Abstract

Climate change is pushing to rethink the paradigm of anthropic activities. From a society strongly based on fossil fuels and their exploitation, there are many initiatives that aim at a transition towards sustainable energy sources such as the European Green Deal and the European Taxonomy on sustainable finance that aim to promote sustainability and circular economy. Thanks to technological improvements over the past decade in electric storage systems, one of the initiatives is related to the electrification of road transport. It is precisely in this transition that lithium-ion batteries have found ample space thanks to their energy density, which allows the accumulation of energy in weights and volumes that are no longer prohibitive. Looking at global electric vehicle adoption trends, it is possible to identify an exponential growth in battery demand and consequently in the consumption of raw materials such as lithium, cobalt, manganese and nickel. The extraction of these raw materials has strong environmental and social impacts and the availability of these raw materials is limited. To reduce the environmental impacts related to the extraction of raw materials and the production of lithium-ion batteries and to make supply chains more sustainable and circular, it is possible to think of recycling processes that allow the recovery of materials contained within them. The current state of the art in lithium-ion battery recycling technology involves two types of metallurgical processes: pyrometallurgy and hydrometallurgy. The former involves the use of heat to alloy the metals of interest while the latter involves the use of organic/inorganic acids for the selective extraction of those metals. This Ph.D. thesis is one of the first available works on the topic that aims to assess the techno-economic and environmental sustainability of those lithium batteries recycling processes considering different chemistries, plant scales and an Italian scenario. This dissertation is organized in three Chapters.

Chapter I describes the state of the art about the application of LCA to lithium-ion batteries and electric vehicles through a critical review of papers published on the topic. The chapter points out the criticalities of LCA applied to the LIBs and to EVs. Furthermore, to highlight strengths and weaknesses of the assessment procedures adopted, the analysis of the reviewed studies was carried out also from a methodological point of view. From a practical perspective, some LCA results were analysed and discussed. From a methodological point of view, an in-depth analysis of the reviewed papers was carried out to highlight the different methodological approaches followed as well as the key aspects of variability based on the LCA phases (Goal and scope definition; Inventory Analysis; Life cycle Impact Assessment; Interpretation).

Chapter II deals with the technical confrontation among electric and thermal vehicles and the methodological confrontation between two LCA software tools: Simapro and Greet. The aim of this section is to firstly obtain data regarding the use phase of lithium-ion batteries to be used in the overall life cycle assessment in chapter III. Secondly the comparison aims to understand if the electrification of the mobility is the solution to reduce the environmental impacts related to the transportation sector. The comparison shows that electric vehicles are better than thermal one only when looking at Climate change impact categories. Performing a broader analysis shows that thermal vehicles represent non the worst solution.

Chapter III presents the assessment of the environmental and economic performances of all the lithium-ion batteries chemistries and recycling processes considered. About the environmental evaluation, Chapter III reports a comparative LCA two recycling processes (i.e., pyrometallurgical and hydrometallurgical ones) in Italy focusing on different lithium-ion battery chemistries that are the best solution available nowadays. The main aim of this LCA study was to identify how the recycling processes contribute to reduce environmental burden related to lithium-ion batteries production and exploitation. Both processes shows results in the same order of magnitude in the overall LCA analysis. For the economic analysis Chapter III shows the results in terms of the plant cost and related economic indicators such as the Return on Investment (ROI), the Discounted Cash

Flows (DCF) and the Net Present Value (NPV). The choice of the recycling process for lithium-ion batteries, indeed, in a cleaner production and sustainability perspective, should consider not only economical aspects but environmental performances of the whole system. The case study was set in Italy. Data for environmental analysis are obtained thanks to the technical design of battery recycling processes. The process is simulated using a spreadsheet in which adjustable parameters are plant capacity and battery chemistry. From an economic point of view the hydrometallurgical process performs better than the pyrometallurgical one.