Life-cycle environmental and economic assessment of electric vehicle lithium-ion batteries using different recycling methods in a closed loop supply chain

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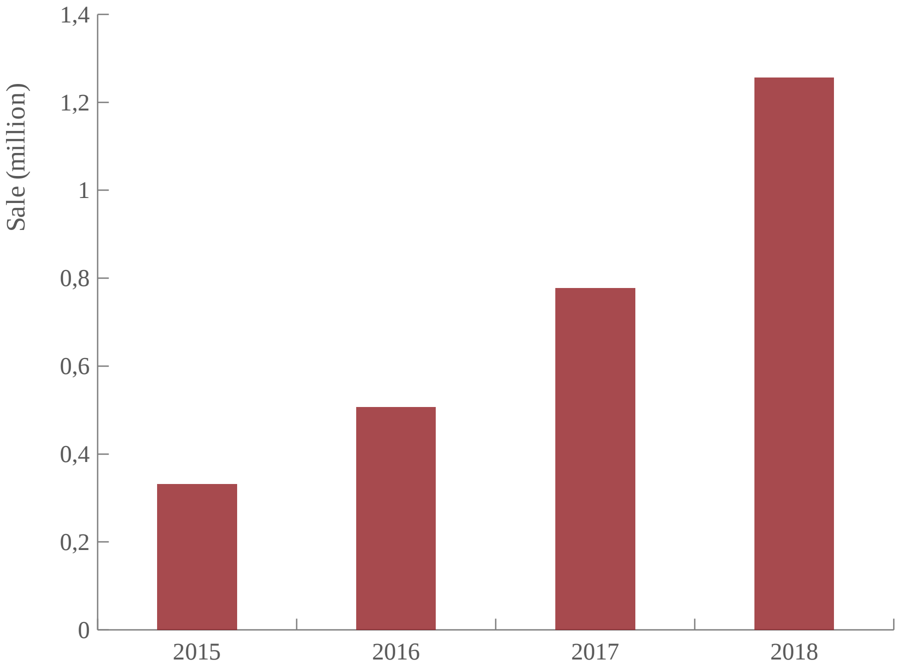
Introduction

Background



- China’s EV market has **rocketed**, with over 1.256 million in 2018 [4], 3.8 times growth from 0.331 million in 2015 [5].
- Due to the rapid adoption of EVs, it raises concerns about waste management of end-of-life batteries.
- LIB (lithium-ion battery) recycling is not yet well-established [8] and its infrastructure is **limited** [13].

Background

- **Pyrometallurgy** and **hydrometallurgy** processes are two **commonly** applied recycling methods, while **direct physical** recycling as a **nascent** but **promising** recovery method is also being developed.

- It is necessary to understand the … **l impact** of LIBs [14,15].

- Furthermore, some studies indicate that the battery recycling process is a crucial factor affecting the life cycle environmental impacts of LIBs.

Pyrometallurgical recycling processes

Hydrometallurgical recycling processes

At scale

Direct physical processes

Nascent but promising

Review

Study	Battery type	Stages	Recycling processes	Country	Environmental indicator
Dunn et al. [14]	**LMO**	Life cycle	Hydrometallurgical, intermediate physical, and direct physical recycling methods	U.S.	GHG
Ciez, Whitacre [13]	**NMC622, NCA** and **LFP**	Life cycle	Pyrometallurgical, hydrometallurgical and direct physical recovery methods	U.S.	GHG
Onat et al. [18] and Liao et al. [20]	No mentioned	**Use stage**	No consideration.	U.S. / China	Water
Kim et al. [21]	No mentioned	Life cycle	(1) Coarse calculation. (2) Only one recycling method.	U.S.	Water

Innovation

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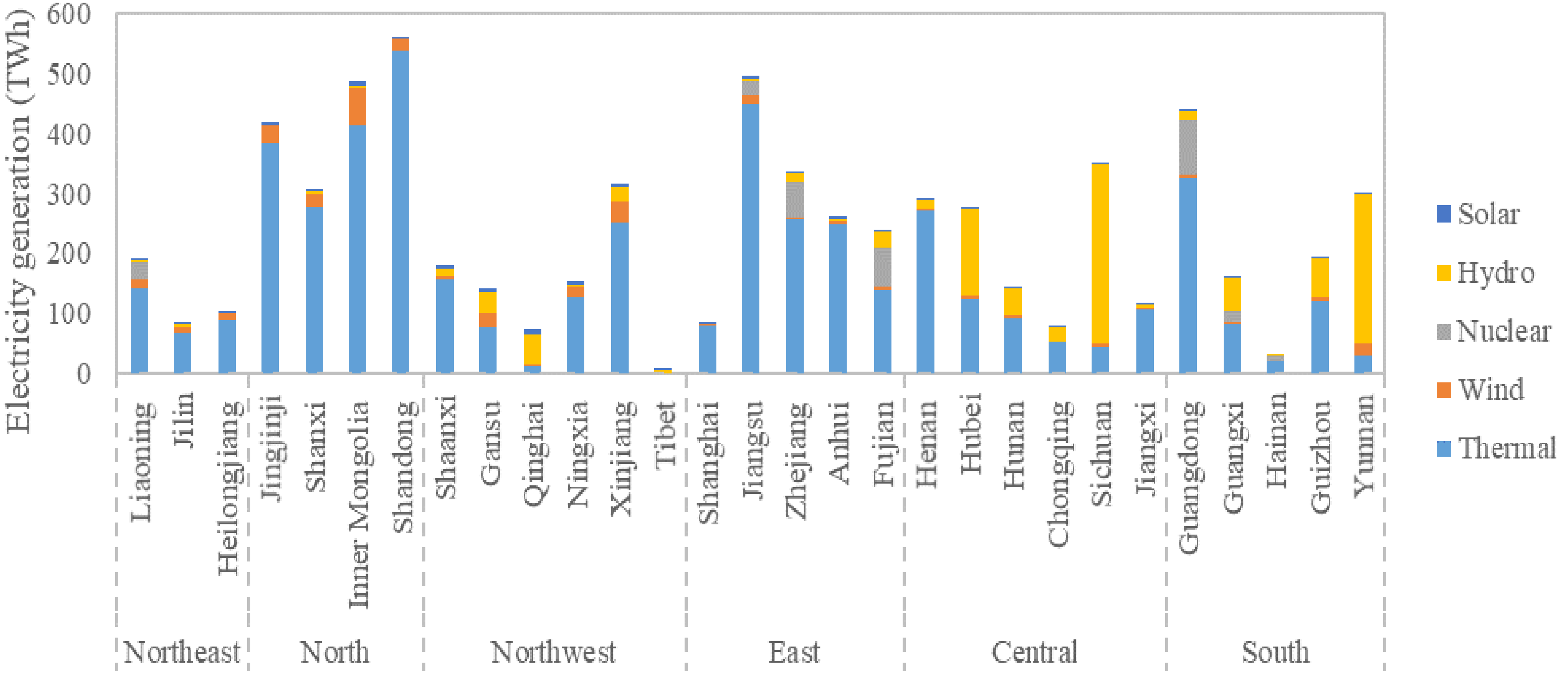

Fig 2. Provincial energy mix in the electric power sector in China in 2018.

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Objective

This study aims to conduct a life-cycle analysis to evaluate the GHG emissions, water consumption and economic impacts of EV LIBs using different recycling methods in a closed loop supply chain.

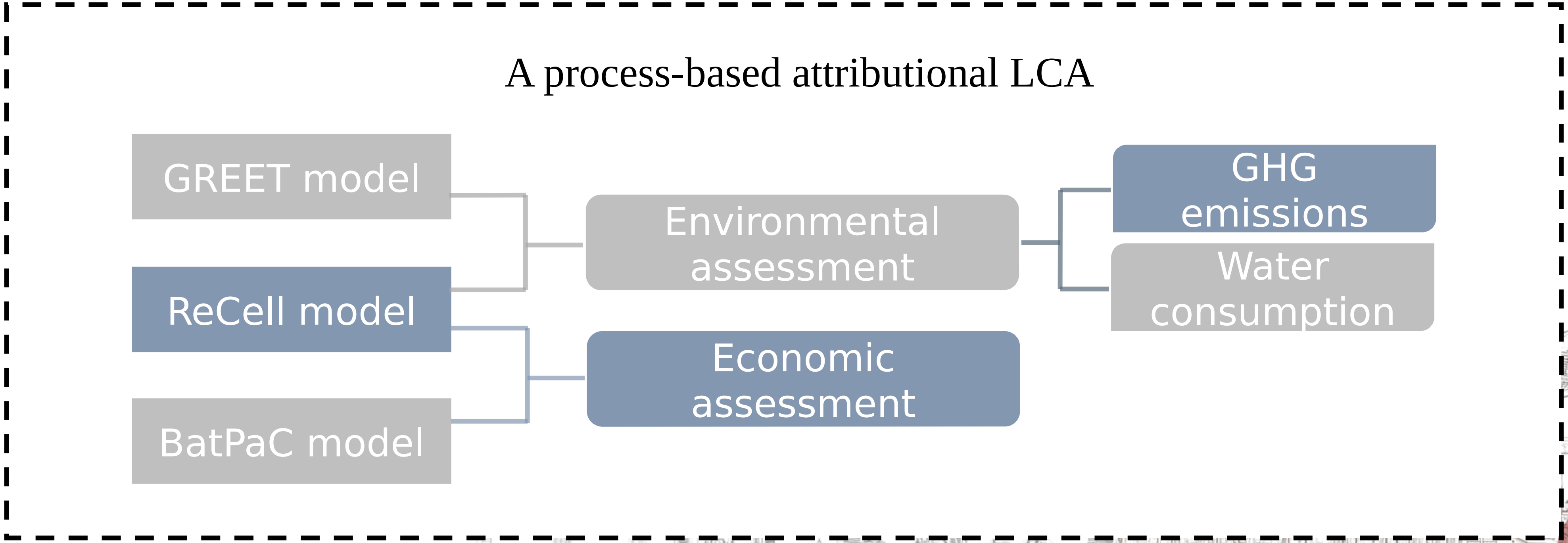
2

Methodologies & Data

Methods

2.1 Life cycle assessment

A process-based attributional LCA is employed in this study. It is worth noting that the use phase of LIBs is not the focus of this paper. A hot spot analysis is conducted to identify the emission-intensive and water-intensive steps.



Methods

2.2 Manufacture and recycling assumptions

Two types of materials, virgin materials and recycled materials recovering from the spent batteries or manufacturing scrap, are considered.

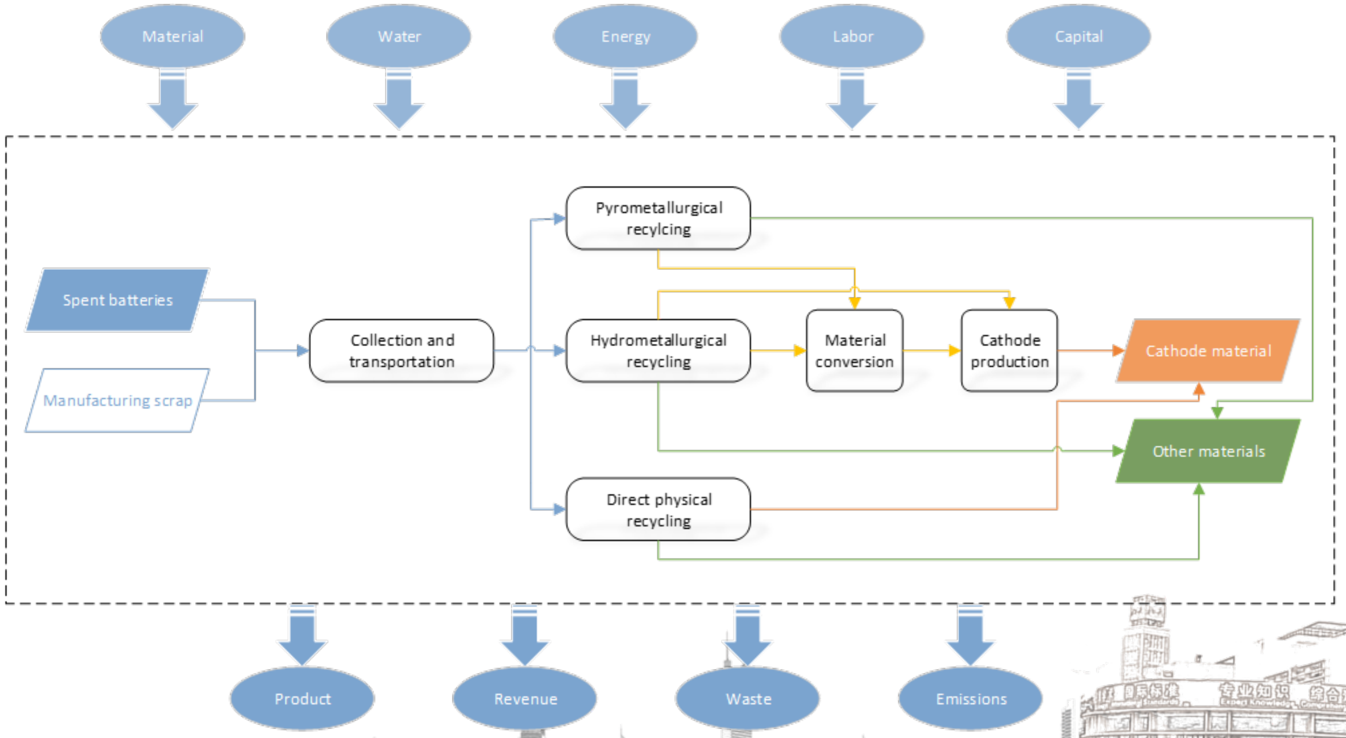


Fig 1. ReCell Model Recycle Module Schematic [23].

Methods

2.3 Recycling methods

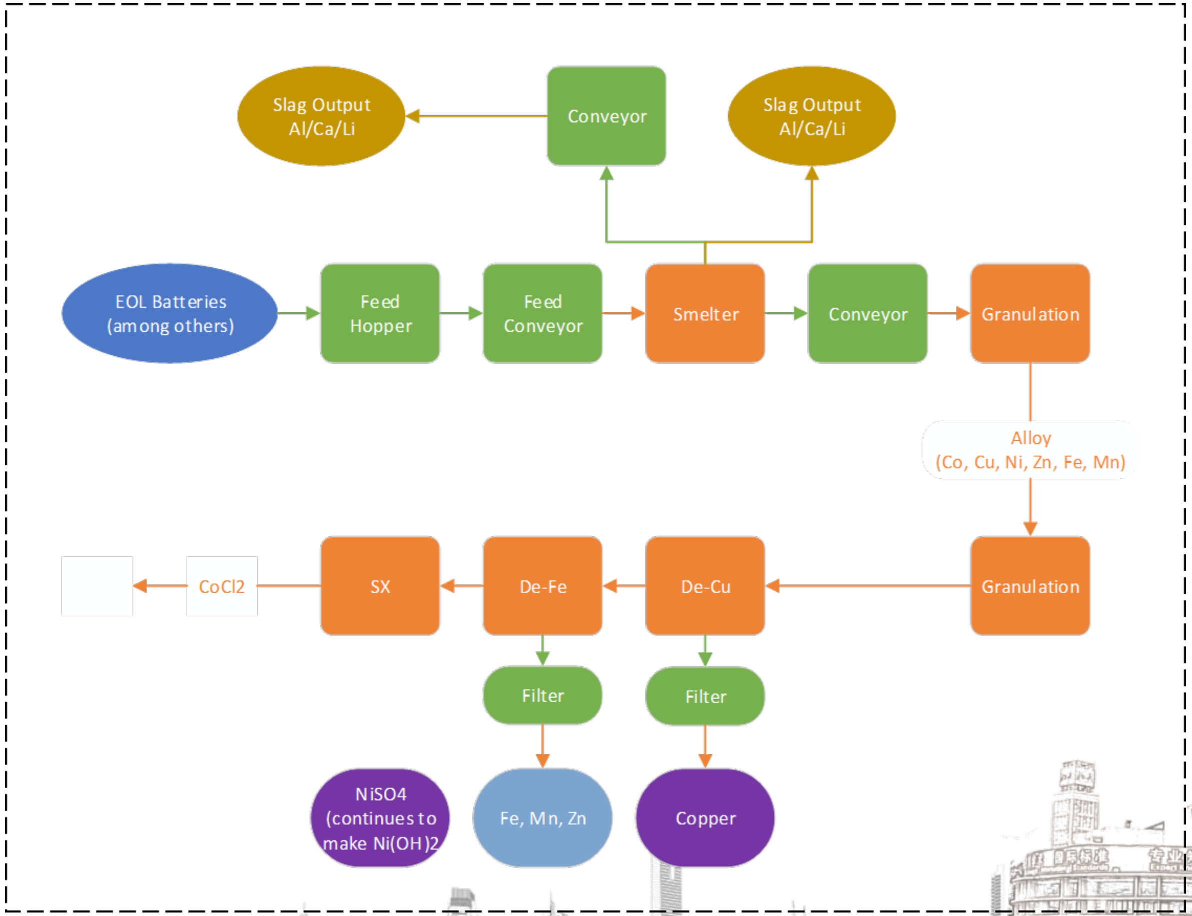


Fig S1. The flow diagrams of pyrometallurgy recycling processes.

Methods

2.3 Recycling methods

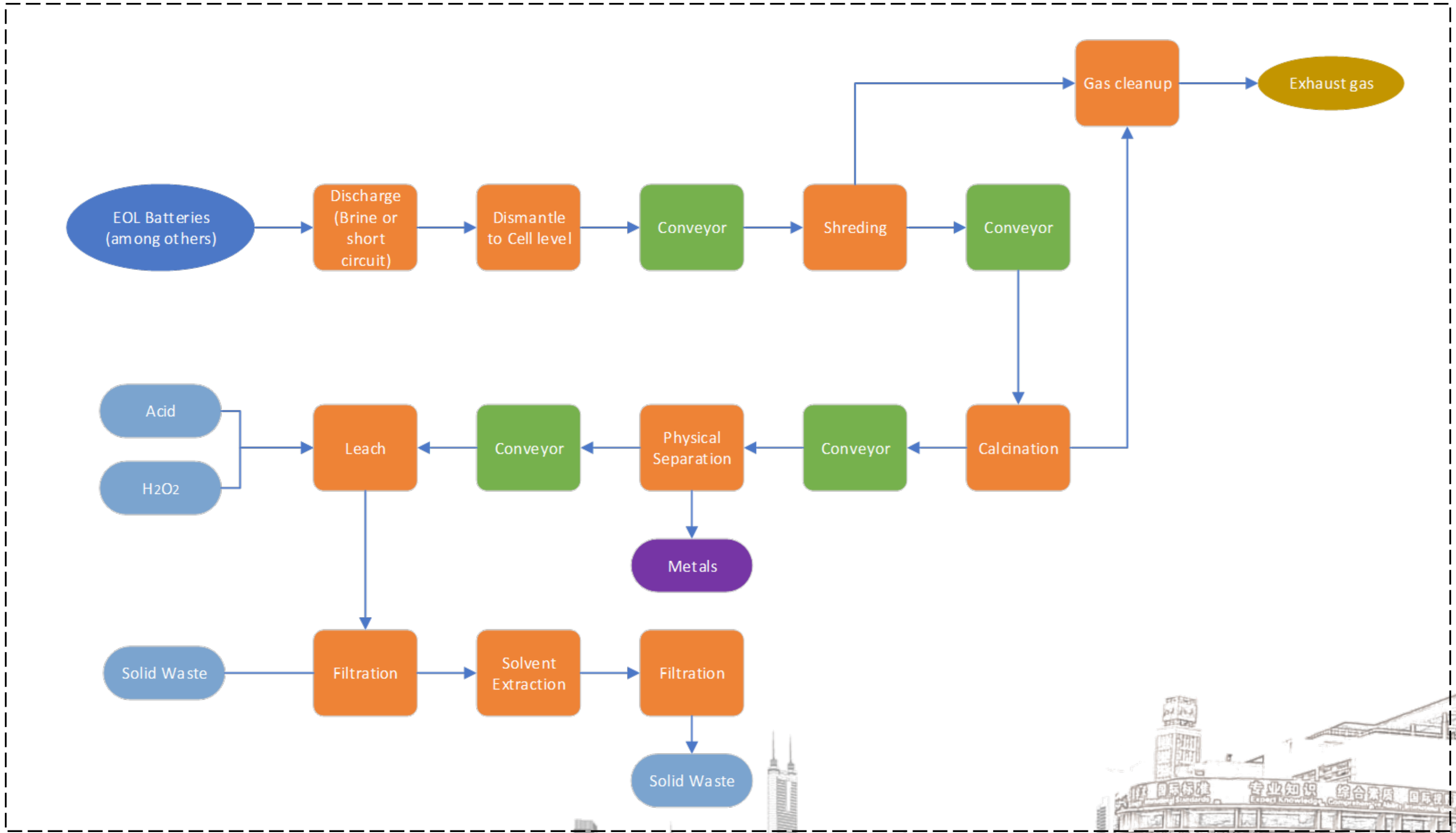
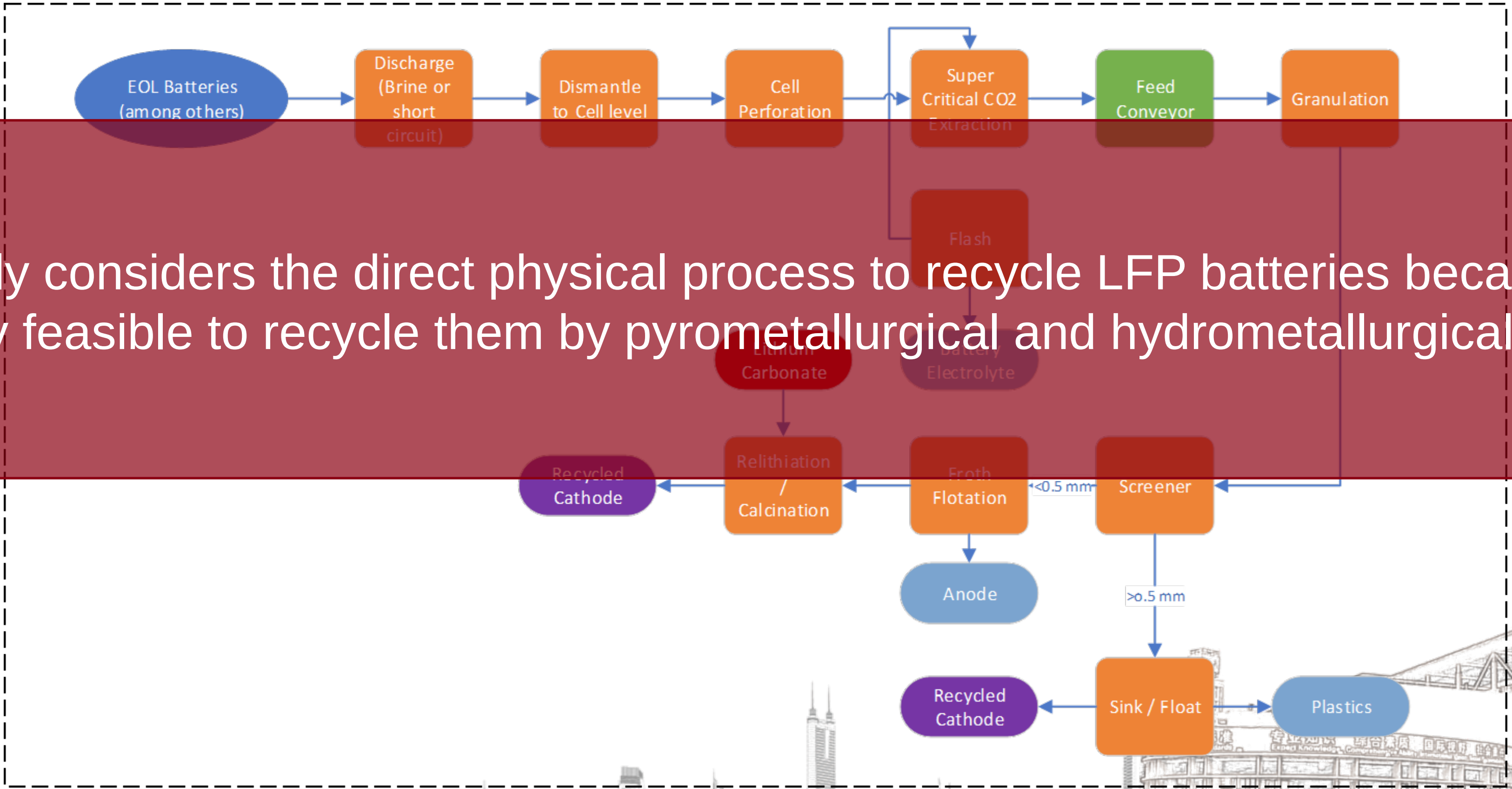


Fig S2. The flow diagrams of hydrometallurgical recycling processes.

Methods

2.3 Recycling methods



This paper only considers the direct physical process to recycle LFP batteries because it is not economically feasible to recycle them by pyrometallurgical and hydrometallurgical methods.

Fig S3. The flow diagrams of direct physical recycling processes.

Methods

2.4 GHG emissions, energy use and water consumption

GHG emissions avoided and water consumption avoided are calculate to reflect the environmental impact of various recovery methods. Eq. (2) below shows how these are calculated.

$$A_{m,r} = (T_{m,v} - T_{m,r})/T_{m,v} \quad (2) \tag{2}$$

The data are obtained from government reports, literature, GREET model, BatPaC model and ReCell model. (Table S1)

Water consumption factors are shown in Table S9. Data sources include Liao et al. [35], Lin, Chen [36] and the default values in the GREET model.

Methods

2.5 Cost model

- This study employs a process-based model (PBCM) to calculate the entire cost of the battery production.

- Meanwhile, in China, the spent battery market is immature, the price information is not sufficiently transparent and the price is volatile. Therefore, a sensitivity analysis is carried out to determine the maximum affordable purchase price of spent batteries at the breakeven recycling cost.

- In addition, in order to assess the impact of production, we conduct a sensitivity analysis to analyze the cost changes of production from 1000 to 100000.

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Result
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3.1 GHG emissions

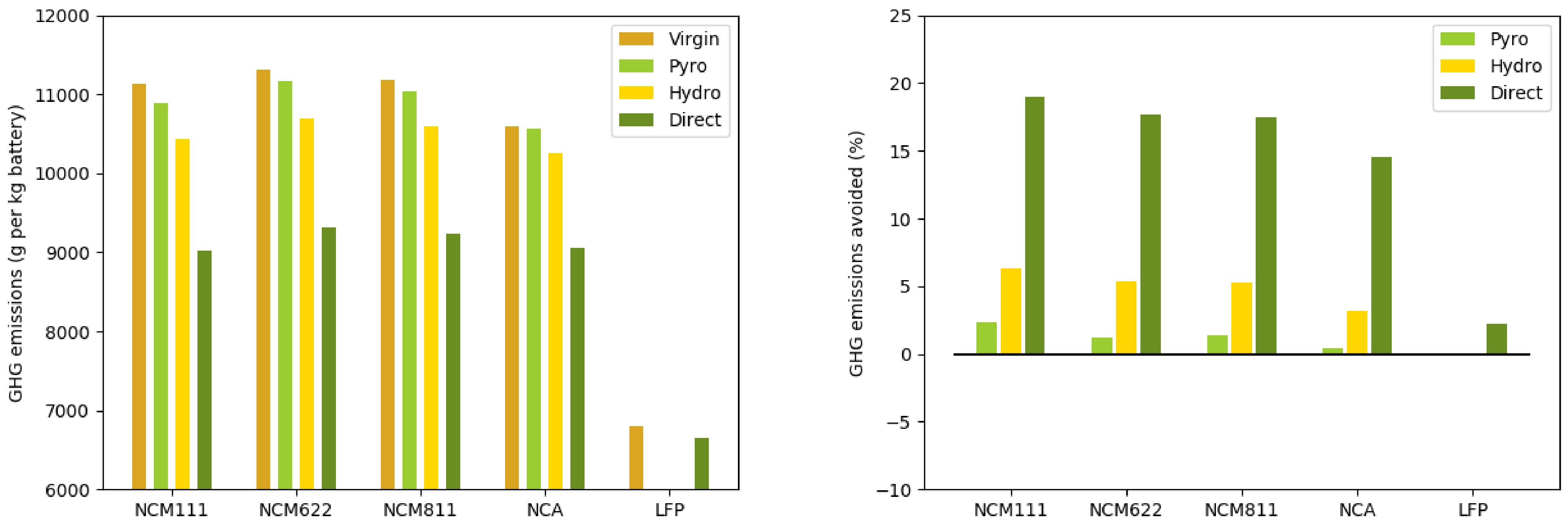


Fig 3. Total estimated GHG emissions (gCO_2e per kg battery) and GHG emissions avoided (%) for NCM111, NCM622, NCM811, NCM and LFP cells. All processes use the national electricity mix data.

3.2 Water consumption

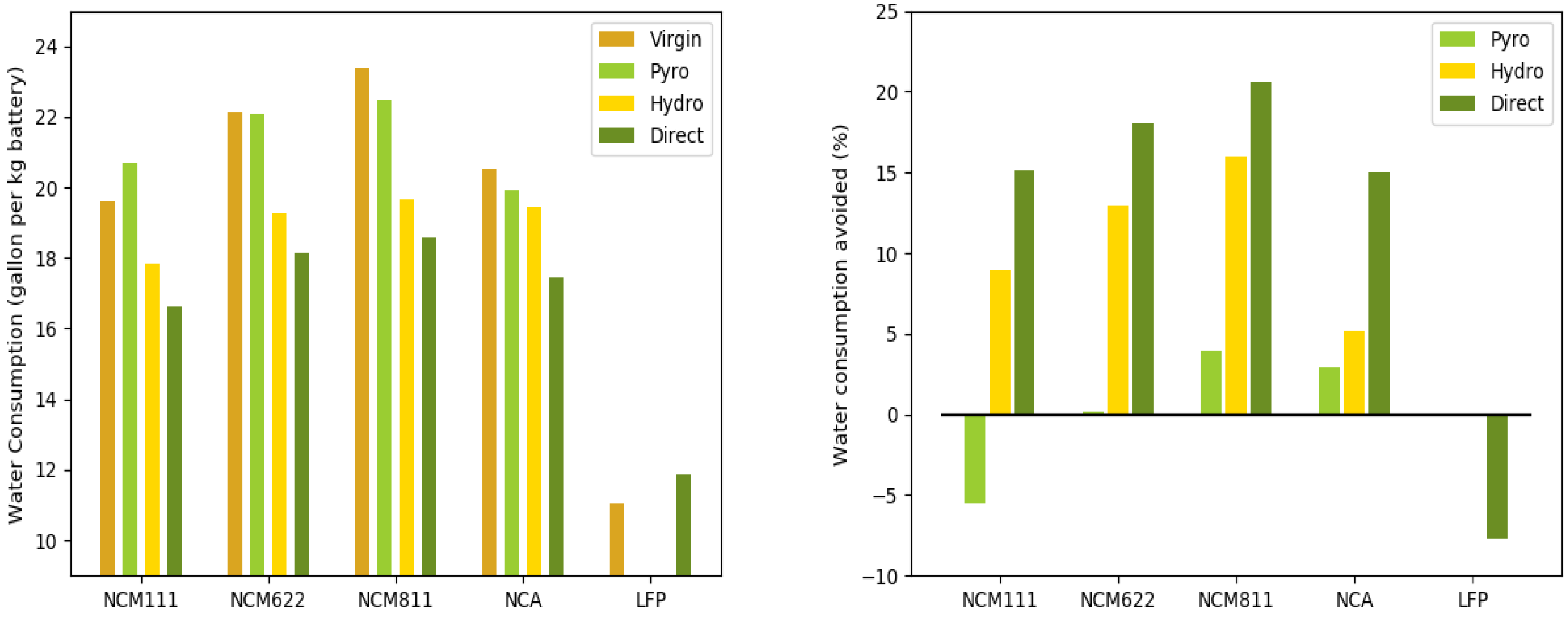
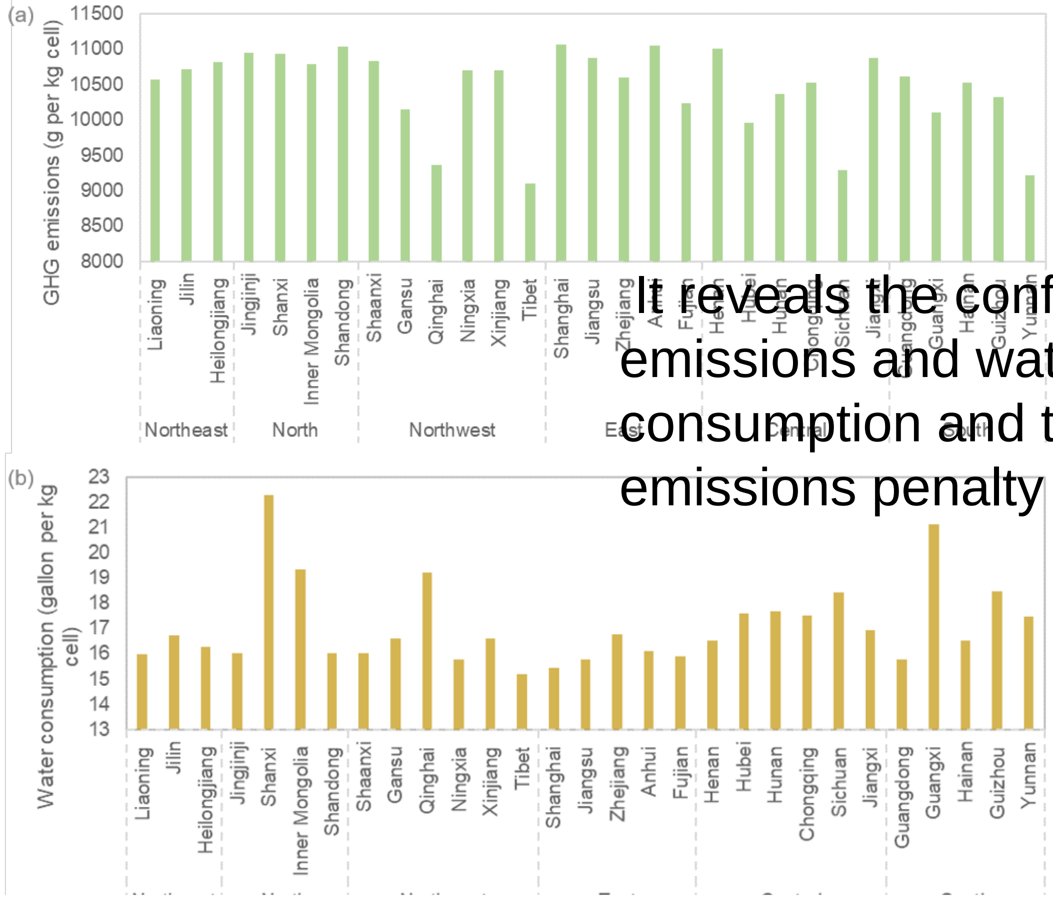


Fig 3. Total estimated water consumption (gallon per kg battery) and water consumption avoided (%) for NCM111, NCM622, NCM811, NCM and LFP cells. All processes use the national electricity mix data.

3.3 Impact of electricity mix structures



It reveals the conflict between GHG emissions and water, i.e. the savings of water consumption and the corresponding GHG emissions penalty of the life cycle LIB.

Fig 7. GHG emissions and water consumption in battery life cycle based on the provincial electricity mix. NCM_{111} cells using hydrometallurgical recycling method are assessed.

3.4 Breakeven cost

Table 5. Cost reduction (%).

	Pyro	Hydro	Direct
NCM_{111}	3.81%	7.34%	14.90%
NCM_{622}	1.97%	5.36%	12.97%
NCM_{811}	1.60%	5.02%	12.57%
NCA	8.79%	11.73%	18.10%
LFP			14.67%

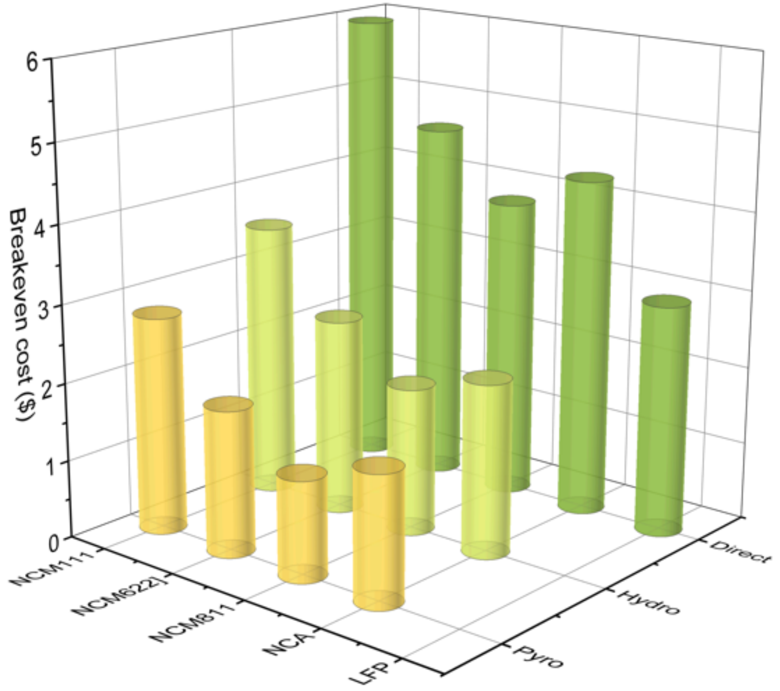


Fig 9. Purchase price of spent batteries at breakeven point.

3.4 Breakeven cost

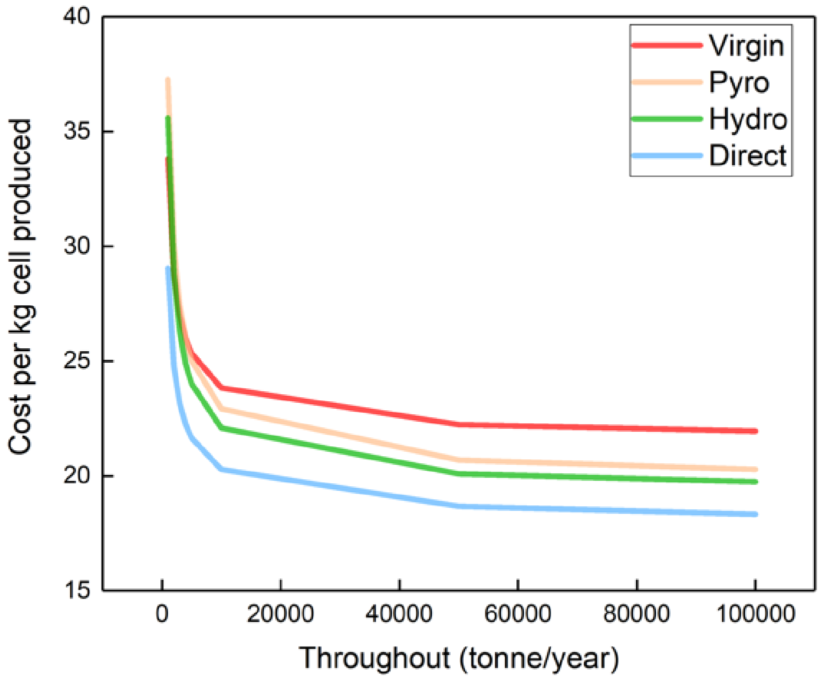


Fig 10. NCM_{111} battery cost varies with throughput. (unit:$)

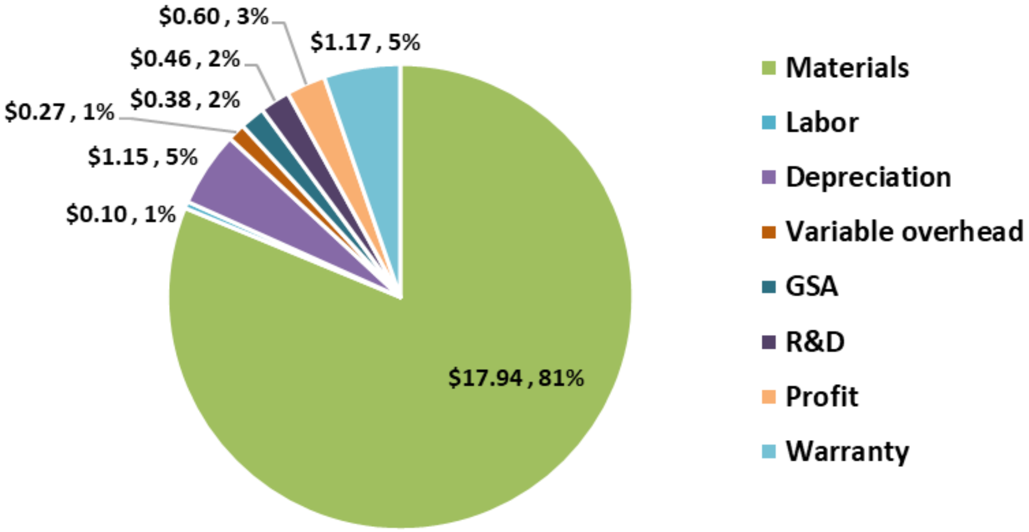


Fig 11. Cell manufacturing cost breakdown. “GSA” represents general, sales and administration. R&D means research and development.

4

Discussion & Conclusion

- Results demonstrates that direct physical recycling process has the lower environmental burdens and higher economic feasibility over the other methods, excluding LFP cells in which mitigated carbon emissions and higher economic viability are observed but meanwhile direct recycling process water consumption increases.

- It should be noted that provinces with higher proportions of hydropower contributions generate lower carbon emissions but have higher water consumption due to reservoir evaporations.

- It shows that the three objectives, i.e. carbon emission reduction, water consumption reduction and economic development, may not be met simultaneously, which requires further studies on their trade-offs and synergies.

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THANKS

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Limitations

- There have some certain limitations in this work. Some studies point out that process-based LCA applied in this study have cutoff errors because it overlooks many upstream processes and is affected by system boundary truncation [46-49]. Thus, as the uncertainty of the results is reduced, an integrated hybrid LCA is recommended for future studies, which integrates the economic input-output system and the process-based LCA [50].

- Furthermore, Ji et al. [51] reveal that replacing the conventional automobiles with the electric vehicles transfers the GHG emissions from city (exhaust pipes) to predominant countryside (electricity power plant), because the power source of automobiles is provided by electricity instead of fossil fuels. Therefore, evaluating the transferring of other negative environmental impacts, such as water consumption, of using LIBs is also an interesting and worth exploring issue.