Title

US-Mexico Second-Hand Electric Vehicle Trade: Battery Circularity and End-of-Life Policy Implications

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Publication Date

2024-12-01

DOI

10.7922/G23T9FKX

US-Mexico Second-Hand Electric Vehicle Trade: Battery Circularity and End-of-Life Policy Implications

December 2024

A Research Report from the National Center for Sustainable Transportation

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NCST-UCD-RR-24-39	N/A	N/A

4. Title and Subtitle US-Mexico Second-Hand Electric Vehicle Trade: Battery Circularity and End-of-Life Policy Implications	**5. Report Date** December 2024 **6. Performing Organization Code** N/A
7. Author(s) Alissa Kendall, Ph.D., https://orcid.org/0000-0003-1964-9080 Francisco Parés Olguín, https://orcid.org/0000-0002-4835-1200	**8. Performing Organization Report No.** UCD-ITS-RR-24-55
9. Performing Organization Name and Address University of California, Davis Institute of Transportation Studies 1605 Tilia Street, Suite 100 Davis, CA 95616	**10. Work Unit No.** N/A **11. Contract or Grant No.** USDOT Grant 69A3551747114
12. Sponsoring Agency Name and Address U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology 1200 New Jersey Avenue, SE, Washington, DC 20590	**13. Type of Report and Period Covered** Final Research Report (October 2022 – March 2024) **14. Sponsoring Agency Code** USDOT OST-R

15. Supplementary Notes

DOI: For this report: https://doi.org/10.7922/G23T9FKX
DOI: For previously published content: https://doi.org/10.1016/j.trd.2023.103934
Dataset DOIs:
Material Flow Analysis: https://doi.org/10.5061/dryad.x95x69ptn
LCA: https://doi.org/10.5061/dryad.cvdncjtcm
Environmental Justice: https://doi.org/10.5061/dryad.sxksn03bw

16. Abstract

International second-hand vehicle (SHV) exports are a multi-billion-dollar market for the US and an integral process in removing older vehicles from the road and enabling a robust new vehicle market. Mexico is the largest importer of SHVs from the US. As the US rapidly increases electric vehicle (EV) sales to meet decarbonization targets for the transportation sector, EVs will be an increasing large fraction of SHVs. While the benefits of EV adoption are numerous, introducing a radically new technology such as EVs without responsive measures in second-hand market regions may lead to an unintended transfer of economic and environmental burdens, especially if waste EV batteries cannot be managed properly. This research undertook a battery material flow analysis, life cycle assessment of SHVs traded from the US to Mexico, and a qualitive analysis of environmental and transport justice implications of SHV trade. The research finds that SHVs disproportionately contribute to waste battery generation in Mexico, and that second-hand EVs are frequently retired early due to a lack of repairability. In terms of life cycle emissions, SH EVs still contribute to reduced GHG emissions and air pollution relative to internal combustion engine vehicles newly sold in Mexico, but at end-of-life, their batteries are being disposed of in landfills, rather than in recycling facilities. From a justice standpoint, coordination between the US and Mexico and anticipatory policies are needed to ensure that only EVs with sufficient remaining battery life are transferred between the US and Mexico, and that sufficient infrastructure exists to safely dispose of waste EV batteries in Mexico.

17. Key Words	18. Distribution Statement
Second-Hand vehicles, electric vehicles, LCA, battery recycling, critical battery minerals, LMICs, Mexico	No restrictions.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	55	N/A

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

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Disclaimer

Acknowledgments

This study was funded, partially or entirely, by a grant from the National Center for Sustainable Transportation (NCST), supported by the U.S. Department of Transportation (USDOT) through the University Transportation Centers program. The authors would like to thank the NCST and the USDOT for their support of university-based research in transportation, and especially for the funding provided in support of this project. The authors would also like to thank Galym Iskakov for his contributions to this work, Prof. Jesus Barajas for his feedback on the research related to environmental justice, and all those that were willing to be interviewed as part of this research.

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December 2024

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EXECUTIVE SUMMARY

International second-hand vehicle (SHV) exports are a multi-billion-dollar market for the US (*1*) and an integral process in removing older vehicles from the road and enabling a robust new vehicle market, particularly as vehicle inspection and maintenance requirements, emission standards, and incentive schemes make replacement of existing vehicles with a newer fleet more attractive (1). Given the geographic proximity, free trade relationship, and the disparity in economic size and average per-capita wealth, Mexico is, by far, the largest market for US SHVs, receiving nearly 15% of the vehicles retired each year from US roads.

Regular SHV trade with Mexico began in 2005, enabled by provisions in the North American Free Trade Agreement (NAFTA). Since then, over 9 million SH light-duty passenger vehicles (LDVs) have been imported from the US, accounting for 30% of all vehicles registered in Mexico during this period. Despite the removal of import barriers, the influx of illegally introduced SHVs has continued to grow. These unregistered vehicles, absent from official data, are estimated to increase Mexico's total in-use vehicle stock by 25%—to 42 million, with SHVs imported legally or illegally from the US comprising 38%.

As the US rapidly increases electric vehicle (EV) sales to meet decarbonization targets for the transportation sector, its SH EVs have started entering international used vehicle markets. While the benefits of the global rise in EV adoption are numerous, including reduced emissions, increased transportation energy efficiency and security, introducing a radically new technology such as EVs without responsive measures in SH market regions may lead to an unintended transfer of economic and environmental burdens to lower and middle-income countries (LMICs) if they are unprepared to manage EVs, especially at the end of life (EOL).

This research project proposed to answer the following questions to provide a comprehensive understanding of the magnitude and impacts of SHV flows between the US and Mexico:

1. What are the projected flows of legally registered SHVs from the US to Mexico that will be electric?
2. What is the contribution of end-of-life (EOL) lithium ion batteries from SHVs in Mexico from the perspective of retired battery material? How does this compare to domestically sources EOL battery material?
3. Does this trade confer net environmental and social benefits to the region and what are policy mechanisms that could be implemented to minimize environmental and economic burdens and maximizes benefits for the region?
4. What are the implications for vehicle life cycle emissions of SH EV trade?
5. What are potential implications and solutions from and environmental justice standpoint?

To answer these questions we employ three research methods: material flow analysis (MFA), life cycle assessment (LCA), and a qualitative environmental justice analysis.

MFA: Results show that SHVs disproportionately contribution to EOL EV battery material flows and accumulation in Mexico driven by two factors; the first is the shorter lifetime of batteries introduced to Mexico in SHVs and the quicker timeline to retirement. The second relates to vehicle type and design: SHVs from the US are larger than vehicles purchased in Mexico and that size different extends to the batteries that power those larger vehicles. The combination of short lifetime and higher capacity batteries means SHVs contribute more waste battery mass every year than EVs sold new in Mexico until 2042. This indicates a need for EV LIB EOL policy in Mexico, and if possible in coordination with the US. This could take the form of import/export restrictions based on battery state-of-health, and/or mechanisms for ensuring the costs of waste battery treatment are not borne entirely by the second-hand market.

LCA: LCA has long been used to compare the environmental performance of electric vehicles (EVs) And internal combustion engine vehicles (ICEVs). Since the earliest EV LCAs, researchers have highlighted the critical role of the electricity grid on which EVs are charged in determining whether EVs outperform ICEVs from the standpoint of greenhouse gases (GHGs), air pollution, and fossil energy use. While the body of work on EV LCA is large, none have evaluated the effect of international SHV trade, and none have considered how comparative LCAs should be designed for SHV trade. Here we explore the effects of SHV trade at different vehicle age (including battery deterioration effects), and consider ICEV comparisons that reflect the reality that SHVs from the US tend to be larger and less efficient than new vehicles sold in Mexico with a novel multi-region LCA model.

We find that EVs still deliver GHG and air quality benefits even when imported second-hand when compared to average ICEVs sold new in Mexico. In fact, even large EV SUVs and compact HEVs imported second-hand exhibit lower lifecycle impacts across various environmental categories when compared to the average ICEV in Mexico. This suggests that the introduction of second-hand EVs and hybrids could potentially confer net environmental benefits to the Mexican vehicle fleet, offering reduced emissions and other environmental advantages.

However, this conclusion must include some caveats. While Mexico's grid is clean and efficient enough for EVs of any age to have lower emissions than the average ICEV on the road, the distribution of benefits and burdens may be uneven. Exporting vehicles at an earlier age could maximize local air pollution benefits for Mexico. In contrast, exporting older vehicles without adequate battery recycling infrastructure could leave Mexico with fewer air quality benefits while bearing the burden of spent batteries, which carry human and ecological toxicity risks as well as significant fire hazards. Thus more research and policy development is needed to ensure that electric SHVs do not become a net burden on Mexico.

Environmental Justice Analysis: The analysis employs a mixed-methods approach, combining qualitative and quantitative research methodologies to examine the mobility injustices that enable the SHV market in the North American region and the risk of imposing economic and environmental injustices through the transfer of used EVs and their batteries on communities that rely on them. The extraordinary US-Mexico SHV trade and the associated increase of EV batteries reaching their EOL in Mexico, presents both significant risks and promising opportunities for communities and industrial development (*1*), including:

Risks:

1. **Prohibitive Cost of Battery Replacement:** As batteries degrade over time, they may eventually become unsuitable for their initial purpose of powering a vehicle. Battery replacements are cost prohibitive for SHV as a new battery can cost more than the vehicle itself. This presents a significant barrier for access for communities who historically have relied on extending the life of SHV and extracting their resale value.
2. **Toxicity Burden:** SH EVs will become a substantial source of batteries in Mexico. If not managed properly, the influx could pose toxicity risks that can impact human health and the environment. Especially for communities most in contact with SHVs.
3. **Repair and Maintenance Challenges and Hazards:** The safe handling, repair, and recycling of EV batteries require specific technical knowledge and adherence to safety protocols, including protection against electrocution and fire risks. This particularly impacts auto maintenance workers, although it also adds to the barriers to access this technology as repair and maintenance costs will necessarily be more costly.

Opportunities:

1. **Battery Recycling Potential:** An increase in the availability of spent batteries presents Mexico with the opportunity for industrial development and economic growth. Recycling and recovering materials like nickel, aluminum, copper, lithium, cobalt, and manganese is critical to reducing environmental impacts and ensuring a stable supply chain for these critical minerals.
2. **Sustainable Supply Chain:** The recovery and recycling of these battery materials are not only environmentally beneficial but also help ensure a sustainable supply chain for the essential minerals needed to produce EVs and other high-tech products. The scarcity and value of these minerals make them particularly significant in terms of both environmental and economic considerations.

Addressing the challenges LIB can build off approaches developed for managing the broader issue of e-waste. Management requires a comprehensive framework that promotes environmental justice and ensures equitable treatment across all stakeholders involved. Key agendas have been proposed to guide decision-making in the nascent EV battery EOL reuse and recycling industry, with the goal of maximizing economic benefits while minimizing environmental and health burdens (*2*). Among 5 agendas laid out in this report, common threads and highlights include the need to meaningfully engage stakeholders early in the process (i.e., before communities are disproportionately burdened by waste batteries); to develop circular economy approaches to battery EOL management solutions that create safe, enduring and desirable jobs, particularly for affected communities; and to ensure that environmental justice priorities are integrated throughout the policy development process.

Introduction

While not evident to most US residents, international trade in used vehicles plays a crucial role in removing vehicles from US roads, thus spurring fleet turnover and new vehicle sales, which are crucial for electrifying the on-road fleet (*3*, *4*). Second-hand vehicle exports are a multi-billion dollar industry in the US (*3*), but its real value and scale has been deeply underestimated by the US government because of trade with Mexico, much of which goes unrecorded by official US tracking (*5*, *6*). Given the geographic proximity, free trade relationship, and the disparity in economic size, Mexico is, by far, the largest market for US SHV, receiving nearly 15% of the vehicles being retired annually from US roads.

These vehicles have been introduced both legally and illegally from the US for nearly a century. As early as the 1920s, farmers in Mexican border states started introducing them to support agricultural work, and later, migrant workers began bringing them back to their families in Mexico (*7*). By 1992, between 600,000 and 700,000 SHV had been illegally introduced into Mexico's fleet, and by 2004, the number had grown to between 1.5 and 2.5 million (*8*).

SHV trade from the US to Mexico was regularized in 2005 under provisions in the North American Free Trade Agreement (NAFTA). Since then, over 9 million SH light-duty passenger vehicles (LDVs) have been imported from the US, representing nearly 30% of Mexico's 2021 in-use LDV stock. Despite the removal of import barriers, the flow of illegally introduced vehicles has continued to increase, reaching an estimated 25% of the country's in-use stock[1].

Stakeholders, including Mexican auto manufacturers, policymakers, and NGOs argue that the flood of SHV causes negative impacts on the environment, public safety, and the country's automotive industry. However, for low and middle-income communities, SHV imports may provide affordable mobility options and are important sources of economic activity via importers, vehicle repair networks, junkyards, etc. (*9*). These networks and industries have for at least a century been organized around internal combustion engine vehicles (ICEVs), though they have in the last decades adapted to hybrid electric vehicles as well. There are fundamental differences in repair and end-of-life management processes required for EVs compared to ICEVs. EV batteries cannot be repaired in the same way as ICEV powertrain components, and EV batteries, which are based on lithium ion chemistries, present heightened risks of fire and explosion, especially when in aged and damaged states, compared to lead acid starter batteries or most hybrid batteries (which were historically based on nickel-metal hydride chemistries). While repurposing of EV LIBs is often offered as a solution to EV EOL waste, ultimately the only safe destination for EOL lithium ion batteries (LIBs) is recycling.

As the US rapidly adopts EVs to meet climate mitigation targets, there will be an inevitable increase in second-hand EVs flowing to Mexico. While the benefits of EVs for reduced GHG emissions and improved air quality may accrue to second-hand markets as well as markets of

[1] Author's own estimates

first sale, there is also a risk of disproportionate risk and environmental burden for countries receiving second-hand EVs.

Considering (i) the anticipated challenges and opportunities arising from the introduction of EVs into the global SHV market, (ii) the well-established US-Mexico SHV trade and how integral it has become for the economy and livelihood of low and middle-income communities in Mexico, (iii) the increasing regional trade integration under the USMCA and nearshoring policies to enhance supply chain resilience (*10*), and (iv) the rapid growth in US EV demand projected over the next decade (*11*), there is a critical need for research to understand the regional SH EV trade dynamics, the accrual of EOL EV batteries in Mexico, and the environmental and transportation justice implications for communities who rely on these vehicles to support a successful technological transition. EOL EV batteries present a risk to host communities given the risk of fire they pose and resulting hazardous emissions, but they could also present an opportunity for recycling and recovery of constituent materials.

To fill this gap in knowledge, this research seeks to answer the following questions:

1. What are the projected flows of legally registered SHVs from the US to Mexico that will be electric?
2. What is the contribution of end-of-life (EOL) lithium ion batteries from SHVs in Mexico from the perspective of retired battery material? How does this compare to domestically sources EOL battery material?
3. Does this trade confer net environmental and social benefits to the region and what are policy mechanisms that could be implemented to minimize environmental and economic burdens and maximizes benefits for the region?
4. What are the implications for vehicle life cycle emissions of SH EV trade?

To answer these questions we develop a coupled system dynamics and material flow analysis model, conduct a regionally-expanded life cycle assessment to analyze the impacts of second-hand EV exports between the US and Mexico. We also include a qualitative analysis of potential environmental and mobility justice issues arising from the second-have EV trade between the US and Mexico. Results quantify the life cycle environmental performance of EVs and domestic material circularity potential, qualitatively explore the risk of imposing environmental injustices via export of used EVs and their batteries, and test possible policy solutions to maximize benefits for both the US and Mexico.

Results from this work can help the federal and state governments of the US and Mexico identify the downstream emerging issues of the EV transition, and design policies and regulations to manage SH EV trade, extended use, and EOL. Ideally, findings could also support the design of alternative systems that reduce dependency on SHV flows and improve the well-being of communities who depend on them.

The research conducted in this project has yielded one peer-reviewed journal article, one manuscript in preparation, and seeded additional research that is expected to be completed in September 2024. This additional research includes:

Modeling unregistered SHVs illegally introduced into Mexico to understand their contribution to Mexico's light-duty vehicle fleet, associated environmental impacts, and the underestimated flow of materials outside US borders. Data for the modeling were collected through an on-the-ground vehicle volume survey, observing and recording traffic in major cities across diverse geographical, economic, and regulatory areas from Central to Northern Mexico. This approach provided insights into the prevalence of illegally introduced SHVs, revealing the previously underestimated volume of transferred material and end users.

Qualitative research to understand the expanded lifecycle of exported EVs and the potential shifting of environmental burdens. Specifically, an expert elicitation process was conducted by interviewing and documenting the experiences and viewpoints of key stakeholders involved in the repair and end-of-life networks of EVs in Mexico, including recyclers, ZEV mechanics, industry leaders, and policymakers. This approach provided in-depth insights into the flows, stakeholder networks, and policy environment governing end-of-life management for EVs in Mexico. Some of these results are used in this research to define the life cycle processes for second-hand EVs in Mexico. Results from relevant expert elicitation are included here, and do not represent the full scope of research conducted.

Methods and Materials

Critical Battery Material Flow Analysis

The methods described here are described in greater detail in a peer reviewed journal article (*1*). To comply with journal publication requirements, we provide a synthesis of the material presented in the published work, rather than a duplication.

We model future EV LIB material flows in Mexico based on two stock turnover models coupled with material intensity estimates:

1. A vehicle stock turnover model of the US fleet to predict deregistrations of ICEVs and EVs. The pool of deregistered US vehicles constitutes the source of SHVs to Mexico
2. A vehicle stock turnover for Mexico to predict total sales of new and imported second-hand vehicles introduced into the Mexican fleet of vehicles based on vehicle technology. This model is also used to predict the annual mileage accrual and time to retirement for new and second-hand EVs (SH EVs) in Mexico, which is important for predicting the accumulation of EOL battery material.
3. New and second-hand EVs in Mexico are characterized based on expected battery capacity and chemistry, which, coupled with the stock turnover model, predicts the quantity of EOL battery material accruing in each year in Mexico.

Figure 1 is reproduced from(1), and illustrates the data inputs, calculation approach and assumptions used in the fleet turnover models.

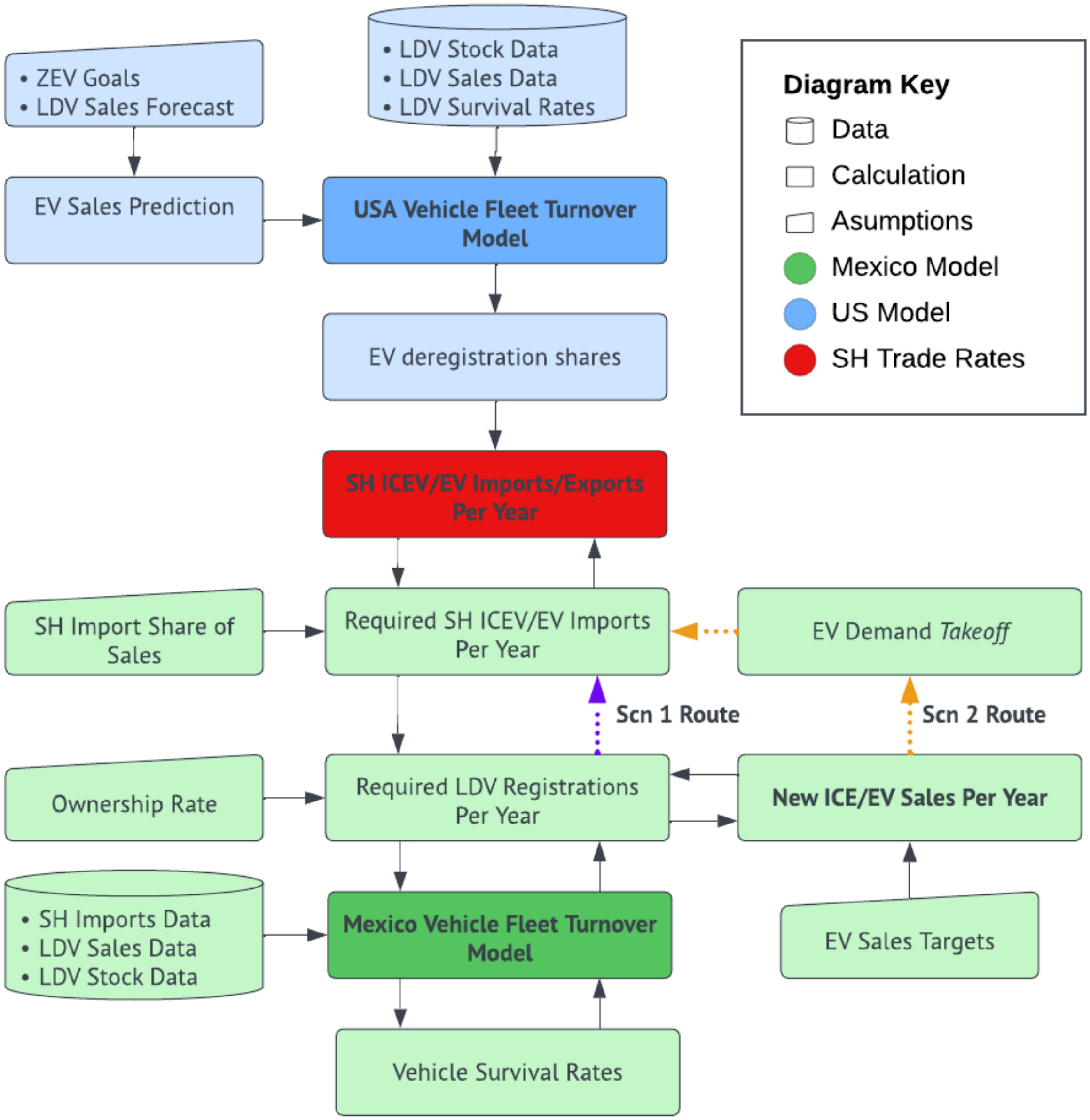

Figure 1. Flow diagram illustrating the full modeling process. Scenario 1 (Scn1) and Scenario 2 (Scn2) indicate different methods for calculating the volumes of SH ICEVs and SH EVs required to meet demand in Mexico, and are described in detail in (1).

The fleet turnover model results for retired vehicles or EV batteries must be coupled with material intensity estimates to yield the ultimate goal of this research—an estimate of EOL battery material accruing in Mexico. Material intensity estimates require knowledge of battery chemistry and capacity. The US and Mexican EV markets have been dominated by vehicles that use lithium Nickel Cobalt Aluminum Oxide (NCA) and Lithium Nickel Manganese Cobalt Oxide (NMC) LIB chemistries (EV-volumes.com, 2023a). However, EV LIB chemistries change over time, and an increase in lithium iron phosphate (LFP) batteries is evident. Because of this trend, we model chemistry evolution as a linear progression from today's nearly equal mix of NCA and NMC, to a mix comprised of equal thirds of NCA, NMC and LFP by 2050. Material intensity estimates allow us to calculate the total quantity of EOL material, but an additional step is required to estimate the quantity of recoverable materials via recycling. For this we use Argonne National Lab's BattPac model (ANL, *12*), and calculate the mass of recoverable material for lithium, nickel, cobalt, manganese, aluminum, copper, and steel.

Regionally Expanded Life Cycle Assessment

LCA has long been a tool for evaluating the performance of EVs relative to their gasoline and diesel counterparts (e.g., (*13*)). The earliest EV LCAs concluded that the grid they charge on is paramount to their GHG and air pollution performance. More recent LCAs come to similar conclusions about the importance of the electricity grid where they are operated, but also highlight the growing importance of the EV battery pack in contributing to life cycle emissions due to two primary causes: (i) as EV LIB battery packs grow in size, the contribution to life cycle impacts grows, and (ii) as electricity grids decarbonize, especially in large EV markets like Europe and the US, the contribution of vehicle operation to life cycle emissions shrinks (*14*). Yet in all previous studies, vehicles are assumed to operate in a single region; the region of first sale. As second-hand EVs enter international trade, their region of operation changes and this has three important and distinct effects on the their life cycle: (i) the grid they charge on changes, (ii) the expected operating conditions change with respect to annual accrual of mileage and climate conditions (though climate is not considered in this study), and (iii) the fate of their EV LIB battery at its end-of-life may not be the same, especially when there are differences in the likelihood of recycling.

To address this gap in knowledge we developed a first-of-its-kind regionally expanded LCA approach and model. The model explores how second-hand international trade of US EVs to Mexico affects the life cycle GHG emissions associated with an EV. It includes dynamic processes that are important to understanding these emissions including: expected grid mixes over time for the US and Mexico, battery degradation and associated roundtrip efficiency losses, different annual average mileage accrual by age of vehicle for the US and Mexico, end-of-life processes including vehicle dismantling and shredding, and battery recycling and final disposition (as a function of recycling technology and probability of recycling in the two markets).

Because no previous work as has been done on LCA of second-hand vehicle trade, and because there has not been formal research on how second-hand vehicles with electric powertrains (including hybrid electric vehicles (HEVs)) are handled in Mexico, we used a systematic expert elicitation process to understand how current SHVs are handled in Mexico and how their maintenance and EOL is managed, including if and how recycling of traction batteries occurs. Though qualitative research like this is not commonly used in LCA, when modeling real-world systems, especially when they include informal sectors of the economy, some systematic process is required to understand how the system functions. Here, we undertook expert elicitation of stakeholders involved in the repair and EOL networks relevant to SHVs.

Expert Elicitation

The expert elicitation process was conducted between the dates 10/01/2023 and 03/01/2024 under IRB approval number 2028194-1. Considering the informal nature of waste management systems in Mexico, particularly concerning repair and maintenance and EOL vehicle management, an expert elicitation process through semi-structured interviews with public and formal and informal private sector stakeholders was conducted. Initially, stakeholders were identified and contacted based on desk research into public agencies and industry associations. As the interview process progressed, a deeper understanding of stakeholder networks and relationships emerged. Participants actively provided referrals for relevant candidates, contributing to the refinement of potential interviewees. This iterative process helped identify key stakeholders more effectively and fostered buy-in from candidates as rapport was established.

In total, twenty-seven interviews were conducted, both remotely and on-site in Mexico City and across 6 states in Northern and Central Mexico. Interviewees included junkyard operators, automotive electricians, dismantling and recycling operators, E-waste Recyclers Association, and Environmental and Waste Management Officials.

The interviews explored questions regarding weather SH EVs had already begun entering the country and inquired about the challenges surrounding their maintenance and repair, as well as the process involved in their collection, dismantling, and recycling at the end of their life cycle (see interview schedules for public and private sectors in Appendix A). Additionally, the interviews investigated existing plans and strategies to accommodate a potential increase in the share of these vehicles in the future.

This approach aimed to provide a comprehensive understanding of the current state and future risks and prospects of SH EV management in Mexico, covering both practical challenges and strategic considerations.

Additional research will be conducted on the data collected via expert elicitation, but for the purposes of the regionally-expanded LCA, we focus on understanding high level, systemic factors to inform relevant modeling assumptions such as if used EVs have already started being introduced into Mexico, the characteristics of common used vehicles and batteries being introduced, maintenance and repair practices, common operative issues, and regulations governing the EOL management system. The interview transcript and questions are provided in Appendix A.

LCA Methods

Goal and Scope Definition

The goal of this study is comparing the life cycle GHG emissions and other environmental impacts of EVs that stay in their country of first sale (the US or Mexico) to second-hand EVs exported from the US to Mexico and gasoline internal combustion engine vehicles and hybrid electric vehicles (HEVs). The study is a cradle-to-grave analysis, taking an attributional prospective approach, and includes projections of changing electricity energy sources in both the US and Mexico and considers dynamic processes in the EV life cycle, such as a decay in roundtrip energy efficiency in EV batteries based on battery cycling, and exploration of the effect of vehicle age at the time of export. The system boundary is further described in Figure 2. The functional unit is 1 km of vehicle travel.

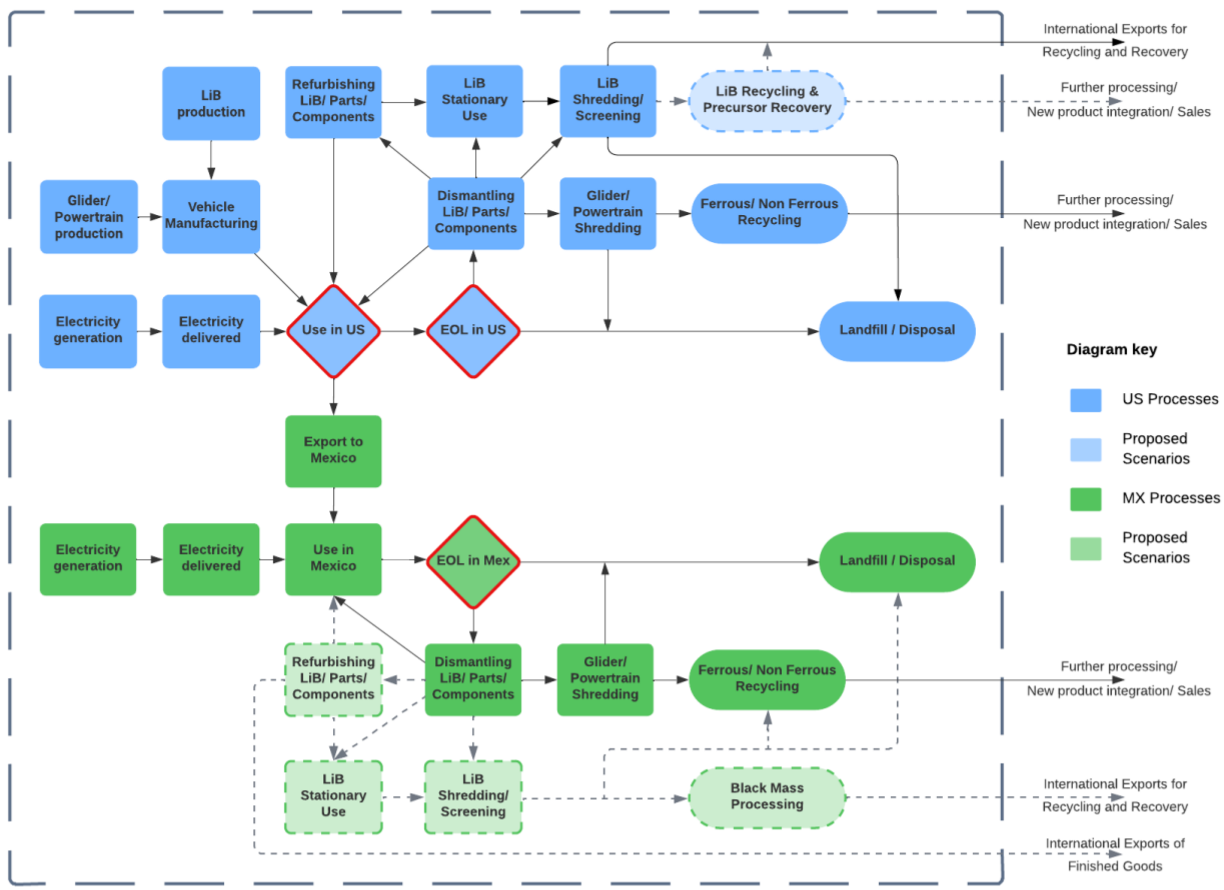

Figure 2. Multi-region LCA model and system boundary.

Vehicle Model Technical Specifications

The vehicle modeling scenarios were chosen based on their status as the highest-selling vehicles in their respective segments and propulsion technologies in the US or Mexico (Table 1). Additionally, the Toyota Prius was included due to its high prevalence as an SHV import in Mexico, as revealed by the expert elicitation process. This selection ensures that the models analyzed are representative of current market trends and consumer preferences and introduce varying performance characteristics, providing a comprehensive and relevant analysis of life cycle GHG emissions for relevant vehicle segments.

The selection includes three vehicle segments (compact, mid-size, and SUV), three propulsion technologies (BEV, HEV, and ICE), and three location scenarios (vehicles purchased and used in the US, vehicles purchased and used in the US and then exported to Mexico, and vehicles purchased and used in Mexico).

Life cycle modeling of the vehicle models chosen was based on their technical specifications. These specifications were obtained from the OEM technical specification sheets, which provide detailed information about the vehicle's design, performance, and other relevant attributes.

Table 1. Vehicle life cycle scenarios.

Category	**Vehicles purchased and operated only in the US**	**Purchased and operated in the US and operated in MX via SH Export**	**Vehicles purchased and operated only in MX**
ICE Compact			Nissan – Versa
HEV Compact	Toyota –Prius	Toyota – Prius	
EV Compact	Chevrolet – Bolt	Chevrolet – Bolt	JAC – E10X
EV SUV	Tesla –Model Y	Tesla – Model Y	Tesla – Model y
Common in	US	Exported	MX

* The color coding indicates the prevalence of a vehicle model in either the US, Mexico, or if the vehicle is commonly exported second-hand. This visual aid explains the rationale behind the modeling choices.

Life Cycle Inventory (LCI)

Background data draws from reference life cycle inventory (LCI) datasets in the ecoinvent version V3.8 (*15*). Table A1 in Appendix B documents the reference LCI datasets used in this analysis. Reference LCI datasets provide comprehensive estimates of environmental flows associated with inputs to the LCA model. For example, the reference LCI dataset for gasoline fuel will include the environmental flows (e.g., GHG emissions and water use) associated with extracting, refining and transporting gasoline to the final consumer. Each input flow (fuel, electricity, vehicles) requires reference LCIs to be created from component LCIs or directly accessed.

Life Cycle Impact Assessment (LCIA)

This study aimed to quantify the life cycle GHG emissions, air quality pollutants, and human and environmental toxicity. These three impact categories were chosen based on their relevance to the product systems: the main objective for transitioning to EVs is to mitigate climate change, this transition has an important co-benefit for air quality, but there is often a great deal of concern related to traction batteries and their potential to harm people and ecosystems during production and EOL toxicity risks such a mismanagement of waste batteries.

Finally, a lifecycle impact assessment (LCIA) was conducted by applying characterization factors from the ReCiPe 2016 model (*16*) using the Hierarchist (H) Perspective scenario. These characterization factors were applied to the reference inventory data for each process and operation associated with the vehicle's lifetime—see Appendix B—and scaled according to the input parameters and values obtained from the processes described in the previous sections. Indicator values are reported for the following impact categories (Table 2):

Table 2. Impact categories used for this research (13).

Impact Category	Damage Pathways	Endpoint area of protection
Terrestrial Acidification	Damage to terrestrial species	Damage to ecosystems
Terrestrial Ecotoxicity	Damage to terrestrial species	Damage to ecosystems
Trop. Ozone (Ecosystems)	Damage to terrestrial species	Damage to ecosystems
Human Toxicity Cancer	Increase in various types of cancer	Damage to human health
Human Toxicity Noncancer	Increase in other diseases/causes	Damage to human health
Ionizing Radiation	Increase in various types of cancer Increase in other diseases/causes	Damage to human health
Pm Formation	Increase in respiratory disease	Damage to human health
Stratos. Ozone Depletion	Increase in various types of cancer Increase in other diseases/causes	Damage to human health
Trop. Ozone (Human Health)	Increase in respiratory disease	Damage to human health
Global Warming Potential	Increase in other diseases/causes Increase in malnutrition Damage to freshwater species Damage to terrestrial species	Damage to human health Damage to ecosystems

LCA Model Structure and Foreground System

Figure 3 describes the LCA model structure from the standpoint of data needs for model inputs and processes. Data for foreground input parameters are drawn from a variety of sources including:

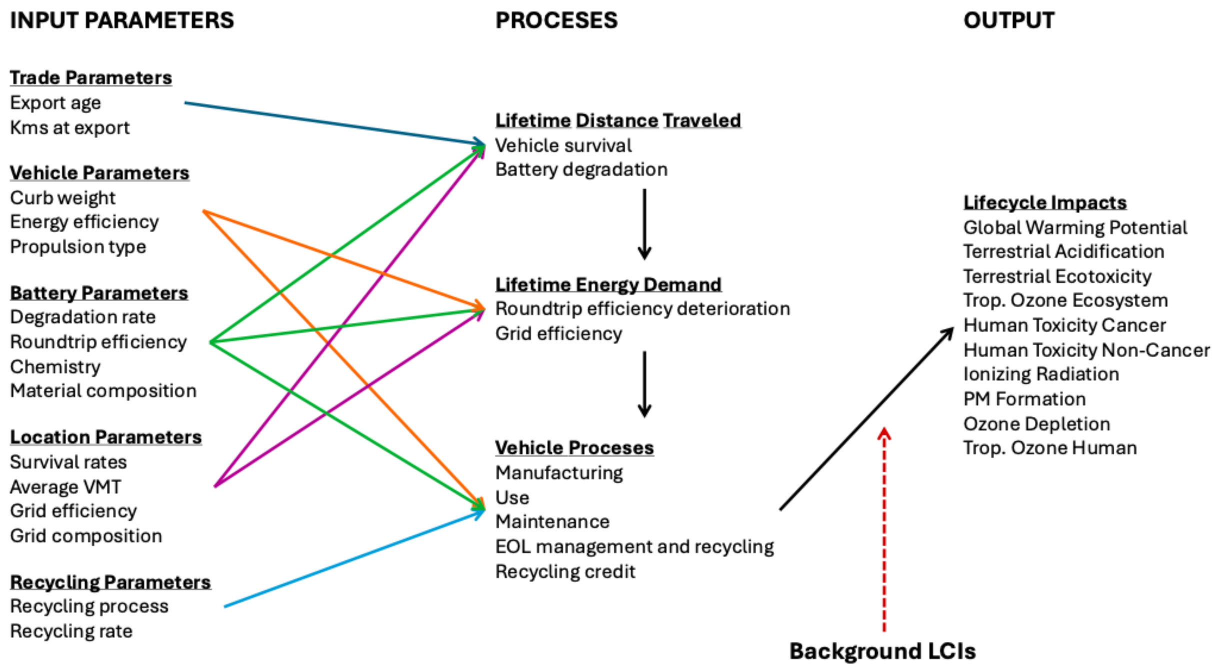

Figure 3. LCA model structure.

Foreground System Data and Processes

Data for foreground input parameters for the life cycle inventory is drawn from a variety of sources including:

- Trade statistics (*5*, *6*)
- Mexico Vehicle Registration and Sales (*17*)
- Electricity generation fuel mixes and transmission and distribution losses (*18–20*)
- Travel statistics including age of retirement and average annual travel distances as a function of vehicle age (Davis et al., 2022)
- Vehicle and battery specs (EV-volumes.com, 2023; ANL, 2022b)

Vehicle Lifetime

The total kilometers traveled by a vehicle during its lifetime is crucial to understanding how vehicles are used in the two markets and were estimated based on two factors: the survivability rate, which is the probability of vehicles of a certain age being retired each year, and the vehicle's annual utilization or Vehicle Miles Traveled (VMT). To generate a single integrated survivability curve (ISC) for both countries given the age or the odometer reading at the moment a vehicle is exported, the following piecewise function was developed:

$$ISC(a) = \begin{cases} Sus(a), & for\ 0 \leq a \leq aX \\ Sus(aX) \cdot Smx(a), & for\ a > aX \end{cases} \quad \textbf{eq. (1)}$$

Where ***a*** represents the age of a given vehicle, ***aX*** represents the age at which it will be exported, ***Sus*** represents the vehicle survivability function in the US, ***Smx*** is the survivability function in Mexico.

Annual Vehicle Miles Traveled (VMT) values are influenced by various factors, including the location where vehicles are operated, the type and propulsion technology of the vehicle, and the vehicle's age. For the U.S. light-duty vehicle (LDV) fleet, average VMT values were sourced from (*21*). However, age-specific VMT data were not available for Mexico's LDV fleet. To address this gap, we estimated the age-based breakdown of VMT for Mexico using the average VMT for the country's entire LDV fleet (*17*), assuming that VMT decreases proportionally with the survivability rate of Mexico's LDV fleet by age.

As EV LIBs undergo cycling and aging, they experience degradation that can eventually render them unsuitable for their initial purpose of powering a vehicle. While EV battery replacements do occur, they can be prohibitively expensive after the warranty period expires (typically 8 years). Therefore, while the rest of the vehicle may still be in good state, the entire vehicle could be retired due to a failing battery. Based on manufacturers' descriptions and current literature, once EV LIBs are degraded to 70–80 % of their nominal capacity, their useful lifespan in an EV ends. Estimates place this useful lifespan between 100,000 and 200,000 miles, or between a low of 8 to a high of 20 years (*24*), contingent on a number of influencing factors, including temperature, cycling patterns, and operating windows (*25*–*27*).

Battery Degradation

In addition to the vehicle survivability rate, battery degradation was modeled separately for EVs and HEVs and included as a potential source of failure. The assumption being that the age of failure for these vehicles would be determined by whichever of these two factors—survivability rate or battery degradation—indicated failure first.

Battery State of Health (SOH) was modeled based on findings from a literature review (*24*, *26*, *27*), which provided empirical annual degradation rates ranging between 2% and 3% for the first 8 to 10 years. Beyond this period, degradation was assumed to accelerate, following an exponentially decreasing rate until the battery reached 75% SOH. To capture this behavior, the following piecewise function was developed, where the battery age $\boldsymbol{a}$ serves as the independent variable:

$$SOH(a) = \max\left(\begin{cases} 1 - Dr \cdot a, & if\ a \leq k \\ 1 - Dr \cdot a \cdot e^{a-\lambda k}, & if\ a > k \end{cases}, 0\right) \quad \textbf{eq. (2)}$$

In this function, $\boldsymbol{Dr}$ represents the proposed annual degradation rate, $\boldsymbol{k}$ *d*enotes the expected "knee" age—when the battery is expected to begin degrading exponentially—and $\boldsymbol{\lambda}$ is a decay rate parameter. This function is evaluated for each age throughout the vehicle's expected lifetime. A Weibull cumulative distribution curve is then fitted to the results of the piecewise function to provide a continuous function that more accurately represents the gradual nature of real-world degradation processes, enhancing the robustness of the analysis and providing consistency with widely used time-to-failure models (*28*).

Finally, the resulting Weibull distribution curve is then used to estimate the annual probability of battery failure. By assuming that a battery failure within the warranty period results in a replacement, this model allows for the estimation of the increase in vehicle life expectancy, as well as the mass of batteries that will need to be produced and recycled for the analyzed vehicle.

Lifetime Energy Delivered

The total energy required to power an EV over its lifetime was estimated based on three key factors: (1) the vehicle's nominal displacement efficiency, or energy consumption per unit of travel; (2) the deterioration of battery roundtrip efficiency, reflecting the gradual decline in charge-discharge cycle efficiency over time; and (3) the efficiency of the electricity grids in Mexico and the US, measured as the energy delivered for end use per unit of energy generated.

Nominal displacement efficiency values for the different vehicle scenarios were sourced from manufacturer technical specifications. This efficiency is adjusted annually to account for the increasing impact of battery roundtrip efficiency deterioration, which raises the energy required per unit of travel. The roundtrip efficiency values used in this research are based on findings from (*29*), which proposes an algorithm to estimate battery pack efficiency, analyzing data from three battery-electric buses over 3.5 years. These values were further adjusted to account for the likelihood of battery replacement during the vehicle's lifetime.

Regional Grid Composition and Efficiency

Additionally, grid inefficiencies, which increase the energy generation needed to meet EV demand, were incorporated into the analysis. Estimates for grid efficiency were derived from historical transmission and distribution loss data, as well as future efficiency targets provided by government agencies in Mexico (*18*, *19*, *30*) and the US (*20*). Additionally, the historical and forecasted energy source composition of electricity grids for both countries was integrated into the analysis. This data was provided by the same agencies.

Finally, lifecycle impacts associated with the use phase of the tested EV scenarios were calculated by applying background LCIs to the integrated grid efficiency and energy mix data. This approach ensured that the influence of changes in the efficiency and composition of the electricity grid on the environmental performance of EVs was accounted for throughout their lifecycle.

Battery Recycling

The environmental impacts of LiB recycling were assessed using a Life Cycle Assessment (LCA) approach. Battery specifications and characteristics, including material composition, chemistry, and mass, were sourced from OEM technical specifications and BatPac v5.0(*22*). Recycling rates were based on BatPac v5.0(*22*) and available literature, providing up-to-date data on material recovery efficiency(*31–33*). An impact credit method (*32*) was applied, allocating a reduction in impacts equivalent to the production of key battery precursor materials—aluminum ingot, cobalt sulfate, copper cathode, lithium hydroxide, manganese sulfate, nickel sulfate, and low-alloyed steel—reflecting the avoided environmental burdens of producing these materials from virgin sources.

Environmental Justice Analysis

Considering (i) the anticipated challenges and opportunities arising from the introduction of EVs into the global SHV market, (ii) the well-established US-Mexico SHV trade and how integral it has become for the economy and livelihood of low and middle-income communities in Mexico, (iii) the increasing regional trade integration under the USMCA and nearshoring policies to enhance supply chain resilience (*10*), and (iv) the rapid growth in US EV demand projected over the next decade (*11*), there is a critical need for research to understand the regional SH EV trade dynamics and the environmental and transportation justice implications for communities who rely on these vehicles to support a successful technological transition.

To fill this gap in knowledge, this research seeks to answer the following questions:

1. Who do SH EVs mainly serve?
2. What are the motivations to acquire SH EVs?
3. What are the main benefits and risks that SH EVs have on wellbeing as perceived by the users?
4. Do communities receive the same level of benefits and burdens from SH EVs as they would from the alternatives? (SH ICE, new ICE, or new EVs)
5. Does this trade confer net environmental and social benefits to the region and what are policy mechanisms that could be implemented to minimize environmental and economic burdens and maximizes benefits for the region?

To answer the questions above, this first of its kind study employs a mixed-methods approach, combining qualitative and quantitative research methodologies to examine the mobility injustices that enable the SHV market in the North American region and the risk of imposing economic and environmental injustices through the transfer of used EVs and their batteries on communities that rely on them. This comprehensive approach allows for a nuanced exploration of the socio-economic and environmental dynamics shaping the EV ecosystem in the region. Based on the findings, possible policy solutions are also proposed to support a successful transition that minimizes environmental burdens and maximizes regional benefits.

This research draws upon resources and data compiled through various projects conducted between 2022 and 2024, as described below.

Literature Review and Document Analysis

An extensive snowballing literature review was conducted, informing the distribution of access to the benefits from SH EVs and the risks associated with inadequate EOL management. This review included compiling academic articles in English and Spanish, government and industry reports and datasets, existing policies and regulations related to vehicle and LIB EOL management in the US and Mexico, as well as bilateral agreements.

Additionally, the literature review revealed major research themes central to the conversation on global SHV exports and the drivers and consequences, on which we base the structure of this work: Demographics and distribution of SHVs, mobility justice issues as drivers of demand, and the environmental justice issues associated with global flows of e-waste.

Dataset Access and Analysis

Many different datasets were compiled and analyzed providing valuable insights into the types and characteristics of vehicles being imported, their destination within Mexico, and vehicle ownership rates. Datasets compiled included international commerce data provided by the National Customs Agency of Mexico (*5*), demographic and migration statistics data from the National Council of Population (CONAPO)(*34*), vehicle registration data from Mexico's Public Vehicle Registry (REPUVE), and income, expenditure, and vehicle sales and stock data from the National Institute for Statistics and Geography (*17*). While the datasets used for SHV imports and registration provide valuable insights, it is important to acknowledge potential limitations in data reliability. Issues such as outdated information or inconsistencies in collection methods might affect the accuracy of findings.

The analysis employed descriptive statistical techniques and data visualization to extract meaningful patterns and trends. For example, by overlaying the geographical distribution of imported vehicles against migration data to provide understanding of market drivers and barriers, or data on commute preferences with socio-economic indicators to uncover patterns of mobility injustices.

Results

Battery Material Flow Analysis

For more detailed and extensive results we direct readers to the peer-reviewed article (*1*). Here we focus on key modeling results for vehicle stocks in Mexico and the implications for battery material flows. Figure 4 shows the vehicle in-use stock and cumulative deregistrations in Mexico from 2005–2050. The stocks are disaggregated by SHV status and by powertrain (ICEV versus EV).

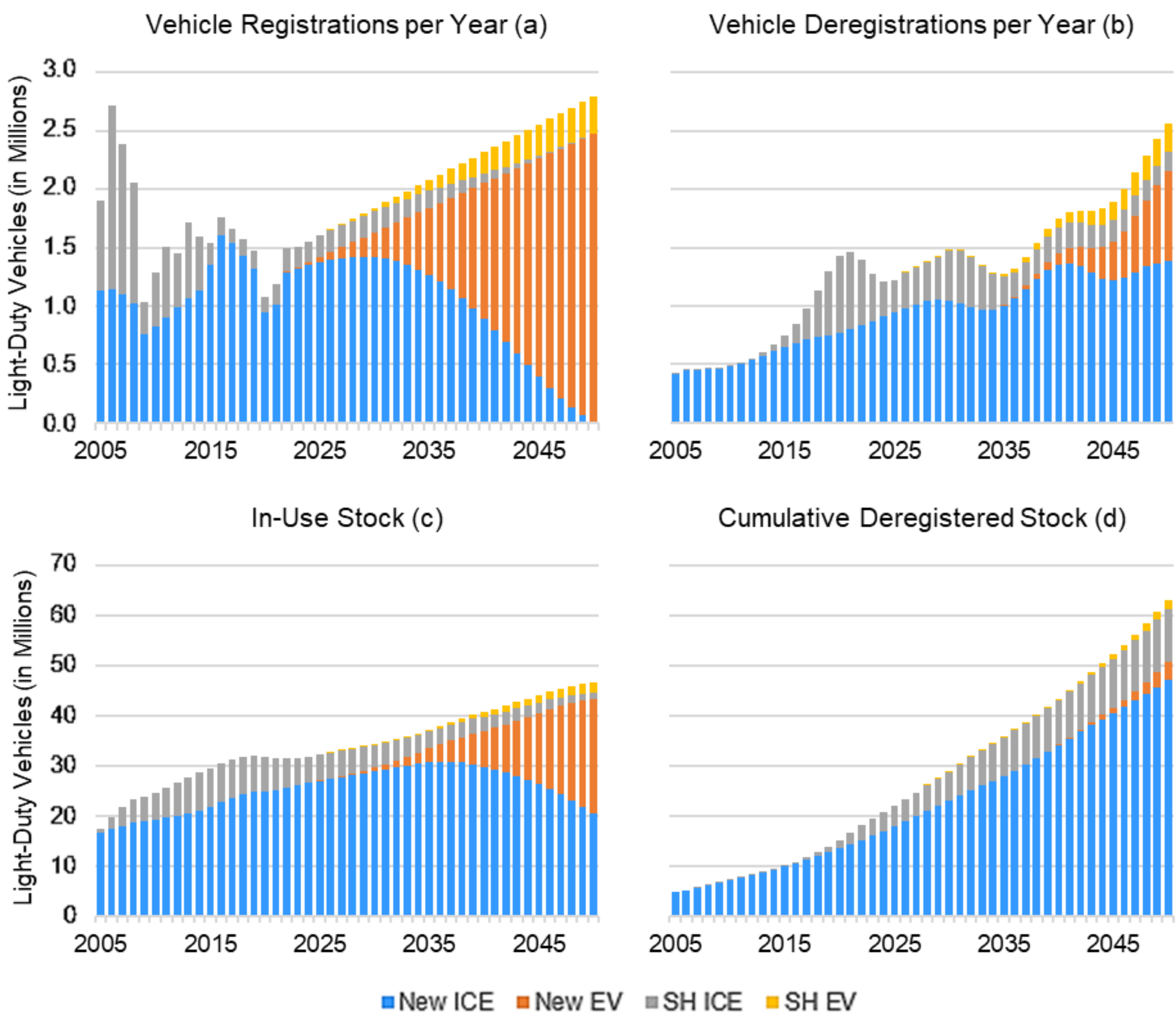

Figure 4. Shift in the composition of yearly LDV registrations (a) and deregistrations (b) in Mexico. Evolution of the composition of the Mexico In-Use Stock (c) and Deregistered (d) Vehicle Stocks. (Reproduced from Parés et al., 2023 (1), Figure 5.)

Figure 4 shows the volatility of second-hand imports prior to 2020 (note SHVs were not legal to the entire country before 2005), a function of changing policy in Mexico. Note that these data and the results of the MFA only includes those SHVs that are legally registered after import (Figure 4a). The yearly deregistrations (Figure 4b) show the increasing contribution of SHVs around 2015, and the growth in SH EVs around 2035. Figure 4c shows that in 2005, Mexico's in-use stock was just over 16 million vehicles, with 100% of them being domestically sold ICEVs. From 2005 to 2015, the total in-use vehicle stock in Mexico increased significantly, driven in large part by SH imports from the US. However, due to higher rates of retirement for SHVs and the normalization of flow after a series of import regulations adopted by Mexico the share of SHV dropped from a high of 26 % in 2014 to a projected low of 7% by 2050. Although they continue representing a very small percentage of vehicles on the road, EVs were first sold in the country in 2016. The cumulative retired LDV stock is shown in Figure 4d. Because of the changes in the rates of SHV imports, their contribution to retired stock peaks at 22% around 2035.

Modeling reveals that while new and SH vehicles are consistently integrated into Mexico's in-use fleet, SHVs comprise a larger share of deregistered vehicles relative to their contribution to in-use stocks because of their shorter lifetimes on Mexico's roads. This means that they contribute disproportionately to EOL vehicle flows, including EV batteries.

Figure 5 shows the cumulative mass of battery materials from EOL EVs in Mexico, and the contribution from SHVs is particularly evident. The disproportionate contribution is both from shorter on-road lifetimes and from the fact that US EVs have larger batteries than those sold new in Mexico. In early years, SHVs are nearly the sole contributor to these flows, and they continue to comprise a majority of the retired material flow for decades to come, despite not being the majority of EVs on Mexico's roads in later years (see Figure 4c).

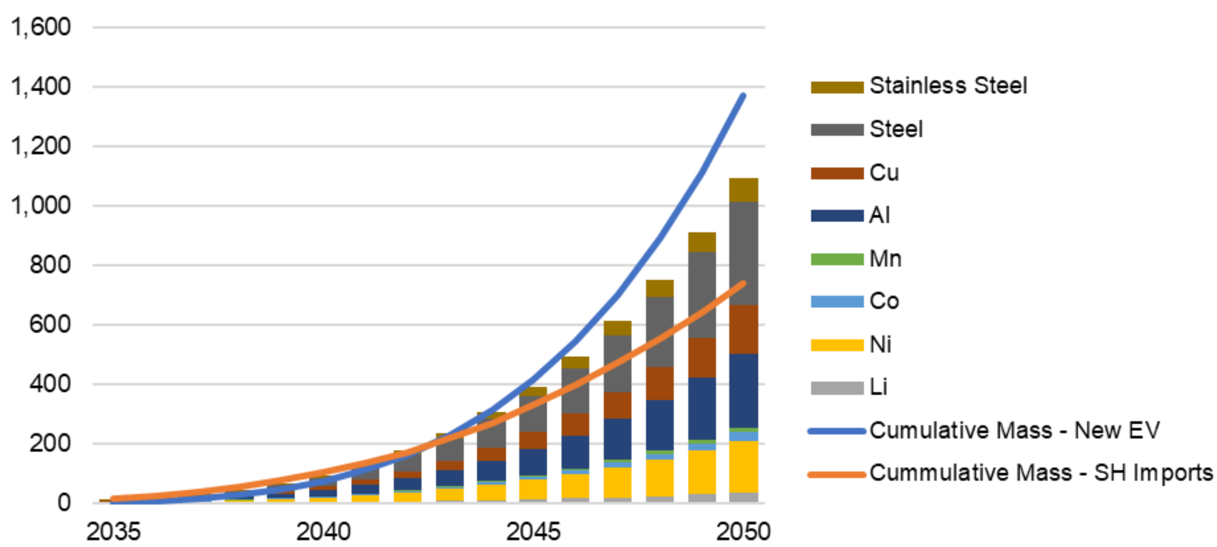

Figure 5. Total cumulative battery mass (thousand metric tons) from deregistered SH Imports and new EVs sold in Mexico, including breakdown of recoverable battery materials from total cumulative deregistered EVs in Mexico (SH imports and new EV sales), from 2035 to 2050. (Reproduced from Parés et al., 2023 (1), Figure 8.)

These findings have important implications for policy in North America. If indeed US SHVs are going to comprise a significant share of waste batteries and recoverable battery materials in Mexico through the year 2050, then it means that domestic policies for EV battery EOL in either country must confront the reality of the significant loss or gain of batteries via cross-border trade.

Expert Elicitation

The expert elicitation process revealed the following insights, which were used to inform how second-hand vehicles in Mexico are modeled in the LCA:

1. Although EVs reaching EOL in Mexico still account for small numbers, the majority are US SH imports.
2. SH HEVs are widespread, SH BEVs remain uncommon
3. Currently, the most common spent traction battery chemistry is NiMH, but LIBs are increasing. NiMH batteries were commonly used in HEVs, but are not used in BEVs.
4. Mechanics working on electric powertrains are operating with informal training in EV/hybrid systems.
5. Reuse and swapping used batteries and modules is common.
6. Unlike for SH ICEV vehicles, difficulty repairing EVs leading to their early retirement.
7. No official regulations exist for EOL EV batteries, meaning there is no requirement to recycling spent batteries.
8. Recyclers in Mexico do not take spent EV batteries, leading to direct landfill disposal.

The results from the expert elicitation inform assumptions in the regionally expanded LCA including:

Battery replacements:

- That warranty-based replacements of EV batteries will happen in either country conditioned on the probability of battery failure prior to warranty expiration date
- Warranty-based replacements only occur if the vehicle is not exported/imported as a second-hand vehicle, i.e., even if it is within the warranty period, a vehicle will not receive a battery replacement if it is exported SH
- After the warranty period, no vehicles will receive battery replacements

Battery recycling:

- All retiring batteries in the US will be recycled, however, batteries from SHV exports to Mexico will not be recycled.
- Concurrently, in Mexico, only batteries from new vehicles retired within the warranty period will be recycled
- The only available choice for battery recycling in Mexico is pyrometallurgy

Vehicle scenarios:

- The choice of testing HEVs with NiMH batteries given the prevalence of these vehicles in export/import flows.

LCA Results

Vehicle performance from a life cycle environmental perspective are significantly influenced by the age at which a vehicle is exported. Generally, vehicles that are exported earlier in their lifecycle spend more time in Mexico, leading to lower use intensity and a higher survival rate. However, this extended period in Mexico also means that the vehicle will draw energy from a less efficient and dirtier grid, potentially increasing its environmental impact relative to operation only in the US. Additionally, vehicles that spend more time in the US before export are more likely to undergo battery replacement and have their batteries recycled, which can improve overall vehicle performance and reduce lifecycle environmental impacts. Thus, the timing of export plays a critical role in determining both the environmental impacts and longevity of a vehicle in its second life.

Figure 6 bellow illustrates the percent change in key system performance metrics as a function of vehicle age at export that, combined, drive the change in environmental performance of a proposed vehicle scenario—an EV SUV based on the Tesla Model Y, in the particular case shown here.

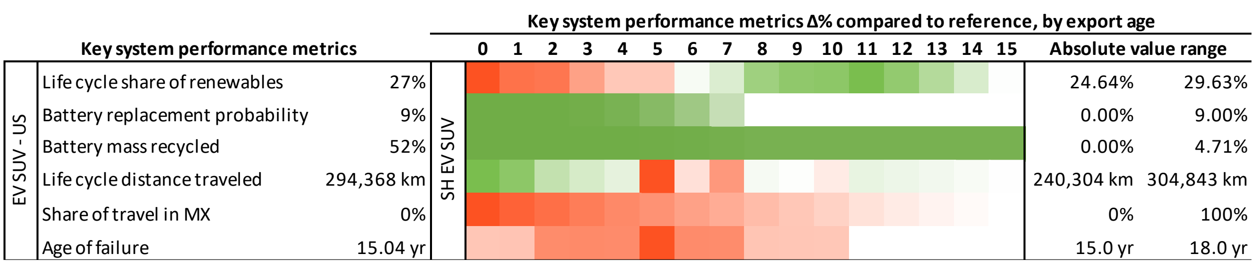

Figure 6. Relative change in key system performance metrics per vehicle age of export.

Figure 7 displays the resulting changes in lifecycle impacts due to variations in vehicle performance metrics by age of export, based on the scenario in Figure 7 comparing a U.S.-bound EV-SUV to an exported SH EV-SUV. The left shows the lifecycle impacts under different environmental categories for a US-sold EV SUV that is never exported. The middle section of the figure highlights the percent differences observed when the same vehicle is exported at various ages, compared to the baseline scenario where it remains in the U.S. Green shades indicate reductions in impact, while red signifies increases. The right side of the figure presents the range of shifts in environmental impacts as the vehicle's age at export changes. It also provides the absolute and relative shifts for the average age of export. Notably, exporting vehicles generally increases their environmental impacts. For example, the analysis reveals a 20% increase in Global Warming Potential (GWP), a 62% increase in human toxicity non-cancer impacts, and a 16% increase in terrestrial ecotoxicity.

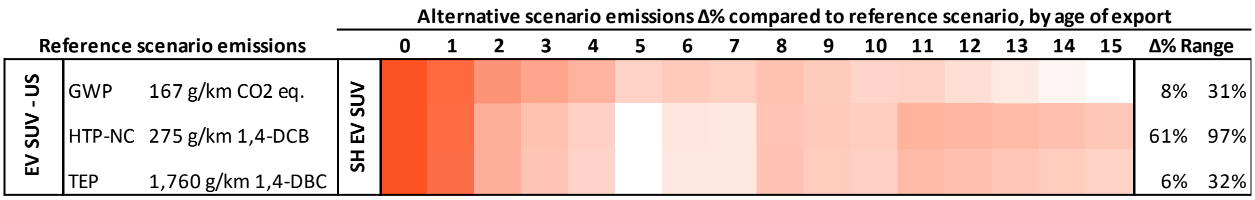

Figure 7. Relative change in emissions rates of a SH EV SUV exported to Mexico compared to the reference scenario—an EV SUV that remains in the US through the entirety of its lifetime.

Figure 8, Figure 9, and Figure 10 present a similar analysis as the previous case of the Telsa Model Y, but with a key difference: the reference point on the left is now the average vehicle on the road in Mexico, specifically a compact ICEV. The right side of the figure compares this baseline to three alternatives: an exported EV SUV—based on the Tesla Model Y, a subcompact EV—based on the Chevy Bolt, and a compact HEV—based on the Nissan Versa. As illustrated, both the EV SUV and the compact HEV exhibit generally lower lifecycle impacts across various environmental categories when compared to the average ICEV in Mexico. This suggests that the introduction of second-hand EVs and hybrids could potentially confer net environmental benefits to the Mexican vehicle fleet, offering reduced emissions and other environmental advantages over the current average. However, making this assertion is complicated by the fact that the LCA aggregates impacts across the entire lifecycle, making it unclear where these impacts occur. While Mexico's grid is clean and efficient enough for EVs of any age to have lower emissions than the average car on the road, the distribution of benefits and burdens may be uneven. Exporting vehicles at an earlier age could maximize local air pollution benefits for Mexico. In contrast, exporting older vehicles without adequate battery recycling infrastructure could leave Mexico with fewer air quality benefits while bearing the burden of spent batteries, which carry human and ecological toxicity risks as well as significant fire hazards.

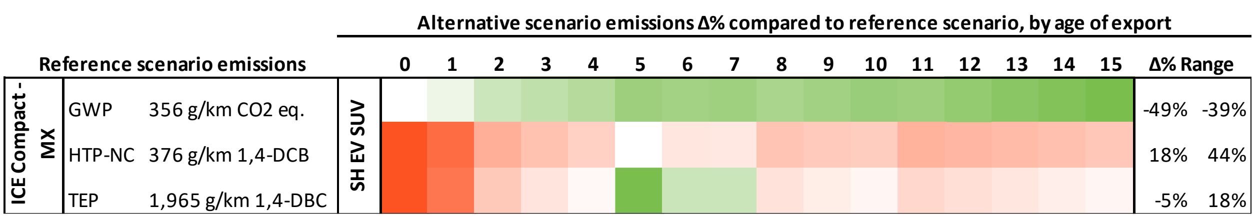

Figure 8. Relative change in emissions rates of a SH EV SUV exported to Mexico compared to the reference scenario—the average vehicle in Mexico (ICE-Subcompact).

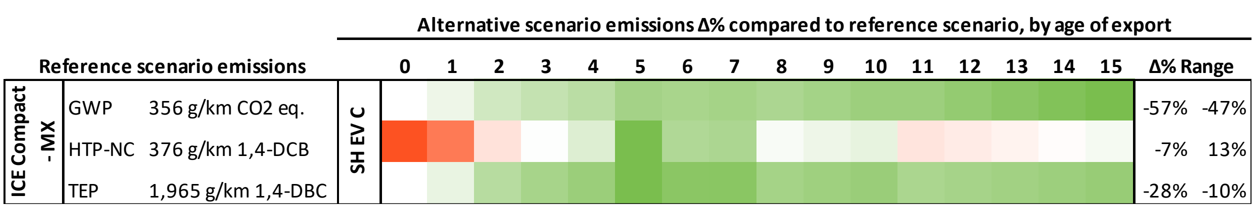

Figure 9. Relative change in emissions rates of a SH EV compact exported to Mexico compared to the reference scenario—the average vehicle in Mexico (ICE-Subcompact).

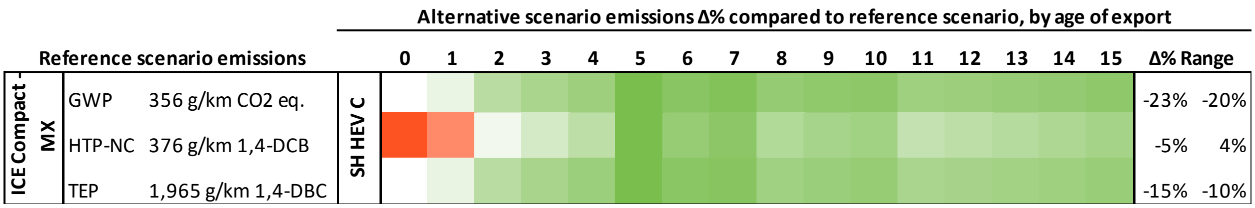

Figure 10. Relative change in emissions rates of a SH HEV compact exported to Mexico compared to the reference scenario—the average vehicle in Mexico (ICE-Subcompact).

Analysis of Mobility and Environmental Justice Implications of SHV trade

This section analyzes the drivers of mobility inequities in Mexico's SHV import market, which have historically concentrated environmental and health impacts in low-income communities, particularly in northern regions. With the anticipated influx of SH EVs, the focus shifts to exploring how environmental and health risks may transition from pollutants associated with internal combustion engines to challenges related to the inadequate disposal of spent lithium-ion batteries. The section also examines the economic growth, job creation, and community development opportunities that could arise from the recovery and recycling of valuable materials embedded in these spent batteries. Finally, the section discusses a policy framework to support environmental and economic justice in the nascent EOL battery industry.

Mobility Inequities Drive the Concentration of Impacts in Low-Income Communities

The primary transportation and mobility issues driving the import of SHVs into Mexico are deeply intertwined with economic disparities, urban sprawl, and inadequate public transportation infrastructure (*1*, *8*, *35*). SHV imports are most prevalent among low-income communities who are drawn to the affordability and relative quality of these vehicles compared to new vehicles available in Mexico (*8*).

The concentration of SHV imports is especially high in northern states and regions with significant migrant populations in the U.S., due to their proximity to the US, historical regulatory frameworks allowing them to be imported as support for certain industries, and robust migrant populations in the US that create transnational networks, facilitating the flow of these vehicles (*34*, *36*).

Urban sprawl, particularly in northern Mexico, has further entrenched the reliance on personal vehicles, as disorderly city expansion and underinvestment in public transit infrastructure make SHVs the most viable transportation option for many (*35*, *37*). For these communities, SHVs offer a practical solution to overcoming the challenges of distance, connectivity, and economic mobility (*35*). However, the widespread reliance on SHVs brings significant environmental and economic externalities. These vehicles, often older, larger, and concentrated in lower income communities, contribute to higher levels of air and water pollution, exacerbating environmental inequities in already vulnerable communities (*35*). Economically, while SHVs provide an immediate solution to mobility, they impose long-term financial burdens due to frequent maintenance, repairs, and higher operating costs (*38*). The lack of investment in sustainable transportation options and the continuation of car-centric policies create a feedback loop that perpetuates the demand for SHVs, deepening disparities and disproportionately affecting low-income communities in regions with the highest SHV concentrations (*38*).

Environmental and Health Risks of E-Waste

The modeling in this research illustrates how spent battery flows could increasingly concentrate in lower-income communities in Mexico through the established SHV trade. This raises concerns about environmental injustice, as these communities may face disproportionate exposure to the risks associated with improper battery disposal.

E-waste, including discarded electrical and electronic equipment, is one of the fastest-growing waste streams globally, containing both hazardous substances and valuable materials (*39*, *40*). While affluent countries benefit from access to advanced technologies, lower-income countries often bear the environmental and health burdens due to weak regulations and limited healthcare infrastructure (*40*). In this context, the export of spent batteries from EVs in the global north to developing regions like Mexico mirrors historical patterns of e-waste disposal that perpetuate environmental inequities (*41*–*43*). Despite the Basel Convention's aim to regulate hazardous waste flows and promote environmentally sound management, enforcement challenges and loopholes have often rendered it ineffective, particularly in protecting vulnerable regions from the risks associated with informal recycling and improper disposal (*30*, *34*).

Improper disposal or informal recycling of lithium-ion batteries (LIBs), which power EVs, exacerbates these risks. Toxic substances such as hydrofluoric acid (HF), hydrogen cyanide (HCN), and heavy metals are released through leaching, disintegration, and degradation of spent batteries, contaminating soil, water, and air(*44*). Fires caused by improper handling further amplify pollution and health hazards(*44*). Vulnerable populations, already burdened by limited resources and weak environmental enforcement, are disproportionately affected, facing health risks such as respiratory problems, neurological damage, and increased cancer rates (*2*, *43*).

To address these challenges, it is essential to implement robust international regulations, strengthen local e-waste management systems, and promote sustainable practices such as battery recycling and the right to repair. Linking the economic benefits of spent battery recycling to community development could mitigate these risks while fostering equitable growth (*2*, *42*). By aligning environmental justice concerns with safe disposal and recycling practices, policymakers can reduce the burdens disproportionately borne by underserved regions like those in Mexico.

Economic Opportunities and Labor Rights in Battery waste Management

As suggested in Figure 5, recovering valuable battery materials from waste streams in Mexico presents new opportunities for economic growth, job creation, and community development. However, improvements in e-waste management practices are essential to establish processing value chains that ensure decent work conditions and tangible benefits for local communities.

According to the International Labour Organization (ILO), decent work in the e-waste processing industry, especially in developing countries, requires a multifaceted approach to protecting and enhancing workers' rights. Countries are urged to adopt, implement, and enforce the protections ratified by ILO Conventions through national laws and regulations, including tackling the prevalence of informal work, a major challenge to realizing workers' rights.

The ILO emphasizes the need for an environment where sustainable enterprises and cooperatives in the e-waste management sector can thrive. This involves increasing access to finance for clean technologies, investing in skills development for a circular economy, and providing education and training programs tailored for e-waste workers in developing countries. Furthermore, there is a call to ensure workers have full access to fundamental principles and rights at work, can organize and bargain collectively, and have access to universal health care and social security. These measures are crucial for improving working conditions, safety, and health for e-waste workers and fostering an e-waste circular economy at all levels, including through international partnerships and collaborations (*39*).

EV Batteries in Mexico: Balancing Environmental Risks and Economic Opportunities

The extraordinary US-Mexico SHV trade and the associated increase of EV batteries reaching their EOL in Mexico observed in Figure 5, presents both significant risks and promising opportunities for communities and industrial development (*1*), including:

Risks:

1. **Prohibitive Cost of Battery Replacement:** As batteries degrade over time, they may eventually become unsuitable for their initial purpose of powering a vehicle. Battery replacements are cost prohibitive for SHV as a new battery can cost more than the vehicle itself. This presents a significant barrier for access for communities who historically have relied on extending the life of SHV and extracting their resale value.
2. **Toxicity Burden:** SH EVs will become a substantial source of batteries in Mexico. If not managed properly, the influx could pose toxicity risks that can impact human health and the environment. Especially for communities most in contact with SHVs.
3. **Repair and Maintenance Challenges and Hazards:** The safe handling, repair, and recycling of EV batteries require specific technical knowledge and adherence to safety protocols, including protection against electrocution and fire risks. This particularly impacts auto maintenance workers, although it also adds to the barriers to access this technology as repair and maintenance costs will necessarily be more costly. Moreover, in the case of fires or disposal of spent batteries without recycling, the communities and ecosystems around affected sites could be harmed via toxic air pollution and leaching.

Opportunities:

1. **Battery Repurposing and Recycling Potential:** The increased availability of spent EV batteries offers Mexico significant opportunities for economic growth through the development of industrial activities across various stages of the battery end-of-life (EOL)

value chain. If done safely, cascading use of batteries can present a number of opportunities for deriving additional value after batteries are no longer useful in their first application. EV batteries are no longer suitable as traction batteries in a vehicle after they reach around 70-80% of their initial capacity, but they may still have sufficient power and energy capacity to serve other less demanding functions, such as for storage of electricity from intermittent renewables or to provide grid services. Both the value of these batteries and the industrial development to support the processes for repair and repurposing of spent batteries, whether for reuse in EVs or repurposing in other applications, presents industrial development opportunities. Furthermore, underserved communities, which are often the most reliant on SHVs, stand to benefit the most from this emerging industry. Potential benefits include increased job creation, higher income opportunities, regional economic revitalization, and urban regeneration.

2. **Sustainable Supply Chain:** Recycling and recovering critical battery materials like nickel, aluminum, copper, lithium, cobalt, and manganese ensures increases the resilience of the supply chains essential to produce EVs and other high-tech products. Reintegrating these materials into new battery production not only reduces the environmental impact of mining and refining but also mitigates the risks associated with the improper disposal of spent batteries, which would be concentrated in underserved communities, which would otherwise disproportionately affect underserved communities.

A Progressive Policy Framework to Address Environmental and Economic Justice from the Nascent EOL Battery Industry

Addressing the challenges of e-waste management requires a comprehensive framework that promotes environmental justice and ensures equitable treatment across all stakeholders involved. Key agendas have been proposed to guide decision-making in the nascent EV battery EOL reuse and recycling industry, with the goal of maximizing economic benefits while minimizing environmental and health burdens (*2*).

1. **The Agenda of Fair Treatment:** This agenda emphasizes the importance of ensuring that no group of people, either domestically or internationally, bears a disproportionate share of the negative environmental impacts resulting from industrial, governmental, and commercial operations. It calls for continuous monitoring and corrective measures to alleviate the unequal burdens faced by certain populations due to e-waste. The objective is to eliminate the unfair distribution of e-waste's harmful effects without shifting these burdens to another population or replacing them with issues like unemployment and poverty.
2. **The Agenda of Meaningful Engagement:** It underscores the necessity of integrating meaningful participation within the environmental justice framework. This involves ensuring that all stakeholders, particularly those affected by e-waste, have a significant role in the decision-making processes related to e-waste management. The goal is to ensure that community concerns are considered, and public contributions can influence regulatory decisions, thereby fostering a collaborative approach to addressing e-waste challenges.

3. **An Inclusive Agenda for Environmental Justice for E-Waste Management:** This agenda highlights the urgency of addressing the growing problem of hazardous e-waste generation and its impacts on vulnerable worker communities and polluted ecosystems. It advocates for a fully circular economy in electronic products manufacturing and disposal to reduce e-waste generation and carbon emissions without compromising employment and safety. The agenda calls for a collective effort to ensure environmental justice in e-waste management by promoting fair worker treatment, especially focusing on the most vulnerable groups such as prisoners and women.
4. **Tempering Antagonistic Agendas to Engage Manufacturers in E-Waste Justice:** Recognizing the, often contentious, relationship between the environmental justice movement and corporate manufacturers, this agenda seeks to transform antagonistic interactions into cooperative engagements. The aim is to involve electronics manufacturers in constructive dialogue and actions to address the e-waste problem, moving beyond litigation towards collaborative efforts to ensure responsible e-waste management and justice.

Discussion

Material Flow Analysis Discussion

Vehicle imports to receiving countries are influenced by regulatory frameworks, economic conditions, public perception, and the availability of supporting technology and infrastructure. The adoption of new EVs and infrastructure in these countries will be pivotal in creating and driving the development of a SH EV market.

This study focuses on the US-Mexico dynamic, shaped by NAFTA-enabled trade and geographic proximity, to examine the environmental risks associated with SH EV exports. The modeling highlights how SH EVs will influence regional flows of critical battery materials, underscoring the importance of addressing technical and regulatory gaps. A regional approach is essential to ensure a successful and equitable transition to low-carbon transportation systems.

Key findings from our modeling indicate that:

1. **SH Imports as a Persistent Source of Concern:**
As EV adoption in the region rises and fleets begin to age, SH EVs and lithium-ion batteries will begin entering the SH vehicle market at an accelerated rate within the next decade, becoming a significant source of material input and a potential environmental concern if not properly managed.
2. **Transformation of the Vehicle Fleet:**
By 2050, a combination of SH EV imports and new EV sales will transform the vehicle fleet, with EVs comprising nearly 50% of vehicles on the road in Mexico.
3. **Reduction in Vehicle Lifespans:**
The increasing prevalence of EVs is expected to reduce the average fleet age to 10 years by 2050. While this reduction could improve air quality, it may also pose challenges for

transportation reliability and increase the burden on end-of-life (EOL) management systems.

4. **Opportunities in Battery Recycling:**
Regional EV adoption presents Mexico with significant opportunities in battery recycling. Significant volumes of recoverable battery materials—such as nickel, aluminum, copper, lithium, cobalt, and manganese—will enter the country annually. While steel accounts for the largest share of recoverable mass, critical minerals like lithium, cobalt, and manganese are more valuable per unit of mass and are vital for ensuring a stable and sustainable supply chain for EV production.

5. **Environmental and Economic Benefits of Recycling:**
The recovery and recycling of critical minerals reduce the need for primary extraction, avoiding landfilling and associated environmental impacts. These processes also secure a stable supply chain for critical materials essential to EVs and other high-tech products, helping Mexico reintegrate them into global battery supply chains.

Lifecycle Assessment Discussion

This study demonstrates that incorporating regional conditions into the LCA of SHVs significantly alters life cycle environmental performance, with benefits and burdens distributed unevenly between exporting and importing countries depending on operational conditions and distance traveled.

Beyond grid energy mix and vehicle production—already established as key drivers of life cycle GWP emissions—this analysis identifies additional factors unique to exported SH EVs. Battery degradation, likelihood of replacement, and access to recycling infrastructure are critical. These factors, tied to the vehicle's age or distance traveled at export, influence life cycle emissions, including toxic pollutants and HTP-NC emissions. Export timing emerges as a pivotal factor, with younger exports potentially maximizing air quality benefits for importing countries like Mexico, while older exports without proper recycling infrastructure could increase toxic risks from spent batteries.

While SH EVs offer clear operational benefits, uncertainties around EOL battery management raise concerns. Without robust disposal and recycling systems, Mexico risks significant environmental and public health challenges from landfilling, stockpiling, or insufficient recycling. Thus, achieving the full environmental potential of SH EVs requires investments in sustainable EOL management and recycling strategies to mitigate these risks and ensure circularity in critical mineral supply chains.

Implications for Policy and Bilateral Cooperation

To minimize environmental burdens and maximize benefits across the USMCA region, EV adoption and SHV trade require coordinated policy interventions. Exporting countries, such as the United States and Canada, must establish strategies that promote circularity and responsible export practices, while Mexico, as the primary importer, should prioritize building EOL management and recycling capacity. Aligning incentives, fostering cooperation, and developing common regulatory frameworks are essential to addressing the unique challenges posed by SH EV trade and ensuring equitable environmental and economic outcomes. Table 3 summarizes the identified opportunities for different stakeholders involved.

Table 3. Policy solutions

Responsible Party	Policy Opportunities	Desired Outcome
Joint Actions	Cooperation to develop robust regional battery recycling infrastructure and supply chains	Reduce human toxicity and ecological impacts associated with SH EVs. Recover critical materials
	Incentives for responsible EOL battery management and recycling	Ensure full environmental benefits of SH EV imports and mitigate battery disposal risks
	Implementing a Regional Extender Producer Responsibility (EPR) System	Incentivize manufacturers to design sustainable systems with a focus on durability and EOL material recovery and recycling
	Establishing a digital battery information protocol and shared database platform	Foster transparency and accountability in the management of EOL vehicles and batteries
	Adopt regional collaboration program between custom agencies	Unify and streamline trade registrations ensuring regulatory compliance and facilitating tracking
Exporting Countries	Implement and enforce battery SOH minimum requirements before export	Reduce environmental impacts in importing countries
	Adopt right-to-repair legislation in the first country of sale to ensure vehicle and battery longevity	Extend the life cycle utility of vehicles before and after export
Importing Countries	Implement and enforce battery SOH minimum requirements for import	Avoid accelerated waste burdens and battery degradation, mitigating impacts associated with SH EV imports
	Invest in grid decarbonization and EV charging infrastructure	Enhance the environmental benefits of SH EV trade
	Implement tariffs, taxes, and selective bans on SH ICEV imports	Reduce fleet emissions and prevent pollution increase from SH ICEVs
	Implementing mechanisms to encourage second-life battery applications	Extract utility from batteries no longer suitable for vehicle use and reduce production and EOL management system burden

Mobility and Environmental Justice Analysis Discussion

As demonstrated by the existing literature examining SHV exports to Mexico, previous studies center around the environmental impact associated with these flows, with a particular focus on emissions and air quality. Additionally, many studies have addressed concerns regarding the potential effects on the domestic automotive industry, as SHVs capture a growing share of the domestic market, potentially impacting industry revenues.

However, a critical gap in the literature is the lack of exploration into the underlying transportation and mobility justice issues that create the conditions and drive the demand for SHV imports to Mexico. Moreover, none of the available studies have considered the technological shift to EVs and the potential environmental and economic benefits and burdens that an increase in these vehicles might deliver for communities who rely on them as a primary source of mobility.

This research took a comprehensive approach to analyzing the structural inequities present in the transportation system in Mexico, which disproportionately affect low-income communities in Northern Mexico and perpetuate the need for SHV imports. It also provided insights into the existing inequities derived from the global flows of e-waste in anticipation of the economic and environmental burdens that an increase in SH EVs imports might impose –some of which have already started to be reported in other SHV import-dependent countries of the global south. These foreseen burdens, however, might be mitigated through policy interventions that considers the impacts of this trade. These may include:

1. **Addressing a built environment that greatly favors private vehicle ownership** over other modes of transportation by updating and enforcing urban development plans, controlling land use, and incentivizing rental housing to encourage denser, transit-friendly communities. Additionally, redirecting public financing away from road-centric projects towards public and non-motorized transportation options is essential.
2. **Strengthening public transportation** by establishing a national sustainable mobility policy that integrates both technical and political considerations, ensuring investments prioritize addressing social inequalities, environmental concerns, and safety. This policy should define clear roles, responsibilities, and funding rules, encouraging investments in sustainable urban mobility over traditional road infrastructure.
3. **Adopting an environmental and economic justice framework to support and guide the development of a national EOL battery industry**. Key policies could include creating subsidies or battery replacement programs targeting low-income communities, creating guidelines and education programs for adequate EOL battery management and disposal, providing incentives for the creation of battery collection, reuse, and recycling businesses in high SHV regions, or promoting partnerships with original equipment manufacturers (OEMs) to create reverse logistics value chains.

While these actions could reduce Mexico’s reliance on SHV imports—offering communities more equitable mobility options and new income opportunities—collaborations with USMCA counterparts should also be leveraged to support a regional transition to EVs, recognizing their extended responsibilities. Key measures include supporting battery recycling programs in Mexico to ensure the circularity of critical minerals, establishing a regional extended producer responsibility (EPR) system, unifying trade records, and promoting sustainable practices such as the right to repair.

High-income countries profit from SHV exports but also shift environmental and waste management challenges to LMICs. Greater reciprocity—through technical expertise, financial support, and shared regulatory frameworks—can help LMICs manage these burdens more effectively, fostering fairness in global trade. Strengthening bilateral cooperation can create a more efficient supply chain while mitigating the risks of environmental dumping.

Further research is required to gain deeper knowledge into the dynamics of the SHV trade, including understanding who participates, the nature of their participation, and the evolving landscape with the advent of EV technology.

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Data Summary

Products of Research

Material Flow Analysis

The data collected, including vehicle sales, stock, propulsion, and trade and battery characterization, was used in modeling efforts to assess the future impact of second-hand electric vehicle trade between the U.S. and Mexico. Results in this dataset show the US' and Mexico's projected vehicle stock turnover and the exports/imports transferred, estimating the recovery of valuable materials from end-of-life EV batteries. These projections also considered the policy changes required to support the growing EV market, particularly in terms of recycling capabilities and regulatory frameworks.

Lifecycle Assessment

This project utilized data from a range of authoritative sources, including OEM technical specifications, trade statistics, vehicle registration records, electricity generation data, and life cycle inventories from the Ecoinvent database. Key vehicle models were selected to represent different market segments and propulsion technologies, ensuring relevance to current market trends. The data was processed through a regionally expanded life cycle assessment (LCA), which modeled the environmental impacts of second-hand electric vehicle (EV) trade between the U.S. and Mexico. This included analyzing vehicle survivability, battery degradation, and energy efficiency. Results in this dataset show the life cycle impact assessment, focusing on GHG emissions, human health, and ecosystem damage, providing insights into the environmental and social implications of this cross-border EV trade.

Environmental Justice

Key datasets were integrated from different sources, including demographic and migration statistics from the National Population Council (CONAPO), vehicle registration data from Mexico's Public Vehicle Registry (REPUVE), and economic data from the National Institute for Statistics and Geography (INEGI). Where data inconsistencies or gaps were identified, standard imputation and projection methods were applied to maintain data continuity and integrity across the dataset.

The data in the resulting dataset were processed using descriptive statistics techniques and visualized to understand how SH EVs are distributed across different communities in Mexico, particularly low-income areas, and the associated environmental risks, such as the EOL management of electric vehicle batteries.

Data Format and Content

Material Flow Analysis

The data is presented in numeric form in an Excel spreadsheet in .xlsx format. The spreadsheet contains multiple modeling results categorized into different tabs, as presented below:

Tab 1	LDV registrations and deregistrations in Mexico, 2005-2050
Tab 2	LDV fleet composition evolution in Mexico, 2005-2050
Tab 3	Comparison of Mexico's LDV Fleet Age, Technology, and Origin, 2022 and 2050
Tab 4	Cumulative retired battery material in Mexico, 2010-2050.

LCA

The data is presented in numeric form in an Excel spreadsheet in .xlsx format. The spreadsheet contains multiple modeling results categorized into different tabs, as presented below:

Tab 1	Tables showing the lifecycle impact of difference vehicle scenarios by age, broken down by lifecycle process
Tab 2	Tables showing the lifecycle impacts of baseline scenario vehicles and their relative difference with respect to a vehicle that is exported/imported, by age of export
Tab 3	Tables showing the lifecycle impacts of vehicle scenarios by age of export, in absolute values
Tab 4	Tables showing the evolution of the US electricity grid energy mix and a forecast to 2050. Absolute values are provided on the right and the relative values on the left.
Tab 4	Tables showing the evolution of the Mexican electricity grid energy mix and a forecast to 2047. Absolute values are provided on the right and the relative values on the left.

Environmental Justice

The data is presented in numeric form in an Excel spreadsheet in .xlsx format. The spreadsheet contains multiple modeling results categorized into different tabs, as presented below:

Tab 1	Table aggregating statistics for all states in Mexico, including New vehicle sales, SH imports, vehicle stock, motorization rate, population, GDP, remittance**s** per capita

Data Access and Sharing

All data associated with the outcomes of the three research projects is available on Dryad through the following DOIs:

Material Flow Analysis: https://doi.org/10.5061/dryad.x95x69ptn

LCA: https://doi.org/10.5061/dryad.cvdncjtcm

Environmental Justice: https://doi.org/10.5061/dryad.sxksn03bw

Reuse and Redistribution

All data associated with this project, including processed datasets and supporting materials, is available as open access (CC-BY) on Dryad. However, due to licensing restrictions, raw life cycle inventory (LCI) data sourced from the ecoinvent database cannot be shared. Additionally, direct transcripts from the expert elicitation process are not included, in adherence to confidentiality agreements made to protect participant anonymity.

Appendix A

Expert elicitation transcripts and questions.

Private Sector Interview

"Thank you for agreeing to participate in this study and providing insight into electric vehicle end-of-life logistics. Before we begin, do you have any questions about the study?

To facilitate the interview, I would like to record our conversation. The recording will be stored confidentially, and I will remove all personal identifiers. Do I have your consent to tape the conversation or would you prefer not to be recorded?"

1. I'd like to begin by asking what company you work for and describe your roles and responsibilities.
    a. For battery recyclers or repurposed,
2. What role does your company play in processing end-of-life vehicles
3. What role do your main partners and suppliers play in the industry?
    a. What is your main source of material input, and where do mainly ship your final product?
4. Where do you operate?
5. What are the Gov. agencies and regulations that you must interact with?
6. Has the influx of hybrid or electric vehicles affected you or your employer? If so, how?
7. Have you interacted with electric vehicles as part of your job?
    a. If yes, fill out survey together (next page)
    b. If not, do you expect to? Do you think people in the same industry in other parts of Mexico are interacting with electric vehicles?
8. Do you expect your job or industry to change when a higher percentage of cars on the road are electric?
    a. If yes, how so? Do you feel prepared for any upcoming changes?
    b. Ask about cost, logistics, and technical expertise if it does not come up
9. Have you received any formal guidance on how to handle electric vehicles? Safety protocol, etc.?
    a. If so, ask to describe. Do they feel this is adequate? Are these guidelines generally followed?
    b. If not, do they think there should be guidance? From whom and about what? Who normally issues similar safety guidelines or regulations?

10. In your understanding, what happens to electric vehicle batteries when the car reaches the end of its usable life?
11. What is your greatest concern regarding EV batteries and what do you see as the greatest opportunity?
12. Is there anything else I should have asked you about electric vehicles or your job?
13. Do you know anyone else I should consider interviewing?
    a. If so, would you be willing to make an introduction or provide me with their contact information?

I am planning to produce a report of my observations and findings from these interviews. Would you like a copy? YES____ NO____

Public Sector Interview

"Thank you for agreeing to participate in this study and providing insight into electric vehicle end-of-life logistics. Before we begin, do you have any questions about the study?

To facilitate the interview, I would like to tape our conversation. The recording will be stored confidentially, and I will remove all personal identifiers. Do I have your consent to tape the conversation or would you prefer not to be recorded?"

1. I'd like to begin by asking you to describe your roles and responsibilities. and what agency you work for:
2. What role does your agency play in regulating end-of-life vehicles?
3. What role does your agency have in overseeing stakeholders in the industry?
4. What are the boundaries of your jurisdiction?
5. What other Gov. agencies do you mainly work with in overseeing the vehicle end-of-life?
6. What regulations do you work with in overseeing the vehicle end-of-life?
7. Have you noticed any changes with the influx of hybrid and electric vehicles?
8. Do you expect your job to change when a higher percentage of cars on the road are electric?
    a. If yes, how so? Do you feel prepared for any upcoming changes?
    b. Technical expertise, new regulations if it does not come up
9. Do you have, or are you developing, any plans to provide guidance and outreach regarding the proper handling of end-of-life batteries and EVs?
10. In your understanding, what happens to electric vehicle batteries when the car reaches the end of its usable life?

11. What is your greatest concern regarding EV batteries and what is the greatest opportunity?
12. Is there anything else I should have asked you about electric vehicles or your job?
13. Do you know anyone else I should consider interviewing?
    a. If so, would you be willing to make an introduction or provide me with their contact information?

I am planning to produce a report of my observations and findings from these interviews. Would you like a copy? YES____ NO____

Appendix B

Reference Lifecycle Inventory Datasets

Table A1. Reference lifecycle inventory datasets (all from ecoinvent (12)).

Sector	ISIC Classification	Activity Name	Reference Product Name	Geography
Chemicals	2011:Manufacture of basic chemicals	cobalt sulfate production	cobalt sulfate	CN
Chemicals	2011:Manufacture of basic chemicals	market for cobalt sulfate	cobalt sulfate	CN
Chemicals	2011:Manufacture of basic chemicals	lithium hydroxide production	lithium hydroxide	GLO
Chemicals	2011:Manufacture of basic chemicals	market for lithium hydroxide	lithium hydroxide	GLO
Chemicals	2011:Manufacture of basic chemicals	manganese sulfate production	manganese sulfate	GLO
Chemicals	2011:Manufacture of basic chemicals	market for manganese sulfate	manganese sulfate	GLO
Chemicals	0729:Mining of other non-ferrous metal ores	market for nickel sulfate	nickel sulfate	GLO
Chemicals	2011:Manufacture of basic chemicals	nickel sulfate production	nickel sulfate	GLO
Chemicals	2011:Manufacture of basic chemicals	cobalt sulfate production	cobalt sulfate	RoW
Chemicals	2011:Manufacture of basic chemicals	market for cobalt sulfate	cobalt sulfate	RoW
Electricity	3510:Electric power generation, transmission and distribution	electricity production, deep geothermal	electricity, high voltage	MX
Electricity	3510:Electric power generation, transmission and distribution	electricity production, hard coal	electricity, high voltage	MX
Electricity	3510:Electric power generation, transmission and distribution	electricity production, lignite	electricity, high voltage	MX
Electricity	3510:Electric power generation, transmission and distribution	electricity production, natural gas, combined cycle power plant	electricity, high voltage	MX
Electricity	3510:Electric power generation, transmission and distribution	electricity production, natural gas, conventional power plant	electricity, high voltage	MX
Electricity	3510:Electric power generation, transmission and distribution	electricity production, oil	electricity, high voltage	MX
Electricity	3510:Electric power generation, transmission and distribution	electricity production, wind, 1-3MW turbine, onshore	electricity, high voltage	MX
Electricity	3510:Electric power generation, transmission and distribution	electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted	electricity, low voltage	MX

Sector	ISIC Classification	Activity Name	Reference Product Name	Geography
Electricity	3510:Electric power generation, transmission and distribution	electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	MX
Electricity	3510:Electric power generation, transmission and distribution	electricity production, deep geothermal	electricity, high voltage	US-WECC
Electricity	3510:Electric power generation, transmission and distribution	electricity production, hard coal	electricity, high voltage	US-WECC
Electricity	3510:Electric power generation, transmission and distribution	electricity production, hydro, pumped storage	electricity, high voltage	US-WECC
Electricity	3510:Electric power generation, transmission and distribution	electricity production, hydro, reservoir, alpine region	electricity, high voltage	US-WECC
Electricity	3510:Electric power generation, transmission and distribution	electricity production, lignite	electricity, high voltage	US-WECC
Electricity	3510:Electric power generation, transmission and distribution	electricity production, natural gas, combined cycle power plant	electricity, high voltage	US-WECC
Electricity	3510:Electric power generation, transmission and distribution	electricity production, natural gas, conventional power plant	electricity, high voltage	US-WECC
Electricity	3510:Electric power generation, transmission and distribution	electricity production, nuclear, pressure water reactor	electricity, high voltage	US-WECC
Electricity	3510:Electric power generation, transmission and distribution	electricity production, oil	electricity, high voltage	US-WECC
Electricity	3510:Electric power generation, transmission and distribution	electricity production, wind, 1-3MW turbine, onshore	electricity, high voltage	US-WECC
Electricity	3510:Electric power generation, transmission and distribution	electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted	electricity, low voltage	US-WECC
Electricity	3510:Electric power generation, transmission and distribution	electricity production, photovoltaic, 570kWp open ground installation, multi-Si	electricity, low voltage	US-WECC
Electronics	2720:Manufacture of batteries and accumulators	battery production, Li-ion, LFP, rechargeable, prismatic	battery, Li-ion, LFP, rechargeable, prismatic	CN
Electronics	2720:Manufacture of batteries and accumulators	battery production, Li-ion, NCA, rechargeable, prismatic	battery, Li-ion, NCA, rechargeable, prismatic	CN
Electronics	2720:Manufacture of batteries and accumulators	battery production, Li-ion, NMC111, rechargeable, prismatic	battery, Li-ion, NMC111, rechargeable, prismatic	CN

Sector	ISIC Classification	Activity Name	Reference Product Name	Geography
Electronics	2720:Manufacture of batteries and accumulators	battery production, Li-ion, NMC811, rechargeable, prismatic	battery, Li-ion, NMC811, rechargeable, prismatic	CN
Electronics	2011:Manufacture of basic chemicals	market for battery, Li-ion, LFP, rechargeable, prismatic	battery, Li-ion, LFP, rechargeable, prismatic	GLO
Electronics	2720:Manufacture of batteries and accumulators	market for battery, Li-ion, NCA, rechargeable, prismatic	battery, Li-ion, NCA, rechargeable, prismatic	GLO
Electronics	2720:Manufacture of batteries and accumulators	market for battery, Li-ion, NMC111, rechargeable, prismatic	battery, Li-ion, NMC111, rechargeable, prismatic	GLO
Electronics	2720:Manufacture of batteries and accumulators	market for battery, Li-ion, NMC811, rechargeable, prismatic	battery, Li-ion, NMC811, rechargeable, prismatic	GLO
Electronics	2720:Manufacture of batteries and accumulators	battery production, NiMH, rechargeable, prismatic	battery, NiMH, rechargeable, prismatic	GLO
Electronics	2720:Manufacture of batteries and accumulators	market for battery, NiMH, rechargeable, prismatic	battery, NiMH, rechargeable, prismatic	GLO
Electronics	2720:Manufacture of batteries and accumulators	battery production, Li-ion, LFP, rechargeable, prismatic	battery, Li-ion, LFP, rechargeable, prismatic	RoW
Electronics	2720:Manufacture of batteries and accumulators	battery production, Li-ion, NCA, rechargeable, prismatic	battery, Li-ion, NCA, rechargeable, prismatic	RoW
Electronics	2720:Manufacture of batteries and accumulators	battery production, Li-ion, NMC111, rechargeable, prismatic	battery, Li-ion, NMC111, rechargeable, prismatic	RoW
Electronics	2720:Manufacture of batteries and accumulators	battery production, Li-ion, NMC811, rechargeable, prismatic	battery, Li-ion, NMC811, rechargeable, prismatic	RoW
Infrastructure & Machinery; Transport	4520:Maintenance and repair of motor vehicles	maintenance, passenger car, electric, without battery	maintenance, passenger car, electric, without battery	GLO
Infrastructure & Machinery; Transport	4520:Maintenance and repair of motor vehicles	market for maintenance, passenger car, electric, without battery	maintenance, passenger car, electric, without battery	GLO
Infrastructure & Machinery; Transport	4520:Maintenance and repair of motor vehicles	market for passenger car maintenance	passenger car maintenance	GLO
Infrastructure & Machinery; Transport	4520:Maintenance and repair of motor vehicles	maintenance, passenger car	passenger car maintenance	RER
Metals	2420:Manufacture of basic precious and other non-ferrous metals	aluminium ingot, primary, to aluminium, cast alloy market	aluminium, cast alloy	GLO

Sector	ISIC Classification	Activity Name	Reference Product Name	Geography
Metals	2410:Manufacture of basic iron and steel	market for steel, low-alloyed	steel, low-alloyed	GLO
Metals	2410:Manufacture of basic iron and steel	steel production, electric, low-alloyed	steel, low-alloyed	RoW
Transport	4921:Urban and suburban passenger land transport	market for transport, passenger car, electric	transport, passenger car, electric	GLO
Transport	4921:Urban and suburban passenger land transport	transport, passenger car, electric	transport, passenger car, electric	GLO
Transport	4922:Other passenger land transport	market for transport, passenger car	transport, passenger car	RoW
Transport	4922:Other passenger land transport	transport, passenger car	transport, passenger car	RoW
Transport	4922:Other passenger land transport	market for transport, passenger car with internal combustion engine	transport, passenger car with internal combustion engine	RoW
Transport	4922:Other passenger land transport	transport, passenger car with internal combustion engine	transport, passenger car with internal combustion engine	RoW
Transport; Infrastructure & Machinery	2910:Manufacture of motor vehicles	market for passenger car, electric, without battery	passenger car, electric, without battery	GLO
Transport; Infrastructure & Machinery	2910:Manufacture of motor vehicles	passenger car production, electric, without battery	passenger car, electric, without battery	GLO
Transport; Infrastructure & Machinery	2910:Manufacture of motor vehicles	market for passenger car, petrol/natural gas	passenger car, petrol/natural gas	GLO
Transport; Infrastructure & Machinery	2910:Manufacture of motor vehicles	passenger car production, petrol/natural gas	passenger car, petrol/natural gas	GLO
Waste Treatment & Recycling	3830:Materials recovery	treatment of used Li-ion battery, hydrometallurgical treatment	cobalt	GLO
Waste Treatment & Recycling	3830:Materials recovery	treatment of used Li-ion battery, pyrometallurgical treatment	cobalt	GLO
Waste Treatment & Recycling	3830:Materials recovery	treatment of used Li-ion battery, hydrometallurgical treatment	lithium carbonate	GLO
Waste Treatment & Recycling	3830:Materials recovery	treatment of used Li-ion battery, pyrometallurgical treatment	manganese dioxide	GLO

Sector	ISIC Classification	Activity Name	Reference Product Name	Geography
Waste Treatment & Recycling	3830:Materials recovery	market for used glider, passenger car	used glider, passenger car	GLO
Waste Treatment & Recycling	3830:Materials recovery	treatment of used glider, passenger car, shredding	used glider, passenger car	GLO
Waste Treatment & Recycling	3830:Materials recovery	market for used internal combustion engine, passenger car	used internal combustion engine, passenger car	GLO
Waste Treatment & Recycling	3830:Materials recovery	treatment of used internal combustion engine, passenger car, shredding	used internal combustion engine, passenger car	GLO
Waste Treatment & Recycling	3830:Materials recovery	market for used Li-ion battery	used Li-ion battery	GLO
Waste Treatment & Recycling	3830:Materials recovery	treatment of used Li-ion battery, hydrometallurgical treatment	used Li-ion battery	GLO
Waste Treatment & Recycling	3830:Materials recovery	treatment of used Li-ion battery, pyrometallurgical treatment	used Li-ion battery	GLO
Waste Treatment & Recycling	3830:Materials recovery	market for used Ni-metal hydride battery	used Ni-metal hydride battery	GLO
Waste Treatment & Recycling	3830:Materials recovery	treatment of used Ni-metal hydride battery, pyrometallurgical treatment	used Ni-metal hydride battery	GLO
Waste Treatment & Recycling	3830:Materials recovery	market for used powertrain from electric passenger car, manual dismantling	used powertrain from electric passenger car, manual dismantling	GLO
Waste Treatment & Recycling	3830:Materials recovery	treatment of used powertrain for electric passenger car, manual dismantling	used powertrain from electric passenger car, manual dismantling	GLO
Waste Treatment & Recycling; Metals	2420:Manufacture of basic precious and other non-ferrous metals	treatment of non-Fe-Co-metals, from used Li-ion battery, hydrometallurgical processing	copper, cathode	GLO
Waste Treatment & Recycling; Metals	2420:Manufacture of basic precious and other non-ferrous metals	treatment of non-Fe-Co-metals, from used Li-ion battery, pyrometallurgical processing	copper, cathode	GLO
Waste Treatment & Recycling; Metals	2420:Manufacture of basic precious and other non-ferrous metals	treatment of non-Fe-Co-metals, from used Li-ion battery, hydrometallurgical processing	manganese	GLO

Sector	ISIC Classification	Activity Name	Reference Product Name	Geography
Waste Treatment & Recycling; Metals	2420:Manufacture of basic precious and other non-ferrous metals	treatment of non-Fe-Co-metals, from used Li-ion battery, hydrometallurgical processing	non-Fe-Co-metals, from Li-ion battery, hydrometallurgical processing	GLO
Waste Treatment & Recycling; Metals	2420:Manufacture of basic precious and other non-ferrous metals	market for non-Fe-Co-metals, from used Li-ion battery, pyrometallurgical processing	non-Fe-Co-metals, from used Li-ion battery, pyrometallurgical processing	GLO
Waste Treatment & Recycling; Metals	2420:Manufacture of basic precious and other non-ferrous metals	treatment of non-Fe-Co-metals, from used Li-ion battery, pyrometallurgical processing	non-Fe-Co-metals, from used Li-ion battery, pyrometallurgical processing	GLO
Waste Treatment & Recycling; Metals	2420:Manufacture of basic precious and other non-ferrous metals	treatment of non-Fe-Co-metals, from used Li-ion battery, hydrometallurgical processing	sulfuric acid	GLO