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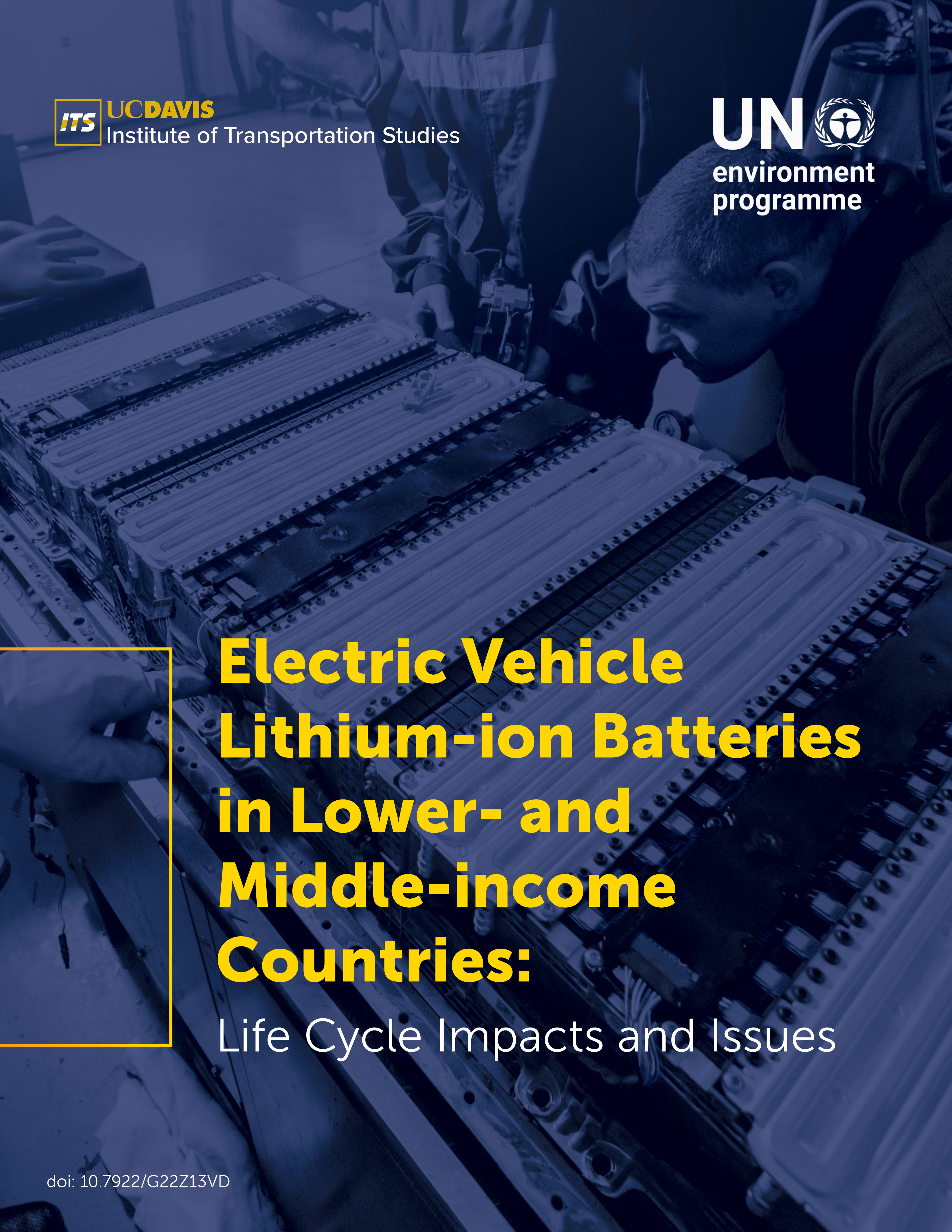

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Electric Vehicle Lithium-ion Batteries in Lower- and Middle-income Countries:

Life Cycle Impacts and Issues

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List of Abbreviations

Abbreviation	Definition
2&3	two- and three-[wheelers]
ANAM	National Customs Agency of Mexico
BEV	battery electric vehicle
BMS	battery management system
E-Bus	battery electric bus
EoL	end-of-life
EPR	extended producer responsibility
ESG	environmental, social, and governance
EU	European Union
EV	electric vehicle
GBA	Global Battery Alliance
GHG	greenhouse gas
HEV	hybrid electric vehicle
HIC	high-income country
ICEV	internal combustion engine vehicle
IEA	International Energy Agency
kWh	kilowatt hour
LCO	lithium cobalt oxide
LFP	lithium iron phosphate
LIB	lithium-ion battery
LMICs	lower- and middle-income countries
LMO	lithium manganese oxide

Abbreviation	Definition
MWh	megawatt hour
NCA	lithium nickel cobalt aluminum oxide
NMC	lithium nickel manganese cobalt oxide
NOX	nitrogen oxides
OEM	original equipment manufacturer
PHEV	plug-in hybrid electric vehicle
SOH	state-of-health
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UNEP	United National Environment Programme
US	United States
US ITA	US International Trade Administration
VIN	vehicle identification number
VOC	volatile organic compound

Key Takeaways

The largest economies in the world are rapidly transitioning new vehicle sales away from gasoline and diesel internal combustion engine vehicles to battery-powered electric vehicles. This transition is material intensive, requiring the rapid development of new supply chains to build the lithium ion batteries that power electric vehicles. These batteries are built on extractive industries located all over the world, including many in lower and middle income countries that are themselves not electrifying, and thus not enjoying the benefits of reduced air pollution and greenhouse gases. In fact, many lower income countries rely heavily on second-hand vehicle imports from wealthier countries, including those that are rapidly electrifying their fleets. Projections of electric vehicle sales in these markets in wealthier countries suggest that second-hand electric vehicle export flows could exceed 2 million by 2035, up from just 30,000–75,000 in 2022.

The life cycle of an electric vehicle differs not just in the materials required for production, but also throughout its life cycle, including during vehicle use and end-of-life. These differences could mean that second-hand electric vehicles rapidly become a burden in markets without the capacity and infrastructure to repair and recycle electric vehicles and the batteries that power them. This report explores the future stocks, flows, and life cycles of electric vehicles to understand the implications for lower and middle income countries and provides a set of strategies for how some of the problems presented by the transition to electric vehicles might be mitigated.

Strategies rely on improved governance or focus to:

- provide improved information about electric vehicle battery condition, technical information for repair and repurposing of batteries, and data on the movement of second-hand vehicles.
    - › The lack of information could be partly addressed by the European Union's proposed **digital battery passport** requirements, which would provide a significant advance in information regarding the battery value chain and some access to dynamic real-time information like state-of-health for in-use batteries.
    - › Ensuring the **right-to-repair** and other measures that can extend the life of electric vehicles and their batteries, ensuring that we see fewer stranded vehicle and battery assets around the world, and particularly in lower and middle income countries.
    - › Create a harmonized reporting system for collecting data at the point of export and import for second-hand vehicles and/or their batteries.
- support the development of supply-side measures (i.e., second-hand electric vehicle export controls), and demand side measures (i.e., second-hand import controls) to prevent second-hand electric vehicle or second-hand battery exports from becoming a least-cost disposal option for exporting markets, burdening rather than benefiting the importing markets.
    - › Minimum performance and condition criteria for importing and exporting markets, such as battery state-of-health or electric vehicle range.
    - › Labeling and other criteria to assist in recycling and improved safety during repair or repurposing of electric vehicle batteries.

Introduction

On-road transportation is responsible for approximately 25% of global energy-related greenhouse gas (GHG) emissions and is an enormous source of local air quality pollutants (European Environment Agency 2019; International Energy Agency 2021). While providing mobility options that do not rely on personal vehicles is the best way to reduce emissions, electrification of the transport sector—and in particular passenger vehicles including personal vehicles, buses and two and three (2&3) wheelers—has been widely promoted to reduce GHG emissions and improve air quality (Pathak et al. 2022). Lithium-ion batteries (LIBs) have proven to be the linchpin technology in advancing electric vehicles (EVs), and recent technological improvements and cost reductions have facilitated rapid increases in EV sales, particularly in China, Europe, and the United States (US) over the last few years (International Energy Agency 2022b). While LIBs are an essential technology for an electrified future, they are also material-intensive during production and potentially hazardous at their end-of-life (EoL).

LIBs are composed of an anode, cathode, separator and electrolyte. The anode is typically made of graphite, coated on a copper current collector, although battery-makers are also innovating silicon-based anode technology to increase energy density. The cathode is typically an aluminum current collector, coated with lithium combined with transition metals such as nickel, cobalt, and manganese (cathode active material). Lithium, cobalt, and nickel are all high-value metals, and lithium and cobalt in particular are classified as critical minerals by several governments including the US and the European Union (EU).

The burdens of LIB production, the benefits during their use, and the potential impacts at end-of-life occur over global value chains that do not confer benefits and impacts equitably. A life cycle perspective is required to understand global value chains and the implications of the technology from production through EoL.

Figure 1 describes the EV life cycle, from raw material extraction through manufacturing, placement in an EV, use which entails charging on regional electricity grids, retirement from use in an EV, and a number of EoL options including repair and refurbishing for reuse or repurposing in a new application, material recovery via recycling, or final disposition without material recovery. Final disposition without recycling can include formalized hazardous waste disposal options or land disposal without hazardous waste protections. In addition, the use phase may include multiple owners, use regimes, and locations.

The life cycle perspective highlights some potential unintended consequences of vehicle electrification, namely the disproportionate burden that might be imposed by the global value chains that build EVs and which may arise from retired EVs in the coming years. To avert unintended consequences requires identifying potential environmental and socio-economic impacts across the life cycle of Li-ion EV batteries with particular focus on communities in lower- and middle-income countries (LMICs). They may be impacted disproportionally by the sourcing of raw materials, processing of battery materials, manufacturing of batteries, and battery disposal.

Of particular interest is the export of used vehicles from high-income countries for resale in LMICs or transfers of EoL LIBs removed from retired electric vehicles to LMICs. In 2021, the UN Environment Programme's updated *Used Vehicles and the Environment* report stated that more than

760,000 hybrid electric vehicles (HEVs)[1], plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs)[2] were exported from three of the four major second-hand vehicle exporting regions (the EU, Japan, and Republic of Korea) (UN Environment Programme 2021).

Based on extensive review of the literature, the global second-hand vehicle trade has been absent from all previous studies focused on the life cycle environmental performance and social sustainability of EVs.

This report documents the current state of knowledge with respect to the global distribution of environmental impacts and benefits from the battery value chain and life cycle, with particular implications for LMICs.

In this report, EVs refer to battery-powered electric vehicles (not fuel cell-powered electric vehicles). EVs may include BEVs or PHEVs. In a BEV, the vehicle powertrain is powered exclusively by a traction battery (a battery that provides motive power, as opposed to a starter battery). PHEVs include a traction battery and are plugged in to charge the battery, just as a pure EV; however, they also have an internal combustion engine (ICE) that powers the vehicle when the battery has insufficient charge. In this ICE-powered mode the vehicle operates like a gasoline or diesel HEV. In this report we mostly focus on BEVs when

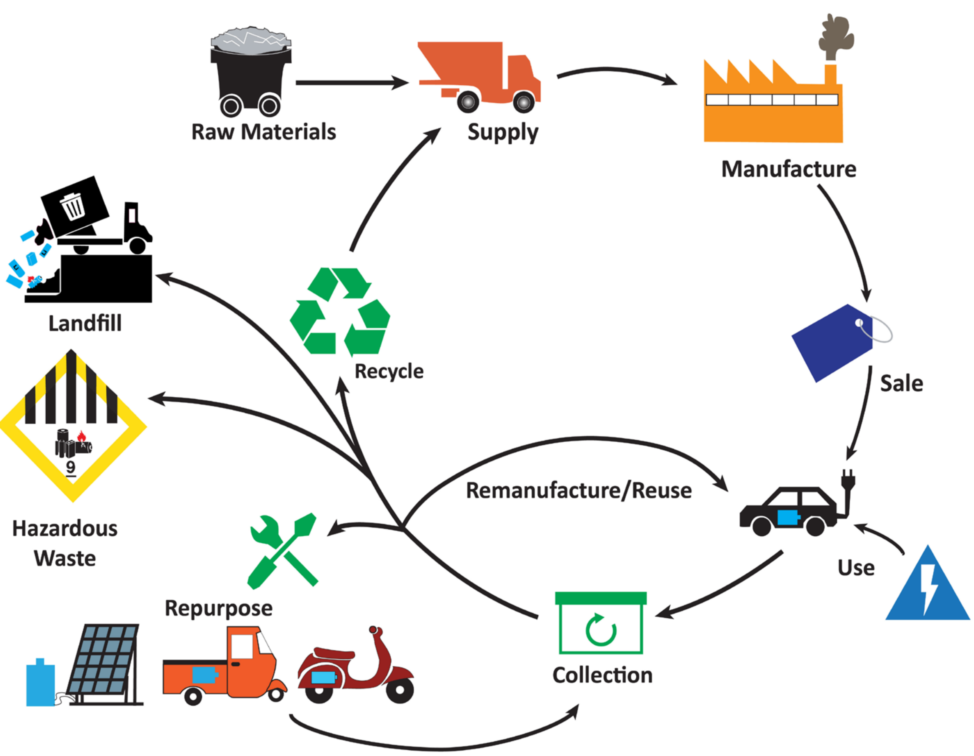

Figure 1. The EV Battery Life Cycle. Note that the use phase may occur in multiple markets due to used vehicle trade.

1 HEVs have much smaller batteries than PHEVs and EVs, and they have historically used nickel metal hydride (NiMH) battery chemistries, not LIBs. HEV batteries present a potential waste problem for receiving countries, but the smaller size of HEV batteries and the more stable chemistry (via reduced risk of thermal runaway) means they present potentially lower hazards at EoL. Some newer HEVs have begun using LIBs in lieu of NiMH batteries due to cost and technical performance characteristics.

2 The term EV is frequently used to describe both BEVs and PHEVs.

discussing vehicle operation and second-hand use of vehicles. This is because even when the EV battery degrades to a point where a BEV might not be operable, a PHEV could continue to operate much like a HEV powered only by fuel. However, the discussion of production and EoL for LIBs applies to both BEV and PHEV batteries given their relatively large size and similar battery chemistries. Moreover, the discussion of the battery production and life cycle, applies not just to personal vehicles, but other on-road passenger modes, including electric buses (E-buses) and 2&3-wheelers.

We begin by examining demand projections of electric passenger cars, E-buses, and electric 2&3-wheelers; we then

- discuss the key technology underpinning these vehicles, the LIB;
- examine the EV life cycle with a critical eye for impacts in LMIC markets across the life cycle, from the extraction of raw materials to EoL;
- identify the existing policies that affect EV LIBs in the largest EV markets;
- provide short vignettes from LMICs that provide insights into the possible futures we may see as used EVs or their batteries enter markets that depend on second-hand vehicle imports;
- and finally propose strategies for securing benefits for these importing markets.

Global Projections of Passenger EV Sales

To date, close to 14 million passenger EVs (BEVs and PHEVs) have been sold worldwide, with a tripling in the past three years (International Energy Agency 2022b). Passenger car EV adoption has been concentrated in The People's Republic of China (China) and the EU and, to a lesser extent, the US, with China comprising 47%, the EU 34%, the US 12%, and the remaining world just 7% of EV sales in 2021 (International Energy Agency 2022a).[3]

Projections of future sales by the International Energy Agency (IEA) show China continuing to lead, with around 40% of global EV sales in 2030 in the IEA's Stated Policies Scenario, and still a leading 33% share of sales in the Announced Pledges Scenario (International Energy Agency 2022a). Based on stated policies, China will approach 10 million EVs in 2030, the EU will exceed 7, and the US will be just under 3. Though Japan and India currently have few EVs, they are both slated to see enormous growth in the next decade (Table 1).

These global sales have different implications for actual battery capacity deployed. The average BEV sold in 2021 had a 43 kWh battery (10.6 kWh for PHEVs), and the average battery size varies by region (Statista Research Department, n.d.). For example, in 2012, the average EV in Europe had a battery capacity of just under 16 kWh while the average EV in China had a battery

Table 1. Global EV Sales Projections (both PHEV and pure EV) based on the IEA's Future Sales Scenarios (millions of vehicles). The Stated Policy Scenario reflects national and regional commitments for EV adoption, and the Sustainable Development Scenario reflects a future where environmental and energy access targets are achieved (IEA Global EV Outlook 2021) Note this excludes E-buses and 2 3-wheelers which have achieved significant sales in the Asia Pacific region, and are addressed below.

	Year	China	Europe	United States	Japan	India	Other
Actual Sales	2020	1.28	1.41	0.3	0.03	0	0.14
Stated Policy Scenario	2030	9.54	7.12	2.86	1.49	1.87	2.88
Sustainable Development Scenario	2030	11.95	13.27	8.08	2.76	3.67	6.91
Global Share, Stated Policy Scenario	2030	37%	28%	11%	6%	7%	11%

*Differences in the number of significant digits reflect how values are reported in the original source.

3 These values are just for light-duty passenger vehicles and include pure electric and plug-in hybrid electric vehicles (PHEVs).

capacity of just over 25 kWh. Since then, the average battery capacity of new EVs has increased significantly across the globe, and by 2040 both regions are projected to have average EV battery capacities of about 80 kWh (Dunn et al. 2021). The IEA reports that by 2021, 4.7 million light-duty EVs were sold, with an additional 1.9 million PHEVs. They project by 2030 that global sales will reach 22 million pure EVs sold, and an additional 5.7 million PHEVs. For EVs alone, this will equate to nearly 2000 GWh of EoL LIBs retiring from EVs in 2040 (Dunn et al. 2021).

Electric Buses and 2&3-Wheelers

Passenger cars are only one form of electric mobility; electric 2&3-wheelers and buses will play a key role, especially in LMICs where electrified on-road transportation will mainly occur through public transportation and micro-mobility. Electrification of the medium- and heavy-duty sectors will also be important. Sales of EVs in these two sectors, which include buses, vans and trucks, reached about one million in 2020, nearly all in China, and sales are expected to rise to nearly 6 million by 2025 with growth outside of China (Bloomberg New Energy Finance 2022).

According to the IEA, global E-bus sales increased 40% over the previous year in 2021, bringing the total global stock of electric buses to more than 670,000 (International Energy Agency 2022b). The global market is overwhelmingly dominated by China, which was the first country to transition to E-buses. Since 2011, approximately 657,000 E-buses have been purchased in China, representing 98% of cumulative sales worldwide (International Energy Agency 2022b). While the industry is less mature elsewhere, cities in over 50 countries have begun the process of electrifying their fleets. India is considered the most significant market for E-buses after China. The government has encouraged E-bus adoption via subsidies covering 60% of the upfront cost, which were included in the Faster Adoption and Manufacturing of Hybrid and Electric Vehicles scheme in 2017. Elsewhere in the Asia-Pacific region, Singapore and Taiwan both plan to electrify their entire bus fleets by 2030, as do the cities of Jakarta, Indonesia and Auckland, New Zealand. TransJakarta is in the early stages of electrifying their bus rapid transit (BRT) system, which is the largest in the world, serving 2 million passengers per year (UNEP, 2019). Meanwhile, Pakistan's

National Electric Vehicle Policy states that 90% of new bus sales should be electric by 2040.

Adoption in Latin America is still in the early stages but growing quickly, with 12 countries preparing to at least partially electrify their public transport systems (C40 Cities and International Council on Clean Transportation [ICCT] 2022). As is the case throughout the world, efforts take place on a city-by-city basis. For example, the C40 Clean Cities Initiative and associated Zero Emission Bus Rapid-Deployment Accelerator (ZEBRA) partnership are supporting efforts to electrify public transportation in Santiago de Chile; Medellin, Colombia; Sao Paulo, Brazil; and Mexico City.

Compared to diesel buses, E-buses have multiple environmental and health benefits. The key environmental benefit is a significant reduction in the local air pollutants such as nitrogen oxides (NOx), particulate matter less than 2.5 microns ($PM_{2.5}$), and volatile organic compounds (VOCs) that are emitted by diesel buses. People living in urban environments with diesel buses are most exposed to these pollutants either by riding the bus directly or being close to bus stops (Yang et al. 2015, Xing et al. 2019). Cyclists and pedestrians are at an especially high risk of being impacted by these emissions. The GHG benefits of electric buses depend on the local electric grid mix but can be significant with high renewable penetration (Cooney et al. 2013; IEA, 2020). Studies using real-world data have found that E-buses reduce well-to-wheel emissions of NOx and VOCs by 60–80%, and CO_2 emissions by 10–40% compared to a Euro IV diesel bus in Macao, China (He et al. 2017).

Several papers and reports have discussed the opportunities and challenges of electric bus adoption, focusing on specific cities as case studies (e.g., IEA, 2020). Shenzhen, China is often presented as a success story as it became the first city with an all-E-bus fleet in 2017 (Li et al. 2017); however, researchers have also studied E-bus adoption in cities in Latin America (Castellanos & Maassen, 2017), Europe (Carlini & Moneta, ; Boren, 2019; Bezruchonak, 2019), India (IEA, 2020), Rwanda (Ministry for Infrastructure 2021), Canada (Mohamed et al. 2018), and the United States (Hanlin et al. 2018; Ambrose et al. 2017). Across regions, the main barriers to electric bus adoption are the higher upfront cost, charging requirements, and technological uncertainty. Adoption generally starts off slowly, as cities begin with a small number of buses to familiarize drivers and technicians with the new technology and build the required infrastructure. For example, Shenzhen Bus Group had purchased a total of 545 electric buses between 2011 and 2015, then electrified their entire fleet of 6,000 buses by 2017 (IEA, 2020). Thus, regions with small E-bus sales today but large overall bus fleets should not be underestimated.

Meanwhile, electric 2&3-wheelers have already seen 300 million vehicles on the road, nearly all in China, but with growth occurring in other regions, particularly in countries in Asia. In fact, among all EVs, 2&3-wheelers displace more petroleum that all other applications combined, averting more than 1 million barrels of oil consumption today (Bloomberg New Energy Finance 2022).

LIB Technology

LIBs used to power vehicles (as opposed to starter batteries which are typically lead-acid) are referred to as traction batteries. A typical traction LIB is composed of a cathode, anode, separator, electrolyte, and cell container. Most LIB anodes are made from graphite, the anode current collector is copper, and the cathode current collector is aluminum. Cathodes are made of a lithium metal oxide, combined with a transition metal, commonly nickel, cobalt, iron, or manganese. Plastics are used for the separator and cell container.

LIBs can be based on a variety of chemistries, typically distinguished by the chemistry of their cathodes. The chemistries of commercial importance to EVs include lithium nickel manganese cobalt oxide (NMC), which are further distinguished by the ratio of nickel to manganese to cobalt (NMC 111, NMC 523, NMC 622, and NMC 811)[4], lithium nickel cobalt aluminum oxide (NCA), lithium cobalt oxide (LCO), lithium iron phosphate (LFP), and lithium manganese oxide (LMO), which was common in early commercial EVs but is not used in new EVs.

The choice in cathode chemistry has implications for vehicle range, performance, cost, material demand, and, potentially, EoL processes as well. NMC and NCA batteries are the dominant chemistries for passenger vehicles. LFP batteries notably omit nickel and cobalt, two high cost and environmentally intensive materials, though they typically have lower energy density than competing chemistries. Because the materials in LFP batteries are less valuable than NMC, they are less profitable to recycle (Ciez and Whitacre 2019). This may mean that repurposing is a more viable option than recycling for LFP batteries, at least in the near-term.

Cathode chemistry market shares vary across regions and applications. NCA dominates the US market, with no LFP in the light duty sector, while NMC is dominant in China. LFP is already by far the dominant cathode chemistry for E-Buses, comprising 98.9% of units sold worldwide between 2010 and 2019 (EV-Volumes 2022), and it is expected to grow in the Chinese passenger car EV sector as well (Dunn et al. 2021). While the use of LFP in passenger cars has been limited, it seems likely that LFP will continue to gain market share globally given its rapid adoption in China in all EV segments.

The global landscape for E-buses is dominated by Chinese manufacturers, most of which use LFP batteries due to lower cost and because they are produced domestically (Sustainable Bus 2019). Regional E-bus manufacturers that use NMC batteries have relatively high market shares in the US, Canada, and Europe; however, these buses represent an extremely small percentage of the overall E-bus fleet. If existing patterns continue, emerging economies in Latin America, Asia-Pacific, and Africa will experience an influx of LFP batteries from E-buses in the coming decades, while the North American and European markets will see more NMC chemistries. Energy density is less of a factor for 2&3-wheelers, but the market for these batteries is less well defined, so the mix of chemistries used in these applications is unknown.

Emerging LIB technologies are distinguished by features other than their cathode chemistries, including different anode materials, the most promising of which is substitution of silicon for graphite, as well as “next-generation” technologies

4 The numbers following NMC refer to the proportional content of the materials in the cathode. In an NMC 111 battery, nickel manganese and cobalt are included in equal proportions. In an NMC 811, there is one eighth the cobalt relative to nickel. There has been a trend towards less cobalt-intensive batteries, because of the human rights violations, including child labor and unsafe working conditions associated with cobalt extraction. Note that LFP and LMO battery chemistries contain no cobalt at all.

that are in early stages of commercialization or development, such as solid state[5] and lithium air batteries[6] (Liu et al. 2020).

Impacts Across the EV LIB Life Cycle

The EV life cycle begins with raw material extraction and refining. Passenger vehicles of all types rely on steel, aluminum, plastics, glass, copper, and rubber, but the powertrain components of electrified vehicles, primarily a lithium-ion traction battery and electric motor, substantially changes the types and quantities of materials demanded for vehicle production. For example, an EV increases demand for copper by nearly 140%, and demands metals for the LIB and electric motor that are entirely absent from petroleum-fueled vehicles, including lithium, cobalt, nickel (though nickel is used in steel alloys common in all vehicles), and rare earth metals (IEA 2021). Following material extraction and refining, manufacturing of components is followed by vehicle assembly, sale of the vehicle, the vehicle use phase and vehicle EoL, namely retirement and scrappage where recovery and recycling operations occur. Depending on where EoL processes occur there may be a significant difference in these processes.

5 Solid state batteries replace liquid electrolyte with solid electrolyte. This leads to a more energy dense form and eliminates some failure modes and risks associated with liquid electrolyte.

6 Lithium air (or lithium oxygen) batteries promise much higher energy densities than current LIBs, which rely on transition metals for their active cathode materials. Energy density increases mean less battery material and volume is needed to store the same amount of energy—a particularly attractive feature for EVs. However, lithium air batteries are still in development because of scientific and technical barriers that have not yet been solved, such as a tendency for degradation to occur due to unwanted chemical reactions within the batteries.

The value chains most relevant to the effects of EV adoption in developing economies and LMICs include the initial phase of vehicle production (raw material extraction) and the fate of EVs retired from the road in their first country of sale—which includes the possibility of export of the whole vehicle for resale in a new country, or the export of the used battery (whether exported as a product or waste).

Let us start by considering the export of used EVs for resale in new markets, and particularly markets in lower-income countries.

The Global Distribution of Burdens and Benefits of the EV Life Cycle

The export of second-hand vehicles is not obviously an environmental benefit or detriment for receiving countries, and the future of second-hand vehicle exports is uncertain as major exporting markets electrify. In fact, the world's biggest EV market, China, has historically (though no longer) prevented the export of used EVs, in part as a strategy to retain materials within the region for recycling and recovery. And increasingly, Europe and the US are working towards developing their own primary and secondary battery material resources and their own manufacturing and production capacity. This leads us to envision two possible futures: one future where second-hand vehicle exports continue to occur under similar conditions we see today, and another future where regions where EV adoption is occurring rapidly opt to restrict or eliminate exports.

In the future where second-hand vehicle trade continues, there are two opposing narratives we can envision: a world where LMICs receive EVs that are nearing their EoL, with batteries nearing the end of their service lives and which in turn provide little value and much waste to the receiving countries; and the other where regulatory measures enacted by exporting and importing markets restrict exports of second-hand EVs to those with sufficient remaining battery life to provide many years of continued service, and where repairability and the availability for replacement components allow for cost-effective extension of EV and traction battery lifetimes.

In the future where EV exports are prevented, as has been the case of China, we would see fleets in exporting regions become saturated with EVs while they continue to export older gasoline and diesel vehicles until the supply of second-hand vehicles essentially dries up. The future of mobility in regions dependent on second-hand transfers, and the potential for these regions to transition to EVs is challenging to predict.

Under such conditions do these importing regions remain dependent on petroleum well beyond wealthier regions and countries, and are they likely to suffer increasing costs of fuels? Or do they instead move heavily away from developing car-dependent mobility and grow access to safe active transport and transit, and lean heavily into lower-cost electric 2&3-wheelers? In all cases, the choices of both exporting and importing countries are crucial in determining the outcomes and indicate that coordination and planning at global scales can help facilitate more positive outcomes. Later in this report, we talk more explicitly about the case of US-Mexico second-hand vehicle trade and implications for Mexico's own electrification targets.

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Geography of the EV Battery Life Cycle

Production

The process for production of EV batteries includes the mining of relevant metals, refining of metals to battery grade quality, cell manufacture, and eventually assembly of battery modules and packs. The critical battery material supply chains are highly concentrated both in terms of the country or region of production and the companies that produce them (International Energy Agency 2022c).

The geographies of production for key LIB metals (lithium, nickel and cobalt) are shown in Figure 2. Material refining may not be in the same location as mineral extraction, and in fact China holds more than 50% of lithium, cobalt, and graphite refining, 70% of cathode manufacturing, and 80% of anode manufacturing, along with more than 75% of battery cell manufacturing capacity.

Concentration is not just geographic, but also corporate. For example, in lithium carbonate and hydroxide production, 5 major companies account for 75% of global production capacity.

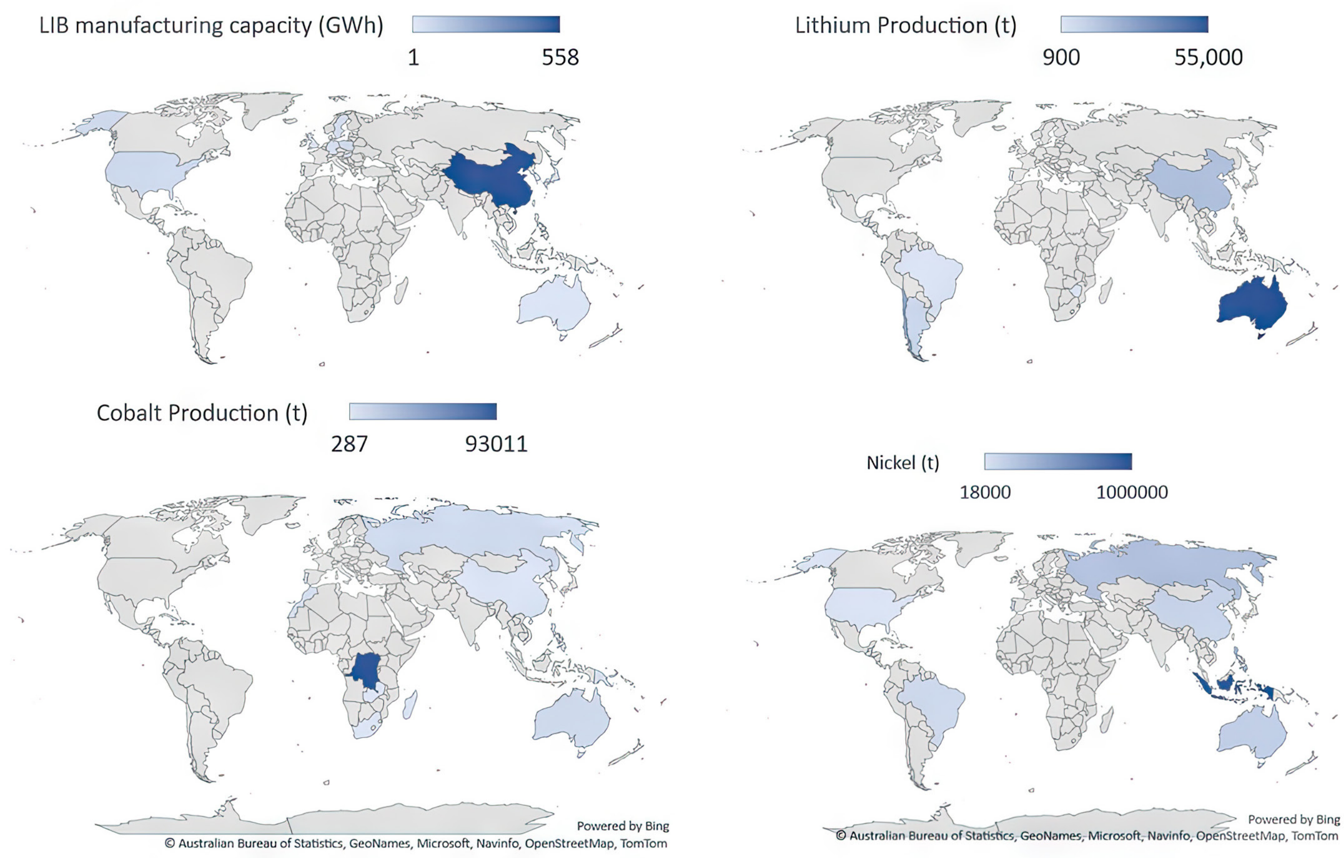

Figure 2. Country-level production volumes (tons of material produced) for key LIB metals and battery manufacturing capacity (GWh of batteries produced). Note, lithium is produced in the U.S., but data have been withheld. China holds nearly 80% of all manufacturing capacity, and metals production shows concentration in particular countries; Australia controls 52% of all lithium production, the Democratic Republic of the Congo produces nearly 73% of all cobalt, and Indonesia 36% of nickel production. (Source: U.S. Geological Survey 2022)

There is an extensive body of work concerned with implications of mining on human rights, a just transition, and broader themes related environmental, social, and governance (ESG) issues (Lèbre et al. 2020; Riofrancos et al. 2023). Work to quantify these risks against real-world mining sites found that many of the key energy transition metals (including those critical for LIBs) have a large share or majority of sites operating in high-risk ESG zones issues (Lèbre et al. 2020). Perhaps the most well known high risk ESG case is cobalt in the Democratic Republic of the Congo (DRC). The human rights violations occurring at cobalt mining sites first garnered global attention after Amnesty International's report on child labor in 2016 (Amnesty International and Afrewatch 2016). Following this report, there was a rush for some well known consumer-facing brands (e.g., Apple) to find alternative sources, but now some of this commitment to alternative sources seems to have been replaced by a mix of commitments to source cobalt from other sites as well as initiatives to improve working conditions and environmental protections at sites in the DRC (Benchmark Mineral Intelligence 2022).

EV Use Phase

Since the earliest life cycle assessments of EVs, research has concluded that where you charge your electric vehicle has a dominant influence on its environmental performance, at least from the standpoint of GHGs, air quality pollutants, and fossil energy consumption. In other words, the means by which electricity is generated to charge an EV is paramount to determining its environmental performance (e.g., Hawkins et al. 2013; Archsmith, Kendall, and Rapson 2015; Samaras and Meisterling 2008). As electricity grids around the world, and particularly in the major markets for EVs, continue to decarbonize, so do the emissions from EV operation. At the same time, EV design trends have led to the adoption of much larger batteries; a desire to both extend range between charging events as well as a trend towards larger and high performance vehicles (Ambrose et al. 2020). The confluence of these two trends will lead to an increase in the relative impact of vehicle (and specifically battery) production compared to vehicle operation. While non-powertrain components of EVs may be very similar to internal combustion engine vehicles (ICEVs), the powertrain is arguably the most crucial and costly system, especially for EVs.

Decarbonizing electricity grids has benefits not only for vehicle operation, but also the industries that produce batteries and vehicles. This is particularly true for manufacturing processes that are electricity-intensive, including LIB manufacturing. For example, reducing electricity grid carbon intensity by 30% leads to a reduction of 17% in battery manufacturing-related carbon intensity (Hall and Lutsey 2018). Thus decarbonizing electricity grids can have synergistic effects on reducing life cycle emissions from EVs.

Repair and Maintenance

EV LIBs are not designed for repair. In fact, some design and vehicle assembly choices made by automotive original equipment manufacturers (OEMs) make repair and disassembly particularly challenging. For example, OEMs may attach batteries via welds to the chassis, making batteries hard to open, and use proprietary battery management system (BMS) hardware and software, often supported by copyright laws that, in some cases, make repair by consumers and third parties illegal.

Currently, there are high barriers to repair EV batteries outside of an OEM's dealer or certified repair network. This is in part a result of battery design (which can exacerbate the safety issues inherent in LIB repair), and also a result of proprietary information held by OEMs. The remanufacturing of batteries has similar barriers. For example, proprietary software to identify battery cells in need of replacement means that only OEMs have access to crucial information for extending the life of EV batteries, at least for the time being (Schartau and Indino 2021). This lack of access to information can also be a barrier to the aftermarket parts industry. Aftermarket parts typically provide lower-cost non-OEM parts for the vehicle repair industry, or provide spare parts for older cars after OEMs stop producing replacement parts.

Adding to these challenges, over the past decades, cars have gotten more complex and computerized. Vehicles increasingly rely on a multitude of sensors and computer chips, and are controlled by obscure proprietary software which non-OEM repair networks do not have access to (Marshall 2022).

Repair and Maintenance in LMICs

The increasing barriers to vehicle repair have implications for LMICs that have historically relied heavily on second-hand vehicle imports to meet their internal demand for reliable transportation and have built a robust system of maintenance and repair to support the sector. For developing regions across the world such as Latin America, Africa, and South and Central Asia, the repair and maintenance industry represents a valuable system that not only ensures the mechanical integrity of vehicles in these regions, extending their useful life well beyond their counterparts in higher income nations, but is also an important source of employment and income for communities, a significant driver of local economies, and an integral component in the countries' waste management systems. What does it mean when vehicles become increasingly computerized, where software determines vehicle performance or where part-pairing can make part replacement and repair impossible or unaffordable?

Consequences of this transition are being felt by traditional independent auto shops and mechanics worldwide, but especially in LMICs where entire communities rely on second-hand vehicles and the ability to service them effectively, and OEM replacement parts and software are virtually inaccessible. Fixing complex vehicles requires increasingly expert and expensive knowledge and tools that are in limited supply. Thus, many users are starting to opt for older models of vehicles with fewer features, as newer models are increasingly more expensive to maintain or remain unfixed and are forced to their EoL sooner than if EoL were determined by mechanical and material failures. It is part of the same trend that has driven some farmers to hack their own tractors and triggered legal fights over what rights consumers have over their own vehicles (Newman 2022).

However, vehicle repair businesses in some LMICs may have an advantage over those in HICs. Many cases worldwide show successful attempts to bypass OEMs by hacking vehicle software for battery replacement and more. The cases are diverse, from ICEVs to EVs, and present a variety of opportunities and problems. In ICEVs, features such as environmental and safety controls can be disabled via hacking, not a benefit to health and safety, and in EVs performance controls can be hacked to improve performance or extend battery life, but cause operating conditions that deteriorate the battery faster or lead to unsafe operation.

The unavailability of replacement batteries or replacement battery parts is also a particular problem for aged EVs in LMICs. Though supply for replacement LIBs is often restricted everywhere due to demand for batteries in new vehicles, this is particularly true in LMICs where EV models may not even be sold new, and thus replacement part supply is not supported by OEMs. This has resulted in some EVs being converted into ICEVs in Sri Lanka, for example, which was an early adopter of second-hand EVs (Ministry of Environment Sri Lanka 2021).

Second-Hand Vehicle Transfers

Among all previous studies looking at the life cycle performance of EVs, none have considered second-hand vehicle transfers to new markets. Yet between 2015 and 2020 some 23 million used passenger cars and trucks were exported to new markets (UN Environment Programme 2021). The EU, Japan, and the US are the three largest exporters of second-hand vehicles. Given that the EU alone made up nearly half of the global EV demand in 2020, markets that import second-hand vehicles can expect to see significant flows of EVs in the coming years and decades.[7] While exporting used vehicles in good condition could improve access to affordable EVs around the world, it will also shift the burden of LIB disposal to the importing countries, which may not have the infrastructure to manage and recycle them safely.

Used vehicles are exported from their original countries for many reasons. They may be too expensive to repair or maintain relative to their value; they may no longer meet safety or environmental regulations; and, demand for older, used vehicles may be higher in the importing (receiving) country than in the first country of sale, due to market distortions introduced by high import tariffs on vehicles (as are present in many LMICs).

Second-hand vehicle markets typically have some kinds of restrictions on imported vehicles. For example, some countries have bans or age limits on used vehicles to protect home-based vehicle manufacturing or for road safety reasons. Apart from total bans and age limits, many have additional motorization management policies for used vehicles, including safety tests, emissions requirements, or financial levers to control their importation (such as differential tariffs based on vehicle characteristics or age). In 2021 the UN Environment Programme reviewed the regulations that govern second-hand vehicle imports for 146 countries and found that about 45% had weak or very weak regulations, and 42% had good or very good regulations (UN Environment Programme 2021). Some of these regulations may explicitly govern the trade of next-generation vehicles such as HEVs, PHEVs and EVs, with some countries favoring HEV and EV second-hand imports, such as in Sri Lanka where second-hand EV and HEV imports were, for a time, afforded lower tariffs.

Unfortunately, the data available on second-hand vehicles from exporting countries and importing countries are limited. Data on vehicles exported are generally not detailed; for example the US tracks simply the export value and vehicle unit count, but does not maintain data on the vehicle age, model, mileage, or vehicle identification number (VIN). In addition, exports are typically recorded with just the first destination after export, which can be an entrepôt country and not the final destination. In addition, even when data are available, their reliability is uncertain. As discussed in the Insight Vignettes section of this report, when import and export data are compared, enormous discrepancies may be revealed.

7 As discussed in future sections of this report, China has historically not been a source of second-hand vehicles. This may be changing as China looks to support new vehicle production and sales within the country. So while China is the largest market for EVs, they are not currently a significant source of second-hand vehicles on the global market, however this is changing.

Importer countries tend to have a bit more information, based on in-country registration data such as vehicle type, engine size, occasionally vehicle age, etc. However, vehicles may be altered between export and import (especially when moving through entrepôt countries), and a vibrant informal/illegal market exists as well. Three reports—the 2020 UN Used Vehicle Report, its 2021 update, and a 2020 Dutch report—point out the many ways in which missing and misreported data are common (Sustainable Mobility Unit of the United Nations Environment Programme 2020; UN Environment Programme 2021; Netherlands Human Environment and Transport Inspectorate 2020).

To understand the implications of these EV flows between countries, in the absence of high quality data, we undertake a projection of future EV flows to second-hand markets from the EU, Japan and US, the three largest second-hand vehicle exporters. To do this, estimates of previous and future EV sales in these three regions were drawn from the IEA's MoMo model (International Energy Agency 2020) to build a vehicle stock model. For each region the expected scrappage rate was then used to estimate the number of vehicles retiring each year (Figure 3). Finally, estimates of the percent of deregistered vehicles that are exported are calculated as described in Table 2. Japan has notably higher export fractions compared to other exporting regions. This is driven largely by the Shaken Law, which requires rigorous and increasingly costly environmental and safety inspections starting 3 years after purchase.

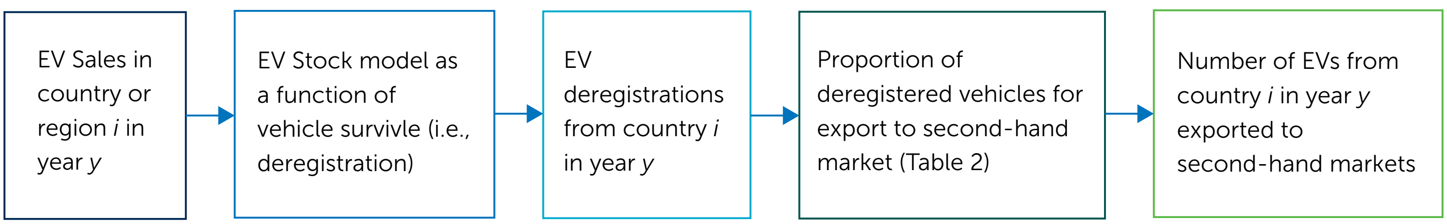

Figure 3. Process for estimating the number of second-hand EV exports over time.

Table 2. Minimum and maximum proportion of deregistered vehicles exported as second-hand vehicles

Region	Min	Max	Millions of EVs exported in 2022	Source	Rationale
EU	10%	40%	0.006–0.023 (min-max)	Lorz 2017	Known extra EU used car exports in 2013 were approximately 10% of deregistered vehicles, and about 30% had unknown whereabouts. The known exports are treated as the minimum, and the maximum possible exports are the sum of known exports and unknown whereabouts.
Japan	55%	92%	0.015–0.026	Wang, Yu, and Okubo 2020	The minimum is based on known exports (55%), and the maximum is based on the fraction of vehicles that are exported but worth less than 0.2 million yen, or are temporarily de-registered (37%). It is not possible to disentangle these two conditions, so the sum of known exports and this category of lower-value second-hand exports and temporarily deregistered vehicles is summed for the maximum possible fraction exported.
US	6%	12%	0.004–0.009	Authors' calculations	The US has no previous estimates of the fraction of deregistered vehicles that are exported to second-hand markets. Instead, these values are estimated based on the following information. About 5% of the US fleet is retired annually (Carlier 2021). Data from the US International Trade Commission (International Trade Commission 2022) and Transportation Energy Data Book (S. C. Davis and Boundy 2022) were then used to estimate the ratio of second-hand vehicle exports to stock, resulting in an estimate of about 0.3%. 0.3%/5% = 6%. We have no knowledge of what the upper bound value might be for US exports. So, we simply doubled this value for an upper bound. Other research that tried to estimate second-hand exports of particular vehicle models found that exports of any given model were expected to be far below 10% (Zhu et al. 2021). Thus, the 12% maximum errs on the side of overestimation.

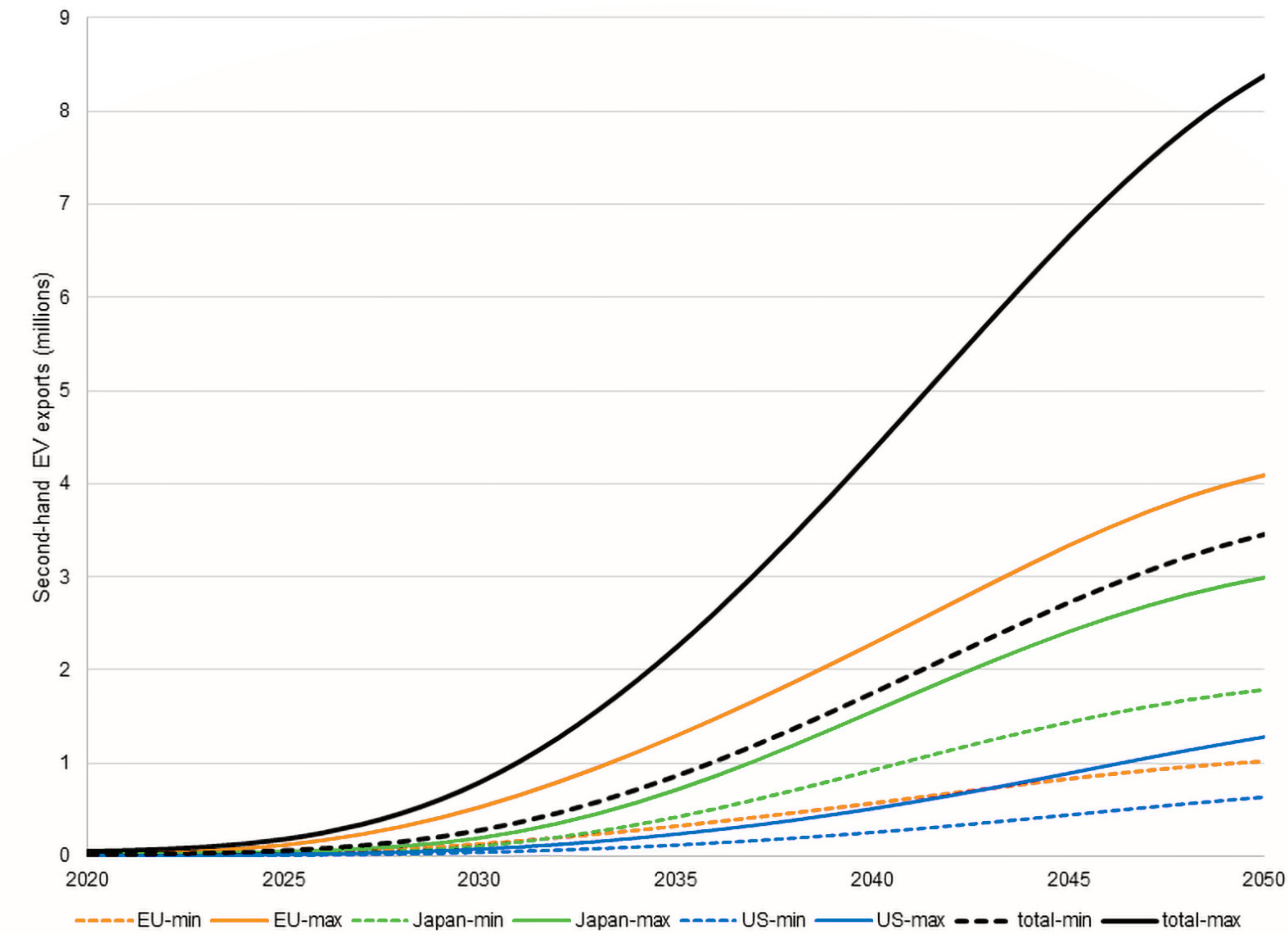

Figure 4. Maximum and minimum estimates of second-hand EV exports from the three top global used vehicle exporters (EU, Japan, and US).

Results of this modeling are shown in Figure 4 and suggest that by 2035 as many as 2 million second-hand EVs could be destined for second-hand vehicle markets, many in LMICs, and this value exceeds 8 million by 2050. Even the minimum expected exports case reaches 2 million by just after 2040. Determining whether this is a net benefit for importing markets is not immediately clear. A systematic review of the literature revealed only one study that examines the performance of EVs in LMICs, focusing on countries in Sub-Saharan Africa (Collett et al. 2021). The study was partly motivated by the expectation that second-hand EVs will inevitably arrive in countries in Sub-Saharan Africa that rely largely on second-hand vehicles. Collette et al. consider the operation of EVs across Sub-Saharan Africa and find that EVs offer significant carbon reductions everywhere except in South Africa, Botswana, Niger, and Chad; a result of their electricity grid resource mix. Perhaps not accidentally, South Africa, Botswana and Niger also provide significant subsidies to petroleum, which could be reduced or transferred to supporting electrification if EVs were adopted. Collette et al. also suggest potential benefits to electricity grids, such as vehicle-to-grid services that could help support grid reliability and renewables integration, and they discuss alternative strategies for deploying EVs that are contextualized for conditions in Sub-Saharan Africa. Absent from their analysis, however, is the risk of second-hand EVs with degraded batteries and short remaining lifetimes being imported, as well as infrastructure and policy required for safely managing EV batteries at their EoL.

Management options for EoL batteries should always lead ultimately to recycling, but between battery use in an EV and ultimate recycling, second-life applications can extend the useful life of a battery and provide a lower-cost source of battery energy storage capacity compared to new batteries. To explore the EoL implications for EV batteries arriving in second-hand markets, we translate the flow of second-hand EVs into battery capacity and mass of material, using the data reported in Figure 4 and current estimates of the average battery capacity of EVs sold in each exporting region (41 kWh, 74 kWh, and 45 kWh for Japan, US, and EU respectively).[8]

Table 3 reports the cumulative number of EVs, mass of batteries, and estimated capacity of used EV batteries traded internationally in 2030 and 2050. Note that batteries lose capacity during their use, meaning that a used battery will have

Table 3. Cumulative flows of internationally traded second-hand EVs and their EV battery mass and expected capacity in 2030 and 2050.

	Minimum Estimate	Maximum Estimate
Cumulative Millions of EVs in 2030	1,143,484	3,161,002
Cumulative Millions of EVs in 2050	38,724,183	95,848,642
Cumulative Tonnes of EV Battery Material in 2030	309,363	846,958
Cumulative Tonnes of Battery Material in 2050	105,361,684	259,514,270
Cumulative MWh of Capacity (2030), assuming 70% SOH	37,897	103,752
Cumulative MWh of Capacity (2050), assuming 70% SOH	1,290,681	3,179,050

8 Two approaches were used to estimate the average EV battery capacity sold in each region. For the US and Japan, data from EV-Volumes were used to identify popular EV models sold from 2015 to 2021 for each region (EV-Volumes 2022). The combination of EV models selected covered an average of 92.9 and 91.9% of EVs sold in Japan and the US, respectively, over the selected time period. The sales-weighted average battery capacity was then calculated and used to represent the estimated capacity of EVs sold in each region; 74 kWh for the US and 41 kWh for Japan. The EU had a larger variety of EV models sold than the US and Japan, which made calculating the sales-weighted average difficult; therefore, an average battery capacity of 45kWh from a market analysis was used instead (Mobility Forsight 2020). An energy density of 175 Wh/kg was used to translate battery capacity sold into mass of battery material.

less capacity than a new battery. Here we assume used batteries will be retired from use in an EV at approximately 70% state-of-health (SOH).[9] SOH is calculated as the percent of a battery's current capacity relative to its initial rated capacity. For example, if a battery is initially sold with 70 kWh of capacity, it would retain 49 kWh at 70% SOH.

The material embedded in the used batteries is an indication of the EoL management needs for these batteries (for example, for waste handling or recycling). For understanding the potential value of retired EV batteries for repurposing, the issue is whether the supply of used EV batteries is reasonably aligned with demand for second-life applications. One promising application for second-life EV batteries is in stationary battery energy storage systems (BESS). Here we examine just the case of Kenya and the potential demand for BESS to support the stability of Kenya's future electricity grid. BESS demand for grid stability is just one potential application for second-life batteries. We extrapolate from Kenya's Ministry of Energy's Least Cost Power Development Plan (Kenya Ministry of Energy 2021) and a study examining the optimal sizing of BESS for Western Kenya's grid stability in 2021 (Ngala et al. 2022). Combining the findings of these two studies, we estimate that Kenya's grid will demand 1000 MWh of BESS by 2030. Based on the UNEP's 2021 report on used vehicle trade, Kenya demanded 0.122% of the total globally traded used vehicles in 2020. Assuming the dominant source of used vehicles in Kenya is from Japan (due to the left-hand drive requirement for used vehicle imports), the average battery capacity of imported used EVs is identical to that of Japan's exported EVs at 41 kWh.

Notwithstanding the many assumptions embedded in these calculations, cumulative EV imports to Kenya will yield 40–111 MWh of battery capacity available in used EV batteries in 2030, substantially lower than the 1000 MWh of total demand for BESS capacity in 2030, indicating the potential for repurposing to be an important EoL management strategy for EV batteries in Kenya. The question of whether BESS demands should be met by second-hand EV batteries or new batteries is important to ask, since new systems would last longer, but it appears that there is a sufficient potential market for second-life EV batteries just for grid stability needs, not to mention demand from other grid-tied applications and other sectors.

9 There is a great deal of uncertainty in when an EV battery will be retired from vehicle use, and perhaps even greater uncertainty in second-hand markets. However, there has long been an assumption that EV batteries will be retired at 70–80% SOH, despite a lack of real-world data confirming this (Canals Casals et al. 2022).

Technologies, Policies, and Standards Affecting the EV Life Cycle

Raw Material Extraction and Refining

There are countless policies and regulations across the world that attempt to encourage extractive industries while moderating their environmental impacts. International bodies including the World Bank, UNECD, OECD, and more have proposed a variety of concepts and programs framed around "responsible mining." These include actions around mitigating environmental hazards (e.g., Tailings Management Facilities), as well as matters focused on affected communities (e.g., Protocol on Pollutant Release and Transfer Registers - PRTRs), and many more (e.g., (Hund et al. 2020; International Finance Corporation, n.d.; OECD 2017). Yet, human rights violations, environmental disasters, and occupation and damage of traditional indigenous lands abound, even in the Global North with well-developed and broadly enforced environmental regulations (see, for example, lithium mine development at Thacker Pass, Nevada, USA [Graham, Rupp, and Brungard 2021]).

There is also a push among countries in the Global North to promote domestic production (International Energy Agency 2022c). As an example, Australia rapidly became the largest global producer of lithium, eclipsing Chile and other producers in South America. Not many years ago Australia's resources were considered unlikely to be a major source of lithium due to Australia's reliance on higher-cost hard rock ores compared to South American brines (Ambrose and Kendall 2020). It is yet unclear if mining will be matched with refining and material processing capacity, which is still dominated by China, or battery cathode manufacturing, dominated by China, Korea, and Japan.

The EU's proposed Battery Regulation has implications across a number of battery production issues—including due diligence requirements that are likely to build on or adopt those described above from the OECD and UN, recycled content standards, and carbon footprint reporting (European Commission, 2020). There have been numerous critiques and analyses of the proposed Battery Regulation, and many believe that, as proposed, it could encourage improved environmental, social, and governance (ESG) factors in EV battery supply chains (e.g., Burlinghaus 2022; Mancini et al. 2021).

EV Use Phase

EVs require battery charging for operation, and their environmental performance and reliability are a function of the electricity grid or distributed electricity resource used to charge them. The EV LIB degrades over time, meaning it stores less energy per full charge and the amount of power it can output attenuates. While ICEV powertrain components also age, the deterioration is not similar; a fuel tank does not shrink in capacity, for example, and while efficiencies of engines and other components reduce over time, components are typically repairable or replaceable.

The LIB in an EV is essentially a closed system, and, currently, diagnostic tools to identify problems or the battery condition are not widely available. Because battery condition (i.e., SOH or other potential faults or misfunctions) cannot be known or easily diagnosed by consumers or even non-OEM repair facilities, their remaining life is often unknown, and the ability to repair hindered. This is a problem faced in all EV markets, but is particularly burdensome on consumers once the vehicle is out of its initial warranty period or has been exported (thus voiding the warranty). In response to some of these challenges, the UN, EU, and states in the US have developed some protocols and regulations that should create a floor for battery durability requirements and may provide for more transparent access to battery information.

The United Nations Economic Commission for Europe (UNECE) has created regulations that provide testing procedures for EV safety during operation (UN Regulation No. 100 / UN GTR No. 20). More recently, the UN adopted a regulation targeting EV battery durability (UN GTR No.22), requiring that batteries maintain at least 80% of their initial capacity for 5 years or 100,000 km, and 70% for 8 years or 160,00 km. A similar proposal will be offered for heavy-duty electric vehicles such as trucks and buses (International Energy Agency 2022c). Given that ICEV's typically start with several hundred more miles of driving range per refueling than EVs (with recharging), such regulations simply slow the further deterioration of EV range.

At least one region has legislation that goes beyond the UN standard; California (which is home to half of the US's EVs) has a regulation requiring that by 2026, EVs must maintain 70% of their certified range for 10 years and 242,401 km (150,000 mi), and this increases to 80% for 2030 and beyond (California Air Resources Board 2022). Range is not exactly the same as battery SOH or battery usable energy; which must be certified to retain 70% for vehicles starting in 2026, and 75% for 2030 and beyond. In addition, for model years 2026 and beyond, EVs must be equipped with a dashboard-readable indicator of battery SOH. This last requirement is intended to provide support for a robust domestic second-hand vehicle market, making EVs more affordable to low income residents (California Air Resources Board 2022). The average vehicle on US roads is nearly 12 years old, and typical mileage at retirement is between 245,000 km (cars) and 290,000 km (light trucks) (S.C. Davis and Boundy 2022). Thus California's standards are better aligned with actual vehicle lifetimes, than those proposed by UNECE. Also, the California standards should mean that these vehicles, if exported, remain operational without the need for battery replacements for longer than EVs on the road today.

One consideration absent from the policies of Europe and California, and which may be particularly relevant for repair networks in LMICs, is the growth of an aftermarket EV LIB supply. While not yet a large share of battery production, internet searches for markets across the world reveal that aftermarket batteries and refurbished batteries can be acquired for common EV models like Nissan Leafs and Teslas. While still expensive, these batteries are often significantly less expensive (and/or higher-performing) than the OEM-supplied battery, and supply may be less constrained than OEM batteries for all markets, but particularly those where second-hand EV models are not sold new.

The European Commission has proposed a technology that could provide information about the operation of batteries, as well as providing traceability of batteries throughout the entire cycle using new IT technologies, such as the Battery Passport. The EU's new Battery Regulation would require manufacturers to provide a 'Battery Passport' for each EV battery placed on the market from 2026 and beyond (Watkins et al., 2021). The Passport is an electronic document containing information about the critical characteristics of the type and model of battery, which will be stored in an electronic system shared across the EU. Non-digital solutions, akin to vehicle identification numbers and engine identification numbers, could also be used. In fact, in the Republic of Korea, EVs and their batteries will now receive two separate titles, enabling new business models such as the purchase of a vehicle and the leasing or renting of a battery service separately (Lee, Lee, and Lee 2022). This requires separate identification numbers for the vehicle and battery.

The Global Battery Alliance (GBA) is currently working on a digital battery passport (possibly a QR code or RFID tag) that will contain details about the components (and possibly recycled content), health, and remaining capacity of a battery, enabling vehicle manufacturers to determine whether it is suitable for reuse or recycling (Global Battery Alliance 2020). According to the EU's planned requirement, the GBA's battery passport would essentially be a "digital twin" of its physical battery (in line with the EU's proposed requirement). The GBA plans to complete its development and make it fully operational by 2022.

Data provided by a battery passport will be valuable for deciding whether a battery should be repurposed or recycled after its first use. Also, it helps repurposers with reliable and precise information about battery health before purchasing and testing (Kendall, Slattery, and Dunn 2022). This technology would bridge information needs from across the battery life cycle with traceability from the raw material stage, use history and SOH from operation, and battery condition and design information to facilitate reuse, repurposing and recycling. It is unknown whether and how locally acquired battery data will be shared across global value chains (Melin et al. 2021).

Repair and Maintenance

Mechanically, BEVs have much simpler drive trains than ICEVs, especially considering some ICEV models have turbocharging and other complex power boosting and emissions control equipment. The long-term ownership advantage of BEVs for maintenance costs is still uncertain, but should be significant. Apart from battery life, the components of BEVs (featuring highly reliable electric motors) have the potential to last far longer than typical ICEVs, limited by their engine life. Still, BEVs will sometimes need to be repaired, including complex electronic control systems. There is currently very little capacity to provide such repairs at dealerships or independent repair shops throughout LMICs.

The world has seen a right-to-repair movement grow since the 1990s, when software in products, particularly electronics, became more common and companies found that they could prevent customers or unauthorized technicians from repairing products by claiming intellectual property rights over the software. This has extended more recently to designing products with software that prevents repair, including via digital locks, software copyrights, and tightly held repair manuals that are unavailable. The problems of repairability may be magnified in LMICs (especially for second-hand product imports), where a manufacturer may have not authorized technicians at all (Matchar 2016). While this movement started with a focus on consumer electronics in high-income countries, the problem of right-to-repair and the movement behind it has extended to durable goods, medical devices, tractors, and vehicles.

While there are, no doubt, right-to-repair movements across the world, a few recent actions in the US and EU are particularly notable, as both are large exporters of secondhand EVs. The regions have seen a surge of proposed and passed legislation in member countries and states for the right-to-repair (European Parliament 2022; Proctor 2022; Stone 2021). Particularly notable among recent actions is a recently-proposed (but not passed) US bill that specifically focused on the right-to-repair of automobiles, including EVs (Rush 2021).

EV End-of-Life

The fate of EoL EVs depends on the infrastructure in place to recycle EoL ICEVs, as well as the capacity to reuse and recycle LIBs. The exact pathway is somewhat uncertain, considering that the first wave of mass-produced EVs is only just starting to retire, even in areas with the highest market penetration.

In many HIC markets, there is a robust automotive dismantling and recycling industry, which recovers high value parts for remanufacturing and reuse (such as engines and transmissions) and recycles scrap metal. In general, auto dismantlers remove and resell parts with remaining value, then the auto body is crushed, shredded, and sent to a scrap metal recycling facility. This industry largely adheres to the principles of the waste hierarchy, prioritizing reuse of parts that can be cost-effectively reused or remanufactured; followed by recycling of metals, glass and other recyclable materials; and finally treating and disposing of only those materials that cannot be reused, remanufactured or recycled. To date, most of these actors have only processed ICEVs or HEVs, and will need to adapt as more EVs begin to pass through the system. EVs replace a number of high-value mechanical parts with a single large LIB and electric motor, which will alter the business model for auto dismantlers.

There are also safety hazards associated with large format LIBs that will require anyone who may be in the position of removing or working on an EV battery to learn to adopt different safety protocols and training. This could include auto recyclers, auto repair shops, repurposers, and battery recyclers. There are two primary hazards: high-voltage electrocution and fire risk. Processing the batteries safely requires personal protective equipment such as high-voltage safety gloves and a safety hook. To prevent fire risk, LIBs must also be stored in an isolated area, and it is recommended that facilities have a fire blanket onsite in the event of a thermal event, as LIB fires can reach temperatures that require extreme amounts of water to put them out. The safety risks are more pronounced for damaged batteries.

These potential hazards have important implications for managing EoL LIBs in LMICs that do not have a regulated afterlife vehicle industry. Many LMICs, especially low-income countries, have extensive networks in place to repair vehicles and recover parts, far beyond the time they would be repaired in HICs. The unique safety hazards associated with LIBs is likely to challenge these networks, as is the complexity and the difficulty of repairing them particularly without access to proprietary software. Furthermore, while extensive repair takes place, many LMICs do not have a regulated industry to recycle parts and materials without remaining value, often leading to EoL vehicles being stockpiled, abandoned, or dumped at informal disposal or recycling sites (Numfor et al., 2021). The improper disposal of even small LIBs from consumer electronics can cause destructive fires; as such, great attention should be paid to the potential for EV and/or LIB dumping in regions that do not have the infrastructure to process them safely.

Reuse and Repurposing

Like all batteries, EV LIBs degrade over time, meaning they can no longer hold as much charge. In the case of EVs, this will be experienced as a loss of range; i.e., drivers will not be able to travel as far on a single charge. However, because EV batteries have much larger capacity and higher power output than most other LIB applications they could still offer significant energy storage services in lower-power applications (e.g., battery storage for intermittent renewables such as solar photovoltaics). This is often referred to as second-life or repurposing. Depending on the condition of the battery when it is retired from its first life in an EV, it could offer stationary services for as much as 10 to 15 years (Shahjalal et al. 2022).

The amount of remaining capacity in a battery is communicated in terms of the SOH. Most standards and OEM warranties consider a battery SOH of 70–80% as the lower bound for use in an EV. The state of California in the US has put forward regulatory requirements for EV battery durability based on SOH and define SOH as the usable battery energy remaining relative to the initial certified value (California Code of Reguations 2022). Understanding SOH is necessary to determine the viability of a retired EV battery for reuse or repurposing, which is challenging without access to data from the BMS.

The second-life battery industry is still largely in a start-up phase, but is growing. There are a number of second-life battery demonstration sites, which are often conducted in partnership or cooperatively with auto OEMs. Additionally, some OEMs are starting to consider the potential for designing batteries with repair, replacement, and repurposing in mind. Nissan was one of the first major automakers to pilot second-life EV batteries in a grid-scale storage installation in 2015. That same year, BMW tested used batteries in demand response events during an 18-month pilot project in partnership with an electric utility, Pacific Gas & Electric (Pyper 2015). Since then countless projects have been pursued, and in 2021 General Motors (GM) designed its new Ultium battery pack with second-life applications in mind and is currently working with partners to develop a business case around battery reuse (Allred 2021). Smaller and new all-electric OEMs have also ventured into this space. American electric truck startup Rivian designed its battery packs from the outset to make end-of-life repurposing as easy as possible. Electric bus manufacturer Proterra has also considered repurposing in its design of batteries, with features such as easy removal, stackability, and modularity for easy removal of components (Rivian 2022; Proterra 2022).

There is a growing body of work characterizing the challenges and barriers to second life applications for EV LIBs. Many of these works assume repurposing will occur in an industrialized setting and will include systematic diagnostic processes to determine SOH; refurbishing, which could include replacement and rebalancing of cells and modules in battery packs; and then a BMS to ensure safe management once the battery is installed (e.g., Hua et al. 2021; Shahjalal et al. 2022). The barriers to repurposing are numerous and include:

1. A lack of standardization across batteries, which means repurposing must be done on a case-by-base basis, with uncertainties in chemistry, battery design, etc.;

2. A lack of transparency and information on battery condition and history (i.e., a lack of on-board diagnostics), which makes the testing and reassembly (where disassembly occurs) more complicated and potentially dangerous;

3. OEMs that initially sell the batteries have little incentive to facilitate repurposing; for example due to concerns about liability in the event of a safety event during repurposing or when a battery is in a second-life use (Kendall, Slattery, and Dunn 2022).

Despite these challenges, there is growing evidence of successful EV LIB second-life applications occurring across the world, including commercial-scale energy storage projects for renewables and grid integration in the US,[10] to household and community scale systems in Kenya (Advancing Transport Climate Strategies' [TraCS] 2021), and industrial micro-grids in South Africa.[11] Second-hand vehicles make up 80% of the total fleet in Kenya. With a growing number of EoL LIBs, many Kenyan companies explored the second-life usage of LIBs from vehicles for energy storage from solar. This is a promising application for backup power and off-grid energy storage, as Kenya has power outages (Advancing Transport Climate Strategies' [TraCS] 2021). As described in the Insight Vignettes in this report (see the case study from Sri Lanka, describing the repurposing of Nissan Leaf batteries for rooftop solar applications). There is evidence that repurposing is also occurring in LMICs that have imported used EVs. In LMICs, second-life batteries could provide a more affordable energy storage solution, which could increase reliable energy access. There is some uncertainty on the economic benefits of repurposed batteries compared to new LIBs (Steckel, Kendall, and Ambrose 2021); however, some estimates put the potential economic advantages of repurposed over new LIBs at 30–70% (Allred 2021).

Despite potential benefits of repurposed EV batteries, the transfer of used EVs and used EV batteries constitutes a moral dilemma for many; is the importation of used LIBs to provide low-cost energy storage systems just a waste transfer from HICs to LMICs in the guise of an energy and environmental solution? A recent joint letter from environmental and community interest organizations in Africa and Europe are pushing for rules to prevent a repetition of previous efforts to provide technology access in LMICs

10 B2U Energy Storage Solutions in California, USA has integrated an industrial-scale photovoltaic installation with 21 MWh of second-life EV batteries to supply electricity during high demand periods on the electricity grid.

11 The company of Eaton in partnership with Nissan installed a microgrid at the Wadeville industrial site to provide backup power and improve reliability using repurposed Nissan Leaf batteries.

via used products from HICs (Oeko-Institut et al. 2022). Activists point to the transfer of old computer equipment to countries in Africa, which rapidly became an e-waste problem rather than a technology solution, as a precautionary tale of why accepting used EV batteries for stationary storage applications should be carefully regulated. They also point out that energy storage systems will be crucial for electrifying rural areas in particular, but these systems need to be durable. Reliance on used batteries of varying conditions, which will not last as long as new batteries, is not necessarily the right solution for lower-cost stationary storage systems.

In Sri Lanka, where favorable tariffs were implemented for EVs and HEVs in 2014 but were later canceled, the Ceylon Motor Traders Association (CMTA) has raised concerns as recently as late 2022 over the condition of imported EVs. They pointed out that some EVs first sold in temperate climate regions may not be fitted with battery cooling systems sufficient for tropical climates, leading to dangerous operating condition. In addition, imported vehicles sometimes arrive in damaged condition, and the internal condition of batteries is unknown, presenting a risk of fire during transport, repair, and use. In addition, batteries may be repaired by untrained technicians, presenting a risk to the technician and battery owner (not to mention poor battery performance) (Draper 2022; Daily News 2022). The CMTA is not without a potential bias on this issue, however, since they are the industry association representing importers of new vehicles from leading manufacturers of both ICEVs and EVs.

Recycling

When they have no more usable life, LIBs can be recycled to recover the constituent materials. The primary industrially proven recycling technologies for LIBs are pyrometallurgical and hydrometallurgical processes, with some companies using a combined pyro- and hydrometallurgical process (Baum et al. 2022). Pyrometallurgical processes rely largely on reductive smelting to recover a mix of precious metals, but leave behind important metals, like lithium and aluminum, in the resulting slag. Pyrometallurgical processing is energy-intensive and results in attendant energy-related emissions from combustion. Hydrometallurgical recycling relies on acid leaching to separate and recover metals and is capable of extracting a larger suite of metals including lithium and at a higher rate of recovery. The acid leaching process results in polluted water streams that require treatment to mitigate potential impacts. Both of these processes require additional processes to recover metals (Baum et al., 2022). Another potential method is direct recycling, which aims to recover components directly in usable form. However, as of 2022, direct recycling was not yet in operation at commercial scale (Baum et al., 2022).

The initial steps in the recycling process are typically discharging, disassembling, and then shredding the packs. The shredded material is then sorted to separate different materials. The lithium, cobalt, and nickel, along with some other metals, are contained in an output called black mass; the product of shredded battery material that is further processed into a product that looks a bit like coarse black sand. This material is easier to handle than spent LIBs since there is no risk of fire, making transport less dangerous and costly. Black mass might be generated on-site at a facility that also recovers metal sulfates, but it might also be at a facility that only generates black mass which is then sent to a centralized hydrometallurgical facility for metals recovery.[12] In fact, in a recent

12 For an example of this kind of business model, see Li-cycle's Hub and Spoke model in North America: https://li-cycle.com/technology/.

development, black mass generated in Poland will be sent to Korea for hydrometallurgical processing, demonstrating that long-distance shipping may be viable for profitable recycling when batteries are first converted into black mass before transport.[13]

This stands in contrast to the cost of transporting spent batteries. The collection and transport of LIBs for recycling may alone make up 50% or more of the cost of recycling (Slattery, Dunn, and Kendall 2021). This problem is not just one of transport costs, nor are the challenges limited only to EV LIBs. In a pilot study in Nigeria focusing on the collection of small e-waste LIBs, namely cell phone batteries to be recycled in Belgium, the operators of the program highlight that while the collection and recycling was technically feasible, administrative burdens of shipment were enormous, and that both national and international agreements such as the Basel Convention proved to be impediments for efficient and low cost transport solutions (Closing the Loop, Fairphone, and Call2Recycle Inc. 2020). Thus the prospect of generating black mass from spent batteries, prior to transport for recovery of metals (either as metal sulfides or battery-grade materials), may have a significant advantage in regions where an LIB recycling industry does not yet exist. Generating black mass averts the technical and bureaucratic hazards of transporting spent batteries, and it potentially provides value in the country generating the black mass, in contrast to the potentially high cost of transporting spent batteries internationally for recycling.

Such a recycling model may be a first step for LMICs to begin development of LIB recycling infrastructure. The generation of black mass alone requires less capital investment than a complete recycling process and, based on current business models, seems to be profitable at a smaller scale. As an example, the Canadian company Li-Cycle has promulgated black mass generation facilities (so-called spokes in their network) in Canada, the US, and Norway. Many of these are designed to process about 10,000 tonnes/year of incoming LIB waste (typically a combination of manufacturing scrap and EoL batteries, and equivalent to about 22,500 retired EV batteries), while their hub facility is able to process the black mass-equivalent of 90,000 tons/year of incoming LIBs into battery grade materials (Li-Cycle Holdings Corp. 2022).[14] Based on industry expert opinion, the cost of processing one tonne of LIB into black mass is about USD90, while profit from black mass and the other recyclables generated (namely copper and aluminum) can sell for USD300 and USD500, respectively (Curran 2022).

Nevertheless, despite mature and improving recycling processes and innovation around business models, LIBs are not necessarily valuable from a recycling standpoint due to the cost of logistics and the fact that formal recycling infrastructure is not available in many parts of the world. Anticipating the growth of EVs in LMICs, and particularly anticipating used EVs with shorter battery lifetimes, is crucial for the timely creation of collection and recycling networks required for safe and environmentally preferable EoL management of EV LIBs.

One potential advantage of EV batteries (or other large format batteries such as those used in stationary energy storage applications) is that they are large; meaning that economies of scale can be achieved faster than for smaller batteries.

13 For an example see POSCO’s new facility in Korea that will source black mass from a subsidiary in Poland: https://www.koreaherald.com/view.php?ud=20210930000786.

14 Equivalent to about 35,000 t black mass, 18 gigawatt (GWh) hours of lithium-ion batteries, or 225,000 electric vehicles (Li-Cycle, 2022).

Final Disposition Without Recycling

Without recycling, the alternatives for disposal include stockpiling and discarding on land. Stockpiling presents a risk because LIBs, and particularly aged or damaged LIBs, pose a risk of fire or even explosion. These fires emit toxic gasses, ranging from furans and dioxins to hydrogen sulfide and SO_2. These gases are emitted from the LIBs themselves, as well as from other materials that may be burned when exposed to an LIB fire (Mrozik et al. 2021). Examples of such fires have occurred around the world (Harper et al. 2019).

If these batteries are discarded on land, they can also result in massive quantities of e-waste, which if managed like other e-waste flows, particularly those that are sent to or are discarded in LMICs, they could be processed in informal environments that threaten the health of all, including children and other vulnerable populations (World Health Organization 2021).

Battery End-of-Life

There is a patchwork of policies across countries and regions that may influence battery EoL management within respective regions. However, just one global, transboundary policy addresses EV batteries at their EoL (and other components deemed hazardous waste): the Basel Convention (Convention on the Control of Transboundary Movement of Hazardous Wastes and Their Disposal). The Basel convention monitors and constrains the transboundary movement of hazardous wastes that can put at risk public health and the environment caused by the improper management of and improper disposal of hazardous waste and is a secretariat of UNEP (UN Environment Programme 2011).

In June 2020, a Basel Working Group published draft guidance on the applicability of the Basel Convention to lithium-ion batteries, confirming a designation of EoL LIBs as hazardous wastes. The guidance defined a terminology for batteries and outlined a process for studying and collecting data on lithium-ion batteries in EVs. The guidance included a recommended method for developing an inventory of lithium waste batteries at a country scale based on knowledge of in-use stocks of LIBs, and understanding of the LIB characteristics and lifetime in particular applications. The resulting information can be used to develop appropriate policies and strategies for collecting and disposing of waste batteries containing lithium and is an essential input into the planning of recycling facilities that require substantial financial investment and regular throughputs of waste.

EV LIB End-of-Life Policies in the Large, New EV markets

European Union

In 2006, the EU established a regulatory framework on batteries through Battery Directive 2006/66/EC. It restricted LIBs from landfilling and required a 50% recycling rate. The primary objective is to minimize the negative environmental impacts of waste batteries. It sets collection and recycling efficiency rates for certain types of batteries and promotes the extended producer responsibility (EPR) system. This Directive also considers three types of applications: consumer portable, industrial, and automotive.

The Directive is considered widely to be out of date due to the pace of technological advancements in this sector. For example, automotive batteries are defined as lead-acid starter batteries and lithium-ion batteries are classed as portable (e.g. consumer batteries for cordless or mobile phones) or industrial—such as lithium-ion propulsion batteries for EVs.

In late 2020, the European Commission proposed a new Battery Regulation for batteries that would replace the 2006 directive. It would require EV batteries to be collected and recycled in full. It sets a recycling target for LIBs of 65% by average weight by 1 January 2025, and 70% by 1 January 2030.

The proposed Battery Regulation attempts to include a life cycle or "cradle-to-grave" approach, thus applying obligations to each stage of a battery's life cycle to promote a circular supply chain. Requirements include supply chain due diligence; a maximum carbon footprint; minimum recycled content; recycling efficiency levels; performance, reporting, and labeling requirements; extended producer responsibility for the collection and recycling of used batteries; and a digital battery "passport" to capture key lifetime events. Notably absent from the proposed Battery Regulation is an explicit treatment of second-hand vehicle exports. Though manufacturers are subject to collection targets for EoL batteries, there is no discussion of batteries exported as part of a second-hand vehicle or other product (European Commission 2020; Popp 2022).

European OEMs have responded to this policy with largely cautionary statements. The European Automobile Manufacturers' Association (ACEA), for example, initially responded with the contention that nearly 100% of industrial and automotive batteries are already being collected, and additional obligations would be costly but without substantial value (ACEA 2017). And as the proposed Battery Regulation has been further developed, ACEA has focused on the need to streamline and harmonize any new regulations with existing ones—particularly those with extended producer responsibility (EPR) implications—and ensure the timing of different regulations and standards be feasible (ACEA 2021).

China

China began developing policies specifically for recycling LIBs, namely, the "Technical Policy on the Recycling and Utilization of Power Batteries of Electric Vehicles" (Yu et al. 2022). This policy aims to guide companies in the design, production and recycling of EV power LIBs. It is worth noting that this policy also emphasizes the implementation of EPR in the power battery recycling industry. Ongoing policy guidance is required for the development of a spent power battery recycling system; hence, the regulation is being upgraded continuously. In 2019, China released the latest and updated regulation, "Industry Standard Conditions for the Comprehensive Utilization of New Energy

Vehicles Waste Power Batteries" (Yu et al. 2022). It divided the recycling of spent power LIBs into two fields: cascade utilization and recovery. The cascade utilization of spent power LIBs relies heavily on rapid classification technology, and considerable traceability information is required in this process (Yu et al. 2022). China has historically prevented the export of used vehicles and EV LIBs, so their internal management of EoL EV LIBs means they are unlikely to affect other countries; however, the Chinese government changed this policy in 2019 (The State Council of the People's Republic of China 2022). In 2021, China is reported to have exported just over 15,000 used vehicles, and exports are growing rapidly based on data from early 2022 (Nan 2022), meaning China may play a significant role in second-hand vehicle and EV flows in the future.

United States

US policies governing EV LIB EoL are driven by hazardous waste management regulations, but no coherent policy focused on battery EoL in particular (Melin et al. 2021). Hazardous waste regulations govern where a battery can be disposed of and how it must be transported, but the US does not have any policies to encourage or require recycling or recovery of EV batteries (Kendall, Slattery, and Dunn 2022).

Insight Vignettes

In this section, vignettes from a number of countries reliant on second-hand vehicles are used to provide insights into the fate of second-hand HEVs and EVs that have or will arrive in LMICs. HEVs include much smaller traction batteries, but, because they entered LMIC markets as second-hand vehicles many years ago, experiences with HEV batteries can still be instructive.

Sri Lanka

Sri Lanka has a history of strong regulations for imported second-hand vehicles, including age limits (currently just 2 years for passenger light duty vehicles) and has progressive import taxes that favor small, efficient engines (though excise taxes are high overall). It also had, for a time, no excise tax for used EVs, and favorable excise taxes for used HEVs (Sustainable Mobility Unit of the United Nations Environment Programme 2020). These conditions were implemented for a relatively short period before they were eliminated in 2018. During this period, a large number of HEVs and some EVs were imported. Sri Lanka's experience with EoL batteries from both EVs and HEVs may illuminate some of the benefits and risks of second-hand, advanced-technology vehicles. Some key insights from an interview with Dr.Thusitha Sugathapala, Senior Lecturer at University of Moratuwa, about the effects of these policies and the fate of imported vehicles under the favorable import conditions for HEVs and EVs are provided here:

- HEVs delivered on vehicle efficiency benefits, but there is currently no process for recovering spent HEV batteries and recycling them; they are currently just landfilled.

- EV batteries are repurposed when their condition is suitable. Right now there are companies and individuals using repurposed Nissan Leaf EV batteries to support rooftop solar and other intermittent renewable generation.

- The majority of EV second-hand imports were Nissan Leafs. These are air-cooled batteries, which degrade more quickly in the Sri Lankan climate than in more temperate climates. Thus battery life is shorter, and access to replacement batteries is difficult, in part because Nissan does not sell new

Nissan Leafs in Sri Lanka. When replacement batteries can be obtained, they are second-hand.[15]

- The electricity grid still requires improvements and upgrades before EV adoption can proceed.
- Most EV owners have two vehicles, one ICEV and one EV because the imported EVs have relatively short ranges and public charging is not available. Thus personal EVs are typically only used for short, city driving. This will limit uptake of EVs.

Mongolia

Mongolia is an enormous importer of used HEVs from Japan, receiving nearly a quarter of all second-hand HEV exports from Japan. In particular, the Toyota Prius makes up more than half of all used vehicle imports to Mongolia (Baskin et al., 2020). The dominance of HEVs is partly a result of tax breaks which eliminate excise and air pollution taxes that non-EVs and non-HEVs are subject to. In addition, other programs have encouraged the adoption of advanced technology vehicles, such as the removal of driving restrictions and other non-monetary instruments for EVs in Ulaanbaatar, Mongolia's capital city (Zegas and Zegas 2018). However, the HEVs imported are typically older vehicles, and the cold temperatures in Mongolian winters make the HEV operation far less efficient (though the battery is also valuable due to its ability to help start vehicles in extremely low temperatures), leading some to question the environmental benefits of second-hand HEVs (e.g., Honningdalsnes 2016).

HEVs have much smaller batteries than EVs, for example the Prius's second and third generation battery has only 1.31 kWh battery. This battery capacity is far smaller than pure battery capacities, which averaged 11 kWh and 45 kWh in 2021 for PHEVs and EVs, respectively (Statista Research Department, n.d.). In addition, HEVs have historically used nickel-metal hydride (NiMH) chemistries, and while some HEVs have opted for lithium-ion chemistries, Toyota has continued to use NiMH[16] batteries in most of their models, including those commonly imported to Mongolia.

A 2019 publication estimates the age of HEVs imported to Mongolia range between 10 and

15 There is also evidence that some Nissan Leafs may be repowered with gasoline engines when battery replacements are not available. While no formal documentation of this is available, Nissan Leaf owner forums, blogs, and YouTube videos confirm this trend.

16 NiMH batteries are less power and energy dense than LIBs, but have the advantage of long life and reduced risk of thermal runaway, a cause for battery fires.

15 years, and that HEV batteries will last 15 to 20 years (Wang, Yu, and Okubo 2019). The publication predicts that by 2030, Mongolia might have 71,000 to 160,000 waste batteries to manage. While there is no clear next-step, the Mongolian government has agreed that a safe collection and disposal process is needed for HEV batteries. Should EVs and PHEVs start to substantially enter the Mongolian market, the battery disposal problem will grow immensely. Not only are these batteries 10–50 times larger, they are also lithium ion chemistries, which present greater risks of explosion and fire, especially when aged or damaged, requiring more careful (and more expensive) handling during transport, storage, and other EoL processes.

Mexico

Globally, second-hand vehicle trade rarely garners much attention from regulatory agencies in major exporting regions. This is in part because of the atomized nature of the market and the complexity of regulatory enforcement and because the impacts of this trade are rendered invisible to exporting nations because the vehicles become the concern of another nation. Thus, second-hand vehicle trade data is notorious for its unreliability and lack of robust documentation.

This gap was made evident in the UN Environment Programme's Global Trade in Used Vehicles reports: while undoubtedly the best reports on the subject so far, examination of just one of the trade flows, from the US to Mexico, shows that the magnitude of the flows is critically underestimated when export data is used to quantify these flows (UN Environment Programme 2021). These reports rely on data from exporting countries, which in the US is supplied from the US International Trade Administration (ITA) (International Trade Commission 2022). However, when compared with the import volume reported by Mexico's National Customs Agency (ANAM) for the same period, US reporting significantly underestimates second-hand vehicle trade flows.[17]

Figure 5 provides an illustration of the magnitude of the issue, from the opening of Mexico to legal second-hand vehicle imports in 2005 to year 2021. The figure compares trade volumes for the US's major export markets (as reported by the US ITA) against those reported by ANAM.

Figure 5 shows that Mexico is historically the US's single largest second-hand vehicle export market, by far, but only when Mexico's import data is consulted. Between 2005 and 2021 the country

17 ANAM provided data directly to the researchers.

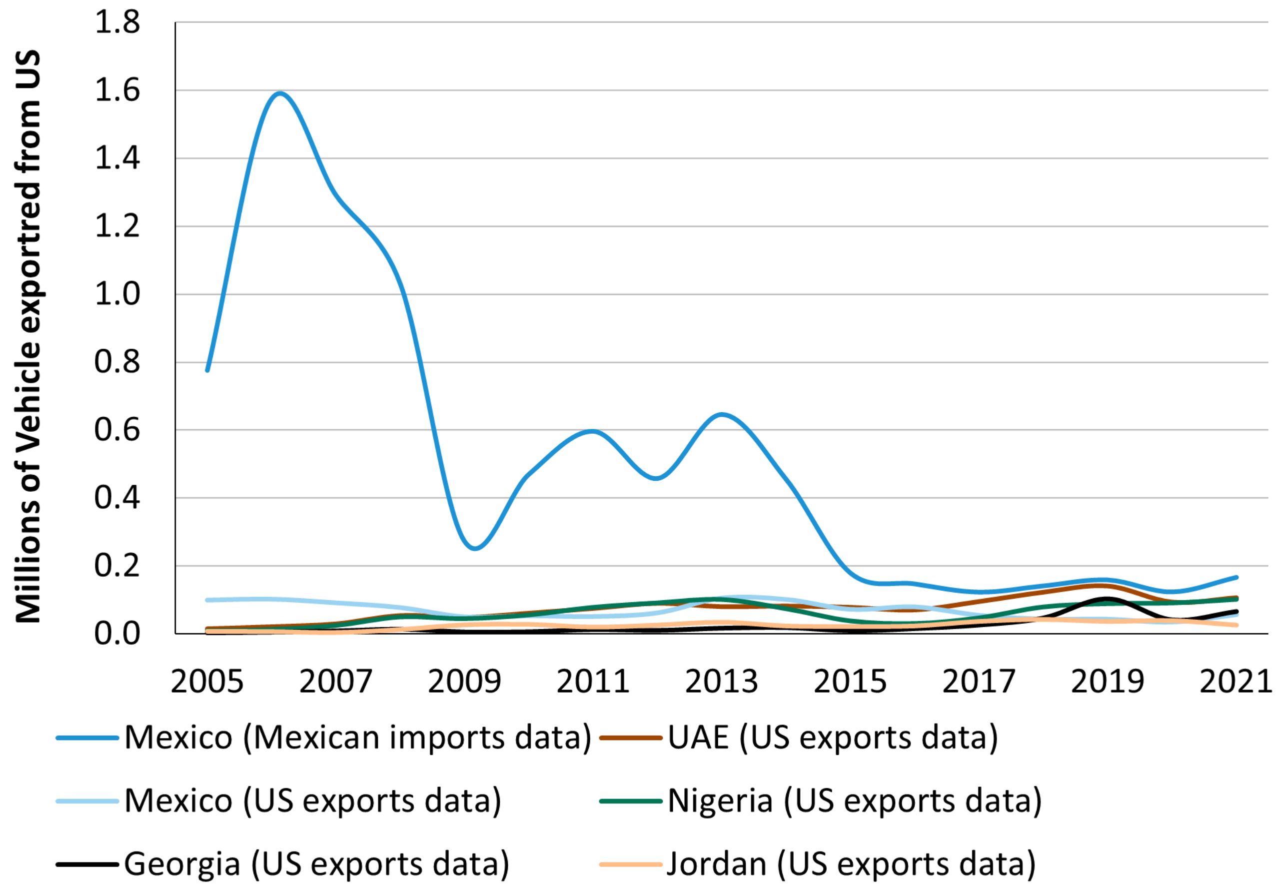

Figure 5. Second-hand vehicle export estimates from US Exports Data for Major US markets and Mexico Import Data from Second-hand vehicles from the US

imported close to 9 million used vehicles from the US, representing nearly 20% of Mexico's total vehicle stock of about 50 million in 2021. While there are surely some errors in other US export data, given that Mexico is the only significant second-hand vehicle trading partner with a land border, it is unlikely that export data for other countries has the same magnitude of error.

Regular (legal) second-hand vehicle trade with Mexico began in 2005, enabled by the provisions of the North American Free Trade Agreement. Initially, the country experienced a dramatic import surge, driven by the lack of age and environmental import restrictions in Mexico coupled with stringent inspection and maintenance requirements, emission standards, and incentive schemes in the US that induce early vehicle retirements and enable a large pool of cheap vehicles to be exported (Partnership for Clean Fuels and Vehicles 2019). In comparison, Mexico has a low retirement rate and it is not uncommon for vehicles to last up to 30 years, increasing total lifetime GHG and criteria pollutant emissions, fuel waste, and road safety problems (L. Davis and Kahn 2011).

In response to the sudden flood of second-hand vehicles, Mexican policymakers, researchers, NGOs, and auto manufacturers began proposing and implementing policy mechanisms to regulate the unchecked flow of harmful second-hand vehicle imports.

By 2015, restrictions began taking effect and the flow was normalized to current levels of close to 200,000 per year. US ITA data show that over the period 2015 to 2018, the US exported around a total of 2.6 million used light-duty vehicles, of which only 281,545 were destined for Mexico, while ANAM reports 593,088 second-hand vehicles were imported to the country from the US.

Second-hand vehicle policy in Mexico changed again at the start of 2022 in an effort to counter a rise in crime in which unregistered second-hand vehicles had played a supportive role. The federal government enacted a decree to promote registration for an estimated 2 million unlawful vehicles, opening up imports for vehicles older than 8 years, which caused a slight increase in imports with respect to the previous 7 years.

The reliance on US export data, in lieu of Mexico's import data, is not without consequences. Mexico is almost never cited in the literature and international discourse as the US's primary market for second-hand vehicles. This may lead stakeholders to underestimate the potential impacts and opportunities that second-hand vehicles from the US pose for the Mexican market and on-road vehicle fleet. As the US fleet electrifies, EVs will enter the US-Mexico second-hand vehicle trade, posing problems and opportunities for the Mexican electricity grid and exacerbating the problem of used and spent LIBs that will be arriving within vehicles. In the absence of policies to prevent vehicles with damaged or near-EoL LIBs from being transferred from the US to Mexico, one could see a future where second-hand EV exports are the lowest cost management strategy for LIB or whole-EV EoL.

The data examined here illustrates the challenge of tracking second-hand vehicle flows and the value of examining import, rather than export, data to understand second-hand vehicle transfers and second-hand vehicle characteristics. While Mexico has yet to see an influx of second-hand EVs from the US, modeling of US EV stocks suggests that Mexico will begin seeing a rapid increase in second-hand EVs starting in the mid 2030s. Forecasting these flows can help Mexico, and the US, develop policies to ensure that EVs that arrive in Mexico serve their new market (e.g., by restricting imports by battery age and condition) and do not become merely the US's least-cost option for EV battery disposal. This requires that the US be a responsible party in restricting the flow of second-hand vehicles—which, given that today the US does not even track the majority of second-hand vehicle exports to Mexico, will require real and coordinated effort on the part of US authorities.

Discussion of Challenges

Distilling the experiences and challenges faced by countries in the global south, and particularly LMICs, due to vehicle electrification into key points is challenging. One particular insight from the vignettes included in this report is that restrictions and responsibilities for second-hand vehicles moving into the international trade market should not solely be the responsibility of importing countries. This challenge requires that exporting countries (and entrepôt countries) must do better when it comes to tracking and regulating the sale and trade of used vehicles outside their borders.

The resulting lack of information is one of many knowledge gaps that make understanding the global impacts of EV value chains and life cycles challenging, and makes understanding the implications across the EV life cycle for LMICs challenging. Figure 6 summarizes key knowledge gaps and risks to LMICs.

Figure 6 illustrates a repeated problem for understanding and addressing the problem of EV LIBs in LMICs, namely **a lack of information**. Perhaps the two most important ones are:

- a lack of transparency in battery information, including static information such as battery chemistry and the provenance of constituent materials, and dynamic information, such as the battery SOH, crucial for decision-making. This must be built into the vehicle at the time of production.

Life Cycle Stage	Raw material extraction	Material processing, battery manufacturing	Vehicle operation and secondhand export	Repair and refurbishment	Final disposition
Knowledge gaps	Battery mineral traceability is still uncertain, growth in mining in new areas rapidly increasing and uncertain in all global regions	Battery grade material processing and battery manufacturing steps less-well mapped/tracked than mining sites.	Lack of sufficiently granular data on exports and imports of second-hand vehicles. LCAs and other measures of environmental performance omit secondhand use in new markets	How will LMIC repair markets respond to LIB repair barriers? Hacking of BMS, etc. which can lead to unsafe operating conditions	The battery recycling landscape is somewhat opaque from a technology standpoint.
Risks to LMICs	Continued extraction at high risk ESG zones, burdening communities and indigenous peoples' health, land rights, and/or livelihoods	High concentration of material processing and battery grade material production in China; High concentration of battery manufacturing in China, Korea, and Japan, meaning raw-material producing countries are missing out on value-added steps	A lack of access to information on battery SOH make assuring sufficient remaining life at the time of exportation nearly impossible. Yet unclear whether secondhand EVs can deliver net environmental benefits. High risk of stranded EoL batteries which could replicate the hazards of E-waste on enormous scales. High-pollution grid mixes could make emissions worse, lack of infrastructure for charging, electricity grid upgrades required to support charging load requirements	Stranded vehicle assets due to a lack of access to EV battery replacements, unsafe or dangerous repair conditions	Most countries lack policies and plans for managing EoL EV batteries. Pilot programs have shown a high cost for collecting and transporting EoL batteries internationally. No clear policy process or structure for managing recycling or extended producer responsibility at global scales.

Figure 6. Knowledge gaps and risks to LMICs

- a lack of data tracking the flow of second-hand vehicles from exporting countries to importing countries due to a lack of information on the specific vehicles leaving one country and arriving in another. Even when vehicles are tracked in some way, the information about the vehicle is limited, omitting even general information like vehicle make and model, vehicle age, and omitting more specific information such as the vehicle identification number (VIN).

These types of challenges cannot be solved by countries importing second-hand vehicles and must be the responsibility of OEMs along with the countries where vehicles are first sold. An international agreement on diagnostics included in new vehicles is needed, as are better controls on the status and quality of vehicles being exported. For example all exported second-hand EVs should be held to some minimum standards on battery SOH and other vehicle quality indicators. Another challenge is the **lack of policy** to address the **problems of diagnostics and repairability** of EV LIBs and measures to minimize the **risk of EV LIB dumping in the guise of second-hand vehicle and battery exports**. Addressing the problem of diagnostics and repairability serves all markets and all consumers.

Strategic Vision

Devising a set of strategies that can minimize impacts and maximize benefits of the EV transition on LMICs, especially in the next 10–20 years when the largest economies in the world (China, Europe, and the US) move through rapid transitions towards EVs as the dominant light-duty vehicle technology, must consider three overlapping issues that require improved governance or focus: technical and information needs, supply-side measures (i.e., second-hand EV export controls), and demand side measures (i.e., second-hand import controls).

Technical needs are largely related to challenges from a lack of information and barriers to EV and LIB repairability. The lack of information is partly addressed by the EU's proposed **digital battery passport** requirements, which would provide a significant advance in information regarding the battery value chain and some access to dynamic real-time information like SOH for in-use batteries. However, the level of granularity and details on the type of information provided for diagnostics is still not entirely clear, and the readability of information after batteries are removed from a vehicle must also be considered. At a minimum, the provision of a reliable estimate of SOH, remaining vehicle range, etc. could help facilitate policies that ensure that exported/imported second-hand vehicles meet some minimum level of performance.

Other technical needs largely focus on how EV batteries are designed and the software that manages them. The **right-to-repair** movement taking hold in the US and Europe could help create EVs that are more repairable and engender an aftermarket parts industry for EV components (and battery components in particular). This could contribute to reduced risk of stranded vehicle assets everywhere, but particularly in second-hand markets. However, enhanced repairability and availability of replacement parts and batteries should be coupled with domestic and global requirements for quality and durability (such as UN GTR No.22, and the US State of California's battery durability and vehicle range requirements). Requirements for quality and durability should apply to aftermarket batteries and battery components, not just those originally supplied by OEMs for new vehicles. One remaining challenge is proprietary software and data in vehicles, and in particular BMSs, which not only impede vehicle repairability but also the ability to remanufacture and repurpose batteries when they are no longer suitable for use in an EV.

Design features for batteries that adhere to **right-to-repair principles could also facilitate battery repurposing**. While there are very good reasons for markets to restrict or altogether ban second-life EV LIBs to reduce the risk of EoL LIB dumping, if batteries arrive in new or used EVs, the ability to repurpose EV batteries for less demanding applications including 2&3-wheelers and stationary storage applications can provide more value to importing markets and provide more time before recycling infrastructure is needed. Second-life batteries could support increased renewable energy sources and resilience via microgrids and distributed energy resources in electricity grids across the world. However, the data, information, and training needed to repurpose batteries safely and effectively must be made available.

Strategies for countries that export used vehicles, or that are likely to export used EV LIBs, could reduce the risk of dumping in the guise of exports by **implementing minimum battery condition standards**. For example, export restrictions could require that used EVs must demonstrate a minimum battery SOH or vehicle range, such as 90% of initial SOH or range, to be eligible. This could be aided by harmonized requirements under the Basel Convention that could, at least when EV batteries are outside of vehicles and could be designated as hazardous waste, require similar conditions to avoid hazardous waste designations, whether destined for reuse in a vehicle or repurposing in a different application. Complementary to this policy could be the requirement for a **battery passport** or other combinations of **battery labeling and onboard diagnostic tools** that would allow for easy, real-time information on a battery's condition and available to all (not just OEM dealership and repair networks).

For LMICs importing used EVs or used EV batteries, the same (or more stringent) conditions for battery SOH, and the same requirement for battery information access should be pursued as in exporting countries. These could reflect durability requirements (i.e., ensuring that most EVs would last a certain number of years or kilometers with the traction battery they arrive with), and such estimates could include considerations for vehicle operating conditions (such as very hot or very cold temperatures). The experience of Nissan Leaf owners in Sri Lanka showcases the problem of relocating EVs designed for cold or temperate climate conditions in their first market to second-hand markets with warm, tropical climates, which led to rapid degradation and failure of EV LIBs.

Finally, at national and regional levels, anticipating the flow of LIBs into secondary markets will be crucial for developing the capacity for handling them at their EoL. Rapidly evolving LIB recycling technology and business models could **support improved domestic and regional capacities for recycling**, which could improve the economics and safety of EoL LIB management in LMICs. The potential, for example, of developing facilities that produce black mass, even in regions where the availability of a sufficient number of EoL LIBs and capital costs are barriers to building recycling facilities, could provide economic benefits from EoL LIB management and improve safety and environmental outcomes.

Limitations

This work focused largely on light-duty passenger vehicles, given the enormous demand for battery materials they will command over time, and the role they might play in LMICs as second-hand vehicles in the coming years. The world over, but particularly in LMICs, electrified buses and 2&3-wheelers are already more important modes of electrified vehicle transport. These modes are also typically more efficient per passenger kilometer traveled and reduce congestion effects relative to personal light-duty vehicles. The right way to decarbonize transportation around the world is not to replicate the car-dependent cultures and infrastructures common in much of the Global North, but rather to pursue more efficient, equitable and safe transportation systems that develop the infrastructure and supportive policies for safe active modes of transport (walking and cycling) and safe and efficient mass transit and non-car modes of shared and personal transport, such as electrified 2&3-wheelers. Policies around second-hand vehicle trade can support, rather than undermine, the opportunities for these better transportation futures.

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