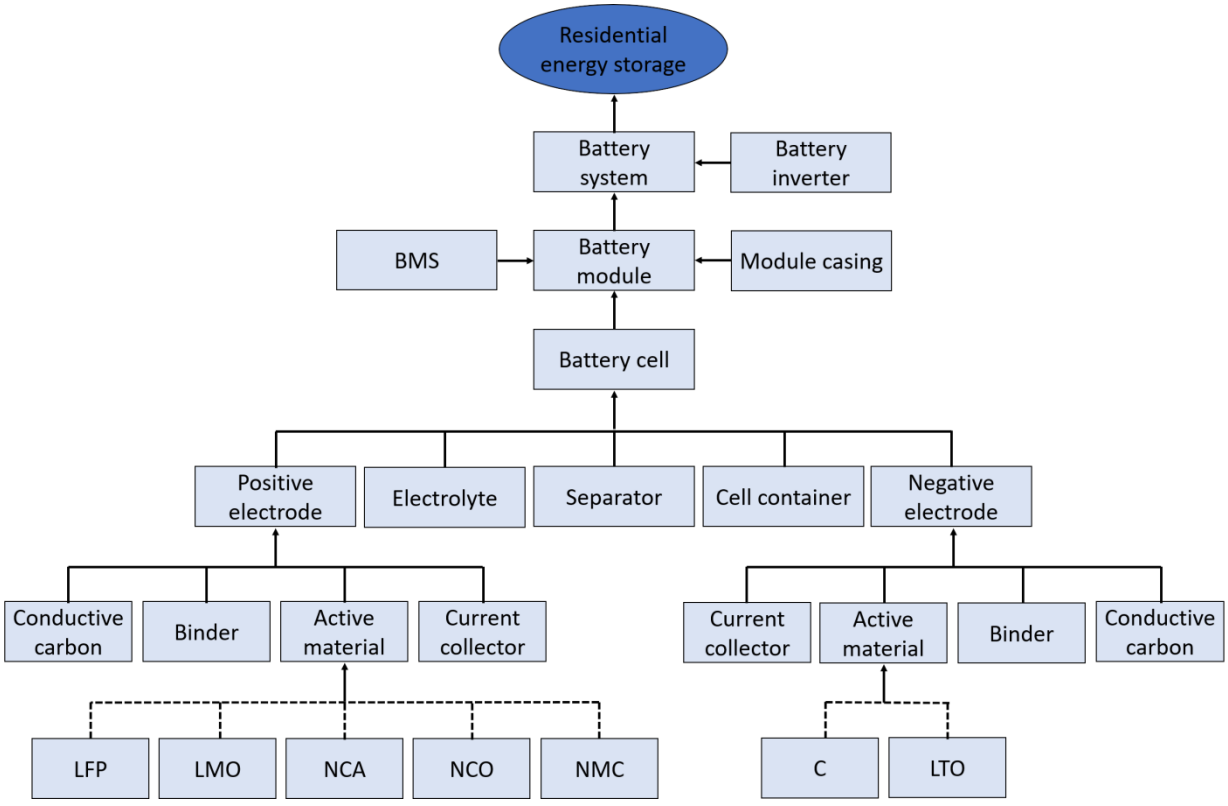

Figure 1: Simplified flow diagram of manufacturing steps for components used in residential lithium-ion battery systems. The electrode combinations investigated in this study are the LFP-C, LMO-C, NCA-C, NCO-LTO and NMC-C. LFP: Lithium iron phosphate ($LiFePO_4$); LMO: Lithium manganese oxide ($LiMn_2O_4$); NCA: Lithium nickel

cobalt aluminium oxide ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$); NCO: Lithium nickel cobalt oxide ($LiNi_{0.8}Co_{0.2}O_2$); NMC: Lithium nickel manganese cobalt oxide ($LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$); C: Graphite (C); LTO: Lithium titanite oxide ($Li_4Ti_5O_{12}$); BMS: Battery management system.

2.2 Data sources for battery composition and manufacturing

The methodology used to determine the mass ratios of the components inside the batteries is inspired from Notter et al.'s[15] work. The mass ratio of the components constituting the LFP-C cells were determined from the mean of Zackrisson et al.[8] and Majeau-Bettez et al's[9] LCI. The LMO-C cells use Notter et al.'s[10] LCI, and the NCA-C's cell uses Bauer's[11]. NCO-LTO cells are derived by combining Bauer's[11] NCA-C and LFP-LTO. Finally, the mass ratio of the NMC-C's cell is determined using the mean of Majeau-Bettez et al.[9] and Ellingsen et al.'s[12] works.

Some components of the batteries needed to have their materials, manufacturing and proportions within the cell standardised over all modelled batteries in order to obtain comparable results for their LCA. As in Peters et al.'s study[15], the same manufacturing processes across all chemistries is assumed for the positive and negative electrodes' binders and current collectors, the electrolyte's carbonate solvent and lithium ions, and the separator all the while preserving their characteristic difference in mass proportions within the cells. The cell container, BMS, and module casing were modelled using Ellingsen et al.'s LCI[12]. As in Notter et al.'s study[15], their mass was made proportional to the mass of the components inside the battery cell as the mass of the packaging and electronics is assumed to correlate with the amount of cell materials required by battery chemistries to achieve a certain storage capacity. The mass of the battery module and the mass proportion of its cells were determined using the information in the datasheets of commercially-available residential lithium-ion batteries. The cell is estimated to comprise 72.5% of the mass of the battery module compared to 76.7% in Notter et al.'s study[15] which unified the mass ratios of electric vehicle batteries of different chemistries. The mass of a 5 kW battery inverter was determined using the datasheets of commercially-available bidirectional inverters which do not include a maximum power point tracker. The LCI for the inverter comes from Tschümperlin et al.'s solar inverter[23]. This study assumes their LCI can apply to a residential battery inverter as both products consist of a transformer, electronic components as control units, a case and some connectors[24]. The 5 kW solar inverter's mass was scaled to the average mass of a 5 kW bidirectional battery inverter: 23.8 kg. A battery inverter with a power rating of 5 kW is expected to suit most residential applications. The carbon intensity of the electricity used to manufacture the battery systems is the same as in previous studies. The life cycle inventories used for each step of the manufacturing can be found in Supplementary material A, sections 3 to 8.

2.3 Data sources for battery technical specifications

The data sheets and installation manuals of commercially-available lithium-ion battery modules were analysed to determine the active materials used in their electrodes (see Supplementary material B section 1). Data sheets also detailed the performance information of both the battery modules and the inverters. When a manufacturer did not reveal a parameter, the chemistry's average was used. In total, 38 LFP-C, 2 LMO-C, 4 NCA-C, 2 NCO-LTO and 26 NMC-C battery modules used for residential application were identified and analysed. All the batteries were scaled to hold 8.1 kWh of initial usable storage capacity, as this is the market-wide mean across all systems (see Supplementary material B section 1). In accordance with the prevailing value in battery manufacturers' data sheets and warranties, at their last cycle, the batteries in this study store 60% of their initial capacity compared to 80% for electric vehicle batteries in Peters et al.'s[13] study. When the manufacturer does not state the storage capacity retention associated to the battery module's cycle life, a value of 60% was assumed (Table 1).

Table 1: Mean technical specifications of the commercially available lithium-ion battery systems analysed. C-rate: Coulomb rate

Parameters	Symbol	LFP-C	LMO-C	NCA-C	NCO-LTO	NMC-C
Number of battery modules analysed		38	2	4	2	26
Nominal capacity (Wh)	ε_{nom}	9200	9000	10400	8100	9200
Depth of discharge (DoD)	D	88%	90%	78%	100%	88%
Cycle life expectancy at <60% (cycles)	λ	7016	5840	9281	30000	7043
Average lifetime capacity retention	χ	80%				
Calendar life (years)	Y	19	15	21	20	18
C-rate (h^{-1})		0.70	0.61	0.81	1.00	0.60
Battery charge efficiency	η_{bat_cha}	98%	99%	97%	95%	98%
Battery discharge efficiency	η_{bat_dis}	98%	99%	97%	95%	98%
Battery's power consumption (W)	P_{bat}	6				
Inverter AC → DC efficiency	$\eta_{inv\_AC\rightarrow DC}$	96%				
Inverter DC → AC efficiency	$\eta_{inv\_DC\rightarrow AC}$	95%				
Inverter's power consumption (W)	P_{inv}	12				
Inverter's calendar life (years)	None	21				

2.4 Battery cycling scenarios

The consideration of cycling scenarios is crucial in determining the battery system's lifetime relative to its calendar life and cycle life expectancy, and so three battery cycling scenarios were investigated. First, the batteries are fully cycled once every two days, corresponding to a scenario where the user

does not use the battery very intensively, perhaps due to an overestimated energy storage need or low solar/wind power generation[25]. Second, the batteries are cycled once a day, corresponding to the expected cycling a normal user would make of the batteries, charging them during the day and discharging them from the evening until the morning[26]. Finally, the residential batteries are cycled intensively at a rate of 4 times a day which could correspond to their use in grid balancing which is a service already offered by some battery manufacturers in residential use cases[27]. Wind turbines, frequency regulation, load levelling, and energy arbitrage also require frequent discharges[28].

2.5 Functional units

Two functional units are considered. The environmental impact per usable storage capacity is able to convey the performances of the batteries in terms of specific energy. This functional unit is useful when considering the battery's environmental impact at the moment of purchase or if it is not expected to be cycled intensively.

Secondly, the environmental impact per lifetime energy delivered, is more comprehensive as it also accounts for the cycle and calendar lives as well as the battery's discharge efficiency and the inverter's DC to AC efficiency. The lifetime energy delivered is calculated as follows:

$$\varepsilon_{\mathrm{del}} = \varepsilon_{\mathrm{nom}} * \mathrm{D} * \lambda * \chi * \eta_{\mathrm{bat\_dis}} * \eta_{\mathrm{inv}\ DC \rightarrow AC} - \mathrm{S}$$

Where ε_{nom} is the initial nominal capacity, D is the depth of discharge (ε_{nom} * D = 8.1 kWh) and λ is the number of cycles the battery can complete before reaching less than 60% of its initial storage capacity. The cycle life expectancy of a given chemistry varies depending on the cycling scenario given the limited calendar life. χ is the lifetime-average usable capacity, considering a linear battery degradation down to 60% of the initial usable storage capacity[29] (and thus χ = 80%). η_{bat_dis} is the battery's discharge efficiency and $\eta_{inv\_DC \rightarrow AC}$ is the inverter's DC to AC efficiency. S is the self-consumption due to the battery system's operation. It is calculated as follows:

$$S = \frac{(P_{bat} + P_{inv}) * t * \lambda}{n}$$

P_{bat} is the battery's power consumption, P_{inv} is the inverter's power consumption, t is the amount of time in a day and n is the number of times the battery is cycled each day.

2.6 Energy delivered on energy invested

An additional metric, the energy delivered on energy invested, is inspired from Barnhart and Benson's energy stored on energy invested[16] and shows the ratio between the energy the battery is able to deliver during its lifetime and the energy required for its manufacturing:

$$EDOEI_{w/o\ charge} = \frac{\varepsilon_{\mathrm{del}}}{\varepsilon_{\mathrm{emb}}}$$

ε_{emb} is the embodied energy of manufacturing the battery system, determined from the cumulative energy demand impact category. EDOEI disregards the energy used to charge the batteries, thus, a second way to present the EDOEI includes the lifetime energy used to charge the batteries in the denominator, giving a more comprehensive way to look at the energy storage efficiency:

$$EDOEI_{w/\ charge} = \frac{\varepsilon_{\mathrm{del}}}{\varepsilon_{\mathrm{emb}} + \varepsilon_{\mathrm{cha}}}$$

ε_{cha} is the lifetime energy used to charge the batteries, calculated as follows:

$$\varepsilon_{\mathrm{cha}} = \frac{\varepsilon_{\mathrm{nom}} * \mathrm{D} * \lambda * \chi}{\eta_{inv_{AC \rightarrow DC}} * \eta_{bat_{cha}}}$$

$\eta_{inv\_AC->DC}$ is the inverter's AC to DC efficiency and η_{bat_cha} the battery's charge efficiency.

2.7 Impact categories

Three impact categories are considered in this work: global warming potential (GWP), mineral resource scarcity (MRS) and cumulative energy demand (CED). These were derived using the ReCiPe Endpoint (H) V1.13 / World ReCiPe H/A method available within the SimaPro software.

Global warming potential was calculated using the IPCC 2013 GWP 100a method, measured in kg CO_2-equivalent[30]. This takes a 100-year time horizon, implying that the GWP of methane and nitrous oxide are 28 and 265 times greater than that of CO_2 respectively.

Mineral resource scarcity was determined using the endpoint method in ReCiPe which uses surplus cost potential, measured in 2013 US Dollars[30]. This quantifies the increase in the cost of future mineral extraction, caused by taking some resources from the environment and thus depleting the quantity and quality of remaining resources[46].

Cumulative energy demand was used for calculating EDOEI, and was measured using the Cumulative energy demand V1.10 method in units of MJ.

3 Results and discussion

3.1 Battery composition

The active material in the positive electrode is the main differentiator between the chemistries. It represents 11% to 23% of the total battery systems' mass. The NCO-LTO cell ($LiNi_{0.8}Co_{0.2}O_2$ - $Li_4Ti_5O_{12}$) is the only one with a negative electrode which does not use graphite as an active material, and has a relatively low specific capacity and a nominal voltage of only 2.3 volts compared to 3.4 V for LFP-C ($LiFePO_4$ - C), 4.1 V for LMO-C ($LiMn_2O_4$ - C), and 3.7 V for NCA-C ($LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$ - C) and NMC-C ($LiNi_{0.4}Mn_{0.4}Co_{0.2}O_2$ - C)[31]. This explains why an NCO-LTO battery module is heavier than the other chemistries for the same usable storage capacity (see Figure 2). The NMC-C battery module exhibits the highest specific usable energy, followed closely by NCA-C, LFP-C, LMO-C and NCO-LTO. This ranking, which is based on the performance specifications from the data sheets of commercially-available battery modules, is consistent with theoretical and experimental expectations[31].

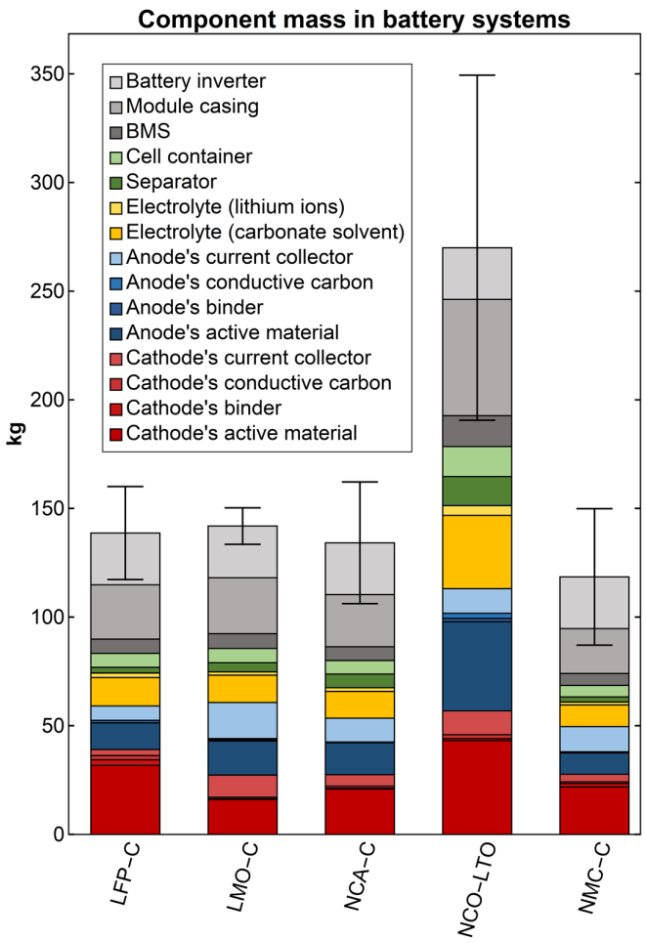

Figure 2: Component mass in battery systems capable of holding 8.1 kWh of usable storage capacity. Higher values are a result of the battery cell's lower specific energy. The error bars represent the standard deviation in relation to the distribution of performances achieved by the manufacturers of battery modules of a same chemistry in our sample. BMS: Battery management system.

The material composition of each battery has an important influence on its environmental impacts, and while there is broad similarity, there is some heterogeneity among the battery chemistries (see Figure 3). It is notable that lithium forms a relatively low percentage of the batteries, and other metals (aluminium, copper and nickel) form a much larger share.

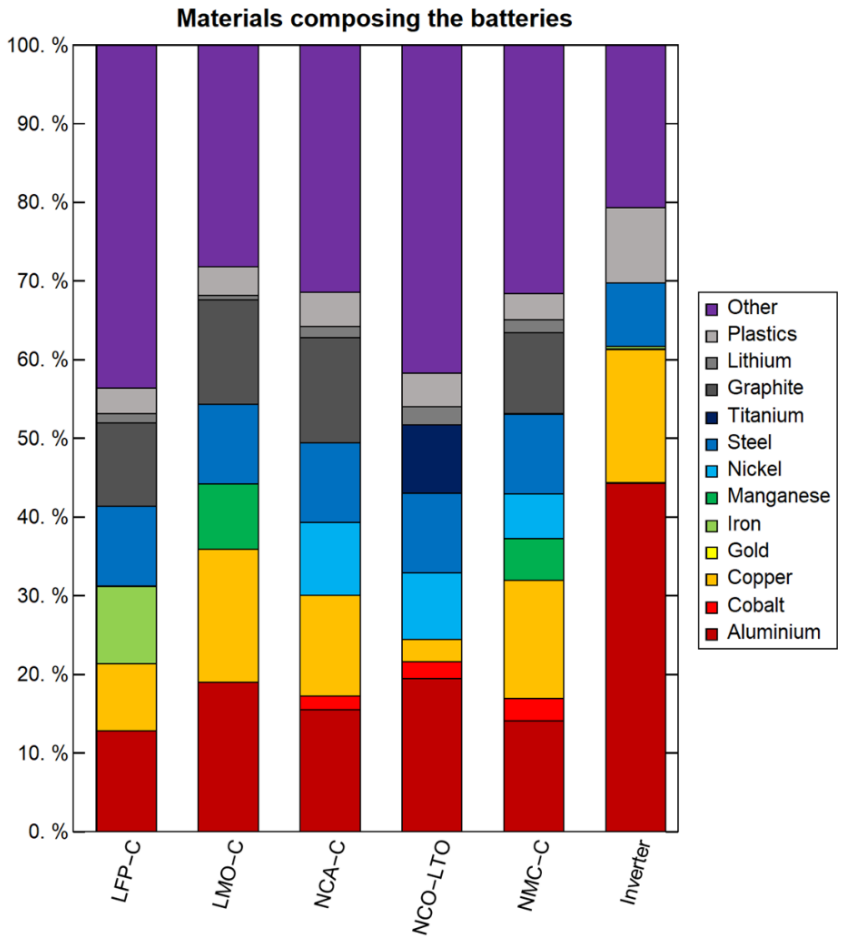

Figure 3: Material composition of the battery modules and the inverter. The twelve materials with highest mass percentage (averaged across all chemistries) are shown, with bright colours signifying metals.

3.2 Environmental impact per usable storage capacity

Since the batteries have similar compositions, their specific energy is an important driver for their environmental impact per unit of usable storage capacity. Naturally, the use of rare metals inside the positive electrode's active material drives the mineral resource scarcity impact but makes little difference in terms of global warming potential and cumulative energy demand. The inverter, which has a fixed mass, has the same contribution for each chemistry.

Across battery chemistries, the cell is responsible for at least a third of the global warming potential (Figure 4a), and the battery module which encapsulates the cells for at least half of it. The battery inverter is responsible for up to half of the global warming potential (GWP) mainly because of the energy required for its integrated circuit, inductor and printed wiring board. Energy use during production is the main driver for the global warming potential therefore the cumulative energy

demand gives the same ranking amongst chemistries as the GWP (see Supplementary material A section 2.2). As the carbon intensity of the electricity used to manufacture the batteries decreases, their GWP could decrease substantially.

NMC-C, LFP-C, LMO-C and NCA-C have a similar global warming potential, respectively 201, 217, 220 and 225 kg CO_2e/kWh of usable storage capacity (see Supplementary material B section 4). Owing to low voltage of individual cells, NCO-LTO has almost twice the impact of the others in terms of GWP (407 kg CO_2e/kWh) because of its high mass per storage capacity. NCO-LTO requires many more cells than other chemistries to reach the same storage capacity. This is expected the be similar for other cathode chemistries used alongside LTO[32]. The high mass of the constituents of its NCO positive electrode and its subsidiary components give the NCO-LTO the highest impact in mineral resources scarcity (MRS) at purchase (Figure 4b). Henckens et al.[33] estimate global reserves of titanium dioxide to last 10,000 years, making its use in the battery's negative electrode not too problematic in terms of MRS. NCA-C and NMC-C exhibit significant impact due to the cobalt and nickel they use, whereas LFP-C has the lowest MRS impact per usable storage capacity, followed by LMO-C. In addition, the presence of 5 grams of gold in the inverter's integrated circuit, cumulated with components like capacitors and the copper and steel the inverter uses give the inverter a significant MRS impact.

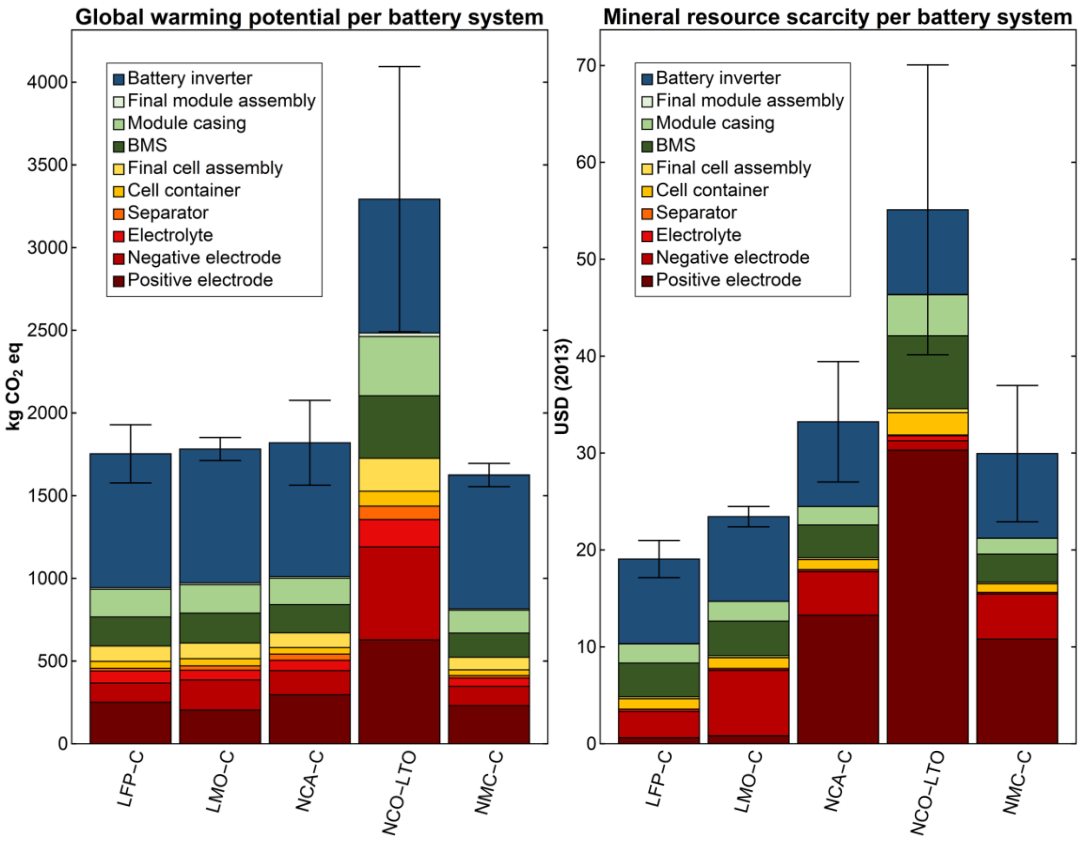

Figure 4: Global warming potential (left) and mineral resource scarcity (right) contribution from different components of an 8.1 kWh residential battery system. Higher values indicate higher ecological impact. The error bars represent the standard deviation across the distribution of performances reported by the manufacturers of battery modules of a same chemistry in our sample. BMS: Battery management system.

In terms of MRS, the use of copper in the negative electrode's current collector is more problematic than its aluminium counterpart in the positive electrode (Figure 5a). Sources estimate there are between 60 and 130 years of copper reserves at current extraction rates, compared to between 1000 and 20,000 years for aluminum[33,34]. The final assembly and transportation of the components in the active materials have an important contribution in terms of GWP.

If the relatively low mineral resource scarcity of the LFP, LMO and LTO's active materials (Figure 4b) is taken into account, the use of lithium, iron, phosphate and manganese in a battery's positive electrode does not pose issues in mineral resource scarcity. For example, the high amount of manganese in LMO is less problematic than if it were cobalt or nickel. Titanium dioxide is the main impact contributor of the LTO active material but only poses a problem in terms of global warming potential. The nickel content of the NCA, NCO and NMC active materials is very high, up to 50% for

the NCA and NCO. Nickel causes 60% to 72% of the compounds' GWP and 43% to 67% of its mineral resource scarcity impact. Estimates for nickel reserves range from 90 to 330 years[33,34].

Although the amount of cobalt in NCA, NCO and NMC active materials is around 10%, it causes between 10% and 20% of the compound's global warming potential and a minimum of 30% of its mineral resource scarcity impact (Figure 5b). Cobalt is not currently scarce, estimated to last 2,000 years[33], however, average annual cobalt prices more than doubled[35] in 2017. The sudden surge in demand is led by battery manufacturers who consume 42% of the world's cobalt production, which coupled with sluggish investment has led the supply to lag behind the demand[33,35]. In addition, 58% of cobalt mining comes from the Democratic Republic of the Congo[35] which is a geopolitical influence on market price[33]. Cobalt is a by-product of copper mining[33] and its extracting and processing costs are relatively high[36]. Significant stress would be put on cobalt reserves if the battery industry continues to grow with it as an important constituent. However, some mining projects with a high output potential such as Katanga, owned by Glencore, have come to a completion and could alleviate some of this stress[36].

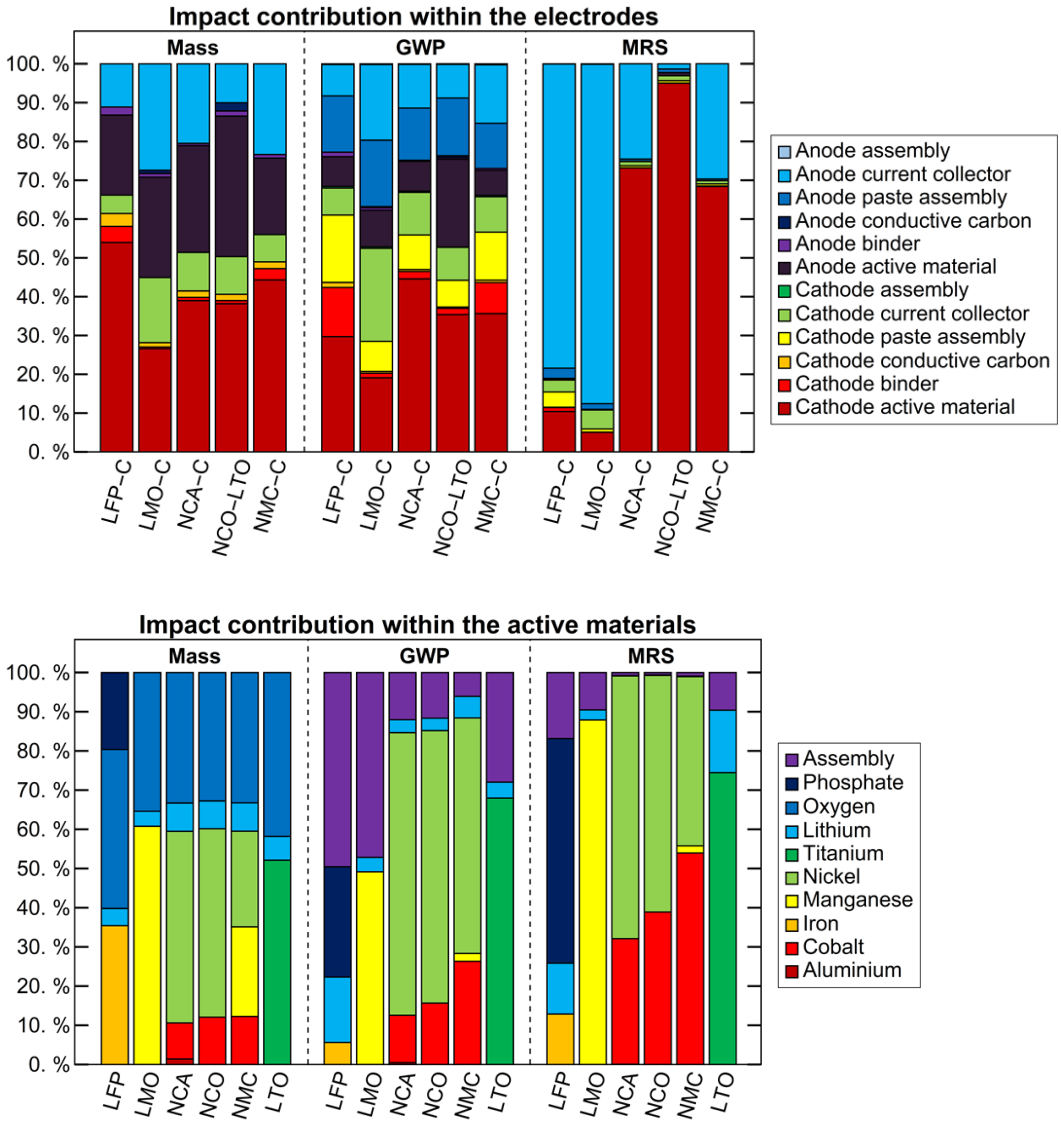

Figure 5: The relative impact contribution of components (top) and active materials (bottom) within the battery electrodes. Higher values have a more important contribution. GWP: Global warming potential; MRS: Mineral resource scarcity.

3.3 Environmental impact per lifetime energy delivered

Environmental impact per lifetime energy delivered depends upon the cycle life associated with the cell chemistry of the battery and the cycling scenario. The low cycle life and calendar life of LMO-C hinder its performance in this functional unit. When cycled once a day, the NCA-C battery system has the best GWP per lifetime energy delivered with 43 ± 3 g CO_2e/kWh which concurs with Peters et al.'s ranking[13]. However, this is based on a small sample size (four) for this technology and a well-designed LFP-C, NMC-C or even LMO-C appears to perform just as well (Figure 6a, middle panel). NCO-LTO will

have the worst environmental impact if it is cycled once a day or every two days, but it will outperform all the other chemistries if cycled more than twice a day due to its increased longevity. Impact reduces by a factor of 9 when comparing its performance between a cycle every two days and 4 cycles a day where it reaches 20 ± 5 g CO_2e/kWh. To put these figures in context, electricity generated from rooftop solar power has an embodied carbon footprint of 41 g of CO_2e/kWh[37].

In terms of MRS, LFP-C provides a balance between material scarcity and cell efficiency, and performs well in all three cycling scenarios (Figure 6b). The high specific energy and cycle life of NCA-C compensates its use of cobalt and nickel. Even though LMO-C has a relatively low cycle life, its low mineral resource scarcity at purchase allows it to have the third lowest mineral resource scarcity when not cycled intensively. The relatively high cycle life of NMC-C does not offset the impact of the high amounts of nickel, cobalt and copper in its electrodes. However, higher performing NMC-C devices can perform as well as an average LFP-C or NCA-C.

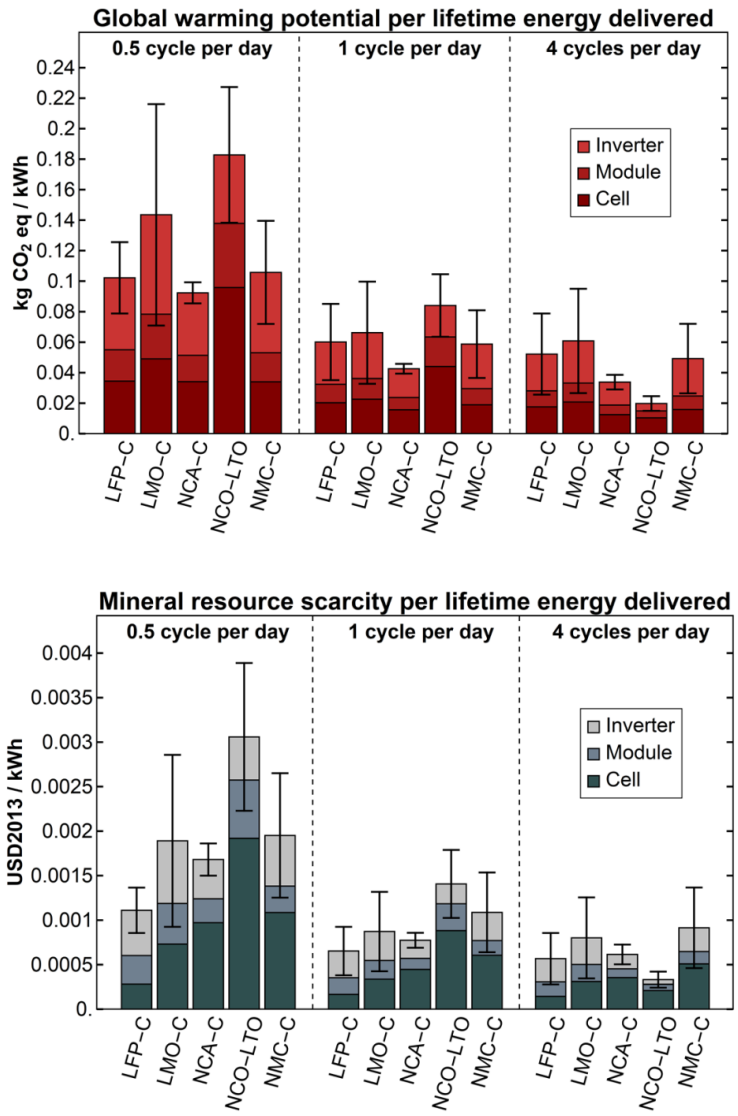

Figure 6: The global warming potential (top) and mineral resource scarcity (bottom) due to battery system manufacture per lifetime energy delivered, across a range of cycling intensities. Lower values indicate lower ecological burden. The error bars represent the standard deviation across the distribution of performances reported by the manufacturers of battery modules of a same chemistry in our sample.

Lower charge and discharge efficiencies result in higher energy losses which increase the overall environmental impacts of operating a storage system. Hiremath et al.[14] described how – where the carbon intensity of electricity feeding the battery is high – the energy loss due to inefficiencies becomes the determining GWP factor when comparing different electrochemical storage technologies. This is not the case for lithium-ion battery chemistries (Figure 7) as their round-trip efficiencies are similar (82.3% to 89.4%) (see Table 1).

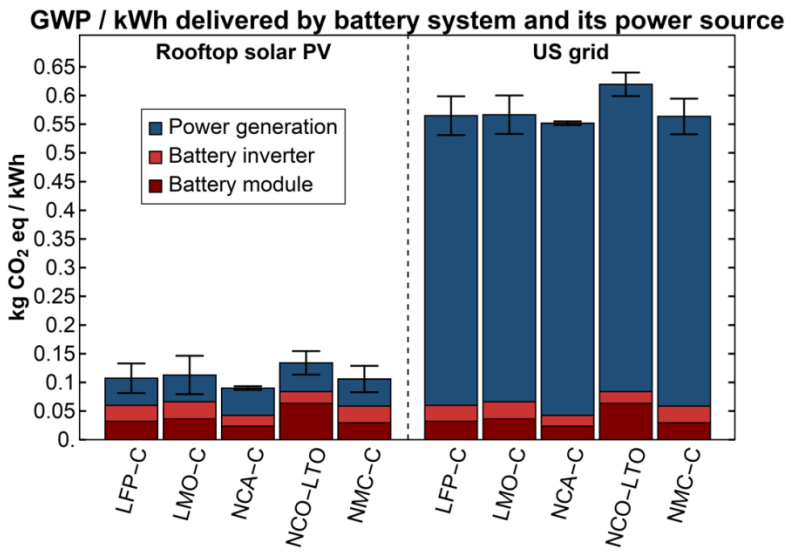

Figure 7: Global warming potential per lifetime energy delivered by battery systems, including the GWP of electricity generation from rooftop photovoltaics and the average electricity generation mix in the US. Batteries were assumed to be cycled once per day. The carbon intensity of electricity production was taken as 41 g CO_2e / kWh for the rooftop solar PV[37] and 439 g CO_2e / kWh for the 2017 US grid[38]. Lower values indicate lower ecological burden. The differences in round-trip efficiencies between chemistries causes the GWP associated with the power generation to vary. The error bars represent the standard deviation across the distribution of performances reported by the manufacturers of battery modules of a same chemistry in our sample. Uncertainty in the carbon intensity of electricity generation is not included.

The global warming potential per kWh delivered by the lithium-ion chemistries analysed is sensitive to their final capacity retention (Figure 8). This study assumes that at their last cycle the batteries can hold 60% of their initial storage capacity. However, if users stop using their batteries once they have reached 80% of their initial storage capacity, the environmental impact of the batteries per kWh delivered almost doubles when cycled intensively. At one cycle per day, the average lithium-ion battery chemistry used until 60% of initial storage capacity retention has the same GWP per lifetime energy delivered as the best performing chemistry used until 80% of initial storage capacity retention (Figure 8). The final capacity retention and definition of end-of-life can therefore be more important than the chemistry choice, which echoes findings from the LCA of other electrochemical technologies[47].

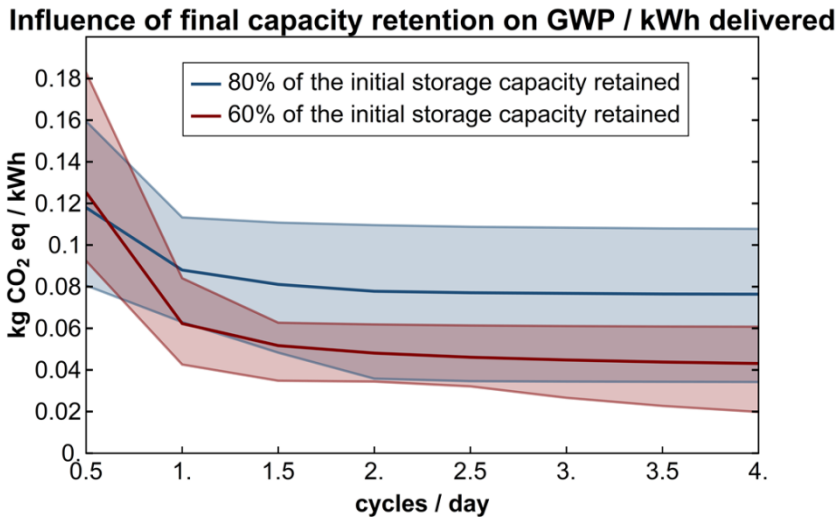

Figure 8: Influence of the cycling intensity and storage capacity retention on lithium-ion battery system's global warming potential per lifetime energy delivered. Thick lines represent the mean values of lithium-ion battery chemistries and the shaded areas represent the spread across the 5 chemistries investigated. Storage retention refers to the last cycle within the battery's lifetime.

3.4 Energy delivered on energy invested (EDOEI)

When excluding the energy used to charge the batteries[16], all the battery systems deliver less than double their embodied energy when cycled 0.5 times a day (Figure 9a). The NCO-LTO battery system even requires more energy to be manufactured than it will redeliver in this cycling scenario. When cycled once a day, the modules achieve an $EDOEI_{w/o\ charge}$ of 4 for LFP-C and LMO-C, 6 for NCA-C and NMC-C and 2 for NCO-LTO. This contrasts Barnhart and Benson's results[16] which shows a lithium-ion battery module at 10. This can be explained by the higher value their study used for the lithium-ion battery's specific energy, and the exclusion of both self-discharge and loss in capacity retention. Cycling the batteries intensively makes an important difference for the NCO-LTO battery system which rises to 8. At 4 cycles a day, a well-designed NMC-C battery system can achieve a similarly high $EDOEI_{w/o\ charge}$ and NCA-C almost reaches 5. LFP-C and LMO-C perform less well but it heavily relies on their manufacturer.

Including the lifetime energy used to charge the batteries to the EDOEI metric shows that storing energy in a lithium-ion battery allows only 38% to 52% of this energy to be redelivered if the battery is cycled once every two days. This rises to 54% to 66% if it is cycled once a day and 65% to 73% if the battery is cycled intensively (Figure 9b). This version of the EDOEI is naturally restricted to being less than 100% due to conservation of energy, but has a practical limit of around 86% as it also accounts for the inverter's AC to DC efficiency as well as the charging efficiency of the battery.

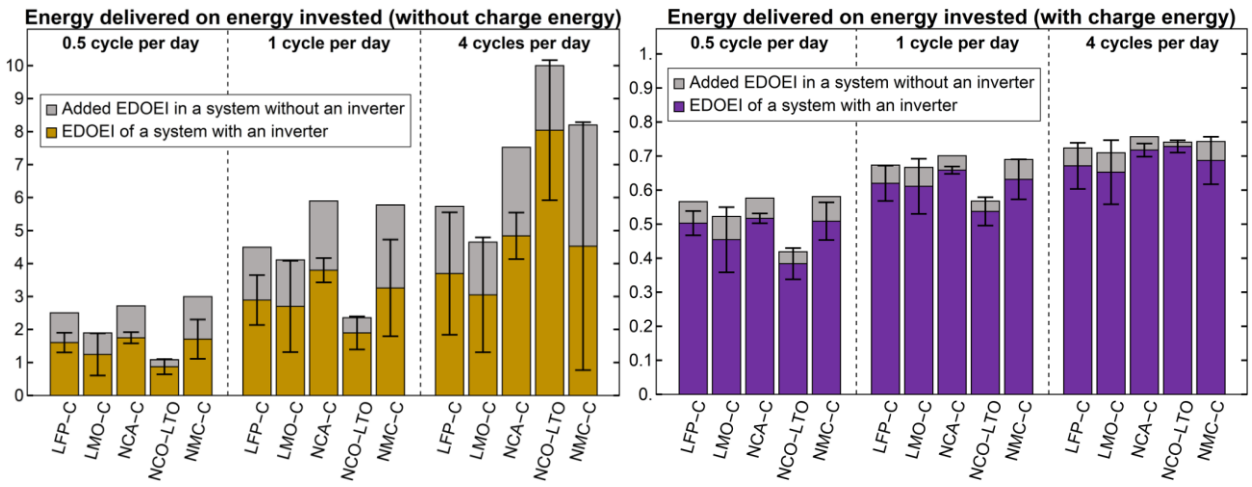

Figure 9: The lifetime energy delivered on energy invested for different lithium-ion battery chemistries and cycling intensities, excluding (left) and including (right) the energy used for charging. This metric is based on the impact indicator for cumulative energy demand. Higher values are more energy efficient. Coloured bars represent the EDOEI of the complete battery system, grey bars show the EDOEI of the battery excluding the inverter. The error bars represent the standard deviation across the distribution of performances reported by the manufacturers of battery modules of a same chemistry in our sample.

3.5 Limitations and potential for further study

Life cycle assessment is an inherently uncertain process. Four areas of uncertainty are highlighted here, around battery performance, composition, usage and disposal.

The batteries included in this study came from a range of manufacturers and dates. Some datasheets lacked technical specifications for particular variables, which were inferred using average values from related systems. Most notably, the capacity retention associated with the cycle life was often not made clear by manufacturers. Battery module manufacturers using the same chemistry often use the same cells from companies like LG, Samsung or Panasonic without disclosing this information, which could lead to redundancy within the dataset. Only two commercially-available LMO-C and two NCO-LTO battery modules were found, which increases the uncertainty of the results for those chemistries. The LMO, NCA, NCO and NMC active materials exist in different versions with varying concentrations of nickel, manganese and cobalt[39] but data sheets do not give the precise concentrations due to commercial sensitivity.

The uncertainty related to the standardisation of the components' mass ratio in the batteries and the differences in the LCIs regarding their manufacturing is likely to be important. A better LCI is required for the battery inverter without a maximum power point tracker as the product used in this study is

an adapted solar inverter. A popular battery inverter weighs 63 kg (see Supplementary material B section 2) and is expected to have a high environmental impact. Choosing a lower-mass, and thus lower-impact inverter might be just as important as choosing a low impact battery module, as the 23.8 kg inverter in our study is already estimated to be responsible for 25% to 46% of the GWP of the battery system and 16% to 46% of its MRS.

In practice, factors other than time and energy throughput will influence battery degradation, including temperature, rate of charge and discharge, and the state of charge at which the battery is stored[29,48,49]. Real-life data on the way the batteries are used by households would help make more realistic cycling scenarios and model more precise storage capacity retention losses. Finally, the different chemistries have different C-rates, operating conditions and safety features, none of which were taken into account in the present study.

The absence in the modelling of an end of life stage has the benefit of making the results unbiased with respect to the location where the batteries are used. However, this could misrepresent the real-life environmental impacts, especially in the mineral resource scarcity impact category. Detailed LCIs for the end-of-life of each chemistry are an urgent requirement for this field as the ones currently available within the Ecoinvent 3[40] database apply to an unspecified chemistry. In addition, given the practice of dumping and burning batteries at their end of life in some developing regions[41], an analysis with different end of life scenarios and which looks at human toxicity is recommended.

3.6 Business and policy implications

With residential batteries still emerging and research and development still active, a policy to discourage the use of any cathode and anode combination on the basis of their environmental impacts would be inappropriate at this stage. Research towards increasing the specific usable energy, cycle life and calendar life of the battery modules should be continued[31] while carefully considering the active materials used. Reducing cobalt and nickel content (such as in LFP-C cells), guaranteeing their availability or limiting their human toxicity through recycling incentives would all be valuable initiatives. Substituting the copper in the negative electrodes' current collectors for more benign materials would also help reduce the overall impact of battery systems. Aluminium is already being used in LTO anodes and in sodium-ion batteries, a possible low-cost alternative to lithium-ion batteries currently at prototype stage[42].

Operationally, it is important to encourage high cycling scenarios to minimise ecological impacts and offer the cell chemistry that fits best the consumer's battery cycling requirements. High cycling scenarios can be encouraged by reducing policy barriers, so multiple services can be provided by residential batteries[43]. For example, Goebel et al.[44] showed the profitability of residential lithium-ion batteries increases when remotely controlled by an aggregator which charges the batteries using grid power during times of negative reserve deployment such as during the night. Similarly, Schmidt showed that intensively cycling batteries is beneficial for reducing their levelised cost of energy production[45]. For applications requiring many charge and discharge cycles per day, the NCO-LTO battery module should be seriously considered and configurations where it could be optimised must be investigated.

4 Conclusion

Battery systems based around four of the chemistries (NMC-C, LFP-C, LMO-C and NCA-C) have a comparable embodied carbon footprint in the range of 200–225 kgCO_2e per kWh of useable capacity. The fifth chemistry considered (NCO-LTO) has approximately twice the environmental impact of the other chemistries. This is primarily due to its low energy density, giving a larger mass for an 8.1 kWh system.

However, the chemistry's greater cycle life means that LTO could be the most environmentally benign technology for applications requiring intensive cycling. If a battery is expected to be cycled more than twice a day, the NCO-LTO is the best option in all impact categories; when cycled once per day or less, it is the worst option. For batteries cycled less than twice a day, LFP-C, NCA-C or NMC-C chemistries are the best options, and these are the dominant chemistries amongst current residential storage batteries. When cycled once per day, the embodied carbon footprint of residential battery storage is in the range 40-80 g CO_2e/kWh across the five chemistries analysed. This range increases to 90-180 for one cycle every two days and falls to 20-60 for four cycles per day.

Manufacturing the inverter is responsible for around half of a residential battery system's global warming impact, and between a third and a half of its mineral resource scarcity. In contrast, lithium forms a relatively small part of the overall environmental impact, contributing around 5-15% of the impacts of the batteries' active materials. This highlights the importance of ancillary power electronics, and a need to shift the debate away from viewing lithium as the main 'environmental hot spot' of battery manufacture which must be improved.

The round-trip efficiency of the batteries is in the range of 82 to 89%. However, when the embodied energy from manufacturing them is included, the whole life-cycle round trip efficiency – or energy delivered on energy invested (EDOEI) – falls to between 54 and 66% when cycled once a day. This leaves open the question of whether society should invest 1.5 to 1.8 kWh of energy to deliver 1 kWh at a preferred time.

5 Conflict of interest

There are no conflicts to declare.

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