Erasmus Mundus Joint Master in Manufacturing 4.0 by Intelligent and Sustainable technologies

MASTER's Degree Thesis

Sustainability Assessment and Optimization of Aluminum Production for Electric Vehicle Manufacturing Using Life Cycle Assessment and Predictive Modeling.

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Abstract:

The automotive shift to EVs emphasizes sustainable materials, along with smart and digital manufacturing, to enhance efficiency and reduce environmental impact. Aluminum, valued for its light weight, strength, and recyclability, is vital for EVs, but it is highly energy-intensive. This underscores the need for detailed regional LCAs. This study examines the environmental impacts of aluminum production for EVs and addresses three key questions. It applies LCA to assess impacts and identify mitigation strategies. Objectives include quantifying impacts, pinpointing high-impact stages, analyzing regional differences, predicting GWP with a machine-learning dashboard, and comparing aluminum with alternative battery enclosure materials. These efforts support sustainability strategies, thus aligning with the 2030 SDG goals and 2050 net-zero goals.

Following ISO 14040 and ISO 14044, a cradle-to-gate life cycle assessment of 1,000 kg of primary and secondary aluminum in the North American and European contexts *was conducted using SimaPro v9.3.0.2, with Tableau and Power BI employed for visualization. The methods applied included TRACI, BEES+, CML-IA, and ReCiPe, with a focus on characterization results. Sensitivity analyses considered energy source and recycling rate. A GWP prediction dashboard was developed in Python to model emissions based on energy mix, region, and production parameters to support decision-making. For primary aluminum, total GWP is 8,294 kg CO_2 eq in North America (using TRACI method) and 6,638 kg CO_2 eq in Europe (using CML method). For secondary aluminum, GWP is 4,672 kg CO_2 eq in North America (using TRACI) and 4,552 kg CO_2 eq in Europe (using CML), indicating that recycling reduces GWP significantly. Smelting and electrolysis are the main hotspots, contributing 5,570 kg CO_2 eq in North America (TRACI) and 4,480 kg CO_2 eq in Europe (CML). A 120 kg aluminum enclosure has a lifecycle GWP of approximately 305 kg CO_2 eq, dominated by alumina refining and electrolysis. During comparison, aluminum outperforms steel, magnesium, and CFRPs in cost, weight reduction, and recyclability. Despite the need for further optimization, the dashboard demonstrated promising results. For example, it predicted 10,400 kg CO_2 eq for a 60% hydro and 40% coal energy mix in Asia for 1,000 kg of primary aluminum production, and this is consistent with benchmarks. In conclusion, findings highlight smelting and electrolysis as key mitigation targets, with energy sources driving aluminum's footprint. It becomes clear that recycling reduces impacts and supports circular economy principles, while variations in LCIA methods, units, dataset scope, and regional energy mixes complicate comparisons, emphasizing standardization. The dashboard aids in optimizing energy choices for sustainable production. Although aluminum production is energy-intensive, adopting renewable energy can lower impacts. Results guide industry and policymakers toward renewable energy transition, enhanced recycling, and standardized LCA metrics, with the dashboard supporting decarbonization decisions. Future work should explore low-carbon technologies, improved red mud management, CCS integration, digital twin simulations, broader social and economic assessments, and dashboard enhancements using diverse energy sources, real-time data, and validation against real-world emissions for greater accuracy and global applicability.*

Keywords: *electric vehicles, aluminum production, life cycle assessment, global warming potential, recycling, net-zero targets*

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