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Sustainable Management of Rechargeable Batteries Used in Electric Vehicles

Jay Meegoda [1,*] , Ghadi Charbel [1] and Daniel Watts [2]

1   Civil and Environmental Engineering, New Jersey Institute of Technology, Newark, NJ 07102, USA; gc383@njit.edu
2   Biology Department, Indiana University—Bloomington, Bloomington, IN 47405, USA; dajwatts@indiana.edu
*   Correspondence: meegoda@njit.edu; Tel.: +1-973-596-2464

Abstract: A Life Cycle Assessment (LCA) quantifies the environmental impacts during the life of a product from cradle to grave. It evaluates energy use, material flow, and emissions at each stage of life. This report addresses the challenges and potential solutions related to the surge in electric vehicle (EV) batteries in the United States amidst the EV market's exponential growth. It focuses on the environmental and economic implications of disposal as well as the recycling of lithium-ion batteries (LIBs). With millions of EVs sold in the past decade, this research highlights the necessity of efficient recycling methods to mitigate environmental damage from battery production and disposal. Utilizing a Life Cycle Assessment (LCA) and Life Cycle Cost Assessment (LCCA), this research compares emissions and costs between new and recycled batteries by employing software tools such as SimaPro V7 and GREET V2. The findings indicate that recycling batteries produces a significantly lower environmental impact than manufacturing new units from new materials and is economically viable as well. This research also emphasizes the importance of preparing for the upcoming influx of used EV batteries and provides suggestions for future research to optimize the disposal and recycling of EV batteries.

Keywords: Life Cycle Analysis; recycling; electric vehicles; Life Cycle Cost Analysis

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1. Introduction

A Life Cycle Assessment (LCA) is a methodology for assessing the environmental impacts associated with all the stages of life of a product from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, as well as eventual disposal or recycling. An LCA aims to identify and quantify the energy and materials used and wastes released to the environment to assess their impacts on the environment, and it aims to identify and evaluate opportunities for environmental improvements. The assessment includes the entire life cycle of the product, process, or service from cradle to grave [1]

In the United States, the market for electric vehicles (EVs), fanned by initiatives to address climate change and global warming, reached a value of USD 49.1 billion in 2022. Forecasts suggest that it will expand to USD 215.7 billion by 2032 with a compound annual growth rate of 15.5% [2,3]. This surge in popularity of EVs has amplified the demand for lithium-ion batteries (LIBs), resulting in increased prices for essential raw materials of batteries such as cobalt, lithium, copper, and nickel. The prices of these raw materials have seen a dramatic increase; for example, the price of lithium increased by four to five times in 2021 and almost doubled again from January 2022 to January 2023 [4]. Such heightened demand has led to environmental and humanitarian concerns at numerous mining sites, which are likely to increase proportionally with demand unless they are addressed.

Managing the surge of used EV lithium-ion batteries presents a significant challenge for the U.S. as well as the rest of the world. The intricate composition of electric car batteries includes elements like lithium, nickel, cobalt, copper, and graphite carbon, some of which

are increasingly difficult to acquire economically. The scarcity and mining intensity of these elements, coupled with pollution-heavy extraction processes, pose serious environmental threats [5]. The improper disposal of LIBs creates the risk of releasing toxic chemicals into soil and water, leading to the long-term contamination of natural resources. Such actions can result in a wide array of health issues, including damage to internal organs, respiratory problems, birth defects, and heart disease.

The ramifications of incorrect battery disposal extend beyond local pollution by contributing to global environmental issues and probable illegal e-waste dumping. With the growing global popularity of electric vehicles, improper disposal is becoming increasingly problematic, elevating pollution levels and toxic waste in various countries. This, in turn, affects water resources and public health while causing substantial harm to diverse ecosystems and wildlife [6]. Given that over 2.5 million batteries for electrical and plug-in vehicles have been sold in the past 12 years [7], efficient recycling solutions are required. The U.S. government is funding recycling projects, with the Environmental Protection Agency investing over USD 100 million in such initiatives and the Bipartisan Infrastructure Law allocating USD 275 million between 2022 and 2026 as part of the Save Our Seas 2.0 Act [8]. This study aims to assess the environmental impacts and the effectiveness of these recycling measures within the electric vehicle sector.

2. Literature Review

Global climate change has become one of the primary problems facing the planet. In response to this threat, investments have been made to facilitate the transition from fossil fuels to renewable energy as a primary power source for vehicles. One of the manifestations of these investments is the surge in numbers of electric vehicles (EVs). As EVs become more accessible and their prices continue decreasing, their adoption is expected to grow significantly, with EVs predicted to make up 10% of all vehicle sales by 2025 and up to 30% by 2030 [9]. However, this increase in EV adoption raises a consequential concern: an optimal strategy is needed for managing EV batteries when they reach their end-of-life stage. This research performed a comprehensive review of the recent scholarly literature to ascertain the most effective way of dealing with the critical issue of EV battery disposal from a Life Cycle Assessment perspective.

As stated by Bobba et al. [10], Fan et al. [11], Quan et al. [12], and Gains et al. [13], once batteries degrade to an 80% charging capacity, they are not effectively usable in EVs; nonetheless, those batteries still have significant capacity within them, making them suitable for reuse in other applications. In fact, Picatoste et al. [14] argue that, given the high cost of manufacturing EV batteries and the impact of their production on the environment, it is imperative to maximize the useful lifespans of these batteries by repurposing them in different scenarios because the energy needed to recycle batteries directly after their initial use in EVs is greater than the environmental benefits resulting from the recycling effort [15,16]. While Kotak et al. [15] contend that when it comes to EV batteries, there are countless possibilities for second-life applications, the majority of the literature identified for this research focuses on repurposing batteries within an Energy Storage System (ESS). Bobba et al. [10] highlight that repurposed EV batteries show promising environmental benefits, especially when they are employed in place of new storage batteries in order to support the self-sustaining energy needs of stand-alone photovoltaic (PV) installation in houses. The environmental advantages are more substantial in regions with a less green energy mix, such as substituting a diesel generator with grid-connected renewable energy. Nonetheless, one problem that arises when building an ESS is the multitude of battery chemistries, different degrees of usage, and the compositions available in the market, making it difficult to build a truly interconnected system [8]. The two most common battery chemistries prevalent within EVs are lithium iron phosphate (LFP) batteries and lithium nickel cobalt manganese oxide (NCM) batteries [11]. To remedy this issue, Kotak et al. [15] propose constructing an ESS with individual cell control, which would allow for the combination of different cell chemistries while maximizing performance. Nevertheless,

such a structure would come with a significantly higher cost. Once the battery reaches 60% of its initial charging capacity, the battery must be disposed of as it can no longer fulfill the system requirements for any potential second-use scenario. [10]. At this stage, recycling becomes imperative in order to maximize the environmental benefits.

As reported by Fan et al. [11], recycling methods for lithium-ion batteries commonly include hydrometallurgy, pyrometallurgy, and direct recycling. They found that when comparing recycling methods, hydrometallurgical recycling lags slightly behind pyrometallurgical recycling and direct physical recycling in terms of environmental benefits, possibly due to the generation of a large amount of acidic wastewater during the hydrometallurgical process. Also, among these methods, recycling NCM batteries was found to offer better environmental benefits. Conversely, in their study, Quan et al. [12] dispute that hydrometallurgy consistently outperformed direct physical recycling and pyrometallurgy in terms of environmental benefits. In fact, their study showcased that pyrometallurgy was less effective in recycling steel, copper, and aluminum from NCM batteries. Similarly, Marchese et al. [17] present a comprehensive examination of the hydrometallurgical process, advocating the utilization of organic acids such as citric acid, oxalic acid, maleic acid, or combinations thereof to foster a more sustainable approach to metal extraction. Their analysis suggests that this method not only aligns with environmental and economic sustainability, but also circumvents the need for costly post-processing of wastewater that is typically associated with hydrometallurgical extraction techniques. Furthermore, the use of organic acids is credited with simplifying the management of the leaching solution, reducing energy consumption, and diminishing carbon dioxide emissions, thereby contributing to a reduction in the environmental footprint of metal extraction.

On the other hand, Rosenberg et al. [8] and Picatoste et al. [14] state that using both recycling technologies, pyrometallurgy and hydrometallurgy, for the entire volume of end-of-life batteries has the potential to achieve the lowest overall environmental impacts within defined limits. Finally, in their study, Zanoletti et al. [18] explore various methods for recycling lithium-ion batteries (LIBs), identifying hydrometallurgy and solvo-metallurgy as standout approaches due to their unique benefits and challenges. Hydrometallurgy is praised for its efficiency in energy use and its ability to purify metals to a high degree, effectively reducing the environmental impact. On the other hand, solvo-metallurgy, an innovative method using non-aqueous solvents like ionic liquids and deep eutectic solvents (DESs), seeks to overcome the shortcomings of hydrometallurgy by reducing the generation of wastewater and facilitating the thorough dissolution of cathode materials at reduced temperatures. This cutting-edge technique is noted for its potential to significantly improve the sustainability and effectiveness of the recycling process. Solvo-metallurgy, with its pioneering strategies and dedication to environmental conservation, has the potential to revolutionize the standards for efficient and eco-friendly battery recycling. However, its scalability and industrial application are currently limited in contrast to pyrometallurgy and hydrometallurgy, which are already widely implemented at the industrial level.

In summary, the above review highlights that while batteries may become unsuitable for EV use when they reach around 80% recharge capacity, they still retain significant potential for reuse, which is crucial given the environmental costs associated with the full scope of battery manufacturing. Repurposing these batteries, especially in Energy Storage Systems (ESSs) for self-sustaining energy needs, presents promising environmental benefits, particularly in regions with a lower availability of green energy. However, challenges exist in building interconnected ESSs due to the diversity of battery chemistries and their usage and compositions. However, it is important to note that none of the studies mentioned in this manuscript have been conducted in the United States, and given that the electricity infrastructure within each country plays a significant role in the LCA comparisons for EVs, such a study was performed and is reported here in order to clarify the true impact that those batteries have on the environment in the U.S.

3. Environmental Impact Categories

To fully understand the total environmental impact associated with EV battery recycling, standard environmental impact categories were used to quantify the adverse environmental and health impacts. Among over 30 environmental impacts considered for inclusion, 19 were selected as being the most relevant for this study: Global Warming Potential (GWP), Acidification Potential (AP), Cumulative Energy Demand (CED), Ozone Depletion Potential (ODP), Particulate Matter Formation (PMF), Abiotic Depletion Potential (ADP), Photochemical Ozone Creation Potential (POCP), Freshwater Ecotoxicity Potential (FETP), Human Toxicity Non-Carcinogenic (HTnc), Human Toxicity Carcinogenic (HTc), Eutrophication Potential for Terrestrial Situations (EPt), Eutrophication Potential for Marine Ecosystems (EPm), Water Depletion, Land Use and Land Change, Biodiversity Loss, Noise Pollution, Soil Quality Degradation, Thermal Pollution, and Groundwater Contamination. A brief description of each selected impact category is provided below:

1. **Global Warming Potential (GWP):** Global Warming Potential (GWP) is a key metric in a Life Cycle Assessment (LCA) for evaluating the impact of greenhouse gases (GHGs) on global warming. It compares the radiative forcing effect—meaning the change in the Earth's energy balance—of different GHGs to that of carbon dioxide (CO_2), the reference gas. The GWP is calculated over different timeframes, typically 20, 100, and 500 years, to account for the varying lifespans and immediate impacts of different gases. Shorter time horizons emphasize the effects of gases like methane (CH4), which are short-lived but initially highly potent, whereas longer horizons focus on gases like CO_2 that persist longer in the atmosphere. The GWP of CO_2 is set as 1 across all timeframes, and other gases are rated based on how their warming effects compare to those of CO_2. This takes into account factors like the gas's ability to absorb and emit infrared radiation, its atmospheric lifespan, and its concentration.

2. **Acidification Potential (AP):** Acidification Potential (AP) is an important category in a Life Cycle Assessment (LCA) that evaluates the potential of emissions to cause acidification in the environment. This process involves pollutants being emitted into the atmosphere that transform chemically and return to the Earth's surface as "acid rain" or other acidic substances or materials that can be converted by natural processes into acidic substances. This can have harmful effects on soil, water, ecosystems, and human health. Key pollutants contributing to acidification include sulfur dioxide (SO_2), nitrogen oxides (NOx), ammonia (NH_3), and volatile organic compounds (VOCs), which can arise from human activities as well as natural sources.

3. **Cumulative Energy Demand (CED):** Cumulative Energy Demand (CED) is a category in a Life Cycle Assessment (LCA) that measures the total primary energy required by a product, service, or system over its entire lifespan. It considers both renewable and non-renewable energy sources, offering insights into the energy efficiency and environmental impact of energy consumption. CED has two primary components, the first being non-renewable energy, which includes energy from finite resources like fossil fuels (coal, natural gas, and oil), nuclear energy, and other non-renewable sources, and the second being renewable energy, which covers energy from sustainable sources such as solar, wind, hydroelectric, geothermal, and biomass energy.

4. **Ozone Depletion Potential (ODP):** The Ozone Depletion Potential (ODP) is a measure in a Life Cycle Assessment (LCA) that assesses how much a substance can damage the ozone layer. The ozone layer is vital for protecting Earth from the sun's harmful ultraviolet (UV) rays. Substances with a high ODP contribute to ozone layer depletion, leading to increased UV radiation reaching Earth, which can harm humans, animals, and ecosystems. Key contributors to ozone depletion include chlorofluorocarbons (CFCs), halons, carbon tetrachloride, methyl chloroform, and some hydrochlorofluorocarbons (HCFCs) and hydro-bromo-fluoro-carbons (HBFCs). These substances emit chlorine and bromine atoms in the stratosphere, which break down ozone molecules.

5. **Particulate Matter Formation (PMF):** Particulate Matter Formation (PMF) is an aspect in a Life Cycle Assessment (LCA) focusing on the potential of emissions to create

particulate matter (PM) in the air. PM comprises small particles or droplets that pose risks to human health as well as to ecosystems and the environment. It varies in size and composition, with PM10 describing particles of 10 μm or less, and PM2.5 describing particles of 2.5 μm or less. Smaller particles are particularly concerning as they can penetrate deep into the respiratory system and even enter the bloodstream. PMF primarily arises from emissions of primary particles, which are emitted directly, and secondary precursors, like sulfur dioxide (SO_2), nitrogen oxides (NOx), ammonia (NH_3), and volatile organic compounds (VOCs), which react in the atmosphere to form particles.

6. **Abiotic Depletion Potential (ADP):** Abiotic Depletion Potential (ADP) is a category in a Life Cycle Assessment (LCA) that examines the potential for depleting non-living (abiotic) resources like minerals and fossil fuels. This depletion is a significant issue due to its impact on the availability of these resources for future generations and the resulting environmental and socio-economic implications. ADP specifically focuses on non-renewable resources, including minerals which encompass metal ores (like iron, copper, and aluminum), industrial minerals (such as limestone and phosphate), and rare earth elements. Also, fossil fuels, with resources like coal, oil, natural gas, and peat, are included in this category.

7. **Photochemical Ozone Creation Potential (POCP):** The Photochemical Ozone Creation Potential (POCP) is a measure used in a Life Cycle Assessment (LCA) to evaluate the likelihood of certain emissions to form ground-level ozone or tropospheric ozone, often referred to as smog. This type of ozone, unlike the protective layer in the upper atmosphere, can negatively impact human health, ecosystems, and crops. Ground-level ozone formation is the result of complex photochemical reactions in the atmosphere, primarily involving volatile organic compounds (VOCs) and nitrogen oxides (NOx). These substances, when released into the air and exposed to sunlight, interact to produce ozone.

8. **Freshwater Ecotoxicity Potential (FETP):** The Freshwater Ecotoxicity Potential (FETP) is an assessment category in a Life Cycle Assessment (LCA) that measures the possible harmful impacts of substances released into freshwater environments. This category evaluates the potential damage to aquatic life in bodies of water like rivers, lakes, and streams, considering both the toxicity and the concentration of the chemicals involved. The substances that contribute to freshwater ecotoxicity vary and include heavy metals, pesticides, industrial chemicals, and pharmaceuticals. These chemicals can negatively affect aquatic organisms by interfering with their biological processes, reproduction, and survival. Such impacts can lead to alterations in the structure and functioning of entire ecosystems.

9. **Human Toxicity Non-Carcinogenic (HTnc):** Human Toxicity Non-Carcinogenic (HTnc) is a category in a Life Cycle Assessment (LCA) focusing on the potential non-carcinogenic adverse health effects on humans from exposure to toxic substances. It addresses a spectrum of health issues, including damage to organs, reproductive and developmental toxicity, neurotoxicity, and endocrine disruption, among others. A wide range of chemicals can contribute to non-carcinogenic human toxicity, including heavy metals, solvents, pesticides, industrial chemicals, and air pollutants. These substances can be absorbed into the human body via inhalation, ingestion, or skin contact, and the resulting health impacts vary based on the amount (or dose), duration, and method of exposure.

10. **Human Toxicity carcinogenic (HTc):** Human Toxicity Carcinogenic (HTc) is a crucial impact category in a Life Cycle Assessment (LCA) that assesses the potential health risks associated with exposure to carcinogenic substances. These substances may cause cancer in living tissues, representing a significant health hazard. The assessment looks at different pathways of exposure, such as inhalation, ingestion, and skin contact. Various substances are identified as potential contributors to carcinogenic human toxicity, including polycyclic aromatic hydrocarbons (PAHs), volatile organic

compounds (VOCs) like benzene, heavy metals (for example, arsenic, cadmium, and chromium), asbestos, formaldehyde, dioxins, and furans, as well as some pesticides and herbicides known to have carcinogenic effects.

11. **Eutrophication Potential for terrestrial (EPt):** The Eutrophication Potential for Terrestrial Ecosystems (EPt) in a Life Cycle Assessment (LCA) evaluates the environmental impacts of excessive nutrient enrichment in land ecosystems. This phenomenon, primarily caused by nitrogen and phosphorus compounds, leads to changes in soil chemistry, alterations in plant communities, and habitat degradation. The major contributors to this issue include nitrogen compounds (like ammonia, nitrogen oxides, and nitrates) and phosphorus compounds (such as phosphates), originating from agriculture, industry, transport, and waste management. This LCA category helps in assessing and mitigating the impacts of nutrient overloading on terrestrial environments.

12. **Eutrophication Potential for Marine Ecosystems (EPm):** The Eutrophication Potential for Marine Ecosystems (EPm) in a Life Cycle Assessment (LCA) focuses on assessing the environmental impacts of excessive nutrient enrichment in oceanic habitats. This enrichment, primarily from nitrogen and phosphorus compounds, can cause issues like harmful algal blooms, oxygen depletion (hypoxia), biodiversity loss, and changes in marine habitats. Nitrogen compounds (such as nitrate and ammonia) and phosphorus compounds (like phosphate) are the main contributors. These nutrients typically come from agricultural runoff, wastewater discharge, industrial emissions, and atmospheric deposition. This LCA category helps in understanding and managing the ecological impacts on marine environments due to nutrient overloading.

13. **Water Depletion**: Water Depletion is a significant impact category in a Life Cycle Assessment (LCA) that aims to evaluate the potential environmental impacts associated with the depletion of freshwater resources. Water Depletion considers both the quantity and quality aspects of water consumption and contamination, assessing the stress placed on water resources and the consequent ecological, societal, and economic implications.

14. **Land Use and Land Change:** Land Use and Land Use Change are crucial categories in a Life Cycle Assessment (LCA) for evaluating the environmental impact of using and altering land for human activities. "Land Use" examines the impact of using land for agriculture, forestry, urban, or industrial purposes, focusing on the duration and intensity of use and its effects on biodiversity, soil, and ecosystem services. "Land Use Change" deals with the transformation of land from one type to another, such as from forests to farmland or from grasslands to urban areas, and its implications on land cover, habitat loss, albedo changes, and carbon and water cycles.

15. **Biodiversity Loss**: Biodiversity Loss is a key impact category in a Life Cycle Assessment (LCA) that investigates the potential adverse effects of human activities on the variety of life on Earth, including the different species of plants, animals, and microorganisms, the genetic differences within these species, and the ecosystems they form.

16. **Noise Pollution**: Noise Pollution is an essential impact category in a Life Cycle Assessment (LCA) that focuses on evaluating the environmental and human health impacts associated with unwanted or harmful sound levels produced during various life cycle stages of products, services, or systems. It is a significant concern due to its potential effects on human health, well-being, wildlife, and the overall quality of the environment.

17. **Soil Quality Degradation:** Soil Quality Degradation is a crucial impact category in a Life Cycle Assessment (LCA) that addresses the decline in the health and functionality of soil as a result of human activities. Soil quality is integral to ecosystem services as good soil quality supports plant growth, regulates water flow, cycles nutrients, and hosts a vast array of biodiversity.

18. **Thermal Pollution**: Thermal Pollution is an important impact category in a Life Cycle Assessment (LCA) that assesses the effects of abnormal changes in the environmental

temperature due to human activities. It typically occurs when industries or power plants discharge heated water or air into the environment, affecting water quality and ecosystems, particularly aquatic life.

19. **Groundwater Contamination:** Groundwater Contamination is a critical impact category in a Life Cycle Assessment (LCA) that evaluates the extent and implications of pollutants entering groundwater resources due to human activities. Groundwater is a vital source of drinking water and irrigation, and its contamination can have severe repercussions on human health, ecosystems, and water availability.

Inclusions and Exclusions of Environmental Impact Factors

In this study, the SimaPro software V7 was first used with its ReCiPe Endpoint (H) V1.06/World ReCiPe H/H method for an environmental impact assessment. This approach allowed for the analysis of 12 out of 19 potential impact categories. Due to software constraints, it was not possible to include the remaining seven critical factors: Global Warming Potential, Cumulative Energy Demand, Water Depletion, Noise Pollution, Soil Quality Degradation, Thermal Pollution, and Groundwater Contamination. In order to provide a full consideration of the LCA effects, a separate discussion about these factors is later provided. The subsequent use of the GREET software V2 provided a broader perspective, offering detailed data on emissions and energy consumption at various stages of the recycling process. This facilitated a more comprehensive understanding of the Global Warming Potential, Cumulative Energy Demand, and Water Depletion. Nevertheless, four elements—Noise Pollution, Soil Quality Degradation, Thermal Pollution, and Groundwater Contamination—remained elusive due to insufficient available data, making their quantification challenging. Table 1 categorizes all 19 environmental factors, indicating those analyzed and those beyond the study's scope, for full consideration.

Table 1. Inclusion and exclusion of environmental factors.

Environmental Factors	Included in SimaPro	Included in GREET	Excluded from Both
Global Warming Potential		X	
Acidification Potential	X		
Cumulative Energy Demand		X	
Ozone Depletion Potential	X		
Particulate Matter Formation	X		
Abiotic Depletion Potential	X		
Photochemical Ozone Depletion Potential	X		
Human Toxicity Non-Carcinogenic	X		
Human Toxicity Carcinogenic	X		
Eutrophication Potential for Terrestrial Ecosystems	X		
Eutrophication Potential for Marine Ecosystems	X		
Water Depletion		X	
Land Use and Land Change	X		
Biodiversity Loss	X		
Noise Pollution			X
Soil Quality Degradation			X
Thermal Pollution			X
Groundwater Contamination			X

4. LCA Simulation

4.1. LCA Software Considered

Two software platforms, SimaPro and GREET, were selected for this Life Cycle Assessment (LCA) analysis. SimaPro stands out for its detailed LCA capabilities, including a rich database such as Eco-invent and support for various impact assessment methods, including Eco-Indicator, EDIP, EPD, ReCiPe, and CML. This set of capabilities positions it alongside other leading LCA software like GaBi Pro and OpenLCA, enabling the direct computation of environmental impacts to evaluate the effects on the environment and human health. Its industry-leading status is bolstered by its robust database.

GREET, in contrast, is a freely available software tool developed by the Argonne National Laboratory with support from the U.S. Environmental Protection Agency. It distinguishes itself with customizable LCA features, particularly in presenting results as actual emissions for each life cycle stage, and it facilitates a comparative, detailed analysis of different recycling methods in this application. When used together, SimaPro and GREET provide a comprehensive view of the entire LCA process, enhancing the accuracy of assessments regarding the impact of recycling EV batteries on the environment and human health.

4.2. SimaPro

The original SimaPro software was released in 1990. It is a leading software tool for Life Cycle Assessments (LCAs) and is widely used in industry, consulting, and academia. It offers comprehensive LCA capabilities, extensive environmental impact databases like Eco-invent, and supports multiple impact assessment methods such as ReCiPe and CML. Its flexibility allows for customized studies and scenario analyses to be conducted, and it also facilitates collaboration and detailed reporting. Additionally, SimaPro can be integrated with other tools for advanced analyses, making it a valuable asset for evaluating the environmental impact of products and services, leading to potential process modifications for impact reduction.

To model an EV battery's life cycle using SimaPro, the nickel–cobalt–manganese (NCM) chemistry was chosen as a representative of the current supply leader. The assessment used the battery composition shown in Table 2.

Table 2. NCM battery composition.

Mineral	Cell Part	Average Content in kg	Content % of Total
Graphite	Anode	52	28.1%
Aluminum	Cathode, Case, Current Collectors	35	18.9%
Nickel	Cathode	29	15.7%
Copper	Current Collectors	20	10.8%
Steel	Case	20	10.8%
Manganese	Cathode	10	5.4%
Cobalt	Cathode	8	4.3%
Lithium	Cathode	6	3.2%
Iron	Cathode	5	2.7%
Total		**185 kg**	**100%**

An Assembly, sourced from SimaPro's Eco-invent library, was created within the SimaPro software to simulate the battery. Because the library did not allow for an exact duplication of materials, as described in Table 1, material equivalents for some components were selected and are shown in Table 3.

Table 3. SimaPro battery assembly.

EV Battery Materials	Equivalent
Anode, lithium-ion battery, graphite, at plant	Graphite
Nickel, 99.5%, at plant	Nickel
Cathode, copper, primary copper production	Copper
Steel, converter, chromium steel 18/8, at plant	Steel
Cathode, lithium-ion battery, lithium manganese oxide, at plant	Lithium and Manganese
Cobalt, at plant	Cobalt
Aluminum alloy, AlMg$_3$, at plant	Aluminum
Iron-nickel-chromium alloy, at plant	Iron

SimaPro enables the integration of production process impacts into the final product analysis. In the case of this assembly, focus was exclusively placed on the battery manufacturing process. With New Jersey used as the benchmark location for this study and considering that natural gas constitutes the primary energy source in the stat (accounting for 46% of energy production [19]), the assumptions were made based on the premise that all of the energy utilized in the battery production facility is derived from natural gas. According to Kim et al. [20], energy use for cell production and battery pack manufacturing amounts to 1500 MJ/kWh, which equates to 28 kg/kWh of natural gas. This amount was divided equally between two processes in SimaPro, with the first being energy for factory operation and the second being energy for machine operation, with 14 kg/kWh of natural gas each. The difference between the energy spent on machine operations and factory operations lies in their scope. Energy used in machine operations is specific to the power consumed by the production equipment and machinery during their active use. In contrast, energy spent on factory operations is more comprehensive, covering all energy usage within the factory. This broader scope includes essential facilities like lighting, heating, cooling, and ventilation, encompassing the overall operational energy requirements of the factory environment. For the disposal scenario, because of the limitations inherent in the available library data, only incineration was considered as a recycling option.

As mentioned previously, for the impact assessment analysis of this assembly, the ReCiPe Endpoint (H) V1.06/World ReCiPe H/H method was considered, which is SimaPro's most comprehensively used method. The impact categories that are utilized in this methodology target 12 of the 19 impact categories of interest that were discussed earlier, with Global Warming Potential, Cumulative Energy Demand, Water Depletion, Noise Pollution, Soil Quality Degradation, Thermal Pollution, and Groundwater Contamination not being accounted for in this particular SimaPro approach.

The SimaPro analysis showed that nickel, copper, and graphite are the primary contributors to environmental impacts during battery production. This important environmental footprint aligns with the usage of these raw materials in battery manufacturing, where graphite is the most used material, followed by nickel and then copper. The impact dominance of these materials is further explained by the environmentally detrimental methods of open-pit and strip mining that are commonly used for their extraction.

In the normalized results for the battery, Human Toxicity emerged as the most significant environmental impact, followed by Particulate Matter Formation, Fossil Fuel Depletion, and Climate Change Human Health. These impacts are largely due to the environmentally negative practice of open-pit mining that is employed in extracting these minerals. Open-pit mining in general leads to deforestation, habitat destruction, and soil erosion, and it leaves excavated sites barren, often without significant efforts to restore the lost vegetation. Additionally, the blasting frequently used during mining generates fine dust that also poses serious health risks. For example, South Africa's mining sector reaches up to ten times the emergency threshold defined by the World Health Organization, with 2500–3000 cases of

tuberculosis per 100,000 individuals, due in part to high levels of particulates in mining operations [21]. As a result of the open-air open-pit mining operations, fine dust, a form of particulate matter, cannot be effectively contained and destroyed.

An examination of the environmental impacts of incineration relative to battery manufacturing revealed that the impacts of manufacturing significantly outweigh those of incineration. The presence of baghouses in incineration plants effectively mitigates particulate matter emissions. These systems work by pulling in air that is laden with particles, filtering these particles out, and then either releasing clean air back into the environment or reusing it within the plant. However, the primary environmental concern with incineration lies in its contribution to climate change, primarily through the emission of greenhouse gases, which remains a challenge despite particle filtration.

Lastly, it is crucial to acknowledge a key limitation of this study: the reliance on SimaPro's libraries that were last updated in 2010. This constraint not only limits the functionalities available in the software but also affects the currency and temporal relevance of the information generated. So, while trends can be identified, the precise delineation of impacts cannot be obtained using this database.

4.3. Using GREET

GREET (Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation) is another LCA software tool, which was developed by the Argonne National Laboratory of the U.S. Department of Energy. First released in the mid-1990s, GREET was designed to evaluate the energy and environmental impacts of various vehicle technologies and transportation fuels over their entire life cycles. The generated model provides a comprehensive analysis of various factors, including energy consumption, greenhouse gas emissions, and air pollution. GREET is widely used for research and policy analysis, helping to inform decisions in transportation, energy policy, and environmental impact assessments. Its regular updates and enhancements have made it a pivotal tool in understanding the complex interactions between transportation technology and environmental outcomes.

In this research, two electric vehicles were considered: the Tesla Model 3, with a battery weight of 480.8 kg, and the Nissan Leaf, with a battery weight of 303 kg. Utilizing the GREET software V2, these vehicles were modeled based on the EV300—Electricity (Type 1 Li-Ion/NMC111 Conventional Material) vehicle template from GREET's library. A key feature of GREET is its ability to customize the electricity mix used for charging the vehicles. For this analysis, the electricity composition specific to New Jersey was applied, as depicted in Figure 1. This composition is based on the data provided by the EIA [19].
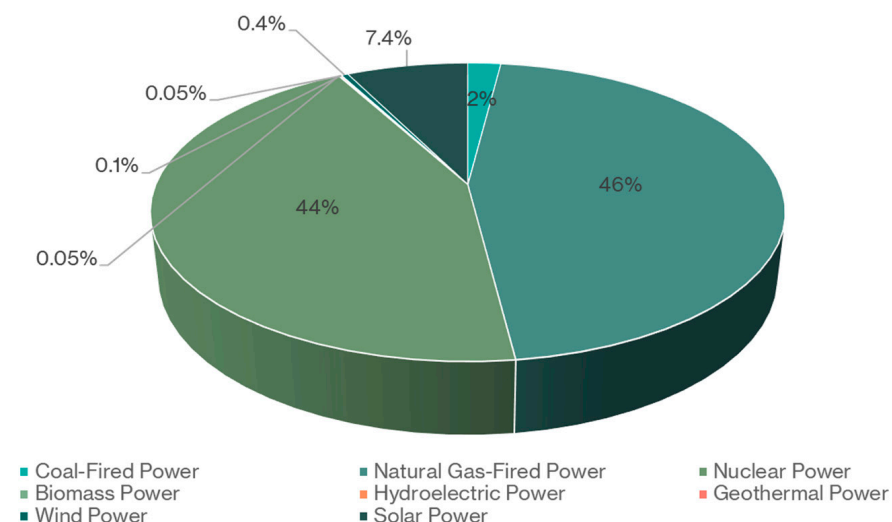
**Figure 1.** Energy distribution in New Jersey.

When analyzing the results from GREET, only variables of interest for this situation are, namely disposal and recycling and battery assembly and manufacturing. These factors will be used here to illustrate the differences in impacts between producing a new battery from raw materials and those generated by producing a battery using recovered materials obtained by battery recycling. The results from GREET are displayed across twenty-three columns, each representing different aspects of environmental impact and energy use related to transportation. A brief description of each column is provided as follows:

1. **Total Energy (J/mi):** This measures the total energy consumed per mile, encompassing all energy sources.
2. **Fossil Fuel (J/mi):** This indicates the amount of energy derived from fossil fuels that is used per mile.
3. **Coal Fuel (J/mi):** This shows the energy from coal used per mile.
4. **Natural Gas Fuel (J/mi):** This represents the energy obtained from natural gas used per mile.
5. **Petroleum Fuel (J/mi):** This denotes the energy from petroleum products used per mile.
6. **Renewable (J/mi):** This represents the amount of renewable energy used per mile.
7. **Biomass (J/mi)**: This represents energy derived from biomass used per mile.
8. **Nuclear (J/mi):** This represents energy from nuclear sources used per mile.
9. **Non-Fossil Fuel (J/mi):** This represents the energy from non-fossil sources used per mile.
10. **VOC (kg/mi):** This represents the emissions of volatile organic compounds per mile.
11. **CO (kg/mi):** This represents carbon monoxide emissions per mile.
12. **NOx (kg/mi):** This represents nitrogen oxide emissions per mile.
13. **PM10 (kg/mi):** This represents particulate matter (10 μm or less) emissions per mile.
14. **PM2.5 (kg/mi):** This represents fine particulate matter (2.5 μm or less) emissions per mile.
15. **SOx (kg/mi):** This represents sulfur oxide emissions per mile.
16. **CH_4 (kg/mi):** This represents methane emissions per mile.
17. **CO_2 (kg/mi):** This represents carbon dioxide emissions per mile.
18. **N_2O (kg/mi):** This represents nitrous oxide emissions per mile.
19. **BC (kg/mi):** This represents black carbon emissions per mile.
20. **POC (kg/mi):** This represents primary organic carbon emissions per mile. (Basically, these are combustible carbon compounds that can be filtered from emissions.)
21. **CO_2_Biogenic (kg/mi):** This represents biogenic carbon dioxide emissions per mile. (Basically, this is CO_2 derived from biological sources other than fossil fuels.)
22. **GHG-100 (kg/mi):** This represents greenhouse gas emissions with a 100-year global warming potential per mile.
23. **GHG-20 (kg/mi):** This represents greenhouse gas emissions with a 20-year global warming potential per mile.

The results yielded from the GREET software V2 for the Tesla Model 3 are shown in Table 4. The data presented in both Table 4 and Figure 2 clearly indicate that manufacturing new (virgin) batteries demands significantly more energy compared to using recycled material in existing batteries. Here, a comparison is made between the production of a virgin battery with the sum of the impacts of the recycling process and the manufacture of a new battery using recovered materials. Specifically, the energy consumption for manufacturing virgin batteries is eight times higher than that based on recycling, emphasizing a substantial disparity between the two processes. This finding highlights the critical importance of investing in recycling facilities, which can lead to considerable energy savings with resulting reductions in environmental impacts. Considering the energy sources in New Jersey, where energy consumption (75.1 TWhrs) surpasses production (65.3 TWhrs), as reported by the U.S. Department of Energy in 2016 [22], and with the prospect of rising energy prices as a result of meeting escalating electricity demands, it becomes increasingly essential to explore innovative approaches for reducing energy consumption.

Table 4. Tesla Model 3—energy emissions.

Name	Disposal and Recycling	Virgin Battery
Total Energy (J/mi)	53,888	434,050
Fossil Fuel (J/mi)	44,512	379,658
Coal Fuel (J/mi)	1041	65,383
Natural Gas Fuel (J/mi)	43,417	260,341
Petroleum Fuel (J/mi)	54	53,934
Renewable (J/mi)	1470	23,001
Biomass (J/mi)	41	1293
Nuclear (J/mi)	7906	31,390
Non-Fossil Fuel (J/mi)	9376	54,391
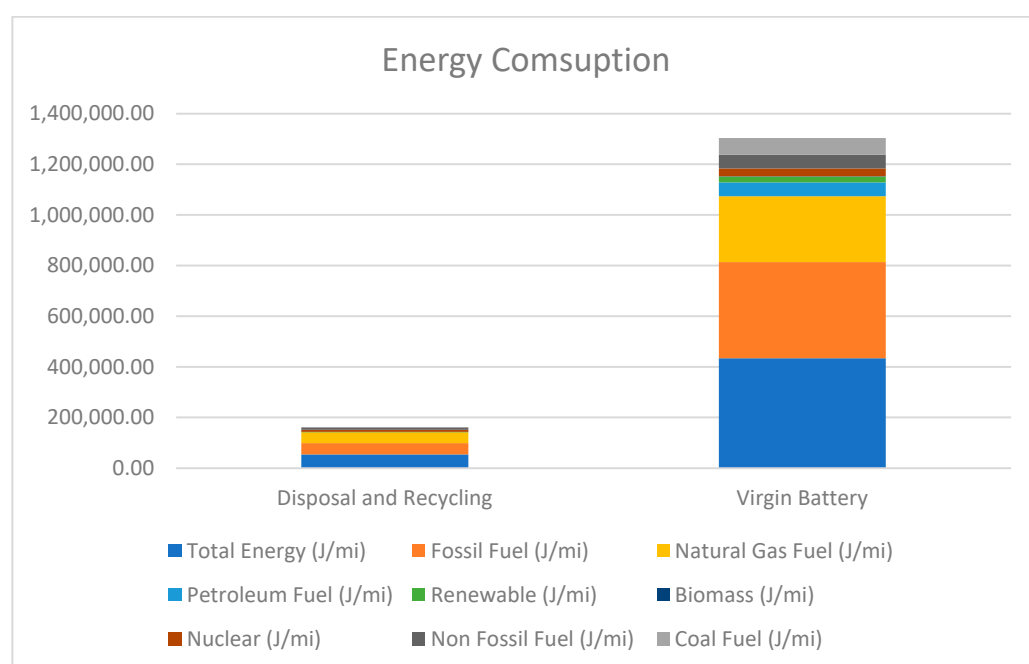
Figure 2. Tesla Model 3 Energy Consumption—recycling vs. virgin battery.

When looking at the energy consumption for manufacturing a battery using virgin raw material versus the energy consumption when using recycled Nissan Leaf batteries, it can be seen that the data paint a very similar story to that seen with the Tesla Model 3 (see Table 4 and Figure 2), with the total energy needed to produce a new battery also being also eight times greater than that needed for raw materials obtained by battery recycling, as shown in Table 5 and Figure 3.

Regarding the environmental emissions of both cars, starting with the Tesla Model 3, as can be seen in Table 6 and Figure 4 the environmental emissions from virgin battery manufacturing far outweigh the total emissions produced by using raw material obtained from battery recycling. One important aspect to note is that CO_2, GHG-20, and GHG-100 are greater than all other impact categories listed, as can be clearly seen in Figure 4. Moreover, for all three categories, virgin battery manufacturing produces about 10 times more emissions than recycling, further highlighting the benefits that the recycling process has.

Table 5. Nissan Leaf—energy emissions.

Name	Disposal and Recycling	Virgin Battery
Total Energy (J/mi)	34,037.09	275,611.2
Fossil Fuel (J/mi)	28,114.89	241,131.1
Coal Fuel (J/mi)	657.43	413,38.32
Natural Gas Fuel (J/mi)	27,423.05	165,701.8
Petroleum Fuel (J/mi)	34.41	34,091
Renewable (J/mi)	928.48	14,554.24
Biomass (J/mi)	26.21	817.8613
Nuclear (J/mi)	4993.72	19,925.82
Non-Fossil Fuel (J/mi)	5922.21	34,480.06
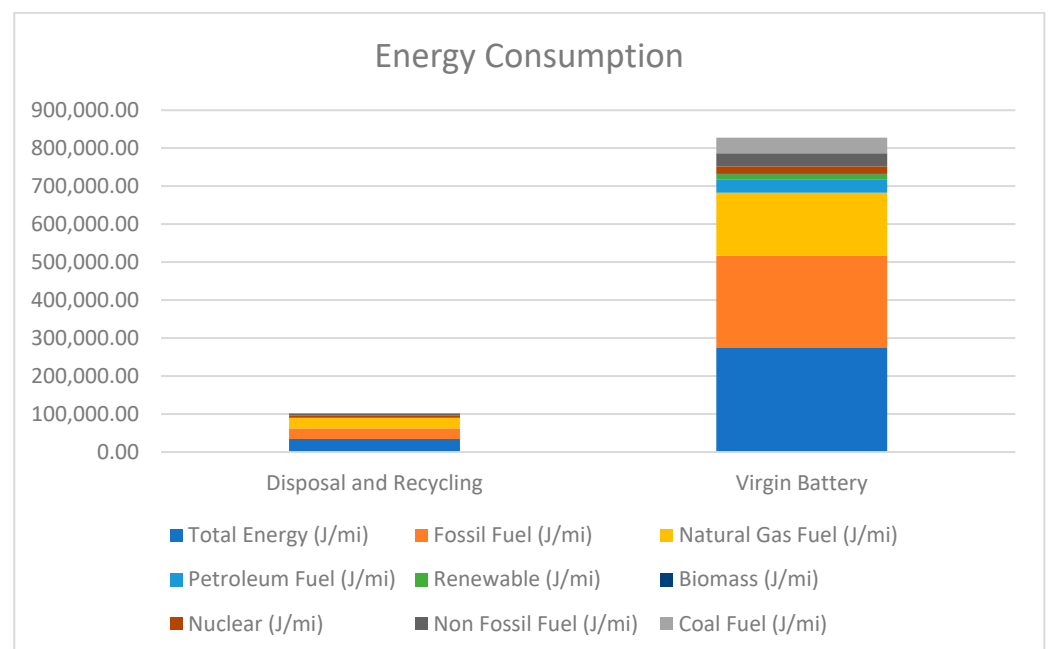
Figure 3. Nissan Leaf Energy Consumption —recycling vs. virgin battery.

Table 6. Tesla Model 3—environmental impacts.

Name	Disposal and Recycling	Virgin Battery
VOC (kg/mi)	6.74×10^{-6}	7.10×10^{-6}
CO (kg/mi)	1.91×10^{-6}	4.70×10^{-5}
NOx (kg/mi)	2.57×10^{-6}	3.11×10^{-5}
PM10 (kg/mi)	3.87×10^{-7}	1.39×10^{-5}
PM2.5 (kg/mi)	2.59×10^{-7}	4.48×10^{-6}
SOx (kg/mi)	5.36×10^{-7}	7.23×10^{-5}
CH_4 (kg/mi)	7.88×10^{-8}	1.32×10^{-4}
CO_2 (kg/mi)	0.002533	0.0242
N_2O (kg/mi)	6.39×10^{-6}	7.06×10^{-7}
BC (kg/mi)	1.77×10^{-8}	2.55×10^{-7}

Table 6. *Cont.*

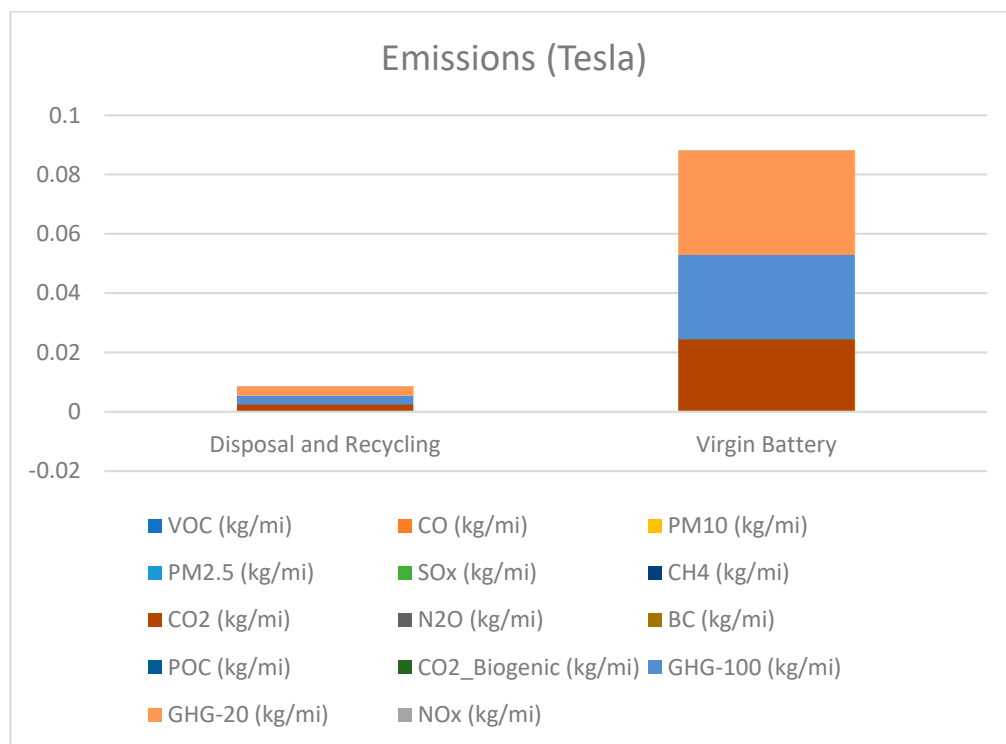| Name	Disposal and Recycling	Virgin Battery
POC (kg/mi)	6.77×10^{-8}	6.00×10^{-7}
CO_2_Biogenic (kg/mi)	-3.81×10^{-6}	-1.17×10^{-4}
GHG-100 (kg/mi)	0.0028	0.0284
GHG-20 (kg/mi)	0.003267	0.0353

Figure 4. Tesla Model 3 Emissions—recycling vs. virgin battery.

The results obtained for the Nissan Leaf model are very similar to those obtained for the Tesla Model 3, as can be seen in Table 7 and Figure 5.

A notable limitation of the methodology used in this study is related to how GREET handles the computation of disposal and recycling. The software automatically depends on its internal database to calculate ADR (Assembly, Disposal, and Recycling). To simplify the conducted analysis, this research assumed an equal distribution across these three components to isolate disposal and recycling. However, this approach restricts the ability to modify or specifically control certain parameters within these calculations. This constraint becomes particularly challenging when attempting to incorporate and analyze specific recycling processes, such as hydrometallurgy or pyrometallurgy, within GREET. To address this limitation, it was assumed that the GREET database accurately represents vehicle materials for recycling and disposal. This simplification helped to navigate the software's constraints, enabling this research to proceed by focusing on an equal distribution across ADR components. However, it is clear that a different approach would be required to assess differences among the specific processes that might be used for EV battery recycling.

Table 7. Nissan Leaf—environmental impacts.

Name	Disposal and Recycling	Virgin Battery
VOC (kg/mi)	6.04×10^{-7}	4.50×10^{-6}
CO (kg/mi)	2.46×10^{-6}	2.98×10^{-5}
NOx (kg/mi)	3.33×10^{-6}	1.98×10^{-5}
PM10 (kg/mi)	1.81×10^{-7}	8.81×10^{-6}
PM2.5 (kg/mi)	1.76×10^{-7}	2.84×10^{-6}
SOx (kg/mi)	5.76×10^{-7}	4.57×10^{-5}
CH_4 (kg/mi)	1.00×10^{-5}	8.36×10^{-5}
CO_2 (kg/mi)	0.0031	0.0154
N_2O (kg/mi)	9.06×10^{-8}	4.48×10^{-7}
BC (kg/mi)	2.66×10^{-8}	1.62×10^{-7}
POC (kg/mi)	7.88×10^{-8}	3.81×10^{-7}
CO_2_Biogenic (kg/mi)	-1.90×10^{-6}	-7.41×10^{-5}
GHG-100 (kg/mi)	0.0034	0.018
GHG-20 (kg/mi)	0.0039	0.0224
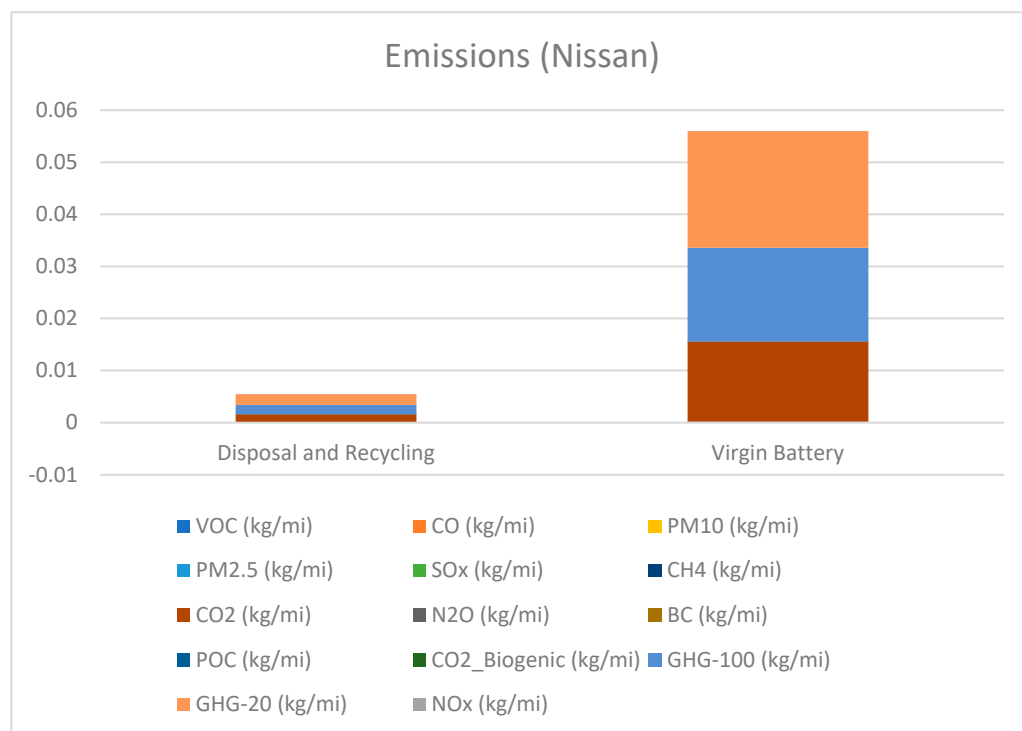
Figure 5. Nissan Leaf Emissions—recycling vs. virgin battery.

4.4. Pros and Cons of LCA Software

SimaPro V7 offered several advantages, primarily its automated generation of environmental impacts, which enables users to quantify various environmental aspects using a diverse range of methods and libraries. These methods include the ReCiPe method for global assessment and the CML 2 method tailored to the European market. This versatility allows researchers to focus on specific environmental aspects, such as Global Warming Potential, Acidification Potential, and the Eutrophication of Freshwater, among others. SimaPro also generates informative graphs and tree networks to visualize the results and

their breakdown, facilitating a deeper understanding of the environmental impacts. Furthermore, users can normalize the results to identify dominant environmental factors. SimaPro's capacity to create and compare different assemblies and LCA systems is another valuable feature. Table 8 shows a comparison of SimaPro with GREET.

Table 8. Comparison between SimaPro and GREET.

Feature/Aspect	SimaPro	GREET
Environmental Impact Generation	Automated generation of environmental impacts using diverse methods and libraries	Offers actual emission data including total energy expenditure and specific emissions (e.g., CO_2, CH_4, and VOCs)
Methodologies	Includes ReCiPe and CML 2 methods, which are suitable for global and European market assessments	Users can tailor entire LCA model, including energy sources, manufacturing processes, and recycling methods
Focus Areas	Focuses on Global Warming Potential, Acidification Potential, Eutrophication, etc.	Customizable focus on various aspects of lifecycle, including raw material extraction and disposal
Visualization Tools	Provides graphs and tree networks for visualizing and understanding environmental impacts	Lacks advanced visualization tools; relies on raw data presentation
Result Normalization	Enables normalization of results to identify dominant environmental factors	Does not inherently provide normalization of results for environmental impact assessment
Database Timeliness	Limited by timeliness of its database, with no user access to update it with latest data	Allows for custom input, adapting to latest data and techniques in rapidly evolving fields
Customization	Limited customization in creating and comparing different assemblies and LCA systems	Exceptional customizability in energy mixes, manufacturing processes, transportation, and disposal techniques
Quantification of Impacts	Effective at quantifying environmental impacts relevant to human health and ecosystems	Requires external methods (like APEEP Model) to quantify impacts on human health and environment
Suitability	Versatile for researchers focusing on specific environmental aspects	Suitable for users needing high customizability and detailed emission data

However, SimaPro has some major drawbacks due to its heavy reliance on the current version of its database because users have no access to updates or later versions, and it also provides a comparison or offers ratios of different environmental categories and not actual data. These limitations become particularly problematic in rapidly evolving fields, such as recycling, where new data and techniques regularly emerge.

In contrast, GREET stands out due to its exceptional customizability. Users can specify energy sources, create unique energy mixes, simulate various manufacturing processes, define transportation modes and methods, and customize recycling and disposal techniques. GREET also provides an extensive library of pre-existing products that serve as starting points for customization. The entire LCA model, from raw material extraction to manufacturing and recycling, can be tailored to specific needs.

Nonetheless, GREET's main disadvantage lies in how it presents results. Unlike SimaPro, GREET offers actual emission data for the entire process, including total energy expenditure and emissions like carbon dioxide (CO_2), methane (CH_4), and volatile organic compounds (VOCs), among others. This format is less useful when quantifying environmental impacts, especially those related to human health. Users are compelled to rely on external methods like the APEEP (Air Pollution Emission Experiments and Policy) Model to transform these emissions into quantifiable environmental impacts [23].

4.5. Qualitative Assessment

Software applications, such as GREET and SimaPro, are well-suited for analyzing environmental impacts in areas with an abundance of quantitative data, including data on Acidification Potential and Ozone Depletion Potential. These tools rely on extensive and comprehensive databases to model and assess the environmental footprints of various processes and products. However, for factors such as Noise Pollution, Soil Quality Degradation, Thermal Pollution, and Groundwater Contamination, the variability and scarcity of data across different projects pose significant challenges. In such cases, the standardized databases and algorithms used by these software applications may not provide accurate or relevant insights, rendering their application less effective. Despite this, the qualitative assessments these software approaches can provide yield insights into the environmental impacts of the products and services being studied. Consequently, the subsequent section will undertake a qualitative analysis to evaluate these factors' environmental effects.

While there are no specific data when it comes to noise pollution in the context of EV battery manufacturing and recycling, results can be inferred from information about car manufacturing. Comparing the noise pollution from the production of new cars to the recycling of old ones requires evaluating the intensity and duration of noise generated by each process. The manufacturing process of new cars involves heavy machinery for metal pressing, welding, and assembly, which can generate noise levels up to 85–90 decibels (dB) or more depending on the specific operations and machinery used [24]. This process is continuous, leading to sustained noise pollution. On the other hand, the recycling of cars involves dismantling, shredding, and reprocessing materials, with noise levels potentially reaching up to 123 dB during the most intensive operations like metal shredding [25]. However, these activities may not be as continuous as car manufacturing, potentially resulting in less sustained, but more intense, periods of noise pollution. The impact of noise also heavily depends on the proximity of these activities to residential areas and the presence and effectiveness of noise mitigation measures. While both processes generate significant noise, manufacturing might contribute to more consistent noise pollution due to its continuous nature, whereas recycling operations can have peak noise levels that are higher during specific activities but might not be as constant.

The impact of producing new LIBs on soil quality versus the impact of making them using recycled materials involves different aspects of environmental interaction. LIB manufacturing using virgin supplies entails extensive resource extraction, including mining for metals and minerals like lithium and cobalt, which can significantly degrade soil quality. These activities lead to soil erosion, heavy metal contamination, and changes in soil composition due to the disposal of industrial waste [26]. On the other hand, LIB recycling can also affect soil quality, primarily through the potential leakage of hazardous substances such as PFAS, lead, mercury, and cadmium during the dismantling process [27]. However, recycling aims to reduce waste and reuse materials, which can mitigate some soil degradation by decreasing the demand for new raw materials and minimizing the footprint of waste disposal [28]. While both processes have the potential to impact soil negatively, the scale and nature of their impacts differ. Manufacturing new LIBs has a broader environmental footprint that includes the degradation of soil quality at resource extraction sites and around manufacturing plants [29]. In contrast, the impact of recycling is more localized and can be mitigated through proper waste management practices and environmental safeguards. Overall, EV battery recycling, when conducted responsibly, tends to have a less detrimental impact on soil quality compared to the extensive soil degradation associated with the resource extraction and waste production from manufacturing new batteries.

When comparing the thermal pollution associated with lithium-ion battery (LIB) manufacturing versus LIB recycling, it is important to consider the energy-intensive processes involved in both. Manufacturing LIBs from new materials is significantly more energy and heat-intensive compared to producing them from recycled materials, leading to higher thermal pollution. This is because new battery production involves energy-consuming stages, such as material extraction and processing, while recycling reduces the need for these

processes by reusing materials. Although recycling also requires energy, particularly for dismantling and chemical treatment, it generally consumes less energy than manufacturing, resulting in lower thermal pollution [30,31]. Consequently, while both manufacturing and recycling LIBs contribute to thermal pollution, the environmental impact of new battery production from virgin raw materials is considerably greater than that using raw materials obtained from battery recycling, highlighting the benefits of recycling in mitigating thermal pollution.

Groundwater contamination risks differ markedly between the production and recycling of lithium-ion batteries (LIBs). During the production phase, the extraction and processing of raw materials such as lithium, cobalt, and nickel can lead to the release of toxic chemicals into the environment, potentially contaminating groundwater sources. These activities often involve the use of hazardous chemicals for metal extraction and processing, which, if not properly managed, can seep into soil and groundwater [32]. On the recycling side, while there is a potential for groundwater contamination through the improper handling and disposal of battery components, advanced recycling processes aim to minimize this risk by safely extracting valuable materials and treating waste products. Recycling facilities are increasingly adopting measures to prevent the leakage of hazardous substances, thus mitigating the risk of groundwater contamination. However, the effectiveness of these measures depends on the particular recycling technologies used and the regulatory frameworks in place. The U.S. Environmental Protection Agency (EPA) has provided guidance on how to handle hazardous waste from lithium-ion batteries under the Resource Conservation and Recovery Act (RCRA) [33]. Overall, while both the production and recycling of LIBs pose risks to groundwater quality, the managed environment of recycling processes, when conducted according to best practices, tends to present a lower risk of contamination compared to the extensive environmental impact associated with raw material extraction and processing as a part of battery production.

Therefore, the qualitative assessment of these factors is aligned with what has been found quantitatively. Recycling decreases the environmental costs associated with the production of virgin batteries from raw material extraction to manufacturing. However, a qualitative assessment adds another layer to this analysis, highlighting how manufacturing can disrupt and reduce the quality of life of citizens, with more pollution that they are forced to deal with, as well as more polluted water and soil, which can have detrimental effects on the health of these citizens, especially children. Hence, this qualitative analysis further supports the use of recycling.

5. Life Cycle Cost Analysis

A Life Cycle Cost Analysis (LCCA) plays a pivotal role in the realm of electric vehicle (EV) battery recycling. By meticulously evaluating the costs associated with the entire life cycle of battery recycling, an LCCA provides invaluable insights into the economic feasibility and sustainability of the recycling process. The ultimate objective of employing an LCCA in this context is to accurately determine the cost of recycling EV batteries. This, in turn, is crucial for calculating the expense involved in manufacturing new batteries from recycled materials. Such an analysis is essential not only for understanding the economic implications of recycling, but also for promoting more sustainable and cost-effective developments in the rapidly evolving EV industry. It helps in making informed decisions that balance environmental benefits with financial viability, thereby contributing to a more sustainable future in the automotive sector.

In this research, the cost of recycling electric vehicle batteries was explored and compared to the cost of new batteries. The price of a new Tesla Model 3 battery is currently USD 15,800, and a Nissan Leaf battery is priced at USD 6500 [34]. To estimate the recycling costs, two methods were employed. The first method, proposed by the Argonne National Laboratory (the developers of the GREET software V2) in 2000 [35], initially set the recycling cost at USD 10 per kilogram of battery. This cost has since decreased to USD 5 per kilogram. This reduction in cost can be attributed to advancements in recycling technologies, increased

efficiency in the recycling process, and economies of scale with the growth in the volume of batteries to be recycled. As illustrated in Figure 6, recycled raw material proves to be substantially more economical than purchasing virgin raw materials for the production of new batteries. Specifically, for a Tesla battery, the acquisition of recycled materials is six times less expensive than obtaining virgin materials, and for a Nissan Leaf battery, the differential is four times cheaper.
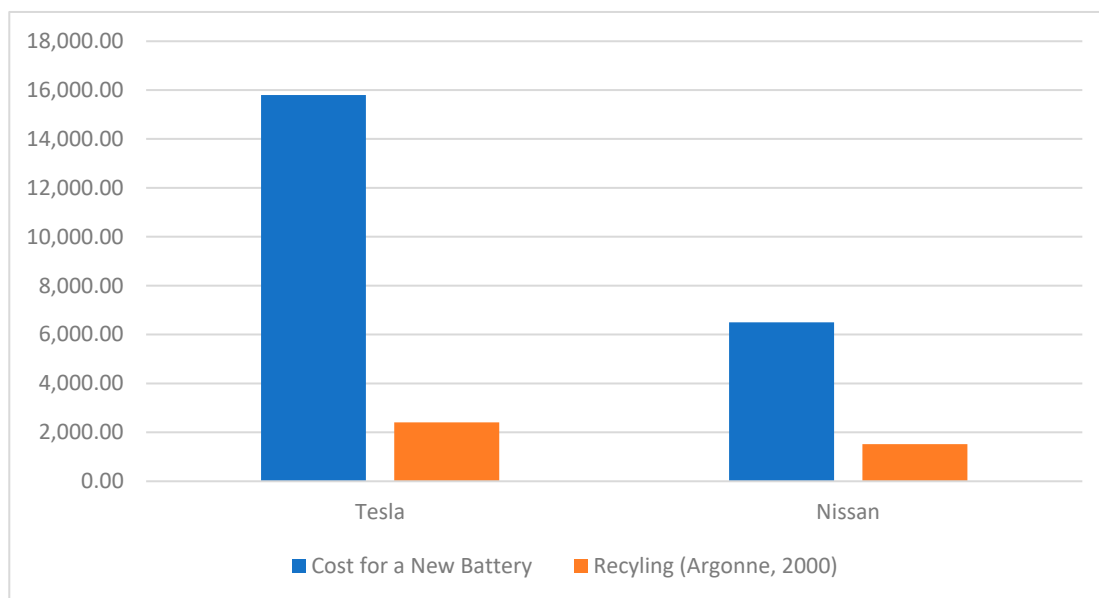
Figure 6. Creating new batteries vs. recycling.

The second approach to estimating battery recycling costs is derived from a 2019 report by the Argonne National Laboratory [36]. According to this report, the current total cost for recycling lithium batteries is approximately USD 26 per kWh. This includes a recycling fee of USD 10 per kWh, a charge applied by recyclers for the collection, processing, and recovery of materials from spent batteries. Figure 7 contrasts the price of a new battery (blue bar) to that of a recycled battery, which was calculated using the formula provided above, developed by the Argonne Laboratory (orange bar). Based on this pricing, the cost to produce a Tesla Model 3 battery is calculated to be USD 1692, while that for a Nissan Leaf battery is USD 1066. These figures represent a significant reduction compared to the cost of manufacturing batteries using virgin raw materials. This further suggests that recycling should be recognized as a more cost-effective option when comparing the results to what is presented in Figure 6, which is likely due to advancements in recycling technology and processes becoming more streamlined and efficient over time, coupled with increased investments in the field. This trend reinforces the potential for even lower manufacturing costs in the future when using recycled materials.

Patrick Curran, a GLG Network Member and the CEO of Lithium Recycling Systems, has provided insightful data on the economics of battery recycling [37]. He noted that processing one metric ton of incoming batteries costs around USD 90. From this process, the black mass obtained—a combination of nickel, manganese, and cobalt oxides with carbon—can be sold for approximately USD 300 or more. Additionally, the metallic components, mainly copper and aluminum found in the batteries, can fetch around USD 500. These figures point to recycling as not only a profitable venture for investors, but also as a cost-effective component of battery production. Recycling batteries to create new batteries is substantially less expensive than using virgin materials, as demonstrated in Figure 8. This highlights the economic advantage and potential savings achievable through the use of recycled materials in the battery manufacturing industry. The analysis performed here is rudimentary, and the economics are likely slightly more complicated for the following

reasons. Assuming the same level of purity and regardless of the source, the materials—lithium, cobalt, copper, etc.—will be sold at market value. So, if the organization that is responsible for collecting spent batteries and processing them to recover the materials also makes the replacement battery, then they will have larger cost savings. Otherwise, if they sell the materials to a manufacturer, they will make a profit, but the price of the manufactured battery will be comparable to that of the battery made from virgin materials. A counter to this argument is the distinct possibility that the recovery of these materials will increase the supply and, as a result, the cost of the materials will decrease, resulting in some lowering of the cost of a battery.
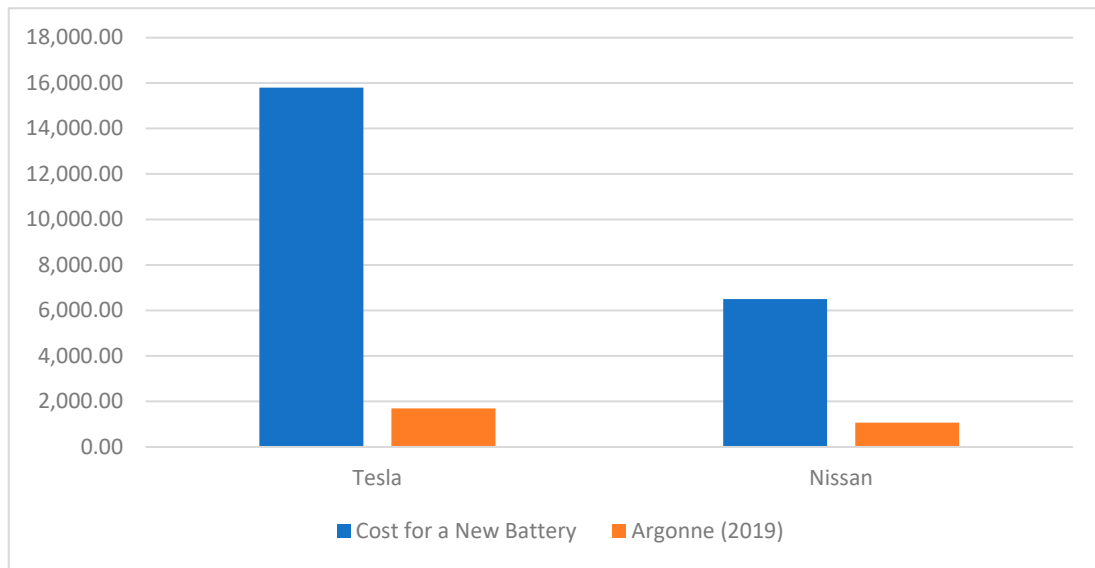
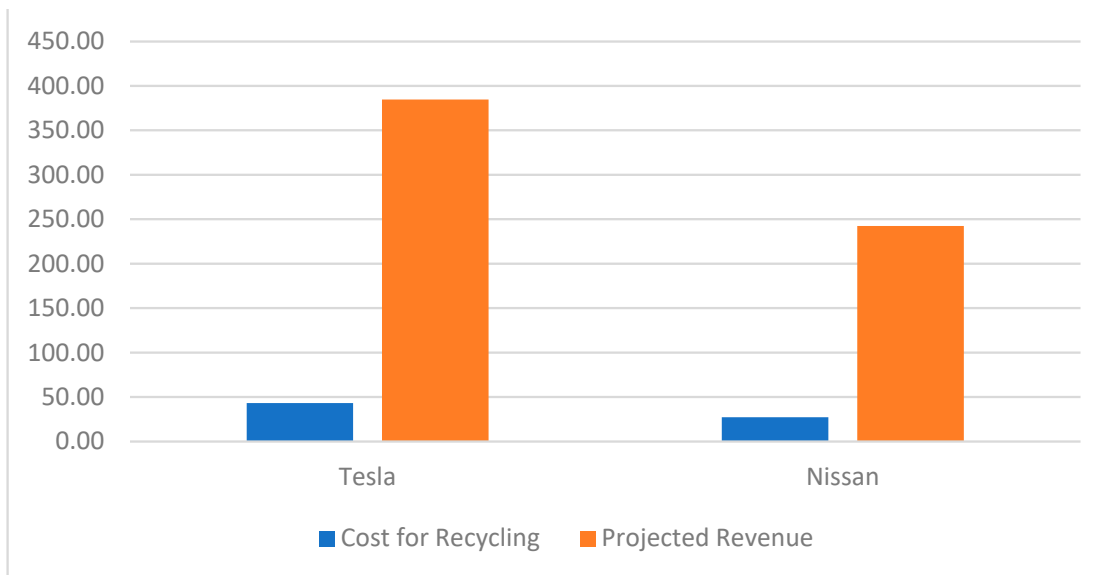**Figure 7.** Creating new batteries vs. recycling.

Figure 8. Recycling cost vs. projected revenue.

6. Discussion

The findings presented in this study advance the field of electric vehicle (EV) battery recycling through a detailed comparison of the Life Cycle Assessment (LCA) results obtained using the SimaPro V7 and GREET V2 software, with an emphasis on the environmental and economic implications of recycling nickel–cobalt–manganese (NCM) chemistry batteries.

This analysis is particularly valuable in light of recent research efforts that have similarly employed these tools to assess the sustainability of EV batteries. Notably, the findings presented here reveal a significant reduction in environmental impact and energy consumption through the use of recycled materials when compared to virgin battery production. A similar observation was made by Harper et al. [38] in their comprehensive review on the life cycle environmental impacts of lithium-ion batteries. However, where Harper et al. [38] underscore the challenges in quantifying the specific contributions of battery components to overall environmental degradation, this study leverages the updated databases and methodologies of SimaPro and GREET to offer a more comprehensive analysis related to materials such as nickel, copper, and graphite.

Moreover, the economic analysis presented in this research, highlighting the cost-effectiveness of recycling when it comes to new battery production, aligns with the findings of Gaines and Cuenca [35,39], who demonstrated the potential for considerable cost savings and revenue in battery recycling. Nevertheless, this study takes a deeper look at these economic impacts by integrating a Life Cycle Cost Analysis (LCCA) to quantify the profitability of recycling operations, hence providing a more detailed understanding of the economics within which these processes occur.

In contrast to Wang et al. [40], who highlighted the technical efficiencies of various recycling processes without fully addressing their environmental or economic contexts, this research adopted a more holistic approach. By doing so, it not only reaffirmed the technical feasibility of battery recycling, as demonstrated by Wang et al. [40], but also broadened the discourse with a thorough environmental and economic analysis. This comprehensive perspective is crucial for stakeholders aiming to optimize both the sustainability and profitability of EV battery recycling.

It is also important to contextualize the findings reported in this study within the limitations acknowledged, particularly when it comes to the reliance on outdated databases and the simplifications inherent in economic analyses. These limitations reflect the broader challenges facing LCA studies in achieving both precision and applicability, as highlighted by Notter et al. [41] in their analysis of the environmental impacts of lithium-ion batteries. As such, this study contributes to the ongoing effort to refine LCA methodologies and data sources, offering a steppingstone towards more accurate and applicable guidelines in the context of the sustainability of EV battery recycling.

Also, the results presented in this research validate and extend the findings of existing research on the environmental and economic benefits of EV battery recycling. They also provide new insights through the application of updated LCA tools and methodologies. By doing so, this study not only reinforces the importance of recycling in mitigating the environmental footprint of EV batteries, but also clarifies the potential for recycling as a profit-generating business, thereby supporting the advancement of sustainable practices in EV battery management.

6.1. Economic Analysis of Recycling Technology

Material recycling is not only advantageous for the environment, but for the economy and society as well. The activities needed to locate, mine, and extract raw materials can be replaced with the use of recovered materials from used batteries. All of these activities need energy, destroy the surrounding landscape, and pollute the environment. Moreover, the search for raw materials has deep political and social implications, with minerals such as cobalt, copper, and lithium being the root causes for several human rights violations [42].

On the global stage, there is a significant push away from the traditional linear economy, where materials are manufactured, used, and then disposed, whereas with the circular economy, after disposal, the raw materials of a product are extracted, and new batteries are manufactured [43]. In Europe, waste management infrastructure is sufficiently advanced to allow for an almost complete collection of solid wastes [44]. However, after collection, there is a notable drop in the recycling of those collected materials. In fact, an EEA report [45] estimated that even when considering the most optimistic economic scenarios, recycled

materials from wastes constitute less than 0.5% of the European GDP, with recovered materials only representing 5% to 15% of the materials used in manufacturing and construction in most EU countries [46].

A total of 5.7 billion tons of material has been consumed by the EU economy to support its population's demand for goods and services in 2013, amounting to approximately EUR 400 billion [43]. The trend of increased consumption is expected to increase as the world population grows, with estimates suggesting an 800% increase in consumption by 2050 when compared to 1990's level [47]. Consequently, experts have asserted that unless the process in which raw materials are disposed of and recycled changes, the current stock of virgin material that is still unextracted will not be enough to support the needs of future generations [48], with around 100 billion tons of raw materials having entered the economy in 2020 alone [49].

On a more positive note, the transition towards a circular economy is expected to yield USD 500 billion in savings for the European economy [50], and it is estimated that it will create one million jobs in the recycling and remanufacturing industries [51]. From a strategic perspective, adopting the CE approach reduces a country's reliance on material imports, shielding it from potential supply disruptions and price volatility, as was seen during the COVID-19 pandemic [43,52].

LIB recycling fits perfectly in the context of a CE. LIBs are the technology of choice for electric and hybrid vehicles, and they can be re-used in the context of stationary energy storage solutions given that LIBs retain about 80% of their capacity at the end of their first use [53,54]. LIBs experience widespread usage in various private and industrial applications, including commercial electronics such as laptops and smartphones [55,56]. In fact, for EVs alone, the global demand for battery capacity is expected to increase from 120 GWh in 2019 to 1525 GWh in 2030 [57]. In addition, China is positioned as the largest EV market in the world and is the primary contributor to this increasing demand, which was made possible through a combination of market dynamics, governmental policies, and manufacturing capabilities [58]. Hence, a global push towards recycling is necessary.

However, the global recycling rate for LIBs is still less than 5% [59]. To tackle this problem and reduce the world's reliance on virgin materials, the CE approach suggests two strategies: recycling LIBs to recover raw materials such as lithium, cobalt, and manganese and re-using LIBs in stationary energy systems or other applications [60,61]. Additionally, innovative recycling technologies are poised to increase the efficiency of material recovery and reduce waste. Nonetheless, while there is a legislative push by policymakers to encourage circular economy implementation, challenges remain such as material losses and the need for further processing in order to reuse LIBs in different applications [61]. Additionally, there are also important technical and economical hurdles that prevent recycling technologies from achieving high recovery rates, as well as a lack of data with regard to reuse and remanufacturing technologies, which are needed in order to evaluate the usage of LIBs in secondary applications [62,63].

6.2. Political Motivations behind Recycling Adoption

The EV battery market is largely dominated by China in terms of production and recycling, which has sparked concerns by U.S. and European lawmakers, given the importance that LIBs have on the global stage. Indeed, China accounted for about 80% of global LIB production, and its EV sales neared six million in 2022. This dominance is the product of substantial investment by the Chinese government in the development of a reliable infrastructure that supports this level of production, in addition to significant investment in research and development efforts [64]. China is also the global leader when it comes to LIB recycling, with this market being expected to increase from USD 11 billion to USD 18 billion by 2028, which represents approximately the entirety of the recycling market [65].

Moreover, current trends suggest that China's role as a global leader in LIB production and recycling is assured for decades to come, with researchers estimating that China will reach lithium self-sufficiency from recycling by 2059, meaning it is way ahead of

competitors such as Europe and the U.S., which are poised to reach self-sufficiency by 2070 [66]. Additionally, researchers found that China will meet its demand for nickel and cobalt by 2045 and 2046, respectively, well before Europe and the U.S. [66,67].

Given the following, Western countries have to make significant efforts in order to overtake China as global leaders in the LIB space. In fact, the Inflation Reduction Act of the U.S., which was signed into law in 2022, includes several provisions that promote local EV recycling initiatives. This has prompted significant investments in companies, such as Ascend Elements and Redwood Materials, with the aims of reaching a closed-loop supply chain and reducing the U.S.'s reliance on Chinese imports [68]. On the other hand, China is taking measures to reinforce its lead, with several policies being implemented that aim to enhance research and set stringent recycling standards, opposing the efforts made by the U.S., which China has accused of being "anti-globalist" [69]. The aggressive implementation of these measures highlights the increasingly political nature of the recycling race, with the level of governmental support playing a crucial role in the trajectory of EV battery production and recycling [70].

6.3. The Specific Contributions of This Study

This study substantially advances the existing body of knowledge regarding the secondary use of lithium-ion batteries (LIBs), which, until now, primarily assessed the impacts at isolated environmental, societal, or economic levels. This research takes a novel approach by offering a holistic analysis that considers the combined downstream effects of LIB misuse, marking a pioneering effort in this field. Through the use of advanced analytical software, namely SimaPro V7 and GREET V2, this research quantifies environmental impacts in fifteen distinct categories. This comprehensive quantification not only provides a direct comparison with the environmental costs associated with manufacturing new batteries, but also clearly showcases the considerable environmental advantages of battery recycling.

Additionally, this study explores qualitative impact factors that are often overlooked due to the difficulty in quantifying them. These include noise and thermal pollution, as well as the degradation of soil and water quality, which significantly deteriorate living conditions. Furthermore, it is often the poorest and most marginalized communities that are disproportionately affected by those actions, as they tend to live closer to industrial sites [71], further exacerbating social inequalities.

Economically, this research outlines the viability of recycling as a profitable business, bolstered by current economic policies and geopolitical dynamics. The findings show that recycling not only has substantial economic benefits but also aligns with recent governmental fiscal incentives aimed at supporting domestic raw material production over imports. This aspect of the study underscores the strategic importance of recycling initiatives in strengthening local economies and reducing the dependency on foreign resources.

Overall, this expanded investigation shows a comprehensive picture of the multi-faceted impacts of LIB recycling. It equips stakeholders, policymakers, and the general public with a deeper appreciation of the benefits of recycling, encouraging broader support for sustainable practices. By providing a thorough analysis of both the quantifiable and qualitative effects, this research offers valuable insights that can lead to more informed decisions, fostering a more sustainable and equitable approach to battery use and recycling in the technological era.

7. Summary and Conclusions

The world must be ready to effectively handle the influx of end-of-life (EOL) electric vehicle (EV) lithium-ion batteries (LIBs). Effective management is crucial to mitigate the significant environmental and economic consequences associated with improper disposal. Recycling presents an optimal solution, enabling the reuse of materials, thereby reducing both the cost of new batteries produced from recycled LIBs and the emissions associated with raw material extraction. Conducting a Life Cycle Assessment (LCA) provides a detailed analysis of each stage in the battery's lifecycle from extraction to disposal. SimaPro

and GREET enabled the evaluation of emissions from both new and recycled batteries despite the differing presentation styles of the two software packages, and both indicated that recycling has reduced levels of environmental impacts compared with the use of new materials.

Additionally, a Life Cycle Cost Assessment (LCCA) revealed the economic viability and commercial potential of recycling. Future research endeavors should include several key initiatives to enhance the understanding and evaluation of EV battery recycling. Hydrometallurgy and pyrometallurgy processes should be incorporated into the GREET software analysis to better assess the environmental impacts of these recycling techniques. Lastly, future research should concentrate on quantifying both the environmental and economic costs associated with producing new batteries using recycled materials. This thorough approach would deepen the insights into the recycling process and assess the practicality and sustainability of using recycled components obtained from alternative processing techniques in second-use battery production.

In the United States, recycling companies have established factories in various states, such as Nevada, which includes companies like Redwood Materials, NV and American Battery Technology Co.; Texas, which includes companies like Ecobat; Massachusetts, which includes companies like Ascend Elements; and New Jersey, which includes companies like Princeton NuEnergy, to name a few. While the topic of this study revolves around the state of New Jersey, states in which recycling companies have factories are making a push towards making their energy mixes more environmentally friendly by increasing their reliance on renewable sources like wind and solar energy and decreasing their reliance on fossil fuels. Ganji et al. [72] denote that the U.S. electric sector is expanding its use of natural gas and renewable energies and moving away from the traditional reliance on coal and oil. The findings in this paper can safely be generalized to other states that house recycling companies; however, future research should still endeavor to study energy mixes in other states primarily to gain better insights on the current state of U.S. infrastructure and its suitability to allow for further transition towards renewables.

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