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Lead Battery Recycling and the Ecologically Unequal Exchange of a Crescive Contaminant Across the U.S.-Mexico Border

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Abstract

In 2008, the United States announced stricter occupational and ambient air emissions standards for lead, the first such change in three decades, but the regulations remained unchanged in Mexico. This has driven hundreds of millions of lead batteries across the border for recycling as U.S.-based companies side-step higher domestic compliance costs. In doing so they perpetuate the unequal valuation of labor and human health commonplace across the U.S.-Mexico border. Leveraging regulatory asymmetries is one dimension of ecologically unequal exchange or the patterned exploitation of nature whereby corporations based in more dominant nations gain access to raw materials and shift the risks of pollution intensive economic production. In this regard, the U.S.-Mexico border produces racialized environmental violence as batteries flow freely but people do not. The veracity of this violence is detectable in the blood of those laboring under a three-fold higher occupational standard and the children living in the shadow of smelter facilities operating with a ten-fold greater threshold for the imposition of ambient, lead-laced, air releases. Battery manufacturing comprises a circular economy in which nearly all lead comes from secondary recovery rather than mining, but there is a detour spanning thousands of miles and traversing through working class communities in Mexico. It is a central contradiction within what is widely touted as the most ecologically modern industry in the U.S.

Keywords: Ecological Unequal Exchange, Trade and Development, Hazardous Wastes, Recycling, Environmental Degradation, Environmental Sociology, Neoliberalism, U.S.-Mexico Border, Ecological Modernization

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In 2012, executives from Johnson Controls assembled in Florence, South Carolina to celebrate the opening of their battery recycling facility. The event drew over 300 people and included local leaders, community members, and state politicians from afar (Johnson Controls 2012). It is a well-worn ritual: individuals dressed in business attire wearing hard hats, awkwardly holding shovels, skirting about some dirt, a large ribbon, ceremoniously cut. Smiles, handshakes, and promises of economic prosperity abound. Indeed, the plant was designed to recycle up to 14 million automotive batteries each year (Johnson Controls 2012). Spent batteries are disassembled and the lead is recovered, smelted to remove impurities, and the refined ingots are remelted to produce plates that are fashioned into new batteries. And company officials stressed that the emissions controls were state-of-the-art (Johnson Controls 2012).

Lead battery recycling is the most ecologically modern industry in the United States. A closed-loop system predominates as state and federal law prohibits unregulated end of life disposal. For the consumer, a spent battery is delivered to a retailer when making a new purchase and then handed back to the manufacturers. Few batteries are disposed of in a landfill, and the transformation of the industry is consistent with the tenets of ecological modernization theory stipulating that the institutions of the state in tandem with market incentives and technological innovation can contribute to less polluting and resource intensive economic development (Mol 2003). A key aspect is the continual reintegration of materials back into production processes.

Soon after the festivities concluded in Florence, however, violations of state and federal law commenced. These violations pertained to workplace conditions and ambient air emissions (Fretwell 2022). Fines were imposed and remediation steps sketched out. And then in 2021 Johnson Controls officials announced they were closing the plant, less than a decade after it opened. They denied that the closure was due to environmental and regulatory considerations, insisting it was necessary to streamline overall operations, and that it would "strengthen our position as a global leader in advanced battery technologies" (Fretwell 2022).

A fuller explanation lies 1,500 miles to the south. Johnson Controls acquired their battery recycling facility in Ciénega de Flores in 2004 and in Garcia in 2011, both on the outskirts of Monterrey, Mexico. And in-between the U.S. Environmental Protection Agency (EPA) announced a tightening of occupational and ambient air standards for lead, the first such update in 30 years. Prior to 2008, regulations were equivalent between the United States and Mexico. After this point the occupational exposure threshold was three times greater and the ambient air standard ten times higher south of the border. And for nearly two decades the export of used car and truck batteries from the United States to Mexico has continually increased.

The automotive battery division of Johnson Controls was sold to outside investors and renamed Clarios in 2019. In a Securities and Exchange Commission filing Clarios stated something rarely spoken of publicly, "As an example of the benefits of our vertically integrated model, in fiscal year 2020, our Mexico recycling facilities were able to operate at a cost basis 70% less than the cost of our average third-party tolling contract when evaluated on a per-ton basis" (Clarios 2023:10). Tolling refers to an agreement in which an independent facility agrees to smelt lead for another party for a fee or "toll." Clarios's operations in Mexico in 2020 engaged in such

processing at a cost 70 percent lower than outsourcing to a third-party in the U.S. Overall, Clarios saves around $30 million annually employing its recycling operations across the border (Clarios 2023).

This cost-reduction is borne by Mexican children. The costs do not dissipate into thin air. The costs migrate south in an undocumented manner. Coating indoor windowsills, toys lying about the yard, mixed in the soil, picked up by foot traffic and the vagaries of the wind, in smelter communities throughout Mexico there are a litany of examples over an extended period depicting a familiar narrative: children burdened by the decisions and non-decisions of adults in distant locales. Indeed, each year millions of spent batteries are transported by truck or rail southward, processed, and then shipped back. Rather than internalizing compliance costs within the production cycle U.S.-based companies leverage regulatory asymmetries and perpetuate the unequal valuation of labor and human health. And Clarios is a key actor—accounting for up to two-thirds of all used batteries exported to Mexico in recent years (Gottesfeld, Chavez Arce, and Macias Raya 2023).

On the outskirts of Monterrey and elsewhere, pollution reflects structural inequities within the world-system and is readily detectable in soil, air, water, and the bodies of laborers and the most vulnerable within society. Power is the capacity to impose upon others the unpaid costs of economic production, on the one hand, while declaring a commitment to corporate responsibility, on the other. In 2025, for the third year in a row, Clarios was recognized as one of the world's most ethical companies (Clarios 2025).

Leveraging regulatory asymmetries is one dimension of ecologically unequal exchange or the patterned exploitation of nature whereby corporations based in more dominant nations gain access to raw materials and shift the risks of pollution intensive economic production. As Immanuel Wallerstein observed (1974), there is an extensive division of labor across the world that is occupational and geographical. The social organization of work or range of tasks performed at different places, and how these tasks are performed and renumerated, enhances the capacity of some to exploit the labor of others (Hickel, Hanbury Lemos, and Barbour 2024; Wallerstein 1974). Ecologically unequal exchange illustrates that an extensive division of labor runs parallel to differential access to natural resources and the imposition of polluting activities.

Spent battery exports between the U.S. and Mexico also illustrates the barriers to ecological modernization amid the persistence of unequal exchange dynamics, and a slow, iterative violence (Nixon 2011). Lead is particularly hazardous for infants and children as it is associated with cognitive impairment and behavioral problems that last a lifetime, and among adults it contributes to high blood pressure, cardiovascular damage, and kidney disease (Muller, Sampson, and Winter 2018). Over the past three decades disability and premature death due to lead pollution in Mexico has more than doubled (Institute for Health Metrics and Evaluation [IHME] 2025).[1]

Battery recycling between the U.S. and Mexico comprises the ecologically unequal exchange of a virulent contaminant as companies side-step higher domestic compliance costs. The greenest

[1] This includes lead exposure from all sources.

industry in the U.S. has a detour in its closed-loop production cycle traversing thousands of miles. It highlights the mobility of capital amid the more constrained movement of labor as batteries move south with ease while people moving north confront the coercive power of the state. Moreover, it underscores central blind spots in ecological modernization theory as efficiency gains in the core countries can coexist with rising global material throughput and the shifting of hazardous production to the semi-peripheral and peripheral countries. Examining lead battery exports from a World-Systems framework highlights how green technology and closed-loop production can mask the expropriation of cheap labor and environmental sink capacity. Given Clarios is responsible for a majority of exports, halting much of the environmental damage is dependent upon the policies of just one company.

The next section outlines the theoretical postulates of ecological modernization and the theory of ecologically unequal exchange. I then outline the data depicting the export of lead batteries and the racialized environmental violence made possible by the differential valuation of life across the U.S.-Mexico border. The discussion then turns to Mexico's neoliberal turn beginning in the late 1970s as this is the larger context in which batteries and a myriad of other hazardous materials are either produced within or transported to the country. The conclusion reiterates the central lessons of lead battery recycling across the U.S.-Mexico border which entails the mobility of capital to leverage regulatory asymmetries and the failure of ecological modernization theory to confront an extensive division of labor in which countries fulfill distinct roles in a larger system characterized by ecologically unequal exchange.

Ecological Modernization and Unequal Ecological Exchange in the World-System

Ecological modernization theory traces its roots to the 1980s and the idea of a fundamental shift occurring in many European countries towards a greater embrace of "ecological rationality" (Mol and Sonnenfeld 2000; Mol, Spaargaren, and Sonnenfeld 2014). This encompasses technological innovation, market incentives, evolving state regulations and initiatives, and new social movements spurring a restructuring of production to reduce natural resource consumption and attendant pollution. Researchers have documented changes within politics, economics, and culture in the most developed countries, and all ostensibly heralding a new era in which the profit-motive can be harnessed to environmental improvement. Ecological modernization theory is thus a counter to de-industrialization and de-growth schools of thought stressing that economic production must be scaled back to within the limits of global ecological systems, and it is distinct from neoliberal economics insisting that markets alone are the optimum mechanism for addressing widespread pollution and landscape change (Mol 2002). In turn, ecological modernization theorists suggest that human societies can pursue economic production, material consumption, and environmental improvement in tandem. As Gibbs notes, "Ecological modernization indicates the possibility of overcoming environmental crises without leaving the path of modernization" (2017:3).

A fundamental principle is reflexive modernization and, in turn, the transition from brute and unrefined capitalist relations of production to something more evolved. It hinges on societal self-correction which may be iterative and uneven across industries but, as Arthur Mol stresses (2003), it is nonetheless semi-permanent. Indeed, Mol argues political economy and neo-Marxist scholars fail to appreciate the significance of processual change over time and the prospect for more sustainable social organization (2003).

A central ecological modernization theme is the progressive de-coupling of economic development and material resource flows (Mol and Sonnenfeld 2000). It entails doing more with less. Decoupling is predicated upon circular production and consumption sequences at scale and the reintegration of materials and waste back into the system. Ecological modernization theorists stress that consumer products should be designed to keep them in circulation for as long as possible.

The lead-acid battery industry is a prominent example of a closed-loop production and consumption cycle. Around 99 percent of used batteries in the United States are recycled, a figure higher than any other consumer product. The Battery Council International argues this constitutes a "near-zero waste model of sustainability" (Battery Council International 2023). In turn, there is significantly less reliance upon the mining of lead to meet consumer demand. It illustrates the productive confluence of state regulations, market restructuring, and self-contained industrial production that ecological modernization proponents advocate.

Ecological modernization research often focuses on detailed case studies at the firm or industry level within a given national context (Ewing 2017; York and Rosa 2003). In this sense, scholarship runs the risk of the fallacy of composition in which inferences derived at a lower level of abstraction are inappropriately applied at a higher level. The fallacy of composition lies in the erroneous conclusion that what is true of the parts, must be true of the whole (Samuelson 1948). A single data point, or indeed a litany of data points, does not necessarily define a more complex structure which often illustrates emergent processes not evident by simply examining any given part(s) from which it is derived. What is crucial is the way the parts interact and how this shapes the overall properties of the system. In turn, ecological modernization theory derived from a purely case study approach is prone to the fallacy of composition because proponents do not recognize the social organization of work across national boundaries.

The "Netherlands fallacy" is a related critique (York and Rosa 2003). It is based on the observation that the Dutch population and their average standard of living are only made possible through reliance upon imported resources. To assume the Netherlands is sustainable because it is a country with a strong environmental state and comparatively lower domestic environmental problems is to miss the "bigger picture."

The modern world-system is that bigger picture. Immanuel Wallerstein argued the Western industrialized countries and Japan constitute the core of a stratified system and illustrate the control of capital, value-added manufacturing, preferential trade relationships, and political and military prowess (1974). Peripheral countries primarily rely upon the export of raw materials and labor intensive, low wage assembly manufacturing. The semi-periphery includes those countries

exhibiting core-like and peripheral economic production processes (Wallerstein 1974). Countries fulfill distinct roles, and this contributes to an over-arching hierarchy. Wallerstein observes (1974:349):

> We have defined a world-system as one in which there is an extensive division of labor. This division is not merely functional – that is, occupational – but geographical. That is to say, the range of economic tasks is not evenly distributed throughout the world-system. In part this is the consequence of ecological considerations, to be sure. But for the most part, it is a function of the *social organization of work*, one which magnifies and legitimizes the ability of some groups within the system to exploit the labor of others, that is, to receive a larger share of the surplus (emphasis added).

The social organization of work across the world-system underlies the patterned exploitation of nature. Enduring uneven development rests upon a material foundation which "magnifies and legitimizes" the capacity of some to exploit the resources and ecological carrying capacity of others. Power is the ability to control how labor is organized and renumerated across national boundaries and the asymmetric environmental flows constituting the matter and deleterious side-effects of production. All production begins with a material foundation (Bunker 1985), and this includes ecologically modern technology. All production begins with nature, but the crucial question is whose nature?

Ecologically unequal exchange is comprised of three dimensions (Givens, Huang, and Jorgenson 2019; Hornborg 2025; Jorgenson 2016a). First, natural resources move up the hierarchy of the world-system. The most developed countries are net importers of raw materials (Dorninger et al. 2021; Hickel et al. 2022; Rammelt and Ylla-Català 2025). Despite importing vast amounts of materials, the core sustains a trade surplus by selling manufactured goods abroad, and often to nations dependent upon resource-exports (Dorninger et al. 2021). The few core countries that are net-exporters of raw materials derive more economic value per unit than do non-core countries exporting the same resource (Dorninger et al. 2021; Rammelt and Ylla-Català 2025). In turn, there is a loss of development potential even as it contributes to economic growth at the upper echelons of the world-system. As Stephen Bunker observes, "Additional value is created when extracted materials are transformed by labor. The important point, however, is that the additional value is generally realized in the industrial center, rather than at the periphery" (1985:45).

This vertical flow of resources, measured as trade with more developed nations, is correlated with undernourishment (Mejia 2023), water pollution (Shandra, Shor, and London 2009), air pollution (Hekmatpour and Leslie 2022), and higher per capita carbon dioxide emissions in non-core nations (Jorgenson 2016b). A variety of primary sector exports from poorer to richer countries are correlated with deforestation outside the core (Austin 2010; Jorgenson 2006; Jorgenson, Austin, and Dick 2009; Noble 2017; Shandra, Leckband, and London 2009). Indeed, developed countries transitioning from deforestation to reforestation over time have done so in large part by importing agricultural and forest products from abroad (Meyfroidt et al. 2020).

Material and pollution intensive manufacturing exports moving up the hierarchy of the world-system comprises a second dimension of ecologically unequal exchange. Foreign capital utilizes

domestic resources and pollution intensive production that is "embodied" in manufactured exports. The degradation and emissions stay behind, but the goods are consumed thousands of miles distant. Accounting for the land, energy, raw materials, and pollution embodied in manufacturing exports points to a long-hidden dimension of the asymmetric flows in the world-system (Jorgenson, Dick, and Mahutga 2007; Hornborg 2006). Bruckner et al. (2023) document a variety of environmental harms "outsourced" to the point of production to meet consumption demands in the European Union: greenhouse gas emissions, land use changes, consumption of surface and ground water, particulate matter formation, photochemical oxidation, and attendant biodiversity loss. Dorninger et al. (2021) highlight that between 1990-2015 all high-income nations are net importers of embodied land, materials, and energy from virtually every other country on the planet. Hickel et al. note (2022:1):

> Our results show that in 2015 the North net appropriated from the South 12 billion tons of embodied raw material equivalents, 822 million hectares of embodied land, 21 exajoules of embodied energy, and 188 million person-years of embodied labor, worth $10.8 trillion in Northern prices—enough to end extreme poverty 70 times over.

Even as natural resources and embodied emissions flow up the hierarchy of the world-system, hazardous materials flow down to what R. Scott Frey labelled the "waste disposable frontiers" (2015:41). Electronic or e-waste, chemical wastes, asbestos, and discarded plastic are prominent examples (Bai and Givens 2021; Frey 2012; Theis 2021; Tong et al. 2022). An estimated 3.3 million metric tons of used electronics were shipped from developed to developing countries in 2022 and often processed within informal or poorly regulated facilities (Baldé 2024). The Basel Convention provides oversight of the trans-border exchange of hazardous materials, but the effort is beset by loopholes, vague definitions, intentional mislabeling, and weak enforcement (Khan 2020; Lucier and Gareau 2015). Of all the loopholes, "recycling" is the biggest. Discarded goods are shipped across borders to leverage juxtapositions in compliance costs and enforcement or mislabeled as destined for secondary recovery when they are fated for end-of-life disposal. Moreover, the transport of toxic materials down the hierarchy of the world-system is characterized by terms of trade ensuring low compensation but high risks. It constitutes one more example whereby richer countries sustain high consumption rates amid comparatively cleaner environmental conditions at the expense of structurally disadvantaged nations.

Lead battery exports across the U.S.-Mexico border illustrate both the second and third dimensions of ecologically unequal exchange. They are a hazardous waste that is legally imported into Mexico only for recycling, but amid the secondary recovery of lead there is a degree of occupational and environmental risk production that is illegal north of the border. The closed loop of the greenest industrial sector in the United States has a detour thousands of miles long and traversing through working class neighborhoods in Mexico possessing little political voice and minimal environmental oversight. It highlights a key weakness of ecological modernization—the distributional effects of technological innovation and attendant economic production. Such environmental cost-shifting operates in tandem with the militarization of the border and rigid

immigration policies. The coercive arm of the state restricts the movement of people northward, but millions of batteries are transported southward each year. These are mutually reinforcing systems as labor and environmental exploitation are interwoven. Occupational and environmental risk run in tandem. In this regard, an industry touted as a model of sustainability reproduces long-standing structural disadvantages in the world economy.

Ecological modernization is predicated upon the adoption of state initiatives, advanced technology, and market mechanisms that incentivize cleaner and less resource intensive industrial production, but such efforts exist in tension with ecologically unequal exchange dynamics in the world-system. The battery trade between the U.S. and Mexico exemplifies this contradiction, and it illustrates that ecological modernization is not an end state, arrived at after a long journey, but an enduring struggle. What may appear to be movement towards an ecological modernity may instead be simply the shifting of the material consequences of production and consumption along the hierarchy of the world-system.

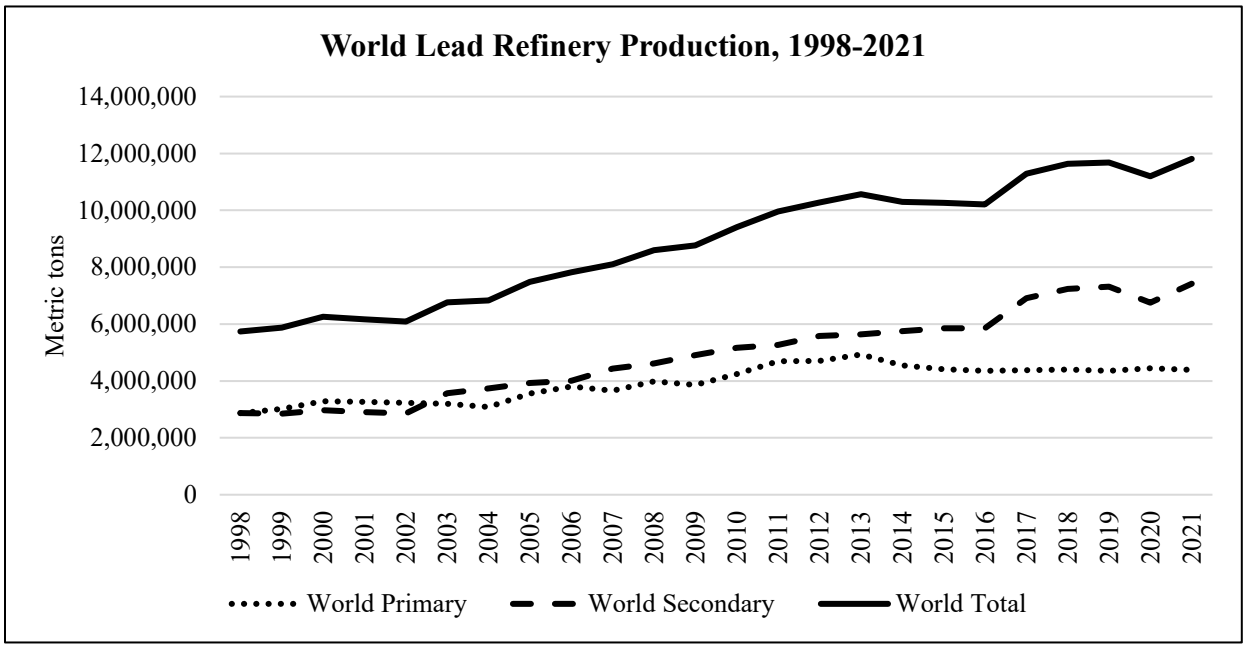
Indeed, ecological modernization theory does not account for an extensive division of labor wherein countries fulfill distinct roles in a larger whole. The mobility of capital is key to the social organization of work spanning national boundaries and contributes to significant distributional effects (Arrighi 1990; Ortiz 2024). These distributional effects are not readily captured through case study research that may point to gains in eco-efficiency within a larger context of increasing material throughput and the imposition of pollution and environmental degradation far afield.

Lead Battery Exports and Ecologically Unequal Exchange Across the U.S.-Mexico Border

Despite the greening of the industry in the U.S. and elsewhere, lead is becoming more ubiquitous rather than less in the world economy. Figure 1 outlines world primary refining based on the smelting of ore and secondary refining from scrap material between 1998-2021.[2] By 2003 global production relied less on mining and more on recycled materials. Mining is environmentally destructive, and primary smelting is more energy intensive and produces greater greenhouse gas emissions. In this regard, greater reliance on secondary recovery around 2003 is consistent with the ecological modernization principle stressing the reintegration of materials back into production. However, as depicted in Figure 1, primary refining continues to increase. An additional 1.5 million metric tons of ore were produced in 2021 than in 1998. China accounts for half of this increase. Total production, combining primary and secondary sources, doubled between 1998-2021. Although secondary smelting is more efficient and less polluting, it is nonetheless accompanied by occupational hazards as well as stack and fugitive emissions. Figure 1 illustrates the increasing reintegration of materials back into production in lieu of end-of-life disposal but greater overall production over the past two decades.

[2] Data presented in Figures 1 and 2 obtained from the U.S. Geological Survey Annual Mineral Commodity Summaries.

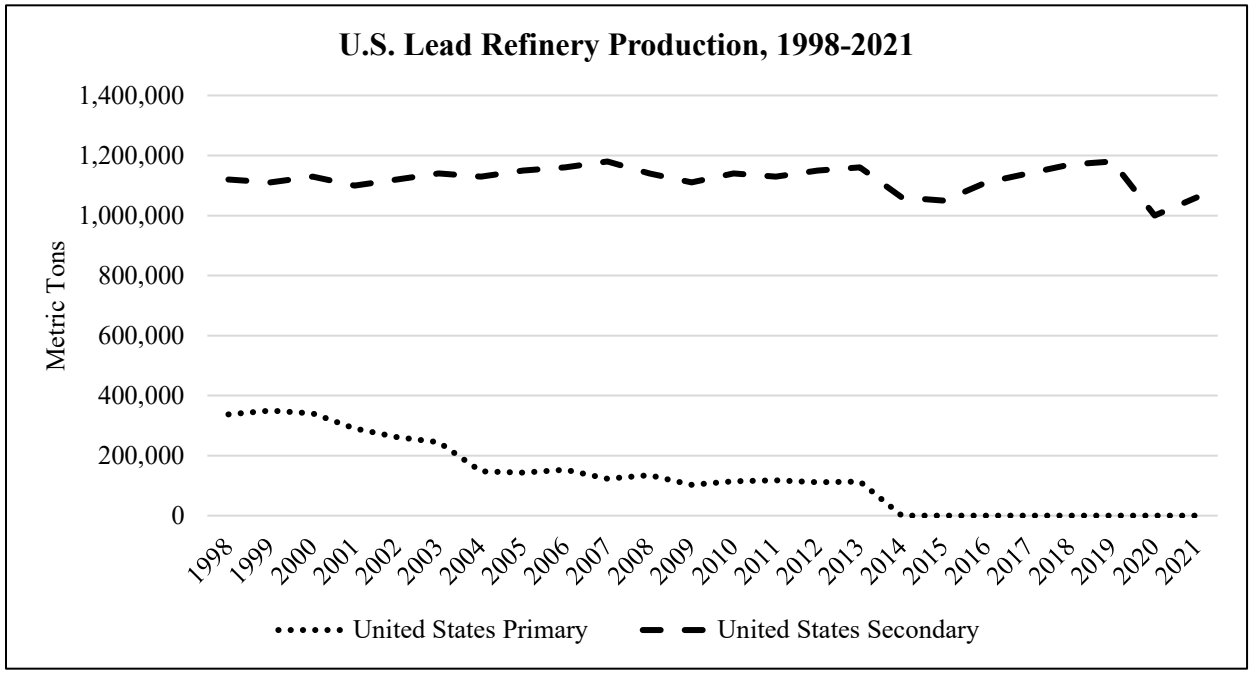
Figure 1. World Primary and Secondary Refinery Production, 1998-2021



It is a central challenge confronting the ecological modernization of industry—efficiency gains relative to the scale of production (York and Rosa 2003). When demand outpaces efficiency, material throughput continues to rise. Indeed, the less of a resource utilized per unit of output, and the declining cost of its production, can contribute to greater overall use of that resource over time (York and Rosa 2003). Described as Jevons paradox, this rebound effect illustrates that technological innovation alone is unlikely to contribute to sustainable social organization (Jorgenson and Clark 2012).

Figure 2 depicts primary and secondary lead refining from 1998-2021 in the United States. Secondary smelting declined slightly over this period and primary refining illustrates a precipitous decrease. In 2013 the last primary lead smelter in the U.S. ceased operations. All refining now encompasses recycled materials--consistent with the tenets of ecological modernization. The reuse of lead is now commonplace. Although primary refining has ceased the mining of lead ore has not, and the U.S. now exports all domestically mined ore abroad and often to places with varying occupational and environmental standards. A large proportion is destined for China. Although secondary refining changed little between 1998-2021, the demand for lead batteries increased over this period. When secondary refining is roughly stable and primary refining is non-existent, but battery sales are growing each year, the difference must be met through export-import patterns. And this is where the challenges of ecological modernization are the most apparent.

Figure 2. U.S. Primary and Secondary Refinery Production, 1998-2021

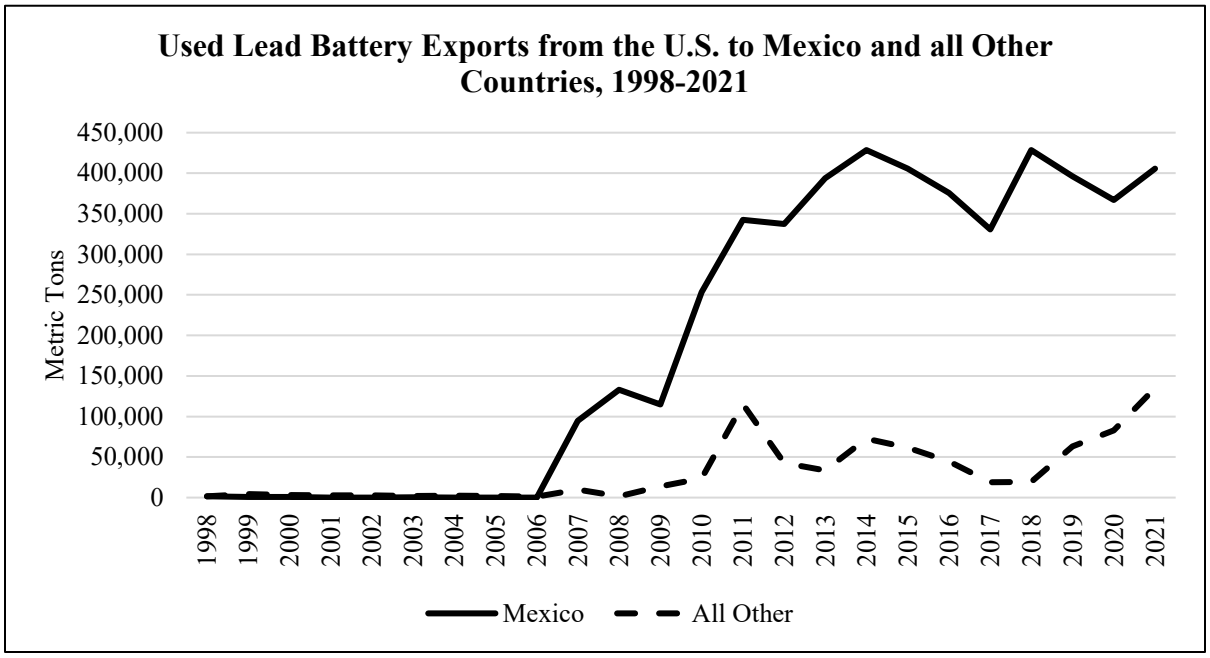


In 2007, the EPA announced plans to reduce the lead emissions standard. The change went into effect in 2008. The National Ambient Air Quality Standard was lowered by a factor of 10 (from 1.5 ug/m3 to 0.15 ug/m3), but it remained unchanged in Mexico (1.5 ug/m3). It is a ten-fold difference, and it has driven millions of used batteries across the border.

Figure 3 illustrates spent battery exports to Mexico abruptly increased coincident to the reduction in the ambient air standard in the United States.[3] Between 2007-2021, an average of 88 percent of all exports were shipped to Mexico. An enormous quantity of lead now travels thousands of miles southward, where it is recovered, and then travels thousands of miles northward to whence it began. In between there is regulatory asymmetry. In 2021, more than 400,000 metric tons, 24 million spent batteries, were shipped to Mexico and U.S.-based Clarios accounted for 68 percent of this total.

[3] Data obtained from the U.S. International Trade Commission's DataWeb database (https://dataweb.usitc.gov/) and include Harmonized Tariff Schedule (HTS) 8548100540. The data are reported in kilograms but have been converted to metric tons.

Figure 3. Used Lead Acid Battery Exports from the U.S. to Mexico and all Other Countries, 1998-2021



Ecologically unequal exchange underpins consumption at the upper echelons of the world-system amid environmental degradation and threats to human health elsewhere. But borders are the crucial transition points making such disparate outcomes possible. And nowhere is this more prominently expressed than the "unequal territorialization of value" enacted across the U.S.-Mexico border (Heyman 2007:327). Batteries flow freely, but people do not. This is key to the arbitrage at the heart of unequal exchange. Arbitrage referring to the practice of taking advantage of differences in valuation of the same or similar things across two or more distinct settings. These differences are not intrinsic but politically and economically enforced, and borders are the enforcement point. As Josiah Heyman observes (2007:328), "At this seam between the territories of two nation-states, a peculiar phenomenon occurs: monetary valuations of people and goods undergo sudden, stepwise changes as they move across the boundary."

Unequal valuation is not an episodic dynamic in the modern world-system. It is the modern world-system.

Lead is not a new problem in Mexico. In 1981, researchers sampled the blood of children living near a smelter in Torreón, Mexico. Three-year old Julieta had 34 micrograms per deciliter (Smith 1999), far beyond what is considered "safe" then or now. As she aged Julieta had difficulty learning to read and write, and this only compounded the challenges of an already impoverished life. Retested in 1999, at the age of 22, her blood lead level had doubled and was so high as to cause kidney and brain damage (Smith 1999). That same year research observed that 90 percent of soil samples collected in neighborhoods surrounding industrial sites in Torreón were higher than the EPA's Superfund cleanup threshold, on the other side of the border (Benin et al. 1999). High

levels of lead pollution were also discovered in Chihuahua and Monterrey (Benin et al. 1999). In 2011, research documented lower average blood lead levels among a sample of children in Torreón due to remediation efforts and enhanced emissions control technology, but the risks remained persistently high, particularly compared to average blood lead levels of children ages 1-5 years, on the other side of the border (Rubio-Andrade et al. 2011; Soto-Jimenez and Flegal 2011).

U.S. exports of spent batteries add a new twist to an ongoing threat to public health. In 2023, non-governmental organizations (NGOs) from both sides of the border attempted to do what Mexican government officials too often do not—account for the influx of contamination downwind of the country's 26 lead smelters. Mexican based Casa Cem and American-based Occupational Knowledge International collected soil samples near seven battery recycling plants and determined that a majority exceeded the Mexican standard for industrial areas (Gottesfeld et al. 2023). Of these, the two owned by Clarios are two of the largest facilities and two of the dirtiest. Despite having only been in operation since 2011, soil collected adjacent to Clarios's facility in Garcia averaged 8,502 parts per million (ppm) or more than ten times the Mexican Standard of 800 ppm (Gottesfeld et al. 2023). Further research documents lower birth weights among infants born within two miles of Mexico's battery recycling facilities in the period after 2009 when exports rose rapidly (Tanaka et al. 2022).

Racial disparities and pollution exist in a parallel manner. This is particularly the case with lead exposure (Muller et al. 2018). Within the United States lead contamination reflects segregated housing markets and a greater proximity of communities of color to sources of industrial pollution. At a broader register, modernity is built upon racial and ethnic marginalization within and across borders (Boatcă 2017; Dunaway and Clelland 2016). It is a crucial fulcrum through which the violence of "progress" is enacted (Morris 2022).

The U.S.-Mexico border does not simply reflect variations in racialized violence; one side contrasted to the other. The border produces legally sanctioned racialized violence (Bermúdez Tapia 2022). Mexican law does not allow for the import of hazardous wastes, including spent batteries, for storage or final disposal but only recycling. But it is a recycling predicated upon differential valuation of human life and health. Moreover, in crucial respects suffering south of the border is invisible to the north because it is expected (Bermúdez Tapia 2022). It is routine.

And profit underlies it all. When EPA officials announced tighter ambient air standards for lead emissions, Clarios officials countered that it would cost the industry $600 million to comply with the new regulations (Amend 2012). This may appear a substantive sum, but Clarios's revenue in 2024 alone was over $10 billion dollars (Clarios 2024). The annual revenue of all U.S.-based battery manufacturers is projected to rise to more than $42 billion by 2030 (Grand View Research 2024).

The United States is the only country exporting spent lead batteries to Mexico at an industrial scale, and this practice is controlled by a handful of firms dictating much of the manufacturing, distribution, and recycling. But Clarios (formerly Johnson Controls) is the "industry leader." In a 2011 *New York Times* story raising concerns about lead-laced emissions, a senior Johnson Controls executive declared that the company would voluntarily upgrade both of their facilities in Mexico

to meet the new American standards (Rosenthal 2011). While emissions controls at the Ciénega de Flores and Garcia facilities have changed little over time, in 2024 it was announced that production at Ciénega de Flores would be increased from 30 to 40 tons per hour (Engitec Technologies 2024).

The Mexican Neoliberal Turn

Mexico is an export manufacturing hub congruent with neoliberal prescriptions and structural adjustment demands (Cypher and Delgado Wise 2010). The 1982 Mexican debt crisis, membership in the General Agreement on Tariffs and Trade (GATT) in 1986, and passage of the North American Free Trade Agreement (NAFTA) of 1994 were pivotal steps. The economy is deeply interwoven with foreign capital and global supply chains amid trade liberalization, fiscal austerity and state downsizing, the privatization of state assets, and deregulation. The shift to export manufacturing as a significant proportion of economic output has been accompanied by social dislocation and a retrenchment of social-class based hardship (Cypher and Delgado Wise 2010; Shefner and Stewart 2011). In tandem, Mexico serves as a central node within the waste-disposal frontier beyond the core of the world-system (Frey 2003, 2015).

Ecological modernization theory has not fully theorized or empirically accounted for the neoliberal transition engulfing many developing countries since the 1980s and the shifting social organization of work. Ecological modernization and neoliberalism are both optimistic about market-based mechanisms and the decoupling of economic growth and environmental intensity. However, the former argues for an active role of the state in disciplining capital accumulation and promoting greener technology and social organization. Neoliberalism favors minimal regulation and the roll back of the state. In particular, ecological modernization has failed to confront *neoliberalism in practice*, which entails the subordination of environmental concerns to market growth and competitiveness.

NAFTA has contributed to the production of large volumes of hazardous waste within Mexico and the importation of toxic and polluting materials (Cruz 2024). In a side accord to NAFTA, it is stipulated but not mandated that Canada, the United States, and Mexico work to harmonize their respective regulations to avoid a "race to the bottom." Mexico is that bottom. Foreign-owned maquiladora assembly factories generate substantial amounts of hazardous materials: solvents, greases, acids, heavy metals, plastics, synthetic chemicals, wastewater, and sludge. By Mexican law the companies owning these facilities are required to repatriate these wastes, but a large proportion never leave the country nor are they processed domestically (Cruz 2024). There is a hazardous waste void somewhere in Mexico. Further, domestic resource consumption has significantly expanded in the post-NAFTA era (Tetreault 2022; Virta 2022). From 1990-2015, Mexico's consumption-based carbon footprint increased by 50 percent, land by 32 percent, materials by 46 percent, and the domestic water footprint increased 566 percent, while gross domestic product (GDP) illustrated only moderate growth (Virta 2022).

The larger logic in which Mexico is enmeshed is visible in the dangerous levels of air pollution enveloping Monterrey, and it extends well beyond the impact of battery recycling. A city of 5 million, it often ranks as the worst metro area for fine-particulate air pollution in all of North America (McCormick and García de León 2025). Factories operated by companies from the core leave their imprint on the area while primarily exporting goods to the U.S. The reclassification of toxic substances on one side of a border to recoverable resources on the other is the linchpin whereby hazardous materials make their way around the world (Lucier and Gareau 2015), including Monterrey. In 2022, nearly 200,000 tons of electric arc furnace dust (steel dust) generated during the smelting and recovery of metals in the U.S., including discarded cars and refrigerators, were transported to the Monterrey area for processing (García de León and Quinto Elemento Lab 2025). Steel dust contains lead, arsenic, cadmium, and other heavy metals. Industrial solvents and chemical wastes, including paints, resins, oils, and greases, are also routinely exported to Mexico for reprocessing (García de León and Quinto Elemento Lab 2025; Lewis and Fry 2023).

The United States is not a party to the Basel Convention, and this gives U.S.-based companies more flexibility in transporting hazardous materials to Mexico. It likely contributes to a greater degree of mislabeling, falsified documentation, and inadequate tracking (Schmidt 1999). This makes it more difficult for Mexican government officials to monitor hazardous waste and easier for actors participating in the illicit trade of toxic materials crossing into Mexico.

Battery recycling and a myriad of other hazardous production processes are emblematic of being "trapped in the middle." Semi-peripheral nations possess greater industrial capacity than the peripheral countries but are not fully integrated into the world-system. They are characterized by economic development, and then stagnation as they have the capacity to elicit foreign investment but struggle to retain the profits generated from export manufacturing and exhibit limited domestic reinvestment (Anastasi 2023). Pollution intensive export manufacturing is one strategy whereby semi-peripheral nations leverage their middling position, but they nonetheless confront structural barriers (Anastasi 2023). They industrialize but illustrate a lack of economic diversification and weak environmental state capacity.

Wages differ globally even in the absence of differences in productivity, and this is perpetuated through the mobility of capital amid the more constrained movement of laborers (Arrighi 1990; Emmanuel 1972; Ortiz 2024). This wage-gap underpins the unequal exchange of labor value through international trade. The most developed economies amassed 826 billion hours of embodied labor through trade with the developing countries in 2021 (Hickel et al. 2024). It is a "net-appropriation" cutting across all skill levels of labor and all major economic sectors, including agriculture, mining, manufacturing, and services (Hickel et al. 2024).

Wages are lower in Clarios's facilities in Mexico, but the new batteries fashioned from recovered lead are not sold at local prices but at the world market price, as are batteries made in the U.S. In turn, batteries remanufactured in Mexico do not sell for less simply because of the lower labor costs incurred in their production, and, in turn, extra surplus value is embodied in each battery relative to their production in the U.S. Value is captured not simply on the factory floor but through trade across the U.S.-Mexico border.

Examining Figure 3, exports to Mexico only grew in anticipation of tighter regulations. Whatever the equation prompting Clarios and other companies to move operations abroad, clearly, environmental considerations were key. This is consistent with Bunker's examination of the under-development of the Amazon region of Brazil (1985). He argued uneven development hinges on separate but complementary types of unequal exchange. The "hidden transfers" of value underpinning relative positioning in the world-system are enacted through the exploitation of labor and the extraction of natural value. Bunker defines natural value as the productive potential inherent to different raw resources, realized through human labor, and the capacity to disrupt or alter ecological systems without accountability or recompense. The underlying thread is uneven material exploitation amid the inherent materiality of all production and consumption. In turn, the procurement of energy, biomass, minerals, and the off-loading of the waste products of industrial production are crucial considerations in addition to wage differences and the cross-national flow of surplus value.

In this regard, the secondary recovery of lead constitutes a form of unequal exchange as surplus value, environmental sink-capacity, and bodily risk are differentially allocated across the U.S.-Mexico border through the combined forces of corporate strategy, state policy, and the materiality of hazardous production. It illustrates the challenges of ecological modernization when the social organization of work spans distinct regulatory regimes and is characterized by the fluid movement of capital and more constrained mobility of labor.

Of note, the extraction of surplus labor and environmental sink-capacity across the U.S.-Mexico border is characterized by contradictory processes. Clarios's decision to recycle spent batteries near Monterrey generates industrialization, albeit an industrialization subservient to the prerogatives of a core-based company, and deindustrialization and the loss of 360 jobs in Florence, South Carolina (Brown 2021). Working class communities on both sides of the border have been impacted. There is social dislocation to the north and threats to human health and the environment to the south. Unequal exchange reproduces differential impacts depending upon class positioning in both the United States and Mexico.

Dependent industrialization or industrialization shaped by and oriented primarily towards the interests of external actors is made possible through the contributing services of domestic elite factions within Mexico (Cypher and Delgado Wise 2010; Morton 2013). They are tied to external capital by way of mutual benefit and serve as political brokers, financiers, subcontractors, and intermediaries. Their economic interests are not linked to broad-based development of the national economy but, rather, industrialization under conditions of external control and trade dependence (Cypher and Delgado Wise 2010; Morton 2013). In this regard, unequal exchange in the world-system is not so much imposed upon a country in a unilateral manner but coordinated with select class segments within a given country (Arrighi 1990; Cardoso and Faletto 1979).

There are localized benefits tied to the recycling of batteries in Mexico that include employment, subcontracting with domestic firms providing support and services, and the payment of taxes. In tandem with ties to domestic elites, these activities help to secure local consent and to shield companies from sustained critique. However, these benefits coexist with, and arguably do

not outweigh, the simultaneous production of risks to human health on the factory floor and in surrounding communities. More broadly, localized benefits do not outweigh the costs tied to the ecologically unequal exchange of a crescive hazard across the U.S.-Mexico border with significant, life-long consequences for children, in particular.

The lead-acid battery industry is an ecologically modernized segment of the U.S. economy and an important component of green technology, including the expansion of renewable energy sources. However, the development of green technology tends to reproduce rather than stand outside the structural inequities of the broader world-system (Bonds and Downey 2012; Ewing 2017). Raw materials are often extracted from countries outside the core and exact a heavy environmental toll (Bonds and Downey 2012; Ewing 2017). And as battery recycling in Mexico illustrates, even the most circular economies may detour far afield to leverage the differences in regulatory regimes. Ecological modernization theorists have not fully confronted such contradictory processes underlying the division of labor in the world economy. It is a challenge to develop profitable, greener industrial production anywhere when the social organization of work across countries is characterized by enduring structural inequities.

Ecological modernization has been described as a fundamental turn in the most developed economies towards less resource-intensive and polluting economic production (Mol and Sonnenfeld 2000). However, as Bunker notes (1985), all production begins and ends with a material foundation, and this includes ecologically modern technology. A "holistic" view of green technology uncovers a variety of contradictions (Bonds and Downey 2012; Ewing 2017). The pervasiveness of lead pollution throughout the world is a further challenge as electric vehicles and renewable energy are dependent upon lead and other materials, including lithium, cobalt, and rare earth minerals. Indeed, green technology necessitates an increasing reliance upon lead in a world already beset by lead-related threats to public health.

Conclusion

The social organization of work across the world-system is dependent upon the patterned exploitation of nature, and these patterns magnify and legitimize the ability of some to exploit the resources and environmental carrying-capacity of others. The most developed countries coordinate the organization and renumeration of work across vast distances and cast "ecological shadows" extending well beyond their political boundaries (Chew 2001). They do so along three intertwined dimensions of ecologically unequal exchange. This includes the trade in under-valued raw materials up the hierarchy of the world-system, the domestic resources and pollution intensive materials "embodied" in manufacturing exports from the non-core nations, and the off-shoring of hazardous wastes down the hierarchy of the world-system. The thread running through all three dimensions is the shifting of the environmental burden.

In 2007, the U.S. EPA announced plans to implement stricter lead pollution standards—the first such change in three decades. The intent was to improve public health, but the outcome, in large part, was the transference of environmental risk. Over the past 20 years the volume of spent

batteries shipped to Mexico has steadily risen. In 2021, more than 400,000 metric tons, 24 million used automotive batteries, were exported to Mexico.

This highlights the ecologically unequal exchange of a crescive contaminant to side-step tighter regulations. Rather than internalizing compliance costs within the production cycle, U.S.-based companies leverage regulatory asymmetries and perpetuate the unequal valuation of labor and human health. In this regard, the border produces racialized environmental violence as batteries flow freely but people do not. The weight and veracity of this violence is readily detectable. It is inscribed in the blood of those laboring under a higher occupational threshold and children living and playing in the shadow of smelter facilities operating under a ten-fold greater threshold for the imposition of ambient, lead-laced, air emissions.

U.S.-based Clarios owns two of the largest lead smelters in Mexico. These facilities process up to two-thirds of the batteries completing the U.S.-Mexico arbitrage cycle. Curbing the bulk of this practice is dependent upon the actions of just one company. A firm ranked "one of the most ethical companies in the world" in 2025, for the third year in a row (Clarios 2025).

Mexico is a central node within the waste-disposal frontier of the world-system, and it encompasses more than battery recycling. But, in important regards, suffering south of the border is invisible because it is expected (Bermúdez Tapia 2022). The tacit endorsement of the slow violence of industrial production between the U.S. and Mexico is commonplace, as it is down the hierarchy of the world-system in general. Indeed, the production of crescive environmental violence is often dismissed in the expectation that, over time, such sacrifices will abate as nations develop. However, as Giovanni Arrighi observes, "Industrialization is not the equivalent of development" (1990:12). Manufacturing has expanded in tandem with Mexico's neoliberal turn. A significant proportion of the manufacturing base, however, is subject to outside control and attuned to the needs of external capital and markets abroad as well as competition from dependent industrialization within other semi-peripheral and peripheral countries (Cypher and Delgado Wise 2010). As ecological modernization theorists stress, the embedding of ecological rationality within multiple spheres in society reflects evolutionary, processual change as nations develop. Dependent industrialization is not development, however, nor does it tend towards ecological modernization.

On paper, the lead battery industry is the greenest sector of the American economy. Nearly all lead comes not from ore but secondary recovery. Such transformations are notable but scarcely the uniformly positive success story portrayed by the industry. And while ecological modernization is predicated upon the adoption of state initiatives, advanced technology, and market mechanisms that incentivize cleaner and less resource intensive industrial production—such efforts exist in tension with ecologically unequal exchange dynamics. Indeed, a key weakness of ecological modernization theory is failure to confront an extensive division of labor in which countries fulfill distinct roles in a larger structure characterized by unequal exchange and reverberating distributional effects.

Most people do not think about batteries, even as they are pervasive in our daily lives. They are crucial to the viability of wind and solar electricity generation as well as the development of electric vehicles and the decarbonization of economic growth. Whether lead-acid or lithium-ion,

we are at the precipice of a "battery-powered future" even as they are already everywhere (Turner 2022:14).

That we are on the precipice of a battery powered future raises a number of challenges. They are already everywhere, and so too is lead-related disability and disease. The disability-adjusted life years foregone attributable to lead exposure worldwide grew from 21.8 to 33.8 million years from 1990-2021 (IHME 2025). This is despite significant strides in banning lead gasoline throughout the world and more moderate success restricting lead-based paint. Disability-adjusted life years (DALYs) refers to the number of years lost to illness, disability, or premature death. One DALY is equivalent to one year of healthy life foregone, and 95 percent of the 33.8 million years of healthy life lost in 2021 occurred outside the core of the world-system (IHME 2025). China and India account for roughly 50 percent of the global years of healthy life lost in 2021 due to lead pollution (IHME 2025). China's lead consumption outpaces that of the core countries due to concerted investment in battery manufacturing and rapid industrialization. This calculation includes exposure from all sources, including food and consumer products, but battery recycling is the largest industrial source of lead pollution, constituting around 85 percent of all lead consumption worldwide (World Health Organization 2017). Although China and India account for a substantial proportion of the total burden, many peripheral nations illustrate higher rates of death and disability due to lead pollution, including Pakistan, Nepal, Zambia, Uganda, and Nigeria (IHME 2025). Over half of children in many peripheral nations have blood levels deemed lead poisoning in the core countries (Ericson et al. 2021).

In 2019 alone there were 5.5 million adult deaths due to cardiovascular disease derived of lead exposure and the loss of 765 million IQ points among children under five, overwhelmingly occurring in the developing countries (Larsen and Sánchez-Triana 2023). The economic cost in 2019 was approximately $6 trillion U.S. dollars, or seven percent of global GDP (Larsen and Sánchez-Triana 2023). In turn, lead exacts a significant toll on human health, and the impact is recursive as it is shaped by structural disadvantage and contributes to its perpetuation.

This raises broader questions regarding lead exposure and the totality of the burden of hazardous production outside the core. How many hazardous materials flow down the hierarchy of the world-system in the name of recycling and secondary recovery? What are the cumulative and recursive effects of these waste recovery circuits on human health and uneven development? What strategies do community groups and NGOs employ in highlighting and contesting differential valuation and the slow violence of industrial production?

Spent battery recycling across the U.S.-Mexico border is but one instance of ecologically unequal exchange in a hierarchical world-system whereby more dominant nations gain access to natural resources and shift the risks of pollution intensive production. Future research examining the export-import of used lead batteries from a social network approach would be valuable in depicting the contours of this practice at a more macro register. Untangling such relational dynamics would contribute to a more comprehensive understanding of the enactment of ecologically unequal exchange and the attendant recursive effects (Theis, Betancourt, and Sikirica 2024). Moreover, it would further highlight the unequal territorialization of value and associated

threats to public health from the flow of lead across borders. This matters as we are on the precipice of a battery-powered future (Turner 2022), even as lead-related disability and death is already a significant burden in Mexico and, indeed, throughout the modern world-system.

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