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Evaluasi Life Cycle Assessment (LCA) Proses Daur Ulang Baterai Nickel Manganese Cobalt (NMC) Menggunakan Metode Carbothermal Reduction -Water Leaching
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INTISARI

Peningkatan penggunaan baterai *lithium-ion* (LIB) pada kendaraan listrik mendorong meningkatnya limbah baterai *end-of-life* (EoL) serta kebutuhan pemulihan material bernilai seperti litium, nikel, mangan, dan kobalt. Salah satu metode yang berpotensi digunakan untuk mendaur ulang baterai *Nickel Manganese Cobalt* (NMC) adalah *carbothermal reduction-water leaching*. Metode ini mengombinasikan proses reduksi termal pada suhu tinggi dengan proses pelindian menggunakan air tanpa penambahan bahan kimia asam. Penelitian ini bertujuan untuk menyusun *life cycle inventory* (LCI), mengevaluasi potensi dampak lingkungan, membandingkan kinerja lingkungan dengan proses hidrometalurgi, dan menganalisis sensitivitas terhadap perubahan sumber listrik. Penelitian menggunakan metode *Life Cycle Assessment* (LCA) dengan batasan sistem *grave-to-gate* dan *functional unit* sebesar 1 kg Li_2CO_3. Data inventori diperoleh dari literatur, data laboratorium, asumsi teknis, dan basis data Ecoinvent, kemudian dimodelkan menggunakan OpenLCA 2.4. Analisis dampak dilakukan menggunakan metode ReCiPe 2016 v1.03 *midpoint* (H). Hasil LCA menunjukkan nilai *climate change* sebesar 30,09 kg CO_2-eq/kg Li_2CO_3, *energy resources: non-renewable, fossil* sebesar 6,99 kg oil-eq/kg Li_2CO_3, *acidification* sebesar 0,09825 kg SO_2-eq/kg Li_2CO_3, *freshwater eutrophication* sebesar 0,04901 kg P-eq/kg Li_2CO_3, dan *water use* sebesar 0,12906 m^3/kg Li_2CO_3. Tahap *carbothermal reduction* menjadi salah satu kontributor utama terhadap dampak lingkungan, terutama karena konsumsi listrik. Setelah diperhitungkan *avoided burden* dari substitusi Li_2CO_3 *virgin*, nilai *climate change* pada skenario *baseline* menjadi 23,10 kg CO_2-eq/kg Li_2CO_3. Analisis sensitivitas dengan mengganti sumber listrik *baseline* menggunakan listrik terbarukan berbasis *hydropower* dan *solar tower* menunjukkan penurunan dampak pada empat kategori sebesar 84,75-97,69%. Pada kategori *water use*, *hydropower* meningkatkan dampak sebesar 175,38%, sedangkan *solar tower* menurunkannya sebesar 75,46%. Hasil tersebut menunjukkan adanya *trade-off* dalam pemilihan sumber listrik pada proses daur ulang baterai NMC.

Kata kunci: Baterai NMC, *Life Cycle Assessment*, *Carbothermal Reduction*, *Water leaching.*

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ABSTRACT

The increasing use of lithium-ion batteries (LIBs) in electric vehicles is driving a rise in end-of-life (EoL) battery waste and the need to recover valuable materials such as lithium, nickel, manganese, and cobalt. One potential method for recycling nickel-manganese-cobalt (NMC) batteries is carbothermal reduction-water leaching. This method combines a high-temperature thermal reduction process with a water leaching process without the addition of acidic chemicals. This study aims to develop a life cycle inventory (LCI), evaluate potential environmental impacts, compare environmental performance with hydrometallurgical processes, and analyze sensitivity to changes in electricity sources. The study employed the Life Cycle Assessment (LCA) method with a grave-to-gate system boundary and a functional unit of 1 kg Li_2CO_3. Inventory data were obtained from the literature, laboratory data, technical assumptions, and the Ecoinvent database, and were then modeled using OpenLCA 2.4. Impact analysis was conducted using the ReCiPe 2016 v1.03 midpoint (H) method. The LCA results showed a climate change value of 30.09 kg CO_2-eq/kg Li_2CO_3; energy resources: non-renewable, fossil at 6.99 kg oil-eq/kg Li_2CO_3; acidification of 0.09825 kg SO_2-eq/kg Li_2CO_3, freshwater eutrophication of 0.04901 kg P-eq/kg Li_2CO_3, and water use of 0.12906 m^3/kg Li_2CO_3. The carbothermal reduction stage is one of the main contributors to environmental impacts, primarily due to electricity consumption. After accounting for the avoided burden from substituting virgin Li_2CO_3, the climate change value in the baseline scenario becomes 23.10 kg CO_2-eq/kg Li_2CO_3. A sensitivity analysis replacing the baseline electricity source with renewable electricity from hydropower and solar towers showed a reduction in impacts across the four categories ranging from 84.75% to 97.69%. In the water use category, hydropower increased the impact by 175.38%, while solar tower power reduced it by 75.46%. These results indicate a trade-off in the selection of electricity sources for the NMC battery recycling process.

Keywords: NMC Batteries, Life Cycle Assessment, Carbothermal Reduction, Water Leaching.