INTISARI

Kendaraan listrik (EV) merupakan salah satu solusi strategis dalam mendukung dekarbonisasi sektor transportasi di Indonesia, sejalan dengan target nasional menuju *net-zero emission*. Pertumbuhan adopsi EV yang pesat didorong oleh kebijakan insentif pemerintah, perkembangan infrastruktur, dan penurunan harga. Namun, meningkatnya penetrasi EV juga menimbulkan tantangan serius berupa akumulasi limbah baterai. Baterai EV yang mencapai akhir masa pakainya tidak hanya mengandung logam berat berbahaya yang dapat mencemari lingkungan, tetapi juga menyimpan nilai ekonomi karena kandungan mineral kritis seperti litium, nikel, kobalt, dan mangan. Oleh karena itu, proses daur ulang tidak hanya berfungsi sebagai upaya mitigasi risiko lingkungan, tetapi juga berpotensi menjadi sumber bahan baku sekunder yang mampu mengurangi ketergantungan pada sumber daya primer sekaligus menekan emisi karbon.

Penelitian ini mengembangkan model matematis berbasis *Mixed Integer Linear Programming* (MILP) untuk merancang sistem rantai pasok pengelolaan limbah baterai EV. Model ini berfokus pada penentuan jumlah, lokasi, serta distribusi fasilitas daur ulang dengan tujuan utama memaksimalkan profit dan meminimalkan emisi karbon, dengan mempertimbangkan aspek multi produk, multi periode, dan multi moda transportasi. Perhitungan dalam model mencakup *acquisition cost,* biaya tetap pembangunan, biaya daur ulang, biaya transportasi, emisi transportasi, dan emisi proses daur ulang.

Model yang dikembangkan berhasil menentukan lokasi fasilitas daur ulang secara konsisten dengan memperhitungkan sebaran limbah serta kedekatan terhadap target konsumen, yaitu produsen baterai dan industri hilir. Analisis sensitivitas menunjukkan bahwa peningkatan penetrasi pasar EV akan mendorong kenaikan profit, tetapi juga berimplikasi pada bertambahnya emisi. Dari sisi teknologi, baterai NMC terbukti jauh lebih menguntungkan dibanding LFP. Sementara itu, variasi harga material hasil daur ulang, biaya transportasi, maupun biaya proses hanya berdampak pada profitabilitas, sedangkan emisi relatif tetap stabil akibat penempatan lokasi fasilitas yang strategis.

Kata Kunci: Kendaraan listrik, daur ulang baterai, MILP, rantai pasok, *facility location allocation*, profit, emisi, optimasi

ABSTRACT

Electric vehicles (EVs) represent a strategic solution in supporting the decarbonization of Indonesia's transportation sector, in line with the national target of achieving net-zero emissions. The rapid growth of EV adoption has been driven by government incentives, infrastructure development, and declining price. However, the increasing penetration of EVs also presents a critical challenge in accumulation of end-of-life (EoL) batteries. EV batteries, once they reach the end of their lifespan, not only contain hazardous heavy metals that can contaminate the environment but also retain significant economic value due to critical minerals such as lithium, nickel, cobalt, and manganese. Consequently, recycling is not merely a means of mitigating environmental risks but also a strategic opportunity to establish a secondary supply of raw materials, reduce dependence on primary resources, and curb carbon emissions.

This study develops a mathematical model based on Mixed Integer Linear Programming (MILP) to design an integrated supply chain system for end-of-life (EoL) electric vehicle (EV) batteries. The model focuses on determining the optimal number, location, and distribution of recycling facilities, with objectives of maximizing profit and minimizing carbon emissions, while considering multi-product, multi-period, and multi-mode transportation aspects. The cost structure incorporated into the model includes acquisition cost, fixed facility construction cost, recycling cost, transportation costs, as well as emissions from transportation and recycling processes.

The developed model successfully determines the location of recycling facilities consistently by considering the distribution of waste and proximity to target consumers, namely battery manufacturers and downstream industries. Sensitivity analysis demonstrates that an increase in EV market penetration drives higher profit but also results in greater emissions. From a technological perspective, NMC batteries prove far more profitable than LFP batteries. Furthermore, variations in recycled material prices, transportation costs, and recycling costs primarily affect profitability, whereas emissions remain relatively stable due to the strategic placement of facilities.

Keywords: *Electric vehicles, battery recycling, MILP, supply chain, facility location allocation, profit, emissions, optimization*