Sustainable Energy Technologies and Assessments 64 (2024) 103683

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

journal homepage: www.elsevier.com/locate/seta

Identification of principal factors for low-carbon electric vehicle batteries by using a life cycle assessment model-based sensitivity analysis

Sung-Hoon Kim, Sang-Ho Park, Seong-Rin Lim *

Department of Environmental Engineering, College of Engineering, Kangwon National University, Chuncheon, Gangwon 24341, South Korea

ARTICLE INFO

Keywords:
Carbon footprint
Electric vehicle battery
Monte Carlo simulation
Principal factor
Sensitivity analysis

ABSTRACT

The electric vehicle battery industry has gone to great lengths to reduce the carbon footprint of batteries, so that they can contribute more to mitigating climate change. Previous life cycle assessment (LCA)-based studies have addressed that fossil-derived electricity and energy should be reduced in battery materials-related processes to develop low-carbon batteries; however, they have not examined the effect of battery performance on the carbon footprint. Thus, this study identifies the most principal factors to be focused on to develop low-carbon batteries based on an LCA model formulating the effect of battery performance and on a sensitivity analysis using the Monte Carlo simulation. By contrast to previous studies, the results of this study show that battery performance metrics (i.e., the number of cycles for charge and discharge, energy capacity, energy efficiency) are more principal factors than the electricity and energy consumption in battery production processes, because these performances lead to comprehensive reductions in the materials and energy used for the life cycle of battery. Therefore, this study can contribute to providing valuable information necessary for battery manufacturers to develop low-carbon batteries.

Introduction

Since climate change is a crucial threat to human society and ecosystems, electric vehicles are globally disseminated to displace internal combustion engine (ICE) vehicles and reduce CO_2 emissions in the transportation sector [1,2]. Electric vehicles have less carbon footprint than ICE vehicles due to the high efficiency of overall energy conversion for well-to-wheel vehicle life cycle [3–6]. Since many countries have been recently establishing various policies (for instance, carbon border adjustment mechanism (CBAM) in European Union [7] to globally direct manufacturers to produce low-carbon products, electric vehicle industry needs to reduce the carbon footprint of automotive electric batteries [1] and subsequently would drives battery industry to reduce CO_2 emissions from the production of battery materials such as cathode, anode, housing, and conductors [8], in order to comply with the EU battery regulation [9] and the US Inflation Reduction Act (IRA) [10] and furthermore to proactively prepare for new policies related with CO_2 reduction.

To help develop low-carbon batteries, previous life cycle assessment (LCA)-based studies have showed what processes and materials need to be improved with priority to effectively reduce the battery-associated CO_2 emissions. The common findings from the studies were that the most significant contributors to CO_2 emissions were fossil-derived energy consumptions in the mining, refining, and materials production stages and that, subsequently, energy should be displaced by renewable energy in the materials-related processes [11–14]. Specifically, carbon-intensive materials were found to be nickel and cobalt for cathode active material, graphite for anode active material, and wrought aluminum for battery housing [15–19]. Carbon-intensive processes were found to be calcination for cathode material production and drying for battery cell production [3]. Also, the recycling of end-of-life batteries has been shown to contribute to reducing energy consumption and CO_2 emissions by avoiding the mining and refining of fresh ores [20–24]. However, these previous studies have not examined whether and how much the carbon footprint of batteries is affected by battery performances such as the number of the cycles for charge and discharge, energy capacity for electricity storage, and energy efficiencies for electricity charging and storage. Also, the effect of battery performances cannot be examined by using the European Commission's Product Environmental Footprint Category Rules (PEFCR) for rechargeable batteries [25], because these rules were inherently designed to quantitatively evaluate the footprints of products.

* Corresponding author.
E-mail address: srlim@kangwon.ac.kr (S.-R. Lim).

https://doi.org/10.1016/j.seta.2024.103683
Received 9 October 2023; Received in revised form 24 January 2024; Accepted 11 February 2024
Available online 20 February 2024
2213-1388/

Battery performances should be taken into account in LCA to comprehensively examine how to reduce CO_2 emissions associated with batteries because the reference flow used to account for the functional unit is affected by battery performances. Since the functional unit is defined as a unit quantity of the energy delivered to the powertrain of an electric vehicle in the use stage, the quantity of the reference flow (for instance, battery weight required to supply the functional unit) would be decreased if battery performances are improved to extend the lifetime of the battery. This implies that a decrease in battery weight can lead to a reduction in CO_2 emissions associated with materials production and battery manufacturing (i.e., mining, refining, and processing for the materials of battery constituents, and battery manufacturing for cell, module, and pack) in the cradle-to-gate system boundary [26]. As other examples, in case the number of battery cycles is increased or battery energy capacity for electricity storage is increased, the reference flow (i.e., battery weight) for the functional unit is decreased because of an increase in the total amount of the energy delivered to electric vehicle during the lifetime of the battery. Thus, the effect of battery performances on CO_2 emissions indirectly associated with the production and use stages should be examined to determine whether battery performances are more significant contributors to CO_2 emissions than energy consumptions in the cradle-to-gate system boundary, which have been identified as the most significant contributor to CO_2 emissions by the previous studies that have not taken into account the effect of battery performances.

Thus, the objective of this study is to identify the most principal factors to be improved with priority to effectively reduce CO_2 emissions associated with automotive electric batteries based on an LCA model-based sensitivity analysis by taking into account the effect of battery performances on CO_2 emissions in the cradle-to-cradle system boundary including battery recycling stage. An LCA is first conducted and then the sensitivity analysis is performed based on an LCA model developed by modifying Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model [27] in order to focus on the life cycle of battery rather than for electric vehicle. The feature of the modified model is to formulate the effect of battery performances on the reference flow for the LCA. The LCA results are analyzed to identify principal contributors to CO_2 emissions associated with the battery. As another approach to finding out the principal contributors, a sensitivity analysis is conducted to figure out what materials- and energy-related factors significantly affect CO_2 emissions. The respective principal contributors from the two approaches are compared with each other to see whether they are identical and whether the best solution for low-carbon battery production is to reduce fossil-derived electricity and energy consumed in the life cycle as addressed in the previous LCA studies. This study can provide automotive battery manufacturers with valuable information on what factors should be targeted and improved technologically to effectively reduce the carbon footprint of electric vehicle batteries.

Methods

Life cycle CO_2 assessment

An LCA was carried out to evaluate CO_2 emissions in the cradle-to-cradle system boundary of an NMC622-based lithium-ion battery by taking into account the supply chains of the batteries produced in South Korea. The NMC622 battery was selected for this study because this type of batteries currently has the highest market shares for electric vehicle industry, as presented in Table S1 in the Supplementary Material. The energy capacity of the battery was set at 75.4 kWh, which represents the average capacity of the batteries installed in the electric vehicles currently selling in the market of South Korea. Table 1 shows the principal specifications related with the performance of the electric vehicle battery selected for the LCA study. The LCA procedure was in accordance with the ISO 14040 series of standards [28].

Table 1
Principal specifications related with the performance of the electric vehicle battery selected for this study.

Specifications	Quality or Quantity
Type of Battery Cathode	NMC622
Battery Cycle for Charge and Discharge (cycles)	1000
Battery Weight (kg)	457
Battery Energy Capacity (kWh)	75.4
Energy Efficiency of Electricity Storage (%)	96.0
Energy Efficiency of Electricity Charging (%)	95.0

Goal and system definition

The goal of this LCA was set to be the same as the objective of this study. The functional unit and reference flow were defined based on the European Commission's PEFCR for high specific energy rechargeable batteries for mobile applications [25] because a PEFCR for electric vehicle batteries is not currently available but similar with that for mobile applications due to the same function of the two types of batteries. In this study the function of the battery is to supply electrical current to electric vehicles at a desired voltage, and thus the functional unit was defined as 1 kWh of the energy delivered to the powertrain of the vehicle during the lifetime of the battery, expressed in 1kWh D. The reference flow was defined as the mass (in kg) of the battery needed to supply 1 kWh D (i.e., the functional unit) to the vehicle because reference flow is the amount of a product required to fulfill the functional unit [29,30]. Thus, the reference flow was calculated as follows:

$$\mathrm{RF} = \frac{M_B}{MC_E N_C F_{EEC}} \tag{1}$$

where RF is a reference flow (kg/kWh); M_B is a mass of the battery (kg); MC_E is a maximum energy storage capacity of the battery per cycle (kWh); N_c is a number of the cycles during the battery lifetime; and F_{EEC} is a fraction of the energy capacity that is effectively used on average during battery lifetime. Eq. (1) was integrated into the GREET model to investigate into the effect of battery performances (i.e., energy capacity, the number of total cycles, and the effective fraction of the battery energy capacity) on CO_2 emissions from the battery. It should be noted that this modification of the existing GREET model enables this study to be differentiated from the previous studies that could not take into account the effect of battery performances, even though they have conducted sensitivity analysis in their LCAs.

The system boundary (Fig. 1(a)) was defined by including the upstream and downstream of the battery product from the cradle-to-cradle perspective: mining and refining, materials production, battery manufacturing for cell, module, and pack, use, and inorganic acid leaching-based closed-loop recycling. Fig. 1(b) shows the battery materials taken into account in the materials production and battery manufacturing stages: more details are presented in Fig. S2 in the Supplementary Material. To reflect the supply chains of the batteries produced in South Korea, the cathode materials were assumed to be imported by China, and the anode material and aluminum were assumed to be produced in South Korea, even though some fraction of these materials are supplied from other countries. Also, the battery cell, module, and pack were assumed to be manufactured in South Korea.

For the battery use stage, the GREET model was additionally modified to take into account the energy efficiencies related with the energy loss incurred during electricity charging and storage, because the model does not include CO_2 emissions from these energy losses. The energy efficiencies for charging and storage were set at 96 % and 95 %, respectively [25].

Life cycle inventory

The bill of material (BOM) for the reference flow was obtained by using the material compositions from Argonne National Laboratory's Battery Performance and Cost (BatPaC) model [31] and the average

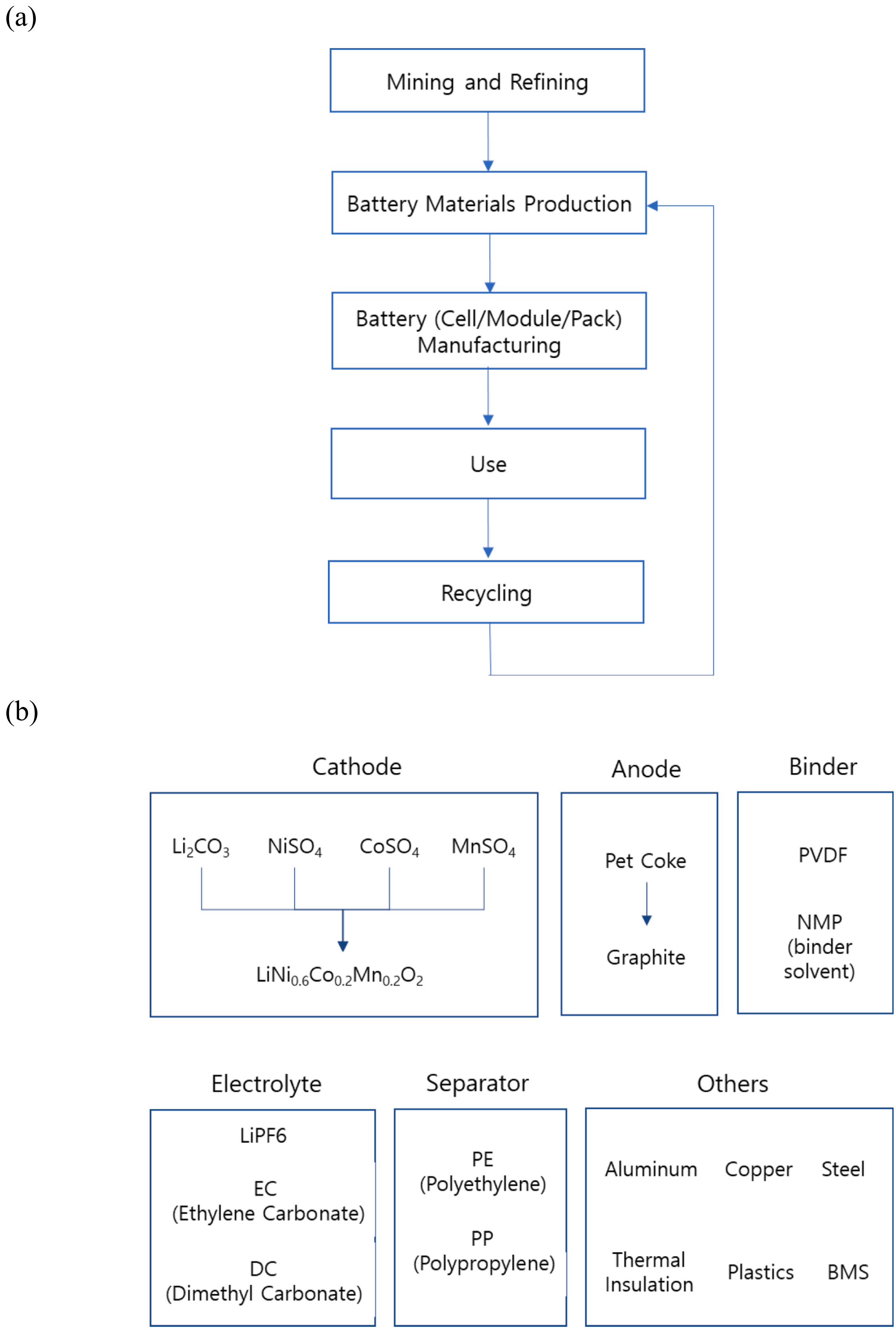


Fig. 1. System boundary of the life cycle assessment: (a) cradle-to-cradle life cycle stages; and (b) battery materials taken into account in the materials production and battery manufacturing stages. More details are presented in Fig. S2 in Supplementary Materials.

energy density (0.165 kWh/kg) from the GREET model. The data for energy and electricity mix in the respective countries for the supply chain were from the United States' Energy Information Administration (EIA) [32]). The statistics data for international trade were used to reflect the real situations of material flows in the supply chains of the batteries produced in South Korea. The inventory data for the principal contributors to CO_2 emissions are presented in Tables S2 to S5 in the Supplementary Material.

Life cycle impact assessment

The CO_2 emissions associated with the materials and processes in the life cycle of the battery were evaluated by using the modified GREET model. The amounts of greenhouse gases (i.e., CO_2, N_2O, and CH_4) were aggregated in CO_2-equivalent by using the global warming potentials with a time horizon of 100 years (GWP100) presented in the Sixth Assessment Report (AR6) of Intergovernmental Panel on Climate Change (IPCC) [33]: the GWPs of N_2O and CH_4 are 29.8 and 273, respectively. All the CO_2 emissions in the life cycle were summed to calculate the amount of the CO_2 emissions incurred to fulfill the functional unit of the battery.

Life cycle interpretation

Based on the life cycle impact assessment results, the principal contributors to the CO_2 emissions of the battery were identified. Also, the input data affecting the principal contributors were reviewed and updated to improve the representativeness, temporal and spatial appropriateness, and completeness of the data and thus increase the confidence of the LCA results.

Sensitivity analysis

A Monte-Carlo simulation was performed to identify what factors (for instance, materials, processes, and battery performances) sensitively affect the CO_2 emissions of the battery. The simulation was applied to the LCA model developed in this study by modifying the GREET model. The input data were assumed to be normally distributed because the type of data distribution could not be examined and identified due to insufficient data availability (note that this assumption was unavoidable, even though the type of the distribution of actual data could affect sensitivity analysis). The mean and standard deviation of the normal distribution function were assumed to be the value of the input data and 10 % of that mean, respectively. The simulation was performed in 100,000 trials by using the Crystal Ball software [34]. The sensitivity analysis results were analyzed to identify principal contributors to the CO_2 emissions of the battery, which were compared to the principal contributors identified based on the LCA results. To verify the sensitivity analysis results, this study quantified how much the 10 % changes of the principal contributors affect the changes in the CO_2 emissions of the battery on the basis of the functional unit.

Results and discussion

Life cycle assessment results

The CO_2 emissions for the functional unit were significantly incurred from the mining and refining stage, as shown in Fig. 2. This result was identical with the previous studies because the mining and refining stage consumes a significant amount of electricity, natural gas, and coal (see Fig. 3); specifically, the aluminum production accounted for the highest CO_2 emissions due to the high consumptions of electricity. In the cradle-to-gate system boundary the materials-related stages (i.e., mining/refining and battery materials production) had higher CO_2 emissions than the battery manufacturing stage. For instance, cathode material processing as a single process had the second highest CO_2 emissions. However, these LCA results did not show the effect of battery performance on CO_2 emissions as not in the previous studies and the European Commission's PEFCR.

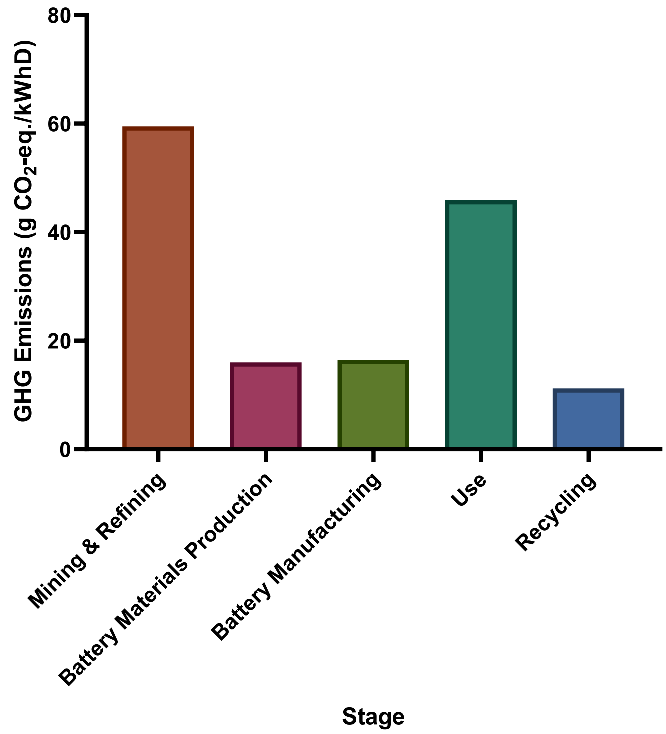


Fig. 2. CO_2 emissions from the respective life cycle stages of the battery on a basis of the functional unit.

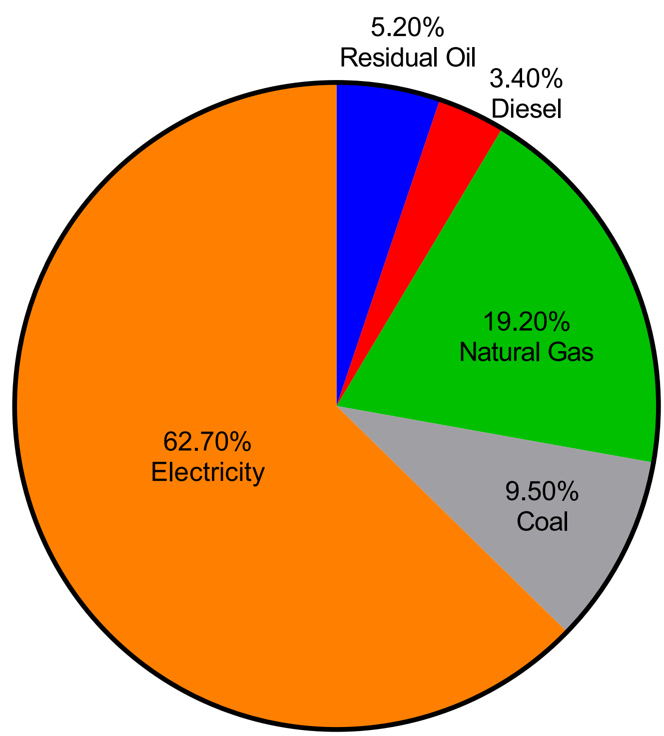


Fig. 3. Shares of the energy used in the stages of mining, refining, materials processing, and battery manufacturing.

The battery use stage exhibited the second highest and more significant CO_2 emissions than the battery manufacturing and recycling stages (see Fig. 2). The CO_2 emissions in the use stage were incurred from the energy loss related with the energy efficiencies for electricity storage and charging. This was interesting because the use stage was not taken into account in most of the previous LCA studies, which have focused on the cradle-to-gate system boundary to reduce the CO_2 emitted in the upstream supply chains of battery products. Even in case the use stage was taken into account in the LCA, the CO_2 emissions from the energy loss have been neglected because the electricity loss was small compared to the electricity used to operate the electric vehicle during a long lifetime of the battery. This study clearly showed that the energy efficiencies of batteries should be improved to develop low-carbon batteries.

The battery manufacturing stage exhibited the third highest CO_2 emissions, and the recycling stage exhibited the lowest CO_2 emissions (see Fig. 2). For the manufacturing stage, CO_2 emissions were incurred primarily from cell production process due to the high consumption of energy in drying process. CO_2 emissions from the recycling stage were significantly less than for the mining and refining stage. Thus, closed-loop materials recycling systems need to be established to significantly reduce the carbon footprint of battery products.

Sensitivity analysis results

Different from the LCA results, the sensitivity analysis results (Fig. 4) showed that all of the top 5 principal contributors to the CO_2 emissions for the functional unit were battery performances and weight rather than energy consumed in the stages of the mining, refining, materials processing, and battery manufacturing. Thus, this study found out that battery performance improvements are more important factors for low-carbon batteries than energy reductions in the supply chains of batteries. The highest principal contributor was the number of the battery cycles for charge and discharge because the battery cycle directly affects the lifetime of the battery. In other words, an increase in the number of cycles leads to an increase in the total energy delivered to the electric vehicle during its extended lifetime, and subsequently results in a decrease in the reference flow (i.e., battery weight implying the quantities of battery materials) for the LCA, as shown in eq. (1). Consequently, this entails a decrease in CO_2 emissions associated with the battery materials-related processes including refining and materials production. The second and third highest contributors were the energy capacity and weight of the battery, which affected the CO_2 emissions for the functional unit in the same way as the battery cycle did. The fourth and fifth principal contributors were the energy efficiencies of the battery, which affect energy loss incurred from electricity charging and storage. This energy loss incurred a significant amount of CO_2 emissions due to the long time of the battery use stage. The next contributors except the recycling ratio of nickel sulfate were directly related with energy consumptions for the production of battery materials (i.e., aluminum, anode, and cathode) and for battery manufacturing. This energy consumption has been identified as the most significant contributors to the CO_2 emissions in the previous LCA studies.

The results of the sensitivity analysis showed a new finding that battery manufacturers should prioritize the improvement of battery performance and the reduction of battery weight to develop low-carbon electric vehicle batteries. This strategy would be necessary in parallel with increasing the supply of renewable energy because renewable energy is not currently sufficient to significantly displace the fossil-derived electricity and energy used in the mining, refining, and materials processing stages.

Table 2 shows the effect of the 10 % changes of the principal contributors identified by the sensitivity analysis on the CO_2 emissions for the functional unit. An increase in the number of battery cycles leads to a 6.3 % decrease in the CO_2 emissions, which was the highest reduction. Lower battery weight and higher energy capacity reduce emissions by 5.8 % and 5.3 %, respectively. Higher energy efficiencies of electricity charging and storage reduce the CO_2 emissions by 2.1 % and 1.7 %, respectively. In case these five battery performances are improved at the same time, a 19.5 % reduction could be obtained. In the same context, Fig. 5 (a) and (b) shows the effect of the 10 % changes of the principal contributors on the CO_2 emissions in the life cycle stages and for the major materials, respectively. The battery performance improvement and a reduction in the amount of materials used had the highest potentials to significantly reduce the CO_2 emissions incurred in all the life cycle stages and from the productions of the materials.

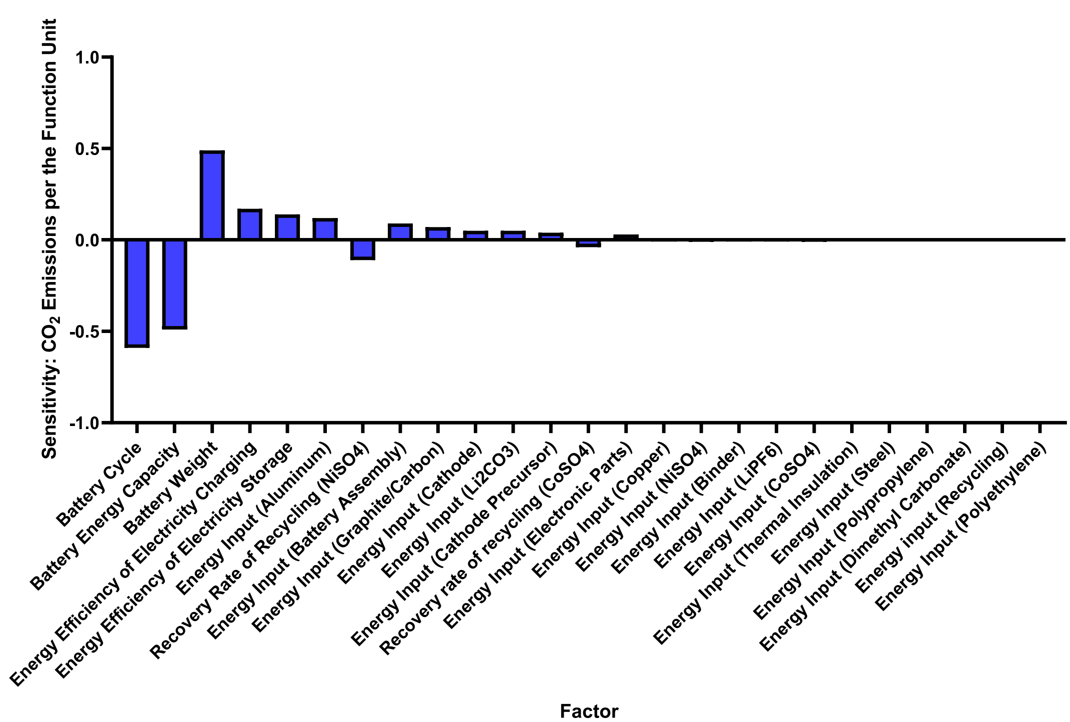
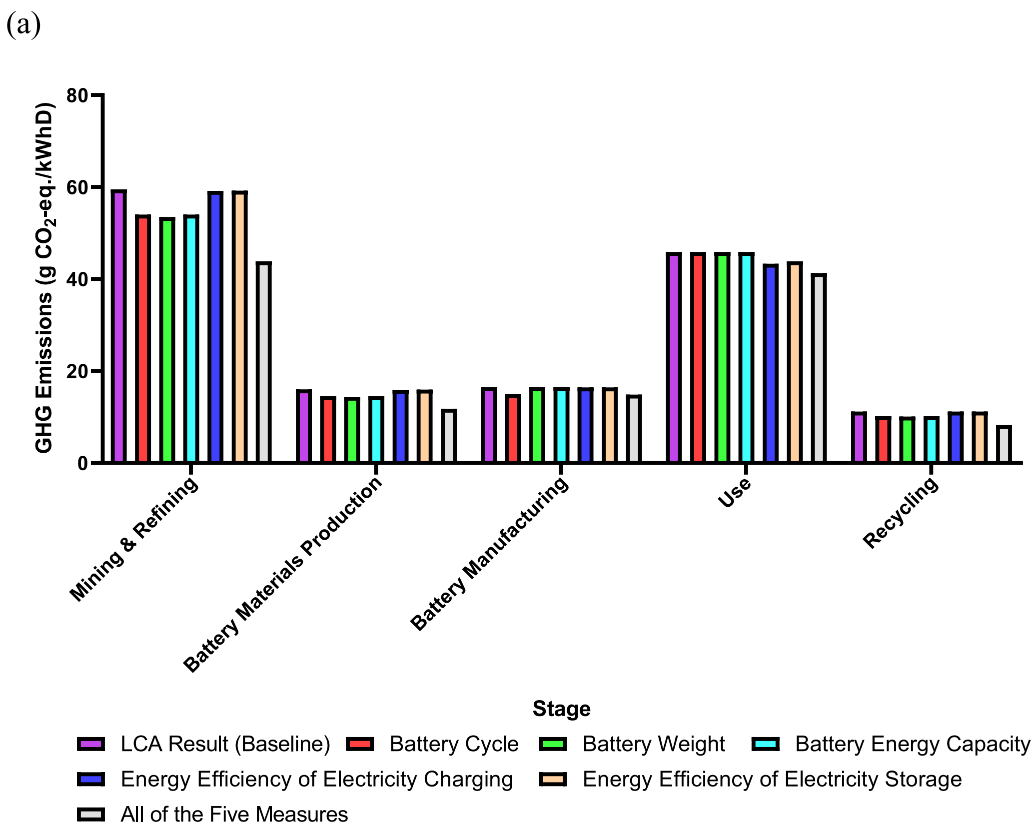


Fig. 4. Sensitivity analysis results for the life cycle assessment of the battery.

Table 2
Effect of the 10% changes of the top 5 principal contributors identified by the sensitivity analysis on the CO_2 emissions for the functional unit of the LCA.

	LCA result (Baseline)	Battery performance improvement and dematerialization					
		Battery cycle (+10 %)	Battery weight (-10 %)	Battery energy capacity (+10 %)	Energy efficiency of electricity charging (+10 %)	Energy efficiency of electricity storage (+10 %)	All of these five measures
CO_2 Emissions for the Functional Unit (g CO_2 –eq./ kWh D)	149.1	139.8	140.5	141.3	146.1	146.7	120.1
Reduction ratio (%)	–	6.3 %	5.8 %	5.3 %	2.1 %	1.7 %	19.5 %



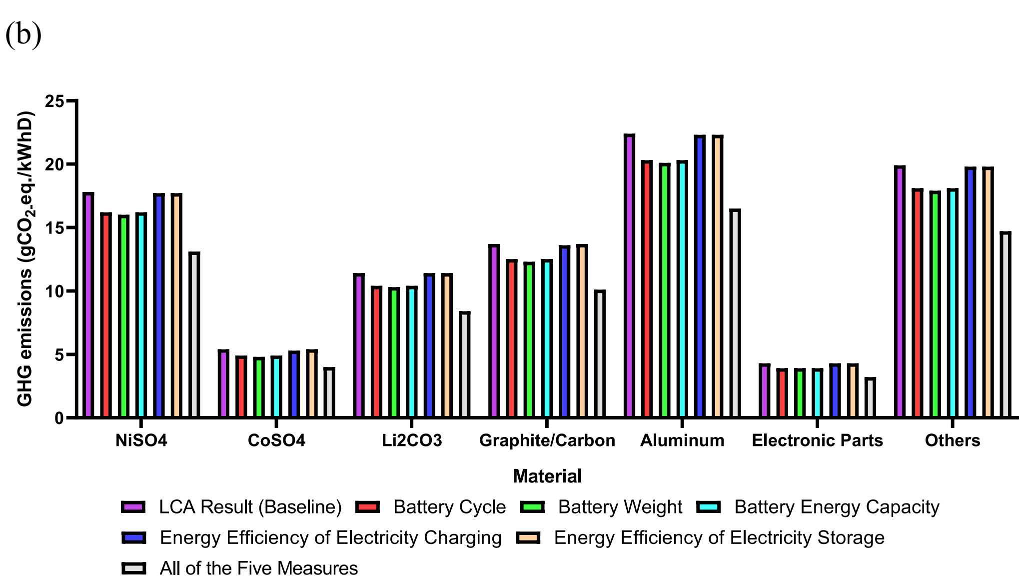


Fig. 5. Effect of the 10% changes of the principal contributors on the CO_2 emissions for the life cycle stages and major materials: (a) life cycle stages; and (b) materials.

Conclusions

The results of the sensitivity analysis showed that the CO_2 emissions of the battery were more significantly affected by battery performance (i.e., number of charge–discharge cycles, energy capacity, and energy efficiencies for charging and storage) and battery weight than by electricity and energy consumption in the materials- and manufacturing-related processes. This is a new finding different from the previous studies that have been based on the LCA that did not take into account the effect of battery performances on the CO_2 emissions of batteries. The previous studies have suggested that renewable energy should be applied to battery supply chains to reduce fossil-derived electricity and energy; however, this way would not be currently realistic due to the low availability of renewable energy. By contrast, this study suggests that battery performance improvement and a reduction in the amount of materials used in batteries are effective directions to the development of low-carbon electric batteries; thus, the development of battery technology should be accompanied by the effort to increase the supply of renewable energy. The findings of this study would be worthwhile to consider in order to reduce the carbon footprint of other types of battery products such as uninterruptible power supply (UPS) and energy storage system (ESS). Therefore, this study can contribute to providing valuable information for battery manufacturers to develop more environmentally friendly batteries for climate change mitigation.

CRediT authorship contribution statement

Sung-Hoon Kim: Investigation, Methodology, Software, Visualization, Writing – original draft. **Sang-Ho Park:** Investigation, Software. **Seong-Rin Lim:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgment

This research was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (NRF-2020R1A2C1008532).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seta.2024.103683.

References

[1] Agency, I.E., 2022. Global EV Outlook 2022: Securing supplies for an electric future.
[2] Kumar RR, Alok K. Adoption of electric vehicle: a literature review and prospects for sustainability. J Clean Prod 2020;253:119911.
[3] Dunn JB, Gaines L, Kelly JC, James C, Gallagher KG. The significance of Li-ion batteries in electric vehicle life-cycle energy and emissions and recycling's role in its reduction. Energ Environ Sci 2015;8(1):158–68.
[4] Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH. Comparative environmental life cycle assessment of conventional and electric vehicles. J Ind Ecol 2013;17(1): 53–64.
[5] Notter DA, Gauch M, Widmer R, Wäger P, Stamp A, Zah R, et al. Contribution of Li-Ion batteries to the environmental impact of electric vehicles. Environ Sci Tech 2010;44(17):6550–6.
[6] Wolfram P, Weber S, Gillingham K, Hertwich EG. Pricing indirect emissions accelerates low—carbon transition of US light vehicle sector. Nat Commun 2021; 12(1):7121.
[7] Council, E., 2022-12-13. EU climate action: provisional agreement reached on Carbon Border Adjustment Mechanism (CBAM). European Council Press Releases.
[8] Agency, I.E., 2021. Global EV Outlook 2021: Supply chains for batteries and electric vehicles.
[9] Melin HE, Rajaeifar MA, Ku AY, Kendall A, Harper G, Heidrich O. Global implications of the EU battery regulation. Science 2021;373(6553):384.
[10] Bistline J, Blanford G, Brown M, Burtraw D, Domeshek M, Farbes J, et al. Emissions and energy impacts of the inflation reduction act. Science 2023;380(6652):1324–7.
[11] Ahmadi L, Young SB, Fowler M, Fraser RA, Achachlouei MA. A cascaded life cycle: reuse of electric vehicle lithium-ion battery packs in energy storage systems. Int J Life Cycle Assess 2017;22(1):111–24.
[12] Carvalho ML, Temporelli A, Girardi P. Life cycle assessment of stationary storage systems within the Italian electric network. Energies 2021;14(8).
[13] Ellingsen L-A-W, Hung CR, Strømman AH. Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions. Transp Res Part D: Transp Environ 2017;55: 82–90.
[14] Ellingsen L-A-W, Majeau-Bettez G, Singh B, Srivastava AK, Valøen LO, Strømman AH. Life cycle assessment of a lithium-ion battery vehicle pack. J Ind Ecol 2014;18(1):113–24.
[15] Burnham A, Lu Z, Wang M, Elgowainy A. Regional emissions analysis of light-duty battery electric vehicles. Atmosphere 2021;12(11).
[16] Dai Q, Kelly JC, Gaines L, Wang M. Life cycle analysis of lithium-ion batteries for automotive applications. Batteries 2019;5(2).
[17] Hao H, Mu Z, Jiang S, Liu Z, Zhao F. GHG emissions from the production of lithium-ion batteries for electric vehicles in China. Sustainability 2017;9(4):504.
[18] Kelly JC, Dai Q, Wang M. Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries. Mitig Adapt Strat Glob Chang 2019; 25(3):371–96.
[19] Wang Q, Liu W, Yuan X, Tang H, Tang Y, Wang M, et al. Environmental impact analysis and process optimization of batteries based on life cycle assessment. J Clean Prod 2018;174:1262–73.
[20] Arshad F, Lin J, Manurkar N, Fan E, Ahmad A, Tariq M-u-N, Wu F, Chen R, Li L. Life cycle assessment of lithium-ion batteries: a critical review. Resour Conserv Recycl 2022;180.
[21] Mayyas A, Steward D, Mann M. The case for recycling: Overview and challenges in the material supply chain for automotive li-ion batteries. Sustain. Mater. Technol. 2019;19.
[22] Quan J, Zhao S, Song D, Wang T, He W, Li G. Comparative life cycle assessment of LFP and NCM batteries including the secondary use and different recycling technologies. Sci Total Environ 2022;819:153105.
[23] Xia X, Li P. A review of the life cycle assessment of electric vehicles: considering the influence of batteries. Sci Total Environ 2022;814:152870.
[24] Yang Y, Boom R, Irion B, van Heerden D-J, Kuiper P, de Wit H. Recycling of composite materials. Chem Eng Process 2012;51:53–68.
[25] Siret C, Tytgat J, Ebert T, Mistry M, Thirlaway C, Schutz B, et al. PEFCR—Product environmental footprint category rules for high specific energy rechargeable batteries for mobile applications. Brussels, Belgium: Recharge; 2018.
[26] Temporelli A, Carvalho ML, Girardi P. Life cycle assessment of electric vehicle batteries: an overview of recent literature. Energies 2020;13(11).
[27] Laboratory, A.N., 2023. Argonne GREET Vehicle Cycle Model (2022 Version). https://greet.es.anl.gov/greet_2_series. (Accessed 01-02 2023).
[28] 2006 (E). ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework. International Standard Organization.
[29] Hiremath M, Derendorf K, Vogt T. Comparative life cycle assessment of battery storage systems for stationary applications. Environ Sci Technol 2015;49(8): 4825–33.
[30] Yudhistira R, Khatiwada D, Sanchez F. A comparative life cycle assessment of lithium-ion and lead-acid batteries for grid energy storage. J Clean Prod 2022;358.
[31] Laboratory, A.N., 2022. Argonne BatPac Model. https://www.anl.gov/cse/batpac-model-software. (Accessed 07-20 2022).
[32] Administration, U.S.E.I., 2023-1-14. Electricity generation by source, country/region, and total electricity generation. https://www.eia.gov/international/data/world/electricity/electricity-generation.
[33] IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, in: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, Ö., Yu, R., and Zhou, B. (Ed.). Intergovernmental Panel on Climate Change.
[34] Bhat A, Kumar A. Application of the Crystal Ball® software for uncertainty and sensitivity analyses for predicted concentration and risk levels. Environ Prog Sustain Energy 2008;27(3):289–94.