Submission No 32

ELECTRIC AND HYBRID VEHICLE BATTERIES

Organisation: University of New South Wales

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Thank you, Shanshan,

It was an absolute pleasure to contribute to this enquiry. The transcript is a true reflection of my presentation.

I would like to add the following three submissions:

1. A short review of battery technologies and risks (attached)
2. The risks associated with Battery End of Life (attached)
3. We need to keep a close eye on the battery management system and battery charging system software, and create appropriate oversight and governance around it. Inappropriate battery management and battery charging creates risks of fires.

Thank you again for the opportunity.

Sincere regards

Vinayak

A Note on Safety of Battery Technologies

Abstract

Recent issues with batteries in electric vehicles catching fire, have increased the scrutiny on battery safety. In particular what are the risks and factors that need to be considered while evaluating the viability and feasibility of the battery technology. This paper discusses the various current battery technologies being considered for electric vehicles. The purpose of this short note is to synthesize current understanding of battery technologies and safety.

1. Introduction

Recent fires on electric bus in France (4 April and 29 April, 2022) not only led to significant mobility disruptions with over 200 buses being grounded, but it has also led to significant concerns regarding safety of electric vehicles and the battery technologies being used.

There are wide range of battery chemistries and technologies and each of them come with their benefits and risks. The efficiency and safety of batteries are determined by (a) electrode materials, and (b) electrolytes. Though there have been significant debates between the use of NMC and Lithium-ion batteries, it is important to realize that not all Lithium-ion batteries are not the same. For instance, the Lithium polymer batteries that were involved in the electric bus fires in France had gelbased electrolytes that expanded suddenly under thermal runaway leading to an explosion. The safety depends not only on the battery chemistry, but also about the operational conditions and potential faults. This short note will introduce the various types of battery chemistry and technologies comparing the efficiencies and risks that need to be carefully evaluated. The rest of the note briefly discusses the battery chemistry, comparison of efficiencies, methods to safeguard against risks and battery end-of-life.

2. Battery Technologies

One of the critical measures to evaluate the safety of batteries is the thermal runaway. As shown in Figure 1 (Doughty, 2005), the thermal runaway is evaluated by applying an external source of heat to the cell known as the to the **Onset** Temperature (T_1), which is typically a self-heating rate of 0.2°C/min. Usually, this low level of heat generation is easily dissipated in battery packs, however, if this heat is not dissipated, the temperature will continue to increase and enters the **Acceleration** stage (T_2), which is characterized by accelerated heat release.

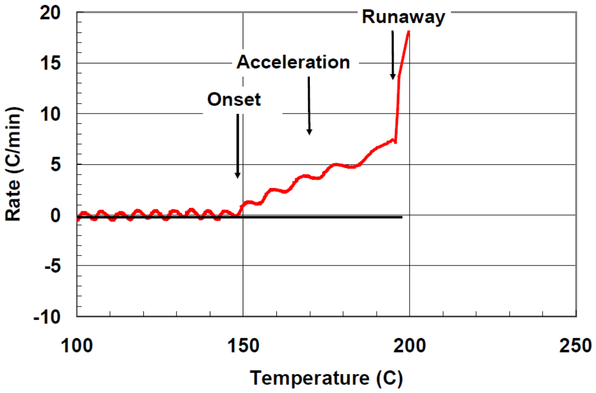


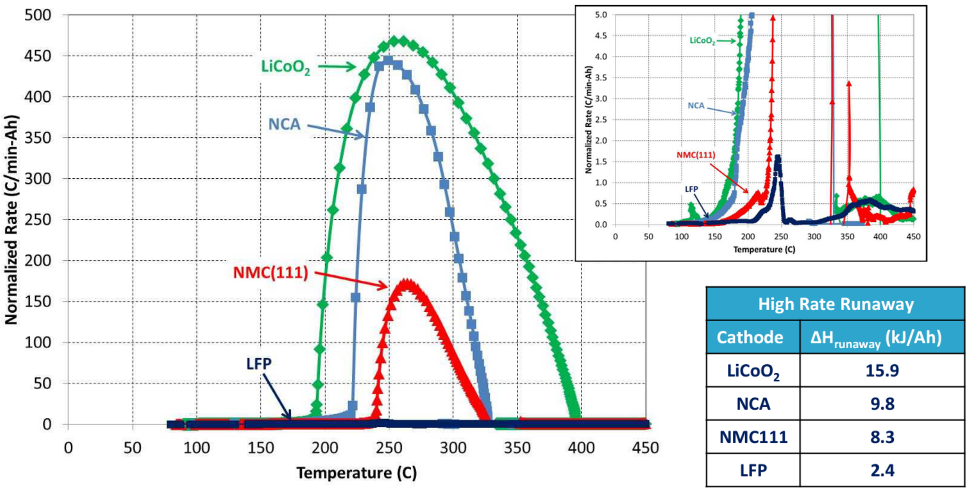
Figure 1: Stages leading to thermal runaway (Doughty, 2005)

The acceleration stage results from increased electrolyte oxidation at the active cathode surface, resulting in venting and release of smoke. These reactions depend highly on the active material chemistries and the state of charge. Additional heating causes the cell to enter a **Thermal Runaway** stage with a self-heating rate of 10°C/min or greater, in which the high rate of reactions at the electrodes causes the temperature to rise rapidly resulting in a flame or explosion.

As discussed, the main characteristics in terms of risks and efficiencies of batteries are predominantly determined by the electrodes and electrolytes.

2.1 Electrodes

An extensive analysis of thermal runaway by Lamb and Orendorff (2015) demonstrated that Lithium Ferro Phosphatw (LFP) batteries had the least thermal runaway of 1.5 C/min-Ah as compared to Nickle-Manganese-Cobalt (NMC) batteries that are close to 180 C/min-Ah (see Figure 2).



High Rate Runaway	
Cathode	ΔH$_{runaway}$ (kJ/Ah)
LiCoO$_2$	15.9
NCA	9.8
NMC111	8.3
LFP	2.4

Figure 2: Thermal runaway for different electrode materials (Lamb and Orendorff, 2015)

A comprehensive assessment of electrode materials by Doughty and Roth (2012) found that though LFP batteries are heavier and might not provide the same range as NMC batteries (Icodean et al. 2017), but they are safer.

Though most of the recent electric bus battery fires were related to solid-state batteries, their exact chemistry is unknown. But based on analysis by Chen et al. (2020) on solid-state batteries, the maximum rate of increase and the temperature reached during thermal runaway are significantly higher than those of LFP and NMC batteries, with LFP batteries seeming to be safer.

Table 1: Comparison of thermal runaway among different batteries

Materials	Onset (°C)	Max Temp (°C)	Max Rate (°C/min)
*LATP + Li	~290	~560	11,083.62
*LAGP + Li	~260	~966	32,076.15
*LLTO + Li	~250	~350	6.584
**LiCoO2	~190	~370	~440
**LFP	~230	~255	~22
**NMC	~180	~320	~260

* Based on Chen et al. 2020, related to solid state batteries.

** Based on assessment of graphs from Doughty and Roth, 2012.

2.1 Electrolyte

As discussed earlier all Lithium ion or all NMC batteries are not the same. Their performance and safety conditions radically depend on the electrolytes used. The electrolyte carries ions, including Li+. The malfunction of these parts, together or individually, can negatively affect LIB safety. During an uncontrolled battery malfunction, the electrolyte acts as a fuel supply for further heat generation, so appropriate safety controls need to be undertaken. As shown in Figure 3, the choice of electrolytes in an NMC battery has a significant impact on the thermal runaway albeit affecting its performance as well.

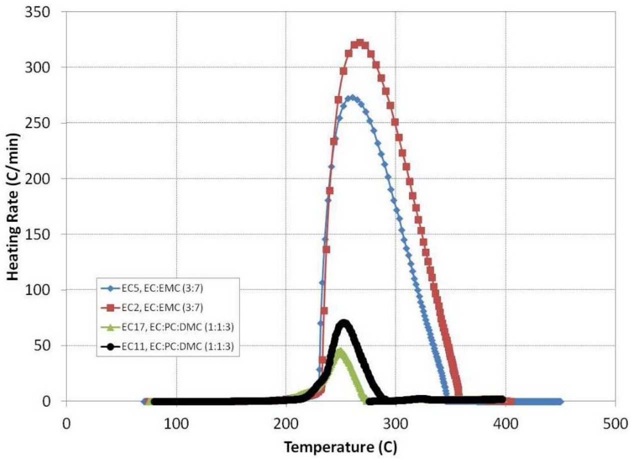


Figure 3: Impact of electrolytes on runaway in NMC batteries (Lamb and Orendorff, 2015)

Lithium-ion batteries usually use organic electrolytes, which are based on linear and cyclic alkyl carbonates. These electrolytes make possible the high power and energy densities in Lithium-ion batteries. These electrolytes are highly flammable and potentially posing risks. At high temperatures sudden gas generation also pose risks of explosion. However, the use of flame retardant additives such as phosphates, phosphazenes, phosphide and ethers have been found to significantly reduce gas generation and thermal runaway. As seen in Figure 4, use of hydrofluoroethers (HFE's) reduces gas formation by 40-60% (Roth and Orendorff, 2012).

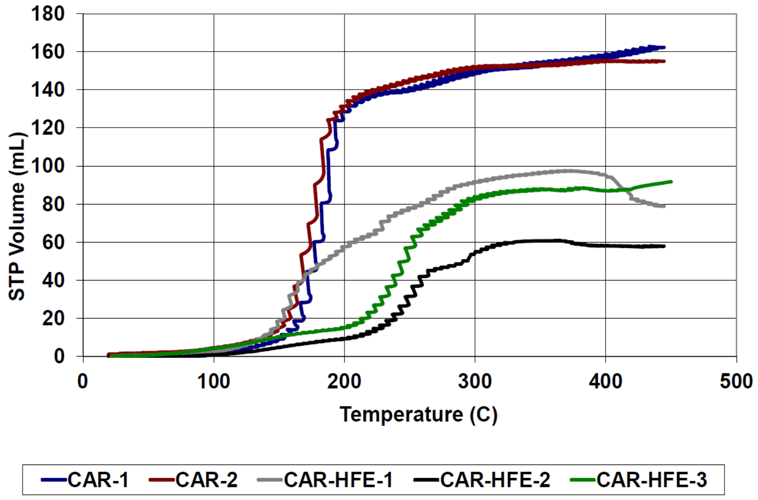


Figure 4: Comparison of gas formation with the addition of HFEs (Roth and Orendorff, 2012)

An alternative to the liquid electrolytes in Lithium-ion batteries is a solid polymer electrolyte formed by incorporating lithium salts into polymer, glassy, or ceramic matrices and forming them into thin films. The polymer may serve the function of separator as well as electrolyte, depending on the cell design. Though the electrode materials in Li-polymer batteries is similar to Li-ion batteries with liquid electrolytes, the electrochemical stability of the polymer used is less stable to oxidation or reduction by the electrodes, making them more reactive. Some of the polymers are true solid polymers without substantial amounts of additives or plasticizers, and others are gels with a large volume of liquid electrolyte (up to 70% by volume). The amount of plasticizer may be as high as 70%, resulting in limited chemical and mechanical stability. The safety of polymer electrolyte cells is strongly influenced by the type of polymer electrolyte. Under extreme conditions of voltage and temperature, electrolytes can react with the active materials of both anode and cathode to release significant heat and gas.

The recent fires on electric buses in France were related to Lithium Polymer based solid-state batteries. Though these batteries hold a lot of potential with regards to energy density, weight and overall efficiency there is a need for further research to manage and control thermal runaway.

3. Safety Considerations and Conclusion

It is clear from studies LFP batteries seem to provide the highest safety and provides reasonable efficiency. However, as seen from recent events the choice of electrolytes in the battery needs to be carefully studied, though polymer based electrolytes provide for a promising technology, there is a need for further research on controlling the thermal runaway and gas generation.

Safety incidents can arise when batteries are used in a manner outside design parameters or beyond useful life or from spontaneous internal failures (called "field failures"). The failures occurring due to use of the batteries outside the design parameter during assembly, operation, or maintenance and are a much more likely occurrence. Field failures usually arise from manufacturing defects are extremely low, being estimated between 1 in 10 million and 1 in 40 million cells.

The most serious consequences occur when the stored energy is rapidly released in an unintended manner, producing large quantities of heat and gas. The fact is that, because failures will occur, however infrequent, the challenge for cell and battery pack designers is to achieve a "*graceful failure*," (i.e., a failure that only has minor consequences and avoids a catastrophic failure). The goal of graceful failure can be realized by:

- Reducing the severity of response of individual cells to abusive events
- Implementing engineering approaches that keep individual cell failures from propagating to adjacent cells, thereby isolating the damage and reducing the risk of injury.

Currently, to manage the consequences of heat and gas generation, many batteries have the following safety features (Doughty and Pesaran, 2012), and see Table 2.

Table 2: Failure triggers, occurrence and how are they managed

Trigger	**Why can this occur ?**	**Is this managed ?**
Overcharge	Defective connections, failure of charging circuit	Yes, battery management system Yes, cell-level safety devices
Overheating from external sources	Battery pack placed too close to a heat source	Yes, cell-level safety devices open the cell at suitable internal pressure
Cell crushing creating massive internal shorts	Physical abuse of battery pack	Yes, design enclosures are built more tolerant to specific abuses
Internal short-circuits (a.k.a., field failures)	Internal-short caused by manufacturing defects	No, new technologies needed
Cascading of thermal energy release	Affected cell can raise the temperature of surrounding cells	No, new technologies needed

*"**Battery Management System (BMS)** controls electrical distribution within a battery pack and protects against over- or under-voltage conditions as well as excessive current. Moreover, it may have temperature sensors that shut down the pack if the upper or lower temperature limits are exceeded.*

***Cell Vent or Tear Away Tab** allows the safe release of gas if excessive pressure builds up within cells. Vents allow predictable pressure relief and are usually activated if the internal cell pressure exceeds 10 bar (~150 psid). These features are incorporated to prevent injury that could be caused by uncontrolled bursting of a battery container.*

***Current Interrupt Device** protects against over-current that breaks the internal electrical connection when the internal pressure reaches a set value. This pressure rise results from internal gas generation caused by thermal or electrical abuse conditions exceeding design limits. This safety mechanism is a one-time device that permanently disables the cell.*

***Current Limiting Fuses** may be used in place of positive temperature coefficient (of expansion) devices when a sustained discharge is not preferred. Fusing of this type may utilize slow-blow time fuses or fast-acting fuses with little current-time latency. Time-delay and especially fast-acting fuses are external to a cell. However, fusible links may be installed in the cell.*

***Diodes** may be used for primary batteries to prevent inadvertent charging (blocking diode) or to steer the discharge current around a weak cell as in a discharge (bypass) diode."*

Batteries must have sufficient safety for their targeted application. The safety and abuse tolerance of electrochemical cells depends on materials, chemical interactions, the nature of the abusive event, as well as battery pack and BMS control engineering.

Though solid-state batteries have concerns with thermal runaway, the high efficiency will drive continues research and development on improve safety. This is critical for them to be viable alternatives for electric vehicles.

4. References

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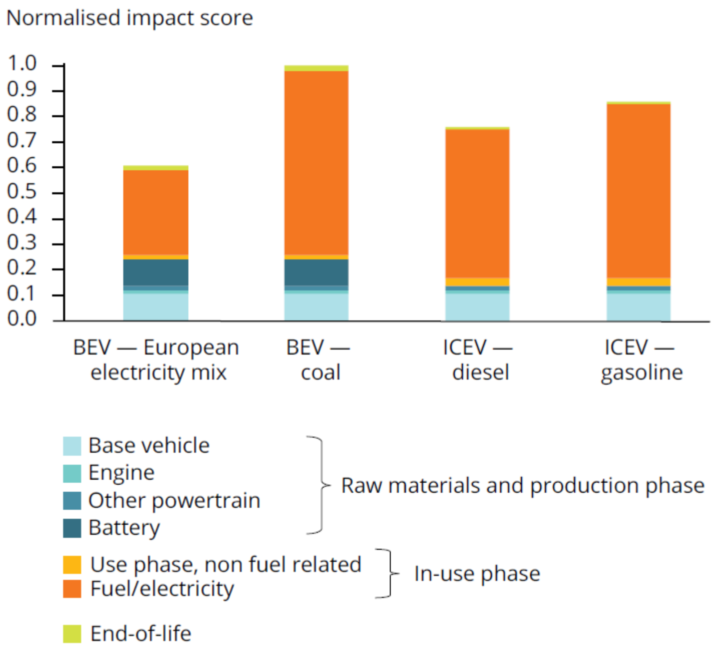
Battery End of Life

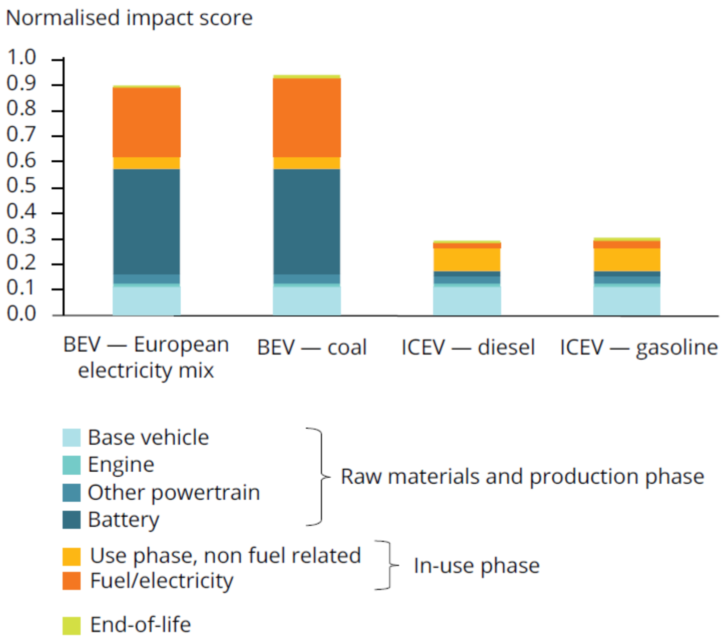
What are the issues and solutions

Comparison of Impacts

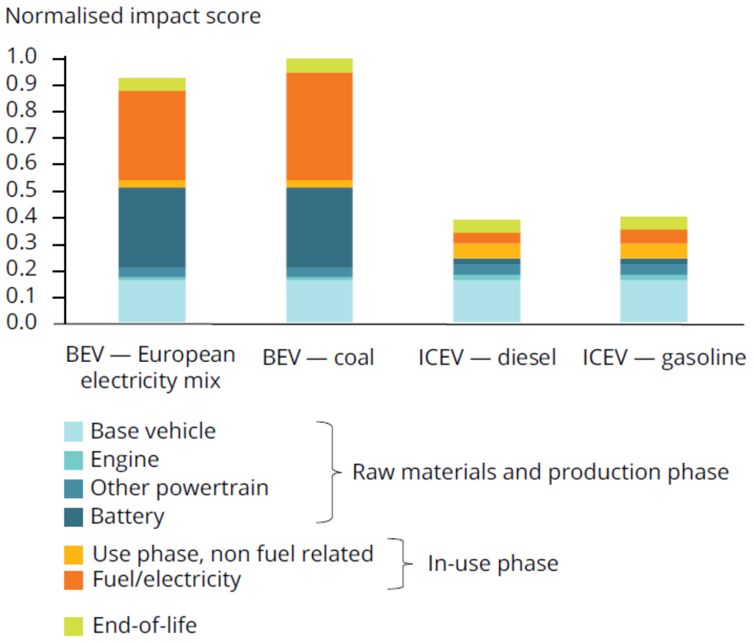
Assuming disposal at end of life



Climate change impacts: example comparison of BEVs with ICEVs



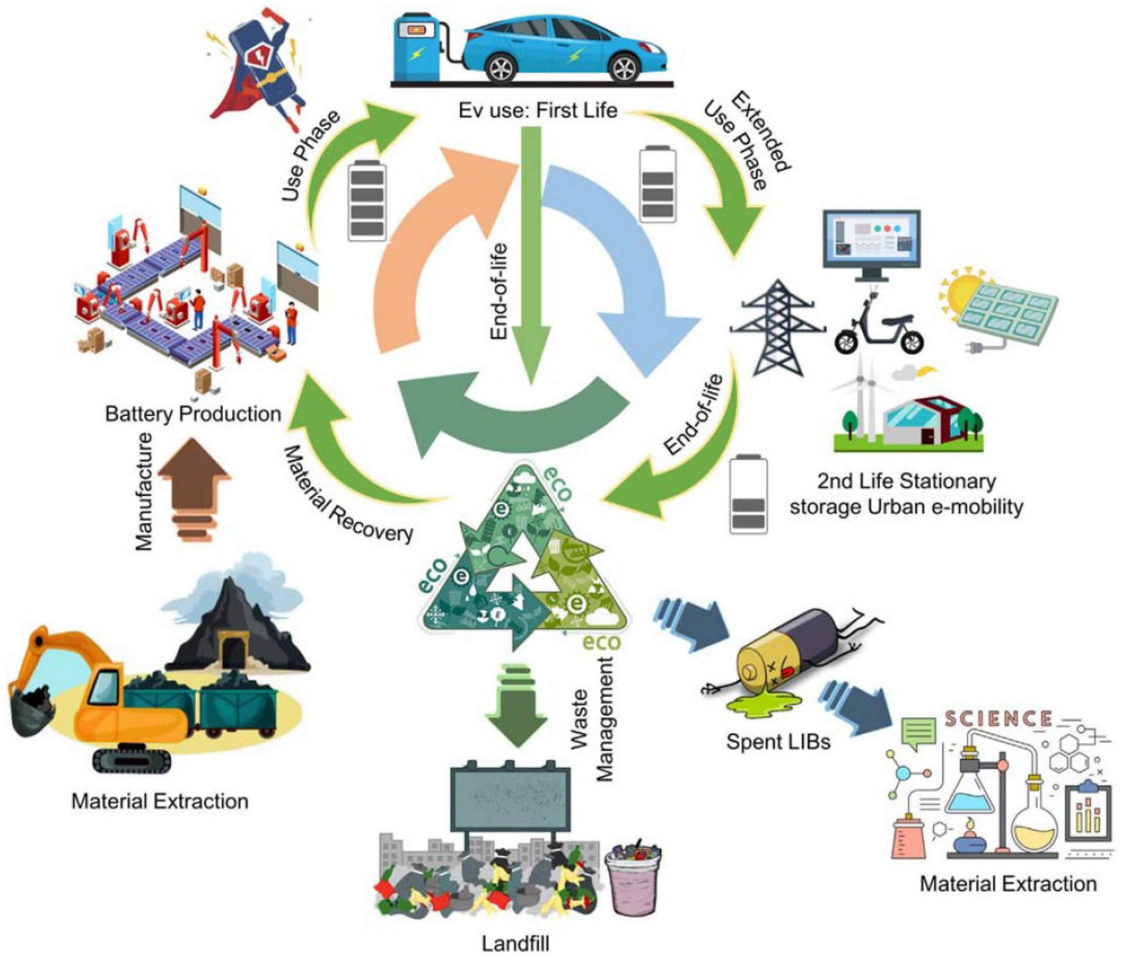
Human toxicity impacts: example comparison of BEVs with ICEVs



Freshwater ecotoxicity impacts: example comparison of BEVs with ICEVs

https://www.eea.europa.eu/publications/electric-vehicles-from-life-cycle

Battery End-of-Life



Remanufacturing : This refers to refurbishing EV battery packs for redeployment in original applications. It has been found to achieve approximately 40% cost savings, as well as reductions in energy consumption and GHG emissions. However, due to low demand there are no large-scale remanufacturing applications.

Repurposing: This indicates that batteries are reconfigured for low-voltage applications such as grid-connected storage, backup power and auxiliary services. This repurposing to stationary energy storage can reduce costs, increase energy efficiency, and photovoltaic self-consumption and have economic and environmental benefits.

Recycling: can help recover valuable cathode materials and using them in the manufacture of new batteries, the demand for virgin resources can be reduced. It has been found that carbon emissions can be reduced by recycling of steel, aluminium, and the cathode materials of traction batteries by almost 61%, 13%, and 20% of the total reduction, respectively.

Xiaoning Xia, Pengwei Li, A review of the life cycle assessment of electric vehicles: Considering the influence of batteries, Science of The Total Environment, Volume 814, 2022, 152870, ISSN 0048-9697

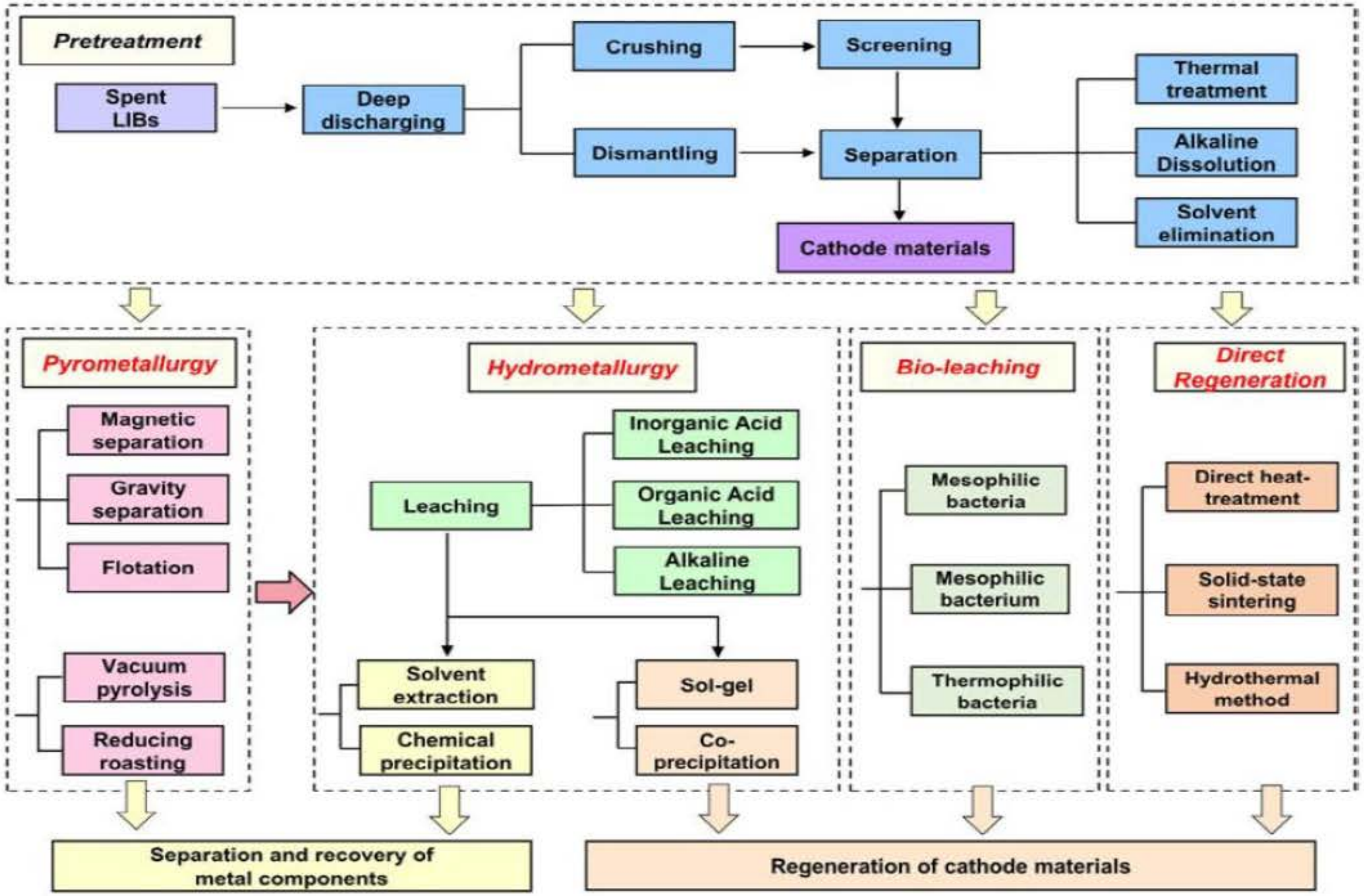
Overview of the overall Impact

		Climate change	Primary energy demand	Human health	Ecosystem health
Reuse	Direct reuse	GHG emissions reduction of 80-95 % from cathode production using directly recycled materials	Least energy intensive of the recycling/reuse options	SO_x emissions reduction of 75-100 % from cathode production using recycled materials Indirect positive impacts through reduction in need for raw materials	SO_x emissions reduction of 75-100 % from cathode production using recycled materials Indirect positive impacts through reduction in need for raw materials
	Cascade reuse	Indirect benefits through support for grid integration of renewables Overall GHG emissions of an electric vehicle, when considered on a per kilometre basis could reduce by 42 %	Delayed need for energy-intensive end-of-life processes	Indirect positive impacts through reduction in need for raw materials	Indirect positive impacts through reduction in need for raw materials
	Magnet reuse and recycling	GHG emissions reductions through use of recycled materials in place of virgin materials	Delayed need for energy-intensive end-of-life processes	Indirect positive impacts through reduction in need for raw materials	Indirect positive impacts through reduction in need for raw materials

		Climate change	Primary energy demand	Human health	Ecosystem health
Recycling	Magnet reuse and recycling	GHG emissions reductions through use of recycled materials in place of virgin materials	Delayed need for energy-intensive end-of-life processes	Indirect positive impacts through reduction in need for raw materials	Indirect positive impacts through reduction in need for raw materials
	Pyrometallurgy	23-43 % reduction in GHG emissions through material recovery (compared to use of virgin materials) GHG emissions reductions from cathode production using recycled materials could be 60-75 %	6-56 % reduction through material recovery	SO_x emissions reductions from cathode production using recycled materials could be 95-100 % Indirect positive impacts through reduction in need for raw materials Indirect positive impact through reduced SO_x emissions compared to production from virgin materials (especially cobalt)	Indirect positive impacts through reduction in need for raw materials SO_x emissions reductions from cathode production using recycled materials could be 95-100 %
		Incineration of plastic has largest impact on global warming potential		Higher emissions of dioxins, mercury and chlorine compounds than hydrometallurgy Harmful impacts from SO_2 emissions if lime scrubbing not employed Indirect impacts from freight transport emissions	Higher emissions of dioxins, mercury and chlorine compounds than hydrometallurgy Harmful impacts from SO_2 emissions if lime scrubbing not employed Indirect impacts from freight transport emissions
	Hydrometallurgy	Gypsum sent to landfill has largest impact on global warming potential	Consumption of citric acid and hydrogen peroxide make this process the most energy intensive recycling/reuse option	Indirect positive impacts through reduction in need for raw materials	Indirect positive impacts through reduction in need for raw materials
				Possible impacts from water scarcity due to water intensive process	Gypsum sent to landfill has largest impact on terrestrial ecotoxicity potential Possible impacts from water scarcity due to water intensive process
Disposal	Landfill	Possibility of truck and landfill fires	Less energy demand for reprocessing	Potential for soil contamination from leakage of electrolytes Potential groundwater pollution from landfill leachate	Potential for soil contamination from leakage of electrolytes Potential groundwater pollution from landfill leachate

Note: White indicates positive effects and pink indicates negative effects. There can be overlap between direct reuse and cascaded reuse, e.g. where direct recycling is referenced.

Methods for Recycling



Pretreatment

Spent LIBs
Deep discharging
Crushing
Screening
Dismantling
Separation
Cathode materials
Thermal treatment
Alkaline Dissolution
Solvent elimination

Pyrometallurgy

Magnetic separation
Gravity separation
Flotation
Vacuum pyrolysis
Reducing roasting

Hydrometallurgy

Leaching
Inorganic Acid Leaching
Organic Acid Leaching
Alkaline Leaching
Solvent extraction
Chemical precipitation
Sol-gel
Co-precipitation

Bio-leaching

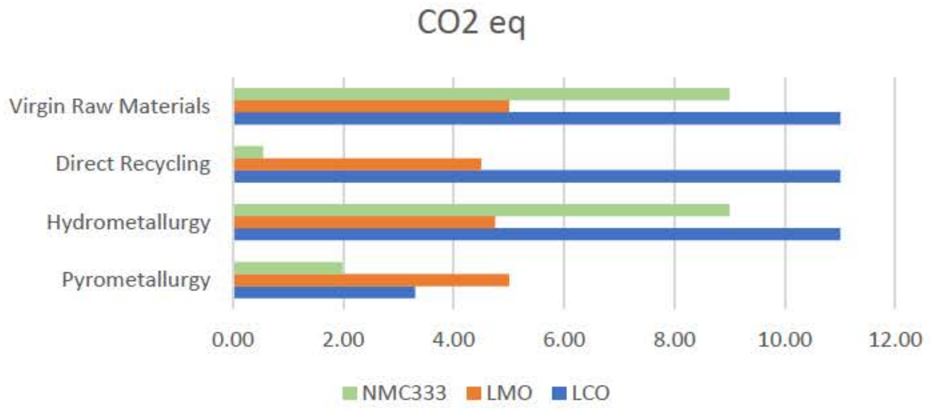
Mesophilic bacteria
Mesophilic bacterium
Thermophilic bacteria

Direct Regeneration

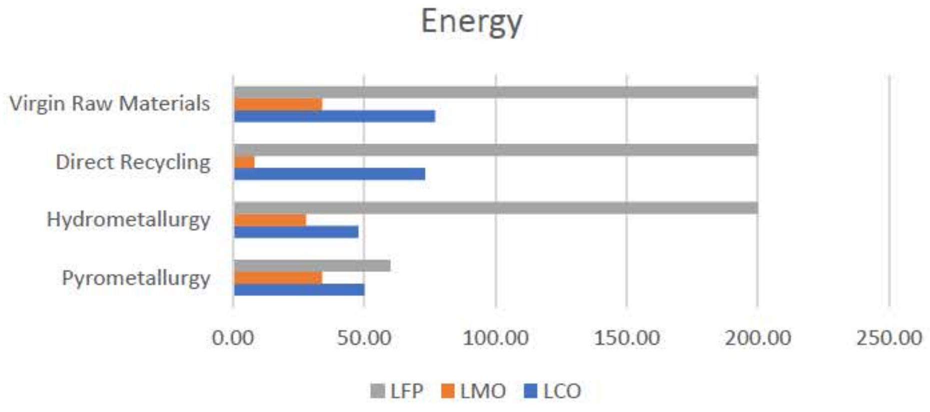
Direct heat-treatment
Solid-state sintering
Hydrothermal method

Separation and recovery of metal components

Regeneration of cathode materials



CO2 eq



Energy

Cost

Recycling poses significant benefits from an environmental, energy and cost perspective